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1997

W9706

ENVIRONMENTAL PROTECTION

Pub. No: T/831
ISBN: 0-7785-4276-9 (Printed Edition)
ISBN: 0-7785-4277-7 (On-Line Edition)
Web Site: http://www3.gov.ab.ca/env/info/infocentre/publist.cfm

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(Received 20 February, 1995; accepted 3 March, 1996)

Abstract. About a third of the lakes surveyed in the Birch Mountains Upland of northeastern Alberta, Canada, have pH below 7.0; 25% have alkalinities below 10 mg/L identifying them as acid-sensitive following criteria established by the National Research Council of Canada (1981). Lakes in this region vary greatly as to surface area and depth. Watersheds also vary in area and in amount of peatland cover. Peatlands in the form of peat plateaus and collapse scars, continental bogs, treed and open fens, and shallow organic deposits cover over 50% of some watersheds. Surface water chemistries of these peatlands form three distinct classes: bogs, poor fens and shallow organic deposits. The acidity of certain lakes in this northern area is best explained by effects from high cover of *Sphagnum*-dominated peatlands in surrounding watersheds. Due to greater flow-through, poor fens appear to be more important than bogs in affecting the acidity of associated lakes.

Key words: acid-sensitive lakes, acidification, organics peatlands, *Sphagnum*

1. Introduction

The sensitivity of Alberta lakes to acidic deposition has been described by several reports (Erickson, 1987; Palmer and Trew, 1987; Trew, 1995). These evaluations indicate that of a total of 1133 lakes surveyed, 49 (4.3%) were defined as acid-sensitive (those having alkalinity of less than 10 mg L^{-1}) (NRCC, 1981). Sensitivity as defined here is a measure of the potential susceptibility of the ecosystem to acidification as determined by selected physical and chemical characteristics (Alberta Environment, 1990). Specifically, reported precipitation data from Alberta (summarized by Peake and Wong, 1992) has a mean pH of 5.5, close to the theoretical pH (5.6) of pure water in equilibrium with atmospheric CO_2, suggesting no significant acidification. Calcium and sulphate, the dominant ions, were found to be statistically correlated, probably resulting from the incorporation of windblown dust with precipitation. No correlations between sulphate and hydrogen ion concentrations were determined.

Acid sensitive lakes in Alberta occur in three distinct parts of the Province, of which those in some northeastern uplands are located near large scale, industrial plants which emit acid-forming gases. The question of whether these lakes are naturally acidic or have been affected by anthropogenic activity is unclear. For this reason, management and future protection strategies, although required, can not be established with confidence as the mechanisms that have resulted in acid characteristics are unknown.

Northern Alberta uplands have a high cover of wetlands (Vitt, 1992; Halsey *et al.*, 1993). Wetlands act as attenuators of precipitation and surface runoff/groundwater, becoming water sources under wet conditions and sinks under drought conditions (Brooks, 1992). Not only do wetlands attenuate incoming water, they can also chemically alter water that passes through them by: 1) retaining some sulphate, nitrate and ammonium, as well as metals often in the form of organic acids (Hemond, 1980; Bayley *et al.*, 1987; Urban *et al.*, 1987); 2) production of organic acids (primarily humic and fulvic), and releasing nutrients through decomposition (Hemond, 1980; Gorham *et al.*, 1984); and 3) increasing acidity through selective cation uptake and assimilation (Clymo, 1963; Vitt *et al.*, 1975). The magnitude of attenuation as well as degree of chemical alteration of water in these systems depends on wetland type, reservoir size, regional climate, and position of the peatland(s) in the watershed (Jones *et al.*, 1986). It has been documented that moderate wetland cover can significantly impact the quality of water output. For example, Brakke (1981) documented that a watershed in Norway containing wetlands in 24% of its catchment area had 62% of its total outflow chemically altered by wetlands.

In Canada wetlands can be subdivided into two types 1) organic wetlands, or peatlands, where >40 cm of organics have accumulated over the majority of the landscape unit and 2) mineral wetlands where <40 cm of organics have accumulated over the majority of the landscape unit (Zoltai and Vitt, 1995). Mineral wetlands have greater seasonal water table fluctuation than do peatlands (Zoltai and Vitt, 1995), and thus a much lower potential for long-term water storage. As a result of fluctuating water tables, decomposition rates in mineral wetlands are higher, leading to increased nutrient availability (Zoltai and Vitt, 1995). In contrast, peatlands have much lower seasonal water table fluctuation, resulting in a much higher potential for long term water storage which alters DOC levels, pH, and cation/anion concentrations.

Peatlands can be classified into ombrogenous bogs and geogenous fens, the latter subdivided into poor, moderate-rich and extreme-rich fens, each with distinctive indicator species, acidity/alkalinity, and base cation content. Fens are ecosystems that are affected by mineral soil waters (surface and/or ground water) that are relatively enriched in mineral elements (Zoltai and Vitt, 1995). When the peatland surface is raised above the influence of the surrounding landscape it receives water and minerals solely from precipitation and is called a bog. Bogs may contain permafrost (peat plateaus and associated collapse scars) or have no present-day permafrost (continental bogs) (Zoltai, 1971). As fens are connected with regional groundwater, discharge is less erratic, and is sustained at higher levels during dry periods than bogs (Brooks, 1992). Thus, bogs store water for longer periods than fens, chemically altering the water to a higher degree, but fens discharge water at a greater rate, potentially impacting the downstream receiving waters to as great a degree as bogs.

The transition from bog to rich fen can be viewed as a vegetation-chemical gradient (reviewed by Vitt *et al.*, 1995). Bogs are highly acid (pH less than 4.5), have no measurable alkalinity, low base cation concentrations, and are dominated by oligotrophic species of *Sphagnum*. Poor fens are less acid (pH 4.5–5.5), have low alkalinities, higher base cation concentrations and are dominated by mesotrophic species of *Sphagnum*. Rich fens have pH greater than about 6.0, alkaline waters rich in calcium and bicarbonate, relatively high base cation concentrations, and are dominated by brown mosses (mostly members of the Amblystegiaceae).

Values for pH of peatland waters collected over a regional temperate and boreal landscape are bimodally distributed, with bogs and poor fens forming one mode between pH of about 3.5–5.5, and rich fens forming a second mode between pH of 5.8–8.0 (Gorham *et al.*, 1984). Between these two modes alkalinity drops to zero, and *Sphagnum* becomes the dominant component of the ground layer. Mesotrophic species of *Sphagnum*, found mainly in poor fens generate acidity largely through the uptake of cations by uronic acid molecules, in exchange for hydrogen ions (Clymo, 1963; Gorham *et al.*, 1987). In contrast, bog acidity less than pH 4.0 is most likely a combination of inorganic cation exchange by oligotrophic species of *Sphagnum* along with organic acidity produced by decomposition (Hemond, 1980).

Along the temperate eastern coast of North America and in central Ontario, numerous acid-sensitive lakes have been attributed to watersheds with high wetland cover (LaZerte and Dillon, 1984; Gorham *et al.*, 1986; Kahl *et al.*, 1989; Baker *et al.*, 1991). However, no studies have directly examined the role that wetlands play in lake acidification in more northern areas where peatland cover is extensive. In addition, the relative contribution of each peatland type to lake acidification has not been documented. This paper examines the role that specific northern peatland types play in lake acidification of watersheds in the northeastern uplands of Alberta, Canada.

2. Study Area

The Birch Mountains Upland is one of several preglacial erosional remnants found in northern Alberta (Figure 1). The upland represents a major drainage divide between the Mikkawa, Ells, Birch and McIvor Rivers (Figure 1). The Birch Mountains Upland is composed of Cretaceous, nonmarine sandstone and shales (Green, 1972) that are draped by glacial deposits of fine-loamy to clayey ground moraine with associated glaciofluvial ice contact deposits (Turchenek and Lindsay, 1982). Chemical analyses of soils developed over ground moraine in the area characteristically have pH values ranging from 5.0–5.5 and calcium oxide concentrations are $<1\%$ (Pawluk and Bayrock, 1969). Groundwaters from surficial sediments are of the $Ca^{2+}/Mg^{2+}/HCO_3^-$ type (Ozoray *et al.*, 1980).

Peatland cover in the region is highly variable, ranging from no peatlands to $>85\%$ cover over areas of 100 km^2 (see Vitt, 1992). The region is dominated by fens in some areas and continental bogs and peat plateaus in others (Vitt, 1992; Halsey

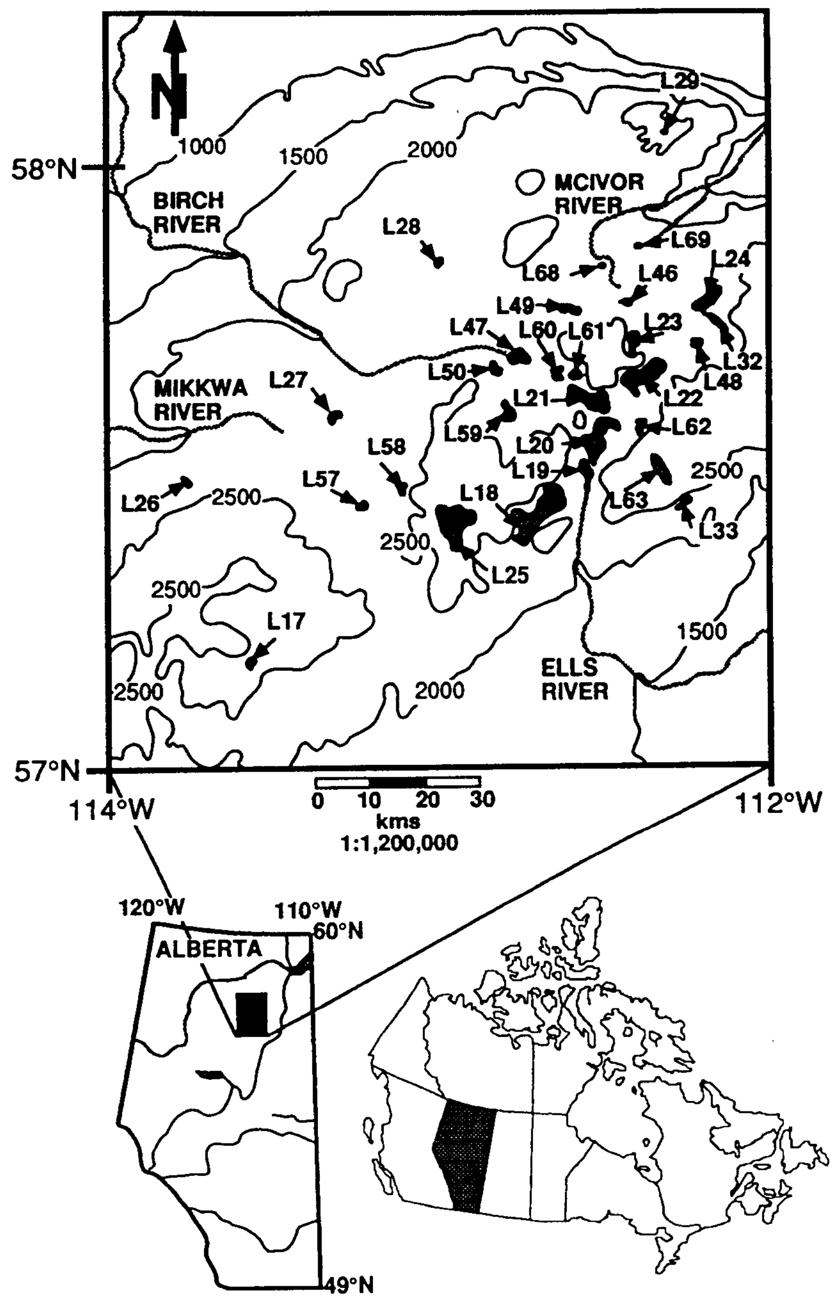

Figure 1. Location of 29 lakes examined in the Birch Mountains Upland of northeastern Alberta.

Table I

Morphometric and chemical data for the 29 study lakes sampled during 1988 and 1992 in the Birch Mountains Upland. $Z_{(max)}$ = maximum observed lake depth, TP = total phosphorus, and Chlor *a* = chlorophyll-a

Lake No.	TWIN-SPAN group	Date sampled	Name	Area (km^2)	$Z_{(max)}$ (m)	pH	Alkalinity (mg/L)	TP (μg/L)	Chlor *a* (μg/L)
L17	B	21/07/88	Osi	1.52	2.0	7.24	23.5	20.1	9.0
L18	B	20/07/88	Namur	43.39	27.0	7.35	18.9	30.4	5.9
L19	C	20/07/88	S. Gardiner	7.25	10.5	7.63	53.3	50.1	10.8
L20	C	20/07/88	N. Gardiner	17.48	12.5	7.76	52.5	51.2	10.0
L21	C	20/07/88	Unnamed	17.17	13.0	7.85	44.4	56.4	13.4
L22	C	20/07/88	Sand	14.58	16.0	8.01	51.8	42.2	9.1
L23	A	20/07/88	Otasan	3.44	7.0	6.74	6.4	27.9	9.0
L24	C	26/07/88	Eaglenest	8.40	3.5	7.49	33.7	130.2	9.9
L25	A	04/08/92	Legend	16.76	9.8	6.65	10.2	42.0	37.0
L26	C	21/07/88	Jean	1.60	2.1	8.23	53.0	24.2	4.5
L27	A	21/07/88	Unnamed	1.25	2.8	6.20	5.6	96.9	8.5
L28	A	21/07/88	Unnamed	1.30	1.8	4.53	0.0	59.7	2.1
L29	A	11/08/92	Clayton	0.65	1.1	4.51	0.0	45.0	9.4
L32	C	26/07/88	Clear	1.16	7.0	7.38	36.7	62.3	3.6
L33	D	26/07/88	Unnamed	0.94	2.5	8.24	134.4	97.0	32.8
L46	A	20/07/88	Bayard	1.20	1.3	6.60	6.9	106.7	6.0
L47	A	20/07/88	Unnamed	4.31	1.5	6.53	7.9	53.5	3.5
L48	C	11/08/92	Unnamed	1.99	1.1	7.43	58.0	98.0	115.7
L49	B	06/08/92	Unnamed	2.61	1.1	6.50	7.8	145.0	10.4
L50	B	06/08/92	Unnamed	1.61	0.6	6.99	26.0	105.0	51.5
L57	C	06/08/92	Unnamed	1.61	1.4	7.74	58.0	50.0	10.4
L58	C	06/08/92	Unnamed	1.64	1.8	9.25	50.0	37.0	15.5
L59	B	06/08/92	Unnamed	5.04	1.6	7.25	18.2	90.0	16.8
L60	B	06/08/92	Unnamed	0.91	3.0	8.74	15.7	140.0	112.5
L61	B	06/08/92	Unnamed	1.68	1.1	7.16	20.7	125.0	113.6
L62	D	11/08/92	Unnamed	1.48	6.0	8.31	104.0	83.0	52.4
L63	C	11/08/92	Unnamed	1.52	1.1	7.64	69.0	113.0	33.6
L68	B	11/08/92	Unnamed	0.21	0.8	6.86	11.4	185.0	80.1
L69	D	11/08/92	Unnamed	0.36	0.8	7.97	109.0	120.0	28.9

et al., 1993). Upland vegetation consists of closed canopy mixed wood forests of *Populus tremuloides*, *Populus balsamifera*, and *Picea glauca* on luvisolic soils and *Pinus banksiana* on brunisolic soils (Turchenek and Lindsay, 1982). Non-peaty wetlands (marshes and swamps) have limited cover in the area, and are restricted to narrow zones around lake margins, riparian bottomlands and areas dammed by beaver.

Only seasonal climatic data (May-September) are available for the area, with 1951–1980 30-year normals for mean summer temperature ranging from 9.9–12.0 °C and total precipitation from 290–324 mm (Environment Canada, 1982). The surrounding area has been classified as a high boreal outlier, while most of the Birch and McIvor River Basins has been classified as boreal subarctic (Strong and Leggat, 1992), corresponding to a region of high peat plateau cover (Vitt *et al.*, 1994). The northern part of the Birch Mountains Upland falls into the zone of discontinuous permafrost as defined by Brown (1967).

3. Methods

3.1. Lake and Peatland Chemistry

Twenty-nine remote lakes in the Birch Mountains were sampled on one occasion each during the summers of 1988 and 1992. These lakes represent a subset of a larger group of 109 lakes surveyed throughout northern Alberta (Saffran and Trew, 1996). The numbering of lakes used in this paper is part of that larger group.

From each lake, vertically integrated samples were taken from the euphotic zone using weighted Tygon tubing. The euphotic zone was defined as the interval between the surface and the depth of 1% of surface penetrating light. Sample units were collected from 5 widespread areas of each lake and combined to form a single composite sample.

Samples collected for total phosphorus were analyzed by the method of Prepas and Rigler (1982). Samples for chlorophyll *a* analyses were extracted in 90% acetone and measured flourometrically by the technique of Yentsch and Menzel (1963) as modified by Holm-Hansen *et al.* (1965). Total alkalinity was determined by potentionmetric titration using the Gran approach (Strumm and Morgan, 1981) and expressed as $CaCO_3$; bicarbonate alkalinity was calculated from alkalinity relationships described in American Public Health Association (1978) and then multiplied by 1.22 to convert to bicarbonate units. The remaining analyses: total dissolved solids, specific conductance, calcium, magnesium, sodium, potassium, chloride, sulphate, aluminum, total kjeldahl nitrogen, ammonium, and total dissolved nitrogen were conducted at the Alberta Environmental Centre in Vegreville (Alberta Environment, 1987).

Preliminary results of the survey revealed that most lakes had sulphate concentrations less than the detection limits available (1988: 5 mg/L; 1992: 3 mg/L). Samples were re-analyzed using ion chromatography (Sawiki *et al.*, 1978) which is more sensitive; calcium and magnesium were also repeated using direct current plasma as a check on sample deterioration. No significant differences were found between initial and final concentrations of either cation ($P < 0.05$).

Representative peatland surface water chemistry was examined in three of the 29 watersheds sampled for lake chemistry (L23, L25 and L59) during 1991 and

1992 (Figure 1). Thirty-two surface water samples were collected for chemical analyses from peatlands identified from aerial photographs as representative of the study area. Water samples were collected from the top of the water table or from open pools when available. Samples were collected from continental bogs, peat plateaus, collapse scars within peat plateaus, wooded fens, open fens, and in areas with shallow organic deposits (20–60 cm of accumulated peat). Conductivity and pH were determined electronically in the field with conductivity values being standardized to 20 °C and corrected for hydrogen ions following Sjörs (1952). Samples were collected for elemental analyses in 50% acid soaked, triple rinsed, polypropylene bottles, filtered through 0.45 μm HAWP filters and fixed with 1.0 ml of concentrated HNO_3 for a total of 25 ml within 48 hours of collection. Analyses for calcium, magnesium, potassium and sodium were determined on an inductively coupled argon plasma emission spectrophotometer. Water samples for NH_4^+–N and NO_3–N were collected in polystyrene bottles and either unfiltered (NH_4^+–N) or filtered (NO_3–N) in the lab or field within 24 hours of collection and analysed in triplicate on a Technicon Auto Analyser II. Samples for total phosphorus and total dissolved phosphorus were collected in polypropylene bottles, with samples for TDP being filtered through GFC filters with a 1.2 μ retention in the lab or field and fixed with 0.4 g of persulfate/50 mL filtered sample within 24 hours. Samples were than analyzed following the methods of Bierhuizen and Prepas (1985).

3.2. Watershed Mapping

Watersheds associated with the 29 lakes were mapped for peatland cover using 1:30 000 aerial photographs. Peatlands greater than 0.2 km^2 were identified as one of five peatland types, with peatlands having less than 0.2 km^2 cover being excluded. Continental bogs were defined by the presence of a uniform cover of *Picea mariana* and uniform topography of the surface. Peat plateaus were distinguished from continental bogs by the occurrence of collapse scars that indicate the presence of permafrost (Zoltai, 1971). Collapse scars were too small to be mapped as individual polygons and so were included with peat plateaus. In recently burned peat plateaus, extensive temporary degradation of permafrost had occurred. Wooded fens were defined by the presence of *Picea mariana* and *Larix larcina* and uniform topography of the surface. Open fens were defined by high reflectance due to the presence of a continuous *Carex* cover. Peatlands are defined as having >40 cm of accumulated organics, however, when mapping from aerial photographs peat depth cannot be determined. For this reason a fifth peatland category of shallow organic deposits was included. Areas of shallow organic deposits were defined by heterogeneous to homogeneous cover of tall *Picea* stands and slightly sloping topography. Field examination of this map unit had peat accumulation of 20 to 60 cm representing peatlands in some cases and humic gleysols in others. Non-peaty wetlands, including marshes and swamps, were not mapped as they had insignificant areal extent in the watersheds examined.

3.3. Statistics

TWINSPAN, a two-way indicator analysis (Hill, 1979), that produces a hierarchical classification of data, was used to determine similarity of the 29 lakes based on their water chemistry. Analyses were carried out on data transformed to a base of 100, with cut levels of 0, 15, 30 and 50.

Water sample data from peatlands in the three watersheds were grouped by peatland type. This classification of chemical data was then subjected to a linear discriminant analysis (SPSS, 1993). The discriminant analysis tested the chemical distinctness of the five peatland types. Peatland types that could not be distinguished on the basis of their surface water chemistry by the discriminant analysis were assumed to have similar hydrological effects and were grouped in later analyses.

Watershed components for all 29 lakes were digitized to determine total cover of each peatland type using BIOQUANT II (R and M Biometrics, 1985). A matrix was constructed for each watershed and included percent cover of each chemically different peatland type as determined from the discriminate analysis, total percent of peatland cover, total percent cover of all open water in the watershed, watershed area and lake area. Other variables included maximum lake depth, lake volume, peatland cover/lake volume, relative amount of watershed with evidence of burn (0 = none, 0.5 = part, 1.0 = all), and a slope index = (elevational change in watershed/watershed area).

To test the hypothesis that peatland cover in a watershed affects lake chemistry an indirect gradient analysis using a linear model (Principle Component Analysis) was performed in CANOCO (Ter Braak, 1988). Indirect gradient analysis examines major gradients in a pseudospecies data set (here lake chemistry) irrespective of environmental variables (Jongman *et al.*, 1987). A "passive analysis" of environmental variables and unconstrained ordination axes by correlation determined the relationship between lake chemistry and the corresponding watershed variables.

4. Results

4.1. Lake Chemistry

TWINSPAN classified the lakes into four ecologically meaningful groups (Figure 2, Table II). Group A consists of lakes previously identified as acid-sensitive, having total alkalinities of less than 10 mg/L. These lakes have low TDS and very low concentrations of calcium and magnesium. Lakes range in pH from 4.5–6.7 and have the highest concentrations of extractable aluminum (Table II). Group B lakes have higher amounts of TDS, bicarbonate, alkalinity, calcium and magnesium. In general, these lakes are not acid-sensitive, although one lake did have less than 10 mg/L of alkalinity. The pH of this group of lakes ranges from 6.5–8.7; the lakes have moderate amounts of extractable aluminum (Table II). Group C is composed of lakes that have higher concentrations of TDS, bicarbonate, alkalinity, calcium

Table II

Summary of chemical components of TWINSPAN groups identified for 29 lakes. The range of variation is followed by the mean and (standard deviation). TDS = total dissolved solids; bd. = below detection; COND = conductivity not corrected for H^+

TWINSPAN group	n	TDS (mg/L)	COND. (μS/cm)	Alkalinity	Bicarbonate (mg/L)	pH (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Extractable Aluminum (mg/L)
A	7	7–27 18(±7)	17–45 30(±11)	0–10 5(±4)	0–12 6(±5)	4.5–6.7 6.0(±1.0)	bd.–5.5	bd.–1.5	0.02–0.22 0.15(±0.09)
B	8	25–36 33(±5)	40–65 59(±11)	8–24 18(±6)	10–29 22(±7)	6.5–8.7 7.3(±0.7)	5.0–9.5 6.3(±1.5)	1.0–2.5 2.1(±0.9)	bd.–0.21
C	11	42–72 59(±6)	78–142 108(±17)	26–69 51(±10)	32–84 61(±13)	7.0–9.2 7.9(±0.5)	7.0–20.0 14.6(±3.0)	3.5–6.0 4.3(±0.7)	bd.–0.05
D	3	107–148 126(±20)	202–261 231(±30)	104–134 116(±16)	125–164 141(±21)	8.0–8.3 8.2(±0.2)	27.0–37.0 32.3(±5.0)	6.0–9.0 7.7(±1.5)	bd.–0.02

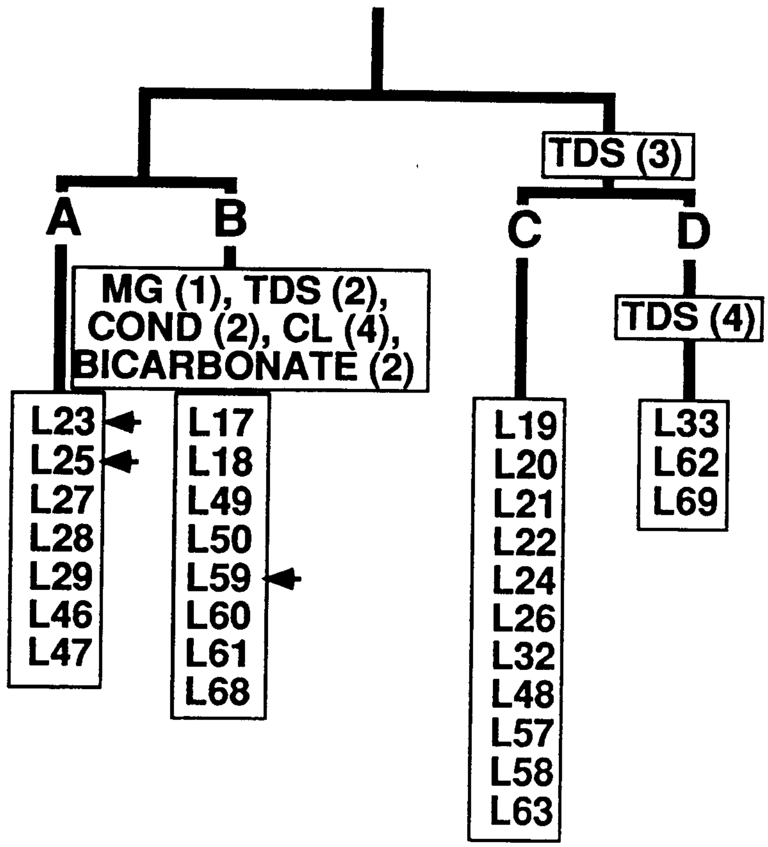

Figure 2. TWINSPAN classification of 29 lakes in the Birch Mountains Upland, Alberta into 4 groups (A-D) based on lake water chemistry. Four cut levels (1–4) indicate level of element present. Boxes contain indicator elements of groups with cut levels in brackets; arrows indicate 3 lakes from which the surrounding watersheds were analyzed. TDS = total dissolved solids, COND = conductivity not corrected for H^+.

and magnesium and a conductivity that is generally greater than 100 μS/cm. These lakes have low amounts of extractable aluminum (Table II). Group D consists of lakes that have the highest concentrations of TDS, bicarbonate, alkalinity, calcium and magnesium; mean pH is 8.2 and mean conductivity is 231 μS/cm (Table II). Total phosphorus, TDP, TKN or TDN were not represented as indicator elements in the TWINSPAN and suggesting that the trophic state of lakes is not an important consideration in determining lake groupings for the cut levels used.

4.2. Peatland Chemistry

A summary of the chemistry of surface water samples from the initial five peatland types indicates that bogs and collapse scars have the lowest pH values and corrected

Table III

Summary of chemical components of 32 wetland sampled from 3 watersheds. Mean values are given with standard deviations in brackets. TDP = total dissolved phosphorus, TP = total phosphorus

Wetland type	Sample Size	pH	Corrected Conductivity (μS/cm)	TDP (μg/L)	TP (μg/L)	NO_3^-–N (μg/L)	NH_4^+–N (μg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)
Bog	12	3.73 (0.35)	42 (5)	135 (75)	276 (167)	31 (29)	893 (2877)	2.46 (0.78)	0.52 (0.22)	0.88 (0.58)	0.46 (0.41)
Collapse Scar	10	3.76 (0.38)	46 (10)	236 (208)	383 (232)	21 (10)	41 (22)	1.34 (0.51)	0.27 (0.13)	1.14 (1.00)	0.77 (0.91)
Bog + Collapse scar	22	3.75 (0.36)	43 (7)	181 (155)	325 (202)	27 (22)	506 (2127)	1.95 (0.87)	0.41 (0.22)	1.00 (0.79)	0.60 (0.69)
Wooded fen	6	4.70 (0.42)	70 (23)	99 (61)	262 (169)	30 (17)	106 (219)	2.85 (0.77)	0.82 (0.15)	1.32 (0.62)	0.48 (0.28)
Open fen	3	4.70 (0.36)	69 (19)	112 (107)	246 (120)	44 (3)	12 (4)	2.34 (0.58)	0.67 (0.11)	1.45 (0.04)	0.58 (0.14)
Wooded + open fen	9	4.70 (0.38)	69 (20)	103 (72)	257 (147)	35 (15)	74 (179)	2.68 (0.72)	0.77 (0.15)	1.36 (0.49)	0.51 (0.24)
Shallow organic deposit	1	5.30	154	212	646	44	38	2.29	0.77	1.48	0.69

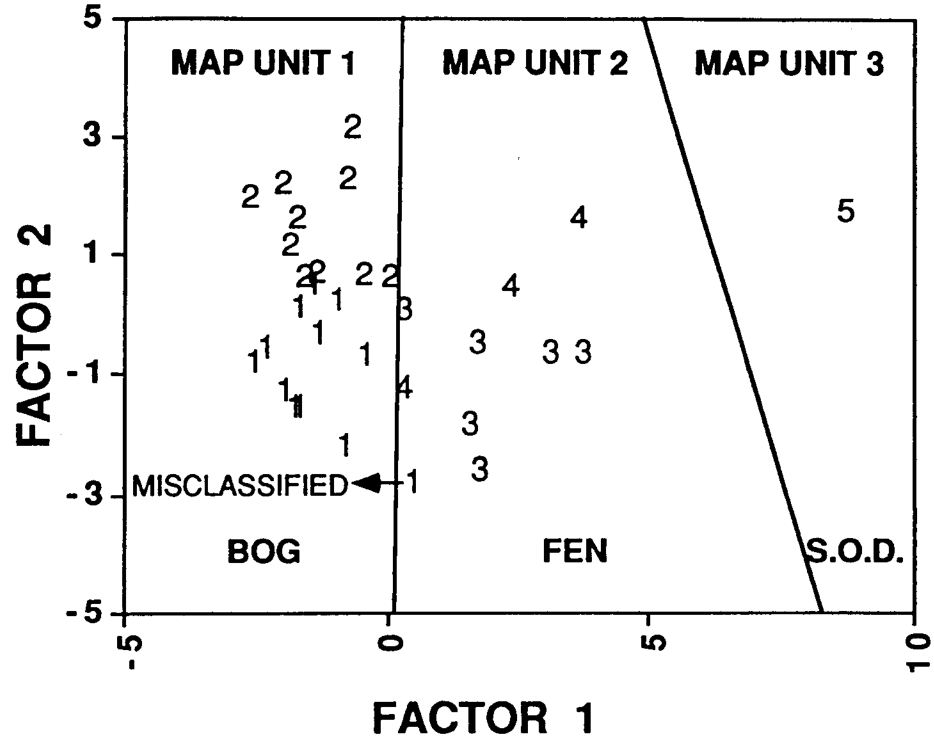

Figure 3. Discriminant analysis of 32 peatland surface water chemistry samples. Bog = 1, collapse scar = 2, wooded fen = 3, open fen = 4 and shallow organic deposit (S.O.D.) = 5. The three units used in the mapping are shown, with bogs (1) and collapse scars (2) comprising the first unit, wooded (3) and open fens (4) comprising the second, and shallow organic deposit (5) the third.

conductivities followed by wooded to open fens, and shallow organic deposits (Table III). Fens and shallow organic deposits have higher concentrations of cations than bogs and collapse scars, and collapse scars have the highest amounts of TDP and TP (Table III). Collapse scars can be chemically distinguished from bogs in the Birch Mountains Upland by higher amounts of K^+ and Na^+ and lower amounts of Ca^{2+} and Mg^{2+} (Table III).

The discriminant analysis of the chemistry from 32 peatland surface water samples reveals that some of the peatland types are chemically distinct, while others are not (Figure 3). Bogs (continental and peat plateau) were correctly classified 83% of the time, with misclassified sites being identified as collapse scars or open fens (Table IV).

The gradation between bog and collapse scar surface water chemistries is not surprising as collapse scars represent former peat plateaus that have locally degraded (Zoltai, 1993), with collapse scars receiving much of their water from the melting of surrounding permafrost (Chatwin, 1981). A similar gradation between north-

Table IV

Peatland type identified from airphotos (rows) and as predicted from the discriminant analysis (columns). Peatland types are 1 = bogs, 2 = collapse scars, 3 = wooded fens, 4 = open fens, and 5 = shallow organic deposits. Wilks' I = 0.029 with an F-statistic of 2.694, degrees of freedom = 40, 70, p <0.0001. When peatland types 1 and 2 and 3 and 4 are grouped the discriminant analysis produces a Wilks' I = 0.079 with an F-statistic of 5.099, degrees of freedom = 20, 40, and p <0.0001

Peatland type	Observed (Air photos)				
predicted	1	2	3	4	5
1	10	1	1	0	0
2	0	10	0	0	0
3	0	0	4	2	0
4	0	0	1	2	0
5	0	0	0	0	1

western Alberta bog and collapse scar surface water chemistries has been reported by Belland and Vitt (1995). In addition to gradational surface water chemistries, there is also a gradation between bog and collapse scar vegetation resulting from the regeneration of permafrost in locally degraded collapse scars (Zolati, 1993; Belland and Vitt, 1995). As collapse scars are always less than 0.2 km^2 in size they were mapped as part of the bog. Collapse scars were only misclassified as fens 8% of the time.

Wooded to open fens were always correctly classified as fens in the discriminant analysis, however, it was not possible to distinguish one from the other chemically (Table IV, Figure 3). For this reason, the areas covered by wooded and open fens in each watershed were not considered separately, and were grouped into one fen map unit.

One water sample taken from an area of shallow organic deposit (30 cm of organics) was correctly classified in the discriminant analysis and no other samples were misclassified into this group making it a unique entity. This suggests that surface water in shallow organic deposits is different from bogs and fens and should be considered as a separate map unit.

The results of the discriminant analysis reveal that there are three map units which are distinguishable on the basis of surface water chemistry. These are: bogs (peat plateaus and continental bogs), fens, and shallow organic deposits. These three units are used in the indirect gradient analysis.

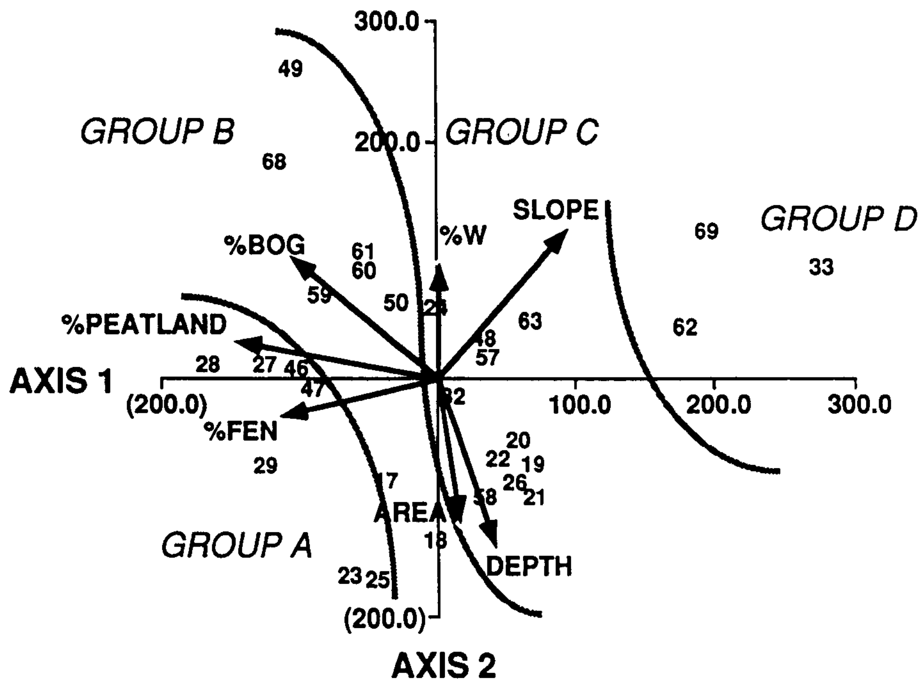

Figure 4. Biplot of 29 lakes based on lake water chemistry with the TWINSPAN classification based on lake chemistry super-imposed. Watershed variables that explain a significant amount of variation on the first two axes are shown by directed arrows. %W = percent of open water in watershed. Numbers = lake numbers.

Table V

Summary of indirect gradient analysis of lake chemistry to watershed variables. The sum of all canonical eigenvalues is 0.60. Eigenvalues listed are fractions of the total variance of pseudospecies data

	Axes			
	1	2	3	4
Eigenvalues	0.44	0.24	0.11	0.06
Lake chemistry-watershed variance	0.86	0.79	0.66	0.62
Cumulative percentage variance of lake chemistry	44.2	67.9	78.8	84.9
Cumulative percentage variance of lake chemistry-watershed relation	53.9	78.5	86.4	90.3

Table VI

Watershed variables that explain lake chemistry at a statistically significant level (**) of p <0.01 when the correlation coefficient is >0.43, and (*) p <0.05 when the correlation coefficient is >0.31 for each axis. The watershed variables are ordered sequentially based on the level they explain the first axis

Watershed variable	Pearson correlation coefficient	
	Axis 1	Axis 2
% Peatland cover	–0.573**	0.121
% Fen cover	–0.443**	–0.125
% Bog cover	–0.409*	0.393*
Slope index	0.375*	0.489**
Lake depth	0.166	–0.560**
Lake area	0.062	–0.479**
% Open water	–0.006	0.377*

4.3. Multivariate Analysis

The results of the indirect gradient analysis between the watershed variables and lake chemistry data are presented as a biplot in Figure 4. The eigenvalues and lake chemistry-watershed correlations, as well as the cumulative percentage variance of lake chemistry and lake chemistry-watershed relations for the four axes are shown in Table V. The sum of all canonical eigenvalues is 0.60. Watershed variables that have statistically significant Pearson correlation coefficients on the first two axes are shown in Table VI. Percentage of peatland cover explains most of the variation on the first axis, with lakes that are acid-sensitive (Group A) having watersheds with the highest overall percent of peatland cover (Figure 4, Table VI). Of the peatland types identified in the discriminant analysis, the percentage cover of fens explains the most variation on the first axis, while the percentage of bog cover explains more of the variation on the second axis.

Lake alkalinity, bicarbonate, conductivity, total dissolved solids, calcium and magnesium all have the best fit (>0.70) with the first axis (Table VII). These variables are most closely related to the percentage of fen cover, increasing as fen coverage decreases (Figure 5). Total dissolved nitrogen, total dissolved phosphorus and the amount of DOC in the lakes are related to the percent cover of bogs in the watershed, with these amounts increasing as bog cover increases (Figure 5). The amount of extractable aluminum is most closely related to the percent cover of peatlands in the watershed. Variables related to lake depth, area, and total percent cover of open water in the catchment area are most closely related to chloride, total phosphorus, and total Kjeldahl nitrogen. Concentrations of these chemical variables decrease as lake size increases, but increase as the percent cover of all

Table VII

Fit of lake chemistry data to the first two axes as a fraction of variance of the lake chemistry. The lake chemistry variables are ordered sequentially based on their cummulative fit to the first axis. TDS = total dissolved solids, TP = total phosphorus, DOC = dissolved organic carbon, TDN = total dissolved nitrogen, TKN = total kjeldahl nitrogen, TDP = total dissolved phosphorus

Lake chemistry	Fit	
	Axis 1	Axis 2
Alkalinity	0.942	0.963
Bicarbonate	0.940	0.965
Conductivity	0.919	0.977
TDS	0.890	0.962
Ca	0.879	0.927
Mg	0.842	0.886
pH	0.483	0.483
Aluminum	0.483	0.576
Nitrate	0.413	0.746
Na	0.373	0.614
SO_4	0.173	0.397
TDP	0.165	0.736
DOC	0.128	0.628
Cl	0.086	0.514
TP	0.006	0.790

open water in the watershed increases (Figure 5). The amount of sodium in the lakes is most closely related to the calculated slope index of each watershed (Figure 5).

The acid-sensitive lakes of Group A have the highest percent cover of peatlands in the watershed (mean 47%). Of the peatlands present in the watershed, fens have the greatest impact (Figure 4). The high amount of peatland cover in the watershed results in lakes having low amounts of total dissolved solids, specifically calcium and magnesium, and thus low conductivity (Figure 5). Group A lakes have little to no inorganic buffering capacity as reflected in the low amount of bicarbonate (Figures 4 and 5). Acid sensitive lakes of Group A can be broken into two types: 1) small to moderate-size lakes that are shallow (maximum depth of <3.0 m), and 2) medium to large lakes that are deep. Small, shallow lakes have lower pH and higher amounts of extractable aluminum and DOC, even when percent peatland cover is lower than in watersheds of large, deep lakes.

Group B lakes have a moderate amount of percent peatland cover (mean of 34%) with fen cover consistently low. Bog cover is higher for Group B lakes as the lakes become smaller and shallower (Figure 4); however, peatland cover almost

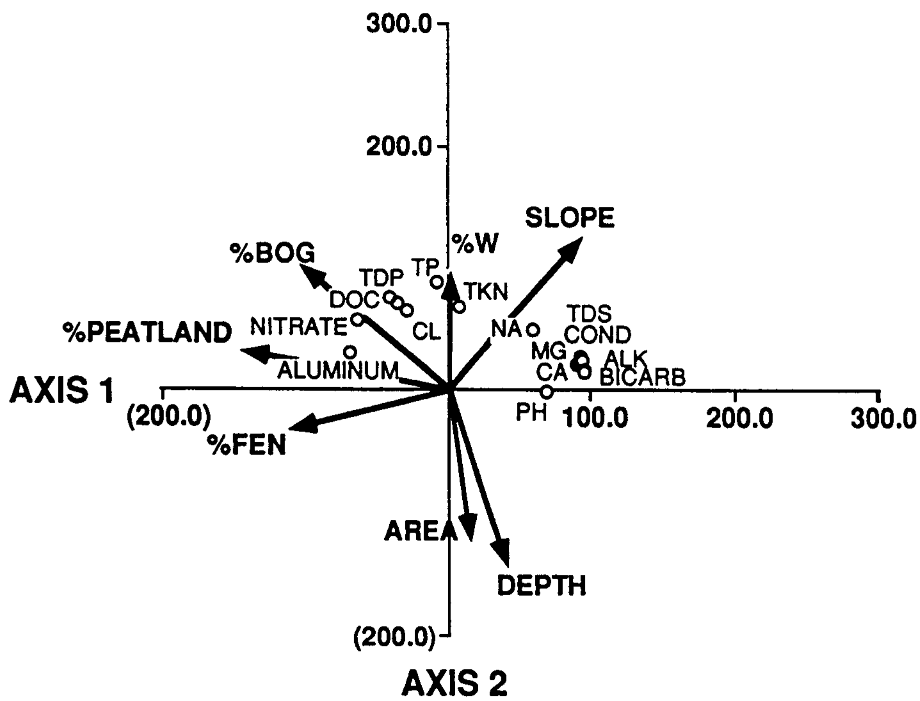

Figure 5. Biplot of the chemical parameters measured in water from 29 lakes that have a cumulative fit which is a fraction of the variance of the chemistry >0.50. Watershed variables that explain a significant amount of the variation on the first two axes are shown by directed arrows. %W = percent of open water in watershed.

always remains below 30%, except for L68 that has >30% peatland cover but also has steep slopes at the southern edge of the watershed resulting in the input of large amounts of TDS into the lake. This is reflected in L68 having the highest amount of chloride of any of the lakes; however, cation exchange and filtering capacity of the surrounding peatlands have resulted in low levels of other total dissolved solids. Similar patterns of declining ion concentrations from the inflow to the outflow of other northeastern Alberta fens have been observed (Vitt *et al.*, 1975; Nicholson, 1989). The higher percent bog cover of lakes of Group B is reflected in a corresponding increase in the amount of DOC, phosphorus, total dissolved nitrogen, and extractable aluminum (Figures 4 and 5).

Lakes of Group C have a very low percent cover of peatlands in their watersheds (Figure 4) (mean of 18%). The low amount of peatland cover results in very little acidification of water, resulting in lakes that have a neutral pH.

Group D lakes are characterized by small, narrow lakes that are surrounded by low amounts of peatland cover (mean 20%) and have steep slopes present within their watershed (Figure 4). These lakes have the highest amounts of total dissolved solids (Figure 5), reflecting the strong telluric nature of the surface/ground waters entering the lakes.

5. Discussion

Lakes in the Birch Mountains Upland are extremely variable in their morphometries and chemistries, as well as in watershed features. About 25% of the lakes sampled can be considered acid-sensitive based on criteria defined by NRCC (1981). These acid-sensitive lakes generally are characterized by <10 mg/L of alkalinity, low amounts of bicarbonate, base cations, conductivity, and total dissolved solids as well as low pH. They also have relatively high amounts of aluminum. Although these lakes each have many similarities in water chemistries, they have very different watershed and morphometric characteristics. Some acid-sensitive lakes are small and shallow, others are relatively large and deep.

Nutrient status of lakes in the study area can be quite dissimilar. Watersheds are also variable in slope and amount of water cover. These morphometric and watershed features do not explain differences in lake acidity or alkalinity to any extent, however they appear to be related to nutrient status, particularly phosphorus, nitrogen and chloride concentrations, with shallow lakes being more nutrient rich (Riley and Prepas, 1985; D'Arcy and Carignan, 1996).

It is well documented that fens and bogs have different vegetative and chemical characteristics (Vitt and Chee, 1990) and it is not unexpected that our multivariate analyses could not separate the three types of ombrogenous peatlands (peat plateaus, collapse scars and continental bogs) based on chemistry especially since collapse scars are totally contained within the peat plateaus. In the study area, almost all fens are poor fens and *Sphagnum*-dominated; rich fens are mostly lacking, thus water chemistries of the fens are relatively constant and clearly the fen components can be treated as one unit. Whereas acidity of the ombrogenous peatlands is higher than that of the geogenous fens and shallow organic deposits of the area, the water through-flow of ombrogenous peatlands is much less than that of geogenous ones. Thus, the cumulative down-stream effects of bogs are not as great as those of poor fens. Additionally, waters from many ombrogenous peatlands of the area flow through fens or shallow organic deposits before they contact lake basins.

Similarities in chemistries of acid-sensitive lakes compared to dissimilar basin and watershed morphometries indicate that the latter physical factors are not related to acid sensitivity. Instead, acid-sensitive lakes of the Birch Mountains are clearly related to percent of peatland terrain in the surrounding watersheds. In particular, the percent of fen and percent of shallow organic deposit in the watershed are factors that explain the highest amount of lake chemistry variation, especially components of acidity and alkalinity. Also associated with lake chemistries is percent slope. As slope decreases, runoff decreases and residence time in peatland terrain increases. In the study area, acid and acid-sensitive lakes occur in watersheds where fens and shallow organic deposits occupy greater than 30% of the watershed, and where the calculated slope index ranges between 1.7 to 16.9 m^{-1}. These acidic lakes range in size from 0.65 to 16.76 km^2 and in maximum depth from 1.1 to 9.8 m. Except for a few larger lakes, acidic lakes in the area have the highest amounts of DOC, TDN and TDP; these generally shallow lakes are most prevalent in watersheds with highest bog cover.

The difference in lake chemistry between watersheds with high percent bog cover and high percent fen cover is a function of how acidity is generated. High DOC concentrations (29.8 $\pm$ 5.2 mg/L) in lakes associated with high percent bog cover reflects the generation of humic acids from decomposition processes that occur in bogs. DOC concentrations are much lower (17.9 $\pm$ 6.2 mg/L) in lakes associated with watersheds having high fen cover in which acidity is largely generated by exchange of cations for hydrogen ions.

Oil sands plants were established in the Birch Mountains area in the 1960's and 1970's. Stratigraphic studies of Otasan Lake (L23) using diatoms, indicate that the lake was originally alkaline at about 8220 B.P. prior to the development of significant peatland cover (Prather, 1993). An abrupt change to slightly acidic conditions occurred around 5200 B.P. corresponding to increased peatland cover in the watershed (Prather, 1993). Peatlands are known to have expanded significantly in other parts of Alberta after 6000 B.P. (Zoltai and Vitt, 1990).

In Alberta, the oil sands have the highest emissions of sulphur dioxide, maximum annual mean SO_2 concentration of 34.47 $\mu g/m^3$, with sulphate deposition decreasing rapidly from this point source (Cheng *et al.*, 1995). As the Birch Mountains Upland is upwind from the predicted emissions plume (see Cheng, 1994), atmospheric pollutant contributions should be low. No significant relationship was observed between sulphate concentrations in the lakes and lake pH ($r^2 = 0.008$, $p = 0.657$), also suggesting that acidic deposition from emission sources has been limited in the Birch Mountains. There is no evidence from this study that these lakes were acidified in recent time due to acid emitting industrial development; however, the current acid-sensitive status of the lakes needs to be carefully monitored for potential future effects from these industrial sources.

6. Conclusions

The extent off peatland terrain in watersheds plays an important role in determining acidity/alkalinity status of lakes on uplands in northeastern Alberta. Fens are particularly important followed by bogs and shallow organic deposits, with all acid-sensitive lakes occurring in watersheds with greater than 30% peatland cover. Lake morphometry and watershed features such as slope do not appear to directly explain lake acidity/alkalinity, however, they are related to nutrient status and TDS. Lake acidity appears to have been initially generated during the mid-Holocene corresponding to a period of peatland expansion in northern Alberta.

Acknowledgments

Funding was provided by NSERC Research Grant (A–6390) and a Central Research Fund (University of Alberta) grant to Dale Vitt. Assistance in the field was provided by Drs. Peter Kuhry, Colleen Prather, Malcolm Sargent and Jiri Vana, for which the authors are grateful. Discussions with René Belland and Barbara Nicholson improved this manuscript. The authors also thank Bryan Kemper for critical suggestions and Alberta Environmental Protection for providing much of the logistic support. Comments of three anonymous reviewers improved this manuscript and are appreciated.

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