Lakeland Industry and Community Association
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Acid Deposition Monitoring Program Expansion Committee

Meeting Minutes

Thursday, September 16, 2021
1:00 p.m. – 3:00 p.m.
LICA Boardroom and via Microsoft Teams

Present:	Heather Harms Desiree Parenteau Salim Abboud Amanda Avery-Bibo Sean Mercer Greg Wentworth Brent McGarry Clarence Makowecki Wally Qiu Jennifer O'Brien Leo Paquin Fin MacDermid Andrea Woods
Observers and Guests:	
Staff and Contractors:	Kristina Martel, LICA Executive Director Michael Bisaga, Manager, Environmental Monitoring Programs Eveline Hartog, LICA Administrative Professional
Regrets:	Larry Turchenek Lindsay Hollands Colin Cooke

1.0 CALL TO ORDER

Heather Harms Committee Chairperson, called the meeting to order at 1:00 p.m.

1.1 Introductions

1.2 Vision, Mission and Values

1.3 Approval of Agenda

#1 Moved by Amanda Avery-Bibo AND CARRIED that the September 16, 2021, Agenda be approved as presented.

2.0. POLICY REVIEW

2.1 ADMPEC Terms of Reference

The Committee reviewed the Acid Deposition Monitoring Program Expansion Committee (ADMPEC) Terms of Reference document.

#2 Moved by Desiree Parenteau AND CARRIED that the ADMPEC Terms of Reference be accepted as presented.

2.2 Policy Review

2.2.1 Policy 1.5 *Decision-Making Process*

The ADMPEC reviewed Policy 1.5 *Decision Making Process*.

2.2.2 Policy 1.14 *Confidentiality*

The ADMPEC reviewed Policy 1.14 *Confidentiality*. Committee members not already sitting on the LICA Board or other LICA Committee are requested to sign the Oath of Confidentiality and submit to lica2@lica.ca or executivedirector@lica.ca.

2.2.3 Policy 1.13 *Volunteer Hours & Sign-In Sheet*

The ADMPEC reviewed Policy 1.13 *Volunteer Hours & Sign-In Sheet.*

2.2.4 Policy 2.8 *Board and Committee Expenses and Remuneration*

The ADMPEC reviewed Policy 2.8 *Board and Committee Expenses and Remuneration.*

2.2.4.1 Expense Claim Form

The ADMPEC reviewed the LICA Expense Claim Form for members who collect a stipend. The Executive Director will complete and send this form to appropriate committee members for their sign-off at the conclusion of the meeting.

2.2.4.2 Direct Deposit Option

The ADMPEC members who collect a stipend were given the option to complete the Direct Deposit form noting that a VOID cheque will be required to accompany the form.

2.2.5 Committee Member Sign-On

The ADMPEC reviewed the Committee Member Sign-On form. All committee members not already sitting on the LICA Board or other LICA Committee are requested to complete the contact information and submit to lica2@lica.ca or executivedirector@lica.ca. Members eligible for stipends must also provide their SIN, date of birth, and CPP status.

3.0 NEW BUSINESS

3.1 Project Overview

3.1.1 AER Approval Conditions

The Manager of Environmental Monitoring Programs reviewed the Alberta Energy Regulator (AER) approval conditions related to this project which were in response to increased Sulphur dioxide emissions from the Cenovus Foster Creek facility and its effects in the region. With relatively sparse information on deposition in this area, it is prudent to begin gathering data on deposition effects on air, soil, and water; the AER noted that approval conditions related to acid deposition will likely become regionally commonplace in order to address this gap. The AER approval conditions do allow for some flexibility on how the plan will be implemented.

3.1.2 Timeline and Deliverables for Monitoring Plan

The Committee was informed that Phase 1 of the plan should be completed by December 31, 2021. The plan was originally supposed to be developed by June 2021 however there were two reasons for the delay: the final version of the Alberta Acid Deposition Management Framework has not been released and Environment and Climate Change Canada (ECCC) modelling work has been postponed. The Framework and ECCC modelling are seen as two key inputs for the development of the monitoring plan. To prevent further delays, the Committee will develop the plan using current Framework policies as well as available emissions and modelling data.

Initials

3.2 Review Information Data, and Other Input Sources for Monitoring Plan Development

3.2.1 Alberta Acid Deposition Management Framework (ADMF)

The new ADMF is still under internal review by Alberta Environment and Parks (AEP). Compared to the existing "multi-tiered" Framework, the new ADMF simplifies the approach to management with emphasis on the most sensitive receptors and using modelling to inform monitoring and subsequent management actions. One of the most useful elements of the new ADMF (with respect to the development of the LICA monitoring plan) is the critical load maps for soils. Sample critical load maps from the new AMDF were reviewed by the Committee.

3.2.2 Oil Sands Monitoring (OSM) Environmental Effects Monitoring (EEM)

The Committee was provided with background information on the OSM Program; OSM is a multi-stakeholder program lead by project leads and a Technical Advisory Committee which were all required to adopt the EEM Framework.

The Committee was informed that OSM does have policies to help with the development of the acid deposition monitoring plan. The Committee reviewed the attached EEM slides which shows how surveillance is used and how the development of the LICA Program may align with existing OSM monitoring and modelling activities. EEM has multiple tiers and notionally (with respect to acid deposition), LICA is currently near the second tier of the six-tiered framework; there is currently some baseline data and the ADMPEC is working towards developing and implementing core monitoring. This data may be used to validate the modelling results.

3.2.3 Past Studies on Acidification in the Cold Lake Oil Sands Region

The attached document provided to the Committee illustrates LICA's exploratory study into acidifying emissions and potential acidification affects in the Cold Lake area. Data collected by multiple organizations, such as ALMS, Industry Partners, and AEP, were used to inform the study. One of the key outcomes of this study was the phased implementation of LICA's soil acidification monitoring program.

The Committee was reminded that it would be important to align monitoring activities between LICA and the Wood Buffalo Environmental Association (WBEA). WBEA is currently expanding their deposition monitoring network along their southern border (shared with LICA's northern border); it will be important to ensure the monitoring plans are complementary and the data are comparable. It was questioned if there was also an information gap for critical loads within the Primrose Lake and Canoe Lake areas and the Manager of Environmental Monitoring Programs informed the Committee that we are looking for these gaps in the data sources in developing our monitoring plan.

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Initials

A Committee member posed the question of whether there has been an overall profile change since the 2007 study. The Manager of Environmental Monitoring Programs responded by stating that acid input numbers may have changed, and we could potentially extract this information from more recent emissions data. The overall spatial pattern of deposition is likely like 2007 however the intensity/amount of deposition has likely changed.

3.2.4 Regional Acid Deposition Modelling Studies

The Manager of Environmental Monitoring Programs informed the Committee that ECCC is the keeper of the GEM-MACH model; the 2018 study reviewed at the meeting, although dated, aligns well with the acid deposition management framework, as they modelled areas where critical loads were expected to be exceeded if all things remain the same. The GEM-MACH modelling data set is also likely complimentary to what Cenovus commissioned for its recent amendment application.

The AEP member indicated that the model runs 2017-18 from Environment Canada will be done in the next few weeks and is hoping to run the GEN-MACH model every year.

3.2.5 Acid Deposition Monitoring in the Athabasca Oil Sands Region

The Manager of Environmental Monitoring Programs apprised the Committee that, although LICA uses data to produce maps using the passive sampling network, the Wood Buffalo area has a very comprehensive program that monitors acid deposition on a variety of parameters. He advised the Committee that their methods would be a good thing to consider when we develop the Cold Lake Region monitoring plan.

3.2.6 Regional Soil Acidification Monitoring Results Overview

There is evidence that acidification is occurring at AEP's soil monitoring site along the western shore of Cold Lake; this site has been in operation since the 1980s. LICA's own soil acidification monitoring began in 2010 with the implementation of 3 plots sampled at staggered 4-year intervals. Data from LICA's program also shows evidence of acidification at 2 of the sites. Sampling interpretations are challenging since there are only results from 3 monitoring events at each site. LICA is currently in discussion with ECCC on how this monitoring data can be used to complement GEM-MACH modelling.

The Committee requested that the Manager of Environmental Monitoring Programs develop an overlay of the different data sets presented at the meeting.

3.2.7 Approaches to Surface Water Acidification Monitoring Site Selection

The publication presented to the Committee will help in identifying which lakes to monitor for the acid deposition monitoring program. Surface water sensitivity to acidification and acidification effects is a regional data gap; we may be able to use ECCC modelling and data collected by other organizations (e.g., industry, indigenous groups)) to inform us on priority lakes.

3.3 Identify Other Sources

3.3.1 Round Table on Other Considerations, Information and Data Sources

A question was asked regarding policy or frameworks on surface water critical loads; this type of information would be helpful in identifying acid sensitive lakes. In response, AEP indicated that there were no plans for this in the future. It was identified that there is a gap in surface water critical loads, and it would be beneficial to consider other usage of lakes, either recreational or culturally-specific, like fishing, indigenous traditions, etc. The Committee was advised that the survey results from LICA's IWMP Committee could assist in filling in this information gap.

The Committee also wondered if AEP was asked to share their data and in reply, yes, they have shared their data, part of which includes the GEM-MACH model results. This is an opportunity for LICA to do something similar in the Cold Lake region by using the existing surface water monitoring modelling what was done in the Athabasca region. Some Committee members noted that it is important to engage with WBEA on their expansion to make sure our monitoring programs are complimentary and can be achieved through the OSM Technical Advisory Committee, in which both organizations participate.

The AEP member did inform the Committee that there would be a meeting of the Technical Advisory Committee next week in which acid deposition monitoring would be discussed; the Manager of Environmental Monitoring Programs will be attending.

The Manager of Environmental Monitoring notified the Committee that he would like to develop a section on the LICA website to house information on the Acid Deposition Monitoring Program Expansion and associated materials. This would mirror the current LICA IWMP section on the website.

It was requested of the Committee that should they have any other thoughts regarding other considerations and data sources they could email their suggestions via the Committee distribution list, which will be shared by the LICA Administration Professional.

3.4 Next Steps and Proposed Approach for Monitoring Plan Development

3.4.1 Identification of Data and Information Gaps

Any gaps currently identified will be listed in the Action Items document which will accompany the minutes.

3.4.2 Desktop Overlay of Input Sources: Site Selection Screening

It was inquired what the target of the committee was. The Manager of Environmental Monitoring Programs explained that there were 3 phases to this committee:
1) development of our plan by December 31, 2021.
2) work on implementing the plan.
3) create the composite out puts/overlays.

The Manager of Environmental Monitoring Programs will obtain the monitoring methodologies from OSM and WBEA. He will also combine the information provided from this meeting to identify any gaps and will present maps with information overlays at the next Committee meeting. No decisions were made at this time.

4.0 UPCOMING MEETING DATES

4.1 Board Meeting – September 23, 2021

4.2 Governance Committee Meeting – September 29, 2021

4.3 LICA Annual General Meeting – October 6, 2021

4.4 Next ADMPEC Meeting

The next ADMPEC meeting will be on Thursday, October 21, 2021, from 1:00 – 3:00 p.m.

5.0 ADJOURNMENT

Meeting adjourned at 2:50 p.m.

#4 Moved by Andrea Woods AND CARRIED that the meeting be adjourned.

Approved on: ______________________________
Date

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Signature

LICA

Lakeland Industry and Community Association

Acid Deposition Monitoring Program Expansion Committee (ADMPEC)

Terms of Reference

The Lakeland Industry and Community Association (LICA) formed an Acid Deposition Monitoring Program Expansion Committee (ADMPEC) to assist in the development and oversight of the expansion of LICA's Acid Deposition Monitoring Program (the Program); the expansion of the Program will be completed in phases and this Terms of Reference applies to Phase One of the ADMPEC. Phase One of the expansion will address development of an acid deposition monitoring plan (the Plan) to meet the needs of new regional regulatory compliance acid deposition monitoring and reporting requirements (Appendix A). Phase Two will address implementation of the Plan. Phase Three will address further enhancement of the Program to implement a complete regional approach to acid deposition monitoring and reporting. The ADMPEC is an ad-hoc committee of LICA which shall report its activities and requests to the Board for approval. The ADMPEC is supported by representation from industry, government, indigenous communities and the public, which allows for a diverse insight, expertise, and support for the development of recommendations for acid deposition monitoring.

1.0 Purpose

1.1 To support the LICA Board's Vision and Mission.

1.2 To operate within LICA Board approved work plans and budget and be accountable to the LICA Board of Directors regarding oversight of the implementation, operation, reporting, and management of the ADMPEC.

1.3 To make recommendations related to messaging about acid deposition monitoring issues, goals, objectives, targets, recommendations and other items related to the AMDPEC.

1.4 Deliver relevant, accurate, reliable, and credible data and information that addresses stakeholder needs and priorities.

1.5 To address Phase 1 objectives by ~~June 1, 2021~~ **December 30, 2021** and develop a monitoring plan that meets regulatory compliance needs including:

(a) for air:

(i) a plan to monitor dry and wet deposition;

(b) for soil:

(i) identification of soils that are sensitive to acid deposition and will likely receive aerial deposition inputs;

(ii) a plan to monitor soil quality at locations representative of the soils identified in (b) (i);

(iii) a description of how soil quality data collected under this program will be used to determine potential acidification effects under periods of increased sulphur dioxide emissions;

(c) for water:

(i) a summary of existing water quality data collected to date and analysis of the results;

(ii) a plan to monitor water quality for water bodies which will likely receive aerial deposition inputs;

(iii) identification of local water bodies that are sensitive to acidification;

(iv) a description of how water quality data collected under this program will be used to determine potential acidification effects under periods of increased sulphur dioxide emissions;

(v) a plan to develop triggers for further enhanced surface water quality monitoring to determine impacts of aerial deposition inputs;

(d) reporting schedule for monitoring activities conducted for (a) through (c)

2.0 Operating Principles

2.1 The ADMPEC will follow LICA's Vision and Mission and will operate within LICA's policies in support of the Strategic Plan.

2.2 The ADMPEC will meet monthly at a minimum.

2.3 The ADMPEC will report to the Board, and when needed, be responsible for facilitating Board discussion regarding their recommendations.

2.4 The ADMPEC will ensure that the Plan effectively addresses regulatory compliance needs.

2.5 Members will actively participate and contribute to regular meetings and the group's work.

2.6 Members will communicate with employers, organizations, and stakeholders they represent about ADMPEC's objectives, priorities and accomplishments, as well as any issues that may need to be resolved.

2.7 Meetings will be documented with summary notes, decision records and action logs to be issued within a reasonable time for review by the ADMPEC prior to the final issue. These will be made available to all ADMPEC members as part of the review process.

2.8 The ADMPEC will strive for consensus recommendations and decisions. If it becomes clear that the ADMPEC cannot make a consensus recommendation, the recommendation of the majority and the non-consensus position(s) will be presented for the Board to decide.

2.9 Outside expertise may be invited to contribute as required as directed by the Technical Staff.

3.0 Membership

The membership of the ADMPEC is made up of the Manager of Environmental Monitoring Program, Executive Director, Manager of Environmental Programs, core members, and resource members. Core members are selected by the sectors that they represent or are appointed by the LICA Board. Resource members are included by invitation of the Manager of Environmental Monitoring Programs or Executive Director.

3.1 The ADMPEC chair shall be a Board Director appointed by the Board and must be present at all committee meetings.

3.2 The Chair of the Board may attend as ex-officio.

3.3 Community members may be appointed by the Board, and shall be eligible for remuneration and expenses according to LICA policy.

3.4 The Board may request additional members from among Industry, Government, and Non-Government organizations to be appointed from their respective sectors and may be eligible for remuneration and expenses according to LICA policy.

3.5 The core membership will be Board approved.

3.6 Core Membership

3.6.1 Alberta Environment and Parks (AEP) – Sector nominated

3.6.2 Alberta Energy Regulator (AER) – Sector nominated

3.6.3 Industry, Oil & Gas – Sector nominated

3.6.4 Agriculture – Sector nominated

3.6.5 LICA Board Directors – Board appointed

3.6.6 Indigenous Communities – Sector nominated

3.6.7 Environmental Organizations & Special Interest Groups – Sector nominated

3.6.8 Municipal Governments – Sector nominated

3.6.9 Community Members – Board appointed

3.6.10 Scientific and Academic Organization & Institutions – Sector nominated

3.7 Resource Membership

3.7.1 Third-Party Contractors

3.7.2 Data and Reporting Specialist, LICA

3.7.3 Fisheries and Oceans

3.7.4 Environment Canada

3.7.5 Government Health Representatives

3.7.6 Industry Representatives

3.7.7 Education and Outreach Committee, LICA

3.7.8 Technical Working Group, LICA

3.7.9 AEP Technical Monitoring Expertise

3.7.10 Agriculture and Agri-food Canada

3.7.11 Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC)

3.7.12 Others as required

4.0 Meetings

4.1 Committee meetings will comply with Policy 1.6 Board and Committee Meetings.

5.0 Roles and Responsibilities of the ADMPEC and its Members

5.1 ADMPEC Members (in general)

5.1.1 Actively participate in meetings and provide technical knowledge and support, as well as the viewpoints of the sector, stakeholder and profession they represent.

5.1.2 Develop monitoring and reporting recommendations for acid deposition.

5.1.3 Assess material monthly and make recommendations as required regarding the development of the Plan.

5.1.4 Provide support for planning future phases of the Program.

5.1.5 Keep the development of the Plan in alignment with LICA's Strategic Plan and budget.

5.1.6 Engage other expertise as needed from member organizations and/or others.

5.1.7 Consider the application of Quality Assurance and Quality Control functions as required by LICA's Quality Assurance Program in the development of the Plan.

6.0 Specific ADMPEC Member Roles

6.1 Manager of Environmental Monitoring Programs

6.1.1 Act as ADMPEC Vice-Chair to convene meetings and prepare agendas.

6.1.2 Report to the LICA Board as a representative of the ADMPEC.

6.1.3 Keep the Oil Sands Monitoring Secretariat (OSMS) informed of the development of the Plan. Seek funding from OSMS for Phase 2 (implementation of the Plan) and Phase 3 (enhancement of the regional Program).

6.1.4 Ensure the ADMPEC operate cost-effectively and within budget.

6.2 Manager of Environmental Programs

6.2.1 Participate in meetings and provide watershed technical expertise in the development of the Plan

6.2.2 Ensure alignment with the Integrated Watershed Management Plan.

6.3 Executive Director

6.3.1 Advise the ADMPEC on LICA policies as required.

6.3.2 Act as a liaison between other LICA committees and the ADMPEC.

6.3.3 Maintain collaborative relationships with stakeholders.

6.4 Education & Outreach Coordinator

6.4.1 Advise the ADMPEC on best practices to engage with the public for input on the Plan.

6.4.2 Assist in coordinating and delivering outreach activities to engage the public, such as forums.

6.4.3 Promote the development and progress of the Plan to the public and disseminate materials as they become available.

6.5 Board Director

6.5.1 Act as a liaison between the LICA Board and ADMPEC.

6.6 Administration Staff

6.6.1 Arrange for minute taking and distribution of minutes and other meeting materials.

6.7 Industry Member(s)

6.7.1 Understand and represent their sector's interests and regulatory requirements.

6.7.2 Fund Phase One activities of the ADMPEC as required.

6.8 Agriculture Representative(s)

6.8.1 Understand and represent their sector's interests and regulatory requirements.

6.9 Community Member(s), Environmental Organization(s) & Special Interest Group(s)

6.9.1 Represent the public interest, bringing a local perspective to the Plan.

6.9.2 Ensure that the programs are operated in a transparent manner.

6.10 Indigenous Representative(s)

6.10.1 Ensure Traditional Environmental Knowledge is recognized and integrated into the Plan.

6.11 AEP and AER Representative(s)

6.11.1 Provide advice and technical input regarding the operations and design of the Plan.

6.11.2 Provide a link to other Government of Alberta and Regulatory staff and resources.

6.11.3 Act as a liaison regarding regulatory requirements, policy development, and approvals.

6.12 Scientific and Academic Organization & Institution(s)

6.12.1 Provide advice and technical input regarding the operations and design of the Plan.

6.13 Third-Party Contractor(s)

6.13.1 Perform duties according to approved standards and protocols as per their current contracts.

7.0 Evaluation

7.1 The ADMPEC shall review its Terms of Reference and evaluate its objectives annually.

Appendix A:

Amending Approval: 68492-01-06

Alberta Energy Regulator

Environmental Protection and Enhancement Act

AMENDING APPROVAL

ALBERTA ENERGY REGULATOR

ENVIRONMENTAL PROTECTION AND ENHANCEMENT ACT
R.S.A. 2000, c.E-12, as amended.

APPROVAL NO.: 68492-01-06

APPLICATION NO.: 027-68492

EFFECTIVE DATE: October 18, 2019

EXPIRY DATE: May 31, 2022

APPROVAL HOLDER: Cenovus Energy Inc.

Pursuant to Division 2, of Part 2, of the *Environmental Protection and Enhancement Act*, R.S.A.2000, c.E-12, as amended, the approval for the following activity:

Foster Creek enhanced recovery in-situ oil sands or heavy oil processing plant and oil production site

is amended as per the attached terms and conditions, and Schedules I to XI.

Shay Dodds, P.Eng.
Manager, In Situ South, Authorizations Branch
Alberta Energy Regulator

October 18, 2019

Environmental Protection and Enhancement Act Approval No. 68492-01-00 is hereby amended as follows:

1. Conditions 3.18, 3.19, 3.20 and 3.21 are deleted and the following is substituted:

3.18 Notwithstanding Table 3.1, the sulphur dioxide emissions from the plant shall not exceed 7.0 tonnes per day (on a calendar day basis) for the period commencing from October 18, 2019 and ending on December 31, 2020.

3.19 Notwithstanding Table 3.1 and Condition 3.18, the approval holder may bypass one (1) non-regenerative sulphur unit train for repair and maintenance provided that:

(a) a minimum uptime of 90% is maintained for each non-regenerative sulphur unit on an annual basis, for the period commencing from February 13, 2019 and ending on December 31, 2020;

(b) the minimum sulphur recovery requirements as outlined in Table 1 of ID2001-03: Sulphur Recovery Guidelines for the Province of Alberta is met except for the period commencing from February 13, 2019 and ending on December 31, 2020; and

(c) the sulphur dioxide emissions from the plant shall not exceed 8.0 tonnes per day (on a calendar day basis) for the periods when the sulphur unit train is bypassed for repair and maintenance, commencing from October 18, 2019 and ending on December 31, 2020;

unless otherwise authorized in writing by the Director.

3.20 In the event that a non-regenerative sulphur unit is bypassed, the approval holder shall provide in the monthly Air Emission Report to the Director, the following:

(a) a description of the events or circumstances that led to the bypass; and

(b) an outline of the action taken to control the magnitude and duration of this event(s).

3.21 The approval holder shall operate a continuous ambient air monitoring station and monitor ambient air parameters as specified in TABLE 3.4, unless otherwise authorized in writing by the Director.

3.22 In addition to the monthly and annual reporting requirements in TABLE 3.2 and TABLE 3.3, the approval holder shall report to the Director the results of the ambient air parameters as required in TABLE 3.4, unless otherwise authorized in writing by the Director.

TABLE 3.1: AMBIENT AIR MONITORING AND REPORTING

MONITORING STATION	PARAMETER	MONITORING PERIOD	REPORTING	
			MONTHLY	ANNUALLY
One continuous ambient air monitoring station, as per *Air Monitoring Directive*	Sulphur dioxide concentrations, wind speed and wind direction	Continuously, starting from February 13, 2019 to December 31, 2020	Yes	Yes

4. The following is added after Condition 3.22:

3.23 The approval holder shall submit an Acid Deposition Monitoring Program proposal to measure aerial deposition effects on aquatic and terrestrial ecosystems to the satisfaction of the Director on or before March 31, 2020, unless otherwise authorized in writing by the Director.

3.24 The Acid Deposition Monitoring Program proposal shall include, at a minimum, all of the following:

(a) for air:

(i) a plan to monitor dry and wet deposition from project activities;

(b) for soil:

(i) identification of soils that are sensitive to acid deposition and will likely receive aerial deposition inputs from project activities;

(ii) a plan to monitor soil quality at locations representative of the soils identified in (b) (i);

(iii) a description of how soil quality data collected under this program will be used to determine potential acidification effects under periods of increased sulphur dioxide emissions;

(c) for water:

(i) a summary of existing water quality data collected to date and analysis of the results;

(ii) a plan to monitor water quality for water bodies which will likely receive aerial deposition inputs from project activities;

(iii) identification of local water bodies that are sensitive to acidification;

(iv) a description of how water quality data collected under this program will be used to determine potential acidification effects under periods of increased SO_2 emissions;

(v) a plan to develop triggers for further enhanced surface water quality monitoring to determine impacts of aerial deposition inputs;

(d) reporting schedule for monitoring activities conducted for (a) through (c); and

(e) any other information requested in writing by the Director.

3.25 If the Acid Deposition Monitoring Program proposal is found deficient by the Director, the approval holder shall correct all deficiencies identified in writing by the Director, by the date specified in writing by the Director.

3.26 The approval holder shall implement the Acid Deposition Monitoring Program as authorized in writing by the Director.

3.27 The approval holder shall only implement changes to the Acid Deposition Monitoring Program as authorized in writing by the Director.

Shay Dodds, P.Eng.
Manager, In Situ South, Authorizations Branch
Alberta Energy Regulator

October 18, 2019

1.5 DECISION-MAKING PROCESS

INTENT:

The Board and committee members make sound decisions which align with the Association's Vision, Mission and Values.

1.5.1 DIRECTIVES:

1.5.1.1 The Board has adopted a consensus model of decision-making for Board and committee meetings.

1.5.1.2 Annual General and Special General Meetings shall follow Robert's Rules of Order.

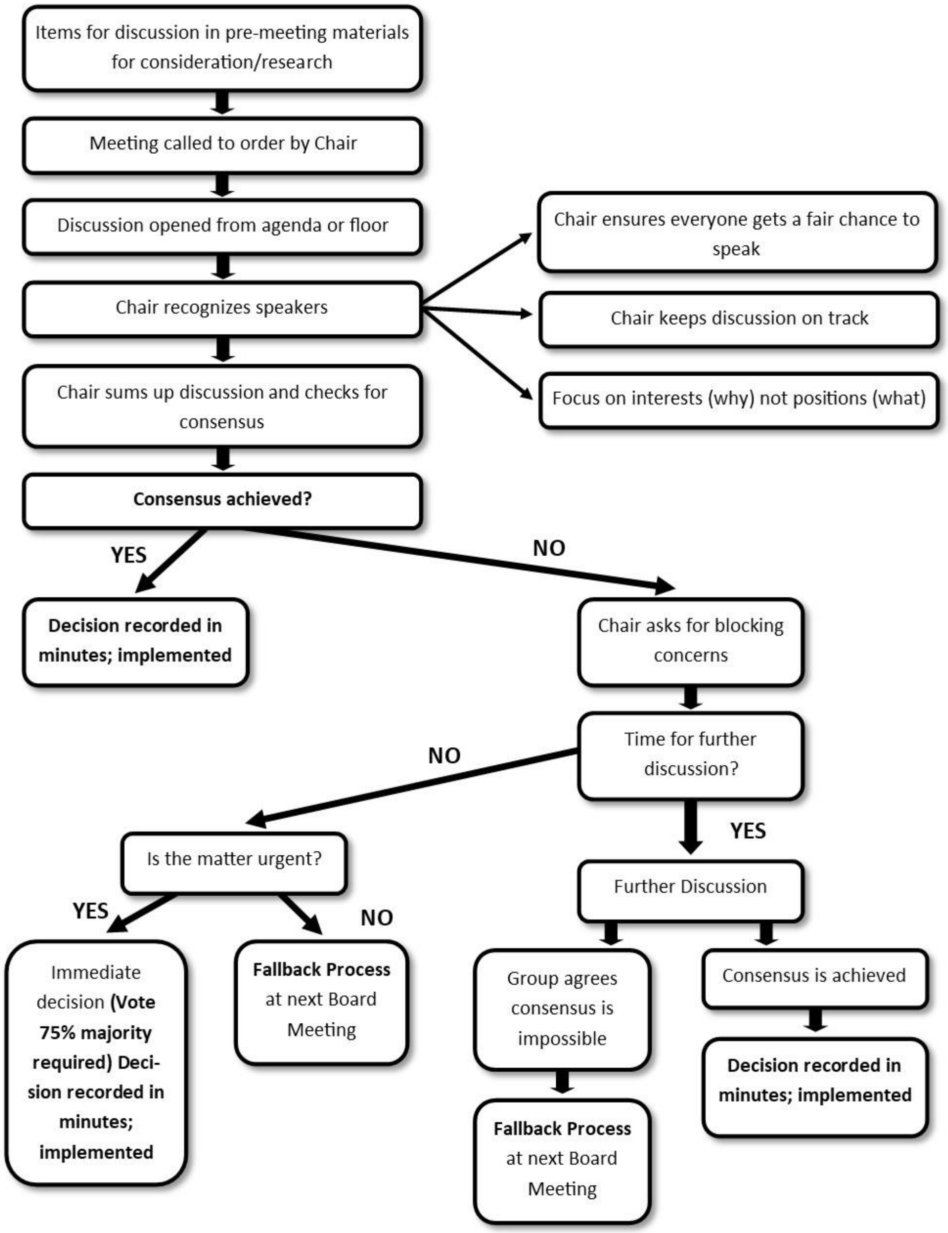
1.5.2 IMPLEMENTATION:

1.5.2.1 At the first meeting of the Board and of each committee, the Chair shall indicate that a consensus decision-making process is to be followed as outlined in Appendix A: LICA's Board and Committee Consensus Decision-Making Process.

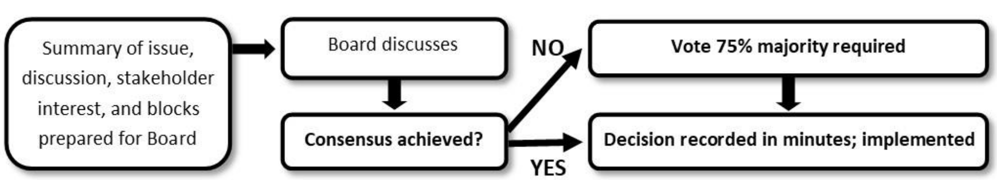
1.5.2.2 Training and guidance in the use of the consensus decision-making process shall be made available to all Board and committee members.

Review Dates: August 25th, 2004; June 12, 2017; September 5, 2018
Approval Dates: November 29th, 2001; September 7, 2017; September 13, 2018

LICA'S BOARD AND COMMITTEE CONSENSUS DECISION-MAKING PROCESS



FALLBACK PROCESS



Review Dates: August 25th, 2004; June 12, 2017; September 5, 2018
Approval Dates: November 29th, 2001; September 7, 2017; September 13, 2018

1.14 CONFIDENTIALITY

INTENT:

Board and committee members may become aware of confidential information during their involvement with LICA. Under Common Law and the Freedom of Information and Protection of Privacy Act (FOIP) such information must remain confidential and may not be used for personal gain.

1.14.1 DIRECTIVES:

1.14.1.1 With regard to confidentiality of information, Board and committee members shall at all times be governed by the Societies Act, Common Law, FOIP and LICA's Vision, Mission, Values, bylaws and policies.

1.14.2 IMPLEMENTATION:

1.14.2.1 LICA may need to collect personal information about an individual or organization. Such information shall be handled in a secure and confidential manner. LICA's records management practices shall be in accordance with FOIP https://www.servicealberta.ca/foip/, and as defined in Policy 2.6-Records Retention.

1.14.2.2 Only the Officers and Executive Director shall have access to confidential files.

1.14.2.3 LICA Board and committee members shall annually sign an Oath of Confidentiality (appended) at the first meeting after their election or appointment, in accordance with Policy 1.6.

1.14.2.4 *In camera* proceedings must remain confidential.

1.14.2.5 Information shall remain confidential during and after LICA tenure, unless released by the owner of the information.

Review Dates: **September 27, 2006, May 8, 2008, June 2, 2011; June 26, 2017, November 26, 2018**
Approval Dates: **September 27, 2006, May 8, 2008, June 2, 2011; September 7, 2017; December 13, 2018**

LAKELAND INDUSTRY AND COMMUNITY ASSOCIATION

LICA – Environmental Stewards

BOARD AND COMMITTEE MEMBER OATH OF CONFIDENTIALITY

I do solemnly declare that I will not disclose any confidential information of any kind that comes to my knowledge respecting any member, employee, contractor or associated organization of the Lakeland Industry and Community Association (LICA) through my involvement with LICA.

I acknowledge that this declaration shall remain in force both during and after my tenure as a LICA member.

I understand that if I choose to disclose confidential information, I may be liable for prosecution for breach of confidentiality, and that LICA shall not indemnify me for any fines or awards of damages against me.

I have read this declaration in its entirety and understand the contents of this declaration.

______________________________ ______________________________

Signature of Witness Signature of Board or committee member

______________________________ ______________________________

Name of Witness (Print) Name of Board/committee member (Print)

____

Date

Review Dates: **September 27, 2006, May 8, 2008, June 2, 2011; June 26, 2017, November 26, 2018**
Approval Dates: **September 27, 2006, May 8, 2008, June 2, 2011; September 7, 2017; December 13, 2018**

1.13 VOLUNTEER HOURS

INTENT:

The Board recognizes volunteer time by members is critical to the success of LICA. These hours require tracking to use as a "contribution in kind", when applying for grants or direct government funding.

1.13.1 DIRECTIVES:

1.13.1.1 Board and committee members are requested to track hours spent on LICA activities. (Board, committee and special meetings including preparation, business, outreach, events, workshops and associated travel)

1.13.2 IMPLEMENTATION:

1.13.2.1 The Executive Director will keep an accounting of total volunteer hours.

1.13.2.2 Individuals are responsible for tracking their volunteer hours on the meeting and/or event sign-in sheet.

1.13.2.3 Any volunteers who require detailed information on hours or duties are expected to keep such logs for themselves. The Executive Director will verify the total number of hours submitted, if requested.

Review Dates: October 27, 2004; Sep 2006; May 2009, February 27, 2017; June 26, 2017, November 26, 2018
Approval Dates: September 29, 2004; Sep 27, 2006; May 28, 2009; April 24, 2017; September 7, 2017; December 13, 2018

2.8 BOARD AND COMMITTEE EXPENSES AND REMUNERATION

INTENT:

Board and appointed committee members who represent the community sector will be reimbursed for pre-approved expenses and time spent on LICA activities. Industry and government members' time is covered by their employers.

2.8.1 DIRECTIVES:

2.8.1.1 **Board and committee members shall endeavour to keep expenses and claims to a minimum.** Pre-approved stipends and expenses shall be paid where participants are providing service as a LICA Board or committee member.

2.8.2 IMPLEMENTATION:

2.8.2.1 LICA Board and committee members attending an approved conference may claim stipend for conference days only.

2.8.2.2 Elected and appointed community members will be paid stipends and be reimbursed for expenses at the following rates:

- Meetings, events, and training - $ 130.00
- Round-trip mileage in accordance with the Alberta Government rate in effect at the time of LICA's annual organizational meeting.
- Parking as per itemized receipt
- Meal allowances, which include gratuity and GST; no receipts required:

  Breakfast - $13.00

  Lunch - $16.00

  Dinner - $22.00
- Accommodation as per itemized receipt

2.8.2.3 The Board Chairperson will receive a flat rate of $100 per month, over and above any stipends paid.

2.8.2.4 The Officers may receive stipends, upon approval of the Board, for additional duties associated with their roles.

2.8.2.5 While there is an expectation of attendance for the complete meeting, event, or training, stipends will be paid only if individuals remain for the major portion of the meeting, event, or training.

Review Dates: Jan 2006; Sep 2006; Oct 2007; May 2008; Sep 2008; Jan 2010; Jun 2010; May 2011; May 3, 2012; April 3, 2014; October 2, 2014; June 26, 2017; January 8, 2018; April 16, 2018; December 8, 2020
Approval Dates: Jan 24, 2002; Sep 27, 2006; Oct 03, 2007; Feb 04, 2010; Sep 02, 2010; June 2, 2011; May 3, 2012; Oct 02, 2014; September 7, 2017; April 12, 2018; December 17, 2020

2.8.2.6 An individual will receive one stipend per committee event, meeting, or training per day.

2.8.2.7 Mileage will be paid to individuals travelling to and from a meeting, event, or training session related to LICA business. LICA reserves the right to verify mileage charges prior to approval.

2.8.2.8 Where two or more individuals carpool to a meeting, training, or event, only the person whose vehicle makes the trip will be reimbursed for mileage.

2.8.2.9 Industry representatives will be eligible for reimbursement of expenses as pre-approved by the Board of Directors.

2.8.2.10 Other members may be approved to attend meetings, conferences, etc., with reimbursement at the discretion of the Board.

2.8.2.11 Reimbursement/payment will be made after expenses are incurred and receipts and invoices are submitted and approved.

2.8.2.12 Claims other than mileage, meals and stipends require original itemized receipts.

2.8.2.13 All expense and remuneration claims will be reviewed and approved by the Executive Director.

2.8.2.14 Where anticipated expenses are known (e.g., conference fees), the Executive Director may pay for them with the LICA credit card.

Lakeland Industry & Community Association
P.O. Box 8237, Bonnyville AB T9N 2J5
Phone: (780) 812-2182 Toll Free: 1-877-737-2182 Fax: (780) 812-2186 E-Mail: lica2@lica.ca Website: www.lica.ca

Receipts must be attached to expense form

EXPENSE CLAIM

NAME: ______________________________

ADDRESS: ____ **POSTAL CODE:** ___________

Date	Meeting Description	Travel To	KM's	Other	Stipend	Chair Approval
TOTALS						

Authorized By:

Stipend $ _______________ **Executive Director** ________________________

KM ________ @ **0.59** $ _______________

Other Travel Expenses $ _______________
(please attach receipts)

TOTAL CLAIM $ _______________ **Signature of Member** ________________________

Includes: travel, meetings, meeting prep/follow-up, tours, conferences, project implementation, services in kind, donations, other

Lakeland Industry & Community Association
P.O. Box 8237, Bonnyville AB T9N 2J5
Phone: (780)812-2182 Toll Free: 1-877-737-2182 Fax: (780)812-2186 E-Mail: lica2@lica.ca Website: www.lica.ca

Receipts must be attached to expense form

6.8 Expenses and Honoraria

Intent:

Board and appointed committee members who represent the community sector are not intended to be out of pocket on LICA's behalf, and so will be reimbursed for pre-approved expenses and time spent on LICA activities. However, it is not intended that LICA stipends become a regular "job" revenue for committee and Board volunteers. Industry and government members' time is covered by their employers, since their LICA activities are employment-related. Board and Committee members shall endeavour to keep expenses and claims to a minimum.

Guidelines:

1. Elected and appointed Community Representatives to the LICA Board and LICA Committee shall be reimbursed for pre-approved meeting and expenses related to:

1.1	Approved Meetings, events, and training	- $130.00 per meeting
1.2	Roadtrip mileage	- 59.0 cents per km up to 5,000 km & 53.0 cents over 5,000 km
1.3	Parking as per receipt	
1.4	Meal Allowances (no receipt required)	- $13.00/Breakfast
		- $16.00/Lunch
		- $22.00/Dinner
1.5	Accomadation as per receipt	

EFFECTIVE DATE: **December 17, 2020**

2. Industry Representatives will be eligible for reimbursement of expenses as approved by the Board of Directors.

3. Representatives will be reimbursed after expenses are incurred and receipts and invoices submitted and approved accordingly.

Procedure:

1. Claims for expense reimbursement must be submitted to the Executive Director prior to the 15th of each month in order to expedite payment. Claims other than automotive mileage and per diem require copies of receipts.

2. All expense claims will be reviewed and approved by the Executive Director.

Approval Date: ____________________ **Review Date:** ____________________

Lakeland Industry and Community Association
Box 8237, 5107W - 50 Street, Bonnyville, AB T9N 2J5
780 812-2182 780 812-2186 www.lica.ca

PRE-AUTHORIZED CREDIT AUTHORIZATION AGREEMENT

Instructions:

Please complete all sections (type or print clearly) to instruct your financial institution to make deposits directly to your account. Return the completed form with a correctly encoded blank cheque marked "VOID" OR a Preauthorized Credit Form from your financial institution to: **Lakeland Industry and Community Association** at the above address

APPLICANT (PAYEE):

Surname: ______________________ First Name: ______________

Surname: ______________________ First Name: ______________

Address/Street: ____

City: ______________________ Province: ______________

Postal Code: ______________________ Telephone: ______________

FINANCIAL INSTITUTION TO BE CREDITED:

Name of Financial Institution: ____________________________________

Branch/Location, Street: ____________________________________

City: ____________ Province: ____________ Postal Code: ______________

Route/Transit Number: ______________________ Account Number: ____________

(Attach a correctly encoded cheque marked "VOID") **OR** a Preauthorized Credit Form from your Financial Institution

TERMS AND CONDITIONS

1. I (We) as the Applicant(s) and Account Holder(s)/Payee(s) hereby **authorize Lakeland Industry and Community Association** as Payor and the above noted Financial Institution to credit my (our) account at the above indicated branch of the Financial Institution, under Terms and Conditions agreed to by Me (Us) with the **Lakeland Industry and Community Association** as Payor.

2. A credit in paper, electronic or other form may be deposited on My (Our) account which amount may be increased/decreased at a future date as agreed to in writing by Me (Us**). Lakeland Industry and Community Association** as Payor will, to the best of their ability, advise Me (Us) in writing of the revised amount in advance of its effective date.

3. The authorization may be cancelled at any time by Me (Us). I (We) will notify the **Lakeland Industry and Community Association**, as Payor in writing of any changes in the Financial Institution or account information or termination of this agreement at least 10 days prior to the next due date of the pre-authorized credit. Revocation of this agreement does not in any way terminate any other obligation (s) between the Applicant (s) and **Lakeland Industry and Community Association**.

4. Any and all notices required will be sent to the addresses provided herein.

5. **Lakeland Industry and Community Association** may apply in writing to the Financial Institution for reimbursement of the credit if the credit is disputed.

   Items credited will be reimbursed by the Financial Institution, subject to notification by **Lakeland Industry and Community Association** to the Branch of account within 90 days of the transaction date subject to meeting any of the following conditions:

   a) I (We) provided the authorization to the Payor.
   b) The pre-authorized credit was deposited in accordance with this authorization.
   c) The credit was posted to the wrong account due to invalid/incorrect account information supplied by the employee.

   LIABILITY

   The **employee shall be solely responsible for the accuracy and completeness of all information furnished to Lakeland Industry and Community Association and Lakeland Industry and Community Association shall not be responsible in any way for error resulting from the inaccuracy or incompleteness of any information furnished to it by the employee.**

   Lakeland Industry and Community Association shall not be responsible or liable for any claim, demand, cost, expense, damage, penalty, delay or inconvenience to the employee or any other person resulting from failure of Lakeland Industry and Community Association to perform any of the services herein contemplated arising out of any cause beyond the control of Lakeland Industry and Community Association or for any reason whatsoever other than the gross negligence or willful default of (Company Name). Lakeland Industry and Community Association shall not be liable to the employee in any event for any special, indirect or consequential damages.

6. I (We) the Applicant (s) hereby acknowledge that I (We) have read and understand and agree to the Terms and Conditions as contained herein.

7. I (We) warrant that all persons whose signatures are required to sign on the account at my (our) Financial Institution have signed this agreement below.

8. I (We) acknowledge that delivery of this authorization **to Lakeland Industry and Community Association** as Payor constitutes delivery by Me (Us) to the above noted Financial Institution.

______________________________ ______________________________________
Date Signature of Applicant

______________________________ ______________________________________
Date Signature of Applicant

FOR JOINT ACCOUNTS: If only one signature is required for the account, then only one Applicant need sign this form. However, if two or more signatures are required for the account, then both or all signatures are required on this form.

CANCELLATION

I (We) wish to terminate this Pre-Authorized Credit Authorization Agreement effective

__________________________, 20____.

________________ ___________________________________
Date Signature of Applicant

________________ ___________________________________
Date Signature of Applicant

Board and Committee Member Sign-On

Contact Information:

Name: ______________________

Mailing Address ______________________

____

Phone # ______________________

Cell # ______________________

Email Address ______________________

Stipend Payment Information (complete if applicable):

SIN # ______________________

Date of Birth ______________________

CPP Exempt (circle one) YES NO

Acid Deposition Monitoring Program Expansion Committee (ADMPEC)

Meeting Support Slides

September 16, 2021

LICA
ENVIRONMENTAL STEWARDS

3.1.1 AER Approval Conditions

The Acid Deposition Monitoring Program proposal shall include, at a minimum, all of the following:

- **for air:**
    - a plan to monitor dry and wet deposition from project activities;
- **for soil:**
    - identification of soils that are sensitive to acid deposition and will likely receive aerial deposition inputs from project activities;
    - a plan to monitor soil quality at locations representative of the soils identified in above;
    - a description of how soil quality data collected under this program will be used to determine potential acidification effects under periods of increased sulphur dioxide emissions;
- **for water:**
    - a summary of existing water quality data collected to date and analysis of the results;
    - a plan to monitor water quality for water bodies which will likely receive aerial deposition inputs from project activities;
    - identification of local water bodies that are sensitive to acidification;
    - a description of how water quality data collected under this program will be used to determine potential acidification effects under periods of increased SO2 emissions;
    - a plan to develop triggers for further enhanced surface water quality monitoring to determine impacts of aerial deposition inputs;
- **reporting schedule for monitoring activities conducted above**

3.1.2 Timeline and deliverables for monitoring plan

- Phase 1: December 31, 2021

AMENDING APPROVAL

ALBERTA ENERGY REGULATOR

ENVIRONMENTAL PROTECTION AND ENHANCEMENT ACT
R.S.A. 2000, c.E-12, as amended.

APPROVAL NO.: 68492-01-06

APPLICATION NO.: 027-68492

EFFECTIVE DATE: October 18, 2019

EXPIRY DATE: May 31, 2022

APPROVAL HOLDER: Cenovus Energy Inc.

Pursuant to Division 2, of Part 2, of the *Environmental Protection and Enhancement Act*, R.S.A.2000, c.E-12, as amended, the approval for the following activity:

Foster Creek enhanced recovery in-situ oil sands or heavy oil processing plant and oil production site

is amended as per the attached terms and conditions, and Schedules I to XI.

Shay Dodds, P.Eng.
Manager, In Situ South, Authorizations Branch
Alberta Energy Regulator

October 18, 2019

Environmental Protection and Enhancement Act Approval No. 68492-01-00 is hereby amended as follows:

1. Conditions 3.18, 3.19, 3.20 and 3.21 are deleted and the following is substituted:

3.18 Notwithstanding Table 3.1, the sulphur dioxide emissions from the plant shall not exceed 7.0 tonnes per day (on a calendar day basis) for the period commencing from October 18, 2019 and ending on December 31, 2020.

3.19 Notwithstanding Table 3.1 and Condition 3.18, the approval holder may bypass one (1) non-regenerative sulphur unit train for repair and maintenance provided that:

(a) a minimum uptime of 90% is maintained for each non-regenerative sulphur unit on an annual basis, for the period commencing from February 13, 2019 and ending on December 31, 2020;

(b) the minimum sulphur recovery requirements as outlined in Table 1 of ID2001-03: Sulphur Recovery Guidelines for the Province of Alberta is met except for the period commencing from February 13, 2019 and ending on December 31, 2020; and

(c) the sulphur dioxide emissions from the plant shall not exceed 8.0 tonnes per day (on a calendar day basis) for the periods when the sulphur unit train is bypassed for repair and maintenance, commencing from October 18, 2019 and ending on December 31, 2020;

unless otherwise authorized in writing by the Director.

3.20 In the event that a non-regenerative sulphur unit is bypassed, the approval holder shall provide in the monthly Air Emission Report to the Director, the following:

(a) a description of the events or circumstances that led to the bypass; and

(b) an outline of the action taken to control the magnitude and duration of this event(s).

3.21 The approval holder shall operate a continuous ambient air monitoring station and monitor ambient air parameters as specified in TABLE 3.4, unless otherwise authorized in writing by the Director.

3.22 In addition to the monthly and annual reporting requirements in TABLE 3.2 and TABLE 3.3, the approval holder shall report to the Director the results of the ambient air parameters as required in TABLE 3.4, unless otherwise authorized in writing by the Director.

TABLE 3.1: AMBIENT AIR MONITORING AND REPORTING

MONITORING STATION	PARAMETER	MONITORING PERIOD	REPORTING	
			MONTHLY	ANNUALLY
One continuous ambient air monitoring station, as per *Air Monitoring Directive*	Sulphur dioxide concentrations, wind speed and wind direction	Continuously, starting from February 13, 2019 to December 31, 2020	Yes	Yes

4. The following is added after Condition 3.22:

3.23 The approval holder shall submit an Acid Deposition Monitoring Program proposal to measure aerial deposition effects on aquatic and terrestrial ecosystems to the satisfaction of the Director on or before March 31, 2020, unless otherwise authorized in writing by the Director.

3.24 The Acid Deposition Monitoring Program proposal shall include, at a minimum, all of the following:

(a) for air:

(i) a plan to monitor dry and wet deposition from project activities;

(b) for soil:

(i) identification of soils that are sensitive to acid deposition and will likely receive aerial deposition inputs from project activities;

(ii) a plan to monitor soil quality at locations representative of the soils identified in (b) (i);

(iii) a description of how soil quality data collected under this program will be used to determine potential acidification effects under periods of increased sulphur dioxide emissions;

(c) for water:

(i) a summary of existing water quality data collected to date and analysis of the results;

(ii) a plan to monitor water quality for water bodies which will likely receive aerial deposition inputs from project activities;

(iii) identification of local water bodies that are sensitive to acidification;

(iv) a description of how water quality data collected under this program will be used to determine potential acidification effects under periods of increased SO_2 emissions;

(v) a plan to develop triggers for further enhanced surface water quality monitoring to determine impacts of aerial deposition inputs;

(d) reporting schedule for monitoring activities conducted for (a) through (c); and

(e) any other information requested in writing by the Director.

3.25 If the Acid Deposition Monitoring Program proposal is found deficient by the Director, the approval holder shall correct all deficiencies identified in writing by the Director, by the date specified in writing by the Director.

3.26 The approval holder shall implement the Acid Deposition Monitoring Program as authorized in writing by the Director.

3.27 The approval holder shall only implement changes to the Acid Deposition Monitoring Program as authorized in writing by the Director.

Shay Dodds, P.Eng.
Manager, In Situ South, Authorizations Branch
Alberta Energy Regulator

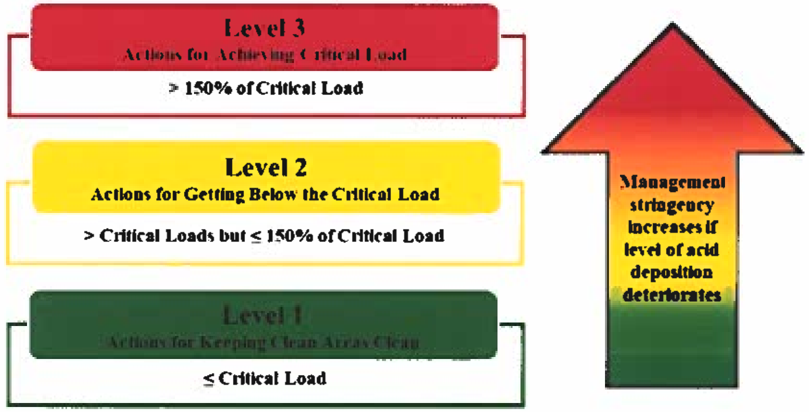
October 18, 2019

Review Information, Data, and Other Input Sources for Monitoring Plan Development

- 3.2.1 Alberta Acid Deposition Management Framework
- 3.2.2 Oil Sands Monitoring (OSM) Environmental Effects Monitoring (EEM)
- 3.2.3 Past studies on acidification in the Cold Lake oil sands region
- 3.2.4 Regional acid deposition modelling studies
- 3.2.5 Acid deposition monitoring in the Athabasca oil sands region
- 3.2.6 Regional soil acidification monitoring results overview
- 3.2.7 Approaches to surface water acidification monitoring site selection

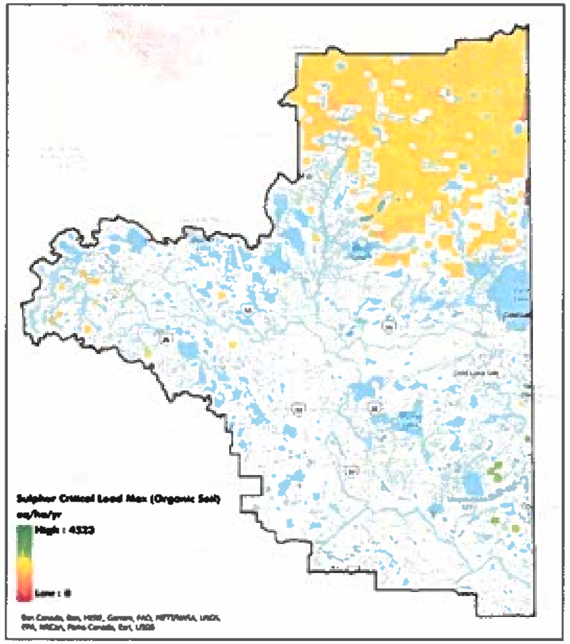
3.2.1 Alberta Acid Deposition Management Framework (ADMF) - 2021 Draft

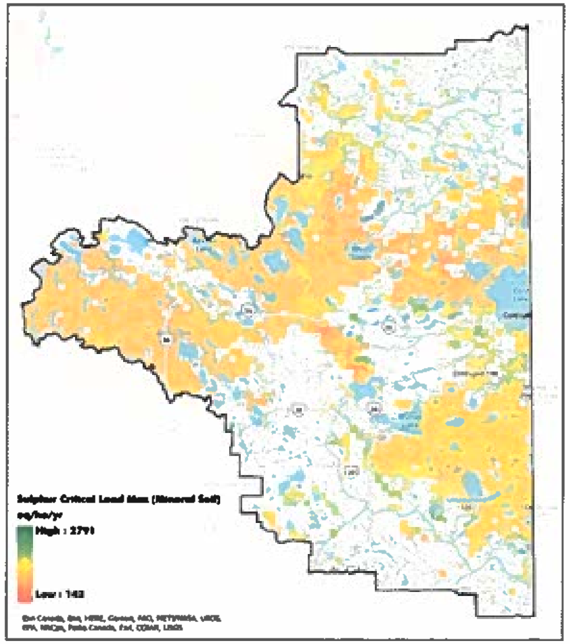
- **Critical Load**
  - A quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge (Nilsson & Grennfelt, 1988).
- **Acid Deposition Management Levels**
  - A tiered monitoring, target and critical load acid deposition management approach was used in the 2008 ADMF.
  - It is being replaced with a new management approach that will provide an early warning of potential areas "at risk" to long-term acidification.
  - The new approach also provides guidance to manage and reduce, where necessary, acidifying emissions adversely affecting the identified areas.



3.2.1 Alberta Acid Deposition Management Framework (ADMF) - 2021 Draft

- **Critical Load Maps**
  - The critical load is based on the soil properties of the ecosystems within each grid cell on the maps. Sensitivity in each grid cell is indicated by the magnitude of the critical loads – the lower the critical load, the greater the sensitivity of the grid cell.





Alberta Acid Deposition Management Framework

JULY 2020

Alberta

Ministry of Environment and Parks, Government of Alberta
Date of publication: TBD
Alberta Acid Deposition Management Framework
ISBN: 978-1-4601-4808-2

Comments, questions, or suggestions regarding the content of this document may be directed to:
Ministry of Environment and Parks, Policy Division, Air and Climate Policy Branch
Air Policy Section
Main floor, Oxbridge Place, 9820 – 106th Street, Edmonton, Alberta T5K 2J6

AEP.ADMF-Information@gov.ab.ca & Sunhee.Cho@gov.ab.ca

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Acronyms and Abbreviations

ADAG	Acid Deposition Assessment Group
ADMF	Acid Deposition Management Framework
ADMZ	Acid Deposition Management Zone
ADZMP	Acid Deposition Zone Management Plan
AENV	Alberta Environment
AEP	Alberta Environment and Parks
AER	Alberta Energy Regulator
AESRD	Alberta Environment and Sustainable Resource Development
CASA	Clean Air Strategic Alliance
$CL_{max}S$	Critical Load Maximum Sulphur
$CL_{max}N$	Critical Load Maximum Nitrogen
$CL_{min}N$	Critical Load Minimum Nitrogen
CLF	Critical Load Function
CLRTAP	Convention on Long-range Transboundary Air Pollution
CMAQ	Community Multi-scale Air Quality
EIA	Environmental Impact Assessments
Energy Resource Enactment	(j) "energy resource enactment" means (i) the Coal Conservation Act, (ii) the Gas Resources Preservation Act, (iii) the Oil and Gas Conservation Act, (iv) the Oil Sands Conservation Act, (v) the Pipeline Act, (vi) the Turner Valley Unit Operations Act, (vii) a regulation or rule under an enhancement referred to in sub subclauses (i) to (vi), or (viii) any enactment prescribed by the regulations; (source: http://www.qp.alberta.ca/documents/Acts/r17p3.pdf)
EPEA	Environmental Protection and Enhancement Act (RSA 2000, cE-12, as amended)

Facilities	A facility that operates under an approval or code of practice as required by Environmental Protection and Enhancement Act and/or the Energy Resource Enactments
N_{dep}	Nitrogen deposition
RELAD	REgional Lagrangian Acid Deposition
Regulator	Means a decision maker who is vested with a power, duty or function under the Environmental Protection and Enhancement Act and includes, without limiting the generality of the foregoing: (i) a designated Director or other official, (ii) the responsible Government of Alberta department, as designated under the Environmental Protection and Enhancement Act, and (iii) the Alberta Energy Regulator, as designated under the Responsible Energy Development Act
S_{dep}	Sulphur deposition
SSMB	Steady State Mass Balance

1.0 Introduction

Many industrial and non-industrial activities result in air emissions of compounds containing sulphur (S) and nitrogen (N) which, when deposited to terrestrial and aquatic systems, may result in acidification of the recipient systems. Long-term and permanent changes in the chemical properties of the soil and water occur when acid deposition exceeds the buffering capacity of the receiving system. These effects can interfere with important ecosystem functions and services, such as forest diversity and productivity, water quality and healthy fisheries. Regardless of changes being subtle or dramatic within an affected area, they must be considered in the context of the long-term equilibrium of the ecosystem.

Management of acidic deposition requires an integrated approach that includes measurement; estimation of emissions and deposition; and evaluation of the effects of deposition on recipient ecosystems. The critical load approach has been developed to address these assessment issues. In 1999, Alberta developed its first framework for managing acidifying emissions (i.e., air emissions containing sulphur and nitrogen compounds) and acid deposition with the goal to prevent an acidification problem from developing due to acidifying emissions (CASA, 1999). Alberta Environment adopted the framework developed by the Clean Air Strategic Alliance (CASA) for management of acid deposition effects in Alberta (AENV, 1999). The Acid Deposition Management Framework (ADMF) is periodically reviewed and revised as necessary to take into consideration advances in knowledge and science. The 1999 ADMF was reviewed and revised by the department in 2008. The Acid Deposition Assessment Group (ADAG), a multi-stakeholder group lead by the department, started its review of the 2008 ADMF after the 2011 provincial acid deposition assessment was completed in 2014. In the 2008 ADMF review process, possible ADMF changes were identified and evaluated and recommended changes are described in Appendix A.

Buffering Capacity

The relative ability of a substance to resist change to its pH despite the addition of an acid or base

This document replaces the "Alberta Acid Deposition Management Framework (2008)."

2.0 Alberta Acid Deposition Management Framework

Controlling acid deposition falls under the *Environmental Protection and Enhancement Act* (EPEA). One of the purposes of the EPEA is to provide government leadership in areas of environmental research, technology and protection standards. Section 14 under EPEA provides the authority for development of a provincial ADMF. The ADMF may be referenced in the Terms of Reference for projects that are required to conduct an Environmental Impact Assessment (EIA) and in project approval application requirements or projects subject to approval requirements as specified directly under EPEA or energy resource enactments.

2.1 Alberta's Critical Load Maps

The critical load is based on the soil properties of the ecosystems within each grid cell on the maps. Sensitivity in each grid cell is indicated by the magnitude of the critical loads – the lower the critical load, the greater the sensitivity of the grid cell. The Steady State Mass Balance (SSMB; CLRTAP, 2015, 2016) method was used to calculate the critical loads of acidity for terrestrial ecosystems in Alberta. The use of the SSMB method required the generation of three critical loads maps ($CL_{max}S$, $CL_{max}N$ and $CL_{min}N$) using 2.5 km x 2.5 km grid cells (Appendix A1 & AEP, 2020). The decision to use a 36 km x 36 km grid in the framework as the management unit size, required that these 2.5 km x 2.5 km grid cells be aggregated to the 36 km x 36 km grid and associated critical load maps generated (Figure 1). Detailed information of the data and methods used are described in the document "Using steady-state mass balance model to determine Critical Loads of Acidity for Terrestrial Ecosystems in Alberta" (AEP, 2020). When the critical load is exceeded, a management plan must be developed and implemented to reduce all point and non-point sources that are significantly contributing to acid deposition in the grid cell(s) that are above their critical load.

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 (Nilsson & Grennfelt, 1988).

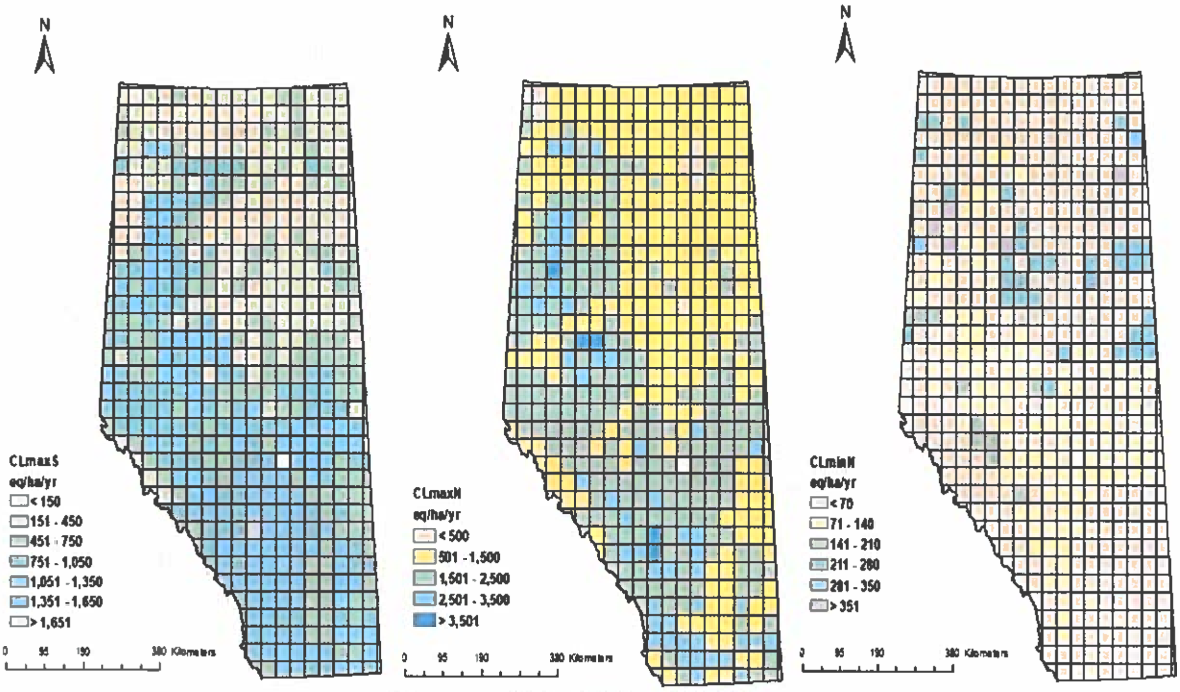

Figure 1 **Maps for three quantities of critical load in Alberta with 36km by 36km resolution: (a) $CL_{max}(S)$, $CL_{max}(N)$ and $CL_{min}(N)$.**

2.2 Acid Deposition Management Levels

A tiered monitoring, target and critical load acid deposition management approach was used in the 2008 ADMF. It is being replaced with a new management approach that will provide an early warning of potential areas "at risk" to long-term acidification. The new approach also provides guidance to manage and reduce, where necessary, acidifying emissions adversely affecting the identified areas.

Figure 2 shows the risk management levels that have been selected to guide responses to the SSMB critical load predictions. The framework consists of three separate critical load based management levels. Of the three levels, Level 1 is the lowest and Level 3 is the highest. Each management level is colour-coded, and associated with a suite of acid deposition management actions that are progressively more rigorous. The greater than 50% above critical loads Level 3 designation is based on uncertainties and limitations associated with the SSMB mathematical calculations and data inputs, the conservatism of the model, and some of the key model input parameters. With this management approach, the critical load becomes the environmental outcome.

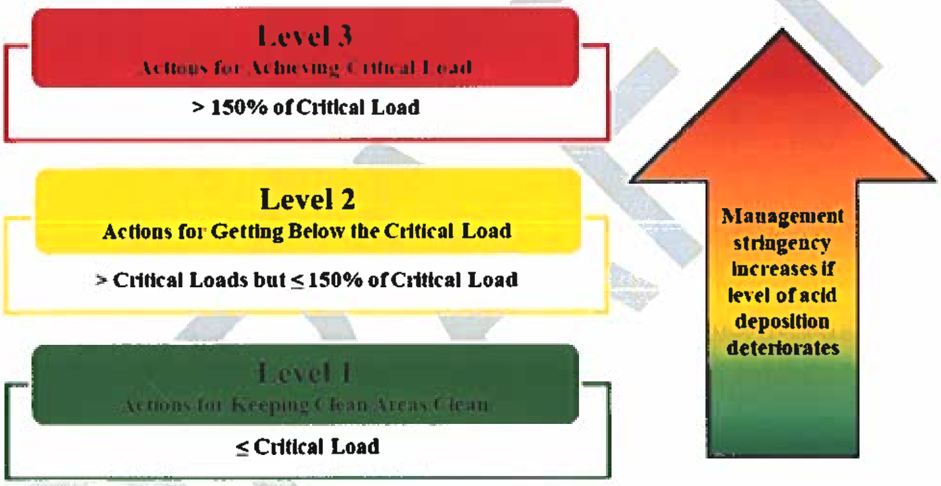

Figure 2 **Action levels for Alberta's Acid Deposition Management Framework.**

3.0 Acid Deposition Assessment for Alberta

The assessment of acidifying emissions and subsequent deposition relative to the critical load will be conducted to reflect Alberta's air quality management system principle of continuous improvement (AENV, 2009) over time. Assessment frequency is currently estimated to be a 5-

year cycle based on the pace of scientific understanding and knowledge advancement in this discipline.

Acid Deposition Assessment

A process in which a clear understanding of baseline conditions and ensuing changes to ecosystems are monitored and documented over time with the goal of establishing long-term environmental outcomes. The assessment is integrated and can capture the full range of processes and responses from emissions to atmospheric transport to deposition to ecological impacts. The end-goal of the assessment is to have evaluated how well current emission control efforts work in reducing environmental impacts, and to determine the potential need for further actions.

The department will conduct the assessment as deemed necessary, to answer the following questions:

- what is the current provincial situation regarding acid deposition?
- are large areas at risk due to deposition of acidifying substances?
- are there likely to be changes in acid deposition patterns over the long term that may result in harmful effects in some areas in the foreseeable future?
- are activities and associated acidifying emissions in Alberta potentially negatively impacting the environment in neighboring jurisdictions?

The flowchart in Figure 3 outlines the general process for conducting an acid deposition assessment. The following sections describe key process components in detail.

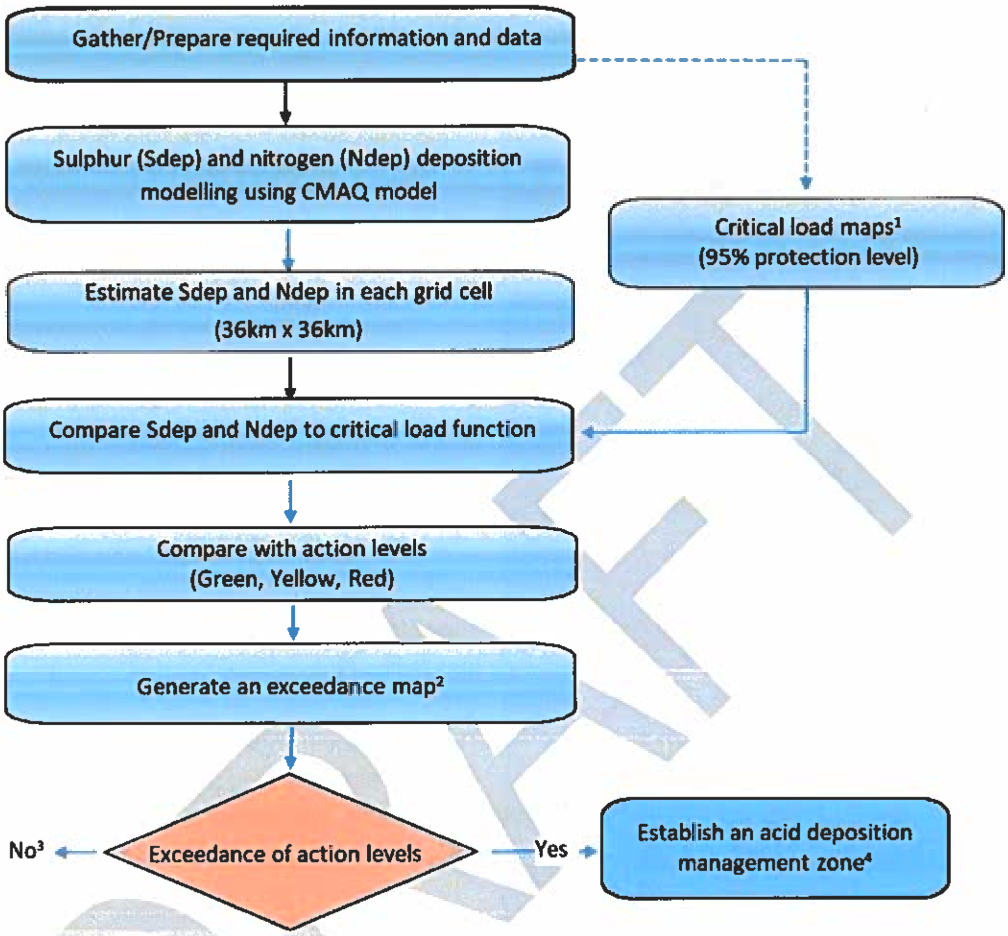

Figure 3 The general process for conducting the provincial acid deposition assessment.

Note: [1]When new data and information is available, critical load maps will be updated by the department through the assessment process. [2]Exceedance is calculated using (Exceedance = Deposition – Critical Load). [3]When the % of critical load is less than 100%, this finding will be documented and no further assessment required. [4]When an acid deposition management zone is established, actions are to be taken as outlined in Chapter 4.

3.1 Estimating Atmospheric Deposition of Sulphur and Nitrogen

Based upon the most recently available and appropriate emissions inventories and a representative meteorological data set, an estimation of wet and dry S and N deposition in each grid cell will be made. Deposition estimates will be made for the entire province with the Community Multi-scale Air Quality (CMAQ) model (U.S. Environmental Protection Agency ((U.S. EPA), 2017) using a 36 km x 36 km grid.

3.2 Level of Protection and Management Unit

An essential component in application of critical loads is the level of protection that is to be applied. A 95% protection level (i.e., 5th percentile) was chosen for Alberta's first framework (CASA, 1999), and during the review of the 2008 framework ADAG agreed that 95% remains an acceptable level of protection. The 95% protection level means that 95% of the most sensitive soils will be protected at the critical load within each 36 km x 36 km grid cell.

3.3 Evaluation of Model Predictions

Any deposition monitoring data that has become available since the previous provincial assessment will be compared to model predictions. The purpose of this comparison is to evaluate how reasonably the model predicts the spatial variability and general deposition magnitudes for a representative Alberta meteorology. Evaluation of air quality modelling elements integral to the framework will be conducted in two ways. These are:

(1) determine the acceptability of the input modelled meteorology used in the framework for precision and accuracy. This will be undertaken using the currently accepted U.S. EPA guidance for evaluation of meteorological models (U.S. EPA, 2013).

(2) examine the general spatial and temporal agreement between available monitoring data and model predictions. Given that the meteorological year of choice may not coincide with the available monitoring data (which may span several years), a direct evaluation of the model performance may not be possible. Therefore, a "weight of evidence" comparison of modelling predictions to the average of the available monitoring data at each station weighted by the quality of data at each monitoring station will be undertaken. This comparison can be done using both paired and unpaired statistics between the two data sets using professional judgment to determine whether the agreement is acceptable and whether or not the model predictions are reasonable and representative of deposition in the province.

3.4 Comparing Modelled Deposition to Critical Loads

The modelled total deposition (wet and dry) estimates are used when calculating critical load exceedances. Positive values reflect the extent to which current pollution loading exceeds the critical load. An exceedance map will provide a magnitude of the exceedance in grid cells (e.g., No Exceedance, 1-1.5 times Exceedance, >1.5 times Exceedance).

3.5 Review of Science Gaps and Recommendations

Consistent with Alberta's initiatives for continuous improvement and keeping clean areas clean, the status of the science gaps identified and recommendations put forth in the previous provincial assessment will be reviewed. Recommendations may be provided to fill science gaps or to improve the assessment method.

3.6 A Report Describing the Results of the Provincial Assessment

The assessment report will be public and available online through the department's website. The report will include:

- a summary of the emissions inventory used and assumptions for projected emissions.
- a brief description of the model used to predict nitrogen and sulphur deposition.
- a discussion of sulphur and nitrogen deposition in Alberta and neighboring jurisdictions.
- a summary of critical loads updates when new data and information are available (note: data obtained between assessments may lead to a revision of the critical load for individual grid cells, should the data indicate that the critical load is different from that assigned in the previous assessment).
- the results of comparing modelled deposition to the critical loads.
- a review of the status of science gap(s) from the previous report and newly identified science gap(s) and recommendation(s).

3.7 Response to Acid Deposition Assessment

Should the assessment indicate that deposition in one or more grid cells exceeds Level 3 or Level 2 (i.e., as the result of two sequential acid deposition assessments), an Acid Deposition Management Zone (ADMZ) will be established by the Department. The ADMZ will include the exceedance cell(s) and all grid cells with acidifying emission sources that substantially contribute to acidifying deposition in the exceedance cell(s). There may be some cells that do not have acidifying emission sources that contribute to the exceedance, but are located between cells that do, and that if development were to occur within those cells they may become acidifying contributors to the exceedance cell(s). These cells would then also be included in the ADMZ.

The framework recommends a suite of management response options for each level (Chapter 4). These actions include a range of potential measures and tools with varying degrees of rigour and flexibility. When mitigative management actions are required, the department will collaborate with stakeholders to identify and implement the appropriate management action. This will include identifying the public, stakeholders and different levels of government that need to be involved in the plan. The department, as accountable for the framework, provides leadership and guidance and will work with stakeholders to identify appropriate parties who will be required to deliver a flexible management response.

Stakeholders share ownership of the concepts, management approach and intent of the framework and in this way demonstrate their partnership commitment to take appropriate action that will maintain and improve acidification issues in Alberta.

This framework will be updated from time to time, to reflect changing standards and objectives, demonstrating continuous improvement over time based on best available knowledge and investigation findings.

3.7.1 Development of an Acid Deposition Management Zone Plan

As structured in Figure 2, the framework maximizes the potential for management on the basis of measurement (monitoring and receptor measurement), and minimizes the reliance on model prediction. Following the collaboration process with relevant stakeholders, details on the chosen management actions and an implementation plan will be provided in the Acid Deposition Zone Management Plan (ADZMP).

The ADZMP includes (but is not limited to):

- a program to evaluate the overall emissions reductions necessary to reduce acid deposition and to establish related long-term emissions management objectives for the ADMZ (this will involve an evaluation of required emission reductions and derivation of an emissions reduction schedule).
- a process to allocate acidifying emission reduction targets to acidifying emission sources regulated under EPEA and/or the Energy resource enactments (section 1(1) (j)) in the ADMZ identified above.
- a process to inform the approval of new acidifying emission sources in the ADMZ in a manner that will not compromise the ability to meet the ADMZ acidifying emission reduction targets and schedules.
- development of an acidifying emissions inventory and acid deposition monitoring programs to verify progress in achieving management plan objectives (the program will include processes for adjusting acidifying emissions reduction targets based on actual performance of the management system).
- measures to reduce point and non-point source emissions where these emissions contribute substantially to the exceedance cell(s).

4.0 Alberta Acid Deposition Management Actions

The framework uses the assessment of the receptor sensitivity by applying the levels in the following tables (Tables 1 to 3) to help select management actions that can be taken to reduce the likelihood of reaching the critical loads. Management actions associated with the lower levels are intended to provide options to address acidification issues and avoid reaching the higher levels. Once it is determined that management actions are necessary, the department will:

- help to ensure that necessary regulatory or management changes are undertaken.
- work with stakeholders to identify the appropriate parties to be involved in the development and implementation of management actions. There will be shared responsibility amongst there parties to make sure the actions are taken.

The following sections outline the key actions that should be followed in initiating and carrying out the management planning process.

4.1 Level 1 – Keeping Clean Areas Clean

Objective: Ensuring clean areas remain clean.

The primary action at this level is ongoing monitoring of acid deposition. No additional/new monitoring or management activities are required.

Table 1 Management actions for Level 1

Action	Description	Primary Responsibility
Acid Deposition Monitoring	Baseline monitoring and data gathering.	The department, with assistance from provincial science and technical experts as needed and available.

4.2 Level 2 – Actions for Getting Below the Critical Load

Objective: Get below the critical load by reducing acid deposition through taking investigative and education actions. The focus of this level is to better understand and quantify the acid deposition risk in Level 2 grid cells. When deposition is predicted to occur that is in excess of Level 2 (i.e., this action level has been exceeded) actions are to be taken as outlined in Table 2.

If, as the result of two sequential provincial acid deposition assessments or an observed (monitoring result) deposition is predicted to occur that is in excess of Level 2, then an ADZMP may be required to be developed within two years after ADMZ establishment. The department will determine the need for development of ADZMP as specified in Table 3.

Table 2 Management actions for Level 2

Action	Description	Primary Responsibility
Acid Deposition Monitoring	Assess the adequacy of existing acid deposition monitoring (i.e., receptor). ○ Collect available data for evaluating/validating the SSMB critical load exceedance result.	The department and stakeholders, with assistance from provincial science and technical experts as needed and available.

Modelling	Conduct additional modelling, as needed, to identify sources of acidifying emissions that contribute to deposition above the Level 2 in the grid cell. ◦ Compile emissions inventory (current and historical where possible), derived from any available and appropriate emissions inventories and supplemented with location specific data as required.	The department and stakeholders, with assistance from provincial science and technical experts as needed and available.
Stakeholder Engagement and Education	Engage local stakeholders as appropriate based on local conditions.	The department, with assistance from the affected stakeholders and partners, as appropriate.

4.3 Level 3 – Actions for Achieving Critical Load

Objective: Achieve ADMZ critical load through advanced ADMZ actions.

For each cell that is predicted (model result), or observed (monitoring result) to exceed Level 3, an ADMZ will be established. Establishment of this zone will be the responsibility of AEP and the boundaries of the ADMZ will be determined based on the acid deposition assessment result. The ADMZ will include the exceedance cell(s) and all grid cells which substantially contribute to acidifying deposition in the exceedance cell(s). There may be some cells that do not have acidifying emissions that contribute to the exceedance, but are located between cells that do. If development were to occur within those cells, they could become acidifying contributors to the exceedance cell(s) and would be included in the ADMZ. At the red level, an ADZMP must be developed within one and a half years after ADMZ establishment. Stakeholders will be engaged to a high degree. As part of the plan development, government and stakeholders should consider current and likely future acid deposition pressures and issues. If stakeholders do not agree to, and/or implement, the management plan within the required timeframe, the department may impose a plan. Associated Level 3 actions are outlined in Table 3.

Table 3 Management actions for Level 3

Action	Description	Primary Responsibility
Acid Deposition Monitoring	Ensure the adequacy of existing acid deposition monitoring (i.e., receptor). o Collect available data for evaluating/validating the SSMB critical load exceedance result.	The department and stakeholders, with assistance from provincial science and technical experts as needed and available.
Modelling and Research	Conduct additional modelling to identify sources of acidifying emissions that contribute to deposition above the Level 3 in the grid cell. o Compile an ADMZ-specific emissions inventory (current and historical where possible), derived from the national emissions inventory and supplemented with location specific data as required. Analyze the trends in acid deposition and acidifying pollutant emissions and evaluate/validate the SSMB critical load exceedance results.	The department and stakeholders, with assistance from provincial science and technical experts as needed and available.

	Discuss the best approach for implementing any required monitoring/research studies and confirm resourcing of these studies.	
Stakeholder Engagement and Education	Engage local stakeholders with roles and deliverables identified. Notify stakeholders, including the public, municipalities, all facilities or activities, of the establishment of the ADMZ that: o operate under an approval or code of practice as required by EPEA and/or AER authorization under the Energy resource enactments approvals for SO_2 and NOx emissions. o are regulated by the Regulator. o are the emitters that contribute to acid deposition in the affected area or their constituents.	The department, with assistance from the affected stakeholders and partners, as appropriate.
Implement Acid Deposition Management Plan	Implement the ADZMP, with clear roles and responsibilities for all participants, timelines, and a defined process for review and revision as necessary.	The department leads the implementation of ADZMP, all stakeholders responsible for the actions committed to the plan.
Progress Assessments	Assess progress in implementing management actions, track the implementation of the action plans, and demonstrate how the management actions are contributing to improved air quality and reduced deposition. Identify and fill in gaps in the information needed for management planning.	The department and stakeholders.

4.4 Guidance for Approval of Facilities within an Acid Deposition Management Zone

There may be situations where a decision needs to be made by a Regulator on the approval for a facility (i.e., new, amended, renewal), where the facility will be located in an established ADMZ, but an ADZMP has yet to be developed. In such situations, the guiding principle for the Regulator will be to ensure that the approval of any acidifying emission(s) associated with the facility will not compromise the ability of the ADZMP to bring ADMZ below the critical load. If the approval of acidifying emission(s) are likely to compromise the efficacy of the ADZMP, the application of sufficiently stringent emissions control measures and/or tools (Table 4) to mitigate this risk is recommended.

The Regulator will notify, in writing, all facilities that contribute acidifying emissions to the ADMZ indicating that additional emissions management actions may be required in the future and these actions may be stipulated in a revised approval issued to the applicant. As a mandatory requirement, applicants will participate in the development of the ADZMP. The ADZMP, and other development and economic viability factors will guide the approval process of acidifying emission sources within an ADMZ.

Table 4 is a list of potential measures and tools that could be used to manage acidifying pollutants as part of the ADMF. The list is not exhaustive, but can be used as a guide.

The framework also recognizes that emission control technology and scientific understanding may change over time; and flexibility is needed to ensure that the desired environmental outcomes continue to be achieved.

Table 4 Potential measures and tools that can be used for acid deposition management

- Emission reduction requirements to allow for new sources.
- Director-initiated approval amendments (in accordance with authority under EPEA).
- More rigorous performance standards.
- Restrictions on additional emission sources.
- Application of practicable control technology to prevent pollution, stringent control technology as needed to meet operational excellence
- Approval conditions or restrictions.
- Environmental Protection Order.

- Approval conditions to participate in the ADZMP.
- Additional acid deposition modelling assessment.

4.5 Acidifying Emissions Modelling Requirement and Protocol

In order to realistically capture the detailed deposition characteristics close to the emission sources when modelling acid deposition, CALPUFF, or any other deposition model recommended by the department, shall be used. This modelling shall be done in accordance with the current version of the Alberta Air Quality Model Guideline.

Facilities emitting SO_2, NOx or NH_3 and requiring an EIA must conduct an acid deposition modelling assessment. All other facilities (new approved, amending, renewing) contributing to the ADMZ should be required to complete acid deposition modelling assessment if:

- the facility's new approved/increased emissions of SO_2, NOx, and NH3 are greater than 0.175 t/d of H+ equivalent.

Acid deposition modelling would not normally be required if:

- the facility's new/increased emissions of SO_2, NOx, and NH_3 are less than 0.175 t/d of H^+ equivalent, and/or
- the facility's emissions have been included in an ADZMP modelling with acid deposition estimates.

If an ADZMP has been initiated, but not completed, the applicant must participate with other stakeholders within the associated ADMZ in completion and implementation of the ADZMP.

There may be situations where a facility is recently approved, but an ADMZ is declared afterwards, that will directly affect the facility. In this situation, the facility is required to fully participate in the development and implementation of the ADZMP. It is prudent for applicants to stay apprised of acid deposition assessments and consider the potential for establishment of ADMZ's when preparing an approval application.

Notwithstanding the foregoing, the Regulator may require an applicant of a project to conduct one or more air quality and/or deposition modelling exercises if there is some overriding concern that must be addressed.

Figure 4 illustrates the steps to follow to determine if acid deposition modelling is required for the proposed project.

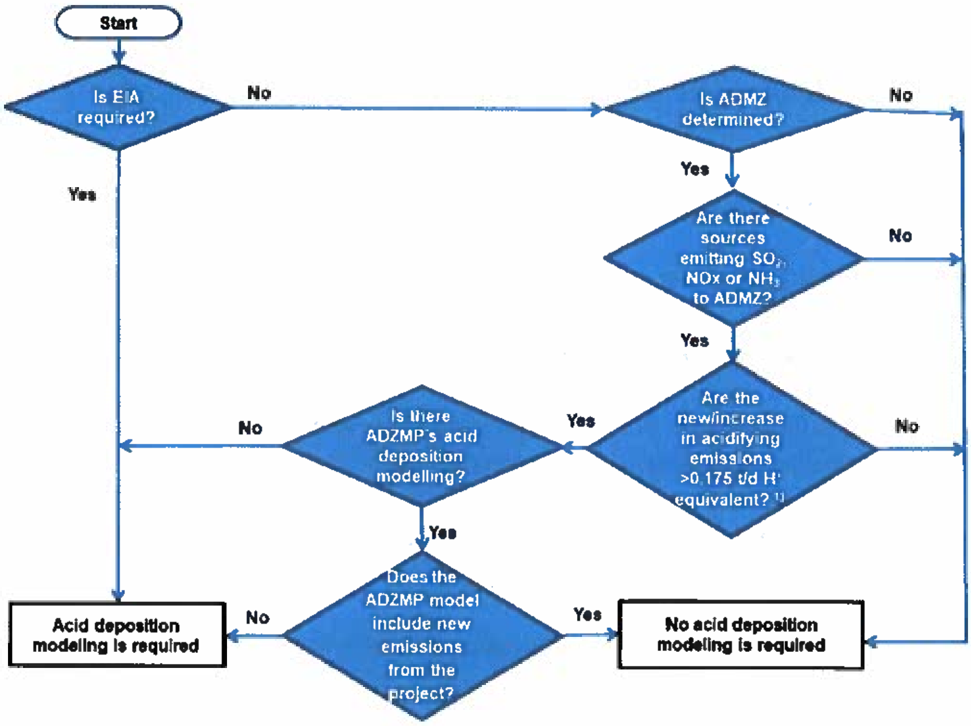

Figure 4 **Flowchart to determine when the applicant will be required to conduct acid deposition modelling as part of their approval application**

Note: Total acidifying emissions of H+ equivalent (t/d H+) = [2×(SO_2 t/d)/(64)] + [1×(NOx t/d)/(46)] + [1×(NH3 t/d)/(17)].

The framework does not in any way alter the existing authority of agencies, departments and organizations to use regulatory mechanisms in the event that the environmental outcomes of the framework are not being achieved.

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Appendix A Review of the 2008 Framework

Alberta's ADMF is periodically reviewed and as necessary revised to take into consideration new knowledge and science. The Acid Deposition Assessment Group (ADAG) started its review of the 2008 framework after the 2011 provincial acid deposition load assessment was completed in 2014. As part of the ADMF review process the following items were identified as a priority for review and possible revision:

- using a more open and supported model to predict sulphur and nitrogen deposition than the REgional Lagrangian Acid Deposition (RELAD) air quality model which is no longer supported.
- the size of the grid/cells used to assess and manage acid deposition.
- the need to examine and update the current critical, target and monitoring load values using less empirical and more transparent and standardized methods.
- updating the provincial critical load map.
- improving base cation deposition estimates.

A1. Review of the Acid Deposition Model

The RELAD model was used for previous assessments (AENV, 2006; AESRD, 2014) but as it is no longer supported, and has been replaced with newer, more comprehensive air quality models, it was decided to look at possible replacement models. The critical characteristics and elements of a replacement model were considered to be that the model should:

- have multi-layer representation of the atmosphere,
- use the resistance model to estimate deposition,
- be able to simulate temporal and spatial variability,
- be able to model at a spatial and temporal resolution that would meet the needs of the framework,
- have the ability to represent atmospheric chemistry as well as dispersion, and
- be publically available and approved by the U.S. EPA.

Given the above criteria, it was decided that the framework should use the U.S. EPA approved photochemical Community Multi-scale Air Quality (CMAQ) Modelling System to estimate acid deposition. As this model is actively updated by the air quality modelling community, the model version and chemistry will be chosen at the time of the framework review to best model acid deposition as judged on the basis of its performance with similar projects and by a literature review. The framework will be based on 36 km x 36 km grid cells to provide a reasonable resolution appropriate for acid deposition loading and potential impact screening purposes.

In regard to the meteorological data used, the 1980 MM5 data at 36 km x 36 km resolution used in the 2013 assessment will be retained for future framework assessments. In the case where there is evidence to suggest that modelled acid deposition using 1980 meteorology is no longer representative of average deposition related meteorology due to a climatological change in Alberta, a new meteorological data set will be created that allows CMAQ to representatively model long term typical acid deposition across the province. Also, if there are additional modelling or other technical demands suggesting an update of the meteorology is necessary a new meteorological data set will be created.

A2. Method to Determine Critical Load Values

In its review of the 2008 ADMF, the ADAG assessed critical load determination options and agreed to use the Steady State Mass Balance (SSMB) model for determining long-term critical loads of sulphur and nitrogen in Alberta. The SSMB model is a widely accepted scientific approach for determining critical loads and is used by many jurisdictions such as Europe, the USA, and Asia (CLRTAP, 2016; Hettelingh et al., 1995; Duan et al., 2010; Williston et al., 2016). The SSMB model assumes a simplified, steady-state input-output description of the most important biogeochemical processes that affect soil acidification (CLRTAP, 2016).

The Critical Load Function (CLF) considers the combined inputs of S and N deposition when determining exceedances of their respective critical loads (CLRTAP, 2015; CLRTAP, 2016). The CLF is a three-node line on a graph defined by the maximum critical load of S (CLmaxS), the minimum critical load of N (CLminN), and the maximum critical load of N (CLmaxN). The CLF is divided into 5 regions. The grey depicts Region 0 which is the area "below" the CLF line where sulphur deposition (Sdep), and nitrogen deposition (Ndep) combined do not exceed the critical loads of acidity. Regions 1 to 4 are the areas "above" the CLF line where a conditional comparison of critical loads and Sdep and Ndep pairs indicate an exceedance. Table A.1 shows these region designation and how they may inform acid deposition management.

Table A-1 S_{dep} and N_{dep} deposition regions and possible reduction strategies when the Critical Load Function is exceeded

Region	Deposition	Example	Exceedance	Optimal reduction*
0	S_{dep} and N_{dep} fall in Region 0 below the Critical Load Function		No	N/A
1	S_{dep} and N_{dep} fall in Region 1	N_{dep1}, S_{dep1}	Yes	Reduction of S_{dep} and N_{dep}

2	S_{dep} and N_{dep} fall in Region 2	N_{dep2}, S_{dep2}	Yes	Reduction of S_{dep} and N_{dep}
3	S_{dep} and N_{dep} fall in Region 3	N_{dep3}, S_{dep3}	Yes	Reduction of S_{dep} and N_{dep}
4	S_{dep} and N_{dep} fall in Region 4	N_{dep4}, S_{dep4}	Yes	Reduction of S_{dep}

*Optimal reduction - the deposition reduction needed for S_{dep} and/or N_{dep} to fall below the CLF.

An Adaptive Environmental Effects Monitoring Framework for Assessing the Influences of Liquid Effluents on Benthos, Water, and Sediments in Aquatic Receiving Environments

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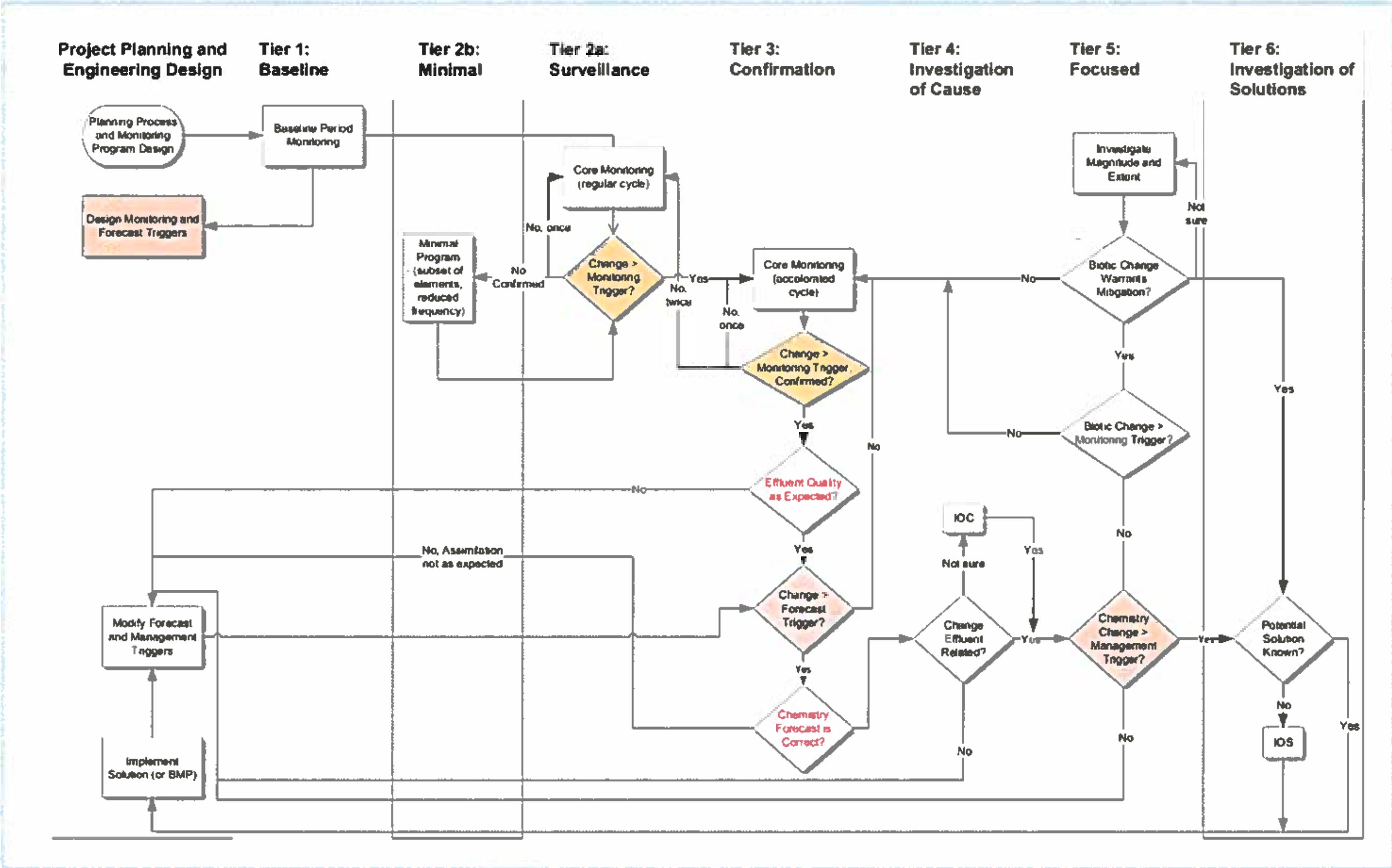
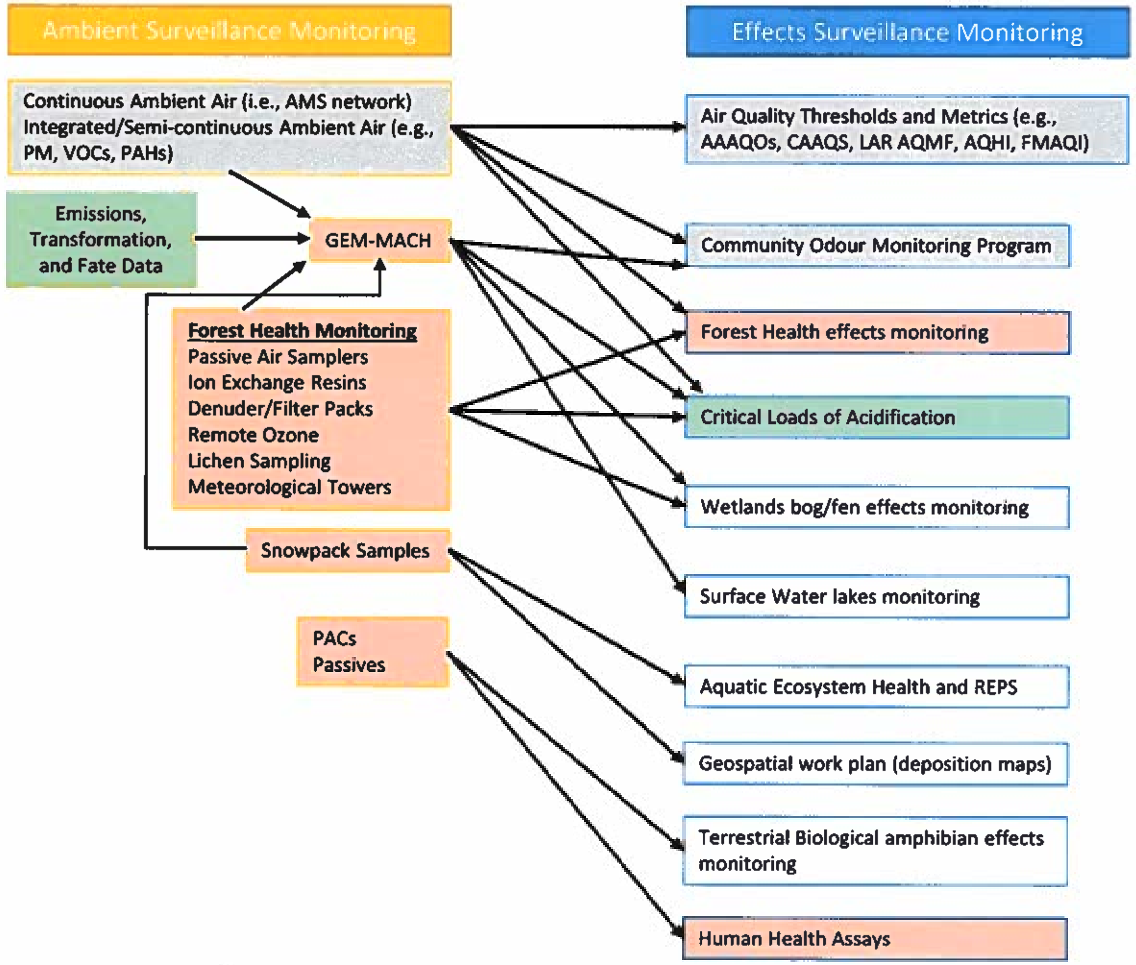


Figure 1. A flowchart illustrating the relationships in a tiered and triggered monitoring system applicable to assessment of effluent release into an aquatic environment. Baseline, forecast, and management triggers are defined as part of the project-planning process. IOS = investigation of solutions; IOC = investigation of cause.

3.2.2 Oil Sands Monitoring (OSM) Environmental Effects Monitoring (EEM)

Phase	Name	Description
Tier 0	Project Planning and Engineering Design	Design monitoring program and establish triggers.
Tier 1	Baseline	Baseline monitoring period
Tier 2	Surveillance/minimal	Core monitoring (regular/reduced cycle)
Tier 3	Confirmation	Model validation. Deposition as expected?
Tier 4	Investigation of cause	Is change emissions/deposition related?
Tier 5	Focused study	Investigate magnitude and extent.
Tier 6	Investigation of solutions	Potential solution known?

Monitoring Activities in an EEM Framework (with existing linkages)



Tools for Investigation of Cause and Cumulative Effects Assessment

GEM-MACH (or other modelling)

Source Apportionment Analysis (e.g., integrated ambient, lichen, snowpack, PACs passives)

Legend

- A-LTM-S-1 (Ambient Air Network)
- A-PD-4 (Emissions, Transformation, and Fate)
- A-PD-6 (Deposition)
- Other TACs

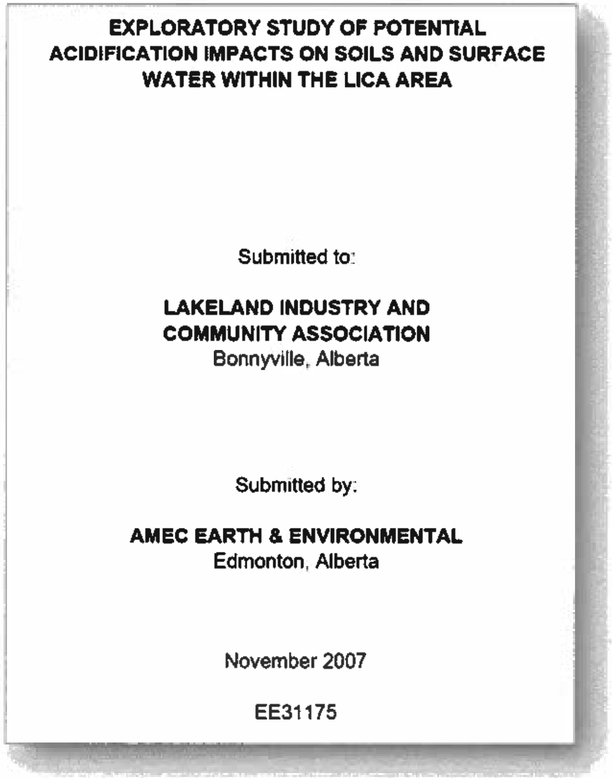
Notes:

- Some activities in A-LTM-S-1 and A-PD-6 are listed in EPEA Approval Clauses
- Some activities in A-LTM-S-1 are needed for CAAQS and LAR AQMF reporting
- Source surveillance activities are complementary (e.g., wetlands effects monitoring require both GEM-MACH and deposition monitoring data)

3.2.3 Past studies on acidification in the Cold Lake oil sands region

Exploratory Study Of Potential Acidification Impacts on Soils and Surface Water Within the LICA Area (2007)

- This study had three main components:
  - The potential effects of emissions of oxides of nitrogen (NOX) and sulphur dioxide (SO_2) on acid deposition in the LICA region. This included an estimation of potential acid input (PAI)
  - The assessment of surface water sensitivity to acidification and analysis in relation to potential acid input levels.
  - A soils component assesses soil sensitivity in relation to PAI estimates



EXPLORATORY STUDY OF POTENTIAL ACIDIFICATION IMPACTS ON SOILS AND SURFACE WATER WITHIN THE LICA AREA

Submitted to:

LAKELAND INDUSTRY AND COMMUNITY ASSOCIATION
Bonnyville, Alberta

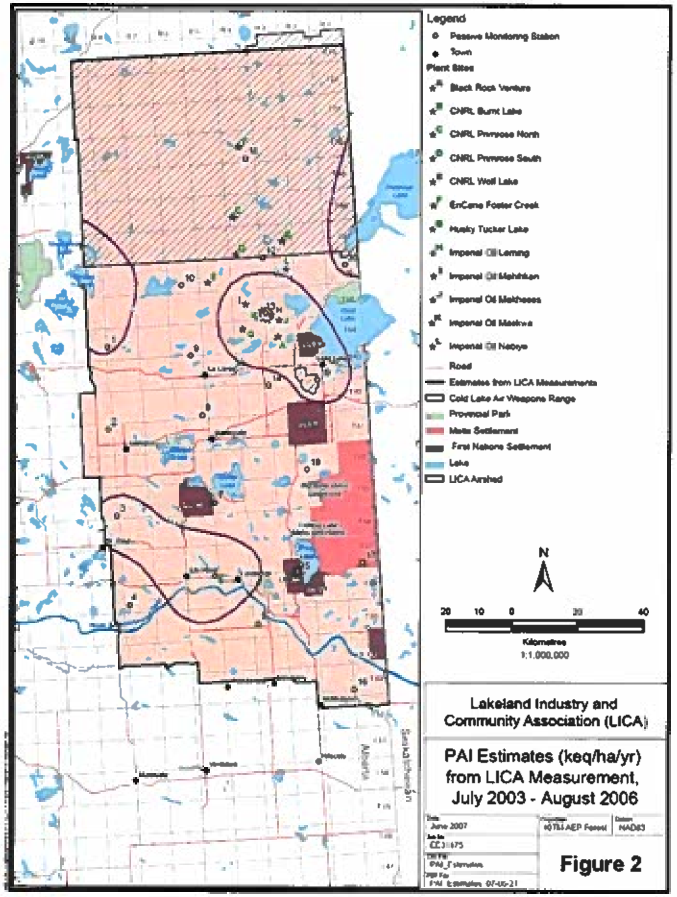
Submitted by:

AMEC EARTH & ENVIRONMENTAL
Edmonton, Alberta

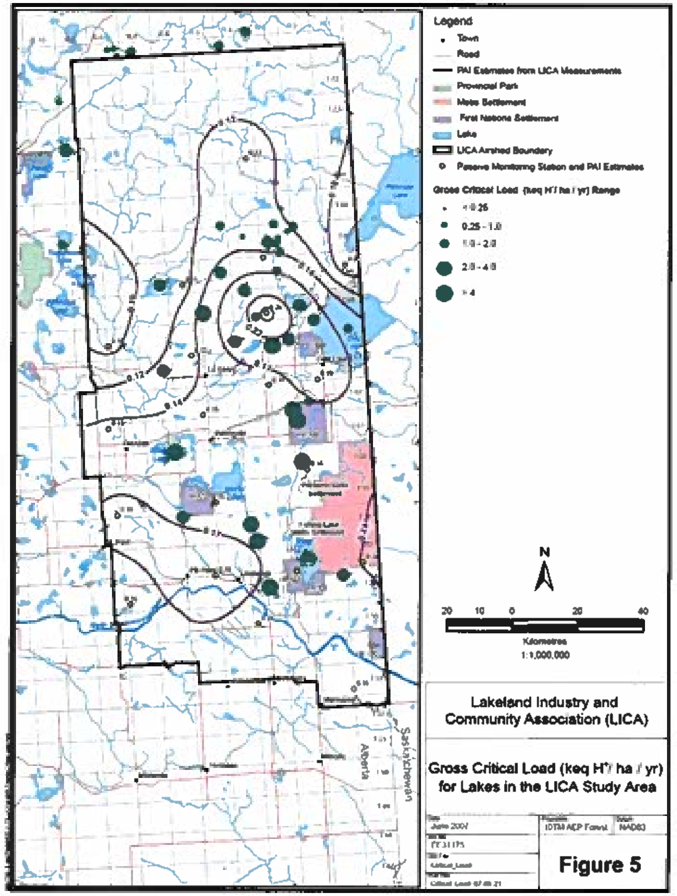
November 2007

EE31175

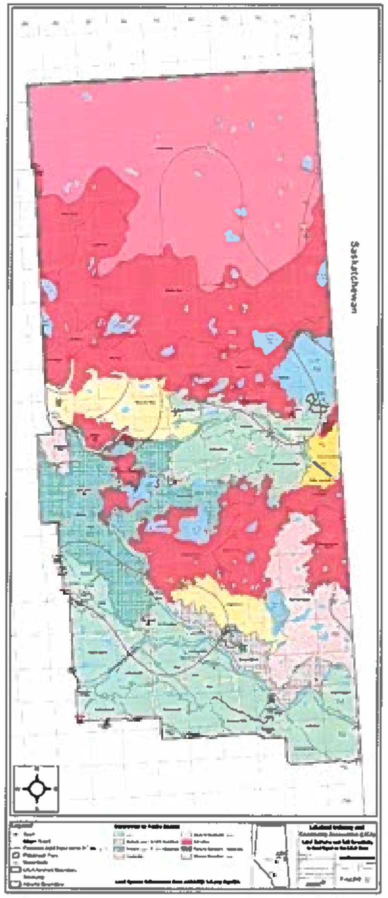
Exploratory Study Of Potential Acidification Impacts on Soils and Surface Water Within the LICA Area (2007)



Potential Acid Input Estimate



Surface Water Sensitivity



Soil Sensitivity

EXPLORATORY STUDY OF POTENTIAL ACIDIFICATION IMPACTS ON SOILS AND SURFACE WATER WITHIN THE LICA AREA

Submitted to:

LAKELAND INDUSTRY AND COMMUNITY ASSOCIATION
Bonnyville, Alberta

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Edmonton, Alberta

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EE31175

EXECUTIVE SUMMARY

An exploratory study was conducted in the Lakeland Industry and Community Association (LICA) area to assess the current levels of deposition of acidic and acidifying substances, and to assess their potential impacts on surface waters, soils and vegetation. This study has three main components. The effects of potential emissions of oxides of nitrogen (NO_X) and sulphur dioxide (SO_2) on acid deposition in the LICA region were examined. The objective of this component was to compile and analyze existing data from the LICA regional air monitoring network to provide an indication of the extent of deposition in the area, and the extent of any resulting impacts. An outcome of this study is the prediction of Potential Acid Input (PAI) levels in the LICA area. The second component involves an assessment of surface water sensitivity to acidification and analysis in relation to the PAI levels. A soils component assesses soil sensitivity in relation to PAI estimates, and accompanies an overview of potential vegetation impacts.

The LICA study area, referred to as the original LICA Geographical Area, extends from the Fourth Meridian (the Saskatchewan border) to Range 8, inclusive, with varying portions of Range 9. North to south, the study area extends from the middle of Township 73 to portions of Townships 52 to 54. The study area spans three ecoregions, namely the Aspen Parkland in the south, the Boreal Transition Ecoregion in the middle, and the Mid-Boreal Uplands Ecoregion in the north.

The objective of the air quality study was to compile and analyze the current data from the LICA regional air monitoring network in order to provide an indication of the extent of deposition in the area, and the extent of any resulting impacts. This evaluation was principally carried out by determining the PAI, which takes into account the acidification effect of sulphur and nitrogen species as well as the neutralizing effect of available base cations. The PAI, in units of keq/ha/yr, was calculated from wet and dry forms of deposition of NOx and SO^2. PAI deposition rates at 20 passive monitoring stations as well as one continuous monitoring station were estimated from measurements from 2003 to 2006.

PAI estimates from observations in the LICA area showed spatial variability. The estimates at some locations between Leming and Marie Lakes exceeded the CASA 0.25 keq/ha/yr critical load for the most sensitive ecosystems. The value appears to be isolated and is likely related to local sources such as the Imperial Oil Limited Maskwa and Lemming plants. Values above the monitoring threshold for the most sensitive ecosystems were also measured in the Lindbergh to St. Paul area.

The study recommended that further examination be made of the locations of passive monitoring stations, particularly in relation to industrial and other known sources in the area, in order to help explain relatively high estimates of PAI in parts of the area. Also, the uncertainties in PAI calculations were discussed, with cation concentration and deposition identified as being poorly understood and quantified. It was therefore recommended that further work be conducted to quantify cation emission and deposition and its contribution to reducing acidification potential.

The surface water component of this study estimated and analyzed the critical loads for different waterbodies in the LICA study area. Potential effects of acidification on water bodies were evaluated by review of water quality information for the LICA area, by classification using an acidification ranking system, and by estimating the critical loads of acidity for different waterbodies. The critical loads for individual lakes were calculated using the Henriksen's steady state water chemistry ratio.

Acid sensitivity ratings were identified for lakes within and bordering the LICA study area, based on average alkalinity, pH and calcium values observed between 1998 and 2006. Alkalinity levels were relatively high, such that all lakes fell into the 'least' sensitive ranking. However, two small lakes in the Burnt Lake area (Tp. 67 - R. 3) were ranked as being moderately sensitive to acidic deposition, based on pH and calcium criteria.

Net critical loads of lakes were calculated by determination of the gross critical load from the Henriksen model, and subtracting the PAI determined in the air quality component of this study. In the southern portion of the study area, the net critical load ranged between 1.49 keq H^+/ha/yr and 9.15 keq H^+/ha/yr. The average net critical load observed in these lakes was 4.47 keq H^+/ha/yr. In the northern portion, the net critical load ranged between 0.42 keq H^+/ha/yr and 3.32 keq H^+/ha/yr. The average net critical load observed in these lakes was 1.28 keq H^+/ha/yr.

Regression analyses between several indicator parameters were computed between major water quality parameters reflecting buffering capacity and critical load for lakes. Strong relationships were found between major cations, alkalinity and conductivity, all of which reflect the buffering capacity in a water body. The use of regression equations developed between gross critical load, alkalinity and specific conductivity is suggested as a useful method to monitor acid deposition and lake sensitivity throughout the study area.

Monitoring is recommended for lakes with critical loads <0.50 keq H^+/ha/yr. Lakes with relatively low critical loads that occur in the Burnt Lake area are particularly recommended for monitoring because future acid deposition could approach critical load levels, based on acid deposition predictions in environmental impact assessments in the region. Monitoring of other lakes within the PAI isopleth >0.17 keq H^+/ha/yr should also be considered. Although these lakes have relatively high critical loads, they may be considered for monitoring as they are located in areas most likely to receive higher PAI in the future.

The information presented, particularly the data from monitoring programs, is suggested as being sufficient to assist design of a monitoring program. An important consideration is that the monitoring locations should be based on habitat sensitivity and acid depositional factors. In this regard, consideration should be given to co-location of water quality and air monitoring stations.

The potential effects of acid deposition on soils and vegetation in the LICA area were examined by assessing and mapping the sensitivity of soils to acidic and acidifying substances, determining the potential exceedances of acidity for soils based on proposed critical load levels, and reviewing information about soil and vegetation monitoring in the study area.

The mapping of soil sensitivity suggests that more than half of the LICA area is characterized by soils that are Sensitive to acidic soil inputs, or are mixtures of Sensitive with Moderate or Low Sensitivity soils. Soils that are recognized as being most sensitive are Brunisols characterized by very sandy textures. These soils have low acid buffering capacity and low nutrient content. However, the largest area of Sensitive soils is represented by the Athabasca and related series, which are Gray Luvisols developed on morainal deposits. While the subsoils of these Luvisols are generally well buffered, the surface textures are mainly very sandy and weakly buffered. These soils occur mainly in the northern part of the LICA area.

Critical load exceedances may occur presently in some areas. A small area located immediately northeast of Leming Lake with PAI >0.25 keqmol H^{+}/ha/yr represents an area in which the critical load of Sensitive soils is potentially exceeded. A relatively small area encircling the latter represents the area of target load exceedance, and a somewhat larger extending southeast beyond the City of Cold Lake represents an area of monitoring load exceedance. A second area exceeding the monitoring load for sensitive systems is located between Lindberg and St. Paul. This area has a small proportion of sensitive soils for which the monitoring load is potentially exceeded.

Current monitoring in the LICA area consists solely of long term assessment of a site within the Alberta Environment monitoring program. In existence since the late 1980s, initial results did not show changes in soils chemistry. Examination of recent results is currently being carried out by Alberta Environment.

Vegetation sensitivity to acidification has been reviewed in environmental impact assessments in the LICA region. Monitoring by remote sensing has not revealed any effects of acidic emissions. Also, field observation and laboratory analysis of plant tissue has indicated generally healthy appearance and low sulphur levels of aspen leaves, indicating that there was no direct impact to vegetation on the study area from SO_2 emissions.

A number of recommendations related to monitoring soil impacts are presented. The main recommendations are: establishment of soil chemistry monitoring sites additional to the single Alberta Environment site; co-location of soil and vegetation monitoring sites with air quality monitoring sites; conducting further in-depth analysis of soil types, their acidification sensitivity, and their critical loads similar to the grid-cell approach applied in the Provost-Esther area; and, maintaining awareness and participating to the extent possible in monitoring and research programs conducted by the NO_X-SO_2 Management Program of CEMA and the Terrestrial Environmental Effects Monitoring programs in the oil sands region.

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Glossary of Terms Abbreviations and Symbols

$\mu g/m^3$	micrograms per cubic metre
AENV	Alberta Environment
anion	Ion with a negative charge
bpd	Barrel(s) per day
Ca^+	Calcium ion
CASA	Clean Air Strategic Alliance
cation	Ion with a positive charge
Cl^-	Chloride ion
cm/s	centimetre per second
CNRL	Canadian Natural Resources Limited
CSS	Cyclic Steam Stimulation
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EUB	Alberta Energy and Utilities Board
Exceedance	An emission whose measured values is more than that allowed by government regulations
HNO_2	Nitrous acid
HNO_3	Nitric acid
in situ	A approach to remove the bitumen from the sand while the oil sands deposits is still in place underground
K^+	Potassium ion
keq	kmol H^+, kilomole hydrogen ion equivalents
keq/ha/yr	Kilomole hydrogen ion equivalents per hectare per year
kg/ha/yr	kilogram per hectare per year
LICA	Lakeland Industry and Community Association
m/s	Wind speed unit, meters per second
mg/L	milligrams per litre
Mg^+	Magnesium ion
Na^+	Sodium Ion
NAD 83	North American Datum 1983, Geographic coordinate system
NAtChem	National Atmospheric Chemistry database
NH_4^+	Ammonium ion
NO_2	Nitrogen dioxide
NO_3^-	Nitrate ion
NO_x	Oxides of nitrogen (NO +NO_2)
PAI	Potential Acid Input
$PM_{2.5}$	Particulate Matter emissions with particle diameter less than 2.5 μm
precipitation	The rain and snow that falls on the earth's surface
RELAD	Regional Lagrangian Acid Deposition model
SAGD	Steam Assisted Gravity Drainage
SO_2	Sulphur dioxide
SO_4^{2-}	Sulphate ion

T/d	tonnes per day
UTM	Universal Transverse Mercator (cartography), map coordinate system
WBEA	Wood Buffalo Environmental Association
WHO	World Health Organization

1.0 INTRODUCTION

The Lakeland Industry and Community Association (LICA) has as one of its goals the collection, analysis, and communication of data regarding water and air monitoring. Through the LICA Airshed Zone and the Regional Environmental Water Monitoring Committee, its goals include understanding of air quality issues and related impacts on soil chemistry and productivity, and on water quality. LICA has to date determined that neither regional nor site-specific monitoring conducted in the LICA area appear to indicate that acidic deposition is an issue locally, but it is a concern in other parts of the province and is included in LICA's terms of reference. In response to growing concerns over the potential effects of projected industrial growth in the Cold Lake region, LICA has commissioned an exploratory study of the potential acidification impacts on soils as well as surface waters within the LICA area.

This study has three main components. The effects of potential emissions of oxides of nitrogen (NO_X) and sulphur dioxide (SO_2) on acid deposition in the LICA region are examined. The intent of this component is to compile and analyze existing data from the LICA regional air monitoring network that can give an indication of the extent of deposition in the area, and the extent of any resulting impacts. An outcome of this study is the prediction of Potential Acid Input (PAI) levels in the LICA area. The second component provides an assessment of surface water sensitivity to acidification and analyzes this in relation to the PAI levels. Likewise, the soils component assesses soil sensitivity in relation to PAI estimates. The latter component also includes an overview of potential vegetation impacts.

1.1 STUDY AREA

The study area is referred to as the original LICA Geographical Area (LICA 2005). It extends from the Fourth Meridian (the Saskatchewan borer) to Range 8, inclusive, with varying portions of Range 9. North to south, the study area extends from the middle of Township 73 to Township 55, inclusive, and includes most of Township 54 within Ranges 7 and 8; about a third of Township 53 within Ranges 3, 4 and 5; Township 53, Ranges 1 and 2; and, and the upper part of Township 52 within Ranges 1 and 2.

The LICA study area lies within three ecoregions as described in the National Ecological Framework for Canada (Marshall and Schut 1999). The descriptions below are taken directly from the National Ecological Framework website (http://www.ec.gc.ca/soer-ree/English/Framework/Nardesc/praire_e.cfm).

The southern part, from Township 52 at the Saskatchewan border to about Townships 57 and 58 in Ranges 8 and 9, occurs within the Aspen Parkland Ecoregion. This ecoregion "extends in a broad arc from southwestern Manitoba, northwestward through Saskatchewan to its northern apex in central Alberta. The parkland is considered transitional between the boreal forest to the north and the grasslands to the south. The climate is marked by short, warm summers and long, cold winters with continuous snow cover. The mean annual temperature is approximately 1.5°C. The mean summer temperature is 15°C and the mean winter temperature is -12.5°C. The mean annual precipitation ranges 400-500 mm. The ecoregion is classified as having a transitional grassland ecoclimate. Most of the ecoregion is now farmland but in its native state, the landscape was characterized by trembling aspen, oak groves, mixed tall shrubs, and intermittent fescue grasslands. Open stands of trembling aspen and shrubs occur on most sites, and bur oak (in Manitoba) and grassland communities occupy increasingly drier sites on loamy Black Chernozemic soils. Poorly drained, Gleysolic soils support willow and sedge species. This broad plains region, underlain by Cretaceous shale, is covered by undulating to kettled, calcareous, glacial till with significant areas of level lacustrine and hummocky to ridged fluvioglacial deposits. Associated with the rougher hummocky, glacial till landscapes are numerous tree-ringed, small lakes, ponds, and sloughs that provide a major habitat for waterfowl. ..... Owing to its favourable climate and fertile, warm black soils, this ecoregion represents some of the most productive agricultural land in the Prairies. It produces a wide diversity of crops, including spring wheat and other cereals, oilseeds, as well as forages and several specialty crops. Dryland continuous cropping methods for spring wheat and other cereal grains are prevalent." This ecoregion generally corresponds with the Black Soil Zone in Alberta.

The middle part of the ecoregion, to the north of the Aspen Parkland and extending to Townships 63 and part of 64 in the northeast, is within the Boreal Transition Ecoregion. "This ecoregion extends from southern Manitoba to central Alberta. The ecoregion is characterized by warm summers and cold winters. The mean annual temperature is approximately 1°C. The mean summer temperature is 14°C and the mean winter temperature is -13.5°C. The mean annual precipitation ranges from 450 mm in the west to 550 mm in the east. The ecoregion is classified as having a subhumid low boreal ecoclimate. As part of the dominantly deciduous boreal forest, it is characterized by a mix of forest and farmland. It marks the southern limit of closed boreal forest and northern advance of arable agriculture. A closed cover of tall, trembling aspen with secondary quantities of balsam poplar, a thick understory of mixed herbs, and tall shrubs is the predominant vegetation. White spruce and balsam fir are the climax species, but are not well represented because of fires. Poorly drained sites are usually covered with sedges, willow, some black spruce, and tamarack. Underlain by Cretaceous shale, this hummocky to kettled plain is covered by calcareous, glacial till and significant inclusions of relatively level lacustrine deposits. Associated with the rougher morainal deposits are a large number of small lakes, ponds, and sloughs occupying shallow depressions. The region drains northeastward via the Saskatchewan River system. Well- to imperfectly drained Gray Luvisols and Dark Gray Chernozemic soils are predominant. Local areas of Black Chernozemic, peaty Gleysolic, and Mesisolic soils also occur. The region also provides habitat for white-tailed deer, black bear, moose, beaver, coyote, snowshoe hare, and cottontail. It also provides critical habitat for large numbers of neotropical migrant bird species, as well as ruffed grouse and waterfowl. Over 70% of the ecoregion is farmland, spring wheat and other cereals, oilseeds, and hay are the dominant crops. Other land uses include forestry, hunting, fishing, and recreation."

The northern part of the LICA area, northward from the southern to middle part of Township 63 in Ranges 1-5, and from the middle of Township 64 within Ranges 6-9, is within the Mid-Boreal Uplands Ecoregion. "This mid-boreal ecoregion occurs as 10 separate, mostly upland areas, south of the Canadian Shield, stretching from north-central Alberta to southwestern Manitoba. Itincludes remnants of the Alberta Plateau in Alberta ...... The climate has predominantly short,cool summers and cold winters. The mean annual temperature ranges from -1°C to 1°C. The mean summer temperature ranges from 13°C to 15.5°C and the mean winter temperature ranges from -13.5°C to -16°C. Some areas of the ecoregion can be very cold with winter mean temperatures exceeding -17°C in northern Alberta. The mean annual precipitation ranges 400-550 mm. The ecoregion is classified as having a predominantly subhumid mid-boreal ecoclimate. These uplands form part of the continuous mid-boreal mixed coniferous and deciduous forest extending from northwestern Ontario to the foothills of the Rocky Mountains. Medium to tall, closed stands of trembling aspen and balsam poplar with white and black spruce, and balsam fir occurring in late successional stages, are most abundant. Deciduous stands have a diverse understory of shrubs and herbs; coniferous stands tend to promote feathermoss. Cold and poorly drained fens and bogs are covered with tamarack and black spruce. Consisting for the most part of Cretaceous shales, these uplands are covered entirely by kettled to dissected, deep, loamy to clayey-textured glacial till, lacustrine deposits, and inclusions of coarse, fluvioglacial deposits. Elevations range from about 400 to over 800 m asl. Associated with rougher morainal deposits are a large number of small lakes, ponds, and sloughs occupying shallow depressions. Permafrost is very rare and found only in peatlands. Well-drained Gray Luvisolic soils are dominant in the region. Significant inclusions are peaty-phase Gleysols and Mesisols that occupy poorly drained depressions. Dystric Brunisols occur on droughty, sandy sites. In Alberta, the ecoregion slopes gently and drains northward via the Athabasca and Clearwater rivers and their tributaries. .... Pulpwood and local sawlog forestry, water-oriented recreation, hunting, and trapping are the main land use activities. Agricultural activities are significant in southern parts of the ecoregion..." main land use activities. Agricultural activities are significant in southern parts of the ecoregion..." Oil and gas extraction and processing, including heavy oil production, has also become a significant land use in the last two decades.

2.0 AIR QUALITY

2.1 INTRODUCTION

Deposition of sulphur and nitrogen compounds includes both wet and dry processes and can result in the long-term accumulation of atmospheric pollutants in aquatic and terrestrial ecosystems. Wet processes involve the removal of these atmospheric pollutants by precipitation. Dry processes involve the removal by direct contact with surface features (e.g., vegetation, soils and surface water). The deposition of sulphur and nitrogen compounds to these systems has been associated with changes in water and soil chemistry and with the acidification of water and soil.

The mandate of the exploratory study is to obtain an understanding of the impacts associated with air emissions of oxides of nitrogen (NO_X) and sulphur dioxide (SO_2) on acid deposition in the LICA area. The study comprises compilation and analysis of current data from the LICA regional air monitoring network that can give an indication of the extent of deposition in the area, and the extent of any resulting impacts. No additional measurements or monitoring were undertaken as part of this study.

2.2 ACID DEPOSITION DEFINITION AND CRITERIA

2.2.1 Potential Acid Input Definition

The preferred method for evaluating acid deposition is to determine the Potential Acid Input (PAI), which takes into account the acidification effect of sulphur and nitrogen species as well as the neutralizing effect of available base cations.

Both wet and dry depositions are expressed as a flux in units of kg/ha/yr. Where more than one acidifying chemical species is considered, the flux is often expressed in keq/ha/yr where a kiloequivalent (keq) is defined as a kilomole (kmol) of hydrogen ions produced from compounds containing sulphur and nitrogen that are deposited to the soil surface.

The potential acid input (PAI) in units of keq/ha/yr can be calculated from wet and dry deposition. In the following equations, the deposition of acid-causing ions (- superscript) and base ions (+ superscript) are in square brackets. Wet deposition values are those measured in precipitation. Dry values are often inferred from concentration measurements. The calculation of PAI is from both the wet deposition and the particulate dry deposition of SO_4^{2-}, NO_3^-, NH_4^+, K^+, Na^+, Ca^{2+} and Mg^+.

$$\mathbf{PAI_{wet}}\,(\text{keq/ha/yr}) = 2\frac{[SO_4^{2-}]}{96} + \frac{[NO_3^-]}{62} + \frac{[NH_4^+]}{18} - \left(\frac{[K^+]}{39} + \frac{[Na^+]}{11} + 2\frac{[Ca^{2+}]}{40} + 2\frac{[Mg^{2+}]}{24}\right) \quad (1)$$

$$\textbf{PAI}_{\textbf{dry}}\ \text{(keq/ha/yr)} = 2\frac{[SO_4^{2-}]}{96} + \frac{[NO_3^-]}{62} - \left(\frac{[K^+]}{39} + \frac{[Na^+]}{11} + 2\frac{[Ca^{2+}]}{40} + 2\frac{[Mg^{2+}]}{24}\right) \qquad (2)$$

The numerical values in the denominator are the molecular weights of the compounds and ions represented in the numerator in the above equations.

$$\textbf{Total PAI} = PAI_{wet} + PAI_{dry} \qquad (3)$$

Although NH_4^+ is a cation, once in the soil it oxidizes into nitrate that can acidify the soil (this is the so-called "nitrification process"). Chloride (Cl^-) is not included in the Alberta PAI definition (Cheng 2007) as it is not a major contributor to the anion count.

2.2.2 Potential Acid Input Criteria

Critical, target and monitoring loads for management of acid deposition in Alberta were established on the basis of the work of the CASA Target Loading Subgroup (CASA and AENV 1999). The loads defined by this committee and accepted by AENV were specifically tied to management of deposition based upon predictions of the RELAD model over 1° latitude by 1° longitude grid cells, and based upon the specific definitions of receptor sensitivity. The management levels for the most sensitive ecosystems (Table 1) proposed by CASA and AENV (1999) are:

- A **monitoring load** of 0.17 keq/ha/yr for the most sensitive ecosystem that will trigger monitoring or research action;
- A **target load** of 0.22 keq/ha/yr that is the maximum acceptable deposition that provides long-term protection from adverse ecological consequences to the most sensitive ecosystem components, and is practically achievable; and
- A **critical load** of 0.25 keq/ha/yr that will not result in chemical changes and long-term harmful effects to the most sensitive ecosystem components.

Table 1: Deposition Loads by Receptor Sensitivity

Deposition Load	Receptor Sensitivity	Potential Acid Input (keq/ha/yr)
Critical	Sensitive	0.25
	Moderate	0.50
	Low	1.00
Target	Sensitive	0.22
	Moderate	0.45
	Low	0.90
Monitoring	Sensitive	0.17
	Moderate	0.35
	Low	0.70

Source: CASA and AENV (1999)

The CASA approach is based on the European approach outlined in WHO (1994).

2.2.3 Approach to Potential Acid Input Estimation

As indicated above, PAI criteria are based on RELAD model predictions. These predictions are made over 1° by 1° degree areas and therefore have limited utility for decision making over an area the size of the LICA airshed zone.

Current AENV criteria are designed for provincial-scale management of PAI and to identify areas that are potentially at risk of becoming acidified. Upon identifying such areas, actions towards confirming the acidification sensitivity of these areas are to be taken. The provincial acid deposition management framework considers only predictions over 1° by 1° degree. AENV has recently remodelled PAI on the provincial scale and is currently reviewing its management plan. A report is expected at any time.

Given that RELAD modelling is at a scale too coarse for LICA decision making, this investigation considered monitoring data in the region. The PAI estimates that are used for the spatial assessment of potential impacts on soil, vegetation and surface water are those calculated from the LICA passive monitors.

The approach herein was to include modelled deposition results from the most recent Application in the area (CNRL Primrose East), to provide context and to serve as a cross check for the values calculated based on LICA measurements. The comparison is valid in the northern part of the region where modelling results and monitoring overlap.

2.3 OBSERVATIONS AND ESTIMATES OF POTENTIAL ACID INPUT

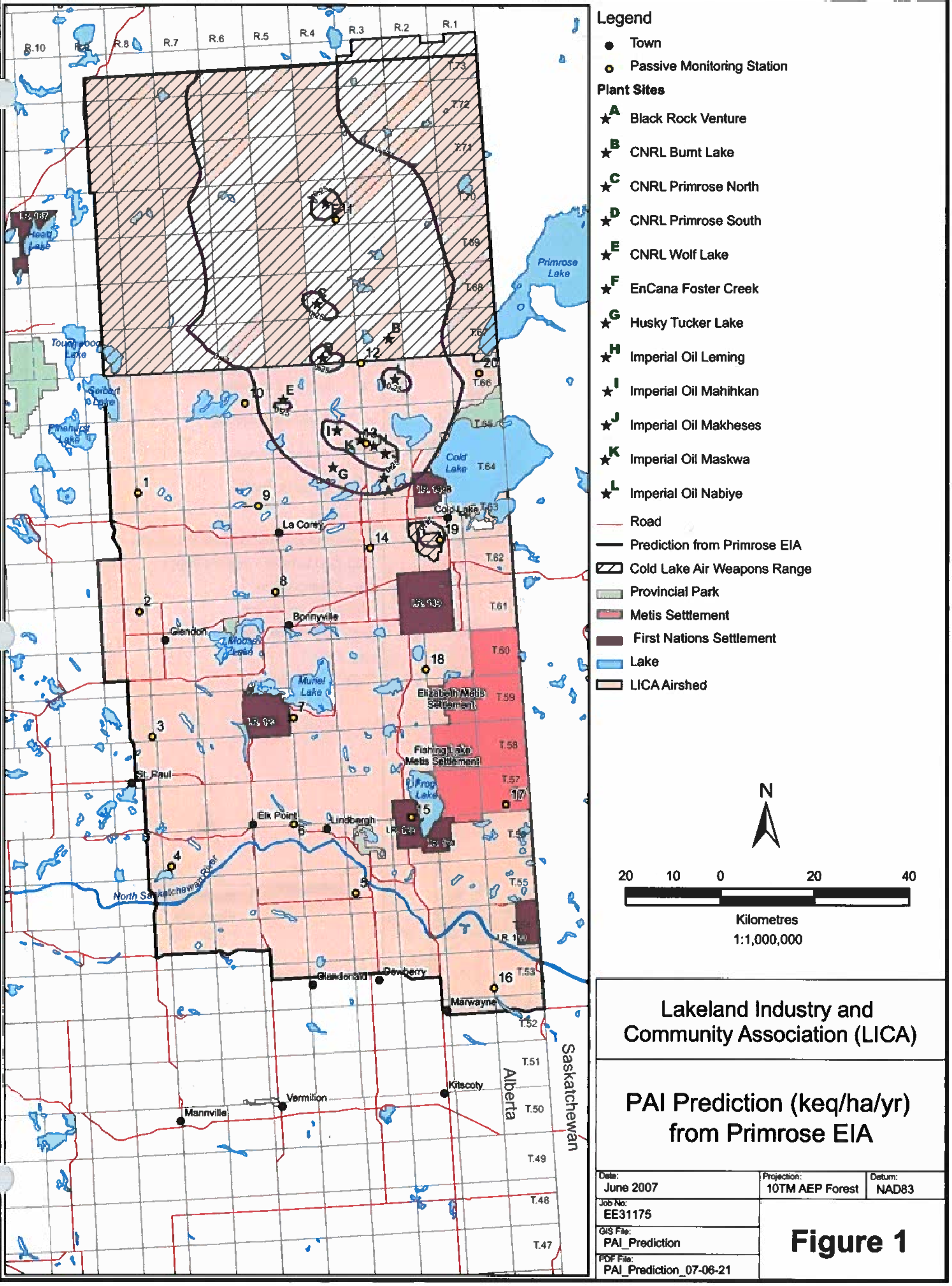
2.3.1 LICA Passive Network

Since July 2003, LICA has operated a 20-station passive network consisting of a strategic distribution of nitrogen dioxide, ozone, sulphur dioxide, and hydrogen sulphide monitors. In late October 2005, LICA commissioned a continuous air monitoring trailer, owned by Alberta Environment (AENV) and operated by LICA, in the City of Cold Lake. The trailer is equipped to continuously measure sulphur dioxide, nitrogen dioxide, oxides of nitrogen, ozone, total hydrocarbons, total reduced sulphur, particulate matter ($PM_{2.5}$), wind speed, and wind direction. A twenty-first station was added in April 2005 but data from this station was not used in this study. Additional stations were added in late 2006 and are also not included in this assessment.

Table 2 lists the locations of the 20 passive monitoring stations in the LICA area. The continuous monitoring is co-located with passive station #19 (Cold Lake South). Figure 1 shows the all stations.

Table 2: Monitoring Stations in the LICA Area

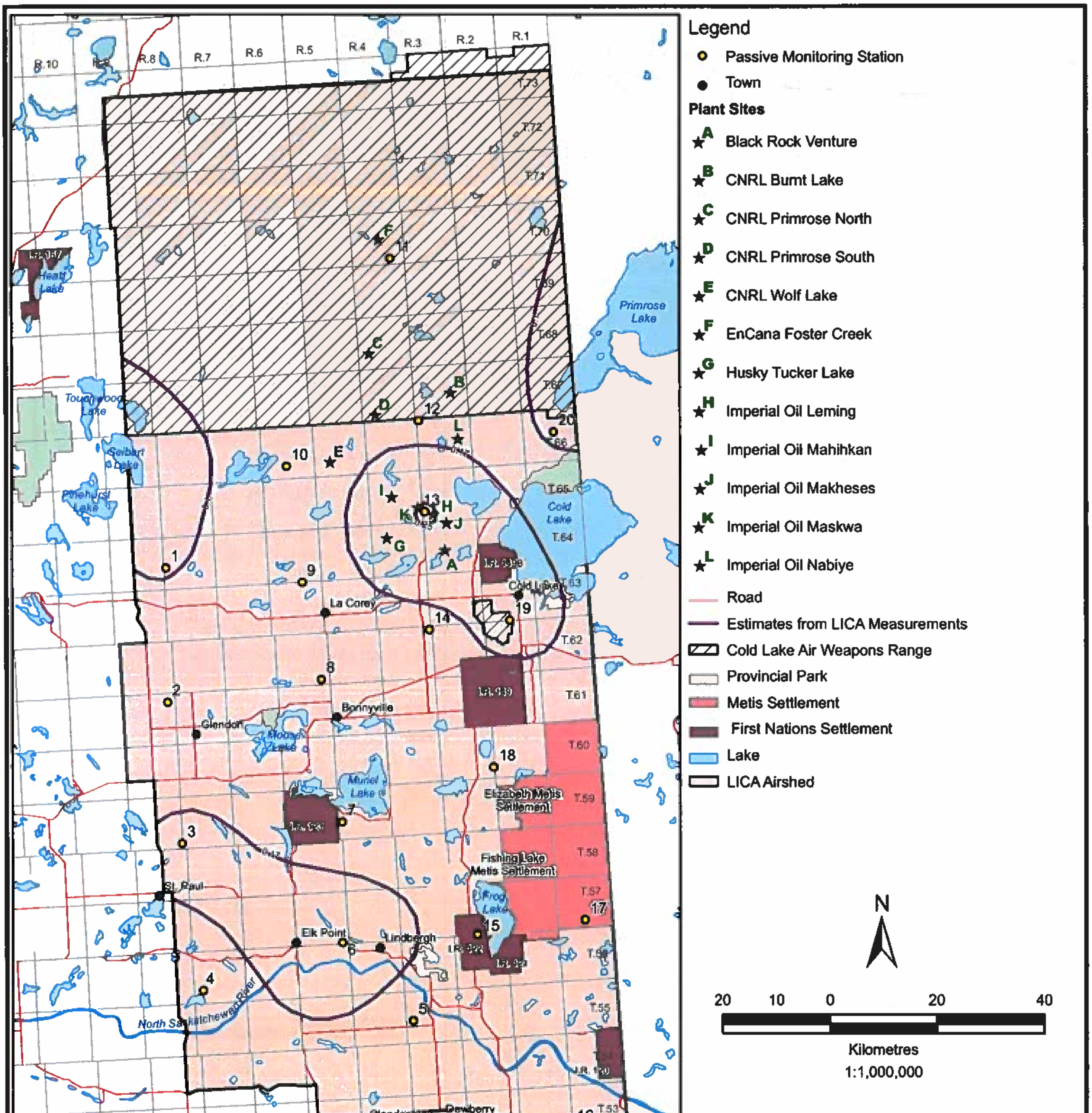
Station No	Station Name	Location				
		Legal	Lat/Long (WGS 84)		UTM (NAD 83, Zone 12)	
			Latitude N	Longitude W	m E	m N
1	Sand River	6-18-64-8-W4M	54.53658	111.20898	486478.0	6043244.9
2	Therien	13-25-61-9-W4M	54.31085	111.22607	485292.0	6018131.4
3	Flat Lake	9-1-59-9-W4M	54.07262	111.20510	486579.2	5991620.6
4	Lake Eliza	12-8-56-8-W4M	53.82417	111.16605	489069.7	5963971.5
5	Telegraph Creek	9-18-55-4-W4M	53.75308	110.57797	527827.4	5956132.8
6	Elk Point Airport	3-1-57-6-W4M	53.89118	110.76460	515470.6	5971440.4
7	Muriel-Kehewin	13-7-59-6-W4M	54.09340	110.74437	516719.1	5993943.7
8	Bonnyville	12-1-62-6-W4M	54.33462	110.77965	514327.7	6020774.7
9	La Corey	8-34-63-6-W4M	54.49967	110.81792	511792.1	6039132.4
10	Wolf Lake	8-9-66-6-W4M	54.69542	110.84253	510149.1	6060910.0
11	Foster Creek	11-02-70-4-W4M	55.03343	110.50453	531667.8	6098624.0
12	Burnt Lake	9-36-66-4-W4M	54.75848	110.45217	535254.1	6068053.8
13	Maskwa	3-7-65-6-3-W4M	54.60518	110.45263	535357.1	6050995.7
14	Ardmore	10-36-62-4-W4M	54.40670	110.46202	534919.7	6028906.2
15	Frog Lake	4-21-57-3-W4M	53.89065	110.38418	540472.0	5971531.2
16	Clear Range	1-12-53-2-W4M	53.55648	110.15423	556026.6	5934510.3
17	Fishing Lake	13-3-57-1-W4M	53.90295	110.07623	560692.5	5973119.3
18	Beaverdam	1-12-60-3-W4M	54.16925	110.30690	545247.6	6002574.7
19	Cold Lake South	4-3-63-2-W4M	54.41370	110.23285	549785.9	6029822.8
20	Medley-Martineau	7-22-66-1-W4M	54.72430	110.06618	560142.9	6064512.6



Lakeland Industry and Community Association (LICA)

PAI Prediction (keq/ha/yr) from Primrose EIA

Date: June 2007	Projection: 10TM AEP Forest	Datum: NAD83
Job No: EE31175	Figure 1	
GIS File: PAI_Prediction		
PDF File: PAI_Prediction_07-06-21		



Lakeland Industry and Community Association (LICA)

PAI Estimates (keq/ha/yr) from LICA Measurement, July 2003 - August 2006

Date: June 2007	Projection: 10TM AEP Forest	Datum: NAD83
Job No: EE31175	**Figure 2**	
GIS File: PAI_Estimates		
PDF File: PAI_Estimates_07-06-21		

2.3.2 Dry Deposition of Nitrate and Sulphate

Average NO_2 and SO_2 concentrations measured from July 2003 to August 2006, as well as calculated sulphate and nitrate deposition, are listed in Table 3. Sulphate and nitrate deposition were calculated as the product of a dry deposition velocity and average ground-level air concentrations. Deposition velocities of 0.58 and 0.19 cm/s were used for SO_2 and NO_2, respectively and are referenced from average values in EPCM (2002).

Equation 4: Dry Deposition (nitrate keq/ha/yr) =

$$[NO_2]\frac{\mu g}{m^3} * 0.19\frac{cm}{s} * \frac{1kg}{10^9\,\mu g} * \frac{0.01m}{1cm} * \frac{1m^2}{0.0001\,ha} * \frac{31536000\ s}{1 year} * \frac{1}{MW\ NO_2\,(46)} * \frac{1keq}{mol}$$

Equation 5: Dry Deposition (sulphate keq/ha/yr) =

$$[SO_2]\frac{\mu g}{m^3} * 0.58\frac{cm}{s} * \frac{1kg}{10^9\,\mu g} * \frac{0.01m}{1cm} * \frac{1m^2}{0.0001\,ha} * \frac{31536000\ s}{1 year} * \frac{1}{MW\ SO_2\,(64)} * \frac{2\ keq}{mol}$$

Table 3: NO_2 and SO_2 Measurements, Nitrate and Sulphate Dry Deposition Estimates, July 2003 to August 2006

Station No.	Meas. Type	NO_2 Concentration ($\mu g/m^3$)	NO_2 Dry Deposition (kg/ha/yr)	Nitrate Equiv. Dry Deposition (keq/ha/yr)	SO_2 Concentration ($\mu g/m^3$)	SO_2 Dry Deposition (kg/ha/yr)	Sulphate Equiv. Dry Deposition (keq/ha/yr)
1	Passive	2.14	1.3	0.03	0.63	1.1	0.04
2	Passive	3.75	2.3	0.05	1.12	2.1	0.06
3	Passive	3.41	2.1	0.05	1.77	3.2	0.10
4	Passive	3.14	2.0	0.04	1.40	2.6	0.08
5	Passive	4.19	2.6	0.06	1.12	2.0	0.06
6	Passive	7.38	4.6	0.10	1.19	2.2	0.07
7	Passive	3.04	1.9	0.04	1.34	2.4	0.08
8	Passive	3.75	2.3	0.05	1.14	2.1	0.07
9	Passive	3.38	2.1	0.05	0.99	1.8	0.06
10	Passive	1.95	1.2	0.03	0.94	1.7	0.05
11	Passive	2.41	1.5	0.03	1.15	2.1	0.07
12	Passive	2.45	1.5	0.03	1.37	2.5	0.08
13	Passive	3.85	2.4	0.05	3.17	5.8	0.18
14	Passive	3.68	2.3	0.05	1.10	2.0	0.06
15	Passive	3.98	2.5	0.05	1.34	2.4	0.08
16	Passive	4.31	2.7	0.06	1.26	2.3	0.07
17	Passive	3.43	2.1	0.05	1.03	1.9	0.06
18	Passive	2.91	1.8	0.04	1.22	2.2	0.07
19	Passive	5.42	3.4	0.07	1.00	1.8	0.06
20	Passive	1.12	0.7	0.02	0.70	1.3	0.04
21[z]	Continuous	6.23	3.9	0.08	1.32	2.4	0.08

[z] Period of record for continuous station is November 2005 through August 2006.

Nitrate dry deposition values ranged from 0.02 to 0.10 keq/ha/yr and sulphate dry deposition values ranged from 0.04 to 0.18 keq/ha/yr in all LICA monitoring stations during the mid-2003 to mid-2006 period. Co-located concentration measurements and deposition estimates using passive and continuous samples show good agreement overall (within about 20%) given the differences in monitoring period.

2.3.3 Wet Deposition

Precipitation chemistry measurements are made periodically throughout the year at the Environment Canada Cold Lake station. Monthly precipitation rates were used to calculate wet deposition. Table 4 summarizes precipitation chemical composition from 2003 to 2005 at Cold Lake, taken from the CASA data warehouse.

Table 4: Wet Deposition Rates (kg/ha/yr) in Precipitation at Cold Lake, 2003-2005

	Sulphate SO_4^{2-}	**Nitrate NO_3^-**	**Ammonium NH_4^+**	**Sodium Na^+**	**Potassium K^+**	**Calcium Ca^{2+}**	**Magnesium Mg^{2+}**
2003	2.10	2.61	1.22	0.03	0.11	0.96	0.14
2004	2.06	2.35	0.86	0.04	0.12	0.56	0.10
2005	2.01	1.29	1.29	0.07	0.31	0.58	0.40
Average	**2.06**	**2.08**	**1.12**	**0.04**	**0.18**	**0.70**	**0.21**

Table 5 summarizes equivalent rates of wet deposition calculated from the precipitation chemistry measurements (equation 1). PAI wet deposition is calculated by the equation listed in Section 2.1. The average PAI wet deposition during 2003 to 2005 at the Environment Canada Cold Lake station, which is taken to be representative of the LICA area because it is the nearest station to the area, was 0.08 keq/ha/yr.

It should be noted that PAI wet deposition appears to be trending lower over the three years considered in this assessment, due largely to a reduction in nitrate deposition. However, reductions in nitrate deposition at this station are unknown; possible reasons for lower nitrate values may be related to year to year variations in atmospheric concentration of the pollutant, and/or varying weather conditions.

Table 5: Wet Deposition Rates (keq/ha/yr) at the Cold Lake Station, 2003-2005

	Sulphate SO_4^{2-}	Nitrate NO_3^-	Ammonium NH_4^+	Sodium Na^+	Potassium K^+	Calcium Ca^{2+}	Magnesium Mg^{2+}	PAI Wet Deposition
2003	0.044	0.042	0.068	0.001	0.003	0.048	0.0118	0.090
2004	0.043	0.038	0.048	0.002	0.003	0.028	0.0084	0.087
2005	0.042	0.021	0.072	0.003	0.008	0.029	0.0326	0.062
Average	**0.043**	**0.034**	**0.062**	**0.002**	**0.005**	**0.035**	**0.018**	**0.080**

2.3.4 Dry Deposition of Cations

Eder and Dennis (1990) developed a general linear regression method to estimate surface-level air concentrations of Na^+, Ca^{2+}, Mg^{2+}, and K^+ from precipitation concentrations. Monthly measured air concentrations at Beaverlodge and Esther from 1991 to 1999 were then used to develop a regression to be used in western Canada by Chaikowsky (2001). Table 6 lists the equations and their regression correlation values for the relationship between air concentrations (in µg/m^3) of Na^+, Ca^{2+}, Mg^{2+}, and K^+ and precipitation concentrations (in mg/L).

Table 6: Alberta (Beaverlodge and Esther) Linear Regression Equations

Cation	Linear Regression Equations[Z]	Correlation
Na^+	Air conc. = 0.5414(Prec. conc.) + 0.0279	0.84
Ca^{2+}	Air conc. = 0.1906(Prec. conc.) + 0.1166	0.32
Mg^{2+}	Air conc. = 0.3459(Prec. conc.) + 0.0147	0.86
K^+	Air conc. = 0.2958(Prec. conc.) + 0.0285	0.35

[Z] From Chaikowsky (2001).

Table 7 lists the mean precipitation chemistry data for 2003 and 2004 at the Environment Canada Cold Lake station obtained from Canadian National Atmospheric Chemistry (NAtChem) database. Table 8 lists the air concentration of cations estimated by the Alberta regression equation shown in Table 6 and their dry deposition rates. The dry deposition rates are estimated by multiplying the air concentration of cations with the dry deposition velocity, and the resulting deposition rate is expressed in units of keq/ha/yr. Because of the large variation in deposition velocities, a typical deposition velocity of 0.01 m/s, as suggested by Eder and Dennis (1990), was used for all cations.

Table 7: Precipitation Cation Composition at Cold Lake, 2003-2004

	Na^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)
2003	0.108	0.366	0.054	0.06
2004	0.103	0.156	0.029	0.037
Average	**0.103**	**0.300**	**0.052**	**0.049**

Table 8: Dry Cation Deposition Rates at Cold Lake, 2003-2004

	Sodium Na^+	Calcium Ca^{2+}	Magnesium Mg^{2+}	Potassium K^+	Total Dry Cation
Concentration (µg/m^3)					
2003	0.086	0.186	0.033	0.046	0.352
2004	0.084	0.146	0.025	0.039	0.294
Dry deposition (keq/ha/yr)					
2003	0.0118	0.0294	0.0087	0.0037	0.054
2004	0.0115	0.0231	0.0064	0.0032	0.044
Average	**0.0117**	**0.0262**	**0.0075**	**0.0035**	**0.049**

The average dry deposition rate of cations is 0.049 keq/ha/yr as illustrated in Table 8. The cation concentration values can be compared to values from the Surmont EIA (Gulf Canada 2001) which indicated that regional background Ca^{2+}, Mg^{2+} and K^+ concentrations in the oilsands area were based on WBEA observations and are 0.048, 0.057 and 0.346 µg/m^3, respectively, which are slightly larger but comparable to the values in Table 8.

2.3.5 Potential Acid Input

Potential acid input (PAI) deposition rates at 20 passive monitoring stations as well as one continuous monitoring station are estimated from measurements from 2003 to 2006 and listed in Table 9. This table is based on information provided in Tables 3 to 8. Total PAI is calculated using equation (3).

The PAI estimates in Table 9 show substantial spatial variability with the smallest values (0.086 keq/ha/yr) based on passive measurements at Medley – Martineau (#20) and the largest values (0.264 keq/ha/yr) at Maskwa (#13).

PAI estimates at three passive stations (Flat Lake, Elk Point Airport and Maskwa) are higher than the CASA monitoring load of 0.17 keq/ha/yr for the most sensitive ecosystems. Subsequent sections of this report present information to determine the sensitivity of ecosystems and water bodies near these locations.

2.4 UNCERTAINTY IN PAI DEPOSITION ESTIMATES

Passive measurements are widely used in Alberta to provide monthly estimates of the concentrations of SO_2 and NO_2 which contribute to acid deposition. The passive monitoring approach is considered to provide reasonable long-term average concentration measurements.

The LICA regional PAI estimates were based on deposition velocity measurements made in the oilsands region. These deposition velocities are applied uniformly throughout the region and are most applicable for northern, non-agricultural parts of the oilsands area. Use of the oilsands deposition velocity measurements lends itself to uncertainty in the PAI estimation for the LICA region, as this region's land use is more diverse than that of the oilsands region.

The level of uncertainty in deposition velocities is governed by key variables such as surface wetness, seasonal leaf area index (LAI), turbulence, temperature, solar radiation and surface characteristics, which add to the level of uncertainty in the estimate of dry acidic deposition. The range in deposition velocity from oil sands measurements at passive monitoring sites in a variety of cover types in 1999 (EPCM 2002) was 0.44 to 0.59 cm/s for SO_2 and 0.13 to 0.25 cm/s for NO_2. The values used in the current evaluation are at the high end of this range for SO_2 and average for NO_2.

Table 9: PAI Estimates from Measurements, July 2003- August 2006

Station No.	Meas. Type	Nitrate	Sulphate	PAI	Cations	Total PAI
		Dry Deposition (keq/ha/yr)	Dry Deposition (keq/ha/yr)	Wet Deposition (keq/ha/yr)	Dry Deposition (keq/ha/yr)	Deposition (keq/ha/yr)
1	Passive	0.03	0.04	0.08	0.049	0.096
2	Passive	0.05	0.06	0.08	0.049	0.146
3	Passive	0.05	0.10	0.08	0.049	**0.178**
4	Passive	0.04	0.08	0.08	0.049	0.154
5	Passive	0.06	0.06	0.08	0.049	0.151
6	Passive	0.10	0.07	0.08	0.049	**0.199**
7	Passive	0.04	0.08	0.08	0.049	0.148
8	Passive	0.05	0.07	0.08	0.049	0.147
9	Passive	0.05	0.06	0.08	0.049	0.133
10	Passive	0.03	0.05	0.08	0.049	0.111
11	Passive	0.03	0.07	0.08	0.049	0.129
12	Passive	0.03	0.08	0.08	0.049	0.143
13	Passive	0.05	0.18	0.08	0.049	**0.264**
14	Passive	0.05	0.06	0.08	0.049	0.144
15	Passive	0.05	0.08	0.08	0.049	0.161
16	Passive	0.06	0.07	0.08	0.049	0.161
17	Passive	0.05	0.06	0.08	0.049	0.136
18	Passive	0.04	0.07	0.08	0.049	0.140
19	Passive	0.07	0.06	0.08	0.049	0.161
20	Passive	0.02	0.04	0.08	0.049	0.086
21 [z]	Continuous	0.08	0.08	0.08	0.049	**0.191**

[z] Period of record for continuous station is November 2005 through August 2006.

Cation concentrations and deposition rates as considered in equations 1 and 2 influence PAI estimates. Cation emissions, ambient concentrations and deposition are not well known and they further contribute to uncertainty in the estimates. There are almost no measurements of dry deposition and only limited data on air concentrations that could be used in connection with inferential models (dry deposition velocities for different land covers) to estimate dry deposition amounts. Bulk deposition, for which there are limited data available in Alberta, capture wet deposition and an unknown part of the dry deposition.

The reliability of wet base cation deposition is relatively high (although few stations in Alberta measure it), while there are greater uncertainties for dry deposition. The estimates of Chaikowsky (2001) are useful but have large uncertainties, as evidenced by the need to infer dry deposition from rainfall chemistry.

2.5 OBSERVATIONS COMPARED TO PREDICTIONS

The acid deposition estimations were compared to modelling results from Primrose East In-Situ Oil Sands Project EIA (CNRL 2006). This step is important as it provides an indication of the relationship between predicted and observed data, and therefore guidance on the use of model results as a performance measure. It also provides guidance on expected increases in acid deposition with projected emissions of acid forming compounds (primarily SO_2 and NO_x) in the region.

Figure 1 shows Existing and Approved case PAI predictions taken from the Primrose East In-Situ Oil Sands Project EIA (CNRL 2006). The model results cover only the area north of Township 60, about two-thirds of the LICA area. Figure 2 shows contours of PAI calculated from observations and Table 10 lists the comparison between observations and predictions based on contour levels.

Model predictions are consistent with measurements where they overlap (8 measurement locations are without corresponding predictions). PAI predictions at Foster Creek and Burnt Lake exceed 0.17 keq/ha/yr, while both estimated PAI are lower than 0.15 keq/ha/yr. PAI estimates from continuous monitoring data are consistent with model predictions and both exceed 0.17 keq/ha/yr, while the PAI estimated from co-located passive samples is 0.16 keq/ha/yr.

Emissions used in modelling may be higher than those contributing to measured values for two reasons:

- Emissions for some facilities used in the Primrose East model are higher than actual (Appendix A)
- Approved projects that are currently not operating are included in the modelling (examples: CNRL Primrose East CSS Project, Orion)

At the same time, smaller emission sources are not accounted for. The net result is that model emissions are expected to be somewhat higher than actual emissions but this does not invalidate the overall consistency of model predictions with observed values. This implies that model results generated to date in the LICA area can be used with reasonable confidence to predict future changes in acid deposition.

Table 10: Comparison between PAI Estimates from Measurements with Prediction from the Primrose EIA

Station No	Station Name	Meas. Type	PAI Estimates from Measurements	PAI Prediction from Primrose EIA
1	Sand River	Passive	0.096	<0.17
2	Therien	Passive	0.146	<0.17
3	Flat Lake	Passive	0.178	n/a
4	Lake Eliza	Passive	0.154	n/a
5	Telegraph Creek	Passive	0.151	n/a
6	Elk Point Airport	Passive	0.199	n/a
7	Muriel-Kehewin	Passive	0.148	n/a
8	Bonnyville	Passive	0.147	<0.17
9	La Corey	Passive	0.133	<0.17
10	Wolf Lake	Passive	0.111	<0.17
11	Foster Creek	Passive	0.129	0.17~0.25
12	Burnt Lake	Passive	0.143	0.17~0.25
13	Maskwa	Passive	0.264	>0.25
14	Ardmore	Passive	0.144	<0.17
15	Frog Lake	Passive	0.161	n/a
16	Clear Range	Passive	0.161	n/a
17	Fishing Lake	Passive	0.136	n/a
18	Beaverdam	Passive	0.140	<0.17
19	Cold Lake South	Passive	0.161	0.17~0.25
20	Medley-Martineau	Passive	0.086	<0.17
19c[z]		Continuous	0.191	0.17~0.25

[z] Period of record for continuous station (19C) is November 2005 through August 2006. For stations 1-20 period of record used is July 2003 through August 2006. Primrose EIA results were based on meteorological data from January through December 1995.

2.6 SUMMARY

PAI estimates from observations in the LICA area show spatial variability:

- PAI estimates at Maskwa exceed the CASA 0.25 keq/ha/yr critical load for the most sensitive ecosystems. The value appears to be isolated and is expected to be due to local sources. The nearest facilities are the Maskwa and Lemming plants.
- Values above the monitoring threshold for the most sensitive ecosystems are measured near Cold Lake and in the Lindbergh to St. Paul areas (Flat Lake and Elk Point Airport).
- Estimated PAI deposition at most stations south of Cold Lake's latitude approaches the monitoring threshold for the most sensitive ecosystems. Knowledge of the sensitivity of soils and water bodies in the area to acid input is key to understanding the form of management framework required for the LICA region.

Measurements at the co-located passive and continuous station are reasonably consistent, to within about 20% of each other. Model predictions and observations are also consistent.

The CASA and AENV (1999) framework provides a tool for provincial scale management of acid deposition. The scale of the provincial approach (RELAD predictions averaged over a 1x1 degree area compared to load thresholds) is too coarse for the framework to be used by an airshed such as LICA. While the load thresholds are likely to be useful, LICA will need to rely on finer scale measurements such as those provided by the passive network and on modelling results.

2.7 RECOMMENDATIONS

A number of specific recommendations would help to reduce uncertainty in PAI estimates.

Primrose East model results could be re-plotted to provide greater detail in the results (i.e., more than just the CASA thresholds for the most sensitive ecosystems). This would help in the comparison of observed and predicted PAI but it would likely not change the conclusions of this report.

The locations of passive stations should be plotted relative to industrial and other known sources in the area. This would provide guidance on the spatial extent (or isolated nature) of specific observations such as those at Maskwa and would provide guidance on a management approach.

PAI observations (and model predictions) are influenced by cation concentration and deposition, which are not well known. Further work is needed to quantify cation emission and deposition and its contribution to reducing acidification potential.

3.0 SURFACE WATER

Water bodies can be affected as a result of acid deposition originated by emissions of nitrogen oxides (NO_X) and sulphur dioxide (SO_2). The resistance of waterbodies to acidification effects is represented by the buffering capacity and commonly is assessed by application of critical load values. In this study, the critical loads for different waterbodies are estimated and analyzed. The applicable database for the estimates was computed and the appropriate regression analyses between major acidification potentials and indicative buffering capacity water quality parameters were completed.

The sources of information include LICA area data archives, provincial database sources, as well as industry water quality monitoring programs. The water quality information review includes data analysis of waterbody chemistry, specifically major cations and anions, alkalinity, pH, and total dissolved solids (TDS) and/or electrical conductivity.

Lakes within and bordering the LICA study area were classified based on an acid sensitivity ranking system developed by Saffran and Trew (1996). This approach ranks the sensitivity of a waterbody to acidification based on alkalinity and calcium concentrations, as well as the pH level. Spatial results of the acid sensitivity rankings are presented in this report.

The potential for acidification of standing water is evaluated by comparison of critical loads with spatially correspondent acid input rates (potential acidification input – PAI). The assessment focuses on the potential effects from air emissions and uses monitoring data rather than modelling to estimate the existing level of potential acid deposition in the LICA airshed. The analysis is based on the Henriksen model, which is widely used for analysis of surface water acidification. This approach provides results comparable to other studies in the area and in Alberta.

Regression analyses between several indicator parameters were computed using the available water quality data. The results of this analysis illustrate the relationships between several water quality indicators, establishing relationships between base cation concentrations, critical load, alkalinity and specific conductivity. These results will aid in the future monitoring of lakes in the LICA study area.

In an effort to clearly present the key water quality indicators in a spatial and/or temporal manner, maps were created displaying baseline water quality data, critical loads and acid sensitivity rankings. These maps were created using Geographic Information System (GIS) software, and they provide a useful tool to highlight areas in the study area that can be more sensitive to acid inputs.

Based on the findings of this report, recommendations are presented including further monitoring approaches. The aim is to provide LICA with the most cost effective and useful methods to continue monitoring acid deposition and lake sensitivity throughout the study area.

3.1 DEFINITIONS

The potential effect of acidified emissions on waterbodies can be evaluated using a comparison between predicted acid deposition and critical loads. The assessment method involves calculations of critical loads of acidity for lakes. Critical loads (CL) are then compared to potential acid inputs (PAI). The PAI values for the derived scenarios are obtained from air quality calculation results and determined for the coordinates of each lake. If the PAI value is greater than the calculated critical load, there is potential for acidification of the lake at the current rates of deposition. If the critical load is not exceeded, it implies that the buffering capacity of the lake is adequate to protect the lake from acidification impacts.

3.1.1 Acidification

Acidification is the process by which acids are added to a waterbody, causing a decrease in its buffering capacity (also referred to as alkalinity or acid neutralizing capacity), and ultimately resulting in a significant decrease in pH that may lead to the waterbody becoming acid.

Acid neutralizing or buffering capacity of water is a measure of the ability of water to resist changes in pH caused by the addition of acids or bases and it is, therefore, the main indicator of susceptibility to acid rain. In natural waters it is due primarily to the presence of bicarbonates, carbonates and to a much lesser extent borates, silicates and phosphates. It is expressed in units of milligrams per litre (mg/L) of $CaCO_3$ (calcium carbonate) or as micro-equivalents per litre (μeq/L) where 20 μeq/L = 1 mg/L of $CaCO_3$. A solution having a pH below 5.0 contains no alkalinity.

A scale used to determine the alkaline or acidic nature of a substance is represented by the pH value. The scale ranges from 0-14 with 0 being the most acidic and 14 the most basic. Pure water is neutral with a pH of 7.0.

3.1.2 Critical Load

The term "Critical Load" can be defined using the following definitions:

- The maximum load of deposition required to protect against further acidification or to allow resource recovery.

- The highest deposition of acidifying compounds or other pollutants that will not cause chemical changes leading to long-term harmful effects on the overall structure or function of an ecosystem.

- The maximum amount of acid deposition permissible to protect 95% of lakes in a particular region from acidification (pH < 6), or the threshold above which the pollutant load harms the environment. (http://www.qc.ec.gc.ca/csl/glo/glo002_e.html)

- A measure of how much pollution an ecosystem can tolerate (i.e., the threshold above which the pollution load harms the environment). Different regions have different critical loads. Ecosystems that can tolerate acidic pollution have high critical loads, while sensitive ecosystems have low critical loads. The critical load for aquatic ecosystems is the amount of wet sulphate that must not be exceeded in order to protect 95% of the lakes in a region from acidifying to a pH level of less than 6.0 (http://www.ec.gc.ca/soer-ree/English/Indicator_series/techs.cfm?tech_id=14&issue_id=3&supp=5).

3.2 METHODS

3.2.1 Lake Sensitivity Classification

Acid sensitivity of 37 waterbodies in the LICA study area and 10 waterbodies bordering the northern edge of the study area was assessed using the classification system presented in Saffran and Trew (1996).

Alkalinity and calcium cations were rated on a scale where "high" indicates an increased acidification potential due to relatively low concentrations, and "least" refers to the potentially higher buffering capacity of a given waterbody due to the presence of a high concentration of these parameters (Table 11). pH was also rated in a similar manner, where a "high" acid sensitivity rank was attributed when the pH value was relatively low; conversely a high pH value was attributed a "least" acid sensitivity rank.

Table 11: Acid Sensitivity Ratings Based on Saffran and Trew (1996)

Parameter	Units	High	Moderate	Low	Least
Alkalinity (as $CaCO_3$)	mg/L	0 - 10	11 - 20	21 - 40	> 40
Calcium	mg/L	0 - 4	5 - 8	9 - 25	> 25
pH	pH Units	0 - 6.5	6 .6 - 7.0	7.1 - 7.5	> 7.5

The variables in Table 11 were used to map the sensitivity of lakes in the study area to acidifying deposition.

3.2.2 Critical Load Calculations

A critical load for each lake was calculated using the Henriksen's steady state water chemistry ratio (Henriksen et al., 1992). This method has also been used in a number of Environmental Impact Assessment (EIA) applications in the Cold Lake area.

In the Henriksen model, the critical load for a lake is calculated as:

$$CL = ([BC]^*_o - [ANC_{lim}]) * Q$$

Where:

CL	Critical load level of acidity [keq/ha/yr]
$[BC]^*_o$	Base cation concentration in the lake [µeq/L]
$[ANC_{lim}]$	Critical value for the acid neutralizing capacity in the water [µeq/L]
Q	Mean annual runoff [L/ha/yr]

In applying the Henriksen steady state model to lakes in the study area, which are not affected by acid deposition to the same extent as European lakes, the current base cation concentrations ($[BC]^*_0$) were assumed to represent pre-industrial base cation levels. The original non-marine base cation concentrations in µeq/L for each lake were calculated based on observed concentrations of calcium, magnesium, sodium and potassium from the various data sources.

The critical load concept in the model assumed a dose-response relationship between a water quality variable and an aquatic indicator organism. The water quality variable is presented as the acid neutralizing capacity (ANC_{lim}) required for maintaining a healthy fish population in each water body. In Henriksen's study, an ANC_{lim} of 20 µeq/L for Northern European lakes was applied. This value of 20 µeq/L was adopted in the Northwest Territories where the natural conditions were considered to be similar to the Northern Europe conditions. However, in the Oil Sands area and the heavy oil region of the LICA study area, 75 µeq/L has been widely used and was thus applied in this study.

This report graphically presents data on the gross critical loads and net critical loads of lakes. The gross critical load is derived using Henriksen's model and is based on the reported concentration of base cations for selected lakes. The net critical load represents the difference between gross critical load and the estimated potential acid input.

3.2.3 Mean Annual Runoff

The runoff to a lake was calculated from a regional hydrological analysis, based on long-term data from gauged catchments in the study area. The mean annual runoff was presented in unit discharge values (L/ha/yr) and calculated from regional water yield, depending on the watershed each lake belonged to.

Runoff data were obtained from different sources and calculations were provided for the study area. Previous reports provided estimates for annual water yield, such as 80 mm (Golder 2000) and 75 mm (BlackRock 2001). The estimated annual water yield was more recently assessed at 68 mm (CNRL 2006). The latter water yield was based on 36 years of observation and was accepted for use in this study. Some estimated annual water yields were calculated for several basins and represented in the Table 12.

Table 12: Estimated Annual Water Yield (CNRL 2006)

Stream	Area km^2	Annual water yield	
		mm	m^3/s
Jackfish Creek Headwaters (to Bourque Lake inlet)	81.5	81	0.18
Marie Creek at Burnt Lake outlet	141.4	60	0.27
Marie Creek at May Lake outlet	270.2	61	0.52
Medley River Headwaters	39.6	68	0.09
Sinclair Creek at Wolf Lake Inlet	131	68	0.28

The mean annual yield of 68 mm/y[1] was most representative of the long-term runoff characteristics of the typical basins in the area. The average precipitation during this period was 427 mm and during 1998 – 2006 water quality observations at some lakes reported variations within +/- 25%.

In the critical load calculations, the runoff was determined from the mean annual water yield of 68 mm/yr. Because this value was used in a number of local EIAs, the results from the current analysis allow comparisons with the other studies.

3.2.4 Critical, Target and Monitoring Loads

The effects of acidifying emissions on lakes were assessed by reference to critical, target and monitoring loads as described in CASA and AENV (1999). Definitions for these are provided in Section 2.2.2 of this report. It is important to note that the provincial framework is explicit in indicating that the target load may be applied as a benchmark but not as a regulatory objective in the context of assessing effects from single or multiple projects.

3.2.5 Trend Detection

The Mann-Kendall test was used to detect trends in the annual critical load values which are monotonic but not necessarily linear. These tests only indicate the direction, and not the magnitude, of significant trends. The Mann-Kendall test is particularly useful because missing values are allowed and the data need not conform to any particular probability distribution.

The computation of Mann-Kendall statistic consists of calculating possible differences between observations in the data population (put in the order in which they are collected over time) followed by computation of the number of positive differences minus the number of negative differences. The Mann-Kendall formula is as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k)$$

Thus, no absolute values are involved, but the count of signs is compared. The algorithm to calculate the Mann-Kendall Test is used in this study to analyze the temporal trend (Gilbert 1987).

The Mann-Kendall Test can be used to show whether concentrations at a monitoring site are increasing, stable, or decreasing. However, it cannot determine the rate at which concentrations are changing over time. The Mann-Kendall Test can be used with a minimum of five sampling results/data points, but the test is not valid for data that exhibit periodicity. Thus, it is not applicable for seasonal data within annual time series; however, it can be used for trend analysis of average annual values.

3.3 DATA SOURCES

Water quality data used in this report were collected from the following sources:

- Alberta Lake Management Society reports (ALMS 2007);
- Imperial Oil Resources Surface Water Quality Monitoring Program (IOR 2007); and,
- Canadian National Resources Limited, Primrose In-Situ Oil Sands Project, East Primrose Expansion (CNRL 2006).

The passive monitoring station data provided by LICA were used to spatially compute the potential acid inputs (PAIs) from air emissions throughout the study area (see Section 2). Isopleths were created from the 20 passive monitoring stations throughout the study area and used to estimate the PAIs of the different lakes with water quality data.

The Alberta Lake Management Society (ALMS) conducts annual water quality testing of several lakes throughout Alberta, including 12 lakes in the LICA study area. Available data between 1998 and 2006 are presented in this report.

Imperial Oil Resources (IOR), Cold Lake Operations collects water quality data on an annual basis for several lakes and streams in the Jackfish and Marie Creek sub-watersheds. Data have been collected since 2000 and are presented in this report. In 2005 and 2006, data were collected in both spring and fall, the results of which were averaged for presentation in this report.

Canadian National Resources Limited (CNRL) completed an environmental impact assessment in the vicinity of Burnt Lake. Data from previous water quality monitoring programs were included in this report. The data for these waterbodies were collected once and no temporal comparisons were available.

3.4 ACID SENSITIVITY RATINGS

Acid sensitivity ratings were identified within and bordering the LICA study area based on average alkalinity, pH and calcium values observed between 1998 and 2006. These results provide a qualitative approach of classifying the sensitivity of lakes to acidic inputs, based on the classification system presented in Saffran and Trew (1996) and presented in Table 13.

All lakes in the study area displayed sensitivity ratings of "least" for alkalinity, indicating that these lakes have a high buffering capacity to acid inputs. Alkalinity ranged between 28 mg/L and 961 mg/L. Concentrations under 100 mg/L were observed in small lakes in the northwestern corner of the study area and in the vicinity of Burnt Lake. The highest concentrations of alkalinity were generally observed in the lakes of the southern portion of the study area.

Sensitivity ratings for pH were considered "least" in 42 (89%) of the surveyed lakes, with pH ranging between 7.5 and 9.2. Four lakes (9%) were rated as "low" sensitivity with a range in pH of 7.1 to 7.4. A small-unnamed lake (Lake ID = 599) west of Burnt Lake was considered to be moderately sensitive to acidification based on pH (pH = 6.8).

The concentration of calcium cations was variable throughout the study area, ranging between 5 mg/L and 37 mg/L. "Least" sensitive ratings were attributed to 21 lakes (45%), which varied in size and location throughout the study area (Figure 3). Most lakes of the least sensitive category ranged in concentration between 26 mg/L and 37 mg/L. "Low" sensitivity ratings were attributed to 24 lakes (49%), found throughout the study area. Most lakes of the low sensitivity category ranged in concentration between 10 mg/L and 25 mg/L. Two lakes (4%) were rated as moderately sensitive to acidification. These are small lakes located in the Wolf River sub-watershed, just west of Burnt Lake.

Lakes of the LICA study area are generally resistant to acidification based on sensitivity ratings. Alkalinity and pH demonstrate that most lakes are well buffered, while only two lakes are moderately sensitive to acidification based on the concentration of calcium ions. The most sensitive lakes are characteristically small headwater waterbodies found in the Wolf River sub-watershed, west of Burnt Lake.

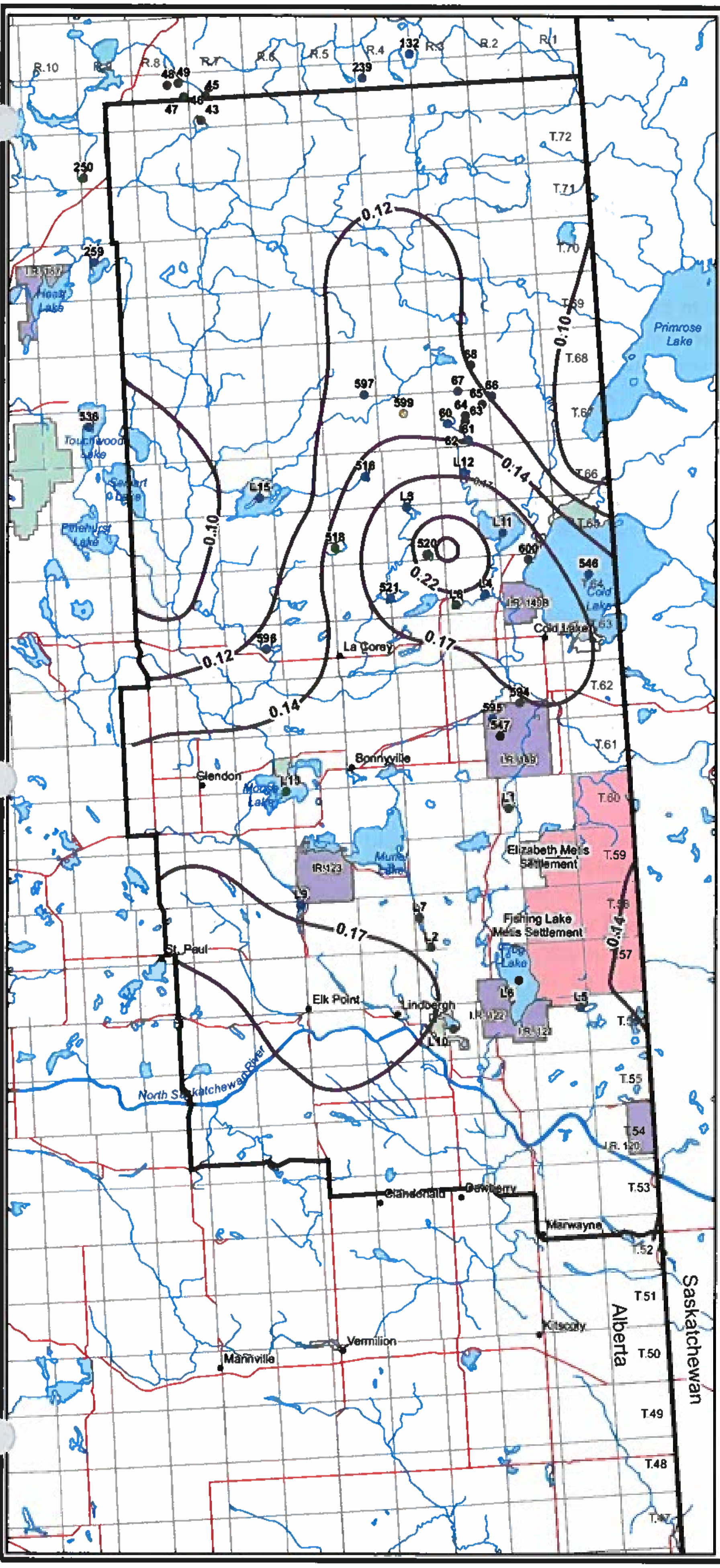
Table 13: Acid Sensitivity Ratings for Lakes in the Study Area

Lake Identifier	Lake Name	Zone	Easting	Northing	Lake Surface Area (ha)	Alkalinity (mg/L)	pH	Calcium (mg/L)	Specific Conductivity (µS/cm)	Total Dissolved Solids (mg/L)	Hardness (mg/L)
LICA Study Area											
43	Ipitiak Lake	12	496692	6127900	-	67	7.5	17	136	67	-
60	Burnt Lake	12	536930	6072588	-	108	8.1	28	200	142	-
61	Unnamed Lake	12	540333	6069577	-	117	8.2	30	207	153	-
62	Unnamed Lake	12	539546	6071719	-	53	7.8	13	105	110	-
63	Unnamed Lake	12	539930	6072774	-	61	7.9	16	124	113	-
64	Unnamed Lake	12	540067	6073823	-	65	7.9	18	127	120	-
65	Unnamed Lake	12	543092	6075676	-	52	7.8	14	105	100	-
66	Unnamed Lake	12	544835	6076985	-	98	8.1	26	182	140	-
67	Unnamed Lake	12	538930	6078203	-	98	8.1	26	180	137	-
68	Unnamed Lake	12	541457	6082627	-	49	7.8	13	96	125	-
516	Sinclair Lake	12	522000	6064200	-	243	8.0	36	430	248	-
518	Marguerite Lake	12	516000	6052000	-	538	9.0	22	538	516	-
520	Leming Lake	12	532000	6050000	-	121	9.0	18	168	35	-
521	Tucker Lake	12	525300	6042700	-	212	8.1	28	400	234	-
546	Cold Lake	12	560000	6045000	-	140	8.3	31	240	155	-
547	Moore Lake	12	543043	6017650	-	340	8.7	15	686	408	-
594	McDougall Lake	12	546792	6023259	-	144	-	22	-	-	-
595	Unnamed Lake	12	541860	6020776	-	316	8.1	33	549	597	-
596	Manatokan Lake	12	503000	6035000	-	203	8.7	35	211	16	-
597	Unnamed Lake	12	522600	6078500	-	162	7.9	29	270	146	-
599	Unnamed Lake	12	529300	6074800	-	41	6.8	8	86	46	-
600	Dolly Lake	12	549700	6048200	-	244	8.5	14	-	239	-
L1	Angling Lake	12	542500	6005000	585	320	8.8	25	584	-	-
L2	Bluet Lake	12	528500	5979500	120	360	9.0	21	-	511	-
L3	Bourque Lake	12	528900	6058400	Unknown	197	8.2	37	371	221	182
L4	Ethel Lake	12	541800	6042450	490	158	8.2	33	289	179	148
L5	Fishing Lake	12	550000	5971000	Unknown	226	8.8	26	455	243	-
L6	Frog Lake	12	543000	597500	5800	386	8.8	18	877	500	-
L7	Garnier Lake	12	527500	5985000	520	364	9.0	18	-	475	-
L8	Hilda Lake	12	536600	6040900	362	428	8.8	19	893	563	280
L9	Kehewin Lake	12	506500	5990000	620	214	8.6	26	-	-	-
L10	Laurier Lake	12	532000	5967000	642	564	8.9	14	-	655	-
L11	Marie Lake	12	547000	6064900	3600	150	8.3	35	282	161	146
L12	May Lake	12	539150	6063900	Unknown	133	8.1	35	251	161	135
L13	Moose Lake	12	505000	6010000	4000	332	8.9	25	919	581	-
L14	Muriel Lake	12	520000	6000000	6410	961	9.3	5	1908	-	-
L15	Wolf Lake	12	503222	6061410	3150	159	8.5	27	-	156	-
Lakes Bordering the LICA Study Area											
45	Unnamed Lake	12	497711	6132160	-	39	7.4	10	83	41	-
46	Unnamed Lake	12	498367	6133579	-	90	8.1	21	180	119	-
47	Unnamed Lake	12	493933	6132222	-	52	7.6	13	108	76	-
48	Unnamed Lake	12	491151	6134421	-	44	7.3	11	97	45	-
49	Unnamed Lake	12	493107	6134651	-	46	7.4	11	96	45	-
132	Grist Lake	12	533788	6137575	-	117	8.5	30	222	119	-
239	Unnamed Lake	12	525364	6133813	-	108	8.3	30	208	-	-
250	Unnamed Lake	12	475613	6118973	-	67	8.7	17	135	-	-
259	Logan Lake	12	476591	6104122	-	147	9.2	33	267	-	-
536	Touchwood Lake	12	474032	6075393	-	142	8.0	31	263	148	-

Legend for Acid Sensitivity Ratings (Saffran and Trew, 1996)

Parameter	High	Moderate	Low	Least
Alkalinity	0 - 10	11 - 20	21 - 40	> 40
pH	0 - 6.5	6.6 - 7.0	7.1 - 7.5	> 7.5
Calcium	0 - 4	5 - 8	9 - 25	> 25

Saffran, K., and D. Trew. 1996. Sensitivity of alberta Lakes to Acidifying Deposition: An Update on Sensitivity Maps with Emphasis on 109 Northern Lakes. Special report prepared by Water Sciences Branch, Water Management Division, Alberta Environment Protection.



Legend

- Town
- Road
- PAI Estimates from LICA Measurements
- Provincial Park
- Metis Settlement
- First Nations Settlement
- Lake
- LICA Airshed Boundary

Acid Sensitivity Ratings (Based on Saffran and Trew, 1996)

- High
- Moderate
- Low
- Least

N

20 10 0 20 40

Kilometres

1:1,000,000

Lakeland Industry and Community Association (LICA)

Acid Sensitivity Ratings of Lakes for Calcium (mg/L)

Date:	Projection:	Datum:
March 2007	10TM AEP Forest	NAD83

Job No: EE31175

GIS File: Acid_Sensitivity_Ratings_Lakes_Calcium

PDF File: Acid_Sen_Ratings_Lakes_Calc_07-03-22

Figure 3

3.5 CRITICAL LOADS FOR LAKES IN THE LICA AIRSHED

3.5.1 Spatial Variability

The gross critical loads for the lakes in the LICA study area were calculated using the average concentrations of base cations (calcium, magnesium, potassium and sodium) for all data available between 1998 and 2006. Gross critical loads varied between 0.53 keq H^+/ha/yr and 9.31 keq H^+/ha/yr (Table 14), with higher values generally observed in the southern portion of the study area (Figure 4).

Muriel Lake (L14) had a gross critical load of 17.64 keq H^+/ha/yr due to high concentrations of sodium (238 mg/L) and magnesium (173 mg/L). Since the gross critical load for this lake is much higher than all other lakes in the study area, it was excluded from further analysis and considered as an anomalous case.

The highest gross critical load values were observed in lakes located in the southern portion of the study area, where the aspen parkland ecosystem is dominant (Figure 5). The southern portion of the study area includes all areas to the south of IOR Cold Lake Operations, Husky Tucker Lake SAGD and Highway 55. Farmland with small patches of a mixed coniferous and deciduous forest is found in this region. The gross critical load for the 16 lakes in this area ranged between 1.73 keq H^+/ha/yr and 9.31 keq H^+/ha/yr, and the average gross critical load was 4.64 keq H^+/ha/yr.

Lakes to the north of IOR and Husky facilities were more sensitive to acid inputs due to their lower overall gross critical load values. This portion of the LICA airshed is located in an area of transition between the aspen parkland and boreal forest ecosystems. Most of the 30 surveyed lakes are found in forests or muskeg and tend to have smaller surface areas than the lakes to the south. The gross critical load in this area ranged between 0.53 keq H^+/ha/yr and 3.47 keq H^+/ha/yr. The average gross critical load was 1.41 keq H^+/ha/yr. The lowest gross critical loads were observed in small waterbodies in the vicinity of Burnt Lake and in the northwestern portion of the study area.

Table 14: Critical Load Results based on Henriksen's Model for Lakes in the LICA Study Area

Lake Identifier	Lake Name	Zone	Easting	Northing	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Base Cations [BC*₀] (µeq/L)	Gross Critical Load (keqH⁺/ha/yr)	Potential Acid Inputs (keqH⁺/ha/yr)	Net Critical Load (keqH⁺/ha/yr)
LICA Study Area												
43	Ipitiak Lake	12	496692	6127900	17	5	0.4	2	1373	0.88	0.11	0.77
60	Burnt Lake	12	536930	6072588	28	40	0.7	3	4935	3.30	0.13	3.17
61	Unnamed Lake	12	540333	6069577	30	10	1.3	4	2548	1.68	0.14	1.54
62	Unnamed Lake	12	539546	6071719	13	6	0.7	2	1239	0.79	0.13	0.66
63	Unnamed Lake	12	539930	6072774	16	6	0.7	2	1443	0.93	0.13	0.80
64	Unnamed Lake	12	540067	6073823	18	6	0.5	2	1499	0.97	0.13	0.84
65	Unnamed Lake	12	543092	6075676	14	5	0.6	2	1199	0.76	0.13	0.63
66	Unnamed Lake	12	544835	6076985	26	8	0.5	3	2122	1.39	0.12	1.27
67	Unnamed Lake	12	538930	6078203	26	8	0.6	2	2068	1.36	0.13	1.23
68	Unnamed Lake	12	541457	6082627	13	5	0.4	2	1141	0.73	0.12	0.61
516	Sinclair Lake	12	522000	6064200	36	24	3	30	5184	3.47	0.15	3.32
518	Marguerite Lake	12	516000	6052000	22	95	30	38	11376	7.68	0.15	7.53
520	Leming Lake	12	532000	6050000	18	14	6	8	2620	1.73	0.24	1.49
521	Tucker Lake	12	525300	6042700	28	24	3	21	4447	2.97	0.20	2.77
546	Cold Lake	12	560000	6045000	31	12	2	9	2977	1.97	0.15	1.82
547	Moore Lake	12	543043	6017650	15	39	6	83	7779	5.24	0.16	5.08
594	McDougall Lake	12	546792	6023259	22	18	8	3	2896	1.92	0.16	1.76
595	Unnamed Lake	12	541860	6020776	33	53	15	19	7273	4.89	0.16	4.73
596	Manatokan Lake	12	503000	6035000	35	27	7	9	4570	3.06	0.13	2.93
597	Unnamed Lake	12	522600	6078500	29	9	1	10	2660	1.76	0.13	1.63
599	Unnamed Lake	12	529300	6074800	-	3	8	0.7	888	0.55	0.13	0.42
600	Dolly Lake	12	549700	6048200	14	32	5	22	4451	2.98	0.18	2.80
L1	Angling Lake	12	542500	6005000	25	44	11	38	6828	4.59	0.15	4.44
L2	Bluet Lake	12	528500	5979500	21	71	20	60	10030	6.77	0.16	6.61
L3	Bourque Lake	12	528900	6058400	37	21	3	14	4282	2.86	0.20	2.66
L4	Ethel Lake	12	541800	6042450	33	15	2	8	3350	2.23	0.21	2.02
L5	Fishing Lake	12	550000	5971000	26	28	11	19	4741	3.17	0.15	3.02
L6	Frog Lake	12	543000	5975000	18	63	17	80	10083	6.81	0.15	6.66
L7	Garnier Lake	12	527500	5985000	18	75	18	45	9505	6.41	0.15	6.26
L8	Hilda Lake	12	536600	6040900	19	55	10	112	10673	7.21	0.21	7.00
L9	Kehewin Lake	12	506500	5990000	26	29	13	35	5605	3.76	0.16	3.60
L10	Laurier Lake	12	532000	5967000	14	94	28	105	13769	9.31	0.16	9.15
L11	Marie Lake	12	547000	6064900	35	13	2	6	3182	2.11	0.20	1.91
L12	May Lake	12	539150	6063900	35	10	0.9	6	2877	1.91	0.17	1.74
L13	Moose Lake	12	505000	6010000	25	51	18	109	10659	7.20	0.15	7.05
L14	Muriel Lake	12	520000	6000000	-	173	39	238	26012	17.64	0.15	17.49
L15	Wolf Lake	12	503222	6061410	27	15	2	12	3175	2.11	0.11	2.00
Lakes Bordering the LICA Study Area												
45	Unnamed Lake	12	497711	6132160	10	4	0.3	1	860	0.53	0.11	0.42
46	Unnamed Lake	12	498367	6133579	21	8	0.3	2	1854	1.21	0.11	1.10
47	Unnamed Lake	12	493933	6132222	13	5	0.5	0.5	1068	0.68	0.11	0.57
48	Unnamed Lake	12	491151	6134421	11	4	0.5	1	976	0.61	0.11	0.50
49	Unnamed Lake	12	493107	6134651	11	4	0.4	0.5	949	0.59	0.11	0.48
132	Grist Lake	12	533788	6137575	30	8	0.9	4	2411	1.59	0.11	1.48
239	Unnamed Lake	12	525364	6133813	30	9	2	2	2341	1.54	0.11	1.43
250	Unnamed Lake	12	475613	6118973	17	7	0.5	2	1521	0.98	0.11	0.87
259	Logan Lake	12	476591	6104122	33	12	2	14	3322	2.21	0.11	2.10
536	Touchwood Lake	12	474032	6075393	31	12	3	8	2988	1.98	0.10	1.88

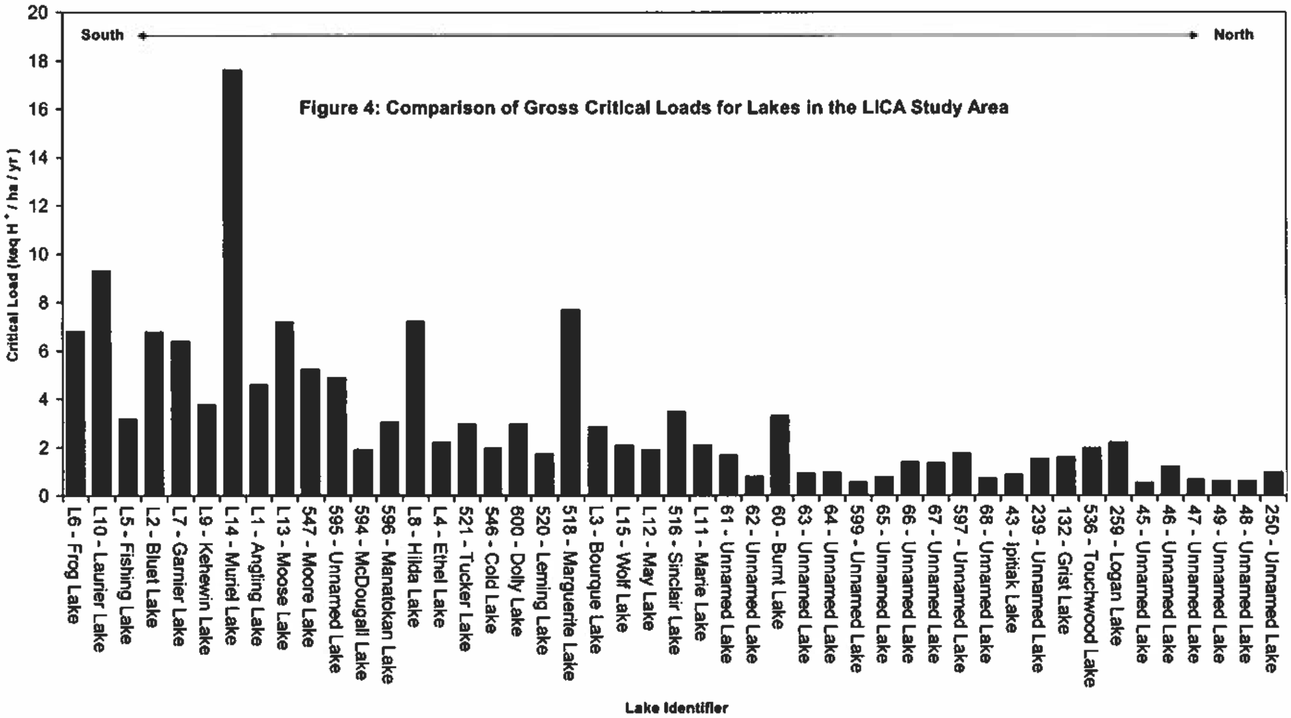
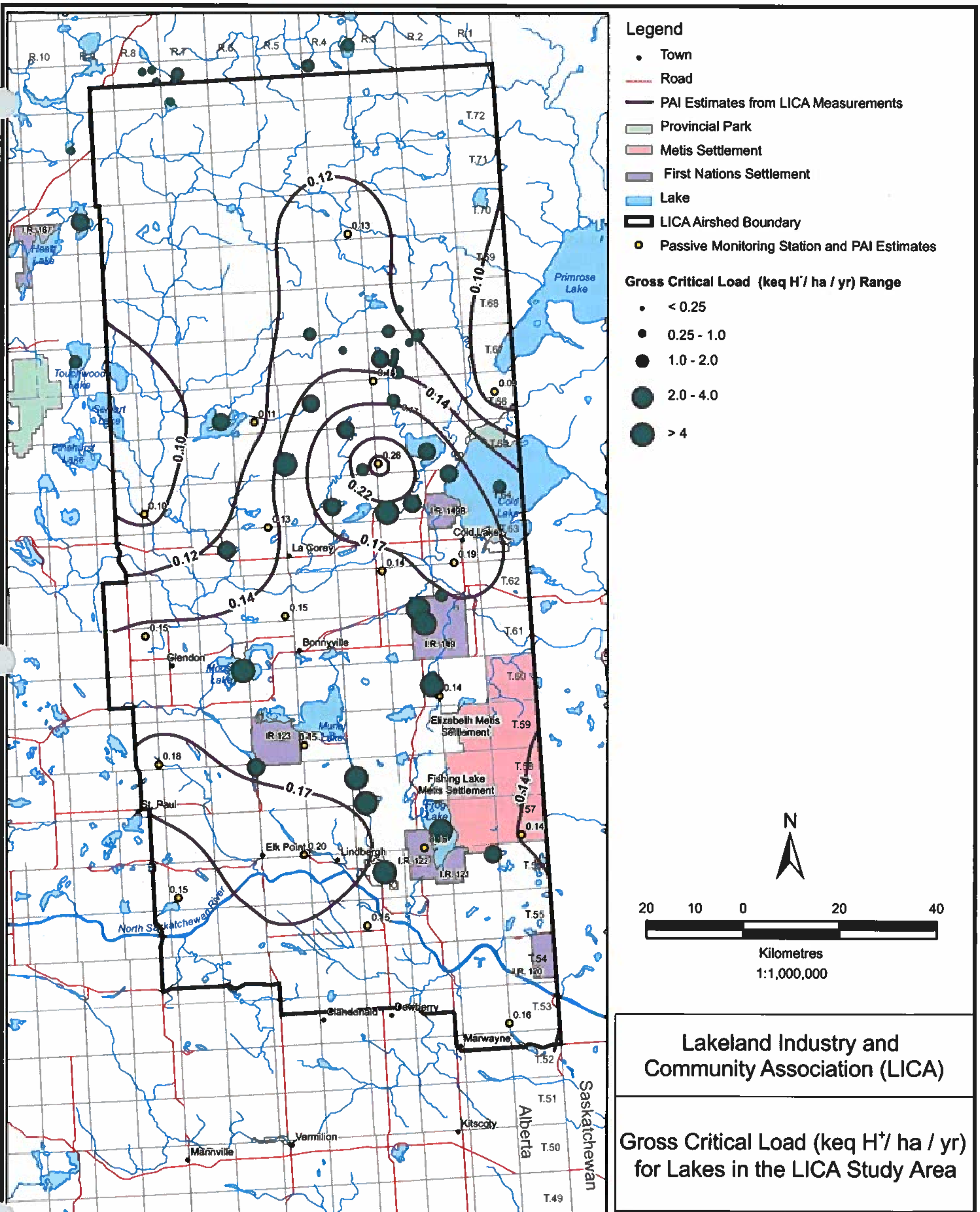


Figure 4: Comparison of Gross Critical Loads for Lakes in the LICA Study Area



Lakeland Industry and Community Association (LICA)

Gross Critical Load (keq H^+/ ha / yr) for Lakes in the LICA Study Area

Date: June 2007	Projection: 10TM AEP Forest	Datum: NAD83
Job No: EE31175	**Figure 5**	
GIS File: Critical_Load		
PDF File: Critical_Load_07-06-21		

3.5.2 Temporal Changes and Trend Analysis

Temporal water quality data between 1998 and 2006 were available for 12 lakes within the LICA study area. The annual gross critical load was calculated and is presented for these lakes in Figure 6. The surveyed waterbodies displayed little fluctuation in gross critical loads between years. No definitive trend was observed within the period of monitoring. The highest gross critical loads compared to other years were generally observed in 2003, while values for other years remained relatively constant. The largest fluctuations were observed in Laurier Lake, varying between 8.4 keq H^+/ha/yr (1998 and 2000) and 10.8 keq H^+/ha/yr (2004).

The Mann-Kendall Test was applied to the gross critical loads of six lakes in the study area that had data available for at least five years. The results of the test indicate that gross critical loads are increasing at the 80% confidence interval in Ethel (L4) and Laurier (L10) Lakes (Table 15). No trend could be confirmed at the 90% level of confidence for Ethel Lake; however, an increasing trend was confirmed in Laurier Lake. May Lake (L12) exhibited a decreasing trend in gross critical load which was not supported at the 90% level of confidence. No trends in annual gross critical loads were observed in Bourque (L3), Hilda (L8) or Marie (L11) Lakes at either level of confidence.

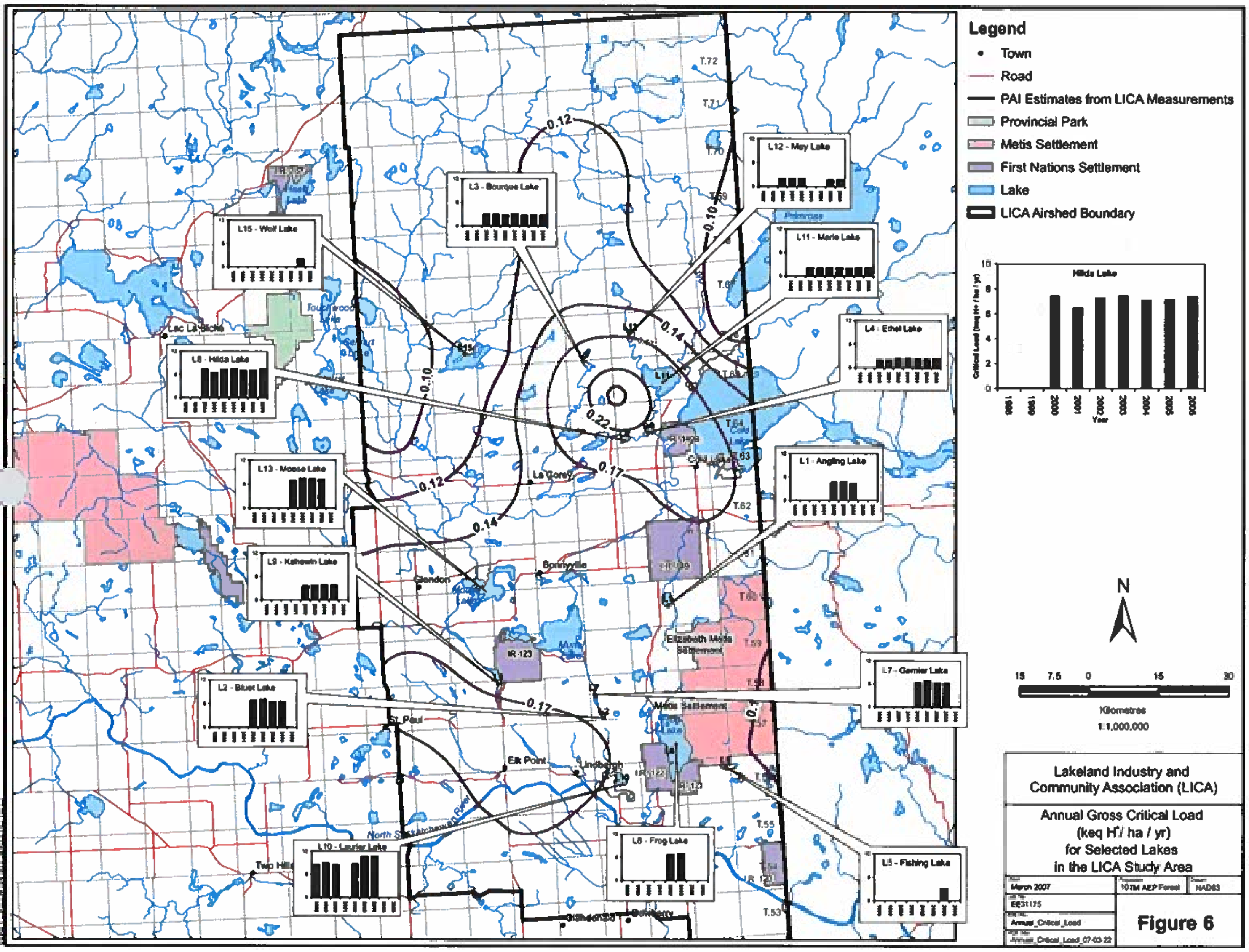
3.5.3 Comparison with Potential Acid Deposition

The net critical loads for the lakes of the LICA study area were calculated by comparing the gross critical loads of the surveyed lakes (see Section 2.5.1) to airborne deposition levels (i.e., PAI levels), which were computed in Section 2. The difference between these two values (gross critical load minus PAI) represents the net critical load for the lakes.

All lakes in the LICA study area have gross critical loads above the monitoring load for sensitive receptors of 0.17 keq H^+/ha/yr and even above the upper limit of critical deposition for sensitive receptors of 0.25 keq H^+/ha/yr (CASA and AENV 1999). An airborne depositional rate exceeding 0.17 keq H^+/ha/yr was observed in the vicinity of Cold Lake and Elk Point, affecting six lakes within the study area. However, the lakes' gross critical loads were consistently greater than the PAI values for sensitive, moderate or low sensitivity systems.

In the southern portion of the study area (Figure 7), the net critical load ranged between 1.49 keq H^+/ha/yr and 9.15 keq H^+/ha/yr. The average net critical load observed in these lakes was 4.47 keq H^+/ha/yr.

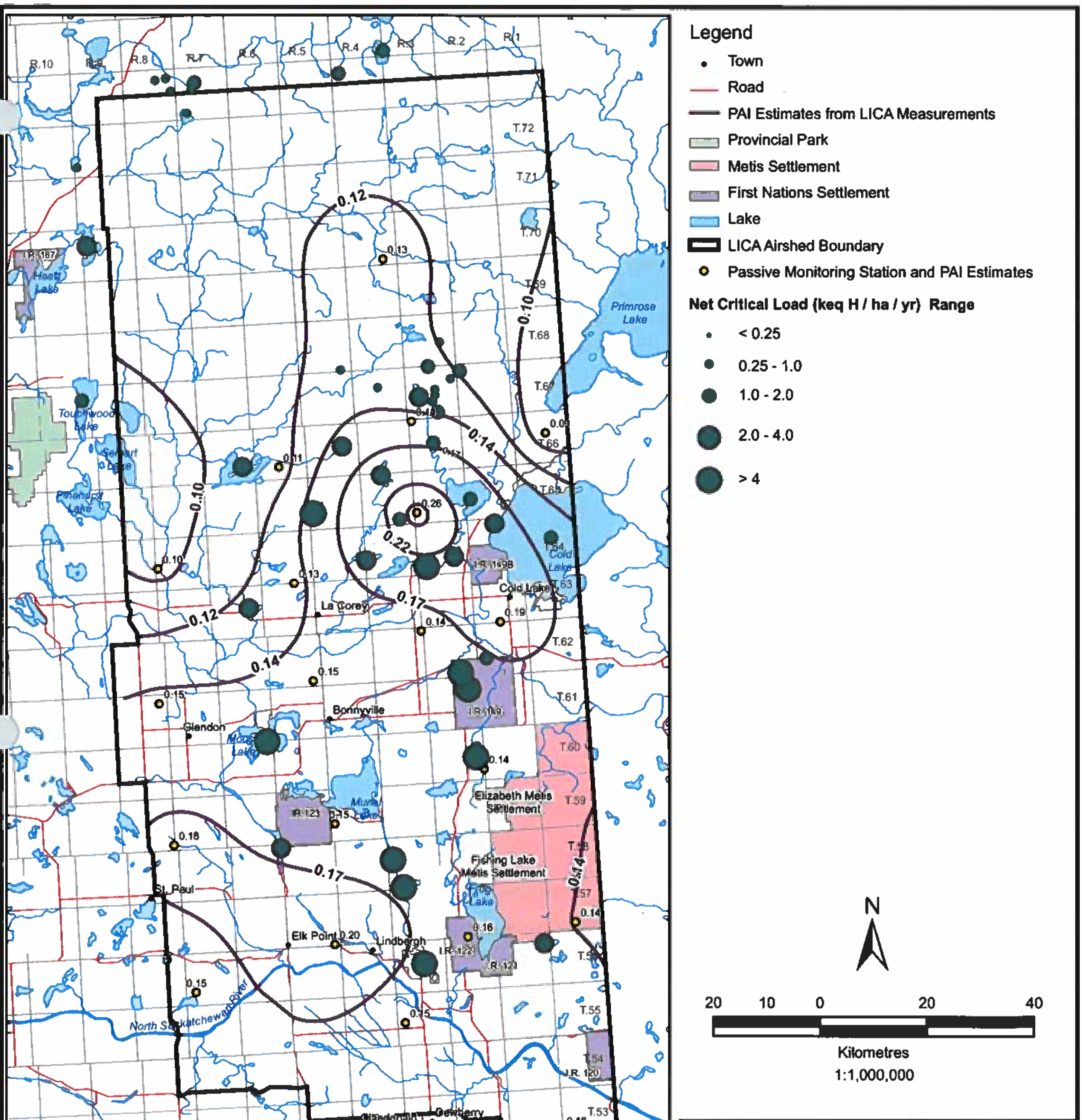
In the northern portion, the net critical load ranged between 0.42 keq H^+/ha/yr and 3.32 keq H^+/ha/yr. The average net critical load observed in these lakes was 1.28 keq H^+/ha/yr.



Legend
Town
Road
PAI Estimates from LICA Measurements
Provincial Park
Metis Settlement
First Nations Settlement
Lake
LICA Airshed Boundary
Hilda Lake
Critical Load (keq H+ / ha / yr)
Year
L12 - May Lake
L3 - Bourque Lake
L15 - Wolf Lake
L11 - Marie Lake
L4 - Ethel Lake
L8 - Hilda Lake
L13 - Moose Lake
L1 - Angling Lake
L9 - Kehewin Lake
L2 - Bluet Lake
L7 - Garnier Lake
L10 - Laurier Lake
L6 - Frog Lake
L5 - Fishing Lake
Lac La Biche
La Corey
Bonnyville
Glendon
St. Paul
Elk Point
Lindbergh
Two Hills
Cold Lake
Elizabeth Metis Settlement
Metis Settlement
North Saskatchewan River
IR 123
0.10
0.12
0.14
0.17
0.22
N
Kilometres
1:1,000,000
Lakeland Industry and Community Association (LICA)
Annual Gross Critical Load
(keq H+/ ha / yr)
for Selected Lakes
in the LICA Study Area
March 2007
NAD83
Figure 6

Table 15: Results of the Mann-Kendall Test for Gross Critical Loads from Selected Lakes in the LICA Study Area

Event	Year	L3	L4	L8	L10	L11	L12
		Bourque Lake	Ethel Lake	Hilda Lake	Laurier Lake	Marie Lake	May Lake
1	1998	-	-	-	8.41	-	-
2	1999	-	-	-	8.95	-	-
3	2000	2.95	2.04	7.44	8.43	2.20	2.06
4	2001	2.91	2.12	6.49	-	2.04	2.07
5	2002	2.79	2.35	7.30	8.70	2.12	2.06
6	2003	3.05	2.36	7.48	10.62	2.17	-
7	2004	2.79	2.21	7.11	10.77	2.01	-
8	2005	2.81	2.19	7.17	-	2.13	1.72
9	2006	2.84	2.29	7.41	-	2.12	1.85
Mann Kendall Statistic (S)		-5.0	7.0	1.0	11.0	-5.0	-6.0
Number of Rounds (n)		7	7	7	6	7	5
Average		2.88	2.22	7.20	9.31	2.11	1.95
Standard Deviation		0.100	0.118	0.342	1.092	0.067	0.159
Coefficient of Variation (CV)		0.035	0.053	0.048	0.117	0.032	0.081
Trend ≥ 80% Confidence Level		No Trend	INCREASING	No Trend	INCREASING	No Trend	DECREASING
Trend ≥ 90% Confidence Level		No Trend	No Trend	No Trend	INCREASING	No Trend	No Trend



Lakeland Industry and Community Association (LICA)

Net Critical Load [keq H[+]/ ha / yr] (Gross Critical Load - Potential Acid Inputs) for Lakes in the LICA Study Area

Date: June 2007	Projection: 10TM AEP Forest	Datum: NAD83
Job No: EE31175		
GIS File: Difference	**Figure 7**	
PDF File: Difference_07-06-21		

3.5.4 Critical Loads and Water Quality

A regression analysis was conducted in order to develop relationships between major water quality parameters reflecting buffering capacity and critical load for lakes. The statistical relationship between base cation concentrations and alkalinity displayed an adequate regression (R^2= 0.97) between these two values (Figure 8). The same R^2 value existed between the gross critical loads and alkalinity (Figure 9).

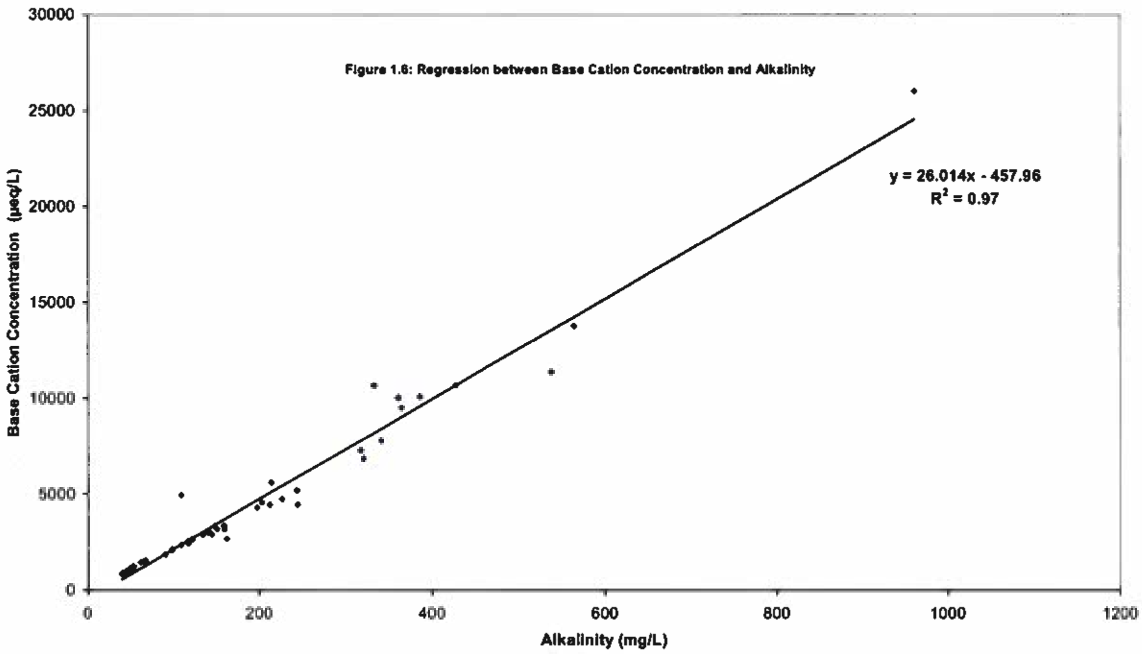


Figure 8: Regression between Base Cation Concentration and Alkalinity

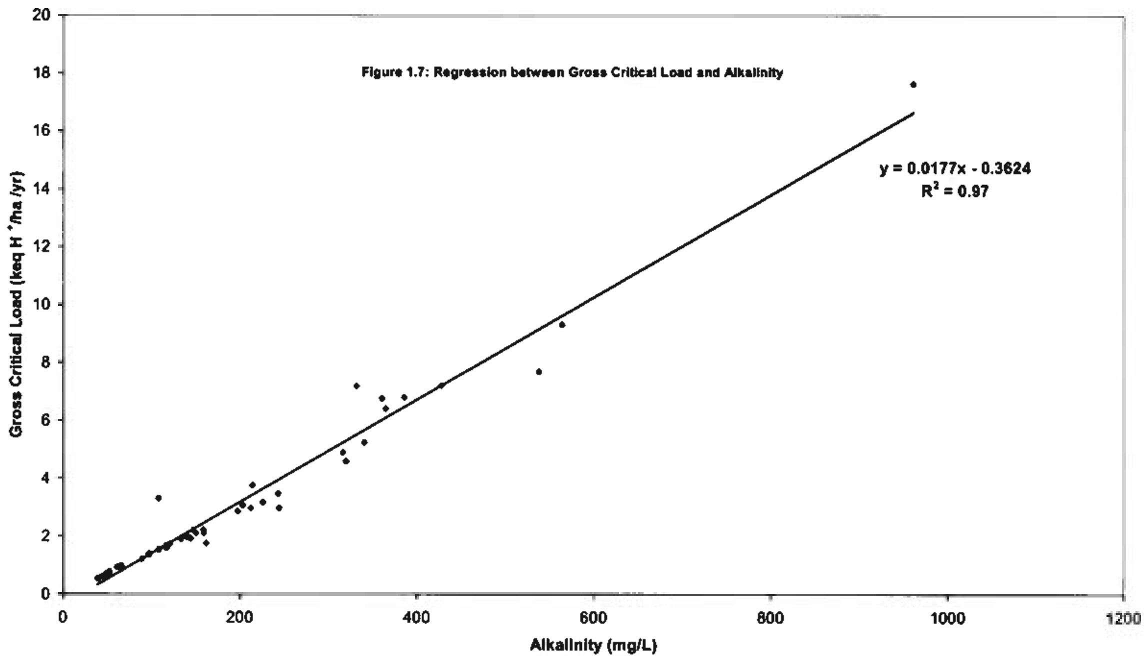


Figure 9: Regression between Gross Critical Load and Alkalinity

The regression of specific conductivity and alkalinity (R^2= 0.91) was developed and can be applied when base cation data are not available (Figure 10).

Under current climate conditions and annual runoff regimes, specific conductivity can be field measured and directly related to gross critical load, as the regression of these two parameters yielded an R^2 value of 0.95 (Figure 11). This regression can also be used in conjunction with the estimated PAI to infer the lowest possible specific conductivity needed to prevent acidification (Table 16). This is useful especially during peak runoffs observed at freshet, where the dilution of base cations can temporarily occur.

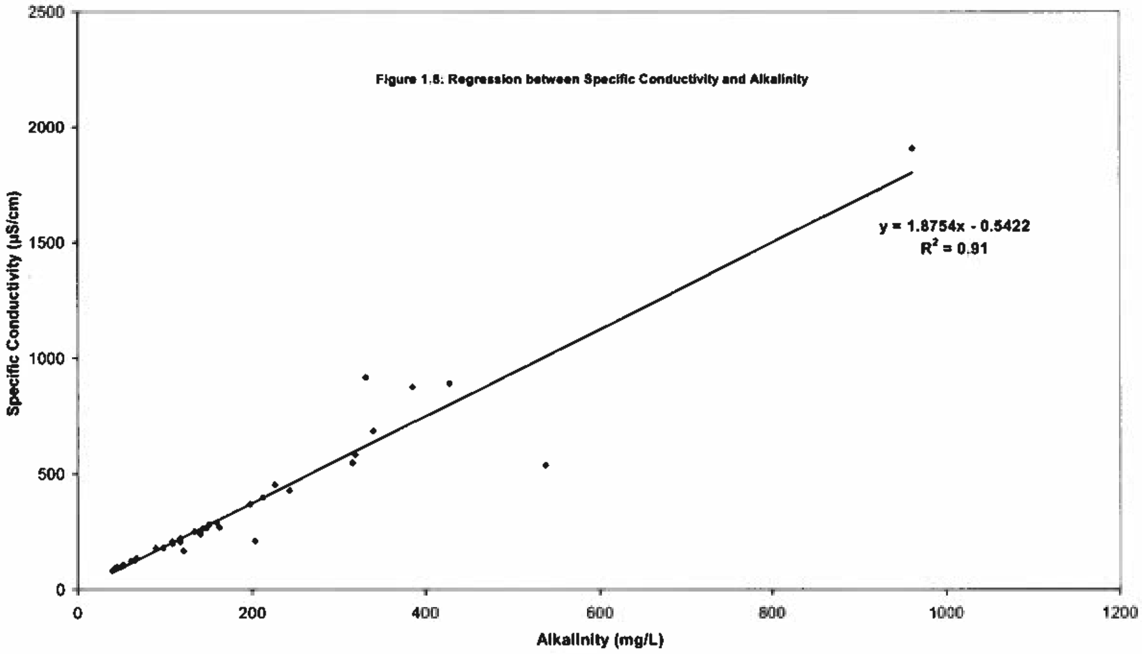


Figure 10: Regression between Specific Conductivity and Alkalinity

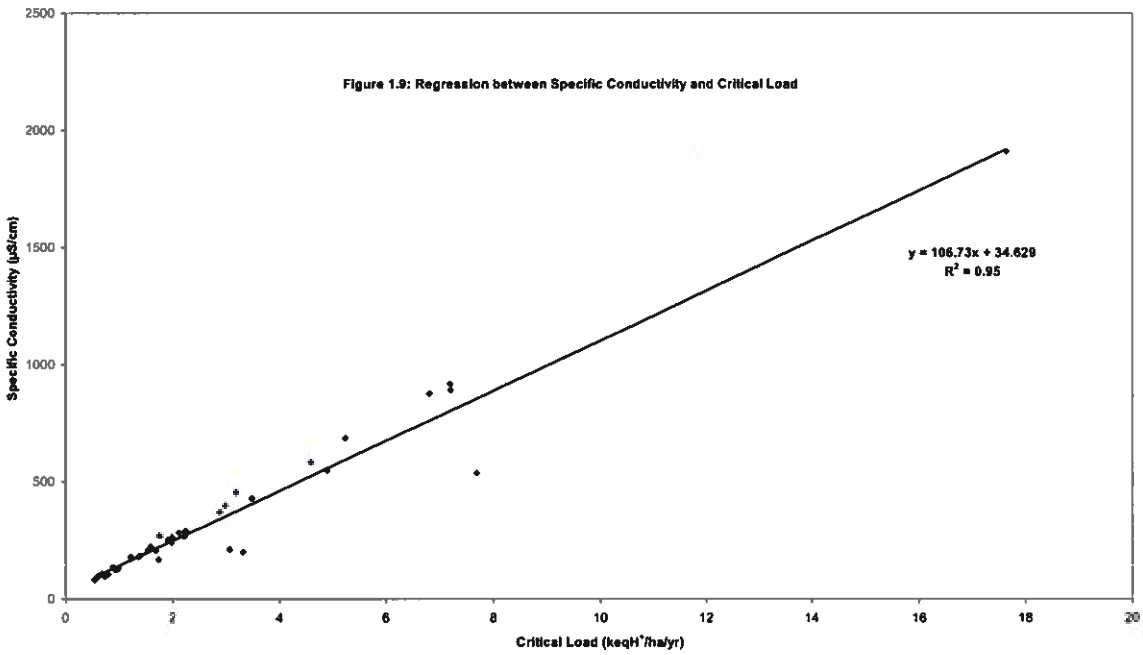


Figure 11: Regression between Specific Conductivity and Critical Load

3.6 MONITORING AND RECOMMENDATIONS

Lakes within and bordering the LICA study area generally have elevated concentrations of base cations, resulting in relatively high critical load. Lakes in the southern portion of the study area have higher critical loads than those found in the northern section. The acid sensitivity ratings based on Saffran and Trew (1996) support the results from the Henriksen steady state model.

Most of the study area has a depositional rate (PAI) below the CASA monitoring load of 0.17 keq H^+/ha/yr. The net critical loads of the lakes remained above 0.25 keq H^+/ha/yr, with most lakes registering no appreciable effect from PAIs.

Some lakes in the study area did have resulting critical loads that were under 0.50 keq H^+/ha/yr,(Table 14) which increases the risks of acidification if acidifying emissions were to increase in the study area. Bourque (L3), Marie (L11), Ethel (L4), Hilda (L8), Leming (520), Tucker (521), and Dolly (600) Lakes are located within the 0.17 keq H^+/ha/yr PAI monitoring load isopleth generated from LICA passive monitors in the region (Section 2). Although these lakes have relatively high critical loads, they could be considered for monitoring by virtue of being located within this PAI isopleth, and being within potentially higher PAI areas in the future as indicated in CNRL (2006). Unnamed Lake 599 has a critical load of 0.42 keq H^+/ha/yr. It is located near Burnt Lake in Tp. 67 - R. 3 - W4M, along with some other small lakes that have relatively low critical loads in the range of 0.50 – 1.00 keq H^+/ha/yr. These lakes occur close to the 0.25 keq H^+/ha/yr isopleth for the 'Existing and Approved Conditions' scenario of the Primrose East Expansion EIA of CNRL (2006). Because of the proximity between critical loads and predicted PAI values, monitoring is recommended for some of these lakes

Relationships exist between major cations, alkalinity and conductivity, all of which reflect the buffering capacity in a water body. The regression equations developed between gross critical load, alkalinity and specific conductivity makes it possible for future monitoring to be conducted in an inexpensive fashion.

Specific conductivity can be measured in-situ, using a conductivity probe. The field results can then be computed into sum of base cations or, in some cases, into gross critical loads through the regression between specific conductivity and alkalinity, and then between alkalinity and gross critical load, or through direct regression between specific conductivity and gross critical loads. Constant runoff is an important condition in application of the regression equation for gross critical loads because it is one of the major components governing the gross critical load calculations.

As noted previously, monitoring is recommended particularly for lakes with critical loads <0.50 keq H^+/ha/yr, and for lakes within the PAI isopleth >0.17 keq H^+/ha/yr. The data presented herein are sufficient to support a monitoring framework; however, the design of a monitoring program would require some time to develop. The locations for monitoring should be identified based on habitat sensitivity and acid depositional factors. In this regard, consideration should be given to co-location of water quality and air monitoring stations. The frequency and timing of

Table 16: Minimum Specific Conductivity Required to Prevent Acidification in Lakes in the LICA Study Area

Lake Identifier	Lake Name	Zone	Easting	Northing	Observed Specific Conductivity (µS/cm)	Current Gross Critical Load (keqH⁺/ha/yr)	Potential Acid Inputs (keqH⁺/ha/yr)	Minimum Specific Conductivity (µS/cm)
LICA Study Area								
43	Ipitiak Lake	12	496692	6127900	136	0.88	0.11	46
60	Burnt Lake	12	536930	6072588	200	3.30	0.13	49
61	Unnamed Lake	12	540333	6069577	207	1.68	0.14	50
62	Unnamed Lake	12	539546	6071719	105	0.79	0.13	49
63	Unnamed Lake	12	539930	6072774	124	0.93	0.13	49
64	Unnamed Lake	12	540067	6073823	127	0.97	0.13	49
65	Unnamed Lake	12	543092	6075676	105	0.76	0.13	49
66	Unnamed Lake	12	544835	6076985	182	1.39	0.12	47
67	Unnamed Lake	12	538930	6078203	180	1.36	0.13	49
68	Unnamed Lake	12	541457	6082627	96	0.73	0.12	47
516	Sinclair Lake	12	522000	6064200	430	3.47	0.15	51
518	Marguerite Lake	12	516000	6052000	538	7.68	0.15	51
520	Leming Lake	12	532000	6050000	168	1.73	0.24	60
521	Tucker Lake	12	525300	6042700	400	2.97	0.20	56
546	Cold Lake	12	560000	6045000	240	1.97	0.15	51
547	Moore Lake	12	543043	6017650	686	5.24	0.16	52
594	McDougall Lake	12	546792	6023259	-	1.92	0.16	52
595	Unnamed Lake	12	541860	6020776	549	4.89	0.16	52
596	Manatokan Lake	12	503000	6035000	211	3.06	0.13	49
597	Unnamed Lake	12	522600	6078500	270	1.76	0.13	49
599	Unnamed Lake	12	529300	6074800	86	0.55	0.13	49
600	Dolly Lake	12	549700	6048200	-	2.98	0.18	54
L1	Angling Lake	12	542500	6005000	584	4.59	0.15	51
L2	Bluet Lake	12	528500	5979500	-	6.77	0.16	52
L3	Bourque Lake	12	528900	6058400	371	2.86	0.20	56
L4	Ethel Lake	12	541800	6042450	289	2.23	0.21	57
L5	Fishing Lake	12	550000	5971000	455	3.17	0.15	51
L6	Frog Lake	12	543000	5975000	877	6.81	0.15	51
L7	Garnier Lake	12	527500	5985000	-	6.41	0.15	51
L8	Hilda Lake	12	536600	6040900	893	7.21	0.21	57
L9	Kehewin Lake	12	506500	5990000	-	3.76	0.16	52
L10	Laurier Lake	12	532000	5967000	-	9.31	0.16	52
L11	Marie Lake	12	547000	6064900	282	2.11	0.20	56
L12	May Lake	12	539150	6063900	251	1.91	0.17	53
L13	Moose Lake	12	505000	6010000	919	7.20	0.15	51
L14	Muriel Lake	12	520000	6000000	1908	17.64	0.15	51
L15	Wolf Lake	12	503222	6061410	-	2.11	0.11	46
Lakes Bordering the LICA Study Area								
45	Unnamed Lake	12	497711	6132160	83	0.53	0.11	46
46	Unnamed Lake	12	498367	6133579	180	1.21	0.11	46
47	Unnamed Lake	12	493933	6132222	108	0.68	0.11	46
48	Unnamed Lake	12	491151	6134421	97	0.61	0.11	46
49	Unnamed Lake	12	493107	6134651	96	0.59	0.11	46
132	Grist Lake	12	533788	6137575	222	1.59	0.11	46
239	Unnamed Lake	12	525364	6133813	208	1.54	0.11	46
250	Unnamed Lake	12	475613	6118973	135	0.98	0.11	46
259	Logan Lake	12	476591	6104122	267	2.21	0.11	46
536	Touchwood Lake	12	474032	6075393	263	1.98	0.10	45

monitoring would need to be identified through further research into the hydrologic regimes, climatic variations and limnological characteristics, in order to provide LICA with representative data of the study area. Monitoring protocols would need to be established to ensure continuity and compatibility between the data.

4.0 SOILS AND VEGETATION

Possible impacts of acidic and acidifying substances on soils include changes in chemical properties such as pH, exchangeable base saturation, and levels of soluble aluminum in soils. The lowering of pH and increase in soluble aluminum beyond threshold levels are associated with plant growth impacts due to toxicity or to inability to take up plant nutrients. Further-reaching effects include changes in the nature of organic matter and changes to overall nutrient dynamics. An in depth review of potential impacts of acidity on soils in Alberta can be found in Turchenek et al. (1987).

4.1 STUDY APPROACHES AND METHODS

The potential effects of acid deposition on soils and vegetation in the LICA area were examined using the following approaches:

- Assessment and mapping the sensitivity of soils to acidic and acidifying substances in the LICA study area;
- Determination of potential exceedances of acidity for soils based on proposed critical load levels;
- Review of information about soil monitoring in the study area; and
- Review of information about vegetation monitoring in the study area.

4.1.1 Soil Sensitivity Mapping

Soil sensitivity to acidification refers to the ease by which soils can be affected or influenced by acidic and acid forming substances. Soil sensitivity rating schemes have been developed for the purposes of grouping soil types and their associated geographic areas into sensitivity classes and for predicting the impact of acid inputs to soil chemical properties such as pH and base saturation. Effects on other soil properties such as organic matter and nutrient dynamics are not considered in these soil sensitivity rating systems because insufficient information exists to support criteria development. Initially, soil acidification may lead to a decrease in soil pH, leaching of base cations, and increased solubility of toxic acid cations such as aluminum (Al) (Turchenek et al., 1987). In sensitivity ratings systems, soils are categorized as having high, medium or low sensitivity ratings based on select criteria; these criteria vary with the sensitivity classification approach. A discussion of sensitivity ratings can be found in Turchenek at al. (1987) and Holowaychuk and Fessenden (1987). A system developed for Western Canada by Wiens et al. (1987) was applied in Alberta by Holowaychuk and Fessenden (1987). The sensitivity mapping was applied to broad areas of land at a small mapping scale. More recently, the system was applied at a higher scale in a study of soil sensitivity in the Provost-Esther area, Alberta (Turchenek and Abboud 2001).

The sensitivity of mineral soils to acid deposition was evaluated using the criteria in Holowaychuk and Fessenden (1987). In applying these criteria, sensitive, moderate sensitivity and low sensitivity ratings, with respect to losses of base cations, to acidification (pH decrease) and to aluminum solubilization, are applied to the pH-CEC categories, and an overall sensitivity category is then assigned (Table 17). In general, decreasing pH and/or CEC of a soil is proportional to increasing overall sensitivity of the soil. [Holowaychuk and Fessenden (1987) used the term 'high sensitivity'; this is changed herein to the term 'Sensitive' based on usage recommended by CASA and AENV (1996, 1999).]

Table 17: Criteria for Rating the Sensitivity of Mineral Soils to Acidic Inputs[Z]

Soil Property		Sensitivity to:			
Cation Exchange Capacity (cmol (+)/kg)[Y]	**pH**	**Base Loss**	**Acidification**	**Aluminum Solubilization**	**Overall Sensitivity**
<6	<4.6	S[X]	S	S	S
	4.6–5.0	S	S	S	S
	5.1–5.5	S	M	S	S
	5.6–6.0	S	S	M	S
	6.1–6.5	S	S	L	S
	>6.5	L	L	L	L
6-15	<4.6	S	L	S	S
	4.6–6.0	M	L	S	M
	5.1–5.5	M	L–M	M	M
	5.6–6.0	M	L–M	L–M	M
	>6.0	L	L	L	L
>15	<4.6	S	L	S	H
	4.6–5.0	M	L	S	M
	5.1–5.5	M	L	M	M
	5.6–6.0	L	L–M	L–M	L
	>6.0	L	L	L	L

Z Source: Holowaychuk and Fessenden (1987)
X Centimoles of cation per kilogram of soil
Y Abbreviations: L - Low sensitivity; M - Moderate sensitivity; S - Sensitive

Holowaychuk and Fessenden (1987) provided sensitivity rating criteria for Organic soils as well as mineral (upland) soils. Turchenek et al. (1998) reviewed the sensitivity of peatlands to acidification and recommended modifications to the ratings of peatlands. The modified ratings, as indicated in Table 18, were applied in the LICA area.

Table 18. Acidification Sensitivity Ratings for Peatlands.

Peatland Type	Sensitivity to:			Rating
	Base Loss	Acidification	Aluminum Solubilization	
Eutrophic - Extreme Rich Fen	Low	Low	n/a	Low
Mesotrophic - Moderate Rich Fen	Low - Medium	Low	n/a	Low
Oligotrophic - Bog & Poor Fen	Medium - High	Medium	n/a	Medium

[z] Source: Turchenek et al. (1998)

Soil map information used for derivation of sensitivity ratings was obtained from the Agricultural Region of Alberta Soil Information Database (AGRASID) (Alberta Soil Information Centre: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6903) for the southern part of the region. The AGRASID database provides soil survey coverage along with descriptions of Soil Series, including typical soil chemical attributes.

Soil distribution is presented in the AGRASID database within a hierarchical framework based on the National Ecological Framework for Canada (Marshall and Schul 1999). The LICA study area is within the Prairies Ecozone. An Ecozone is an area that is representative of large and very generalized ecological units characterized by interactive and adjusting abiotic and biotic factors. Canada is divided into 15 terrestrial ecozones.

An Ecoregion is a part of an Ecozone characterized by distinctive ecological responses to climate as expressed by the development of vegetation, soil, water, fauna, etc. (Marshall and Schul 1999). The study area is located within the Aspen Parkland, Boreal Transition and Mid-Boreal Uplands Ecoregions. Descriptions of each of these are presented in Section 1.

An Ecodistrict is a subdivision of an Ecoregion characterized by distinct assemblages of landform, relief, surficial geologic material, soil, water bodies, vegetation and land uses (Marshall and Schul 1999). The soil mapping system in AGRASID further subdivides Ecodistricts into Land Systems. A Land System is a subdivision of an Ecodistrict recognized and separated by differences in one or more of general pattern of land surface form, surficial geologic materials, amount of lakes or wetlands, or general soil pattern. All Land Systems within one Ecodistrict have the same general climate for agriculture, but differences in microclimatic pattern can be recognized. Land Systems are further divided into Soil Landscapes, which are land areas that display a consistent and recognizable pattern of distribution of soils and landscape elements (Alberta Soil Information Centre: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6903). Soil Landscapes are the level at which most soil survey information is presented. The AGRASID database provides soil survey information at a scale equivalent to about 1:100,000. Somewhat larger scale information is available from the soil surveys carried out for environmental impact assessments in the LICA area. However, for purposes of assessing soil sensitivity to acidification on a regional basis, use of a smaller scale is spatially more appropriate (e.g., for presentation purposes) and also less wieldy as compared to the large amount of data that would be handled at a larger scale. Therefore, soil types as identified at the more generalized Land System level were applied in assessing sensitivity. This provides information at a lower level of detail, but at a somewhat greater level than that of the land units applied in soil sensitivity mapping by Holowaychuk and Fessenden (1987). Consequently, Land System information was considered to be a practical basis for refining the previous soil sensitivity mapping and for calculating critical loads.

Land Systems coverage in the AGRASID database is provided only for the agricultural regions of Alberta. For the northern part of the study area beyond the agricultural zone, a similar mapping concept was applied based on the CanSIS database for land systems (National Land and Water Information Service: http://res.agr.ca/cansis/nsdb/slc/intro.html). The level of detail in the national system lies between that of the Land System in the AGRASID database, and the Ecodistrict in the National Ecological Framework for Canada. Thus, the delineations in the northern part of the LICA area are more generalized and larger than those on the southern boreal and agricultural regions. The term 'Land System' was adopted for both of these mapping concepts in this report.

Each of these databases describes soil composition of Land Systems in terms of proportions of Soils Series. A Soil Series is a fundamental taxonomic level in the Canadian System of Soil Classification, defined as a particular Soil Subgroup on a specific parent material (Soil Classification Working Group 1998). For example, the Athabasca soil series is defined as an Orthic Gray Luvisol developed in moderately fine textured Morainal (glacial till) material. Naming of Soil Series is based on Alberta Soil Names, Generation 3 in the AGRASID soil names file (Alberta Soil Information Centre: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6903). Within AGRASID, each Soil Series is described in terms of a typical soil profile within the associated database referred to as the Soil Layer File. This file was the source of information for soil pH and cation exchange capacity required to develop a sensitivity rating from the system of Holowaychuk and Fessenden (1987), as presented in Table 17 above.

Since the Soil Layer File provides only one soil profile description (with chemical analysis of horizons), other soil survey reports both within and neighbouring the LICA area were referenced to corroborate the data provided. Information from environmental impact assessments and development plans of oil production companies in the LICA area was also applied in this way. A list of publications referred to for soil information is included in the annotated bibliography in this report, and available soil chemistry information is summarized in Appendix B1.

The Sensitive, Moderate sensitivity, and Low sensitivity categories were developed for each of the Land Systems in the LICA area. In some cases, combinations of sensitivity classes were applicable. The spatial coverages of the Land Systems were superimposed on a base map of the study area using ARCGIS©. The colour scheme of the original Holowaychuk and Fessenden (1987) report, with modifications for complex map units, was applied in designating the sensitivity class or classes of the Land Systems.

4.1.2 Potential Critical Load Exceedance Mapping

The critical load represents the level of sustained deposition of a substance that will not cause long-term harmful change to an ecosystem. The critical load is thus dependent on the inherent characteristics of the ecosystem, and is a property of the ecosystem. Nilsson and Grennfelt (1988) specifically defined the critical load for acidic deposition to soils as "*the highest deposition of acidifying compounds that will not cause chemical changes in the soil which will lead to long-term harmful effects on the structure and function of the ecosystem*".

The critical load concept has been applied to the deposition of acidifying substances, heavy metals and other contaminants on soils, waters and other receptors. Essentially, the concept of critical loads was originally adopted in the European Union and later in North America as a method for development and implementation of control strategies for air pollutants. A recent description of approaches and methods for critical load derivation is provided by Task Force on Mapping and Modelling (2004). In Canada, the history of critical loads applications has been discussed by Jeffries and Ouimet (2004), and critical loads studies have been carried out on upland forest ecosystems throughout eastern Canada, and most recently for forest soils in Manitoba and Saskatchewan (Aherne and Watmough, 2006).).

In 1999, Alberta Environment implemented the Acid Deposition Management Framework for the long-term, provincial management of acid deposition (Clean Air Strategic Alliance and Alberta Environment, 1999). This framework is based upon the current understanding of the levels of acid deposition and the sensitivity of soil and water receptors in the province. Critical loads are the foundation of the framework. Potential effects on soils in the LICA area were assessed by reference to critical loads, as well as to target and monitoring loads. The framework within which these loads are applied is described in Section 2.2.2 of this report.

The possible exceedance of monitoring, target and critical loads for soils in the LICA study area was examined by superimposing the PAI isopleths (Section 2) on the Land System map using ArcGIS© (ESRI Canada). Areas of soils exceeding the monitoring, target and critical loads were then determined using GIS techniques.

4.1.3 Soil and Vegetation Monitoring

Soil and vegetation monitoring programs in the LICA study area and in other parts of the province were reviewed using currently available information.

4.2 ACIDIFICATION SENSITIVITY RATING OF SOILS

4.2.1 Sensitivity Ratings of Soil Series

A list of the main soil series occurring in the LICA study area was derived from the component listings of each Land System. Soil chemical attributes of the soil series were then tabulated from the AGRASID database and the sensitivity classes were derived by reference to the criteria presented in Tables 17 and 18. The soil series sensitivity ratings are presented in Table 19, which is based on the sensitivity class derivation presented in Appendix B2.

Table 19: Acidification Sensitivity of Soil Series in the LICA Study Area

Symbol	Series	Drainage	Calcar	Salinity	PM1 Texture	PM1 Type	PM2 Texture	PM2 Type	Soil Subgroup	Sensitivity Rating
Soils of the Thick Black Soil Zone of Central and East Central Alberta										
AGS	Angus Ridge	W	M	N	MF	TILL	-	-	E.BL	L
BVH	Beaverhills	W	M	N	MF	TILL	-	-	O.BL	L
COA	Cooking Lake	W	M	N	MF	TILL	-	-	O.GL	L
FTH	Ferintosh	W	W	N	GRVC	GLFL	-	-	O.BL	L
GBL	Gabriel	W	M	N	MC	GLFL	MF	TILL	D.GL	L
GRZ	Gratz	W	M	N	ME	FLUV	-	-	CU.HR	L
HBG	Horburg	R	M	N	GRVC	GLFL	-	-	BR.GL	M
HLW	Helliwell	W	W	N	VC	GLFL	-	-	O.DG	L
KVG	Kavanagh	MW	W	W	MF	SRFS	-	-	BL.SS	M
MDR	Mundare	W	W	N	VC	FLEO	-	-	O.BL	L
MSW	Mooswa	W	M	N	MC	GLFL	-	-	E.BL	L
PHS	Peace Hills	W	W	N	MC	GLFL	-	-	O.BL	L
PRM	Primula	R	N	N	VC	GLFL	-	-	E.EB	S
RDW	Redwater	W	W	N	MC	GLFL	-	-	O.DG	L
RLV	Rolly View	W	M	N	MF	TILL	-	-	O.DG	L
SLW	Slawa	W	W	N	FI	TILL	-	-	E.BL	L
TWH	Two hills	W	W	N	GRVC	GLFL	-	-	O.DG	L
UCS	Uncas	W	M	N	MF	TILL	-	-	D.GL	L
UKT	Ukalta	W	M	N	MC	GLFL	MF	TILL	O.BL	L
Soils of the Dark Gray – Gray Soil Zone of Northeast Central Alberta										
ADM	Ardmore	W	M	N	ME	GLLC	-	-	E.BL	L
EDW	Edwand	R	W	N	VGVC	GLFL	-	-	E.EB	S
FNC	Franchere	W	M	N	MF	GLLC	-	-	O.GL	M
FRY	Fergy	W	M	N	MF	TILL	-	-	E.BL	L
KHW	Kehiwin	W	M	N	MF	TILL	-	-	O.DG	L
LCY	La Corey	W	M	N	MF	TILL	-	-	O.GL	M
MNT	Manatokan	VP	N	N	O	FNPT	MC	GLFL	T.M	L-M
MPV	Mapova	P	M	N	MF	TILL	-	-	HU.LG	L
NIT	Nicot	R	W	N	VC	GLFL	-	-	E.EB	S
NTW	Nestow	R	N	N	VC	GLFL	-	-	E.DYB	S
SDN	Spedden	W	M	N	MF	TILL	-	-	D.GL	L
TNW	Tawatinaw	W	W	N	GRMC	TILL	-	-	O.GL	S
VIL	Vilna	I	M	N	MF	TILL	-	-	GLE.BL	L
Soils of the Central Mixedwood Area of Northeastern Alberta										
ABC	Athabasca	W	W	N	MF	TILL	-	-	O.GL	S
BLA	Birkland	VP	N	N	O	SPPT	MF	TILL	T.F	L-M
GMT	Grosmont	W	W	N	MF	TILL	-	-	D.GL	S
GOG	Goodridge	W	W	N	MC	TILL	-	-	O.GL	S
LIZ	Liza	R	N	N	VC	GLFL	-	-	E.DYB	S
LRD	Lessard	W	M	N	ME	GLLC	-	-	O.DG	L
PIN	Pinehurst	R	W	N	VGVC	GLFL	-	-	E.EB	S
SLN	St. Lina	VP	N	N	O	FNPT	MF	GLLC	THU.M	L-M
TCK	Tucker	VP	W	N	O	SPPT	VC	FLUV	TME.F	M

Table 19: Acidification Sensitivity of Soil Series in the LICA Study Area (concluded)

Symbol	Series	Drainage	Calcar	Salinity	PM1 Texture	PM1 Type	PM2 Texture	PM2 Type	Soil Subgroup	Sensitivity Rating
Soils of the Central Mixedwood of Central and Northern Alberta										
MUS	Muskeg	VP	N	N	O	SPPT	-	-	TY.M	M
HLY	Hartley	VP	N	N	O	FOPT	MF	TILL	T.F	L-M
MIL	Mildred	R	N	N	VC	GLFL	-	-	E.DYB	S
MLD	McClelland	VP	N	N	O	FNPT	-	-	TY.M	L-M
Miscellaneous Soil and Land Types										
ZCOzdg	Coarse textured with Dark Gray soils									L
ZERzbl	Eroded with Black soils									L
ZERzdg	Eroded, with Dark Gray soils									L
ZGW	Poorly drained % Shallow water									L
ZOR	Organic soils									L-M
ZUN	Undifferentiated									L
ZWA	Water bodies									na

Abbreviations:
Drainage: VR - very rapid; R - rapid; W - well; MW – moderately well; I - imperfect; P - poor; VP - very poor.
Calc (calcareousness) and Salinity: N – non; W – weak; M – moderate
PM1 (upper parent material), PM2 (lower parent material):
PM Texture: VC – very coarse; C – coarse; GRVC – gravelly very coarse; MC – moderately coarse; GRMC – gravelly moderately coarse; ME – medium; MF – moderately fine; FI – fine;
PM Type: TILL – glacial till, or morainal; GLFL – glaciofluvial; FLUV – fluvial; FLEO – fluvioeolian; GLLC – glaciolacustrine; SRFS – soft rock; FNPT – fen peat; SPPT – sphagnum peat
Soil Subgroup: Defined below in context of the Canadian System of Soil classification

Order	Great Group	Subgroups
Brunisolic - Sufficient development to exclude from the Regosolic order, but lack degrees or kinds of development specified for other orders.	Eutric Brunisol - Ah<10 cm, pH>5.5 Dystric Brunisol - Ah<10 cm, pH<5.5	E.EB - Eluviated Eutric Brunisol E.DYB - Eluviated Dystric Brunisol
Regosolic - Development too weak to meet requirements of any other Order.	Regosol – Ah<10 cm, Bm absent or <5 cm Humic Regosol – Ah≤10 cm, Bm absent or <5 cm	(Non in above table)
Chernozemic - Surface horizons darkened by accumulation of organic matter from decomposition of grassland vegetation.	Black Chernozem - Black Ah, semiarid climate Dark Gray Chernozem - Dark Gray Ah, semiarid climate	O.BL – Orthic Black E.BL – Eluviated Black O.DG – Orthic Dark Gray
Gleysolic - Features indicative of periodic or prolonged water saturation, and reducing conditions - mottling and gleying.	Humic Gleysol - Ah≥10 cm, no Bt Gleysol - Ah≤10 cm, no Bt Luvic Gleysol - Has a Btg, usually has an Ahe or an Aeg	O.LG - Orthic Luvic Gleysol HU.LG - Humic Luvic Gleysol O.G - Orthic Gleysol
Luvisolic - Light coloured eluvial horizons - Ae; illuvial B horizons of silicate clay accumulation - Bt; developed under forest vegetation.	Gray Luvisol - May or may not have Ah, has Ae and Bt, usually MAST ≤8 degrees Celsius[Y]	O.GL - Orthic Gray Luvisol D.GL - Dark Gray Luvisol GL.GL - Gleyed Gray Luvisol GLD.GL - Gleyed Dark Gray Luvisol BR.GL - Brunisolic Gray Luvisol
Organic (Composed dominantly of organic materials; most are water saturated for prolonged periods)	Mesisol - Dominantly mesic Fibrisol - Dominantly fibric	T.F. - Terric Fibrisol T.M. - Terric Mesisol TF.M - Terric Fibric Mesisol TM.F - Terric Mesic Fibrisol TY.F - Typic Fibrisol M.F - Mesic Fibrisol TY.M - Typic Mesisol F.M - Fibric Mesisol

Z Source: Soil Classification Working Group (1998). Y MAST = mean annual soil temperature.

4.2.2 Soil Series Composition of Land Systems

Land Systems are characterized by a number of soil types due to variations in parent materials and to factors such as drainage and topography. The predominant soil types in the Land Systems mapped in the LICA study area are indicated in Table 20. The same table with additional information is presented in Appendix B3.

Table 20: Soil Composition of the Land Systems in the LICA Study Area.

Land System Symbol & Name	Soil Zone	Major Soil Series	Minor Soil Types or Series
Vermilion River Valley	Thin Black	Eroded, with misc. Black Chernozems	
Reilly Plain	Black-Dark Gray	Beaverhills Mundare Peace Hills	Gleysols
Pasatchaw Plain	Black-Dark Gray	Beaverhills	
Dewberry Plain	Black-Dark Gray	Beaverhills Mundare	Ukalta
Irish Creek Plain	Black-Dark Gray	Angus Ridge Gabriel	Helliwell
Gadois Upland	Black-Dark Gray	Angus Ridge Uncas	Redwater; with Eroded & misc. Black Chernozems
Clandonald Upland	Black-Dark Gray	Slawa	Angus ridge
Queenie Plain	Black-Dark Gray	Angus Ridge Uncas	Slawa, Gleysols
Tomas Upland	Black-Dark Gray	Rolly View	Gleysols, Redwater
Beaver River Valley	Dark Gray-Gray	Eroded; with misc. Dark Gray Chernozems	Gleysols; with Coarse soils & misc. Dark Gray Chernozems
North Saskatchewan River Valley	Black-Dark Gray	Eroded; with misc. Black Chernozems	Water
Atimoswe Creek Plain	Black-Dark Gray	Uncas Angus Ridge	Gleysols, Eroded
Kawatt Plain	Black-Dark Gray	Angus Ridge	Uncas, Gleysols
Kerensky Plain	Black-Dark Gray	Angus Ridge Uncas	Gleysols
Val Soucy Plain	Black-Dark Gray	Angus Ridge	Uncas, Mooswa
Laurier Upland	Black-Dark Gray	Angus Ridge	Primula, Uncas
Makaoo Upland	Black-Dark Gray	Angus Ridge	Kavanagh, Mundare
Cherry Grove Plain	Dark Gray-Gray	La Corey	Spedden, Birkland
Beaver Crossing Plain	Dark Gray-Gray	Kehiwin Spedden	Fergy, La Corey
Lessard Plain	Dark Gray-Gray	Spedden Lessard	Franchere, Gleysols

Table 20. Soil Composition of the Land Systems in the LICA Study Area (continued).

Land System Symbol & Name	Soil Zone	Major Soil Series	Minor Soil Series
Wolf Plain	Dark Gray-Gray	Fergy Ardmore	Spedden Nestow
Ardmore Plain	Dark Gray-Gray	Fergy Kehiwin	Spedden
Danuta Plain	Dark Gray-Gray	Spedden	La Corey Kehiwin
Glendon Plain	Dark Gray-Gray	Spedden	La Corey Vilna
Denning Lake Upland	Dark Gray-Gray	Spedden La Corey	Gleysols
Goodridge Plain	Dark Gray-Gray	Spedden Goodridge	Nicot
Moose Lake Plain	Dark Gray-Gray	Nicot	Nestow Manatokan
Manatokan Plain	Dark Gray-Gray	Spedden La Corey	Gleysols
Stebbing Lake Plain	Dark Gray-Gray	Nicot	Edwand Nestow
Punk Creek Plain	Dark Gray-Gray	La Corey Tawatinaw	Organic; with Eroded & misc. Dark Gray Chernozems
Bangs Plain	Dark Gray-Gray	Eroded, with misc. Dark Gray Chernozems	Gleysols
Owlseye Lake Upland	Black-Dark Gray	Cooking Lake Uncas	Angus Ridge Gleysols
Beauvallon Upland	Black-Dark Gray	Cooking Lake Uncas	Rolly View Gleysols
Eliza Upland	Black-Dar Gray	Cooking Lake Peace Hills	Uncas Two Hills
Canard Upland	Black-Dark Gray	Uncas Angus Ridge	Cooking Lake Gleysols
Beauvallon Plain	Black-Dark Gray	Rolly View Uncas	Gleysols Mundare
Landon Upland	Black-Dark Gray	Redwater Cooking Lake	Rolly View Gleysols
Kopernik Upland	Gray	Athabasca	St. Lina
Fredro Plain	Gray	Athabasca	Grosmont Birkland
Reita Lake Plain	Gray	Athabasca	Grosmont Gleysols
Murial Lake Plain	Gray	Athabasca	Grosmont
Redspring Upland	Gray	Athabasca	St. Lina
Asnyk Upland	Dark Gray-Gray	Spedden La Corey	Gleysols Eroded & misc. Dark Gray Chernozems
Hilda Lake Plain	Gray	Athabasca Liza	Spedden St. Lina

Table 20: Soil Composition of the Land Systems in the LICA Study Area (concluded).

Land System Symbol & Name	Soil Zone	Major Soil Series	Minor Soil Series
Silesia Plain	Gray	Athabasca	Eroded & misc. Dark Gray Chernozems Gleysols
Odra Plain	Gray	Athabasca	Organic; with Coarse textured soils and misc. Dark Gray Chernozems
Artur Upland	Gray	Athabasca	St. Lina
Meridian Lake Upland	Gray	Athabasca	
Cold Lake	Gray	Water	Eroded & misc. Dark Gray Chernozems
Bourque Plain	Gray	Athabasca Nicot	St. Lina Tucker
Standish Plain	Gray	Athabasca St. Lina	Nicot Tucker
Heart Upland	Gray	Athabasca	St. Lina
Seibert Plain	Gray	Athabasca Goodridge	St. Lina Tucker
Mostoos Upland	Gray	Kinosis McLelland Mildred	Hartley

4.2.3 Mapping of Soil Sensitivity

The sensitivity categories are Sensitive, Moderate Sensitivity and Low Sensitivity. In Land Systems composed mainly of a individual Soil Series, or a combination of Soil Series with the same sensitivity rating, a single Sensitive, Moderate or Low rating was applied. Where co-dominant Soil Series had different sensitivity ratings, mixtures were mapped (e.g., Sensitive with Low). Land Systems were differentiated in cases where the dominant soil series sensitivity was Low, but there was a 5-10 percent component of Sensitive or Moderate soils. These types of Land Systems were identified in keeping with the CASA and AENV (1999) criteria that a grid cell with more than 5% Sensitive soils would have the lowest critical load.

The categories of soil sensitivity to acidic and acidifying substances, and the areas and proportions of Land Systems characterized by the different sensitivity categories are given in Table 21. A map of land systems and their soil sensitivities to acid input is presented in Figure 12.

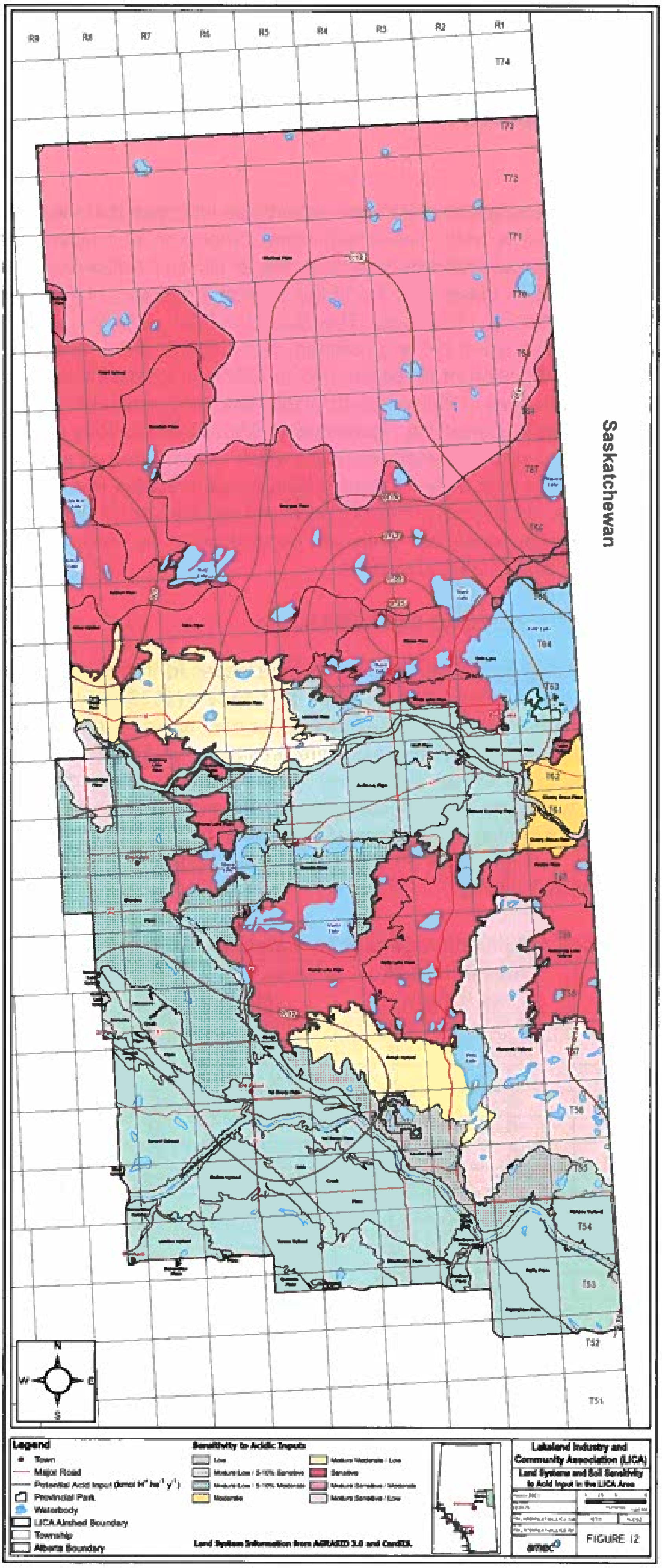
Table 21: Categories of Soil Acidification Sensitivity and their Extent in the LICA Area

Acidification Category	Area (ha)[z]	Area (% of LICA Area)
Low	343,520	21.2
Low, with 5-10% Moderate	122,848	7.6
Low, with 5-10% Sensitive	33,633	2.1
Moderate	13,840	0.9
Moderate with Low	88,851	5.5
Sensitive	512,151	31.6
Sensitive/ Moderate Mixture	396,454	5.1
Sensitive/ Low Mixture	82,165	24.4
Cold Lake[z]	28,547	1.8
Total	1,622,009	100.0

[z] Except for Cold Lake, lake areas and other miscellaneous land types such as roads and urban areas have not been subtracted from the sensitivity category areas.

The mapping of soil sensitivity suggests that more than half of the LICA area is characterized by soils that are Sensitive to acidic soil inputs, or are mixtures of Sensitive with Moderate or Low Sensitivity soils. Soils that are recognized as being most sensitive are those of very sandy texture, these mainly being the Nicot and Liza Soil Series (Table 19). These soils have low acid buffering capacity and low nutrient content. The Land Systems characterized by predominance of these soils are the Stebbing Lake Plain and Moose Lake Plain. The Hilda Lake Plain, Bourque Plain and Goodridge Plain Land Systems have a significant component of these soils.

Most of the Sensitive Land Systems in the LICA area are characterized by the Athabasca Soil Series. This is an Orthic Gray Luvisol soil developed on medium to moderately fine textured glacial till. The Goodridge soil series is a close associate of the Athabasca soil, the main difference being a sandier and stonier composition. These soil are rated in the Sensitive category because their surface mineral horizons (the A horizons) are generally very sandy and/or their A horizons are relatively acidic. The A horizon is underlain by a Bt horizon (a horizon of clay accumulation) with considerably higher buffering capacity. The closely related La Corey soil is rated as having Moderate Sensitivity to acidification because its A (i.e., topsoil) horizon is not as acidic as that of the Athabasca soil. Similarly, Cooking Lake soils, which occur to a much lesser extent in the southern part of the LICA area, are also characterized by higher buffering A horizons. In some locations, the Athabasca soil has a relatively thick sandy surface layer. Where these layers are greater than 30 cm thick, the soils are classified as a different Soil Series in more detailed soil surveys. Such soils have not been recognized within the Land System descriptions provided in the AGRASID and CanSIS databases. However, they do exist, as evidenced by the soil and terrain baseline report for the CNRL Primrose East Expansion project (CNRL 2006). The Moose Hills Soil Series, for example, is an Orthic Gray Luvisol developed on relatively thin, sandy glaciofluvial material overlying glacial till. The Moose Hills soils are Sensitive to acidification, based on their soil chemistry (see CNRL soils in Appendix B1).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T51
Saskatchewan
N
S
W
E
Legend
Town
Major Road
Potential Acid Input (kmol H⁺ ha⁻¹ y⁻¹)
Provincial Park
Waterbody
LICA Airshed Boundary
Township
Alberta Boundary
Sensitivity to Acidic Inputs
Low
Mixture Low / 5-10% Sensitive
Mixture Low / 5-10% Moderate
Moderate
Mixture Moderate / Low
Sensitive
Mixture Sensitive / Moderate
Mixture Sensitive / Low
Land System Information from AGRASID 3.0 and CanSIS.
Lakeland Industry and Community Association (LICA)
Land Systems and Soil Sensitivity to Acid Input in the LICA Area
amec
FIGURE 12

The CNRL Primrose East Expansion soil survey report also indicates that the Mostoos Plain, in the northern part of the LICA area, has a significant proportion of Caslan soils, which are Brunisols on sandy glaciofluvial deposits overlying glacial till, and Amisk-Liza soils, which are Brunisols in deep sands. Both these soils are in the Sensitive category of acidification because of the their low acid buffering capacities. The Mostoos Plain is rated in this study as a Sensitive/Moderate mix because of the large proportion of Organic soils, most of which are fens The fens are likely a combination of moderate rich to rich fens (relatively low acidity and high nutrient content) and poor fens (relatively high acidity and poor nutrient content), which are rated as Low and Moderate Sensitivity, respectively. Thus, the Mostoos Plain does have a relatively small component of Low Sensitivity soils, which is not reflected in the overall rating. However, inclusions of soils with different ratings than those indicated likely characterize all of the Land Systems. Thus, an overall rating of Sensitive/Low mixture or even of Sensitive and Sensitive/Medium categories does not preclude occurrence of a small component of well buffered, Low Sensitivity soils in a Land system.

4.3 POTENTIAL CRITICAL LOAD EXCEEDANCE

Critical loads corresponding to the sensitivity classes discussed in the previous section have been suggested in Alberta as described in CASA and AENV (1999) and Foster and Eastlick (2001). Monitoring, target and critical loads expressed as potential acid input (PAI) for Sensitive, Moderate Sensitivity and Low Sensitivity soils were previously presented in Section 2.2.2. The PAI isopleths developed in the Air Quality section of this report (i.e., those determined using the LICA air monitoring network data – see Section 2) were superimposed on the Land System map to calculate the areas of potential exceedance of the critical, target and monitoring loads. These areas of the sensitivity ratings within >0.25, 0.22 – 0.25, and 0.17 – 0.22 keq H^+/ha/yr PAI isopleths are presented in Table 22.

Table 22: Areas of Soil Acidification Sensitivity Categories within PAI Ranges

Acidification Category	Area with >0.25 keq H^+/ha/yr		Area with 0.22–0.25 keq H^+/ha/yr		Area with 0.17–0.22 keq H^+/ha/yr	
	(ha)	(%)^z	(ha)	(%)^z	(ha)	(%)^z
Low	0	0	0	0	75,032	4.6
Low, 5-10% Moderate	0	0	0	0	25,831	1.6
Low, 5-10% Sensitive	0	0	0	0	7,567	0.5
Moderate	0	0	0	0	180	0.01
Moderate with Low	0	0	0	0	9,065	0.6
Sensitive	1,197	0.07	12,437	0.8	57,327	3.5
Sensitive/Moderate	0	0	0	0	0	10.8
Sensitive/Low	0	0	0	0	0	0
Cold Lake	0	0	0	0	3,271	0.2
Total	1,197	0.07	12,437	0.8	178,273	10.8

^{z} % of LICA area.

A small area (1,197 ha) with PAI >0.25 keq H^+/ha/yr occurs immediately northeast of Leming Lake. This represents an area in which the critical load of Sensitive soils is potentially exceeded. A relatively small area encircling the latter represents the area of target load exceedance. A somewhat larger area of 0.17 to 0.22 keq H^+/ha/yr, surrounding the latter two, is oblong in shape and extends southeast beyond the City of Cold Lake. A second area exceeding 0.17 keq H^+/ha/yr is located between Lindberg and St. Paul, more or less centring on Elk Point. These areas have a small proportion of sensitive soils within them, and the monitoring load is potentially exceeded for these soils.

Comments and implications of the PAI exceedances in the LICA area are as follows:

- When considered in the context of the acid deposition management strategy for Alberta as described by Clean Air Strategic Alliance and Alberta Environment (1999), about two-thirds of the LICA area falls within a grid cell corresponding to the 73L East Half National Topographic Sheet. The proportion of Sensitive soils in this grid cell is more than 5%, and the potential exceedance would trigger management principles as outlined in the above document. [The 73L E½ NTS sheet extends from the Saskatchewan border to the middle of Range 7, and from Townships 58 to 76 inclusive.]
- The CASA and AENV (1999) document should be referred to for details of management implications.
- Possible exceedance of the monitoring load for sensitive soils represents the largest exceedance area in the LICA area. In general, recommended actions include application of air quality (specifically PAI) modelling in neighbouring grid cells to determine contribution to the grid call of concern, accompanied by implementation of monitoring and receptor sensitivity studies.
- In order to adequately assess receptor sensitivity, verification of acid inputs is necessary.
- A portion of the 0.17 keq H^+/ha/yr, isopleth between Lindberg and St. Paul passes through an area of sensitive soils.
- In the grid cell context, most of the monitoring load exceedance surrounding Elk Point is located within the 73E East Half grid cell. This would not trigger action according to CASA and AENV (1999) because most of the soil receptors are of Low sensitivity to acidic inputs. However, this is an uncertain statement because this area is the northernmost part of the grid cell, and investigation of other parts of the grid cell would be required to asses it fully.

4.4 SOIL MONITORING IN THE LICA AREA

Monitoring refers to a process of checking, observing or keeping track of something for a specified period of time or at specified intervals (Gregorich et al. 2001). Soil monitoring for acidification effects involves measurement of specific soil properties that respond to acidity. Two major Alberta programs involve soil monitoring, namely the Long Term Soil Acidification Monitoring Program of Alberta Environment (Roberts et al. 1989) and the Terrestrial Environment Effects Monitoring (TEEM) program of the Wood Buffalo Environmental Association (AMEC 2000). The main soil parameters included in these monitoring programs are pH, cation exchange capacity, exchangeable cations, and soil solution ions (including aluminum).

The AENV monitoring program consists of eight sites distributed around the province. One of the sites is within the LICA area, located in NW20/SW29-64-2-W4. This location is close to Cold Lake, lies southeast of the heavy oil production areas, and lies within the 0.17 – 0.22 keq H^{+}/ha/yr PAI isopleth zone. As such, it is ideally situated for monitoring in the 0.17 keq H^{+}/ha/yr potential exceedance zone.

The Cold Lake monitoring site is located on Eluviated Dystric Brunisol soils developed in sandy, glaciofluvial deposits that thin out in places to a veneer (<1m sand) overlying loamy glacial till materials. It was established in 1981, and has had six sampling events since that time. Although the sampling interval was initially intended to be four years, various factors led to inconsistent intervals in the 1990s.

An initial report on the Long Term Monitoring Sites was completed on the initial two sampling events in 1981 and 1985 (Roberts et al. 1989). There were no detectable changes in pH, base saturation percentage or other acidification parameters at that time. A report on five sampling events is currently in preparation by Alberta Environment, with publication expected during 2007.

The Wood Buffalo Environmental Association sites are located mainly in the Fort McMurray area, with long distance sites located in each direction. After the initial site selection, as reported in AMEC (2001), additional near and long distance sites were selected in 2001 and 2004. The southernmost site is located in Township 84, Range 3, West of 4th Meridian. It is thus quite distant from the LICA area. While the TEEM program does not extend to the LICA region, the site establishment and procedures would have applicability to the LICA area, as would those of the Alberta Environment program.

4.5 VEGETATION SENSITIVITY AND MONITORING IN THE LICA AREA

4.5.1 Effects of Acidification on Vegetation

Emissions of substances such as the oxides of sulphur and nitrogen can have short-term and long-term effects on vegetation and the surrounding environment. Short-term effects can include the deterioration of the waxy outer layers, causing chlorosis of the plant tissues in localized areas, eventually resulting in mortality. Long-term effects involve direct effects of acidity on plant tissues, from either deposition onto the soil and uptake through the roots or from absorption from the surface of the plant. Acidification effects on plant tissues include interference with the plant's chemical processes, such as respiration, thereby decreasing the ability to repair tissues, resist disease and reproduce.

Indirect effects of acidification on vegetation involve development of imbalance in the chemistry and biology of the surrounding soil and water, thereby impacting soil nutrients. The amount and type of soil nutrients can be increased or decreased through acidification, in turn changing the availability to plants and increasing uptake of toxic elements. Availability of nutrients is also directly linked to the mass of fine root growth. With increased acidification there is a reduction in fine root growth, thereby reducing nutrient uptake. Change in soil pH is another imbalance created by acidification. As the soil pH becomes more acidic the current vegetation can give way to acid tolerant vegetation moving in and changing the species diversity. Stress placed on vegetation from acidification can also predispose plants to other stresses and injuries such as insect infestation, disease, drought and frost.

Vegetation acidification assessments in Alberta use critical loads for vegetation based on the CASA and AENV (1999) framework for soil critical loads. Acidification is considered in terms of indirect effects to vegetation; therefore, vegetation will be potentially affected in areas where the corresponding soils are affected (>0.25 keq H^+ /ha/yr level). Consequently, critical load exceedances areas for soils as determined in the previous section are also areas of potential acidification effects on vegetation. The species composition can be determined by overlaying the soil exceedance information on vegetation (i.e., ecosite) maps. Based on a review of literature, plant sensitivities to acidification as indicated in Table 23 were reported in the environmental impact assessment of the Primrose East Project area in CNRL (1999).

Table 23: Plant Sensitivity to Acidifying Emissions

Common Name	Species Name	Ranking[z]
Trees		
Jack pine	*Pinus banksiana*	high
Paper birch	*Betula papyrifera*	high
Trembling aspen	*Populus trembuloides*	high
White spruce	*Picea glauca*	medium
Balsam fir	*Abies balsamea*	medium
Balsam poplar	*Populus balsamifera*	low
Black spruce	*Picea mariana*	unknown
Tamarack	*Larix laricina*	unknown
Mosses		
Brown moss	*Drepanocladue spp.*	high
Schreber's moss	*Pleurozium schreberi*	high
Knight's plume moss	*Ptilium crista-castrensis*	high
Stair-step moss	*Hyloconium splendens*	high
Peat moss	*Sphagnum spp.*	variable
Golden moss	*Tomenthypnum nitens*	variable
Lichens		
Lichen	*Cladina spp.*	high
Lichen	*Stereocaulon lividum*	high
Reindeer lichen	*Cladina spp.*	high

[z] From CNRL (2006)

In terms of vegetation cover classes, the CNRL (1999) report indicated sensitivity classes as follows:

Sensitive (High Sensitivity):
- deciduous-aspen/aspen-balsam poplar dominant
- mixedwood -aspen/white spruce dominant
- mixedwood - jack pine-aspen dominant
- coniferous- jack pine

Moderate Sensitivity:
- coniferous- white spruce dominant
- coniferous- black spruce-white spruce (jack pine) dominant
- poor wooded fen/wooded bog
- graminoid fen

Low Sensitivity:
- wooded fen
- shrubby fen
- marsh
- upland shrubland
- agriculture
- cutblocks
- burn

According to these sensitivity classes, most aspen, Mixedwood, or jack pine forests fall into the sensitive category, where they occur on Sensitive soils. Spruce forests are of Moderate sensitivity, presumably because they tend to occur in richer sites. Fens and marshes have Low sensitivity due to higher nutrient content, including relatively high calcium (and alkalinity) in the associated waters.

4.5.2 Vegetation Monitoring Programs in the Cold Lake Region

Vegetation monitoring has been carried out in the Cold Lake Operations area of Imperial Oil Resources as reported by AMEC (2001, 2003, 2006). In 2000, a study of vegetation stress with particular reference to sulphur dioxide (SO_2) emissions was conducted. Through the use of false colour infra-red (FCIR) air photos and field inspection, the type of stress on the plant was evaluated. With FCIR photography, uniform patterns of pink to brownish colours widespread and downwind of processing facilities with SO_2 emissions are indicative of stress. Direct observations focussed on vascular plants. Non-vascular plants are more sensitive to air emissions because they absorb all their nutrients through the rain and water, whereas vascular plants are less sensitive. Non-vascular plants were not used in the study, however, due to lack of readability on the air photos and visibility in the field. Vascular plants also have the advantage of demonstrating measurable symptoms including chlorosis and necrosis.

Stress symptoms in conifers include chlorosis of older needles and brown discolouration, desiccation and necrosis, leading to chlorosis, stunted growth and premature needle drop. In deciduous species, symptoms are wet appearance and chlorosis of underside of leaf, leading to stunted growth, chlorosis and foliar death.

Using both of the direct observation and photographic approaches, no stress directly caused by SO_2 emissions was apparent. Insect and disease stress were present throughout the area at low levels. The most common forms of stress were logging and excess moisture stress associated with flooding due to beaver activity and to obstruction to water flow by roads.

In 2002, the monitoring program was expanded to include the Cold Lake First Nations Reserve (I.R. 149A) (AMEC 2003). In 2006, the monitoring was again carried out in the Cold Lake Operations area (AMEC 2006). Results of these two studies were similar to the previous report. Vascular vegetation was re-assessed for stress from air emissions, particularly SO_2. False-Colour air photos were examined, and field inspections were carried out for visible symptoms. As in the 2000 study, it was found that there were no direct long-term effects or vegetation stress from air emissions on the vascular plants in the study area.

In these monitoring programs, additional testing was carried out through tissue sampling and analysis of aspen leaves. Sulphur is an essential element for plant metabolism. Through sampling and analyzing aspen leaves, it was found that the concentrations of sulphur in the aspen leaves in the study area were similar to that of a control site. The low sulphur levels and healthy appearance of aspen leaves indicated that there was no direct impact to vegetation on the study area from SO_2 emissions.

4.6 SUMMARY AND RECOMMENDATIONS

A soil map of the LICA area was developed at the Land System level of detail wherein Land Systems are defined as areas recognized and separated by differences in one or more of general pattern of land surface form, surficial geologic materials, amount of lakes or wetlands, or general soil pattern. The application of a western Canadian rating system for potential acidification of soils resulted in about 32% of the LICA area rated as Sensitive to deposition, and another 29% rated as a mix of Sensitive and Moderate or Low Sensitivity soils. The Moderate category was dominant in about 6% of the LICA area, and the remainder (31%) was rated as having Low sensitivity. Cold Lake occupies about 2% of the area. Most of the sensitive soils occur in the northern part of the area, although there is also a sizable area in the southeast part of the region.

Small areas of PAI isopleths in the 0.22 – 0.25 and the >0.25 keq/ha/yr zones are characterized by soils rated as Sensitive to acidification. Somewhat larger areas of Sensitive soils fall into the 0.17 – 0.22 keq/ha/yr zone. This range exceeds the monitoring load as defined by CASA and AENV (1999), and the area is sufficiently large that actions such as increased monitoring and receptor research are recommended.

Soil monitoring to date consists of the operation by Alberta Environment of a long term program of monitoring eight sites around the province, one of which is located ion the Cold Lake area.

The site is located within the PAI monitoring zone indicated above. One report in 1989 indicated no change between the first and second monitoring events. A second report on five monitoring events is to be published in 2007. With respect to vegetation, monitoring in recent years has not indicated any vegetation damage attributable to SO_2.

In considering enhanced soil chemistry monitoring, the programs of Alberta Environment and of the TEEM program of the Wood Buffalo Environmental Association serve as suitable models. THE AENV program involves establishment of two plots at a site, with each plot sampled at 12 sample points. Eight soil layers are sampled, and analyses are carried out for a number of parameters including pH, exchangeable base cations, and soluble ions. All samples are analysed, or only samples from the uppermost layers have been analysed, depending on available funding. The analyses are costly, and therefore the overall costs for samples from a number of sites could be high.

The TEEM program involves establishment of four soil sampling plots surrounding a vegetation monitoring plot (AMEC 2001). Four subplots are sampled from each plot, and the samples from each layer are composited into a single sample. The composite samples considerably reduce the analytical costs. The TEEM program has had two sampling events to date, in 1998 and 2004. Higher sulphur content in forest floor (litter) layers in near-source sites as compared to far-from-source sites has been the only trend detected to date. The vegetation component of the TEEM program has not revealed any trends to date.

Elements of a soil and vegetation monitoring program that should be considered are as follows:

- Continuation of periodic sampling at the AENV monitoring site, located in the monitoring exceedance zone, should be encouraged.
- Additional monitoring sites in the monitoring exceedance zone for sensitive soils should be established to determine regional trends. At least one of the sites should be located in the monitoring exceedance zone near Elk Point, provided suitable forest stands are available.
- Establishment of a site near the 0.25 keq/ha/yr PAI isopleth would provide the opportunity not only to monitor but to research soil response to higher PAI.
- At least one control site should be established in the region to enable comparison of near source with relatively pristine sites.
- Preferred soil and vegetation types for establishment of monitoring sites are highly sensitive, sandy Brunisolic soils, as well the extensively occurring Luvisols on glacial till capped by coarse textured materials (the Athabasca Soil Series). Vegetation types should be uniform across sites. The Brunisols are mostly associated with jack pine/lichen stands. Mixedwood stands would be appropriate for the Athabasca soils, although some effort may be required in locating forest stands with similar characteristics.

- Consideration should be given to establishing paired sites in a monitoring program. One of the main reasons for establishing paired sites in the AENV program was to increase the probability of retaining a site should fire or other mishap destroy a site.
- A recurring criticism of other monitoring sites entails lack of establishment of acid deposition monitoring at the same sites, thus precluding investigation of true dose-response relationships. To the extent possible, soil and vegetation monitoring sites should be co-located with air quality monitoring sites.
- Prior to establishment of monitoring sites, consideration should be given to more in-depth analysis of soil types and their acidification sensitivity. Within the CASA and AENV grid cell context, this has been conducted for soils of the Provost-Esther area by soil sampling, laboratory analysis and calculation of critical loads using a predictive acidification model developed at the Alberta Research Council. Similar work is being conducted in the Edmonton area, with results to be published in 2007. This type of investigation would assist in verifying sensitivity ratings in the current study, and would provide a framework for locating monitoring sites. The level of soil mapping is the same as that applied in the current study (i.e., the Land System level of detail). The main problem in thorough assessment of the complete LICA area is the lack of information in the Cold Lake Air Weapons range, and means of acquiring additional information would need to be considered.
- The LICA Airshed Zone should maintain awareness of research programs conducted by the NO_X-SO_2 Management Program of CEMA in the oil sands region. These include the refinement of critical load determinations for soils and waters, and the establishment of research watersheds in which detailed soil, surface water and groundwater investigations are being conducted.

5.0 ANNOTATED BIBLIOGRAPHY

AEC East. 1999. Foster Creek In-Situ Oil Sands Project. Submitted to Alberta Energy and Utilities Board and Alberta Environment.

Foster Creek In-Situ Oils sands Project is situated near La Corey, Alberta. This is a detailed application and environmental impact assessment with information on physiography,, soils and geology including soil chemistry ratings, water resources, aquatic resources, vegetation and forests, climate, air quality and noise among others. This also includes mitigation and monitoring measures, as well a conservation and reclamation plan has been completed.

Aherne, J. and S.A. Watmough. 2006. Calculating Critical Loads of Acid Deposition for Forest Soils in Manitoba and Saskatchewan. PN1372. Canadian Council of Ministers of the Environment. Ottawa.

Presents a description and application of a model for deriving critical loads of acidity for soils in Manitoba and Saskatchewan at a broad, regional level.

Agriculture Canada and Alberta Research Council. 1989. Soil Survey of the Frog Lake Indian Reserve, Alberta. Open File Report No. 1989-11. Edmonton, AB.

Agriculture and Agri-Food Canada. 2006. Soil Landscapes of Canada. http://res.agr.ca/cansis/nsdb/slc/intro.html. Accessed March 2007.

GIS coverage of the major characteristics of soils and landscape for Canada. It is based on existing soils survey maps and each area is described by a standard set of attributes including a distinct type of soil and its soils composition.

Agriculture Canada and Alberta Research Council. 1989. Soil Survey of the Fishing Lake Metis Settlement, Alberta. Open File Report No. 1989-12. Edmonton, AB.

Both of the above reports provide soil map information in the Frog Lake area. The reports consist only of maps, and do not include soil chemistry information with which acidification ratings could be determined.

Alberta Economic Development. 2006. Oil Sands Industry Update.

Oil Sands Industry Update provides an overview of current status of oil sands expansion in Alberta. This update is used to facilitate communication between various groups including oil sands developers, Alberta government and stakeholders.

Alberta Lake Management Society (ALMS). 2007. Alberta Lakewatch Reports (2001 – 2005).Accessed 20 February 2007. http://www.alms.ca/Pages-Main/LakeWatch.htm#Data.

The Alberta Lake Management Society has compiled a series of reports based on water quality data collected by volunteers at several lakes throughout Alberta. The electronic reports provide water quality data, bathymetric information and lake trophic status. Individual ALMS reports for 12 lakes in the LICA study area were downloaded and pertinent water quality data were presented in the LICA report.

Alberta Soil Information Centre, Alberta Agriculture and Food and Rural development. 2007. Agriculture Region of Alberta Soil Inventory Database (AGRASID 3.0). http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6903).

'Provides soils information in digital files, published maps and reports. It also includes the Alberta Soil information finder which allows to view and query soils information with landscape images, ortho photographs and cadastrals. AGRASID has an extensive soil information for 26 million hectares that make up the agricultural land of Alberta.

AMEC Earth & Environmental. 2001a. Supplemental Soil Survey. In Conservation & Reclamation Plan. Internal Report to Imperial Oil Resources.

Provides limited soil chemistry information for three soil profiles in the IOR Cold Lake Operations area.

AMEC Earth & Environmental. 2001b. Vegetation Conditions in the Vicinity of the Cold Lake Operations Area 2000. Prepared for Imperial Oil Resources. Cold Lake, Alberta.

'This report is a study of vegetation stress in the Cold Lake Operations Area fro 2000, to find potential effects of sulphur dioxide (SO_2) emissions. The vegetation conditions were interpreted from false color infrared (FCIR) air photos and a field inspection. No direct evidence of damage from SO_2 emissions was evident.'

AMEC Earth & Environmental Limited (AMEC). 2000. *Monitoring Long-term Effects of Acid Emissions in Northeast Alberta- 1998 Annual Report.* Report prepared for Wood Buffalo Environmental Association. Calgary, Alberta.

Describes the soil and vegetation monitoring program in the oil sands area. Ten sites were established for the program, consisting of near source or High deposition sites and relatively distant, or Low, deposition sites. No differences were found in between High and Low sites, with the exception that total sulphur content was higher in the litter layer of soils of High sites. The program was initially intended to consist of four year sampling intervals; this was subsequently changes to six year intervals.

AMEC Earth & Environmental. 2003. 2002 Reclamation Monitoring Program Report- Soils, Vegetation and Wildlife Imperial Oil Resources Cold Lake Operations (Section 5.3.25 of Alberta Environment approval 73534-00-00). Prepared for Imperial Oil Resources. Cold Lake, Alberta.

'This report is a study of vegetation stress in the Cold Lake Operations Area for 2002, to find potential effects of sulphur dioxide (SO_2) emissions. The vegetation conditions were interpreted from false color infrared (FCIR) air photos and a field inspection. No direct evidence of damage from SO_2 emissions was evident. This study also used leaf tissue chemistry, to find the total amount of sulphur content found in aspen trees. It was shown that the total sulphur content with similar to the content of the control site, therefore it was found that there was no direct impact to vegetation from sulphur emissions.'

AMEC Earth & Environmental. 2006. 2005 Reclamation Monitoring Program Report- Soils, Vegetation and Wildlife Imperial Oil Resources Cold Lake Operations (Section 5.3.25 of Alberta Environment approval 73534-00-00). Prepared for Imperial Oil Resources. Cold Lake, Alberta.

'This report is a study of vegetation stress in the Cold Lake Operations Area for 2005, to find potential effects of sulphur dioxide (SO_2) emissions. The vegetation conditions were interpreted from false color infrared (FCIR) air photos and a field inspection. No direct evidence of damage from SO_2 emissions was evident. This study also used leaf tissue chemistry, to find the total amount of sulphur content found in aspen trees. It was shown that the total sulphur content was similar to the content of the control site; therefore, it was found that there was no direct impact to vegetation from sulphur emissions.'

Black Rock Orion EOR Project. 2001. Volume 2 Environmental Impact Assessment. Calgary, Alberta.

Hydrologic information from this report was used to compare mean annual runoff.

Canadian Natural Resources Limited (CNRL). 2006. Primrose In-Situ Oil Sands Project, Primrose East Expansion, Application for Approval and Supplemental Information. Submitted to Alberta Energy and Utilities Board and Alberta Environment.

Primrose In-situ Sands Project is an expansion project for Canadian Natural Resources Limited situated in the Cold Lake region of Alberta. This detailed project description and Environmental Impact Assessment encompasses assessments of air, noise and health, terrestrial resources, aquatic resources, and social aspects. It also includes mitigation and monitoring measures for all of the different assessments that occur.

Volume 8: 'Air Emission Effects' provided regulators with supplemental information, specifically on the potential effects of acidifying emissions on local and regional lakes. Several lakes in the LICA study area had relevant water quality data that were used in the LICA report. Lake identifiers, coordinates and analytical water quality data were used.

Chaikowsky, C.L.A. 2001. Base Cation Deposition in Western Canada, 1982-1998. Alberta Environment Pub. No. T/605.

'This study investigated base cation deposition for 31 precipitation monitoring stations in western Canada. Using precipitation chemistry data from each station, wet, dry, and total deposition of the base cations Na^+, Ca^{2+}, Mg^{2+}, and K^+ were analyzed over the general time period of 1982-1998. A spatial analysis was performed using shaded contour plots of the deposition data to contrast the magnitude of deposition between stations in the study area.'

Cheng, L., K. McDonald, D. Fox and R. Angle. 1997. Total Potential Acid Input in Alberta. Alberta Environmental Protection. Edmonton, AB. 26 pp.

'Total potential acid input for Alberta was calculated using the Regional Lagrangian Acid Deposition model and precipitation chemistry monitoring data. The total potential input is the European method to estimate deposition fluxes of acidifying substances, including wet and dry deposition of SO_x (SO_2 and aerosols of $SO_4^=$), NO_y (NO, NO_2, HNO_2, HNO_3 and aerosols of NO_3^-), NH_x (NH_3, aerosols of NH_4^+) and base cations (Na^+, Mg^{2+}, Ca^{2+} and K^+)." The study found that total acid input is generally less that 20% of the critical load in Alberta.

Cheng, L. 2007. Private communication.

Clean Air Strategic Alliance and Alberta Environment. (CASA) 1999. Application of Critical, Target and Monitoring Loads for the Evaluation and Management of Acid Deposition. Prep. by Target Loading Subgroup. Alberta Environment Publication No. T/472.

This report describes a framework for managing acidifying emissions and acid deposition in Alberta based on critical and target load. The framework is based on scientific assessment of acid deposition and its effects, as well as stakeholder consultation to integrate economic, social and technological considerations with scientific advances.

Devon ARL. Corporation. 2004. Application for the Approval of the Devon Jackfish 1 Project. Submitted to Alberta Energy and Utilities Board and Alberta Environment.

This report for Devon Jackfish 1 project in the Conklin region includes a complete project description and full baseline data, impact assessments, cumulative assessment and monitoring for soils (including soil acidification), air quality, vegetation, wetlands, wildlife and resource uses.

Devon ARL. Corporation. 2006. Application for the Approval of the Devon Jackfish 2 Project. Submitted to Alberta Energy and Utilities Board and Alberta Environment.

This report includes a complete project description and full baseline data, impact assessments, cumulative assessment and monitoring for soils (including soil acidification), air quality, vegetation, wetlands, wildlife and resource uses for the Conklin study area.

Eder, B.K. and R.L. Dennis, 1990. On The Use of Scavenging Ratios for the Inference of Surface Level Concentrations and Subsequent Dry Deposition of Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}. Water, Air and Soil Pollution 52: 197-216.

An inference technique is developed that allows estimation of the annual and monthly dry deposition of Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}. Conceptually, this technique is based on the premise that precipitation efficiently scavenges aerosols, resulting in a strong correlation between concentrations within precipitation and the surface-level air. Empirically, it is based on the linear relationship exhibited between the measured surface-level air and precipitation concentrations at 23 stations in Ontario, Canada, for the period 1983–1985. Correlations ranged from 0.513 for K^{+} to 0.946 for Mg^{2+}. Because of the stochastic nature of such an approach, the assumptions inherent to the concept of scavenging ratios, and therefore this inference technique, must be carefully considered. Under such considerations, annual and monthly dry deposition of alkaline aerosols can be estimated at many locations across North America where precipitation concentrations are routinely measured.

Environment Canada. 2007. The Canadian National Atmospheric Chemistry Database and Analysis System. http://www.on.ec.gc.ca/NatChem. Accessed March 2007

'The purpose of the NAtChem database is to enhance atmospheric research through the archival and analysis of North American air and precipitation chemistry data. Such research includes investigations into the chemical nature of the atmosphere, atmospheric processes, spatial and temporal patterns, source-receptor relationships and long range transport of air pollutants.'

Environment Canada. 2005. Narrative Descriptions of Terrestrial Ecozones and Ecoregions of Canada. http://www.ec.gc.ca/soerree/English/Framework/Nardesc/canada_e.cfm. Accessed March 2007

National Map and narrative descriptions of terrestrial ecozones and ecoregions of Canada.

EPCM Associated Ltd. 2002 (Peake, E). Estimation of dry acid deposition at TEEM passive monitoring sites. Prepared for WBEA TEEM Committee. 169 pp.

This report describes a model developed to estimate dry acidic deposition at TEEM passive monitoring sites within the oil sands region. The inferential model, named TEEMDEP, utilizes meteorological measurements and surface conditions at Fort McKay to determine monthly NO_2 and SO_2 deposition velocities (Vd) for major regional surface types (land use types).

Foster, K.R., McDonald, K., Eastlick, K.. 2001. Development and application of critical, target and monitoring loads for the management of acid deposition in Alberta, Canada. Water, Air, and Soil Pollution: Focus 1, 135-151.

Gilbert, R.O. 1987. Statistical Methods for Environmental Pollution Monitoring. John Wiley & Sons. Toronto, ON. 315 pp.

This book contains statistical techniques and their application in the environmental pollution monitoring. Most of the statistical techniques discussed are relatively simple, and examples, exercises, and case studies are provided to illustrate procedures. The book is a valuable guide to statistical applications and can be used as a general reference source in practical applications.

Golder Associates. 2000. Canadian Natural Resources Limited (CNRL) Primrose and Wolf Lake (PAW) Project. Volume V, Appendix D, Climate and Hydrology, Calgary, Alberta.

Hydrologic information from this report was used to compare mean annual runoff.

Golder Associates Ltd. 2004. Acid Deposition Sensitivity Mapping and Critical Load Exceedances in the Athabasca Oil Sands Region. Prepared for NO_x – SO_2 Management Working Group. 41 pp.

'This report summarizes the mapping of sensitive receptors for soils (mineral and organic) and water bodies (ponds and lakes). As part of this receptor sensitivity mapping, several air deposition scenarios were run to evaluate potential implications of various air management options on the receptors on available data in north eastern Alberta.

Gregorich, E.G., L.W. Turchenek, M.R. Carter and D.A. Angers. 2001. Soil and Environmental Science Dictionary. CRC Press, Boca Raton.

Gulf Canada Ltd. 2001. Application for the Approval of the Surmont In-situ Oil Sands Project. March 2001.

Surmont In-situ Oil Sands Project in the Fort McMurray region of Alberta includes a project description and commercial application. This project also encompasses a biophysical and resource (air, water and soil) use and socioeconomic assessments. There is also an environmental baseline study, wildlife habitat suitability modelling, traditional land use study cumulative affects assessment and hydrogeology modelling.

Henriksen, A., J. Kamari, M. Posch, and A. Welander. 1992. Critical Loads of Acidity: Nordic Surface Waters. Ambio: 21: 356-363.

This paper describes the major results for the Northern European lakes. It serves as one of the major sources and explanations for the assessment of critical loads in the water bodies. It includes concepts and explanations on analytical model – calculations to determine critical loads in lakes using input parameters for base cations and alkalinity.

Husky Energy. 2003. Tucker Thermal Project. Submitted to Alberta Energy and Utilities Board and Alberta Environment.

Tucker Thermal Project for the Cold Lake region of Alberta includes an application and environmental impact assessment. The project is includes baseline data, impact assessments, cumulative assessment and monitoring for soils (including soil acidification),air quality, vegetation, wetlands, wildlife and resource uses.

Holowaychuck, N. and J.D. Lindsey. 1982. Distribution and Relative Sensitivity to Acidification of Soils Sand River Area, Alberta. Prepared for Alberta Environment and Canadian Petroleum Association. RMD 82/13.

Due to increasing SO_2 admissions in the Sand River area of Alberta, understanding the nature and magnitude of the effects of acidification is an integral part of soil forming processes and vegetation considerations. In this report the main objectives are to investigate the possibility of using soil survey information to develop criteria for classifying soils into 3 broad categories, as well to develop procedures for using soil survey maps to show the distribution of soils classified according to their sensitivity.

Holowaychuk, N. and R.J. Fessenden, 1987. Soil Sensitivity to Acid Deposition and the Potential of Soils and geology in Alberta to reduce the acidity of Acidic Inputs. Alberta Research Council. Earth Sciences Report 87-1.

'Maps were prepared of the province of Alberta showing the distribution of soils relative to their sensitivity to acid deposition and the distribution of soils and geology relative to their potential to reduce the acidity of atmospheric deposition.'

Imperial Oil Resources Ltd. 1998. Cold Lake Expansion Project. Submitted to Alberta Energy and Utilities Board and to Alberta Environmental Protection.

Appendix B-Soil Survey of the Proposed Mahkeses Plant site gave detailed information on soil series and soils chemistry for the Cold Lake region, used for the LICA study.

Imperial Oil Resources (IOR). 2007. 2006 Regional Surface Water Quality Monitoring Program and Trend Analysis, Cold Lake Operations. Calgary, Alberta.

Water quality data were obtained and analyzed annually as part of a monitoring program that has been conducted since 2000. This report provides current data for five lakes in the LICA study area and contains all data for these lakes from previous monitoring years. Pertinent water quality data from this report was used in the LICA report.

Jeffries, D. and R Ouimet (eds). 2004. Critical loads: are they being exceeded? *In:* The 2004 Canadian Acid Deposition Science Assessment, Chapter 8. Environment Canada, 341-370.

Macyk, T.M., G.M. Greenlee, C.F. Veauvy. 1985. Soil Survey of the County of Two Hills No. 21 Alberta. Alberta Soil Survey Report No. 35. Alberta Research Council. Edmonton, AB.

This report provides soil series information for the County of Two Hills, including information on soil chemistry. Some of the soil series correspond with the LICA study area.

Marshall, I.B., P.H. Schut. 1999. A National Ecological Framework for Canada. Agriculture and Agri-Food Canada. http://sis.agr.gc.ca/cansis/nsdb/ecostrat/intro.html. Accessed March 2007.

'Describes the methodology used to construct the ecological framework maps, the concepts of hierarchical levels of generalization, narrative descriptions of each ecozone and ecoregion, their linkages to various data sources and a list of contributors and collaborating agencies.

NatChem (National Land and Water Information Service):
http://res.agr.ca/cansis/nsdb/slc/intro.html)

Nilsson, S.I. and P. Grennfelt (eds.). 1988. Critical Loads For Sulphur and Nitrogen. NORD 1988: 97, Nordic Council of ministers. Copenhagen, Denmark. 418 pp.

PanCanadian Resources. 1998. Christina Lake Thermal Project. Submitted to Alberta Energy and Utilities Board and Alberta Environmental Protection.

Roberts, T.L., G.E. Nason, and H. Regier. 1989. Long Term Soil Acidification Monitoring in Alberta from 1981 – 1988. Prepared for Alberta Environment. 175 pp.

This report describes the long term monitoring of soil acidification at eight different sites within the province of Alberta, including Cold Lake and Fort McMurray. Samples were collected every four years beginning in 1981 at each site at differing depths in the soil to determine if any changes had occurred over the four year period.

Saffran, K.A., and D.O. Trew. 1996. Sensitivity of Alberta Lakes to Acidifying Deposition: An Update of Sensitivity Maps with Emphasis on 109 Northern Lakes. Water Sciences Branch, Water Management Division. Alberta Environmental Protection. Edmonton, Alberta.

This report provides acid sensitivity ratings based on alkalinity, pH and calcium for 109 lakes in northern Alberta. The findings are based on analytical results of water quality collected for the lakes and compares concentrations to the potential for acidification.

Soil Classification Working Group. 1998. The Canadian System of Soil Classification. 3rd ed. Agriculture and Agri-Food Canada Publ. 1646. NRC Research Press, Ottawa. 187 pp.

Target Loading Subgroup. 1996. Final Report of the Target Loading Subgroup on Critical and Target Loading in Alberta. Clean Air Strategic Alliance. Edmonton, Alberta. 14 pp.

'This report about acid deposition is broken into three main parts. The first part presents information on framework and reviewing data which developed the framework and evaluation of the current state of acid deposition in Alberta. The second part applies the framework to the long-term management of emissions and deposition, as well as discussing effects of new projects. The third part provides information on monitoring for deposition, inter-jurisdictional issues and future development.'

Task Force on Mapping and Modelling. 2004. Manual on methodologies and criteria for modelling and mapping critical loads & levels and air pollution effects, risks and trends. UNECE Convention on Long-range Transboundary Air Pollution.

This manual describes concepts, approaches and methods to derive critical loads for soils and other receptors in Europe.

Turchenek, L.W., S.A. Abboud, U. Dowey. 1998. Critical Loads for Organic (Peat) Soils in Alberta. Target Loading Subgroup, Alberta Clean Air Strategic Alliance. Edmonton, AB. 71 pp.

'Review of the current status of critical loads for organic soils, objectives being to adopt a critical load for organic soils in Alberta based on published literature and regulatory criteria from Europe and North America. It is concluded that the recommended interim critical load for sensitive ecosystems in Alberta is 0.25 keq/ha/yr. It is considered that this critical load will likely protect all categories of peatlands, but verification is required.'

Turchenek, L.W., S.A. Abboud. 2001. Site-Specific critical loads of Acid deposition on soils in the Provost-Esther Area, Alberta. Prepared for Air and Water Branch, Alberta Environment. 128 pp.

This study first reviews available methods for deriving critical loads, and are then applied to an area in east central Alberta (Provost-Esther grid cell or study area). There are two main objectives in this study. The first was to develop a methodology by mapping soil types, land uses and aquatic systems within the study area and analyzing samples collected, then estimating the site-specific critical load for each sample using one or more mathematical receptor models. The second objective was to estimate the critical load using derived methods, providing an estimate of the critical load for the Provost-Esther area.

Turchenek, L.W., S.A. Abboud, C.J. Tomas, R.J. Fessenden and N. Holowaychuk. 1987. Effects of Acid Deposition on Soils in Alberta. Alberta Research Council. Edmonton, Alberta. 202 pp.

'The objectives of this report to describe and discuss present concepts of the nature of soils acidity, to describe and discuss influences of acidity from both natural and anthropogenic source on soil attributes, describe major soils in Alberta and evaluate the potential impact of the deposition of varying levels of acidic and acid-forming substances on agricultural and forest soils and potential changes in soils properties and chemical cycles.'

Wiens, J. H. and others. 1987. Soils and Geology Sensitivity Mapping in Western Canada. Prepared by J.H. Wiens on behalf of the Coordinating Committee on Soil and Geology Sensitivity Mapping for Western Canada LRTAP Technical Committee. Ministry of Environment. Victoria, B.C.

Presents western Canada soil sensitivity rating system and maps. Applied by Holowaychuk and Fessenden 1999), referenced above, for mapping in Alberta.

APPENDICES

APPENDIX A

Air Emissions In LICA Area – Context For Modelling

Table A1 provides a summary of the existing and approved SO_2 and NO_x emissions of the major oil sands projects in the LICA area. Emission data were taken from Primrose In-Situ Oil Sands Project EIA (CNRL 2006). Total existing SO_2 and NO_x emissions in the LICA area are 31 and 26 t/d, respectively.

Table A1: Maximum Approved SO2 and NOx Emissions of the Major Oil Sands Projects in the LICA Area

	Existing Emissions (t/d)		Existing & Approved Emissions (t/d)	
	SO_2	NO_x	SO_2	NO_x
Canadian Natural Primrose, Wolf Lake and Burnt Lake[1]	4.30	7.14	6.20	10.02
Imperial Cold Lake, Nabiye and Mahihkan[2]	18.56	12.8	18.56	12.8
EnCana Foster Creek	4.95	5.93	4.95	7.49
Husky Tucker			1.16	1.41
BlackRock Orion			0.90	1.16
Total Emissions in LICA Area	**28**	**26**	**32**	**33**

[1] The emissions shown in the table were those used by Canadian Natural in their air modelling work for the Primrose East EIA. They represent CNRL's estimation of maximum approved emissions and do not represent actual emissions.

[2] The value shown for Imperial Cold Lake is the sum of the individual plant maximum approved emissions. The operations are subject to a maximum cumulative SO_2 emission limit of 13.15 t/d, so the 18.56 t/d figure significantly overstates SO2 emissions from Imperial Cold Lake facilities. Actual SO_2 emissions in 2005 were 6.615 t/d and actual NO_x emissions were 5.48 t/d.

The current SO_2 EPEA approval limit for Primrose South and Wolf Lake is 6.7 t/d. However CNRL expects that when the approval is amended for the Primrose East Expansion (~ May 31 2007) the Primrose South Limit will be reduced to 2.0 t/d and this also reflects the approximate current emission rate. As a result, for Primrose East, for the Existing/Approved case it was decided to model Primrose South at the lower limit (2.0 t/d).

3.2.4 Regional acid deposition modelling studies

"Estimates of exceedances of critical loads for acidifying deposition in Alberta and Saskatchewan"

- In 2018, a Environment and Climate Change Canada (ECCC) - led paper was published regarding modelling acid deposition in the Oil Sands Region using GEM-MACH model
- The data used in the model runs are for the 2013 emissions year which was the most complete data set available at the time
- As part of this year's OSM workplans, ECCC is repeating the simulations, with an upgraded version of the model and a more recent dataset


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Abstract. Estimates of potential harmful effects on ecosystems in the Canadian provinces of Alberta and Saskatchewan due to acidifying deposition were calculated, using a 1-year simulation of a high-resolution implementation of the Global Environmental Multiscale-Modelling Air-quality and Chemistry (GEM-MACH) model, and estimates of aquatic and terrestrial ecosystem critical loads. The model simulation was evaluated against two different sources of deposition data: total deposition in precipitation and total deposition to snowpack in the vicinity of the Athabasca oil sands. The model captured much of the variability of observed ions in wet deposition in precipitation (observed versus model sulfur, nitrogen and base cation R^2 values of 0.90, 0.76 and 0.72, respectively), while being biased high for sulfur deposition, and low for nitrogen and base cations (slopes 2.2, 0.89 and 0.40, respectively). Aircraft-based estimates of fugitive dust emissions, shown to be a factor of 10 higher than reported to national emissions inventories (Zhang et al., 2018), were used to estimate the impact of increased levels of fugitive dust on model results. Model comparisons to open snowpack observations were shown to be biased high, but in reasonable agreement for sulfur deposition when observations were corrected to account for throughfall in needleleaf forests. The model–observation relationships for precipitation deposition data, along with the expected effects of increased (unreported) base cation emissions, were used to provide a simple observation-based correction to model deposition fields. Base cation deposition was estimated using published observations of base cation fractions in surface-collected particles (Wang et al., 2015).

Both original and observation-corrected model estimates of sulfur, nitrogen, and base cation deposition were used in conjunction with critical load data created using the NEG-ECP (2001) and CLRTAP (2017) methods for calculating critical loads, using variations on the Simple Mass Balance model for terrestrial ecosystems, and the Steady State Water Chemistry and First-order Acidity Balance models for aquatic ecosystems. Potential ecosystem damage was predicted within each of the regions represented by the ecosystem critical load datasets used here, using a combination of 2011 and 2013 emissions inventories. The spatial extent of the regions in exceedance of critical loads varied between 1×10^4 and 3.3×10^5 km^2, for the more conservative observation-corrected estimates of deposition, with the variation dependent on the ecosystem and critical load calculation methodology. The larger estimates (for aquatic ecosystems) represent a substantial fraction of the area of the provinces examined.

Published by Copernicus Publications on behalf of the European Geosciences Union.

Selected model outputs and predictions

- Predicted forest ecosystem critical load exceedances with respect to acidity
- Predicted aquatic ecosystem critical load exceedances with respect to sulfur and nitrogen deposition
- Predicted terrestrial ecosystem critical load exceedances with respect to sulfur and nitrogen

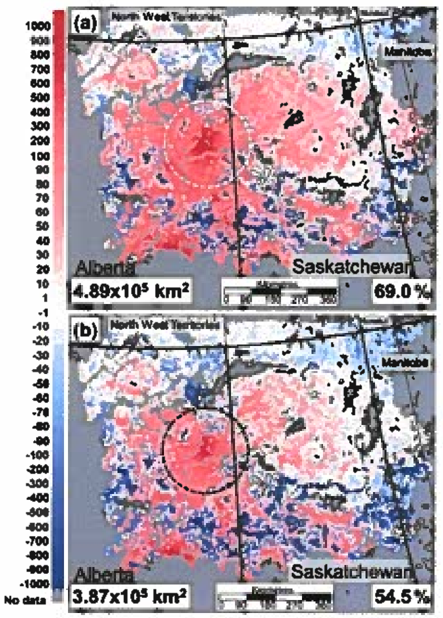
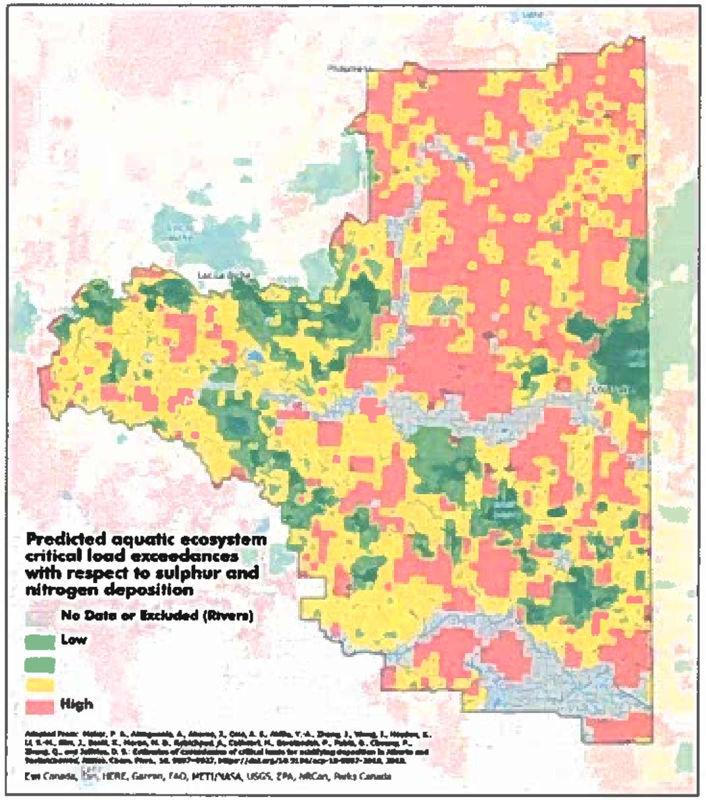


Figure 19. Predicted aquatic ecosystem critical load exceedances with respect to sulfur and nitrogen deposition. (eq ha^{-1} yr^{-1}). Boxed numbers are the area in exceedance and the percent of the total area for which critical loads are available which is in exceedance. **(a)** Calculated using original model sulfur and nitrogen deposition. **(b)** Calculated using model sulfur and nitrogen deposition corrected to match precipitation observations. Circled region: 140 km radius diameter circle around the Athabasca oil sands.



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Estimates of exceedances of critical loads for acidifying deposition in Alberta and Saskatchewan

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Abstract. Estimates of potential harmful effects on ecosystems in the Canadian provinces of Alberta and Saskatchewan due to acidifying deposition were calculated, using a 1-year simulation of a high-resolution implementation of the Global Environmental Multiscale-Modelling Air-quality and Chemistry (GEM-MACH) model, and estimates of aquatic and terrestrial ecosystem critical loads. The model simulation was evaluated against two different sources of deposition data: total deposition in precipitation and total deposition to snowpack in the vicinity of the Athabasca oil sands. The model captured much of the variability of observed ions in wet deposition in precipitation (observed versus model sulfur, nitrogen and base cation R^2 values of 0.90, 0.76 and 0.72, respectively), while being biased high for sulfur deposition, and low for nitrogen and base cations (slopes 2.2, 0.89 and 0.40, respectively). Aircraft-based estimates of fugitive dust emissions, shown to be a factor of 10 higher than reported to national emissions inventories (Zhang et al., 2018), were used to estimate the impact of increased levels of fugitive dust on model results. Model comparisons to open snowpack observations were shown to be biased high, but in reasonable agreement for sulfur deposition when observations were corrected to account for throughfall in needleleaf forests. The model–observation relationships for precipitation deposition data, along with the expected effects of increased (unreported) base cation emissions, were used to provide a simple observation-based correction to model deposition fields. Base cation deposition was estimated using published observations of base cation fractions in surface-collected particles (Wang et al., 2015).

Both original and observation-corrected model estimates of sulfur, nitrogen, and base cation deposition were used in conjunction with critical load data created using the NEG-ECP (2001) and CLRTAP (2017) methods for calculating critical loads, using variations on the Simple Mass Balance model for terrestrial ecosystems, and the Steady State Water Chemistry and First-order Acidity Balance models for aquatic ecosystems. Potential ecosystem damage was predicted within each of the regions represented by the ecosystem critical load datasets used here, using a combination of 2011 and 2013 emissions inventories. The spatial extent of the regions in exceedance of critical loads varied between 1×10^4 and $3.3 \times 10^5\ km^2$, for the more conservative observation-corrected estimates of deposition, with the variation dependent on the ecosystem and critical load calculation methodology. The larger estimates (for aquatic ecosystems) represent a substantial fraction of the area of the provinces examined.

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Base cation deposition was shown to be sufficiently high in the region to have a neutralizing effect on acidifying deposition, and the use of the aircraft and precipitation observation-based corrections to base cation deposition resulted in reasonable agreement with snowpack data collected in the oil sands area. However, critical load exceedances calculated using both observations and observation-corrected deposition suggest that the neutralization effect is limited in spatial extent, decreasing rapidly with distance from emissions sources, due to the rapid deposition of emitted primary dust particles as a function of their size. We strongly recommend the use of observation-based correction of model-simulated deposition in estimating critical load exceedances, in future work.

1 Introduction

Acidifying deposition was one of the first transboundary air pollution issues recognized as having ecological and economic consequences. In the late 1970s the UN Economic Commission for Europe (UNECE) developed a framework to assess the impacts of acidifying deposition, via the Convention on Long-Range Transboundary Air Pollution (LRTAP, or CLRTAP). The convention described the scientific basis for the assessment of acidifying precipitation, and provided an internationally binding legal framework for mitigation and control of this and associated issues relating to transboundary air pollution, and entered into force in 1983 (CLRTAP, 2017). This and similar legislation elsewhere resulted in a requirement to be able to link sources of acidifying pollutants with downwind ecosystem impacts. While measurement networks were constructed to estimate acidifying deposition in sensitive ecosystems (and continue to be used for this purpose today; see Vet et al., 2014, for a review of current global acidifying precipitation networks and their status), the measurement sites are sparse due to their expense and the availability of the infrastructure to make observations in remote sensitive ecosystems. A further requirement thus arose: to provide estimates of acidifying pollution to sensitive ecosystems to complement the available observations.

This requirement drove the development of the first generation of chemical transport models (CTMs), which made use of inventories of the emissions of different pollutants, detailed descriptions of gas, aqueous-phase, and particle chemistry, and speciated gas and particle and meteorological forecast model information, to describe the downwind transformation and deposition of acidifying pollutants (cf. Eliassen et al., 1982; Calvert and Stockwell, 1983; Venkatram and Karamchandani, 1988; Chang et al., 1987). The models increased in sophistication over the years to include more detailed descriptions of gas and aqueous chemistry, particle chemistry, and particle microphysics (cf. Binkowski and Shankar, 1995; Binkowski and Roselle, 2003; Gong et al., 2006). The next generation of models was extended to merge previously separate chemistry and meteorological forecasting models into unified frameworks (Grell et al., 2005; Vogel et al., 2009; Moran et al., 2010; Baklanov et al., 2014). The most recent versions of these models included incorporation of the impacts of model-generated aerosols into radiative transfer, and hence estimation of the impacts of feedbacks between atmospheric pollution and weather forecasting (ensemble comparisons of these fully coupled models with observations may be found in Makar et al., 2015a, b, and Im et al., 2015a, b).

Concurrent to the ongoing CTM development, methodologies were extended to improve the estimation of the effects of acidifying emissions on sensitive ecosystems. Key tools for this work are spatial maps of ecosystem "critical loads", where a critical load is defined (Nilsson and Grennfelt, 1988) 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". In the context of acidifying deposition, the critical load is the upper limit to the deposition flux of acidifying pollutants, below which ecosystem damage due to that deposition will not occur. A critical load *exceedance* is thus defined as the *excess* deposition of acidifying pollutants *above* the critical load. Guidelines for the determination of UNECE CLRTAP critical load data were first published in 1996, with subsequent updates (CLRTAP, 2017). In North America, modified critical load calculation methodologies were initially adopted, to provide upper limit estimates of critical loads, for cases in which more detailed data were unavailable, via an agreement between the eastern US states and eastern Canadian provinces (New England Governors – Eastern Canadian Premiers; NEG-ECP, 2001).

Critical loads for acidifying deposition for different ecosystems are calculated using different models, but all are predicated on the concept of charge balance at steady state; the critical load models determine the excess flux of cations available in the natural ecosystem, which could potentially balance the anions added due to acidifying deposition. The critical load calculations may thus depend on estimates of the deposition flux of both anions and cations. The anions of interest are the total (wet plus dry) atmospheric deposited sulfur, S_{dep}, and total atmospheric deposited nitrogen, N_{dep}, where the sulfur deposition is assumed to have two negative charges (all forms of S_{dep} are assumed to eventually be transformed to, and contribute to deposition as, SO_4^{2-}) and nitrogen is assumed to have one negative charge (all forms of N_{dep} are assumed to eventually be transformed to, and contribute to deposition as, NO_3^-). Cations of interest include Mg^{2+}, Ca^{2+}, K^+, and Na^+, collectively referred to as base cations, and their net deposition from the atmosphere when converted to molar charge equivalents is referred to as BC_{dep}. For terrestrial ecosystems BC_{dep} must be estimated from observations or CTM predictions, while for aquatic ecosystems, the total base cation concentrations within water due to atmospheric deposition and other sources are derived from direct sampling and laboratory analysis of ecosystem surface water.

We note that while an exceedance of critical loads identifies the *potential* for ecosystem damage to occur, critical loads are based on the concept of a chemical steady state, and depending on the buffering mechanisms available in an ecosystem, the steady state defined by an exceedance of critical loads may not take place until some point in the future. Once exceedances of critical loads have been identified, dynamic models may be used to assess the time delay until damage occurs and/or the time required for recovery of the ecosystem subsequent to that damage (CLRTAP, 2017).

Atmospheric deposition of S_{dep}, N_{dep} and BC_{dep} may thus influence the estimation of critical load exceedances. Both terrestrial and aquatic critical loads are based on the concept of ion charge balance (cations–anions), as well as terms describing the perturbation of the charge balance through, for example, removal of specific ions or groups of ions through, leaching, harvesting of biomass, etc. For aquatic ecosystems, if the value of the total charge balance of the critical load (which includes all forms of input of base cations to the system including BC_{dep}) is greater than the added anions, critical loads will not be exceeded. Emissions sources of base cations may thus act to counteract the emissions sources of S_{dep} and N_{dep}, depending on the relative emission levels, the locations of the sources, etc. For example, some observations in the immediate environs (within 135 km) of emission sources located within the Athabasca oil sands region of Canada have shown that BC_{dep} exceeds S_{dep} and N_{dep}, implying that alkalinization (rather than acidification) may be happening in this region (Watmough et al., 2014). While the disturbance to the ecosystems due to the increase in pH associated with the excess base cations may cause other ecosystem effects, this finding has been used to imply that acidifying deposition, and the consequent potential ecosystem damage due to emissions from these facilities is unlikely. This implication has been re-evaluated on a larger scale in the present work.

The provinces of Alberta and Saskatchewan are home to the majority of Canada's petrochemical extraction and refining infrastructure, in addition to other industries such as coal-fired power generation, and account for a substantial fraction of the Canadian anthropogenic emissions of sulfur dioxide (34 %), nitrogen oxides (43 %), and ammonia (50 %); see Zhang et al. (2018). Emissions originating within the Athabasca oil sands region account for approximately 6.5, 1.3, and 0.3 % of the Canadian anthropogenic emissions of these three chemicals, based on inventories used in Zhang et al. (2018). These three pollutants, and their gas, particulate, and aqueous-phase reaction products, are the main anthropogenic sources of S_{dep} and N_{dep} within this region. As we will show below, the provinces are also home to terrestrial and aquatic ecosystems which are sensitive to acidifying deposition (i.e. have relatively low critical loads for acidifying deposition). Calculations of exceedances of critical loads within this region are therefore of interest, to assess the potential for ecosystem damage associated with these emissions, and are the focus of our work.

We use a combination of a fourth-generation CTM (the Global Environmental Multiscale-Modelling Air-quality and CHemistry; GEM-MACH), critical load estimates for aquatic and terrestrial ecosystems determined using different methodologies, and two different surface deposition observation datasets, to predict the extent to which critical loads are being exceeded, over large portions of the Canadian provinces of Alberta and Saskatchewan.

We begin with a description of the critical load data used in our evaluation, follow with a description of GEM-MACH (with a focus on its components which pertain to S_{dep} and N_{dep}), an evaluation of the model performance, and corrections to the model predictions based on observations, and end with estimates of exceedances for terrestrial and aquatic ecosystems and our conclusions.

2 Methodology

2.1 Global Environmental Multiscale-Modelling Air-quality and CHemistry (GEM-MACH), Version 2

2.1.1 GEM-MACH v2 overview

GEM-MACH is Environment and Climate Change Canada's comprehensive chemical reaction transport model. The model follows the online paradigm (in that atmospheric chemistry modules have been incorporated directly into a weather forecast model (GEM) (Moran et al., 2010; Makar et al., 2015a, b). The parameterizations include gas-phase chemistry (42 species, ADOM-II mechanism, Lurmann et al., 1986; Stockwell and Lurmann, 1989), aerosol microphysics (Gong et al., 2003a, b), and cloud processing of gases and aerosols including uptake and wet deposition (Gong et al., 2006, 2015). The model's aerosol size distribution makes use of the sectional (bin) approach, with two possible configurations: (1) a processing-time efficient 2-bin configuration used for operational forecasting and longer scenario simulations (fine and coarse particle sizes are subdivided within certain aerosol microphysics processes in order to preserve solution accuracy while minimizing advective transport time) and (2) a more detailed 12-bin size distribution used to more accurately simulate aerosol microphysics and the size spectrum of particles. The aerosols in GEM-MACH are also speciated chemically into particle sulfate, nitrate, ammonium, primary organic aerosol, secondary organic aerosol, elemental (a.k.a. "black") carbon, sea salt, and crustal material, within each size bin. The crustal material component includes all particulate matter not speciated under the other components, and hence includes base cations as a fraction of its total mass.

As will be discussed below, the observations of Wang et al. (2015) were used to approximate the base cation fraction of GEM-MACH's crustal material, and hence estimate the mass of base cation deposition predicted by the model.

A comparison of GEM-MACH version 1.5.1 against other peer online models appears elsewhere (Makar et al., 2015a, b), as does a description of the main updates associated with version 2 of the model (Makar et al., 2017). Comparisons of the operational two-bin version of the model against observations have also appeared in the literature (Pavlovic et al., 2016; Munoz-Alpizar et al., 2017). Our description below will focus on the model's modules for gas-phase dry deposition, particle-phase dry deposition, cloud processing, and aqueous-phase chemistry (wet deposition).

2.1.2 Gas-phase dry deposition in GEM-MACH

A detailed description of the gas-phase dry deposition module of GEM-MACH (with an emphasis on the chemical species which contribute to S_{dep} and N_{dep}) appears in the Supplementary Information; here we provide an overview. Gas-phase deposition is handled using the commonly used "resistance" approach, where the deposition velocity is the inverse of the sum of aerodynamic, quasi-laminar sublayer and net surface resistances. The aerodynamic resistance is the same for all gases, the quasi-laminar sublayer resistance depends on gas diffusivity, but these terms are relatively minor compared to the net surface resistance, which tends to control the deposition velocity for many of the gases (notable exceptions being HNO_3 and NH_3 which have a relatively low surface resistance and hence the overall resistance is strongly dominated by meteorological factors). The net surface resistance follows the approach of Wesely (1989) with a parameterization following Jarvis (1976) for the stomatal resistance. For plants, the overall resistance has terms for the contributions associated with the stomata, mesophyll, and cuticles, the resistance of gases to buoyant convection, the resistance associated with leaves, twigs, bark and other exposed surfaces in the vegetated canopy, the resistance associated with the height and density of the vegetated canopy (referred to here as canopy resistance), and the resistance associated with soil, leaf litter, etc., at the surface. The net surface resistance includes a term to account for the impact of precipitation and high humidity on stomatal and mesophyll resistances, and a temperature-dependent correction term for snow-covered surfaces.

Soil resistances are calculated following Wesely (1989) with a parameterization based on the values for SO_2 and O_3, with a seasonal dependence (Midsummer, Autumn, Late Autumn, Winter and Transitional spring). Canopy resistances are based on Zhang et al. (2003), with the same seasonality as above. The resistance for the lower canopy follows Wesely (1989) using a function of the effective Henry's law constant and terms for SO_2 and O_3 resistances. The mesophyll and cuticle resistances follow Wesely (1989), with seasonal variations as above and vegetation-dependent leaf area index values. The resistance of gases to buoyant convection follows Wesely (1989), and is a function of the visible solar radiation. The stomatal resistance follows a similar approach to Jarvis (1976), Zhang et al. (2002, 2003), Baldocchi et al. (1987), and Val Martin et al. (2014), and results from several terms describing its dependence on light ($k_s\left(Q_p\right)$), water vapour pressure deficit ($k_s\left(\delta e\right)$), temperature (k_{st}), CO_2 concentration (k_{sca}), the leaf area index (LAI), and the ratio of the molecular diffusivities of water to the gas being deposited ($\frac{D_{H_2O}}{D_{gas}}$). The approach taken for the dependence on light provides stomatal resistance values similar to those of Baldocchi et al. (1987), but are lower than those of Zhang et al. (2002) for the same vegetation types, decreasing stomatal resistances and thus increasing the stomatal contribution to deposition velocities, relative to Zhang et al. (2002). The other terms in the stomatal resistance employed curve fitting where possible across different sources of deposition data, due to the wide variation noted in the underlying measurement literature.

Deposition velocities are calculated for the S_{dep} and N_{dep} contributing gases SO_2, H_2SO_4, NO, NO_2, HNO_3, PAN, HONO, NH_3, organic nitrates, as well as several other transported gases of the ADOM-II gas-phase mechanism. We note that the rapid conversion of gaseous sulfuric acid (H_2SO_4) to particulate sulfate due to its low vapour pressure ensures that the direct contribution of H_2SO_4 deposition to S_{dep} is relatively minor. Further details on the deposition velocity formulation, and tabulated coefficients for the species contributing to S_{dep} and N_{dep}, appear in the Supplement.

Gas-phase dry deposition velocities are incorporated as a flux lower boundary condition in the solution of the vertical diffusion equation within GEM-MACH.

2.1.3 Particle-phase dry deposition in GEM-MACH

Particle dry deposition in GEM-MACH makes use of the size-segregated formulation of Zhang et al. (2001), which in turn follows Slinn (1982). The gravitational settling velocity (a function of the particle density, wet diameter, air viscosity, and the temperature and air pressure) is calculated for each particle size at each model level. At the lowest level, the settling velocity is added to the inverse of the sum of the aerodynamic resistance above the canopy and the surface resistance. The aerodynamic resistance is a function of atmospheric stability, surface roughness, and the friction velocity, while the surface resistance is the inverse of the sum of collection efficiencies for Brownian diffusion, impaction, and interception, multiplied by correction factors to account for the fraction of particles which stick to the surface. The Brownian diffusion is a function of the Schmidt number of the particle (ratio of the kinematic viscosity of the air to the particle's Brownian diffusivity). The impaction term is dependent on the Stokes number (itself a function of the gravitational settling velocity) and the land-use type, and the interception term is taken to be a simple function of the particle diameter and a land-use and seasonally dependent characteristic radius.

The resulting deposition velocities have the characteristic strong dependence on particle size noted in observations, with minimum deposition values occurring at particle diameters of about 1 µm, with an increase in deposition velocities of up to 2 orders of magnitude with decreasing or increasing particle size. As will be discussed later in this work, one of the consequences of the size dependence of particle deposition velocity is that particles which are larger (or smaller) than 1 µm diameter settle more rapidly than the latter particles, and hence have shorter transport distances than 1 µm diameter particles. This phenomenon is responsible for the rapid decrease in surface deposition with increasing distance from sources of base cations.

Particle gravitational settling and deposition velocities are handled in this version of GEM-MACH using a semi-Lagrangian advection approach in the vertical for each column; vertical back-trajectories are calculated from the settling and deposition velocities, and mass-conservative interpolation is used to determine the new concentration profile and the flux to the surface. The particle deposition component of S_{dep} and N_{dep} (via the deposition of particle sulfate, particle nitrate, and particle ammonium) is typically very small compared to the gaseous dry deposition of primary emitted gases (SO_2, NO_2, NH_3), secondary gases (HNO_3), and wet deposition of ions (HSO_3^-, SO_4^{2-}, NO_3^-, NH_4^+).

2.1.4 Cloud processing of gases and aerosols, and inorganic particle chemistry in GEM-MACH

The cloud chemistry and aqueous processing of gases and aerosols in GEM-MACH makes use of the methodologies used in GEM-MACH's precursor model, A Unified Regional Air-quality Modelling System (AURAMS), and is described in detail in Gong et al. (2006). Aqueous chemistry includes the transfer of gaseous SO_2, O_3, H_2O_2, ROOH, HNO_3, NH_3, and CO_2 to cloud droplets, along with the oxidation of S (IV) to S (VI) within the cloud droplets by several pathways. The stiff system of equations described by the aqueous chemistry is solved using a bulk approach and a computationally efficient predictor–corrector algorithm. Aerosol sulfate, nitrate, and ammonium may be taken up into cloud droplets following activation, and may be returned to the aerosol phase following aqueous chemistry via particle evaporation. Rebinning of mass transferred back to the particle phase is accomplished through a mass-conservative rebinning algorithm similar to that described in Jacobson (1999).

Wet deposition processes (tracer transfer from cloud droplets to raindrops, scavenging of aerosols and soluble gases by falling hydrometers, downward transport by precipitation, and evaporation of raindrops and potential loss of mass prior to deposition) are explicitly included in GEM-MACH. Cloud droplet to raindrop tracer transfer is handled using a bulk autoconversion rate obtained from the meteorological model. Impact scavenging of size-resolved aerosols is parameterized using a scavenging rate based on the precipitation rate and the mean collision efficiency. Irreversible scavenging of soluble gases makes use of the Sherwood number and diffusivity of the gas, the precipitation rate, the Reynolds and Schmidt numbers, and the raindrop diameter, while reversible scavenging makes use of equilibrium partitioning.

The cloud fields provided to the aqueous-phase chemistry module depend on the model resolution – for the high-resolution simulations carried out here, the hydrometeors are explicitly simulated and transported using the two-moment scheme of Milbrandt and Yau (2005a, b). A full description of the cloud processing model and the formulation of its components appears in Gong et al. (2006).

Inorganic particle chemistry makes use of the HETV system of equations for sulfate, nitrate, and ammonium described in detail in Makar et al. (2003), based on the ISORROPIA algorithms of Nenes et al. (1999). The concentrations of particle sulfate, nitrate, ammonium, and gaseous NH_3 and HNO_3 are solved in bulk for non-ideal high concentration solutions by first determining the chemical subspace in which the total nitrate, sulfate, ammonium, and relative humidity reside (breaking the problem into 12 subspaces for the different combinations of gases, salts, and aqueous ions which may exist under those conditions), and then solving a double iteration including the full system of equations incorporating activity coefficient calculations and vectorization across the subspaces for computational efficiency. Following the bulk calculations, the resulting aerosol masses of sulfate, nitrate, and ammonium are rebinned using an approach similar to that of Gong et al. (2006).

2.1.5 Emissions and simulation setup

The emissions used in the simulations carried out here are described in detail in Zhang et al. (2017, this special issue).

All simulations used a nested model setup, feeding into the meteorological and chemical boundary conditions for a 2.5 km resolution Alberta and Saskatchewan simulation. Figure 1 shows both the outer North American domain (10 km × 10 km grid cell resolution, green region) and the inner Alberta and Saskatchewan domain (2.5 km × 2.5 km grid cell resolution, blue region). Archived GEM 10 km forecast simulations were driven by data assimilation analysis fields, and were used to in turn drive successive overlapping 30 h forecasts of both a Canadian domain 2.5 km resolution meteorological forecast and a 10 km GEM-MACH forecast. The final 24 h of these simulations provided the meteorological and chemical boundary conditions, respectively, for a series of 24 h simulations of GEM-MACH on the inner domain shown in Fig. 1. This nesting approach was selected to provide the best possible meteorological and chemical inputs for the 2.5 km high-resolution domain. The outputs from the 24 h simulations were then brought together to create the continu-

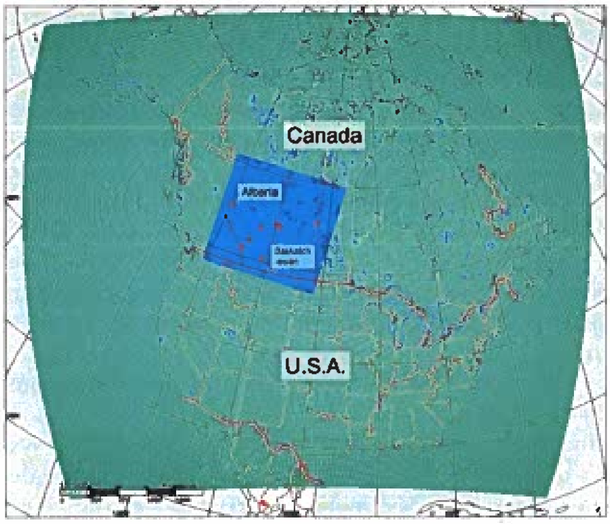

Figure 1. GEM-MACH domains. Green region: outer North American domain (10 km × 10 km grid-cell resolution). Blue region: inner Alberta and Saskatchewan domain (2.5 km × 2.5 km grid-cell resolution). Red diamonds: locations of Canadian Acid Precipitation Monitoring Network (CAPMoN) stations used in this work.

ous time record of concentrations and deposition on the high-resolution model grid.

Three simulations were carried out with this setup. The first of these made use of the two aerosol bin configuration of GEM-MACH, for an entire year of simulated chemistry and meteorology (1 August 2013 to 31 July 2014), in order to obtain a year of model output, required for critical load calculations. The outer 10 km North American domain of the simulation made use of the operational GEM-MACH forecast emissions inventories for the years 2010 (Canada), 2011 (USA) and 1999 (Mexico), while the inner nest made use of 2013 (Canada) and 2011 (USA) inventories (see Zhang et al., 2017). The predicted deposition thus represents the model predictions using emissions reported under current Canadian regulatory requirements. Two additional simulations were then carried out, for the period 13 August to 10 September, making use of the 12-bin version of the model: a base case and a primary particulate scenario. The primary particulate scenario made use of aircraft-based estimates of primary particulate emissions from six oil sands facilities, and both making use of continuous emissions monitoring data for Alberta for SO_2 and NO_x emissions from large stack sources (see Zhang et al., 2017, this issue, for the full description of these emissions). This second pair of simulations was carried out to investigate the potential impact of possible under-reporting of primary particulate emissions on model critical load exceedance predictions. About 96 % of these primary particulate emissions by mass are associated with fugitive dust emissions sources, and over 68 % of this mass is in the coarse mode (diameters greater than 2.5 µm) (Zhang et al., 2017). The potential impact of these sources of base cations on acidifying deposition will be discussed in Sect. 3.3, 3.5 and 3.6.

2.2 Deposition observations

2.2.1 Deposition of ions in precipitation

Wet-only precipitation measurements were collected at six sites in Alberta (AB) by Alberta Environment and Parks and two sites in Saskatchewan (SK) by the Canadian Air and Precipitation Monitoring Network (CAPMoN) (Fig. 1, red diamonds). In wet-only samples, a heated precipitation sensor opens the collector lid when precipitation is detected, and closes the lid when precipitation ends. For the SK samples, the collector bucket was lined with a polyethylene bag which was removed, weighed, sealed, refrigerated, and shipped to the laboratory for major ion analysis. For the AB samples, the samples were transferred from the clean collection bucket to a smaller sample bottle, capped, refrigerated if stored on site, and shipped to the laboratory for analysis. Collection occurred approximately daily at the SK sites and approximately weekly at the AB sites. Quality control was performed by the collecting networks.

Annual precipitation-weighted mean concentrations of SO_4^{2-}, NO_3^-, and NH_4^+ were calculated from the daily or weekly samples using recommended methods and completeness criteria (WMO/GAW, 2004, 2015) and the resulting deposition fluxes were compared with model values. Where there were measurement gaps of >3 weeks (two sites), or where there was only partial coverage of the 12 months (one site), fluxes were compared over shorter measurement periods. The collector buckets described above tend to underestimate the total precipitation, so the flux of ions derived from their records must be corrected using independent observations of total precipitation. At the SK sites, separate on-site rain and snow gauges were used to manually record the daily precipitation amount. At the AB sites, precipitation gauges for independent quantification of total precipitation were not available, and hence weekly deposition fluxes were calculated using daily precipitation depth data from the nearest meteorological station, or combination of meteorological stations, with the most complete coverage (ECCC, 2017; AAF, 2017).

Total precipitation depth collected in the AB wet deposition collectors, summed over all collection periods at the sites, was 51–96 % of the estimated precipitation depth at meteorological stations. Our deposition flux calculations implicitly assume that the ion concentrations measured in the sample are representative of all the precipitation during the period. However, the mechanism of precipitation loss (undercatch due to wind, evaporative loss, delay in lid opening) may lead to unrepresentative concentration values. Additional uncertainty is introduced by the use of precipitation depth from collectors that are not co-located, particularly at

Kananaskis. Therefore, wet deposition fluxes from the AB sites have higher uncertainty than the fluxes at the two SK sites, where 105 and 78 % of the standard gauge precipitation was captured by the collector.

2.2.2 Deposition of S and N compounds to snowpack

Observations of total deposition of sulfur, nitrogen, and base cations to snow-covered open surfaces were collected in two separate studies. Samples were collected in the immediate vicinity of the oil sands by Environment and Climate Change Canada, and snowpack samples in northern Saskatchewan were collected by Saskatchewan Environment (snowpack station locations are discussed in Sect. 3.4). Both sets of data were collected in open clearings and thus deposition is to snow-covered *open* surfaces. They thus provide *minimum* estimates of deposition, particularly for gases. One method of accounting for deposition to forests and related vegetation is via collection of precipitation samples below foliage, which assumes that deposited materials leave the vegetation via precipitation and/or melting of snow, to reach the collector ("throughfall"). Watmough et al. (2014) compared winter throughfall versus open deposition in the oil sands region, and showed maximum throughfall values to be about 1.9 times their open deposition counterparts. However, throughfall observations do not account for the portion of the deposited material which remains on or within the vegetated surfaces, and hence must also be considered a conservative estimate of total deposition. Using the algorithms of GEM-MACH's gas-phase deposition module, typical ratios of dry deposition velocity between a needle-leaf forest and an open snow-covered surface for SO_2 and NH_3, respectively, are 2.63 and 1.97 (temperature $-5\,°C$, $u^* = 0.1\,m\,s^{-1}$, solar radiation $= 100\,W\,m^{-2}$, $z_0 = 0.1\,m$, Monin–Obukhov length $= 50$). However, the ratios for dry deposition of particles with diameters of 2.5 and $10\,\mu m$ are 0.76 and 0.82, respectively (Zhang et al., 2001), indicating that the open snowpack observations may slightly overestimate BC_{dep} and BC_{dep} (in contrast to the Watmough et al., 2014, observations) but significantly underestimate S_{dep} and N_{dep}.

Further details on the methodology used for snowpack analysis may be found in the Supplement for this paper.

2.3 Estimates of critical loads of acidic deposition in Canada – a review of recent work

In this section, we review recent work on the estimation of critical loads in Canada, starting from the UNECE definitions, in order to provide a complete description of the critical load datasets used in our subsequent estimates of exceedances.

2.3.1 Critical loads and critical load exceedances – definitions

Critical loads were estimated following methodologies set out under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP, 2017; de Vries et al., 2015). We define first the equations used for determining critical loads, and follow with the description of the data used to estimate critical loads of acidifying sulfur (S) and nitrogen (N) for terrestrial and aquatic ecosystems in Alberta and Saskatchewan, based on a Canada-wide implementation (Carou et al., 2008), and two more recent studies focused on terrestrial ecosystems in the province of Alberta, and aquatic ecosystems in northern Alberta and Saskatchewan (Cathcart et al., 2016).

For terrestrial ecosystems, critical loads of acidity were estimated using the steady-state (or simple) mass balance (SSMB) model which links deposition to a chemical variable (the "chemical criterion") in the soil, or soil solution, associated with ecosystem effects (Sverdrup and DeVries, 1994). The violation of a specific value (the "critical limit") for the chemical criterion is associated with potential ecosystem damage. The most widely used soil chemical criterion is based on the molar ratio of base cations to aluminum (BC : Al where BC is the molar sum of calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+)) in soil solution (the factor of 3/2 in Eq. 4 below converts this term to equivalents). The acidifying impact of S and N define a critical load function (CLF) incorporating the most important biogeochemical processes that affect long-term soil acidification (CLRTAP, 2017). The function is defined by three quantities (see Eqs. 1 to 4): the maximum critical load of S ($CL_{max}(S)$); minimum critical load of N ($CL_{min}(N)$); and the maximum critical load of N ($CL_{max}(N)$). The critical level of the leaching of acid neutralizing capacity for the ecosystem ($ANC_{le,crit}$) is defined via Eq. (4). Critical loads of acidity for terrestrial ecosystems are defined in units of "equivalents" (ionic charge × moles).

$$CL_{max}(S) = BC_{dep} + BC_w - Cl_{dep} - BC_u - ANC_{le,crit} \quad (1)$$

$$CL_{max}(N) = CL_{min}(N) + \frac{CL_{max}(S)}{1 - f_{de}} \quad (2)$$

$$CL_{min}(N) = N_i + N_u \quad (3)$$

$$ANC_{le,crit} = -Q^{\frac{2}{3}}\left[\frac{3}{2}\left(\frac{BC_w + BC_{dep} - BC_u}{(BC:Al)_{crit} K_{gibb}}\right)\right]^{\frac{1}{3}} - \frac{3}{2}\left(\frac{BC_w + BC_{dep} - BC_u}{(BC:Al)_{crit}}\right) \quad (4)$$

The remaining terms in these equations include BC_{dep}, the non-marine annual base cation deposition, BC_w, the release of soil base cations owing to physical and chemical breakdown (weathering) of rock and soil minerals, CL_{dep}, the non-marine chloride deposition, BC_u, the average base cation removal due to the harvesting of base-cation-containing biomass from the ecosystem, f_{de}, the denitrification fraction (loss of nitrogen to N_2), N_i, the long-term annual net immobilization of nitrogen in the rooting zone, and N_u, the average removal of nitrogen from an ecosystem due to e.g. harvesting); Q, defined above, $(BC : Al)_{crit}$, is the critical value of the non-sodium base cation to aluminum ion ratio described above, and K_{gibb} is the Gibbsite equilibrium constant.

For aquatic ecosystems, two steady-state models have been widely used for calculating critical loads (Henriksen and Posch, 2001; CLRTAP, 2017; de Vries et al., 2015): the Steady-State Water Chemistry (SSWC) model and the First-order Acidity Balance (FAB) model.

The SSWC model requires volume-weighted mean annual water chemistry and runoff volume (Q) to calculate critical loads of S acidity.

$$\mathrm{CL}(A) = Q\left([\mathrm{BC}]_0^* - \mathrm{ANC}_{\mathrm{limit}}\right), \tag{5}$$

where $[\mathrm{BC}]_0^*$ is the sea salt corrected pre-acidification concentration of base cations in the surface water, and $\mathrm{ANC}_{\mathrm{limit}}$ is the ANC (concentration) limit above which no damage to the specified biological indicator (e.g. fish) occurs. The sea salt correction, denoted by a superscript asterisk, assumes all chloride originates from sea salt; the current concentrations of base cations, SO_4^{2-}(aq) and NO_3^-(aq) in water along with empirical functions (see below), are used to estimate $[\mathrm{BC}]_0^*$, following CLRTA methodologies (CLRTAP, 2017); further details regarding the sensitivity of the critical load estimates to these functions are described in Cathcart et al. (2016).

The FAB model (Posch et al., 2012) allows the simultaneous calculation of critical loads of acidifying S and N deposition similar to the SSMB model widely used for forest soil critical loads. In addition to processes in the terrestrial catchment soils, such as uptake, immobilization, and denitrification, the FAB model includes in-lake retention of N and S. The derivation of the FAB model starts from the charge balance at the outlet of a lake:

$$\begin{aligned}\mathrm{S}_{\mathrm{runoff}} + \mathrm{N}_{\mathrm{runoff}} =& \mathrm{Ca}_{\mathrm{runoff}} + \mathrm{Mg}_{\mathrm{runoff}} + K_{\mathrm{runoff}} + \mathrm{Na}_{\mathrm{runoff}} \\ &- \mathrm{Cl}_{\mathrm{runoff}} - \mathrm{ANC}_{\mathrm{limit}}.\end{aligned} \tag{6}$$

Steady-state mass balance equations for the runoff terms for each ion (X) are then derived as a function of the total number of ions entering the lake (X_{in}) and dimensionless retention factors (ρ_X):

$$X_{\mathrm{runoff}} = (1-\rho_X)\, X_{\mathrm{in}}. \tag{7}$$

The formula for X_{in} depends on the specific ion; S_{in} depends on deposition alone, N_{in} includes terms for net immobilization (subscript i), growth uptake (subscript u), and denitrification (f_{de}), and base cations include terms for deposition (subscript dep) and weathering (subscript w). An equation of the following form results (the summation is over the different components within the catchment, usually simplified to be "lake" and "non-lake", i.e. $m = 1$ in the equation which follows), and A_j/A is the relative area of the components (A_j) to the total catchment area (A):

$$\begin{aligned}&(1-\rho_S)\sum_{j=0}^{m}\frac{A_j}{A}\mathrm{S}_{\mathrm{dep},j} + \sum_{j=0}^{m}\frac{A_j}{A}\left(1-f_{\mathrm{de},j}\right) \\ &\left(\mathrm{N}_{\mathrm{dep},j}\left(1-f_{\mathrm{u},j}\right) - \mathrm{N}_{\mathrm{i},j} - \mathrm{N}_{\mathrm{u},o,j}\right)_+ = \\ &\sum_Y\left[(1-\rho_Y)\sum_{j=0}^{m}\frac{A_j}{A}\left(Y_{\mathrm{dep},j} - Y_{\mathrm{w},j} - Y_{\mathrm{u},j}\right)_+\right] \\ &- Q\cdot\mathrm{ANC}_{\mathrm{limit}},\end{aligned} \tag{8}$$

where the "+" subscript refers to the maximum value of the term within the brackets across the catchment components j (lake and non-lake). S_{dep} includes all forms of sulfur deposition (gaseous SO_2 dry deposition, particulate dry deposition, and wet deposition of bisulfate and sulfate ions), converted to charge × mole equivalent deposition of SO_4^{2-}. N_{dep} includes all forms of nitrogen deposition (gas-phase dry deposition of NO, NO_2, NH_3, HONO, HNO_3, peroxyacetylnitrate, organic nitrates, dry deposition of particulate nitrate and ammonium, and wet deposition of ammonium and nitrate ions), converted to the charge × mole equivalent deposition of NO_3^-. Setting $N_{dep} = 0$ in Eq. (8) results in a formula for $\mathrm{CL}_{max}(S)$, and setting $S_{dep} = 0$ results in a formula for $\mathrm{CL}_{max}(N)$. The denitrification fraction was estimated as $f_{de} = 0.1 + 0.7 \cdot f_{peat}$, where f_{peat} is the fraction of wetlands in the terrestrial catchment, $\mathrm{CL}_{min}(N)$ was taken to be $N_i + N_u$ (N_i was set to the regional default value of $35.7\,\mathrm{eq\,ha^{-1}}$), and N_u was based on estimates of forest biomass (Canadian Forestry Service National Forest Inventory) and literature data for the concentration of N in biomass. The net uptake of N on land was assumed to be constant ($f_{u,1} = 0$), and the flux of base cations (right-hand side of Eq. 8) is determined using the SSWC model via Eq. (5). In both the SSWC and FAB models, the value of $[\mathrm{BC}]_0^*$ is derived using an "F-factor" equation describing the change in charge balance over time from pre-industrial (time 0) to current (time t) conditions:

$$\begin{aligned}[\mathrm{BC}]_0^* =& [\mathrm{BC}]_t^* - F \\ &\cdot\left([\mathrm{SO_4}]_t^* + [\mathrm{NO_3}]_t - [\mathrm{SO_4}]_0 - [\mathrm{NO_3}]_0\right).\end{aligned} \tag{9}$$

The F-factor in Eq. (9) depends on the pre-industrial base cation concentration and Eq. (12) is solved iteratively. The in-lake retention coefficients for S and N (ρ_S and ρ_N, respectively) are modelled by a kinetic equation (Kelly et al., 1987) making them a function of runoff, the lake : catchment ratio, and net mass transfer coefficients for S and N. It is assumed that the lakes and their catchments are small enough to be properly characterized by average soil and lake-water properties; furthermore, all of the lakes examined here are treated as headwater lakes, and larger lakes are excluded from the analysis.

The risk of negative impacts owing to acidifying S and N deposition, i.e. deposition in excess of the critical load, is

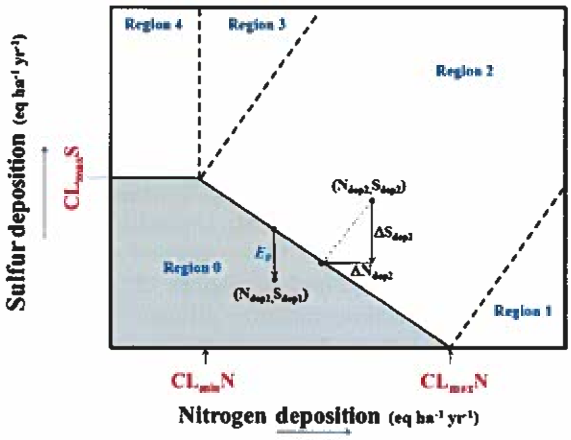

Figure 2. Critical load function, showing exceedance Regions 1 through 4 and the "below exceedance" Region 0.

based on the magnitude and areal extent of exceedance. Exceedance of the critical load of S acidity for aquatic ecosystems under the SSWC model is defined as

$$\mathrm{Ex}\left(\mathrm{S_{dep}}\right) = \mathrm{S_{dep}} - \mathrm{CL}(A), \tag{10}$$

where S_{dep} is the sum of deposition of all forms of S, where each mole of S is treated as SO_4^{2-} (i.e. two equivalents per mole of S deposited). Exceedances of acidity are defined as instances where the addition of acidity in the form of S exceeds the net buffering capacity. In contrast, under the SSMB and FAB models there is no unique amount of S and N to be reduced to reach non-exceedance; Exceedance for a given S and N deposition pair is the sum of the S and N deposition reductions required to reach the critical load function (CLF) by the "shortest" path (Fig. 2). The computation of the exceedance function followed the methodology described in CLRTAP (2017).

Region 0 in Fig. 2 denotes cases for which S_{dep} and N_{dep} to an ecosystem are *below* exceedance levels (i.e. deposition does not exceed critical load). For this region, we introduce a term E_0, a negative number indicating the proximity of deposition in Region 0 to the nearest bordering exceedance region. Exceedances are calculated as follows.

$$\mathrm{Ex}\left(\mathrm{N_{dep}},\mathrm{S_{dep}}\right) = \begin{cases} E_0 & \left(\mathrm{S_{dep}},\mathrm{N_{dep}}\right) \in \text{Region 0} \\ \mathrm{N_{dep}} - \mathrm{CL_{max}}(\mathrm{N}) + \mathrm{S_{dep}} & \left(\mathrm{S_{dep}},\mathrm{N_{dep}}\right) \in \text{Region 1} \\ \mathrm{N_{dep}} - \mathrm{N_0} + \mathrm{S_{dep}} - \mathrm{S_0} & \left(\mathrm{S_{dep}},\mathrm{N_{dep}}\right) \in \text{Region 2} \\ \mathrm{N_{dep}} - \mathrm{CL_{min}}(\mathrm{N}) + \mathrm{S_{dep}} & \\ \quad -\mathrm{CL_{max}}(\mathrm{S}) & \left(\mathrm{S_{dep}},\mathrm{N_{dep}}\right) \in \text{Region 3} \\ \mathrm{S_{dep}} - \mathrm{CL_{max}}(\mathrm{S}) & \left(\mathrm{S_{dep}},\mathrm{N_{dep}}\right) \in \text{Region 4} \end{cases} \tag{11}$$

For Region 2, the exceedance is defined with respect to the closest point between the diagonal line joining the points (CL_{min} (N), CL_{max} (S)) and (CL_{max} (N), 0), defined via

$$\mathrm{N_0} = \frac{\mathrm{N_{dep}} + \mathrm{mS_{dep}} + \mathrm{m^2CL_{max}(N)}}{1+\mathrm{m}^2}, \tag{12}$$

$$\mathrm{S_0} = \mathrm{m}\left(\mathrm{N_0} - \mathrm{CL_{max}(N)}\right), \tag{13}$$

where

$$m = \frac{\mathrm{CL_{max}(S)}}{\mathrm{CL_{min}(N)} - \mathrm{CL_{max}(N)}}. \tag{14}$$

We define here E_0, a negative quantity defining the smallest decrease in deposition from the critical load function (i.e. the boundary between the exceedance and non-exceedance regions of Fig. 2) to reach the N_{dep}, S_{dep} point in Fig. 2.

$$E_0 = \begin{cases} \mathrm{S_{dep}} - \mathrm{CL_{max}(S)} & \text{for } \mathrm{N_{dep}} \leq \mathrm{CL_{min}(N)} \\ \mathrm{S_{dep}} - \mathrm{mN_{dep}} - \mathrm{CL_{max}(N)} & \text{for } \mathrm{CL_{min}}\,(\mathrm{N}) < \mathrm{N_{dep}} \\ & \quad < \mathrm{CL_{max}(N)} \end{cases} \tag{15}$$

For deposition levels *below* exceedance, i.e. within the grey region of Fig. 2, the value of E_0 describes the proximity to exceedance; the fastest path by which exceedance could occur, relative to current deposition levels. Given that Eq. (2) guarantees that the slope of the line joining (CL_{min}(N), CL_{max}(S)) and (CL_{max}(N), 0) will always have an inclination of less than 45°, the shortest path to exceedance will always be via the S_{dep} path. E_0 is of potential interest to policymakers, in that this term describes the proximity of regions which are not yet in exceedance of critical loads to exceedance. Small magnitude values of E_0 thus describe ecosystems for which small increases in S_{dep} or N_{dep} may result in exceedances of critical loads. We also note that Eqs. (11)–(14) themselves are a slight simplification for the FAB model, which allows for a slight inclination of the CLF for $N_{dep} < CL_{min}$(N).

Three different sources of critical load data were used in this work. We begin with Canada-wide critical loads of acidity, which employ modifications to the above UNECE methodology (CLRTAP, 2017), used in eastern North America (NEG-ECP, 2001; Ouimet, 2005), and then expanded across Canada (Carou et al., 2008; Jeffries et al., 2010; Aherne and Posch, 2013). We follow with more recent estimated critical loads determined using the UNECE methodologies, for terrestrial ecosystems for the province of Alberta (Aklilu et al., 2018), and aquatic ecosystems in northern Alberta and Saskatchewan (Cathcart et al., 2016).

2.3.2 Canada-wide critical loads of acidity: lakes and forest soils

The earliest critical load data used in the current work are for forest and lake ecosystems, and resulted from updates to Environment and Climate Change Canada databases, subsequent to the publication of the Canadian Acid Deposition Science Assessment (ECCC, 2004; Jeffries and Ouimet, 2005).

Lake chemistry surveys were conducted in Canada in order to obtain data for critical load estimates (Jeffries et al., 2010). Critical loads of acidity for each sampled lake were estimated using the SSWC model (Henriksen and Posch, 2001). In addition to the lake survey data, other inputs to the SSWC include ecosystem-specific characteristics that were estimated using a mixture of methods, including broad mineralogical, geological, hydrological, and biological surveys. At the time these aquatic critical load data were collected, acidic deposition estimates at ECCC were created using A Unified Regional Air-quality Modelling System (AURAMS; Gong et al., 2006). The critical load values for lakes were therefore gridded to the map of Canada used by the AURAMS model, with a grid-cell resolution of 45 km × 45 km. The SSWC critical load values for each surveyed lake contained within each AURAMS grid cell were compared – when data from multiple lakes within the same grid cell were available, the fifth percentile of the resulting critical load values was assigned to that grid cell (for grid cells containing less than 20 lakes, the critical load for the most sensitive lake was used). The lake critical load data thus represent the most sensitive lake ecosystems within the given grid cell based on the available data. We note, however, that this procedure used in the creation of this dataset (Jeffries et al., 2010) becomes less accurate as the number of lakes per grid cell becomes small, with either over- or under-estimates of local ecosystem sensitivity. This was one of the factors leading to more recent updates in aquatic critical load maps for Canada, discussed in more detail in Sect. 2.3.4. The resulting 45 km resolution CL maps were subsequently re-mapped to the higher-resolution GEM-MACH grid used here; the centroids of those 2.5 km GEM-MACH grid cells falling within the AURAMS lake critical load polygons were assigned the corresponding AURAMS grid critical load values. The resulting critical loads are shown in Fig. 3a, with red values indicating the most sensitive ecosystems and blue values indicating the least sensitive ecosystems. AURAMS cells for which no lake information was available were assigned "null" values (shown in grey). These critical load data identified lake ecosystems in north-eastern Alberta, northern Saskatchewan, and north-western Manitoba as particularly sensitive to acidifying precipitation.

The forest ecosystem critical loads used here began with provincial and regional surveys that were combined to form a unified Canada-wide critical load dataset (Carou et al., 2008). Critical load and exceedance of S and N were estimated for forest soils following the methodology and guidelines established by the NEG-ECP (NEG-ECP 2001; Ouimet 2005), which largely follow the UNECE methodology (CLRTAP, 2017). The long-term critical load was estimated using the SSMB model; the key spatial datasets (or base maps) or formulae required for calculating critical loads are atmospheric deposition, base cation weathering rate, and a critical base cation to aluminum ratio (used to calculate critical alkalinity leaching). Average annual total (wet plus dry) atmospheric base cation deposition data during the period 1994–1998 were estimated using observed wet deposition, observed air concentrations, and modelled meteorological data along with land-use-specific dry deposition velocities, and mapped on the Global Environmental Multiscale (GEM) grid at a resolution of 35 km × 35 km (see Sect. 2.1 for details on GEM and its companion online chemistry module, GEM-MACH). Under the NEG-ECP methodology, weathering rates were estimated using a soil type-texture approximation method (Ouimet, 2005). The approach estimates weathering rate from texture (clay content) and parent material class. This method was used in conjunction with the Soil Landscapes of Canada (SLC, version 2.1) to estimate base cation weathering rates across western Canada. Under the NEG-ECP (2001) methodology, several simplifying assumptions and/or specified functions and values were applied to terms in Eqs. (1) through (4): (a) a critical BC : Al molar ratio of 10, and a K_{gibb} of $3000.0\,m^6\,mol_{charge}^{-2}$ were used, and (b) harvesting removals were not considered; therefore, long-term net uptake N_u and BC_u were set to zero. (c) As in Sect. 2.3.3, net N immobilization (N_i) was based on a 50 cm depth rooting and assumed to be equivalent to $0.5\,kg\,N\,ha^{-1}\,yr^{-1}$ ($35.7\,eq\,ha^{-1}\,yr^{-1}$) (CLRTAP, 2017). (d) Denitrification (N_{de}) was also set to $0.5\,kg\,N\,ha^{-1}\,yr^{-1}$ ($35.7\,eq\,ha^{-1}\,yr^{-1}$) following recommendations in CLRTAP (2017) and Aherne and Posch (2013) as an upper limit for well-drained soils, (e) the deposition of Cl ions was assumed to be zero, (f) the weathering release of soil base cations (BC_w) was assumed to be dependent on temperature, (g) BC_w was assumed to be equal to $0.75\,BC_w$, and (h) BC_{dep} was assumed to be equal to $0.75\,BC_{dep}$. The net critical load functions for the forest ecosystems with these simplifications become

$$\begin{aligned} CL(S+N) = {} & BC_{dep} + BC_w(T) \\ & + Q^{\frac{2}{3}}\left[\frac{3}{2}\left(\frac{0.75\left(BC_w(T)+BC_{dep}\right)}{3\times 10^4}\right)\right]^{\frac{1}{3}} \\ & + \frac{3}{2}\left(\frac{0.75\left(BC_w(T)+BC_{dep}\right)}{10}\right) + 71.4, \end{aligned} \tag{16}$$

with

$$BC_w(T) = BC_w e^{\left[3600\left(\frac{1}{281}-\frac{1}{274+T}\right)\right]}, \tag{17}$$

where T is the temperature in degrees Celsius (NEG-ECP, 2001; Nasr et al., 2010; Whitfield et al., 2010; Aherne, 2011).

The resulting critical load values were referenced to the corresponding GIS polygons under the SLC containing that soil type, resulting in a Canada-wide map of forest soil critical loads for acidity. These polygons were superimposed on the map of GEM-MACH 2.5 km × 2.5 km resolution grid cells. Similar to the approach for lake critical loads described above, the 5th percentile value from the forest critical load polygons existing within each GEM-MACH grid cell was assigned to that grid cell. The forest soil critical load values on the resulting GEM-MACH grid cell thus represent the most sensitive forest ecosystems within that grid cell. Polygons for which forest soils were not present were assigned "null" values. Under the NEG-ECP methodology (NEG-ECP, 2001) critical loads were simplified deposition of sulfur and nitrogen, as such exceedance was defined for combined deposition:

$$\mathrm{Ex}\left(\mathrm{N_{dep}}, \mathrm{S_{dep}}\right) = \mathrm{S_{dep}} + \mathrm{N_{dep}} - \mathrm{CL(S+N)}. \quad (18)$$

We note that Eq. (18), which follows the NEG-ECP methodology (Ouiment, 2005), may lead to potential errors at very low values of $\mathrm{N_{dep}}$, in that the nitrogen sinks could potentially compensate sulfur deposition. To avoid that possibility, we have added the caveat to Eq. (16) that the rightmost term is replaced by the minimum of $71.4\,\mathrm{eq\,ha^{-1}\,yr^{-1}}$ and $\mathrm{N_{dep}}$ (that is, the calculated nitrogen sink will not be used to compensate $\mathrm{S_{dep}}$, in the event that $\mathrm{N_{dep}}$ is below the sum of nitrogen immobilization and denitrification ($71.4\,\mathrm{eq\,ha^{-1}\,yr^{-1}}$)). In our application of this methodology (see Sect. 3.6.1), this additional correction was found to bring areas which were already below exceedance further below exceedance, but had no impact on the estimate of the size areas over exceedance, to three significant figures.

The resulting critical load map for forest soils for the first of these approaches is shown in Fig. 3b, with the same colour scale as Fig. 3a. The lake ecosystems can be seen to be more sensitive to acidic deposition compared to forest soil ecosystems (lower critical load values, red shades in Fig. 3).

Later in this work, we discuss the effect of different estimates of the assumed level of atmospheric base cation deposition in the above calculations towards the resulting estimates of critical load and critical load exceedances.

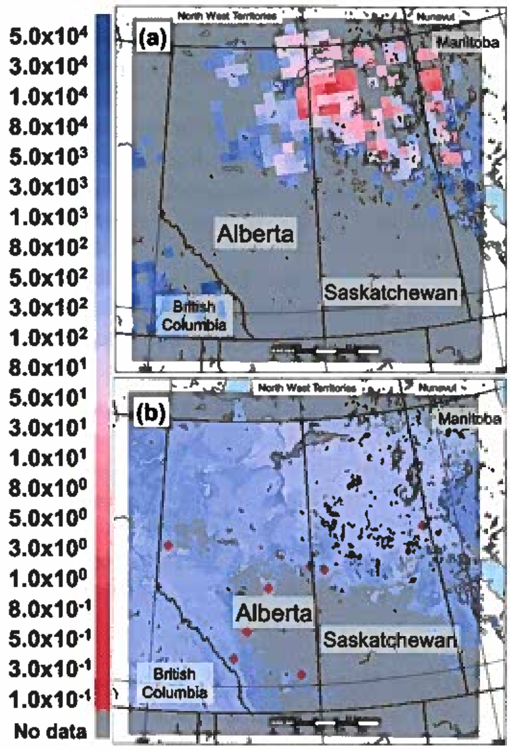

Figure 3. Critical loads of acidity on the 2.5 km GEM-MACH domain, based on a Canada-wide implementation: **(a)** Critical load for acidity (Eq. 5) and **(b)** forest ecosystems (Eq. 18) ($\mathrm{eq\,ha^{-1}\,yr^{-1}}$). Forest values were calculated using 1994–1998 interpolated/extrapolated $\mathrm{BC_{dep}}$ observations (diamonds show the location of those Canada-wide stations used to estimate $\mathrm{BC_{dep}}$, which reside within the 2.5 km resolution model domain). Red regions (low numbers) on the scale have the lowest critical loads, hence are the most sensitive to deposition. No data: **(a)** no lake observations were available in the given 45 km × 45 km grid cell; **(b)** No forest data were available and/or the "no data" regions were not forested.

2.3.3 Province of Alberta: critical loads of acidity for terrestrial ecosystems

The SSMB model was used to estimate $\mathrm{CL_{max}(S)}$, $\mathrm{CL_{max}(N)}$, and $\mathrm{CL_{min}(N)}$ for terrestrial ecosystems in the province of Alberta following methods recommended under the Convention on Long-Range Transboundary Air Pollution (CLRTAP, 2017). Critical loads were not derived for areas comprising cultivated or agricultural land, rock, and exposed or developed soil. Our initial estimate of non-marine annual base cation deposition ($\mathrm{BC_{dep}}$) was the interpolated/extrapolated 1994–1998 base cation database described above. The release of base cations as a result of chemical dissolution from the soil mineral matrix ($\mathrm{BC_w}$) followed the soil texture approximation method (Eq. 17), with soil information vertically weighted to a rooting depth of 50 cm to create a homogeneous soil layer for calculations. Soil information for this calculation was obtained from the Soils Landscape Canada version 3.2 database (AAFC, 2010). The average base cation removal in harvested biomass ($\mathrm{BC_u}$) was calculated using the Alberta Vegetation Index dominant forest cover database to determine type and distribution of forests (ABMI, 2010), harvest information (AAF, 2015), and information on nutrient uptake by forest type (Paré et al., 2012). For unmanaged ecosystems (i.e. not harvested) $\mathrm{BC_u}$ was set to zero, and the removal of biomass due to grazing in grasslands was set to $8\,\mathrm{eq\,ha^{-1}\,yr^{-1}}$. The acid neutralization capacity leaching ($\mathrm{ANC_{le,crit}}$) was determined using critical BC : Al ratios applied by vegetation type (a $\mathrm{(BC:Al)_{crit}}$ ratio of 6 was used for mixed forest, shrubland, and broadleaf forest, while coniferous forest and grassland made use of ratios of 2 and 40, respectively). The denitrification fraction (f_{de}) was assigned using a seven-level scale (AAFC, 2010; CLRTAP, 2017). f_{de} values for "very rapid", "well", "moderately well", "imperfectly", "poorly", and "very poorly" drained soil were, respectively, 0.0, 0.1, 0.2, 0.4, 0.7, and 0.8. The long-term net immobilization of N in the 50 cm depth rooting zone was assumed to be $0.5\,kg\,N\,ha^{-1}\,yr^{-1}$ ($35.7\,eq\,ha^{-1}\,yr^{-1}$) (CLRTAP, 2017). The average removal of N from an ecosystem (N_u) followed Pregitzer et al. (1990), using Alberta Vegetation Index dominant forest cover data to identify the type and distribution of forests (Alberta, 2016), and nutrient information from the Canadian Tree Nutrient Database (Paré et al., 2012). For grasslands the value of N_u was set to $43\,eq\,ha^{-1}\,yr^{-1}$ to account for nitrogen removal due to grazing.

The resulting maps for $CL_{max}(S)$, $CL_{max}(N)$, and $CL_{min}(N)$ for Alberta Terrestrial Ecosystems are shown in Fig. 4 (using the same colour scale as Fig. 3). $CL_{max}(S)$ and $CL_{max}(N)$ values (Fig. 4a) are lower than the forest critical load values created under the NEG-ECP (2001) methodology (Fig. 3b), reflecting the more detailed treatment of the acid neutralizing capacity term, and the impacts of harvesting on estimated critical loads. NEG-ECP (2001) methodology critical load estimates were intended as "upper limits", that is, they were expected to underestimate ecosystem sensitivity, relative to the more detailed calculation used in the creation of Fig. 4.

2.3.4 Northern Alberta and Saskatchewan: critical loads of acidity for aquatic ecosystems

The critical load data for lake ecosystems described in Sect. 2.3.2 were updated for aquatic ecosystems in northern Alberta and Saskatchewan, as part of an ongoing project to update previous Canada-wide critical load data, following the full UNECE methodologies (Eqs. 1 through 14, with the addition of our Eq. 15), resulting in new spatially georeferenced critical load maps for acidity with respect to S_{dep} and $S_{dep} + N_{dep}$ (Eqs. 1–10 and 11–15, respectively).

Water chemistry from 2409 observations of 1344 lakes was used to produce maps of lake concentrations for three target variables across northern Alberta and Saskatchewan for the determination of critical loads: base cations (BC), dissolved organic carbon (DOC), and sulfate (SO_4^{2-}). A regression kriging approach was used to generate (predict) water chemistry for 137 587 lake catchments following Cathcart et al. (2016). Regression kriging is a spatial interpolation method wherein a regression of the target variable on covariate variables (e.g. landscape characteristics such as soil, climates, and vegetation; a total of 185 covariates were included) is combined with kriging on the regression residuals (Hengl et al., 2007; Hengl, 2009). The water chemistry (target variable) data were obtained from Environment and Climate Change Canada's Level 1 and 2 monitoring networks in Saskatchewan, Alberta, and the Northwest Territories (Jeffries et al., 2010), lake surveys undertaken by the Government of Saskatchewan (Scott et al., 2010), the RAMP monitoring network in Alberta (RAMP, 2016), and the Alberta Environment and Parks surface water quality data portal (Alberta Environment and Parks, 2016). Critical loads of acidity for lakes were calculated from the predictive maps of lake concentration using the SSWC and FAB models. As previously noted, the FAB model extends the SSWC model to consider terrestrial and aquatic sources and sinks of S and N, similar to the SSMB (Henriksen and Posch, 2001; Posch et al., 2012). A variable ANC_{limit} was used, adjusted for the strong acid anion contribution from organic acids (DOC) following Lydersen et al. (2004). Long-term normals for catchment runoff (Q) were estimated from meteorological data and soil properties using a model similar to MetHyd

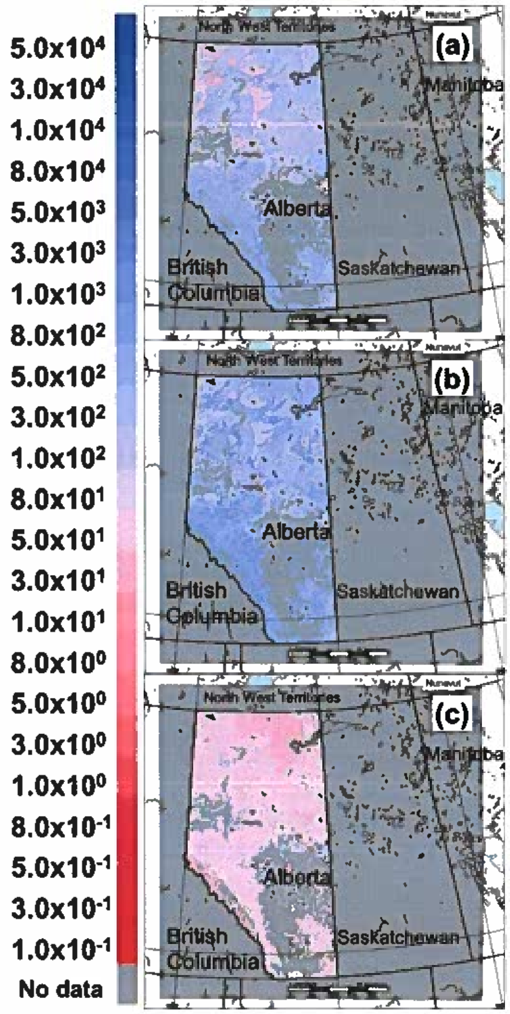

Figure 4. Critical loads of acidity with respect to sulfur and nitrogen for terrestrial ecosystems, Province of Alberta implementation ($eq\,ha^{-1}\,yr^{-1}$), using BC_{dep} from interpolated/extrapolated 1994–1998 observations. **(a)** Maximum critical load for sulfur. **(b)** Maximum critical load for nitrogen. **(c)** Minimum critical load for nitrogen. No data: data were only collected within the province of Alberta (outside of Alberta, no data reflect the limitation of data collection); within Alberta, data were only collected for natural terrestrial ecosystems (no data within Alberta thus refer to landscapes modified by human activities such as agriculture).

(a meteo-hydrological model; Slootweg et al., 2010). Long-term (1961–1990) average monthly temperature, precipitation, and cloudiness were derived from a $0.5^{\circ} \times 0.5^{\circ}$ global database (Mitchell et al., 2004). Default net mass transfer coefficients for N ($6.5\,\mathrm{m\,a^{-1}}$) and S ($0.5\,\mathrm{m\,a^{-1}}$) were applied to all lakes (Kaste and Dillon, 2003; Baker and Brezonik, 1988). Nitrogen immobilization in catchment soils was set at $0.5\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ ($35.7\,\mathrm{eq\,ha^{-1}\,yr^{-1}}$) following the Mapping Manual (CLRTAP, 2017). The denitrification fraction in the catchment soils was estimated as $f_{de} = 0.1 + 0.7 \cdot f_{peat}$, where f_{peat} is the fraction of wetlands in the terrestrial catchment; land-cover fractions of peat were obtained from the 2010 USGS North American Landcover database (USGS, 2013). Nitrogen removal in harvested biomass was estimated using biomass and species composition obtained from the National Forest Inventory (Beaudoin et al., 2014) in combination with nutrient concentrations from the Canadian Tree Nutrient Database (Paré et al., 2012) and the Tree Chemistry Database (Pardo et al., 2005).

The resulting CL(A), $CL_{max}(S)$, $CL_{max}(N)$, and $CL_{min}(N)$ maps created using the above data (Fig. 5) cover much of the same region as depicted in Fig. 3a. Figs. 3, 4, and 5 have matching colour scales, showing the relative sensitivity of the different ecosystems estimated using the critical load calculation methodologies employed in each dataset. The lakes and aquatic ecosystem data, shown in Figs. 3a and 5, are in general more sensitive to acidifying deposition than the forest (Fig. 3b) and terrestrial ecosystem data (Fig. 5), a theme which recurs in our subsequent calculation of critical load exceedances (Sect. 3.6).

3 Results

3.1 GEM-MACH estimates of annual S_{dep} andN_{dep}

The model estimates of total S_{dep} and N_{dep} ($\mathrm{eq\,ha^{-1}\,yr^{-1}}$), along with the percentage contribution of the different resolved components of sulfur and nitrogen deposition, are shown in Figs. 6 and 7, respectively. The bulk of the relative fraction of total S_{dep} close to the sources of emissions is due to dry deposition of SO_2(g) and wet deposition of HSO_3^-, while the wet deposition of $SO_4^{(2-)}$ dominates in downwind regions. The relative fraction of N_{dep} near the sources is dominated by dry deposition of NO_2(g) and NH_3(g) near sources and dry deposition of HNO_3(g) and $NH_4^{(+)}$ further downwind. Figures 6b–e and 7b–i show that for sites downwind of the source regions (hotspots in panel a of these figures), wet deposition dominates. We note that the mass of S_{dep} and N_{dep} deposited decreases with distance from the sources; for example, $NH_4^{(+)}$ dominates the relative fraction of N_{dep} in locations more distant from the sources, where total N_{dep} is relatively low. Air-quality models such as GEM-MACH are quite complex, with many possible sources of model error; some possibilities include but are not limited to errors in the input emissions data (as we examine below for base cation emissions and deposition), errors in the plume rise algorithms leading to potential errors in the relative distribution of deposition near versus far from the sources (Gordon et al., 2017; Akingunola et al., 2018), potential errors in the magnitude of N_{dep} associated with the absence of bi-directional fluxes of NH_3 (Whaley et al., 2018) in the simulations carried out here, and biases within the meteorological forecast components of the model. As we discuss below, the model predictions nevertheless correlate well with wet deposition observations at precipitation-monitoring stations located downwind of emissions sources, and these relationships allow for an approximate correction of model S_{dep} and N_{dep} estimates using observations. This allows us to reduce the potential impact of sources of model error on estimates of critical load exceedances.

3.2 Model evaluation: wet deposition

The observed wet deposition of deposited sulfur (as SO_4^{2-}), nitrogen ($NH_4^+ + NO_3^-$), and base cations (sum of Ca^{2+}, Mg^{2+}, Na^+, and K^+) are compared to model estimates in Fig. 8b, c, and d, respectively (station locations are shown in Fig. 8a). Note that GEM-MACH's particle speciation includes a "crustal material" component, of which base cations are a component. The model wet and dry estimates of crustal material deposition were combined, and the fraction of crustal material which is composed of base cations was estimated from the observations of surface dust collected by Wang et al. (2015), in the vicinity of the oil sands, in order to estimate base cation deposition. Model estimates of deposited sulfur in precipitation were biased high, with a slope of 2.2, but the model accounts for most of the observed variation with a Pearson correlation coefficient (R^2) of 0.90. Model estimates of deposited nitrogen were biased slightly low (slope = 0.89, $R^2 = 0.76$), and the model estimate of base cations were biased low (slope = 0.40, $R^2 = 0.72$).

The positive bias in simulated sulfur deposition may reflect an underestimation of the SO_2 deposition flux closer to the sources (the precipitation sites are located far from SO_2 emissions sources; a model underestimate of upwind SO_2 deposition flux may thus result in excess sulfur being transported downwind, increasing simulated wet deposition of sulfur at these downwind precipitation sites). The negative bias in simulated base cations may result from an underestimate in the model's emissions inputs for the "crustal material" component of primary particulate matter from either reported anthropogenic or natural sources (and/or in the base cation fraction of these emissions). We discuss the potential impact of under-reporting to the National Pollutant Release Inventory (NPRI), below. The deposition velocity of particulate matter is a strong function of particulate size, with submicron and supermicron particles having the highest and micrometer-sized particles having the lowest deposition velocities, respectively. The size distribution of particles

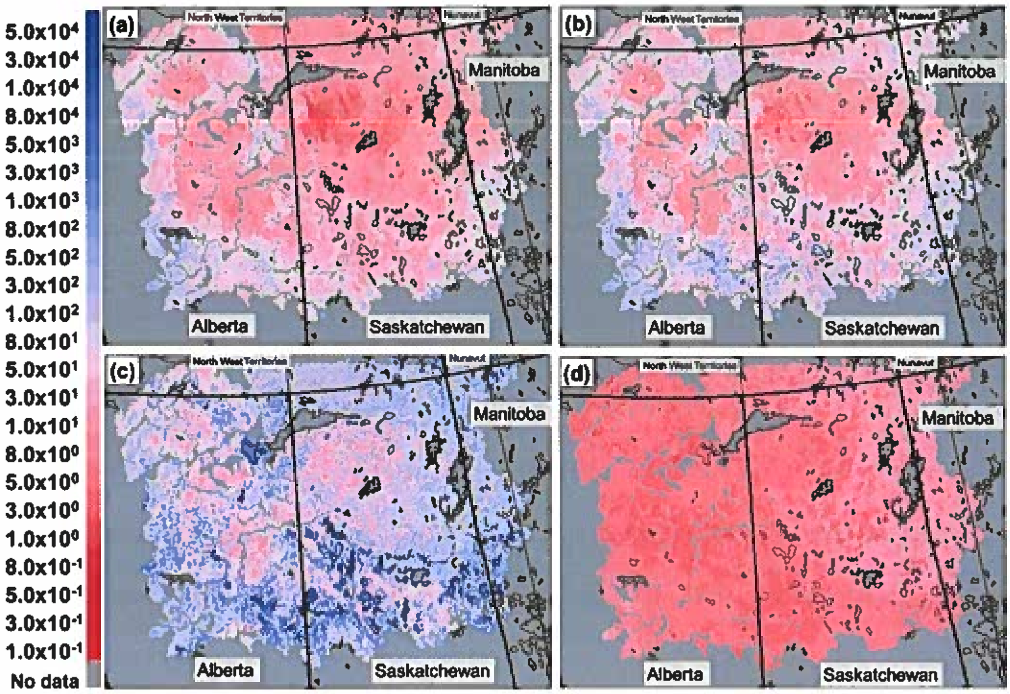

Figure 5. Critical loads of acidity with respect to S_{dep} (CL(A)), and S_{dep} and N_{dep} (FAB model) for aquatic ecosystems (eq ha^{-1} yr^{-1}). **(a)** CL(A) **(b)** CL_{max} (S). **(c)** CL_{max} (N). **(d)** CL_{min} (N). No data: data were not collected for the largest lakes and river systems within the coloured region; the boundaries of the coloured region represent the limit of the catchment basins for which data were collected.

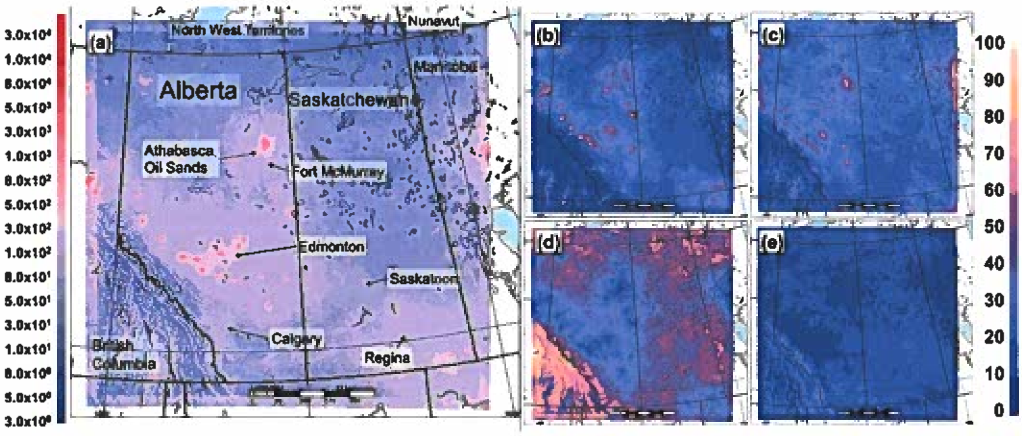

Figure 6. GEM-MACH predictions of total sulfur deposition and its speciation. **(a)** Total sulfur deposition (eq ha^{-1} yr^{-1}) and percentages of total sulfur deposition due to **(b)** SO_2 (dry), **(c)** HSO_3^- (aq) (wet), **(d)** SO_4^{2-} (aq) (wet), and **(e)** particulate sulfate (dry).

thus determines their residence time prior to deposition, and hence errors in the spatial pattern of estimated BC_{dep} may also reflect errors in the assumptions on the size distribution of emitted particles. Both of these possibilities are discussed further in Sect. 3.5.

The relatively high correlation for all three deposited quantities suggests that the linear relationships between model estimates and observed ions in precipitation may be used as a means of providing observation-corrected estimates of the S_{dep}, N_{dep}, and BC_{dep} required for the critical load and critical load exceedance calculations described in Sect. 2.3. Therefore, critical load exceedances were calculated using the original model deposition for sulfur, nitrogen, and base cations, and also using model deposition corrected using the model–observation linear relationships shown in Fig. 8. We note that the resulting corrected values may underestimate

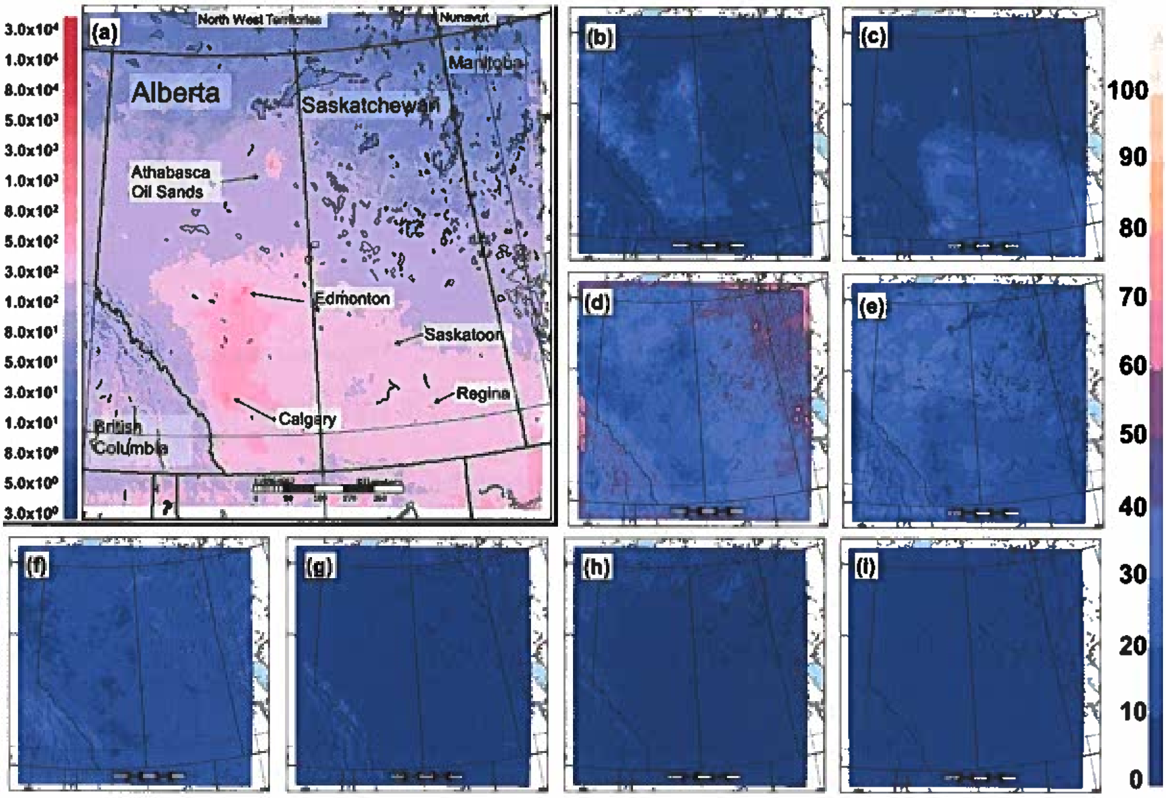

Figure 7. GEM-MACH predictions of total nitrogen deposition and its speciation. (a) Total nitrogen deposition (eq ha^{-1} yr^{-1}), percentages of total nitrogen deposition due to: (b) NO_2 (dry), (c) NH_3 (dry), (d) NH_4^+ (aq) (wet), (e) HNO_3 (dry), (f) NO_3^- (aq) (wet), (g) particulate ammonium (dry), (h) peroxyactylnitrate (dry). (i) each of particulate nitrate (dry), gaseous organic nitrate (dry), NO (dry) and HONO (dry) (each contribute less than 10 % to N_{dep}).

exceedances near the sources of S_{dep} and N_{dep} precursor species emissions. For example, if the positive bias in wet sulfur deposition of Fig. 8b results from a model underestimate of dry deposition of SO_2 near its sources, an overall downwind correction of SO_2 as per Fig. 8b may underestimate sulfur deposition from SO_2 near the sources. The resulting corrected values should thus be considered a lower bound for exceedances in the near-source environment.

3.3 Estimates of primary particulate emissions and resulting BC_{dep} from aircraft observations near the Athabasca oil sands

An airborne measurement campaign was undertaken in August and September of 2013 in the Athabasca oil sands region as part of a broader measurement plan (the Joint Oil Sands Monitoring program) to characterize emitted air pollutants, determine the extent of subsequent atmospheric transport and chemical transformation, and support the improvement of air quality models and satellite column retrieval algorithms. "Enclosure" (box) flights were carried out around individual emitting facilities, in order to characterize their emissions fluxes. As part of that work, a mass balance model was de-

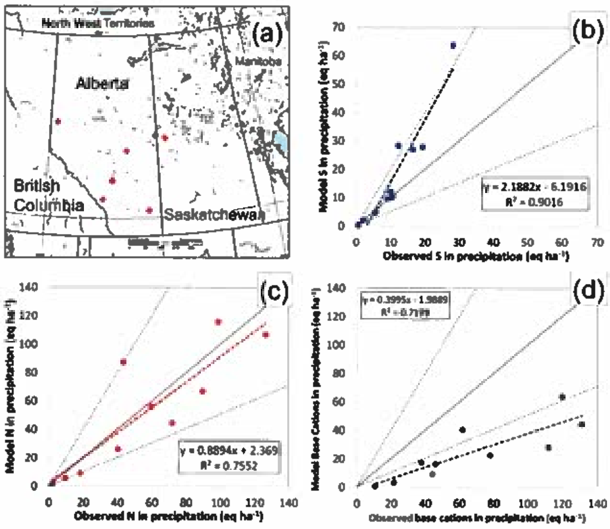

Figure 8. (a) Ions-in-total-precipitation sample collection sites. Scatterplots compare model and observed wet deposited (a) S, (b) N, and (c) base cations in precipitation (eq ha^{-1}).

veloped (the Top-down Emission Rate Retrieval Algorithm, TERRA, Gordon et al., 2015). TERRA makes use of aircraft flux data and mass conservation equations to estimate emissions from facilities, and was shown to produce SO_2 emissions estimates which were within 5 % of direct within-stack estimates from Continuous Emissions Monitoring. The algorithm has more recently been used to estimate the emissions fluxes of intermediate volatility organic compounds (Liggio et al., 2016), volatile organic compounds (Li et al., 2017) and the primary emissions of gaseous organic acids from these facilities (Liggio et al., 2017).

The TERRA algorithm, aircraft observations of total particulate matter number concentration and size close to the sources, and the fugitive dust speciation reported in Wang et al. (2015) were used to estimate fugitive dust emissions for six oil sands facilities, for the 12-particle bin version of the GEM-MACH model (Zhang et al., 2017). We refer to these emissions and corrections to deposition based on them hereafter as "aircraft-based". As shown in Zhang et al. (2017), the aircraft-based primary particulate emissions estimates are much higher (on average, by a factor of 10) than the values reported to the National Pollutant Release Inventory by the facilities, with 96 % of the primary particulate emissions being associated with fugitive dust, and 68 % of this mass being at particle sizes greater than 2.5 µm diameter. Larger particles have higher deposition velocities compared to particles with diameters of 1 µm (cf. Zhang et al., 2001), and hence these larger, "coarse mode" primary particles would be expected to more rapidly deposit downwind of their emissions sources. This in turn implies a reduction in BC_{dep} with increasing distance from the sources, associated with this differential deposition of the larger fugitive dust particles earlier in the transportation process. The mean Wang et al. (2015) base cation fractions of primary particulate matter in the 0 to 2.5 µm particle diameter size range and the 2.5 to 10 µm particle size ranges were found to be quite similar; we have used the former here, to describe the mass fraction of the aircraft primary particulate emissions assumed to be composed of base cations. While we have used the reported emissions inventory in annual acid deposition modelling, this comparison between the inventory and the aircraft emissions estimates suggests that the former may significantly underestimate the BC_{dep} and BC_{dep} terms used in critical load and critical load exceedance estimates.

The potential impact of higher-than-reported primary particulate emissions on the estimation of base cation deposition was investigated here via two 29 day simulations of the 12-bin version of GEM-MACH, employing the reported emissions versus the aircraft-based estimates. The ratio of gridded net model wet and dry deposition of "crustal material" between the two simulations was calculated. Figure 9 shows the average value of this ratio, derived from sampling the resulting gridded field at 10 km distance and 20° angles about a reference point within the oil sands emissions area, out to 600 km distance. As noted above, most of the primary par-

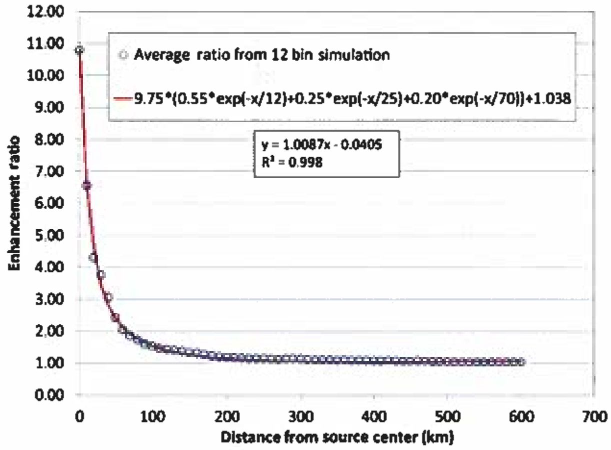

Figure 9. Temporal and spatial average ratio of total deposited crustal material as a function of distance from a reference point within the oil sands emissions region: ratio of deposition from the model simulation using aircraft-based primary particulate emissions to the model simulation using reported fugitive dust emissions.

ticulate matter in the aircraft-based emissions resides in the coarse mode (particle sizes greater than 2.5 µm). These larger particles have higher deposition velocities and consequently undergo rapid deposition close to the sources. The use of the aircraft-based emissions thus results in enhancements in crustal material deposition relative to the reported emissions simulation by a factor of 11 close to the sources. The ratio drops exponentially with distance from the sources, and shows the impact of the size fractionation observed from the aircraft data. A combination of exponential decay functions (see Fig. 9) was found to fit the average ratio to a very high correlation ($r^2 = 0.998$). Zhang et al. (2017) used the observations of Wang et al. (2015) to show that 93 % of the primary particulate matter emissions were composed of crustal material. Wang et al. (2015) also includes the relative fraction of base cations within these particles. The exponential decay function thus describes the average relative enhancement of crustal material (and hence base cation) deposition, associated with the use of the aircraft-based primary particulate emissions, relative to the reported values.

Figure 9 shows that the additional fugitive dust emissions result in a substantial enhancement in crustal material (hence base cation) deposition close to the sources, but this enhancement approaches only 3.8 % further downwind due to size-dependent particle deposition en route, with the more rapid deposition of super-micron sized particles. This result was expected, given that the aircraft observations showed that 93 % of the emitted primary PM_{10} mass resides in particle sizes greater than 2 µm diameter. Particle deposition velocities have a well-established size dependence (cf. Wesely et al., 1985; Zhang et al., 2001), with a rapid increase in deposition velocities occurring as particle diameters increase from 1 to 10 µm (a factor of 28.6 between these two particle diameters, for particle deposition to needle-leaf trees and a wind speed of $2\,m\,s^{-1}$, Zhang et al., 2001).

While the reported fugitive dust emissions in the reported inventory were used in the two-bin annual GEM-MACH simulations carried out here, the aircraft-based emissions estimates and the shorter duration model simulation described above suggest that the primary particulate emissions in the reported inventory may greatly underestimate the base cation deposition. The scaling function shown in Fig. 9 along with the correction to downwind base cation observations from the precipitation data shown in Fig. 6d were therefore used to create a combined corrected estimate of base cation deposition. We note that this combined estimate would increase base cation deposition by a factor of ~ 25 in the immediate vicinity of the oil sands operations, and drop off to a factor of 2.5 further downwind. However, as is shown in the next section, the use of this and other observation-based corrections on the original model estimates improves both the correlation and the slope of the model-derived estimates of S_{dep}, N_{dep}, and BC_{dep} relative to observations of winter deposition to snow.

3.4 Comparison of model and observed snowpack deposition

The observed snowpack-derived deposition fluxes are compared to the modelled values for total sulfur, nitrogen, and base cations in Fig. 10b, c, and d, respectively (site locations are shown in Fig. 10a). The uncorrected model and observation pairs for each site are shown in blue for each of these figures. The model slopes for sulfur and nitrogen are relatively high and correlations relatively low in comparison to the total deposition in precipitation comparisons carried out at stations further downwind (compare Figs. 8 and 10). The model values however represent the total deposition to all surface types within each model grid square, while the snowpack observations correspond to values in forested clearings; thus, as noted in Sect. 2.2.2, the snowpack observations may underestimate the total deposition by factors of 2.6 (S_{dep}) and 2.0 (N_{dep}).

The nitrogen deposition (Fig. 10b) is dominated by deposition of ammonium, and other work (Whaley et al., 2018) has found that model overestimates of surface concentrations of ammonia in the immediate vicinity of oil sands emissions sources likely result from incomplete stack information for the relevant facilities' ammonia emissions records (missing volume flow rates, temperatures). In the absence of this information, default EPA values for stacks are used in the emissions processing, which likely underestimates the vertical dispersion of emitted ammonia (Whaley et al., 2018; Zhang et al., 2017).

The model estimates of base cation deposition to snowpack have a strong negative bias (slope = 0.05, $R^2 = 0.22$). This bias is considerably stronger than noted for the precipitation sites further downwind (compare Fig. 10d to 8d). The additional bias is likely due to the under-reporting of primary particulate emissions in the emissions inventories.

Purple lines and symbols in Fig. 10b and c depict the relationships between modelled and open snowpack S_{dep} and N_{dep} loads, when the latter are corrected to approximate throughfall values using the model-derived SO_2 and NH_3 deposition velocity ratios for needle-leaf forest to open snow-covered surfaces. These corrections result in a considerable improvement to the slope between model-derived and snowpack S_{dep} and fluxes, and the apparent N_{dep} overestimate is halved.

Green lines and symbols in Fig. 10d compare model values of BC_{dep} corrected by the combination of precipitation and aircraft-based scaling factors described earlier, to the observations, which are also corrected using the expected ratio of needle-leaf forest to open snow-covered particle deposition velocities. Red symbols and lines indicate the fit occurring when only the model values are corrected. The correction of modelled values improves both the slope and correlation coefficient of the best fit line, while correction of observations for the expected influence of snowfall versus snowpack further improves the slope. We note that the combination of precipitation and aircraft-based correction factors on the model's original estimates of base cation deposition increase that estimate by a factor of 25, yet result in a substantial improvement to the fit and slope relative to observations. These results suggest that the primary particulate emissions derived from aircraft observations are an underestimate, and/or that the base cation mass fraction derived from collection of deposited surface dust (Wang et al., 2015) is biased low relative to fugitive dust in the atmosphere in this region. Further observation flights are planned for the spring and summer of 2018 to sample both base cation mass fractionation and particulate size distribution in order to further improve estimates of base cation emissions from oil sands operations and other sources.

3.5 Comparison of base cation fluxes

Given the dependence of critical loads on base cation levels in both terrestrial and aquatic ecosystems, we compare the observation-based base cation catchment export from aquatic ecosystems (Fig. 11a) to three different estimates of base cation fluxes used in the subsequent critical load exceedance calculations. Figure 11a is equivalent to the sum of atmospheric deposition, soil weathering, soil cation exchange and groundwater contributions within catchment water, and consequently has larger values than the remaining three estimates, which depict different estimates of the atmospheric component (BC_{dep}). Figure 11b shows the BC_{dep} values estimated via interpolation and extrapolation of Canada-wide observation station data collected between 1994 through 1998, with the observation stations within GEM-MACH's 2.5 km domain shown as diamond symbols. Figure 11c shows the original GEM-MACH-derived base

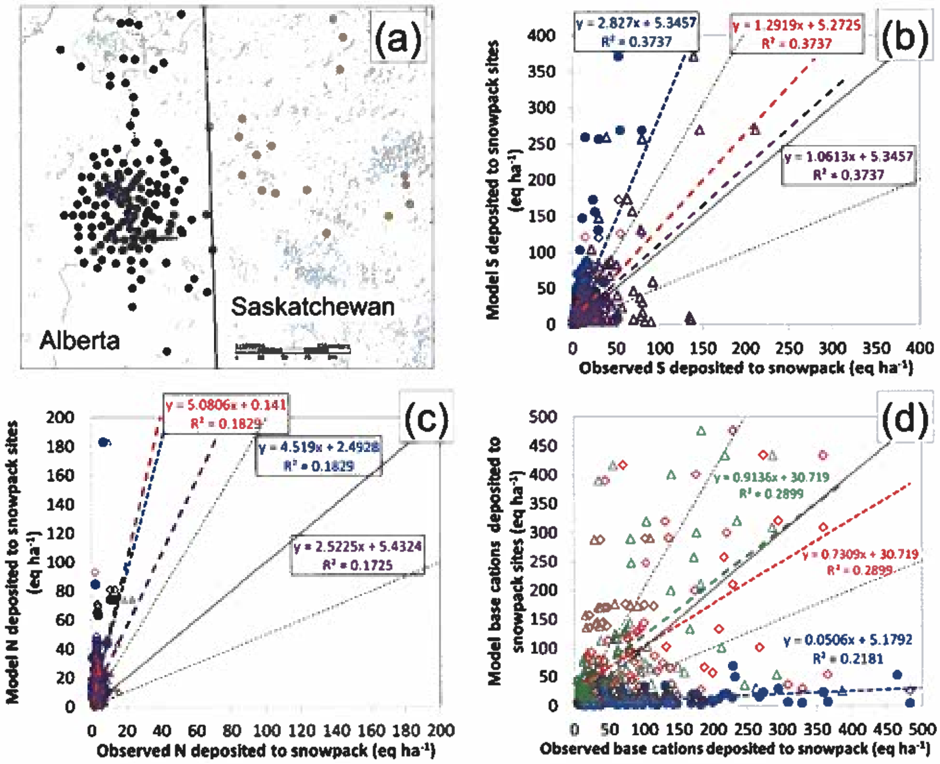

Figure 10. **(a)** Snowpack sample collection sites (purple: Environment and Climate Change Canada sampling sites; orange: Saskatchewan Environment sampling sites). **(b, c, d)**: Relationships between modelled and snowpack-derived S_{dep}, N_{dep} and BC_{dep}, fluxes, respectively. Blue lines: uncorrected model estimates compared to uncorrected snowpack observations. Red lines: Model estimates corrected using downwind precipitation observations **(b, c, d)** and aircraft-obervation-based fugitive dust emissions estimates **(d)**. Purple lines: original model values compared to snowpack-derived loads corrected by the expected ratios of throughfall to open surface collection for S_{dep} **(b)** and N_{dep} **(c)**. Green line **(d)**: model BC_{dep} estimates scaled using precipitation and aircraft observations paired with observations corrected by the expected ratio of throughfall to open surface collection for $PM_{2.5}$. Units are eq ha^{-1} for the snowpack sampling periods; model values are the sum of hourly values during snowpack sampling times.

cation deposition (using the reported fugitive dust emissions, the model's summed wet and dry crustal material deposition, and the Wang et al. 2015 base cation fractionation reported above). Figure 11d shows the base cation deposition fields which result from correcting the model values of Fig. 11c with the precipitation-observation-based and aircraft-based emission scaling factors of Figs. 8c and 9, and represent an observation-corrected estimate of base cation deposition. We note that the observation stations of Fig. 11c measure only the wet component of base cation deposition. However, model calculations show that the dry particulate matter flux of base cations drops off rapidly with distance from the sources. The precipitation sites are intended as background sites, located far from sources, and the bulk of base cation deposition at these locations is expected to be via wet deposition.

Three important features should be noted from Fig. 11. First, the net base cation flux exported from aquatic ecosystem catchments (Fig. 11a, data described in Sect. 2.3.4) is usually much larger than any of the three estimates of BC_{dep} in the remaining panels of the figure. This implies that the aquatic ecosystem base cation load is usually dominated by soil weathering, soil cation exchange, and groundwater inputs. The area of the lowest cation flux exported from aquatic systems is observed in north-western Saskatchewan.

Second, the observation-derived estimates of BC_{dep} derived from sparse measurement station data, at station locations designed to be relatively remote from sources (Fig. 11b), are relatively spatially homogeneous compared to the two remaining BC_{dep} estimates, which are derived from model estimates of crustal material emissions. However, the model results suggest that these station locations may consequently miss much of the base cation deposition associated with large sources of fugitive dust emissions, which is highly localized. The largest values in the model estimates are in close proximity to the anthropogenic sources (Fig. 11c, d). The latter show a rapid drop-off of estimated base cations with distance from the sources, as was expected from Fig. 9. Within these anthropogenic emission "hotspots" of Fig. 11c and d, BC_{dep} estimates reach as high as 3×10^4 eq ha^{-1} yr^{-1},

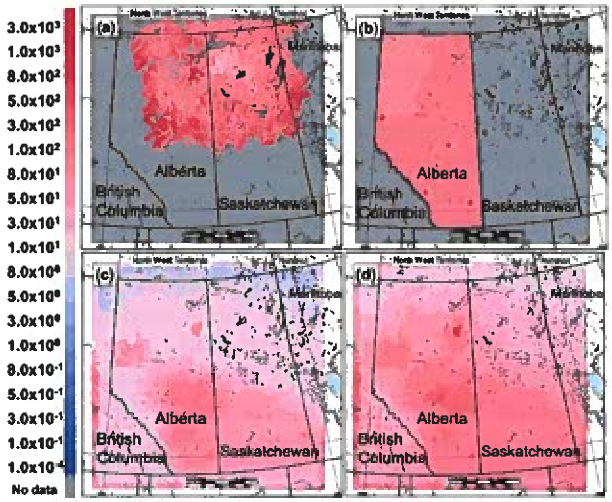

Figure 11. Base cation fluxes (eq ha^{-1} yr^{-1}). **(a)** Total export flux of base cations from aquatic ecosystem catchments. **(b)** Atmospheric deposition flux of base cations from surface data collected between 1994 through 1998, monitoring station locations shown as red diamonds, **(c)** base cation deposition from GEM-MACH, making use of Wang et al. (2015) speciation, **(d)** GEM-MACH BC_{dep} corrected using and precipitation measurements and aircraft observations of fugitive dust.

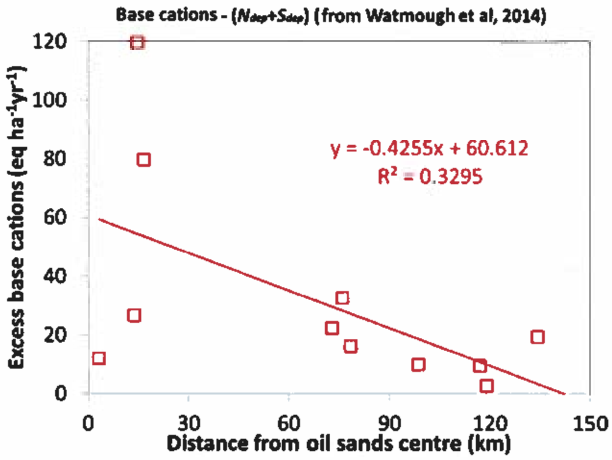

Figure 12. BC_{dep}–N_{dep}–S_{dep}, using the data of Watmough et al. (2014).

compared to background levels in the 10s of eq ha^{-1} yr^{-1} (note that the colour scale in Fig. 11 is logarithmic).

Third, the corrections applied to Fig. 11c, to create the combined aircraft-based and precipitation-observation-based corrected field of Fig. 11d, are in reasonable agreement with the 1994–1998 observation station values at the remote-from-sources observation station locations (diamond symbols, Fig. 11b), and also reflect the increases in base cation deposition expected from the aircraft-based fugitive dust emissions estimates in the immediate vicinity of the oil sands. As noted in the previous section, these final estimates of BC_{dep} also have a greater degree of agreement with snowpack observations of base cations in the immediate vicinity of the oil sands (Fig. 10d).

Watmough et al. (2014) presented observations within 135 km of the oil sands which compared $S_{dep} + N_{dep}$ to BC_{dep}. The base cations were found to be in excess of S_{dep} and N_{dep}, and hence one of their conclusions was that "despite extremely low soil base cation weathering rates in the region, the risk of soil acidification is mitigated to a large extent by high base cation deposition". However, the rapid decrease in base cation deposition with distance from the sources in Figs. 11c, d and 9 suggests that this neutralization effect may be limited with increasing distance from the sources of base cation emissions. We re-examined the summer throughfall data presented in Watmough et al. (2014), and show the excess in base cation deposition (i.e. $BC_{dep} - N_{dep} - S_{dep}$) as a function of distance from the oil sands emissions region in Fig. 12. The data show a rapid decrease in neutralization with distance from sources in the oil sands region, with a linear best fit crossing the intercept, from neutralizing to non-neutralizing conditions, at a distance of 142 km. The data also show a wide variation within the 30 km central region, suggesting neutralization is not uniform. Both these observations (Fig. 12) and the model estimates of BC_{dep} (Fig. 11c, d) thus suggest the neutralization impact of base cation deposition from oil sands sources will be limited in spatial extent. A circle with radius 140 km around the oil sands emissions region appears on the maps of critical load exceedance in Sect. 3.6, to serve as a visual guideline of this observation-based cross-over distance between base cation neutralization and acidification.

The estimates of BC_{dep} from Fig. 11b and d are shown as ratios to the base cation catchment export flux (Fig. 11a) in Fig. 13a, b, respectively. The ratios are usually less than unity (blue shades) indicating that contributions aside from BC_{dep} control the base cation budget, while regions where BC_{dep} is greater than the observation-based total base cation export in catchment water (red shades) occur in the centre of the oil sands region and in part of northern Saskatchewan. The latter indicate regions where atmospheric base cation deposition is expected to exceed catchment export in surface water, and hence where accumulation of base cations may occur over time, resulting in neutralization. The measured in situ concentrations in surface water (cf. Cathcart et al., 2016), combined with our model estimates of S_{dep} and N_{dep} indicate that at the current time this potential accumulation is insufficient to counteract much of the exceedances of critical loads (see following sections). However, we note that these regions may warrant further future water sampling to monitor changes in base cation concentrations, due to their potential for future neutralization.

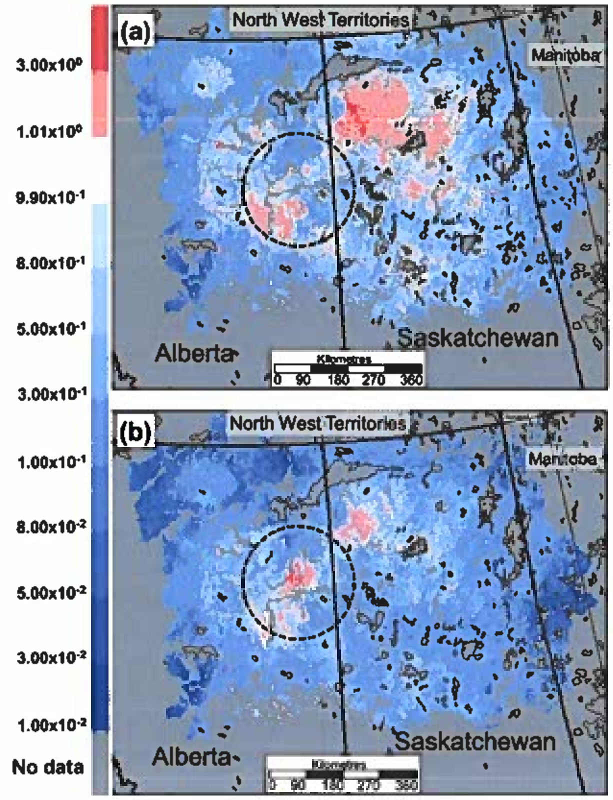

Figure 13. Ratio of estimates of base cation deposition to base cation fluxes exiting aquatic ecosystems. **(a)** Ratio of interpolated/extrapolated base cation flux from 1994 to 1998 observations to aquatic base cation flux. **(b)** Ratio of model-generated and precipitation and aircraft-based corrected base cation flux to aquatic base cation flux. Circled region: 140 km radius diameter circle around the Athabasca oil sands.

3.6 Estimates of critical load exceedances

We now estimate critical loads and their exceedances, using both uncorrected and observation-corrected model estimates of S_{dep}, N_{dep}, and BC_{dep}, along with the different sources of critical load data and methodologies described above. The data of Wang et al. (2015) showed that the equivalent units sodium fraction of BC_{dep} was 4.3 %, so we assumed $BC_{dep} = 0.957\ BC_{dep}$, in the work which follows.

3.6.1 Exceedances of forest and terrestrial ecosystem critical loads

The forest critical load exceedances for $S_{dep} + N_{dep}$ calculated using the upper limit NGE-ECP (2001) critical load estimates (Canada-wide data, Eqs. 1 and 17), and the full CLRTAP (2017) calculation methodology (Alberta data), are shown in Figs. 14 and 15, respectively. All critical load exceedances in this section are depicted using the same logarithmic colour scale for easy cross-comparison: red regions represent exceedances, and blue regions are below exceedance. Lighter coloured shades are closer to net neutral conditions. Each critical load exceedance figure includes the total area in exceedance, and its percentage compared to the area of available critical load data. The portions of the model domain which do not coincide with the given dataset are depicted as "no data", in grey.

Figure 14 shows the predicted levels of exceedance using different S_{dep}, N_{dep}, and BC_{dep} estimates. Figure 14a shows the predicted exceedances when the 1994–1998 BC_{dep} values inferred from Canada-wide station observations are used (those stations within the 2.5 km model domain appear as yellow diamonds). Figure 14b shows the predicted exceedances using the model's uncorrected values of BC_{dep}, S_{dep}, and N_{dep}. Figure 14c shows the predicted exceedances using precipitation and aircraft-based deposition fluxes. The different deposition estimates result in a factor of 7 variation in the predicted area of exceedance, with the observation-corrected values having the smallest area at $1.20 \times 10^4\ km^2$ in exceedance, or about 1 % of the total (coloured) area of available critical load data. The strong impact of the model's spatially distributed base cation field and the precipitation-observation reduction in S_{dep} may be seen by comparing Figs. 14b and c. Within the 140 km radius circle centered on the Athabasca oil sands, acidification is predicted by the original model fields constructed using the reported emissions (Fig. 14b), while most of this region is neutralized with the scaling of model values to match observations (Fig. 14c). Many of the other exceedance regions of Fig. 14b are greatly reduced in size with the scaled information (Fig. 14c). Nevertheless, the size of the total region in exceedance of critical loads for forest ecosystems across the entire domain using the NGE-ECP (2001) methodology, designed to create a lower estimate of critical load exceedances, is still considerable, about the size of Qatar ($1.14 \times 10^4\ km^2$).

The terrestrial ecosystem critical load exceedances for the same estimates of BC_{dep}, N_{dep}, and S_{dep}, for the Alberta data using the full CLRTAP (2017) methodology appear in Fig. 15a, b, c. While the critical load data in this case are only available for the province of Alberta itself, the regions of exceedance within that province are larger than the estimates of the NGE-ECP (2001) methodology. The influence of the precipitation observation and aircraft-based corrections on model-estimated deposition are evident, comparing Fig. 15c to Fig. 15a, b, particularly within 140 km distance of the oil sands. The increases in BC_{dep} and decreases in S_{dep} result in exceedances falling below zero in the central part of the circled region within the province of Alberta, and being reduced in magnitude elsewhere. However, it is important to note that despite these corrections, predicted exceeded areas nevertheless have a significant spatial extent, within some parts of the 140 km radius, and remain spatially significant outside of that zone (Fig. 15c). The total within-Alberta area in exceedance for terrestrial ecosystem critical loads using the corrected fields is $7 \times 10^4\ km^2$ (roughly equivalent in spatial

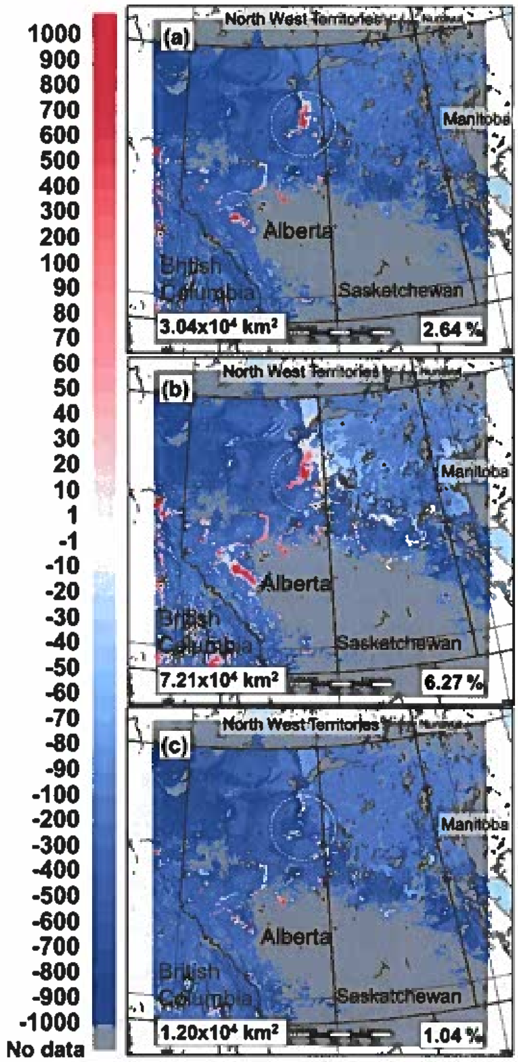

Figure 14. Predicted forest ecosystem critical load exceedances with respect to acidity (S + N deposition), using NEG-ECP (2001) methodologies (eq ha^{-1} yr^{-1}). White to red regions: exceedance, white to blue regions: below exceedance. **(a)** GEM-MACH S + N deposition, interpolated and extrapolated base cation deposition from 1994–1998 observations. Station locations for base cation observations are shown as yellow diamonds. **(b)** GEM-MACH S + N deposition, model base cations from reported emissions of crustal material and Wang et al. (2015) cation fractionation. **(c)** GEM-MACH S + N deposition scaled according to precipitation observations, base cations scaled using precipitation and aircraft data Lower left of each panel: total area in exceedance, in km^2. Lower right of each panel: percentage of the entire critical load data area which is in exceedance. Circled region: 140 km radius diameter circle around the Athabasca oil sands.

extent to Ireland, and accounting for about 10 % of the area of the province of Alberta).

The total area of exceedance falling within each of the four regions described in Sect. 2.3.1 and Fig. 2, along with the percentage of the total area in exceedance, are shown in the boxed portion of each panel of Fig. 16. Exceedances predominantly occur in Region 2 in all cases, suggesting that both S_{dep} and N_{dep} are contributing most frequently to the total exceedance. The BC_{dep} field in Fig. 16b is in general lower than for Fig. 16a, resulting in lower values of CL_{max} (N), and a greater proportion of Region 1 exceedances in Fig. 16b compared to Fig. 16a. In Fig. 16c, both BC_{dep} and N_{dep} have increased; while the total region in exceedance has decreased, the relative proportion within Region 1 between Fig. 15b and c therefore remains almost unchanged. The proportion of the terrestrial ecosystems where exceedances are with respect to S_{dep} alone (Region 4) is the smallest for the exceedance estimate using observation-based corrections of S_{dep}, N_{dep}, and BC_{dep} (Fig. 16c).

Figure 16 presents possible avenues to reduce the impacts of deposition. Areas within Regions 1, 2, and 3 with respect to Fig. 2 may be brought below exceedance levels through a combination of reductions in S_{dep} and N_{dep}, the relative magnitude of each depending on the location of the current N_{dep}, S_{dep} in Fig. 2, with more than one reduction strategy often possible. However, areas within region 4 may only be brought below exceedance by reductions in S_{dep}. Figure 16 thus may be of use to policy-makers in determining strategies to reduce deposition to levels below critical load exceedance.

3.6.2 Exceedances of aquatic ecosystem critical loads

SSWC model: Canada-wide versus Alberta and Saskatchewan critical load datasets

As noted earlier, aquatic ecosystems tend to be more sensitive to acidifying precipitation (i.e. have lower critical loads) than the forest/terrestrial ecosystems. Exceedances with respect to S_{dep}, calculated using Eq. (5), for the Canada-wide and the Alberta and Saskatchewan critical load data, are shown in Figs. 17 and 18, respectively. Unlike the forest and terrestrial ecosystem critical loads, the base cations of the SSWC model are derived from observations of surface water; hence, only the observation-based corrections to S_{dep} are applied to these figures. Figures 17 and 18a thus use the uncorrected model S_{dep}, while panel (b) of each figure uses the precipitation-observation-based S_{dep} correction discussed earlier.

The Canada-wide data (Fig. 17) cover a smaller spatial extent, and utilize a coarse 45 km resolution superimposed on the 2.5 km resolution of GEM-MACH; spatial variation of the exceedances within the 45 km squares are thus the result of variations in the 2.5 km S_{dep} values. The S_{dep} correction reduces the critical load exceedance percentage area in both cases (from 24.9 to 15.9 % for Fig. 17, and from 79.6 to 47.1 % in Fig. 18). Aquatic ecosystems in the more recent of the two datasets (Fig. 18) are clearly more sensitive than the older data (Fig. 17); the use of more recent water sampling observations, and georeferenced soil and other

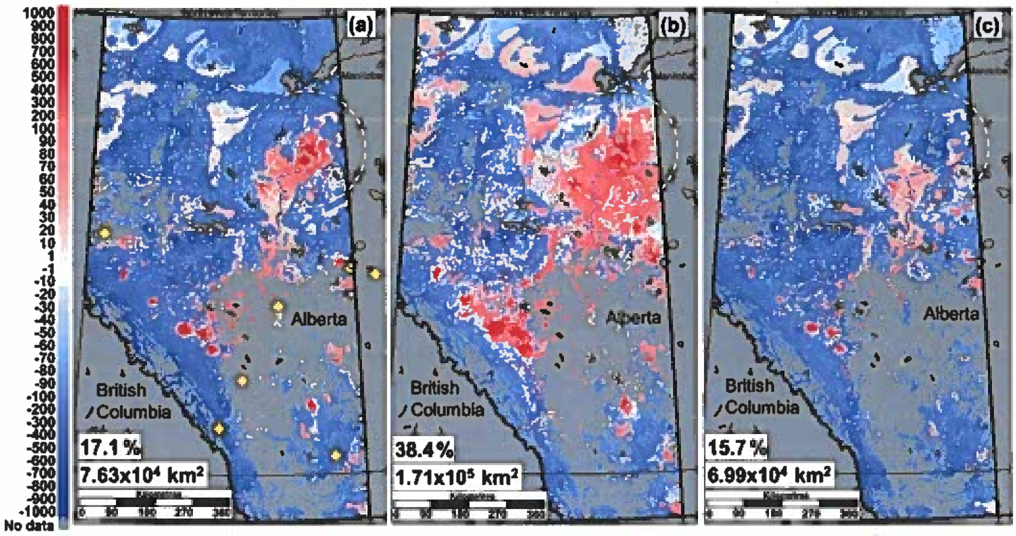

Figure 15. Predicted terrestrial ecosystem critical load exceedances with respect to sulfur and nitrogen (eq ha^{-1} yr^{-1}), Alberta Environment and Parks data. **(a)** GEM-MACH S and N deposition, 1994–1998 observed base cation deposition. Observation stations shown as yellow diamonds. **(b)** GEM-MACH S and N deposition, NPRI/Wang et al. (2015) base cation deposition. **(c)** GEM-MACH S and N deposition, base cation deposition scaled according to aircraft and precipitation-based corrections. Circled region: 140 km radius diameter circle around the Athabasca oil sands.

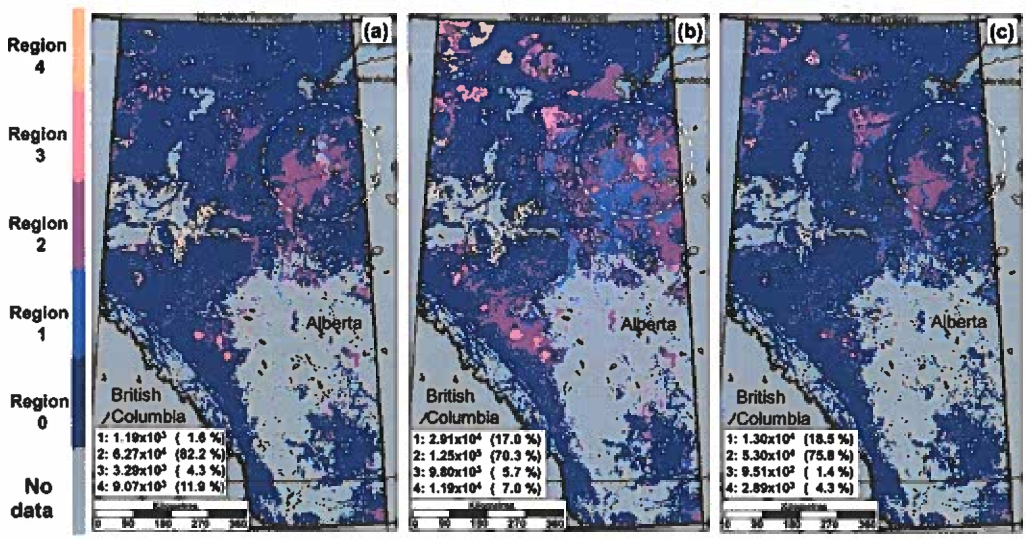

Figure 16. Predicted sub-types of terrestrial ecosystem critical load exceedance (see Fig. 2), with panels arranged as in Fig. 15. Inset information shows the area within S + N exceedance sub-types 1, 2, 3, and 4 (km^2) and the corresponding percentage of the total area of exceedance. Circled region: 140 km radius diameter circle around the Athabasca oil sands.

data, have resulted in critical load estimates being somewhat lower than the earlier data (compare also Figs. 3a and 5b). The georeferenced data (Fig. 18) also give a more complete spatial coverage for the region, allowing greater local detail, but also showing that portions of the region for which no data were previously available (e.g. grey areas in northern Saskatchewan, Fig. 17) are likely to be in exceedance of critical loads for S_{dep} (corresponding regions in Fig. 18).

The lower estimates of the net area of the exceedance region in these two figures is 7.8×10^4 km^2 for the older critical load data, and 3.3×10^5 km^2 for the new georeferenced critical load data. The former area is roughly equivalent to that of the Czech Republic (7.9×10^4 km^2), the latter that of Germany (3.6×10^5 km^2).

It is worth noting here that the extent of neutralization implied by comparing the atmospheric deposition of base

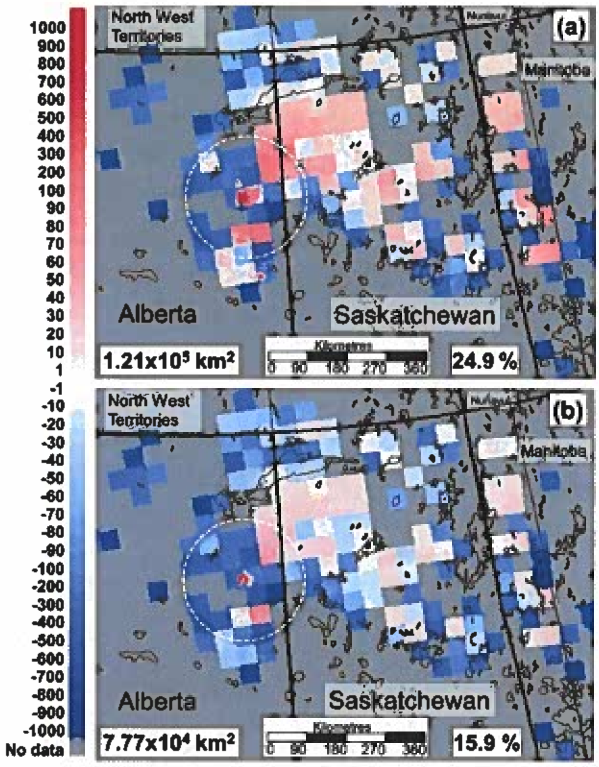

Figure 17. Predicted lake ecosystem critical load exceedances with respect to S_{dep}, NEG-ECP (2001) methodology (eq ha^{-1} yr^{-1}). **(a)** Exceedances calculated using original GEM-MACH S_{dep}. **(b)** Predicted exceedances calculated using GEM-MACH S_{dep} scaled using precipitation deposition observations. Circled region: 140 km radius diameter circle around the Athabasca oil sands.

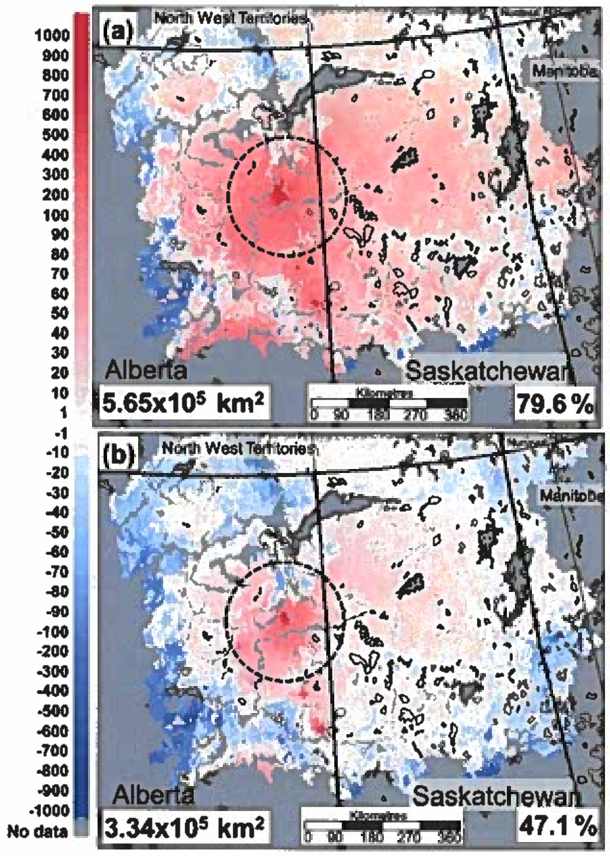

Figure 18. Predicted aquatic ecosystem critical load exceedances with respect to S_{dep}, CLRTAP (2017) methodology (eq ha^{-1} yr^{-1}). **(a)** Exceedances with uncorrected model S_{dep}. **(b)** Predicted exceedances with model S_{dep} corrected to match precipitation observations. Circled region: 140 km radius diameter circle around the Athabasca oil sands.

cations (BC_{dep}) to S_{dep} and N_{dep} does not seem to be reflected in the lake water samples used to create the critical loads used in Figs. 17 and 18, although some effects due to oil sands fugitive dust deposition may be seen in the observation-corrected exceedance estimates for the areas on the northern side of the oil sands (blue regions Figs. 17b and 18b, northern end of the circled region in each figure). The estimated export of base cations from catchments is usually higher than the BC_{dep} values (see Figs. 11 and 12 and related discussion), implying a net loss of deposited base cations. However, some areas within the domain have higher predicted base cation deposition than observed export in surface waters, indicating the potential for an accumulation of base cations over time. This implies a potential lag time between atmospheric deposition and surface water response.

FAB model: exceedances with respect to $N_{dep} + S_{dep}$ for aquatic ecosystem critical loads

The exceedances for aquatic ecosystems with respect to both N_{dep} and S_{dep} are shown in Fig. 19, using the original (Fig. 19a) and precipitation-observation-corrected (Fig. 19b) model fields for N_{dep} and S_{dep}. The total area of exceedance again decreases with use of the observation-corrected fields (though not to the same degree as Fig. 18). The total area in exceedance is similar to the SSWC results (decreasing slightly for the original model S_{dep} and N_{dep}, and increasing slightly for the corrected fields: compare panels (a) and (b) between Figs. 18 and 19). The FAB model critical loads suggest deposition significantly below exceedance takes place in specific lakes (dark blue, Fig. 19), while the SSWC model (Fig. 18) suggests a more smoothly distributed variation between exceedance and non-exceedance regions.

Both the SSWC and FAB exceedance estimates show the oil sands region as a prominent "hotspot" of aquatic critical load exceedance, with an influence extending far beyond the 140 km circle shown in Figs. 18 and 19. Exceedances to aquatic ecosystem critical loads are predicted as far east as northern Manitoba, and into the Northwest Territories on the northern end of the data region. The exceedances using the uncorrected model deposition estimates are roughly

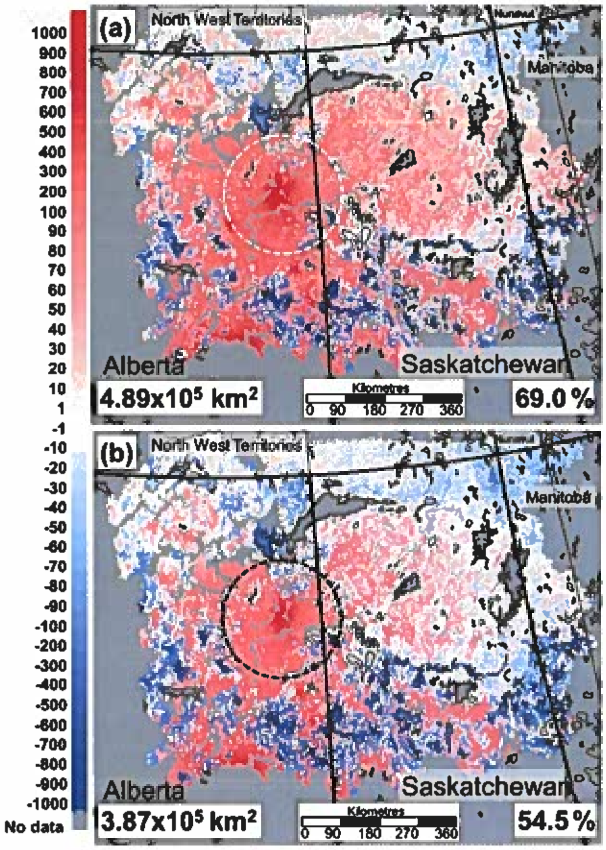

Figure 19. Predicted aquatic ecosystem critical load exceedances with respect to sulfur and nitrogen deposition, (eq ha^{-1} yr^{-1}). Boxed numbers are the area in exceedance and the percent of the total area for which critical loads are available which is in exceedance. **(a)** Calculated using original model sulfur and nitrogen deposition. **(b)** Calculated using model sulfur and nitrogen deposition corrected to match precipitation observations. Circled region: 140 km radius diameter circle around the Athabasca oil sands.

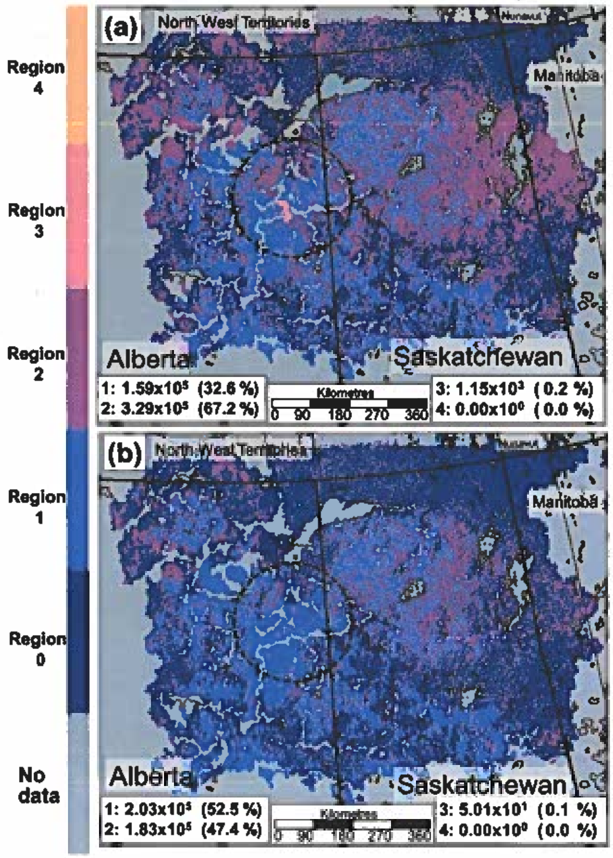

Figure 20. Predicted sub-types of aquatic ecosystem critical load exceedance (see Fig. 2), with respect to deposition of sulfur and nitrogen deposition. Boxed numbers give the area in exceedance within each of exceedance sub-types 1, 2, 3, and 4 (km^2) and the corresponding percentage of the total area in exceedance. **(a)** Calculated using original model sulfur and nitrogen deposition estimates. **(b)** Calculated using model S_{dep} and N_{dep} estimates corrected to match precipitation observations. Circled region: 140 km radius diameter circle around the Athabasca oil sands.

equivalent in size to Spain (5.0×10^5 km^2), while the exceedances using the observation-corrected model deposition are closer to the size of Germany (3.6×10^5 km^2). By comparison, Alberta and Saskatchewan have areas of 6.6×10^5 and 6.5×10^5 km^2, respectively: the predicted area in exceedance of aquatic ecosystem critical loads is a significant fraction of the spatial extent of these provinces.

Figure 20 shows that most of the exceedances for aquatic ecosystems reside within Regions 1 or 2 with respect to the regions shown in Fig. 2, and thus may be brought to below exceedance conditions by different combinations of reductions in S_{dep} and N_{dep}, depending on the location of the current N_{dep}, S_{dep} in Fig. 2.

4 Discussion

The critical load exceedance calculations described in the previous section were carried out with the best currently available datasets and modelling tools. However, the work has also identified limitations of those sources of information, which, if improved, would lead to improved critical load exceedance predictions. In addition, while the calculations identify the potential for ecosystem damage to be taking place now or at some point in the future, additional analysis would be required to estimate the time span to the occurrence of that damage, or to subsequent recovery. We discuss these issues, and make specific recommendations for future work, below.

Clearly, better estimates of the emissions of primary particulate matter and their base cation fractionation are needed, as well as additional ambient concentration and deposition observations of the species contributing to S_{dep}, N_{dep} and BC_{dep} in sensitive regions. We have attempted to correct model results using the available data: comparisons between modelled and observed deposition, and the impact of aircraft-based estimates of base cation emissions on deposition. Combined, these corrections greatly reduce the bias and improve the correlation fit between observed and estimated base cation deposition to snowpack in the vicinity of the oil sands in winter. Observation-corrected model BC_{dep} values are therefore recommended for future critical load exceedance work. However, in the region examined here, this combined correction amounts to a twenty-five fold increase in base cation emissions relative to the reported values for oil sands sources. We note that the increase may represent underestimates of primary particulate matter emissions by mass, and/or a higher base cation fractionation of that mass than was observed in surface dust collected by Wang et al. (2015). Additional measurement-based estimates of speciated primary particulate emissions and ambient concentrations are required to carry out exceedance calculations with improved model performance.

Other work (Whaley et al., 2018) has suggested that bidirectional fluxes of ammonia in the boreal forest region may be taking place, and would account for GEM-MACH underestimates in the column ammonia concentration relative to satellite and aircraft observations. Further research is needed to improve bi-directional flux parameterizations (the parameterization used in the given case improved ammonia performance for the boreal forest, but decreased it for agricultural regions). However, we also note that the bidirectional flux system will result in increased "natural" ammonia fluxes from land, but will not result in upward fluxes of ammonia over water. We have carried out tests which suggest that bidirectional fluxes of ammonia will increase the net flux of ammonia to water-covered surfaces, and hence the net N_{dep} to aquatic ecosystems calculated in the current work should be considered a lower estimate.

As noted earlier, exceedances to critical loads indicate the *potential* for ecosystem damage, but not the timeline over which damage may be expected to occur or has occurred, the time to ecosystem recovery (if acidifying deposition is reduced), or the magnitude of the ecosystem impacts of exceedance. These time estimates may be obtained with the use of dynamic models (CLRTAP, 2017), and their use is recommended for targeted studies in the areas we have predicted to be in exceedance of critical loads. These dynamical modelling studies should be accompanied by measurements in the same specific exceedance areas. In past observational studies of lakes in the environs of the Athabasca oil sands (Hazewinkel et al., 2008; Curtis et al., 2010; Laird et al., 2013), 2 out of 20 lakes were found to show signs of acidification. These observation locations are depicted in Fig. 21, overlaid on the map of exceedances for aquatic ecosystems with respect to S_{dep} of Fig. 18b. Lake sediments

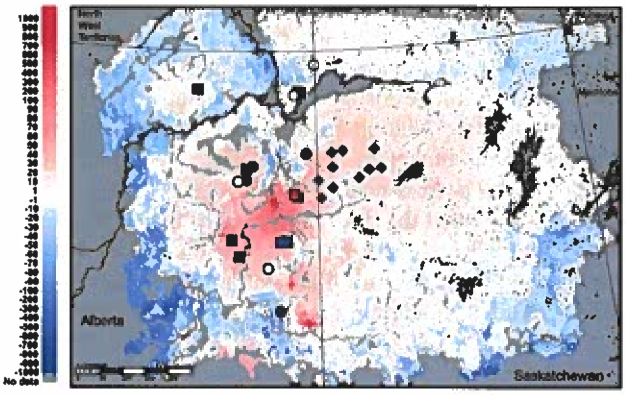

Figure 21. Comparison of predicted exceedances with model S_{dep} corrected to match precipitation observations (Fig. 18b, units eq ha^{-1} yr^{-1}) with lake observation data of Hazewinkel et al. (2008) (circles), Curtis et al. (2010) (squares) and Laird et al. (2013) (diamonds). Blue symbols: sample locations showing no acidification at the current time, white symbols: locations with decreasing pH, but within natural variability; red symbols: locations where signs of acidification were detected. Note that the colour of the symbols, which are for illustration purposes only, does not correspond to numerical exceedance values on the colour scale.

from four locations (white symbols, Fig. 21) were found to have increasing levels of acidity, but within natural variability (Hazewinkel et al., 2008), two lakes (red symbols, Fig. 21) were found to have undergone recent acidification (Curtis et al., 2010; Laird et al., 2013), and the remaining locations (blue symbols, Fig. 21) were not found to be acidifying. However, the sediment core stratigraphy within the region was found to be "broadly consistent with increased anthropogenic pressures in the region" (Hazewinkel et al., 2008), and an examination of 50 years of six lake sediment cores found evidence of a factor of 2.5 to 23 increase in the flux of polycyclic aromatic hydrocarbons since the 1960s (Kurek et al., 2013). One of the acidifying lakes was noted to be relatively shallow and in peaty soil, with the implication that similar lakes may show the effects of acidification first (Curtis et al., 2010). Twelve lake sediment cores showed that the signs of ecological changes such as sediment enrichment have been increasing over the last 3 decades, and increased phosphorus concentrations in several lakes were attributed to the dry deposition of NO_x ($=NO + NO_2$) and other forms of N_{dep} (Curtis et al., 2010). However, a study of sediment cores from 15 non-acid-sensitive lakes in northern Saskatchewan did not show evidence of lake enrichment by N_{dep}, based on analysis of algal communities (Laird et al., 2017; Mushet et al., 2017). Our calculations of aquatic critical load exceedances imply that acidification will eventually occur; Fig. 21 highlights the need for ongoing monitoring of aquatic ecosystems in this region. Dynamical modelling (CLRTAP, 2017) would also aid in prioritizing locations for further studies to quantify acidifying effects.

Future GEM-MACH simulations should include the full 12-bin particle size distribution rather than the more computationally efficient operational forecast 2-bin particle size distribution used here for the annual simulation, in order to better capture the variation in base cation particle deposition with distance as a function of particle size. We also note that the 142 km drop-off distance associated with BC_{dep} shown here is a function of the size distribution of the emitted fugitive dust particles – while our expectation is that the bulk of fugitive dust emissions are likely to be in the coarse mode (sizes greater than 2.5 mm diameter) as they are here; differences in the initial size distribution may lead to different decrease functions with distance from fugitive dust sources. However, a general result from our findings is that fugitive dust base cation neutralization will be limited in spatial scope, due to the effect of particle deposition increasing with increasing size in the coarse mode.

New measurement studies are needed in order to acquire the data to improve the current parameterizations used for estimating deposition velocities, particularly for gas-phase dry deposition. For example, most current parameterizations are based on direct observations of SO_2 and O_3, with deposition parameters for other gases being inferred by indirect means, and the temperature dependence of deposition to snowpack has been measured directly for only two species, SO_2 and HNO_3 (see Supplement). Future work to characterize gas deposition, particularly under cold conditions, is therefore recommended. Snowpack deposition observations should attempt to measure both "throughfall" and "open" deposition, in order to more accurately estimate total deposition to snow-covered vegetation.

5 Summary and conclusions

Our work has predicted that critical loads for acidifying deposition will be exceeded in the provinces of Alberta and Saskatchewan, for both terrestrial and aquatic ecosystems. Model predictions indicate that total deposition downwind of sources is dominated by the wet component. Model comparisons of sulfur, nitrogen, and base cation deposition with observations indicate that the model has some skill in accounting for the observed variability in wet deposition (R^2 of 0.90, 0.76, and 0.72, respectively). We therefore used the model versus observation linear relationships from wet deposition to provide a correction to model values for total deposition of sulfur, nitrogen, and base cations. Aircraft-based estimates of primary particulate matter emissions were shown to result in a factor of 10 increase in atmospheric base cation deposition close to the oil sands emissions regions, and corrections for base cation deposition based on these estimates were also incorporated into our investigation of exceedances. Making use of both the original model predictions and the corrected fields, exceedances of critical loads were calculated using simplified methodologies designed to provide lower-limit estimates of exceedances (NEG-ECP, 2001) and more rigorous methodologies to take into account additional factors such as ecosystem buffering capacity (CLRTAP, 2017). While atmospheric base cation deposition was shown to have a significant neutralizing impact for terrestrial ecosystems close to the sources of fugitive dust emissions, this effect was shown in both observations and model results to drop off rapidly with distance in comparison to the size of the predicted areas of aquatic critical load exceedance, in accordance with well-known physics controlling the deposition velocities of atmospheric particles as a function of their size. Exceedances were predicted further downwind, despite these corrections to the original model estimates (which include an assumed factor of 25 increase in primary particulate matter emissions from oil sands sources, relative to reported emissions). Aquatic ecosystem critical load data suggest that the base cation loading within catchment waters is insufficient to counteract much of the atmospheric deposition of sulfur and nitrogen. The results thus indicate that potential ecosystem damage may be taking place, due to acidifying deposition in the provinces of Alberta and Saskatchewan. The use of dynamic models to determine the timelines until damage occurs and/or recovery may take place, and observational studies for the presence of ecosystem damage, are recommended for future work, with a focus on the highest exceedance regions predicted here. Further observations of deposition of sulfur, nitrogen, and size-resolved base cations are also recommended, at distances greater than 140 km from the sources, to further evaluate and improve on our findings.

Specific results of our work include that the spatial extent of predicted exceedances of forest and terrestrial ecosystem critical loads ranges from 1×10^4 to 6.69×10^4 km^2 (10 % of the area of the province of Alberta), with the latter estimate based on the more comprehensive critical load calculation methodology.

The spatial extent of predicted exceedances of aquatic ecosystem critical loads in the region studied is larger than that of forest and terrestrial ecosystem critical loads. Estimates using both earlier lake observation data and more recent georeferenced data indicate that a significant fraction of northern Alberta and Saskatchewan lakes are predicted to be in exceedance. Some neutralization due to base cation levels in water observations may be occurring immediately to the north of the oil sands, but overall, exceedances are predicted over much of the north of the two provinces, and extend eastwards into Manitoba, for all three of the critical load datasets and methodologies employed here.

Our work suggests that other sources of base cations, aside from atmospheric deposition, usually controls the surface water base cation concentration. Our model results and our re-examination of the throughfall data of Watmough et al. (2014) suggests that the neutralization associated with base cation deposition from sources of fugitive dust in the oil sands area will be limited in spatial extent. Despite this near-source neutralizing effect, potential ecosystem damage associated with acidifying precipitation may take place further downwind. Nevertheless, our work demonstrates that both natural and anthropogenic base cation emissions may have a significant impact on, and should be included in, critical load exceedance calculations.

We predict that in some portions of the study region, base cation deposition from the atmosphere may exceed the estimated removal of base cations from catchments in water. While the observations of surface water ion content and estimates of the export of water from catchments used to create the critical loads employed here indicate that the base cation level in surface water is insufficient to counteract acidification, there exists the potential for this to change over time. Repeat measurements of catchment water in these regions of potential base cation buildup, and follow-up work to improve and evaluate catchment water export rates, are therefore recommended. Strategies to measure deposition to very acid-sensitive regions (e.g. exceedance (red) regions in Figs. 15c, 18b, and 19b), which are distant from existing conventional deposition monitoring sites, should be considered.

We have found that corrections of model estimates of S_{dep}, N_{dep}, and BC_{dep} using observations, and using direct observation-based emissions data for base cations, have a significant impact on model estimates of critical load exceedances. Here, relatively simple corrections using model–observation relationships were employed. We note that other means of model–measurement fusion for acidifying pollutants are under investigation, and show great promise for creating observation-corrected air-quality model deposition fields (e.g. Robichaud et al., 2018).

Data availability. The aircraft observations used in this study are publicly available on the ECCC data portal (ECCC, 2018a). The precipitation monitoring network data are publicly available from the Canadian Acid Precipitation Monitoring Network (CAPMoN, 2018). Snowpack data are accessible by email request to Jane Kirk (jane.kirk@canada.ca) and Ken Scott (kscott@gov.sk.ca). The model results are available upon request to Paul Makar (paul.makar@canada.ca). GEM-MACH, the atmospheric chemistry library for the GEM numerical atmospheric model (©2007–2013, Air Quality Research Division and National Prediction Operations division, Environment and Climate Change Canada), is a free software which can be redistributed and/or modified under the terms of the GNU Lesser General Public License as published by the Free Software Foundation – either version 2.1 of the license or any later version. The specific GEM-MACH version used in this work may be obtained on request to paul.makar@canada.ca. Many of the emissions data used in our model are available online at ECCC (2018b, c) and more recent updates may be obtained by contacting Junhua Zhang or Mike Moran (junhua.zhang@canada.ca; mike.moran@canada.ca). The critical load data used in this work are available from Environment and Climate Change Canada, by email request to Amanda Cole (amanda.cole@canada.ca) and Alberta Environment and Parks, by email request to Yayne-abeba Aklilu (yayne-abeba.aklilu@gov.ab.ca). Gridded shapefiles of the model output, along with critical load values, and critical load exceedances used to generate this work on the 2.5 km GEM-MACH domain may be obtained by email request to Paul Makar (paul.makar@canada.ca).

The Supplement related to this article is available online at https://doi.org/10.5194/acp-18-9897-2018-supplement.

Author contributions. PAM: study concept and design, analysis of model output and critical load exceedances, writing of manuscript and modifications of same; AA: GEM-MACH simulations, assistance with model evaluation and analysis; JA: critical load data section of text, provision of aquatic ecosystem critical loads; ASC: preparation of precipitation deposition data, assistance with new and historical aquatic critical load data sections of manuscript; YA: AEP terrestrial ecosystem critical load data and description and AEP precipitation data; JZ: creation of emissions files used in the model,; IW: provision of ECCC lakes and forest critical load data; KH and SML: provision of aircraft data; JK: provision of ECCC snowpack data and text on same; KS: provision of Saskatchewan Environment snowpack data and text on same; MDM: assistance with emissions data for model; AR: creator of the gas-phase dry deposition module in GEM-MACH, and assistance with Supplement 1 text; HC: creation and provision of aquatic critical load data; PB: assistance with generation of emissions data; BP and PC: assistance with GEM-MACH setup, model simulations; QZ: assistance with emissions generation. In addition, the first author would like to thank all co-authors for extensive comments on different versions of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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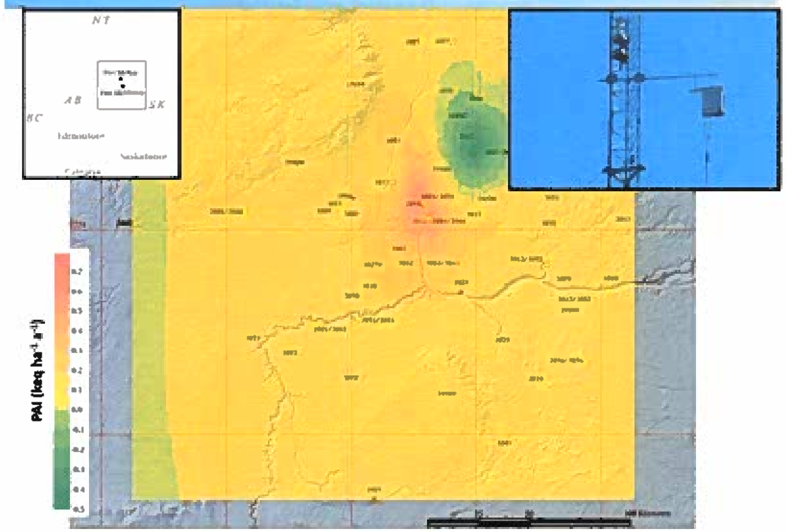
3.2.5 Acid deposition monitoring in the Athabasca oil sands region

"Ambient concentrations and total deposition of inorganic sulfur, inorganic nitrogen and base cations in the Athabasca Oil Sands Region"

- A region-wide passive sampling network was established in 1998–99 to monitor above-canopy concentrations of SO_2, NO_2, O_3, HNO_3 and NH_3 at Forest Health Monitoring (FHM) sites.
- A second network was established in 2008 to measure bulk and throughfall deposition of inorganic acids and base cations at FHM sites
- A third network was established in 2013–17 to measure above canopy concentrations of gases and $PM_{2.5}$ composition at several solar-powered FHM sites.
- Together, these networks provide a dense array of measurements for examining patterns and trends of deposition and air quality.

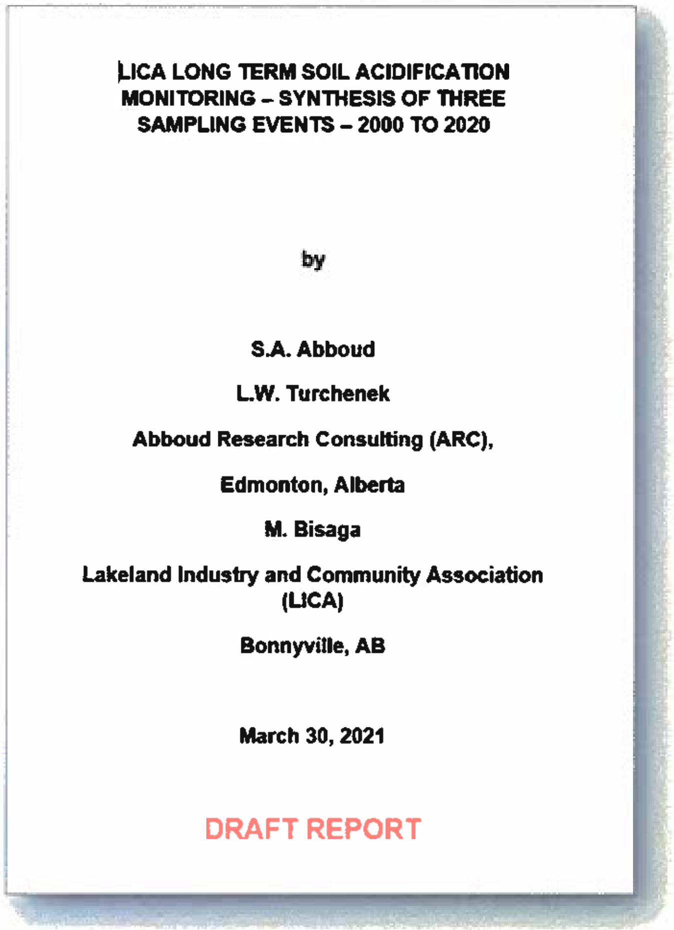
Potential Acid Input (PAI) Exhibits Significant Variability across Jack Pine Sites within the AOSR



3.2.6 Regional soil acidification monitoring results overview

"LICA Long Term Soil Acidification Monitoring – Synthesis Of Three Sampling Events – 2000 To 2020"

- LICA initiated soil acidification monitoring in 2010 by establishment of three long-term soil sampling plots within the LICA area
  - Moose Lake Provincial Park in 2010
  - Whitney Lakes Provincial Park in 2011
  - Crown Land near Tucker Lake in 2012
- Soil sampling is being carried out at these plots every four years in a staggered manner (one site per year).
- A fourth site, located near the west shore of Cold Lake and operated by Alberta Environment, was added to the LICA sites in the analysis of monitoring results to date.


LICA LONG TERM SOIL ACIDIFICATION MONITORING – SYNTHESIS OF THREE SAMPLING EVENTS – 2000 TO 2020

by

S.A. Abboud

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Edmonton, Alberta

M. Bisaga

Lakeland Industry and Community Association (LICA)

Bonnyville, AB

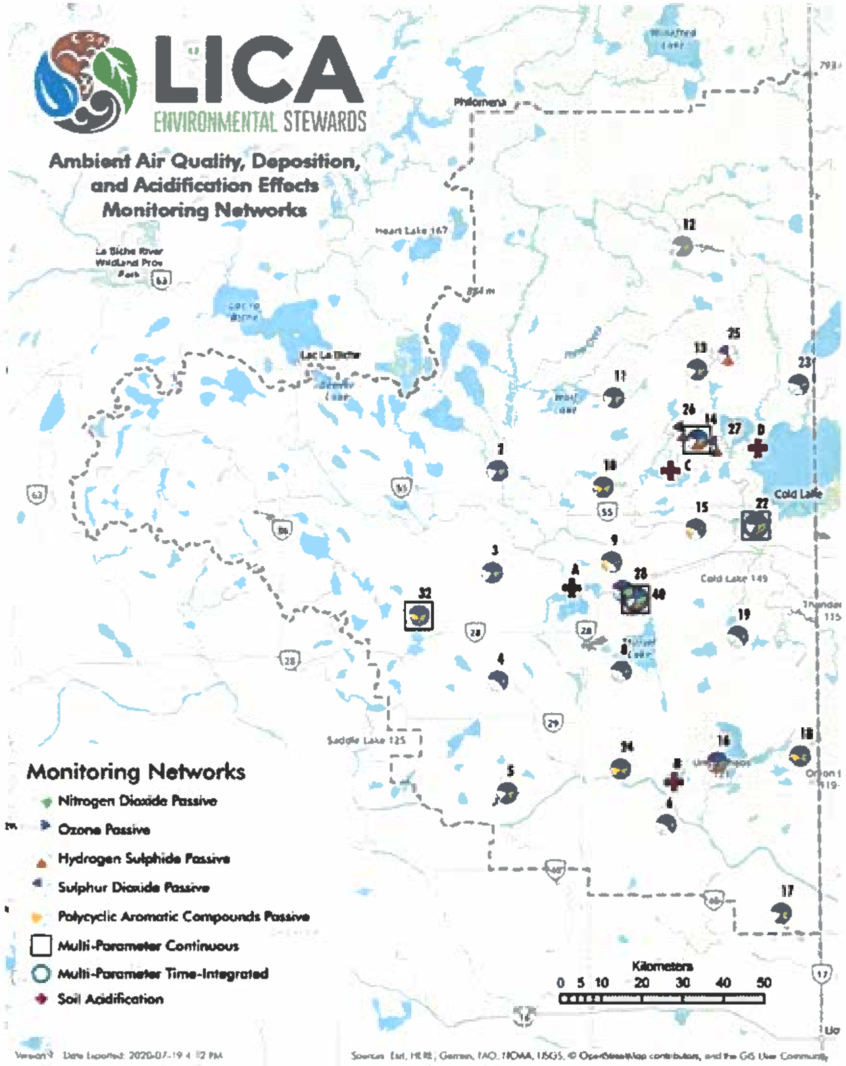
March 30, 2021

DRAFT REPORT

Summary of Results

- Some indications of acidification among the LICA sites were found mainly for Tucker Lake **(C)** and Moose Lake **(A)** sites. No indications were found for Whitney Lakes **(B)** site.
- Overall, interpretations are challenging with results from just three monitoring events at the LICA sites to date.
- After eight monitoring events, the LTSAM Cold Lake **(D)** site showed acidification trends since initiation of monitoring in 1982.
- Measurements of pHc provide the strongest evidence for acidification, supported to some extent by total sulphur measures.
- Currently, in discussion with ECCC on how these monitoring data can be used in GEM-MACH modeling

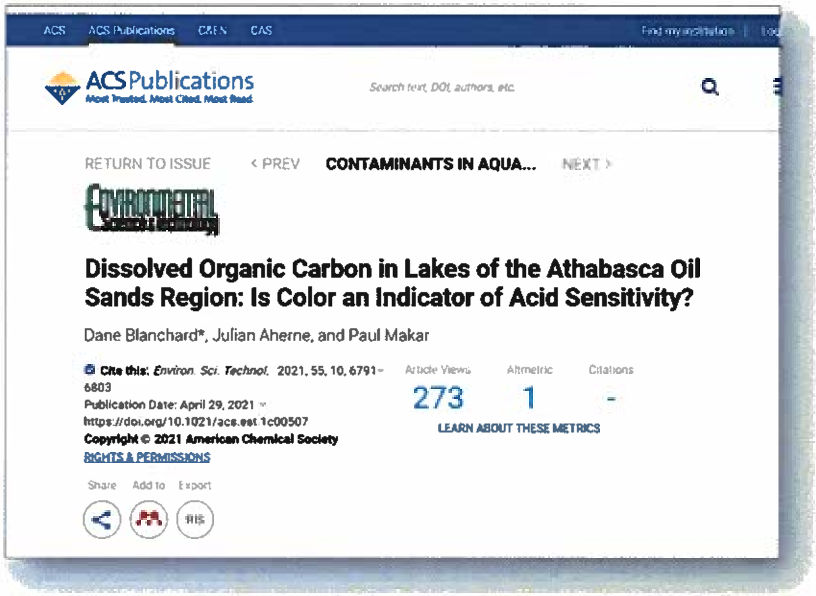
Monitoring Station Identification					
2	Sand River	13	Primrose	25	Burnt Lake
3	Therien	14	Maskwa	26	Mahihkan
4	Flat Lake	15	Ardmore	27	Mahkeses
5	Lake Eliza	16	Frog Lake	28	Bonnyville
6	Telegraph Creek	17	Clear Range	32	St. Lina
8	Muriel - Kehewin	18	Fishing Lake	40	Bonnyville East - Charlotte Lake
9	Dupre	19	Beaverdam	A	Moose Lake Soil Plot
10	La Corey	22	Cold Lake South	B	Whitney Lakes Soil Plot
11	Wolf Lake	23	Medley - Martineau	C	Tucker Lake Soil Plot
12	Foster Creek	24	Fort George	D	Cold Lake Fish Hatchery Soil Plot



3.2.7 Approaches to surface water acidification monitoring site selection (novel)

"Dissolved Organic Carbon in Lakes of the Athabasca Oil Sands Region: Is Color an Indicator of Acid Sensitivity?

- Surface-water data from 50 lakes were analyzed in Athabasca Oil Sands Region.
- Variables known to be associated with the light-absorptive properties were evaluated in the context of lake acidification and buffering capacity.



Environmental Science & Technology

Dissolved Organic Carbon in Lakes of the Athabasca Oil Sands Region: Is Color an Indicator of Acid Sensitivity?

Dane Blanchard*, Julian Aherne, and Paul Makar

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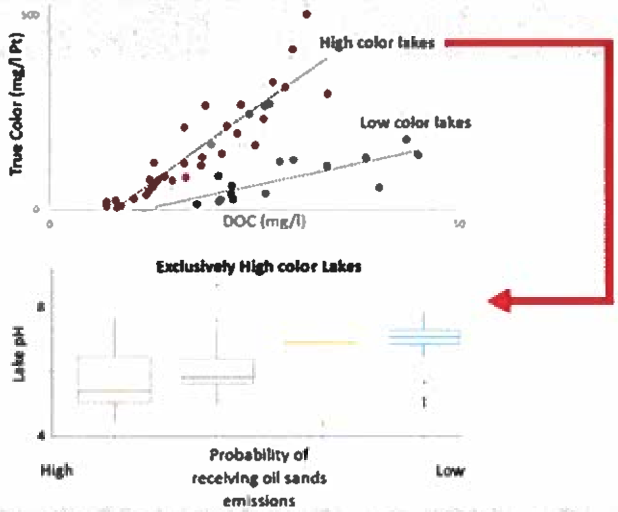
https://doi.org/10.1021/acs.est.1c00507

SUBJECTS: Lipids, Ions, Dissolved organic matter, Deposition, Basicity

Abstract



The Athabasca oil sands region (AOSR) in north-eastern Alberta, Canada, contains the world's third largest known bitumen deposit. Oil sands (OS) operations produce emissions known to contribute to acidic and alkaline deposition, which can alter the chemistry of the receiving surface waters, including dissolved organic carbon (DOC). Little is known regarding the natural variability of aquatic DOC among lakes within the AOSR. Surface-water data from 50 lakes were analyzed; variables known to be associated with the light-absorptive properties of DOC (true color [TC]) were evaluated to investigate the potential variability of chromophoric DOC (CDOC). Comparison of TC and DOC revealed two distinct "high" (H) and "low" (L) lake subpopulations, the former being characterized by high relative TC and low DOC, and the latter by the inverse. The H lakes were defined by variables known to be associated with CDOC, while L lakes appeared well-buffered potentially owing to groundwater inputs. The divergent optical properties between subpopulations appeared partially attributable to pH-limited Fe complexation. Trajectory analysis indicated that H lakes most likely to receive atmospheric deposition from OS sources experienced significantly lower pH. These results are contrary to previous studies that found OS emissions to have minimal acidifying effect over lakes throughout the AOSR.

KEYWORDS: Athabasca oil sands, atmospheric deposition, dissolved organic carbon

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c00507.

- Spearman correlation matrix, comparison of maximum lake depth and surface-water pH among ASL sites, boxplot, distribution of WPSCF values among ASL sites (Figures S1–S5); Spearman correlation analysis, summary of Mann–Kendall monotonic trend analysis (Tables S1 and S2) (PDF)

Dissolved Organic Carbon in Lakes of the Athabasca Oil Sands Region: Is Color an Indicator of Acid Sensitivity?

Supporting Information for

Dissolved Organic Carbon in lakes of the Athabasca Oil Sands Region: Is colour an indicator of acid sensitivity?

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7 pages containing 5 figures and 2 tables.

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Identify Other Sources

- 3.3.1 Round table on other considerations, information, and data sources

Next Steps and Proposed Approach for Monitoring Plan Development

- 3.4.1 Identification of data and information gaps
- 3.4.2 Desktop overlay of input sources: site selection screening