Atmospheric Environment xxx (2016) 1–10

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Critical loads of acidity for 90,000 lakes in northern Saskatchewan: A novel approach for mapping regional sensitivity to acidic deposition

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HIGHLIGHTS

- Regression kriging was used to map critical loads of acidity for ~90,000 lakes in northern Saskatchewan.
- A region greater than 13,500 km^2 was predicted to be very sensitive to acidic deposition.
- Predicted critical loads are low, with 5938 lakes <5 meq m^{-2} yr^{-1} and 23, 043 lakes <10 meq m^{-2} yr^{-1}.
- An estimated 12% of lakes are in exceedance of their critical loads under 2006 modelled sulphur deposition.

ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form
15 August 2016
Accepted 16 August 2016
Available online xxx

Keywords:
Acid rain
Sulphur dioxide
Critical loads
Regression-kriging
Steady state water chemistry (SSWC) model
Athabasca Oil Sands

ABSTRACT

Atmospheric emissions of sulphur dioxide (SO_2) from large point sources are the primary concern for acidic deposition in western Canada, particularly in the Athabasca Oil Sands Region (AOSR) where prevailing winds may potentially carry SO_2 over acid-sensitive lakes in northern Saskatchewan. A novel catchment-scale regression kriging approach was used to assess regional sensitivity and critical loads of acidity for the total lake population of northern Saskatchewan (89,947 lakes). Lake catchments were delineated using Thiessen polygons, and surface water chemistry was predicted for sensitivity indicators (calcium, pH, alkalinity, and acid neutralizing capacity). Critical loads were calculated with the steady state water chemistry model using regression-kriged base cations, sulphate, and dissolved organic carbon concentrations modelled from surface water observations ($n > 800$) and digital landscape-scale characteristics, e.g., climate, soil, vegetation, landcover, and geology maps. A large region (>13,726 km^2) of two or more indicators of acid sensitivity (pH < 6 and acid neutralizing capacity, alkalinity, calcium < 50 μeq L^{-1}) and low critical loads < 5 meq m^{-2} yr^{-1} were predicted on the Athabasca Basin. Exceedance of critical loads under 2006 modelled total sulphate deposition was predicted for 12% of the lakes (covering an area of 3742 km^2), primarily located on the Athabasca Basin, within 100 km of the AOSR. There have been conflicting scientific reports of impacts from atmospheric emissions from the AOSR; the results of this study suggest that catchments in the Athabasca Basin within 100 km of the AOSR have received acidic deposition in excess of their critical loads and many of them may be at risk of ecosystem damage owing to their sensitivity.

1. Introduction

Anthropogenic emissions of acidifying compounds such as sulphur dioxide (SO_2) have contributed to an acid rain problem in Canada for decades, causing biological damage to aquatic life and terrestrial ecosystems in eastern Canada (Schindler, 1988; Neary et al., 1990; Jeffries et al., 2003). As a result, SO_2 emissions in the east have declined steadily since 1985 owing to policy changes; in contrast, by 2006 emissions in the western provinces (British Columbia, Alberta, Saskatchewan, and Manitoba) overtook eastern Canada, driven primarily by emissions from large point sources such as smelters and mines (Environment Canada, 2014).

The largest point source of SO_2 and nitrogen oxides (NO_x) in Canada, the Athabasca Oil Sands Region (AOSR), is located in northern Alberta within 50 km of the Saskatchewan border.

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http://dx.doi.org/10.1016/j.atmosenv.2016.08.048
1352-2310/© 2016 Published by Elsevier Ltd.

Average AOSR SO_2 emissions were approximately 116,000 kT annually between 2002 and 2012 (Environment Canada, 2014) in a region with otherwise little background atmospheric SO_2. Prevailing winds are from the west, and the emissions footprint from the AOSR has been shown to extend into the north, and eastward into Saskatchewan (Hazewinkel et al., 2008; Kurek et al., 2013).

Downwind of the AOSR in northern Saskatchewan lie more than 90,000 lakes, rivers, and other bodies of water, many of which sit on extremely acid-sensitive granitic bedrock overlain with coarse, sandy soils. Historic surveys have broadly mapped this region as acid-sensitive or highly acid-sensitive (e.g., Liaw and Atton, 1981; Shewchuk, 1982; Saffran and Trew, 1996) based on indicator surface water chemistry such as pH, calcium (Ca^{2+}), alkalinity (ALK), and acid neutralizing capacity (ANC). Large-scale regional surveys since 2006 have reinforced the suggestion that these lakes are predominately acid-sensitive; 60% of 259 lakes in northern Saskatchewan were considered sensitive with an ANC below 200 μeq L^{-1} (Scott et al., 2010). Furthermore, lakes receiving sulphur (S) deposition in excess of their critical loads of acidity (defined as the "quantitative estimate of exposure to acidic (S and nitrogen [N]) deposition below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (after Nilsson and Grennfelt, 1988)), have been found across northern Saskatchewan, but exceedances, i.e., lakes receiving acidic deposition in excess of their critical load, were greatest closer to the Alberta-Saskatchewan border (Jeffries et al., 2010).

The growing concern of deleterious ecosystem impacts from AOSR emissions (e.g., Environment Canada, 2011) has sparked regional investigations into the acid status of lakes. While these regional surveys provide information on the acid status of lakes in northern Saskatchewan, they represent <1% of an estimated 90,000 lakes, and leave large geographic gaps. In the current study, a geospatial approach was proposed to assess the total lake population owing to the large number of lakes in the region, and because the large range in reported lake sensitivity suggested an influence from landscape features (Jeffries et al., 2010). Geospatial techniques for assessing acid sensitivity are not new and have been popular in regional soil assessments but specialized spatial regression techniques such as regression kriging have not yet been applied to surface waters or critical loads assessments. A common approach is to use multiple linear regression models to estimate water chemistry from observed data (e.g. Berg et al., 2005; Sullivan et al., 2007; Wolniewicz et al., 2011; Povak et al., 2014); however, regression kriging has the added benefit of incorporating the stochastic component of the regression as well as modelling spatial autocorrelation, performing better than regression or spatial interpolation alone (Hengl et al., 2007). With an abundance of geochemical and landscape attribute data for northern Saskatchewan available in databases and digital maps, regression kriging is an intriguing new tool for predicting surface water chemistry at a regional scale. The goal of this study was threefold; firstly, to determine if catchment-scale regression kriging was a viable approach to developing critical loads of acidity for ~90,000 lakes in northern Saskatchewan; and secondly, to estimate critical loads of acidity and exceedance for the total lake population in northern Saskatchewan under total S deposition during 2006. Lastly, the overarching objective of the paper was to determine if acid sensitive lakes in northern Saskatchewan are at risk from acidic deposition.

2. Material and methods

2.1. Study area

The defining feature of northern Saskatchewan (for the purposes of this study, an area of approximately 280,000 km^2 above 54° latitude) is its multitude of small lakes; more than 200,000 water bodies dominate the landscape (Government of Canada, 2007). Most of northern Saskatchewan sits on the Precambrian Shield, an acid-sensitive bedrock structure. Within the Shield is the Athabasca Basin (see Fig. 1), which is comprised of Athabasca sandstone (Ramaekers, 1990). Note that portions of the region located off the Precambrian Shield were excluded from the study area due to underrepresentation in the surface water data set and to bring focus to the acid-sensitive Precambrian Shield (see Fig. 1). The boreal forest covers the majority of northern Saskatchewan and forest stands are comprised primarily of jack pine (*Pinus banksiana*), black spruce (*Picea mariana*), tamarack (*Larix laricina*) and trembling aspen (*Populus tremuloides*) with a ground cover of lichens (Wiken, 1986). Fens and bogs occupied by dense sphagnum moss and black spruce are found in poorly drained areas throughout northern Saskatchewan. While exposed bedrock is present in all regions on the Precambrian Shield, it is more prominent in the Taiga Shield (see Fig. 1), where it is accompanied by thin soils and frequent fens and bogs (Wiken, 1986). Soils are predominately sandy throughout and in particular on the Athabasca Basin (Fig. 1), which features exposed sand dunes; in contrast, the Boreal Plain is covered with loamy to clayey glacial till (Wiken, 1986).

The AOSR is located approximately 50 km west of the Saskatchewan border at approximately 57° latitude with eastward prevailing winds. Northern Saskatchewan is a remote region with few observations of atmospheric deposition; the only monitoring station in the study region, located near Cree Lake, was discontinued during 1992. The most recent comprehensive acidic deposition estimates are from Environment Canada's A Unified Regional Air Quality Modelling System (AURAMS, Moran et al., 1998) and were modelled using 2006 emissions inventory data. Sulphur dioxide emissions did not change substantially between 2006 and 2013 in the AOSR or Saskatchewan (Fig. 2). However, the downturn in the oil and gas industry beginning in 2014 resulted in a large drop (38% from 2013) in AOSR SO_2 emissions. While the future of oil sands production is uncertain, the 2006 data are representative of emissions during the greater part of the last decade, and generally illustrate the regional and provincial spatial trends from 2006 to 2013.

Modelled total sulphate (SO_4^{2-}) deposition estimated by AURAMS ranged from 0.1 to 5 kg ha^{-1} in northern Saskatchewan during 2006, except where elevated near large point sources in the AOSR and Flin Flon, Manitoba, where extreme values between 60 and 90 kg ha^{-1} were predicted (see Supporting Information Fig. SI.1). The deposition footprint of the Hudson's Bay smelter in Flin Flon was evident within the 2006 dataset (Fig. SI.1) and at the time was the greatest point source of emissions in Saskatchewan, but by 2010 its production was greatly scaled back.

2.2. Catchment delineation

A single-lake catchment scale was chosen to model water chemistry and determine critical loads of acidity for the total lake population of northern Saskatchewan. Small lakes (below 0.02 km^2), large lakes (above 40 km^2) and water bodies considered impermanent or explicitly defined as non-lakes in the National Hydro Network (NHN) database (Government of Canada, 2007) were considered unrepresentative of the general lake population and removed from the dataset.

Traditional catchment delineation typically involves using a Digital Elevation Model (DEM) to compute flow direction and outline the hydrologically contributing area. The low relief of the terrain and coarse resolution of the DEM available for northern Saskatchewan, as well as the large number of lakes, made such