Physical and chemical limnology of 24 lakes located between Yellowknife and Contwoyto Lake, Northwest Territories (Canada)

Reinhard Pienitz, John P. Smol, and David R.S. Lean

Abstract: Data on the water chemistry and limnology of 24 lakes located between Yellowknife (62°27′N, 114°21′W) and Contwoyto Lake (65°30′N, 110°00′W) in the central Northwest Territories were examined using principal components analysis and other statistical techniques. The study sites were mostly shallow (Z_{max} = 2.5–25 m; mean = 8.2 m), nutrient-poor (3.4–12.7 μg total phosphorus/L; mean = 6.6 $\mu g \cdot L^{-1}$), low-alkalinity lakes. Water was typically low in solutes (specific conductance near 0–100 $\mu S \cdot cm^{-1}$), with slightly acidic to alkaline pH (6.2–8.9). Levels of all nutrients and major ions showed identical trends of decreasing concentrations with increasing latitude, with the highest concentrations generally in lakes with conifer-forested catchments in the south.

Résumé : Les données sur les caractéristiques chimiques et limnologiques de 24 lacs situés entre Yellowknife (62°27′N, 114°21′W) et le lac Contwoyto (65°30′N, 110°00′W) dans le centre des Territoires du Nord-Ouest (T.N.-O.) ont été examinées à l'aide de l'analyse des composantes principales. Les sites d'étude étaient pour la plupart des lacs peu profonds (Z_{max} = 2,5 à 25 m; moyenne = 8,2 m), pauvres en éléments nutritifs (3,4 à 12,7 $\mu g \cdot L^{-1}$ en phosphore totale, moyenne = 6,6 $\mu g \cdot L^{-1}$) et de faible alcalinité. De manière typique, l'eau était pauvre en solutés (conductivité électrique près de 0 à 100 $\mu S \cdot cm^{-1}$), et son pH variait de légèrement acide à alcalin (6,2 à 8,9). Les concentrations de tous les éléments nutritifs et des ions majeurs ont montré des tendances identiques, c.-à-d. qu'ils diminuaient avec l'augmentation de la latitude, les concentrations les plus élevées se trouvant généralement dans les lacs méridionaux avec forêts de conifères dans le bassin versant.
[Traduit par la Rédaction]

Introduction

This is the second of two papers (Pienitz et al. 1997) related to the chemical and limnological characteristics of lakes from the Canadian Arctic. Here we report on the results obtained during a survey of 24 lakes located between Yellowknife and Contwoyto Lake in the Northwest Territories. This survey was designed to examine the relationship between algal distributions and environmental variables (Pienitz and Smol 1993). The lakes are distributed across treeline along a latitudinal gradient (62°47′–65°27′N) that includes a strong vegetational gradient of boreal forests in the south to arctic tundra conditions in the north (Fig. 1). In addition to discussing the water chemistry and limnological characteristics of lakes within the study area, we also present a regional comparison of our results with data obtained from previous investigations in the area.

Received October 11, 1995. Accepted July 31, 1996.
J13106

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Although some water chemistry data have been reported for several lakes located in the vicinity of Yellowknife as part of assessments of their fishery potential (e.g., Healey and Woodall 1973*a*, 1973*b*; Wallace and Hardin 1975; Falk 1979*a*, 1979*b*; Moore 1979, 1981; Moore et al. 1979; Patalas 1984), most of the data are restricted to single observations of limnological variables and very few complete ion analyses. Despite the relatively large number of these earlier studies, information on the limnological characteristics of lakes in more remote areas of the Northwest Territories remains sparse.

The objectives of the present paper are the same as those outlined in Pienitz et al. (1997), namely to describe the physical and chemical characteristics of our study sites. We also attempted to identify patterns in limnological conditions and to relate these patterns to watershed characteristics. For this purpose, we applied principal components analysis (PCA), an ordination technique that is useful for detecting the internal structure in data sets including a large number of interrelated variables (Van Tongeren et al. 1992). This study should provide reference data for evaluating future changes in the limnological conditions of northern lakes.

Description of study area

Regional climate and hydrology

The more than 500 km long south–north transect that makes up the study area spans three major ecoclimatic provinces (Boreal, Subarctic, Arctic), including the boundaries between high boreal, low subarctic, high subarctic, and low arctic ecoclimatic regions (Ecoregions Working Group

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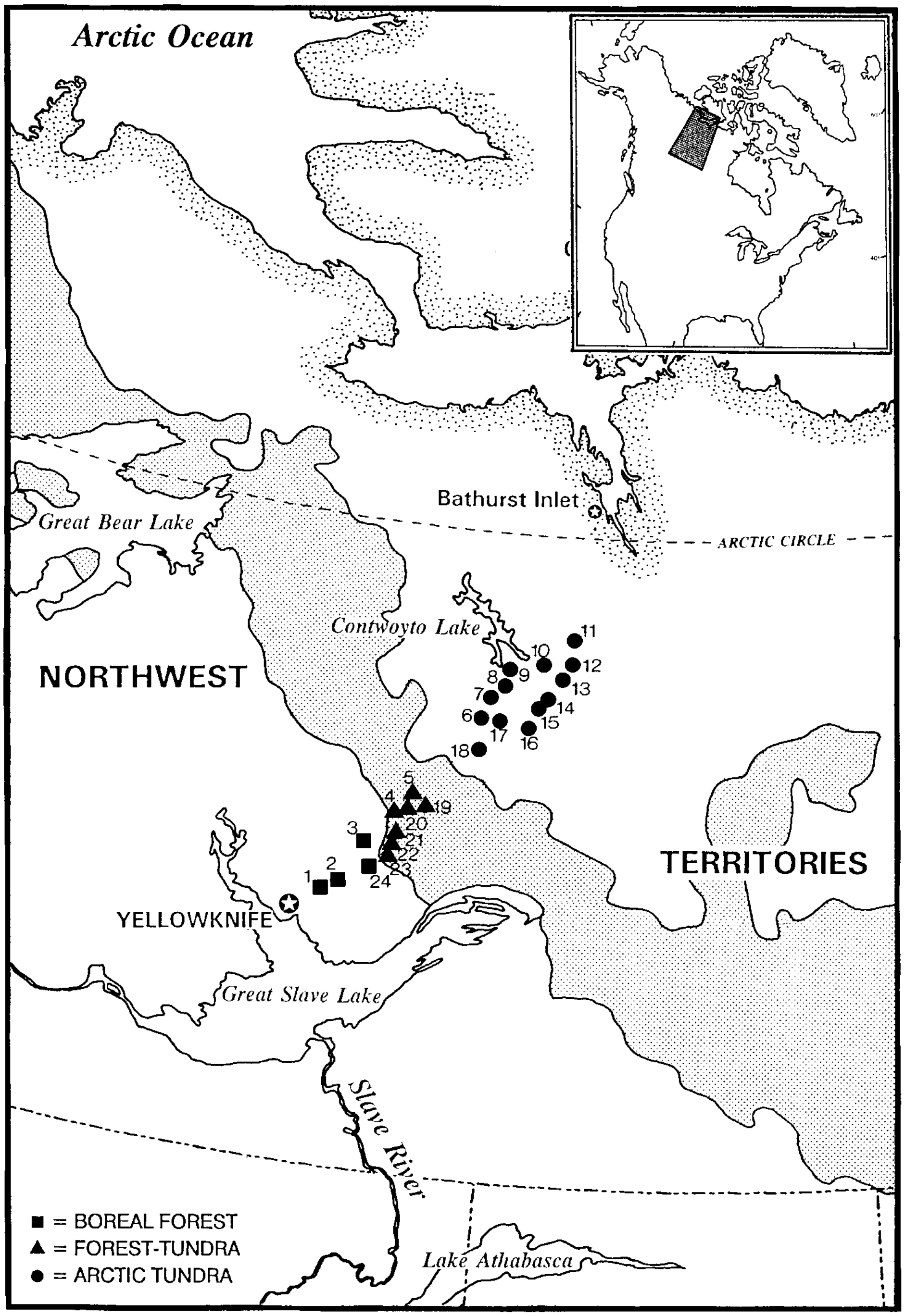
Fig. 1. Location of the 24 study sites and major towns in the central Northwest Territories.



1989). It crosses the steep climatic gradients that characterize the treeline region (summarized in Table 1). Sharp declines in mean annual precipitation and temperature are due to large differences in climate that prevail south and north of the mean summer position of the Arctic Front (Bryson 1966) as well as changes in albedo from forested to treeless areas (Hare and Ritchie 1972).

Lakes within the boreal forest near Yellowknife are usually ice covered by late October and break up in late May to early June (Environment Canada 1985–1991). In small- to medium-sized tundra lakes (50–250 ha), such as sites 6–18, the ice cover forms about 2 weeks earlier and usually remains until the end of June (ice reports, Yellowknife weather station). Thus, the southern lakes have nearly 5 months of open water and a growing season at least 4–5 weeks longer than those in the north. On small lakes, about 1–1.5 m of ice forms (Healey and Woodall 1973*a*; G.M. MacDonald, UCLA, personal communication). In 1991, some of the larger lakes in the northern part of the study area near Contwoyto Lake were still partly ice covered on July 12.

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Table 1. Climate data from the study area.

	Yellowknife (62°27′N, 114°21′W)	Contwoyto Lake (65°30′N, 110°00′W)
January mean daily air temperature (°C)	−28.8	−32.1
July mean daily air temperature (°C)	16.3	9.7
Mean annual daily temperature (°C)	−5.4	−12.0
Mean annual precipitation (mm)	266.7	251.3
Growing degree-days above 5°C	1027.1	339.8

The study area belongs to the Precambrian Shield (Canadian Shield) geological region, which is characterized by rolling terrain with gentle relief. The Yellowknife area lies within the Slave Structural Province, which is an Archean craton comprising numerous supracrustal belts and extensive gneissic–granitoid plutons (Padgham and Fyson 1992). Supracrustal rocks are characterized by a predominance of sedimentary over volcanic rocks and are collectively termed the Yellowknife Supergroup (Henderson 1970, 1981). According to Padgham and Fyson (1992), the Yellowknife Supergroup consists of three distinct assemblages of which the most widespread and abundant consists of metasedimentary turbidites. The scouring action of inland glaciers left ridge tops and steeper slopes nearly till free and lower slopes and valleys with a shallow overburden of coarse glacial till. Most of the numerous lakes in the area occupy ice-scour depressions in bedrock (Livingstone 1966) whereas extensive muskegs and bogs result from poor drainage in these regions of low relief. Soil conditions are influenced by permafrost, which is continuous north of the treeline and discontinuous throughout the rest of the region. For more detailed information on the geology and glacial history of the study area, refer to Pienitz (1993).

Vegetation

Boreal forest, forest–tundra, and tundra comprise the vegetation of the study area. The forest is characterized by a closed or continuous canopy, with *Picea mariana*, *Picea glauca*, *Larix laricina*, *Pinus banksiana*, *Betula papyrifera*, *Populus tremuloides*, and *Populus balsamifera*. Poorly drained soils are extensive and are usually dominated by black spruce (Rowe 1972).

Moving northward to the forest–tundra, trees are restricted to areas with favourable local conditions of slope, aspect, and edaphic conditions. Forest patches are dominated by *Picea mariana*, but may include *Picea glauca* and *L. laricina*. Open areas are occupied by *Alnus crispa*, *Betula glandulosa*, *Salix* spp., and diverse sedges, grasses, herbs, mosses, and lichens. Peatlands often include *Picea mariana* with an understory of herbs and shrubs, including *A. crispa*, *B. glandulosa*, *Myrica gale*, sedges, heaths, and *Sphagnum* spp.

Further north the forest disappears, although lone individuals or small stands of black spruce krummholz can be found well beyond the mapped limits of the forest–tundra. The tundra vegetation includes *A. crispa*, *B. glandulosa*, *Salix* spp., grasses, sedges, herbs, as well as mosses and lichens. Vegetation in low-lying areas is dominated by members of the Cyperaceae, especially *Carex* and *Eriophorum*. On upland sites, characterized by exposed bedrock, tundra herbs and lichens are common.

Materials and methods

The study sites were sampled on July 12, 1991, using a helicopter equipped with pontoons. All 24 lakes are unnamed, and therefore are referred to as sites 1–24. Full details of field sampling methods and analytical protocols are provided in Pienitz et al. (1997) and the *Analytical Methods Manual* (Environment Canada 1979). Water chemistry analyses were performed by the National Water Research Institute (Burlington, Ont.). For logistical reasons, no measurements of O_2 were carried out.

Data analysis

The physical and chemical characteristics of the 24 sampling sites are shown in Tables 2 and 3, along with their respective minimum, maximum, median, and mean values. These data included water chemistry (pH, specific conductance (COND), total unfiltered phosphorus (TPU), total filtered phosphorus (TPF), soluble reactive phosphorus (SRP), nitrite (NO_2), nitrate (NO_3), ammonia (NH_3), total Kjeldahl nitrogen (TKN), total nitrogen (TN), particulate nitrogen (PN), particulate organic carbon (POC), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), silica (SiO_2), chloride (Cl), sulphate (SO_4), sodium (Na), potassium (K), calcium (Ca), iron (Fe), and manganese (Mn)), Secchi depth (TRANS), surface water temperature (TEMP), maximum depth (DEPTH), lake area (AREA), altitude (ALT), latitude (LAT), and longitude (LONG), shortest distance from northern treeline (DIST), as well as concentrations of uncorrected chlorophyll *a* (CHLAU) and corrected chlorophyll *a* (CHLAC). The above abbreviations in parentheses correspond to the labels used for all 36 variables in the figures and tables.

In general, criteria for initial data screening and subsequent data transformation followed those outlined in Pienitz et al. (1997). The variables DIC, Ca, Na, K, Cl, Fe, and COND were positively skewed, and therefore were $\ln(x + 1)$ transformed to normalize distributions (Zar 1984), where x is the environmental variable under consideration.

Patterns of correlation (discussed below) between the variables were identified from a Pearson correlation matrix (Table 4) with Bonferroni-adjusted significance values (Wilkinson 1988). We used PCA, available on the computer program CANOCO 3.1 (Ter Braak 1990*a*, 1990*b*), to summarize the major patterns of variation within the data and to ordinate the lakes with respect to their chemical and limnological characteristics. Catchment vegetation (FOREST, closed-canopy boreal forest; WOOD, forest–tundra and lichen–woodland; TUNDRA, arctic tundra) was included as binary codes (value 0 or 1) in the PCA.

A PCA correlation biplot was derived from a PCA of the physical, chemical, and environmental data (Fig. 2). The five environmental variables LAT, ALT, FOREST, WOOD, and TUNDRA, as well as the biological variable CHLAU, were included only as passive

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Table 2. Field data collected in 1991 for the 24 lakes.

Lake No.	LAT (°N)	LONG (°W)	ALT (m)	AREA (ha)	Z_{max} (m)	pH	TEMP (°C)	COND (µS · cm^{-1})	TRANS (m)	DIST (km)
Boreal forest										
1	62.47	113.40	274	180.3	13.0	8.5	14.5	100	4.8	−120.0
2	62.50	113.28	305	83.4	25.0	8.0	14.5	48	3.3	−112.5
3	63.18	112.55	396	223.7	10.0	8.7	13.0	30	7.5	−55.0
24	63.06	112.42	380	301.1	9.0	8.9	14.0	32	3.0	−68.0
Forest–tundra										
4	63.33	112.22	427	113.8	2.5	8.2	12.0	12	2.0	−15.0
5	63.43	112.05	427	79.2	3.0	7.7	12.0	11	**3.0**	12.5
19	63.35	111.54	450	130.5	7.0	8.2	13.0	0	2.5	12.5
20	63.39	112.08	427	288.4	6.0	8.2	11.5	0	2.5	5.0
21	63.22	112.23	427	97.5	2.5	7.5	14.0	20	2.0	−30.0
22	63.16	112.28	389	283.8	10.0	7.8	13.0	20	2.8	−47.5
23	63.13	112.29	396	98.2	5.5	8.8	14.0	22	2.5	−52.5
Arctic tundra										
6	64.37	110.43	457	254.4	8.0	8.0	10.0	10	4.0	130.0
7	64.51	110.25	471	488.5	5.0	8.1	8.0	10	**5.0**	157.5
8	64.55	110.12	457	111.6	6.0	7.9	9.0	10	5.5	170.0
9	65.06	110.13	488	262.5	8.0	8.2	8.0	8	5.0	185.0
10	65.13	109.11	457	175.6	20.0	8.6	7.5	9	6.5	220.0
11	65.27	108.33	427	263.1	5.0	8.4	9.0	8	4.5	262.5
12	65.16	108.29	396	421.1	15.0	8.0	8.0	10	5.0	242.5
13	65.05	108.30	442	244.5	8.5	6.3	8.5	10	6.5	227.5
14	64.50	109.11	440	68.3	3.5	7.4	8.0	8	2.3	195.0
15	64.47	109.13	440	52.7	3.5	7.5	9.5	8	**3.5**	190.0
16	64.31	109.38	430	501.7	7.0	6.2	9.5	8	4.3	155.0
17	64.35	110.17	457	119.8	6.0	6.2	10.5	8	3.5	142.5
18	64.18	110.38	459	317.1	8.0	8.0	10.5	8	3.5	107.5
Minimum	62.47	108.29	274	52.7	2.5	6.2	7.5	0	2.0	−120.0
Maximum	65.27	113.40	488	501.7	25.0	8.9	14.5	100	7.5	262.5
Median			430	223.7	7.0	8.0	10.5	10	3.5	130.0
Mean			421.6	215.0	8.2	7.9	10.9	17.1	3.9	79.8

Note: TRANS, Secchi disk transparency (bold numbers are readings where TRANS = Z_{max}); DIST, shortest distance from northern treeline (defined as 80% tree cover).

variables (represented by arrows with broken lines in Fig. 2). In addition, the five variables NO_2, NO_3, NH_3, SRP, and Mn were excluded from the analysis because their concentrations were frequently below or near the analytical detection limit. In all cases, the criterion level for significance was $P \leq 0.05$.

Results and discussion

The correlation matrix of environmental variables shows that many of the variables were highly correlated (Table 4). As expected, altitude and latitude were both negatively correlated with temperature, conductivity, major ions, and macronutrients (TPU, TN). Lake depth had little correlation with lake water chemistry. DOC was highly correlated with LAT, TEMP, and nutrients whereas DIC was highly correlated with Ca ($r = 0.99$, $P < 0.01$), as well as Cl, Na, and K. Both DOC and DIC were highly correlated with catchment vegetation. The inclusion of a limited range of catchment characteristics (albeit run as passive variables in the PCA) suggested that levels of all organic forms of nutrients and major ions were generally highest in lakes with conifer-forested catchments, with concentrations decreasing as distance from the northern treeline increased.

Physical and geographic–environmental variables

A regular shoreline, a circular outline, and the absence of major inflows were the main criteria we used to select lakes. The altitudinal gradient was comparatively small in this calibration set of lakes, since lake elevation was quite uniform, ranging only from 274 to 488 m above sea level (Table 2).

Lake surface area varied between 53 (15) and 502 ha (16), the average area being 215 ha (Table 2). Thus, we were dealing mainly with small shallow lakes with maximum depths ranging from 2.5 (4, 21) to 25 m (2).

Summer surface water temperatures were low and showed a strong latitudinal gradient, with a particularly sharp drop in temperature in lakes located north of the treeline. Temperatures ranged from 14.5°C (1, 2) in the boreal forest to 7.5°C (10) in the tundra and averaged 10.9°C for all lakes. The aver-

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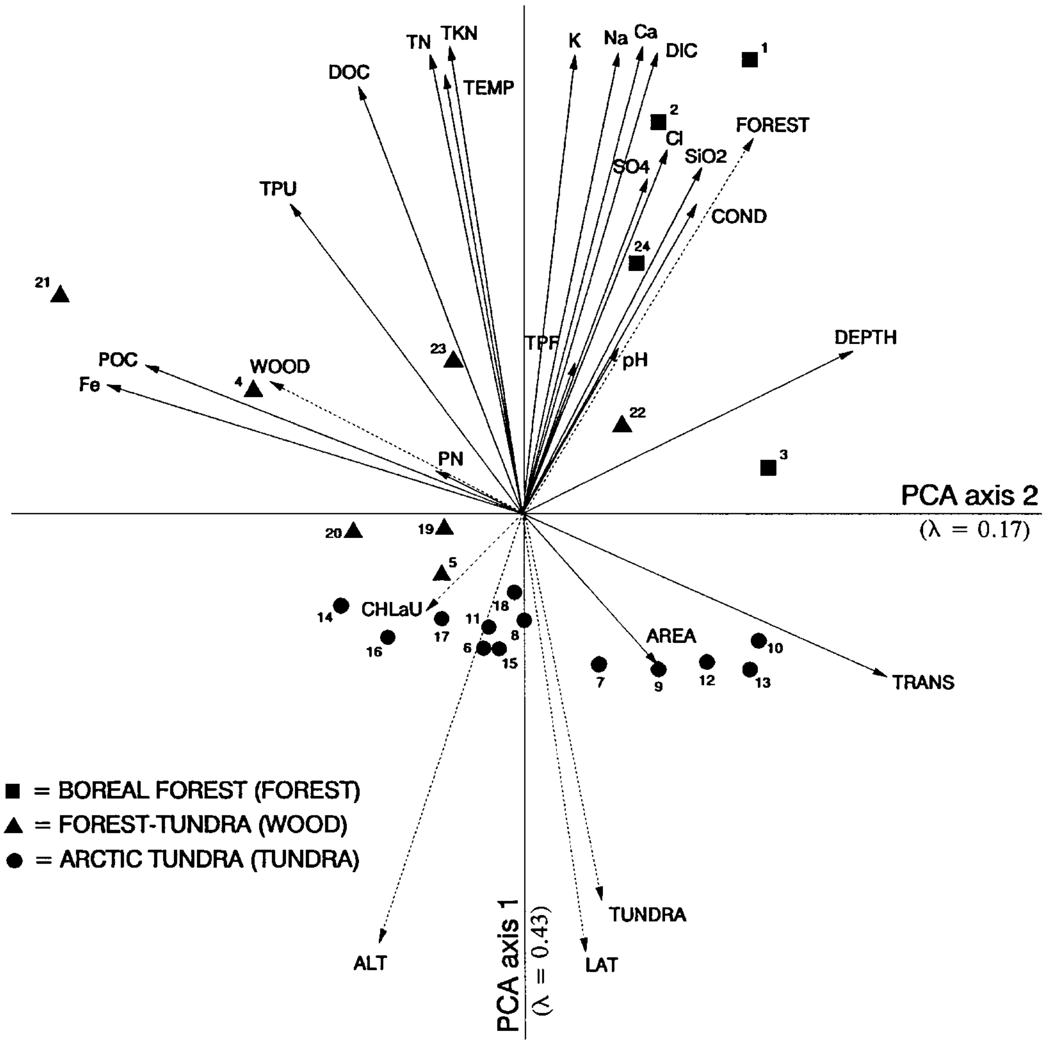
Fig. 2. PCA of the physical, chemical, and environmental variables in the 24-lake data set. Passive variables are represented by arrows with broken lines.



age water temperature was 14.0°C in boreal forest and 12.8°C in forest–tundra lakes whereas it was considerably lower in arctic tundra lakes (8.9°C). A strong relationship exists between thermal features (i.e., lake surface water temperature) of lakes and climatic gradients (represented by latitude in Fig. 3). The temperature pattern observed in our lake transect was consistent with results reported from studies of thermal regimes in North American lakes (e.g., Shuter et al. 1983; Robertson 1989; Hobbie et al. 1995).

Owing to logistic constraints of sampling from a helicopter, we could not obtain temperature profiles along this transect. Information available from previous investigations (Healey and Woodall 1973*a*, 1973*b*; Falk 1979*a*, 1979*b*) indicates that most lakes in the Yellowknife area stratify during the summer months. The unusually low water temperatures show that heat income during the open-water season of 1991 was minimal owing to a very cold and rainy summer.

The lowest water transparencies were observed in lakes surrounded by peatlands (most of which were found in the forest–tundra), where Secchi depths were commonly between 2.0 and 3.0 m (e.g., sites 4, 5, 21). The latter may be due to high loadings of humic compounds from terrestrial vegetation and soils in the drainage basin, as demonstrated by the relatively high concentrations of DOC, POC, and Fe (Table 3) in these coloured lakes.

Chemical variables

pH

Measurements of pH exhibited a high variability for lakes located in an area of relatively homogeneous geological and edaphic conditions, ranging from 6.2 to 8.9 (Table 2). All 24 lakes lie on granitoid basement rock and receive most of their drainage from similar rocks, although there are extensive outcrops of metasedimentary rocks (i.e., mainly carbonate-containing greywacke and mudstone turbidites belonging to the Burwash Formation of the Yellowknife Supergroup) in the Yellowknife area (Henderson 1981; Padgham and Fyson 1992), where pH values tended to be higher. Likewise, locally elevated pH values may also be related to isolated, narrow

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Table 3. Water chemistry data (1991) for the 24 lakes.

Lake No.	TPU ($\mu g \cdot L^{-1}$)	TPF ($\mu g \cdot L^{-1}$)	SRP ($\mu g \cdot L^{-1}$)	NO_2 ($\mu g \cdot L^{-1}$)	NO_3 ($\mu g \cdot L^{-1}$)	NH_3 ($\mu g \cdot L^{-1}$)	DOC ($mg \cdot L^{-1}$)	DIC ($mg \cdot L^{-1}$)	TKN ($\mu g \cdot L^{-1}$)	TN ($\mu g \cdot L^{-1}$)	SiO_2 ($mg \cdot L^{-1}$)	SO_4 ($mg \cdot L^{-1}$)
Boreal forest												
1	9.5	5.2	0.6	2.0	ADL	ADL	5.6	12.1	352	425	0.41	2.1
2	9.6	7.6	0.8	2.0	ADL	13.0	8.5	5.6	371	478	0.92	2.3
3	3.9	2.3	0.6	2.0	ADL	6.0	4.7	3.5	176	247	0.61	0.6
24	9.2	5.8	0.8	2.0	14.0	13.0	8.1	3.1	282	344	0.77	1.4
Forest–tundra												
4	9.6	4.7	1.0	3.0	ADL	12.0	8.7	0.4	325	389	0.32	1.4
5	3.6	2.7	0.5	ADL	ADL	9.0	4.0	0.6	178	242	0.24	0.3
19	6.1	3.2	1.3	3.0	ADL	6.0	4.9	0.6	173	260	0.34	1.2
20	5.2	4.0	0.6	1.0	ADL	12.0	4.5	1.1	183	264	0.13	0.9
21	12.7	7.8	1.1	3.0	ADL	6.0	9.1	1.7	321	429	0.16	0.8
22	6.5	5.3	0.7	3.0	ADL	8.0	5.7	2.1	203	267	0.64	1.4
23	5.9	5.7	0.8	2.0	ADL	9.0	6.4	2.4	270	375	0.38	1.0
Arctic tundra												
6	7.7	2.8	0.4	1.0	ADL	11.0	1.7	0.5	63	135	0.08	0.5
7	5.5	9.0	0.4	1.0	ADL	6.0	2.4	0.3	102	212	0.10	0.4
8	6.3	3.3	0.5	ADL	ADL	11.0	2.0	0.2	150	266	0.26	1.0
9	4.5	8.7	0.5	3.0	ADL	5.0	2.2	0.2	141	211	0.19	0.4
10	3.4	2.2	0.5	1.0	ADL	ADL	2.7	0.2	126	240	0.18	0.9
11	9.7	3.0	0.5	1.0	ADL	12.0	2.6	0.3	147	211	0.27	0.3
12	3.6	3.1	0.4	1.0	ADL	8.0	2.0	0.1	105	161	0.21	1.5
13	4.6	9.2	0.4	2.0	ADL	5.0	1.6	0.5	88	147	0.26	1.4
14	7.3	2.7	0.6	1.0	ADL	8.0	3.2	0.2	160	233	0.19	1.0
15	5.5	1.8	0.5	1.0	ADL	9.0	2.5	0.3	123	164	0.18	0.7
16	7.7	2.9	0.6	3.0	ADL	ADL	3.2	0.2	32	146	0.19	1.0
17	4.0	2.9	0.5	2.0	ADL	ADL	2.4	0.3	115	222	0.33	0.9
18	6.7	2.3	0.6	3.0	ADL	6.0	3.8	0.1	157	213	0.29	1.2
Minimum	3.4	1.8	0.4	1.0	ADL	5.0	1.6	0.1	32	135	0.08	0.3
Maximum	12.7	9.2	1.3	3.0	14.0	13.0	9.1	12.1	371	478	0.92	2.3
Median	6.3	3.3	0.6	2.0		8.0	3.8	0.5	160	242	0.26	1.0
Mean	6.6	4.5	0.6	1.9		8.1	4.3	1.5	181.0	261.7	0.32	1.0

Note: ADL, at detection limit; TPU, total phosphorus (unfiltered); TPF, total phosphorus (filtered); SRP, soluble reactive phosphorus; CHLAU, chlorophyll *a* (uncorrected); CHLAC, chlorophyll *a* (corrected).

belts of volcanic rocks of the Supergroup, which include both mafic–felsic series and calc–alkaline intermediate series (e.g., Frith 1987; Cunningham and Lambert 1989).

In general, fresh waters within Shield areas in the Northwest Territories are known to be highly sensitive to acidification because of their low buffering capacity (Tibbatts et al. 1987). Previous surveys of lakes in the area between Yellowknife and Contwoyto Lake yielded consistently low and uniform pH values between 6.3 and 7.3 (e.g., Moore 1979; Tibbatts et al. 1987). However, Healey and Woodall (1973*b*) and Falk (1979*a*) reported summer pH values ranging from 7.4 to 9.3 and from 6.6 to 7.9, respectively, for several lakes in the Yellowknife area.

Conductivity and major ions

In general, the surface waters of our study sites were very dilute. Conductivity was consistently low and ranged from 0 to 100 $\mu S \cdot cm^{-1}$ (mean = 17.1 $\mu S \cdot cm^{-1}$) (Table 2), which was similar but slightly lower than previously reported values (10–350 $\mu S \cdot cm^{-1}$) for arctic lakes on Precambrian rock (Rawson 1960; Healey and Woodall 1973*a*; Hobbie 1984; Welch 1985; Welch and Legault 1986). Most variability seemed to be related to local vegetation; values in boreal forest lakes greatly exceeded those recorded in forest–tundra and arctic tundra lakes.

The concentrations of major ions were also consistently low. The data obtained for SO_4, Ca, Na, K, and Cl yielded identical trends of decreasing concentrations from boreal forest to tundra sites. The relative concentration of cations in all lakes was Ca > Na > K (Table 3). All but one variable (SO_4) tended to be highly positively correlated with each other ($P < 0.05$), as well as with DIC (Table 4). In lakes along the Yellowknife – Contwoyto Lake transect, where granitic–gneissic rocks predominate, Ca levels were very low, with an average summer concentration of 2.2 $mg \cdot L^{-1}$ for all lakes (Table 3). This value is much lower than that reported from Yukon lakes (mean = 19.7 $mg \cdot L^{-1}$; Pienitz et al. 1997), where waters from regions with deposits of limestone, dolo-

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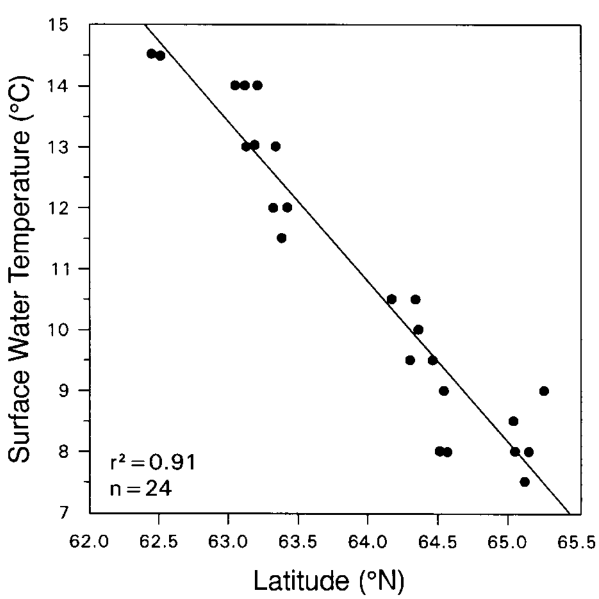
Table 3 (*concluded*).

Ca (mg·L⁻¹)	Na (mg·L⁻¹)	K (mg·L⁻¹)	Cl (mg·L⁻¹)	CHLAU (μg·L⁻¹)	CHLAC (μg·L⁻¹)	POC (μg·L⁻¹)	PN (μg·L⁻¹)	Fe (μg·L⁻¹)	Mn (μg·L⁻¹)	TN:TP	POC:PN
13.5	4.66	1.95	4.8	0.8	0.5	488	60	36.6	4.0	45	8
6.3	1.82	1.16	1.0	0.8	0.6	641	94	31.2	2.0	50	7
5.1	0.81	0.58	0.7	0.4	0.2	390	58	17.5	3.0	63	7
4.9	1.55	0.67	2.1	0.6	0.4	525	46	23.9	ADL	37	11
1.2	0.79	0.51	0.7	0.8	0.6	532	50	178.0	8.0	41	11
1.1	0.67	0.40	0.6	0.8	0.7	483	52	43.6	4.0	67	9
1.3	0.67	0.42	0.8	0.7	0.3	580	73	30.1	ADL	43	8
1.6	0.77	0.60	0.7	0.7	0.4	899	69	44.3	3.0	51	13
2.6	0.93	0.70	0.8	1.4	0.9	1080	94	210.0	12.0	34	11
2.9	0.79	0.68	0.6	0.6	0.2	465	50	18.7	ADL	41	9
3.4	0.83	0.83	0.6	0.8	0.5	592	92	17.0	10.0	64	6
0.7	0.44	0.46	0.6	0.5	0.1	595	60	49.3	ADL	18	10
0.6	0.46	0.37	0.7	1.2	0.9	484	98	16.1	ADL	39	5
0.5	0.42	0.34	0.5	0.8	0.2	550	104	27.2	ADL	42	5
0.6	0.38	0.33	0.6	1.3	1.1	375	56	10.2	ADL	47	7
0.7	0.42	0.34	0.8	0.8	0.1	387	102	10.3	ADL	71	4
0.7	0.46	0.30	0.6	1.0	0.7	521	52	34.3	ADL	22	10
0.7	0.44	0.35	0.6	1.1	0.4	484	44	17.1	ADL	45	11
1.2	0.36	0.27	0.5	0.9	0.8	354	46	7.5	ADL	32	8
0.7	0.38	0.40	0.5	1.0	0.8	578	61	134.0	ADL	32	9
0.7	0.42	0.38	0.6	1.8	1.4	528	29	21.7	ADL	30	18
0.7	0.46	0.47	0.7	0.7	0.6	598	100	53.1	26.0	19	6
0.6	0.46	0.44	0.5	0.6	0.2	549	94	51.3	4.0	56	6
0.8	0.40	0.34	0.8	0.7	0.3	577	42	33.5	2.0	32	14
0.5	0.36	0.27	0.5	0.4	0.1	354	29	7.5	2.0	18	4
13.5	4.66	1.95	4.8	1.8	1.4	1080	104	210.0	26.0	71	18
1.1	0.46	0.44	0.7	0.8	0.5	532	60	31.2	4.0	42	9
2.2	0.82	0.55	0.9	0.9	0.5	552.3	67.8	46.5	4.3	43	9

Fig. 3. Plot of surface water temperature versus latitude in the 24-lake data set.



mite, and gypsum are more prevalent. Waters with [Ca] ≤ 10 mg · L^{-1} are usually oligotrophic. The higher levels of Ca in lakes near Yellowknife (sites 1–3, 21–24) may be related to the more widespread sedimentary rocks of the Burwash Formation (see above).

Nutrients and carbon

Patterns in nutrient concentrations paralleled our observations of ionic concentrations, with values decreasing from forested to barren landscapes. Concentrations of dissolved nutrients were generally low; many variables (SRP, NO_3, NO_2, NH_3, and SiO_2) were near or below analytical detection limit, particularly in the arctic tundra lakes. NO_3 levels were consistently below the analytical detection limit (11.0 μg · L^{-1}) in all but one lake (24). The concentrations of SiO_2 were very low, ranging from 0.08 to 0.92 mg · L^{-1} (Table 3).

The concentrations of both DIC and DOC displayed strong latitudinal gradients, with concentrations decreasing as latitude increased. This strong relationship was also demonstrated in the highly significant negative correlation between DIC–DOC and LAT (Table 4; Fig. 2). The concentrations of DIC ranged from 0.1 to 12.1 mg · L^{-1} and were generally

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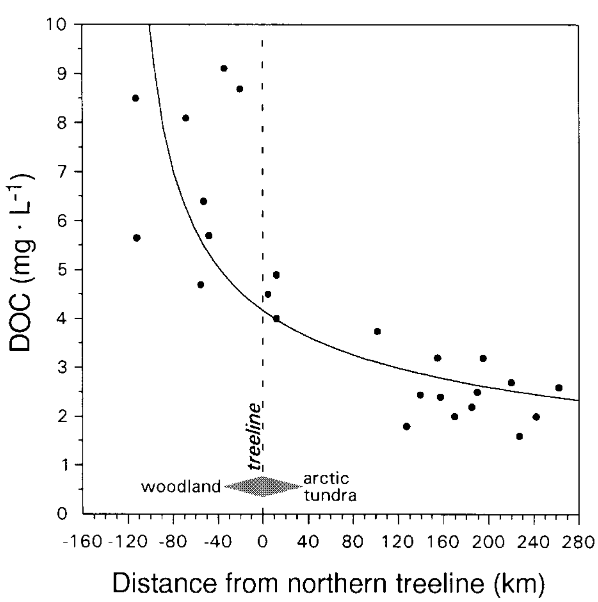
Table 4. Pearson correlation matrix for environmental variables (following transformations) measured in the 24 lakes included in the PCA.

	LAT	LONG	ALT	DEPTH	AREA	TEMP	TRANS	COND	pH	ZOOPL	CHLAU	CHLAC	TPU	TPF	SRP	NO_2	NO_3
LONG	−0.96**																
ALT	0.69	−0.59															
DEPTH	−0.11	0.11	−0.52														
AREA	0.31	−0.29	0.13	0.09													
TEMP	−0.95**	0.91**	−0.68	0.09	−0.34												
TRANS	0.46	−0.38	0.08	0.38	0.32	−0.45											
COND	−0.36	0.36	−0.65	0.35	−0.10	0.38	0.20										
pH	−0.32	0.41	−0.20	0.22	−0.08	0.34	−0.06	−0.02									
ZOOPL	0.01	−0.05	−0.05	0.03	0.30	0.02	0.22	0.03	0.05								
CHLAU	0.35	−0.37	0.21	−0.24	−0.13	−0.34	−0.09	−0.04	−0.18	−0.41							
CHLAC	0.17	−0.21	0.11	−0.35	−0.11	−0.20	−0.15	0.03	−0.28	−0.40	0.86**						
TPU	−0.42	0.36	−0.40	−0.09	−0.13	0.47	−0.47	0.35	0.02	−0.17	0.09	0.15					
TPF	−0.14	0.21	−0.13	0.09	0.14	0.14	0.01	0.27	−0.05	−0.24	0.26	0.40	0.25				
SRP	−0.62	0.56	−0.20	−0.10	−0.36	0.66	−0.60	−0.10	0.31	−0.21	−0.08	−0.05	0.52	0.12			
NO_2	−0.37	0.36	−0.07	−0.05	0.06	0.43	−0.27	0.09	−0.12	0.04	−0.15	−0.01	0.33	0.30	0.62		
NO_3	−0.22	0.21	−0.18	0.03	0.14	0.27	−0.13	0.22	0.38	−0.03	−0.18	−0.09	0.23	0.12	0.15	0.03	
NH_3	−0.25	0.24	−0.23	0.00	−0.20	0.25	−0.39	0.01	0.34	−0.24	−0.12	−0.06	0.36	−0.09	0.11	−0.33	0.36
TKN	−0.79**	0.79**	−0.70	0.19	−0.47	0.80**	−0.43	0.50	0.40	−0.17	−0.04	0.03	0.61	0.32	0.61	0.31	0.23
TN	−0.78**	0.79**	−0.66	0.23	−0.46	0.77**	−0.40	0.49	0.38	−0.15	−0.07	−0.03	0.60	0.35	0.63	0.30	0.18
PN	−0.06	0.10	0.07	0.18	−0.02	0.02	0.06	−0.01	−0.02	0.03	−0.14	−0.24	0.07	0.16	0.14	−0.01	−0.20
POC	−0.36	0.31	−0.05	−0.25	−0.16	0.37	−0.61	−0.21	0.01	0.08	0.15	0.07	0.56	0.06	0.47	0.12	−0.04
DOC	−0.83**	0.80**	−0.56	0.09	−0.31	0.84**	−0.55	0.38	0.35	−0.08	−0.13	−0.02	0.65	0.29	0.77**	0.49	0.34
DIC	−0.82**	0.79**	−0.89**	0.39	−0.20	0.82**	−0.05	0.65	0.53	0.08	−0.27	−0.14	0.39	0.28	0.30	0.18	0.25
SiO_2	−0.63	0.59	−0.68	0.51	−0.16	0.66	−0.06	0.53	0.25	−0.11	−0.41	−0.26	0.23	0.17	0.33	0.30	0.45
Cl	−0.53	0.50	−0.72*	0.30	0.02	0.50	0.01	0.52	0.33	0.04	−0.14	−0.08	0.40	0.14	0.16	0.12	0.40
SO_4	−0.49	0.36	−0.74*	0.59	−0.09	0.45	−0.14	0.39	0.04	0.04	0.22	−0.22	0.31	0.20	0.31	0.29	0.15
Na	−0.76**	0.73*	−0.89**	0.36	−0.17	0.74*	−0.13	0.60	0.31	−0.03	−0.19	−0.09	0.48	0.23	0.31	0.17	0.27
K	−0.80**	0.75*	−0.89**	0.36	−0.20	0.76*	−0.20	0.61	0.24	0.07	−0.19	−0.10	0.47	0.23	0.31	0.20	0.10
Ca	−0.82**	0.78**	−0.89**	0.39	−0.18	0.83**	−0.06	0.65	0.36	0.13	−0.28	−0.14	0.39	0.27	0.35	0.25	0.29
Fe	−0.32	0.25	−0.04	−0.43	−0.31	0.27	−0.66	−0.03	−0.22	−0.08	0.00	0.06	0.63	−0.20	0.45	0.17	−0.07
Mn	−0.28	0.22	−0.09	−0.30	0.05	0.30	−0.29	0.13	−0.23	0.34	−0.03	0.10	0.34	0.03	0.34	0.43	−0.12
DIST	0.99**	−0.98**	0.67	−0.14	0.27	−0.96**	0.40	−0.40	−0.39	−0.02	0.38	0.21	−0.39	−0.20	−0.60	−0.40	−0.25
FOREST	−0.61	0.59	−0.77**	0.51	−0.06	0.59	0.20	0.64	0.31	0.01	−0.32	−0.15	0.27	0.14	0.13	0.07	0.47
WOOD	−0.51	0.51	−0.02	−0.36	−0.30	0.51	−0.64	−0.29	0.25	−0.04	−0.08	−0.05	0.13	0.07	0.63	0.32	−0.13
TUNDRA	0.92**	−0.91**	0.59	−0.05	0.32	−0.91**	0.43	−0.22	−0.46	0.03	0.31	0.16	−0.32	−0.17	−0.68	−0.34	−0.23

Note: Significant correlations based on Bonferroni-adjusted probabilities: *, $P \le 0.05$; **, $P \le 0.01$.

Fig. 4. Plot of DOC concentrations versus distance from the northern treeline in the 24-lake data set.



highest in boreal forest and forest–tundra lakes in the vicinity of Yellowknife (sites 1–3, 20–24) (Table 3). This corresponds to an alkalinity range of approximately 0–1 mequiv. $\cdot$ L^{-1}, which was calculated from [DIC] and pH using the carbonate species relations in Stumm and Morgan (1981).

[DOC] ranged from 1.6 to 9.1 mg $\cdot$ L^{-1}, with a mean of 4.3 mg $\cdot$ L^{-1} for all lakes (Table 3). Because measurements of DOC were usually not included in standard water analyses of lakes in other regions, only a few values were available for comparison. Allochtonous DOC, composed largely of terrestrial humic compounds (humic and fulvic acids), is the primary source of DOC in oligotrophic waters (Wetzel 1983). According to Wetzel (1983) and Engstrom (1987), DOC concentrations in surface waters of small oligotrophic lakes in boreal regions are mainly a function of external humus loading from catchment vegetation and soils. This strong correlation between catchment vegetation and [DOC] is also evident from the Pearson correlation matrix of the present lake set (Table 4), as well as from Fig. 4. Strong colour and high [DOC] were characteristic of shallow basins surrounded by peatlands, especially in the forest–tundra and boreal forest zones.

The three phosphorus variables (TPU, TPF, and SRP) did not exhibit any pronounced gradient such as we recorded, for example, in the Yukon–Tuktoyaktuk survey of lakes (Pienitz et al. 1997). However, levels were generally highest in boreal

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Table 4 (*concluded*).

NH_3	TKN	TN	PN	POC	DOC	DIC	SiO_2	Cl	SO_4	Na	K	Ca	Fe	Mn	DIST	FOREST	WOOD
0.35																	
0.29	0.97**																
−0.17	0.02	0.26															
0.24	0.34	0.40	0.30														
0.34	0.89**	0.88**	0.07	0.46													
0.13	0.75*	0.73*	0.03	0.12	0.63												
0.32	0.59	0.56	−0.06	−0.15	0.60	0.69											
−0.03	0.56	0.52	−0.09	−0.01	0.39	0.74*	0.36										
0.11	0.56	0.54	−0.01	0.02	0.47	0.57	0.60	0.54									
0.12	0.77**	0.75*	0.00	0.13	0.61	0.92**	0.55	0.91**	0.64								
0.09	0.76*	0.76**	0.13	0.23	0.61	0.93**	0.52	0.79**	0.64	0.95**							
0.11	0.77**	0.74*	−0.03	0.10	0.67	0.99**	0.72	0.75*	0.60	0.91**	0.91**						
0.24	0.34	0.35	0.09	0.66	0.45	−0.01	−0.15	0.03	0.02	0.12	0.17	0.00					
−0.17	0.16	0.25	0.38	0.42	0.37	0.09	−0.14	0.03	−0.01	0.12	0.23	0.11	0.48				
−0.23	−0.81**	−0.79**	−0.05	−0.31	−0.84**	−0.83**	−0.65	−0.53	−0.46	−0.76*	−0.78**	−0.84**	−0.24	−0.26			
0.18	0.56	0.53	−0.06	−0.12	0.47	0.83**	0.77**	0.70	0.51	0.77**	0.69	0.84**	−0.10	−0.11	−0.62		
0.17	0.39	0.38	0.02	0.46	0.53	0.11	−0.01	−0.14	−0.03	0.08	0.14	0.13	0.35	0.36	−0.51	−0.29	
−0.28	−0.78**	−0.75*	0.03	−0.33	−0.83**	−0.72	−0.57	−0.40	−0.35	−0.65	−0.64	−0.75*	−0.24	−0.25	0.93**	−0.49	−0.70

forest and lowest in arctic tundra lakes. Interestingly, none of the three variables was significantly correlated ($P > 0.05$). TPU concentrations ranged from 3.4 to 12.7 $\mu g \cdot L^{-1}$ (mean = 6.6 $\mu g \cdot L^{-1}$). TN:TP ratios ranged from 18:1 to 71:1, with an average value of 43:1 for all 24 lakes (Table 3).

Concentrations of all nutrients were extremely low, thereby reflecting the oligotrophic nature of these lakes. Similarly low nutrient concentrations have been reported from tundra lakes located northeast of Yellowknife (Moore 1979), where concentrations of TP, NO_3, and SiO_2 usually did not exceed 3.0 $\mu g \cdot L^{-1}$, 10.0 $\mu g \cdot L^{-1}$, and 0.2 $mg \cdot L^{-1}$, respectively. Phosphorus and especially nitrogen are strongly retained by terrestrial tundra ecosystems (Chapin et al. 1980; Dowding et al. 1981), which may explain the tendency for freshwater ecosystems in tundra regions to be limited by both nitrogen and phosphorus. According to the general trophic classification of lakes and reservoirs in relation to phosphorus and nitrogen concentrations (Wetzel 1983), the mean values and ranges of TP and TN concentrations observed in the Yellowknife area indicate that all 24 lakes can be characterized as oligotrophic to ultraoligotrophic.

Iron and manganese

The concentrations of the trace metals Fe and Mn were lower than those reported from the Yukon. Their average concentrations were 46.5 and 4.3 $\mu g \cdot L^{-1}$, respectively (Table 3). Mn concentrations were extremely low (2.0–26.0 $\mu g \cdot L^{-1}$) and decreased below the analytical detection limit of 2.0 $\mu g \cdot L^{-1}$ in most of the lakes. Despite the low concentrations of trace metals, these elements can play an important role as micronutrients in limiting algal photosynthesis in oligotrophic lakes of arctic and temperate regions (e.g., Kalff 1968; Goldman 1972; Wetzel 1983; Hobbie 1984).

Biotic variables

Chlorophyll a

No clear pattern was evident from the CHLAU data, since all lakes had extremely low concentrations. CHLAU values ranged from 0.4 to 1.8 $\mu g \cdot L^{-1}$, averaging 0.9 $\mu g \cdot L^{-1}$ in all lakes (Table 3). Thus, according to Likens' (1975) classification, most of our lakes seemed to be oligotrophic whereas concentrations in two lakes (3, 6) fall into the ultraoligotrophic (0.01– 0.5 $\mu g \cdot L^{-1}$) category.

Principal components analysis

The eigenvalues for the four PCA axes were $\lambda_1 = 0.43$, $\lambda_2 = 0.17$, $\lambda_3 = 0.07$, and $\lambda_4 = 0.06$. Thus, the first two axes of the PCA captured 60% of the variance in the data. Almost all variables related to nutrients and major ions had high scores

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on the major PCA axis 1, which explained almost 43% of the total variance. The contrast in the relative size of the first two axes suggests that there is one overriding gradient of variation in the chemical data, namely axis 1 with the gradient from high to low organically bound nutrients and major ions. The passive variable LAT was negatively correlated with TEMP, COND, nutrients (TN, TKN, TPU, DIC, DOC, and SiO_2), and major ions (K, Na, Ca, SO_4, and Cl), as indicated by the arrows pointing more or less into the opposite direction of the LAT arrow (Fig. 2). Thus, the first axis effectively contrasted boreal forest and forest–tundra lakes (sites 1– 4, 22–24), having relatively high nutrient and major ion levels, with dilute arctic tundra sites (6–18), which clustered in the lower two quadrants of the ordination biplot. Site 21, which scored highest on axis 2, was a strongly coloured, shallow lake, which had the highest Fe and POC concentrations, as well as the lowest water transparency.

In a PCA correlation biplot, variables with high positive correlations generally have small angles between their biplot arrows, identifying groups of mutually redundant variables, such as TN and TKN, as well as K, Na, and Ca (Fig. 2). Variables with long arrows have high variance and are often the most important within the data (Jongman et al. 1987). The direction of each arrow indicates ascending values for each variable.

The lack of statistically significant relationships between CHLAU and the organically bound nutrients was no surprise, as chlorophyll *a* concentration largely depends on the loading of inorganic nutrients, which was not measured in these oligotrophic systems.

Fe, POC, TRANS, and DEPTH are loading highly on the second PCA axis, with Fe and POC being negatively correlated with TRANS and DEPTH. Their distributions basically illustrate a gradient in water colour, with lowest transparencies occurring in shallow lakes characterized by high concentrations in POC and Fe.

As expected, the passive variable LAT, which scored highly on the first PCA axis, exhibited highly significant negative correlations with both TEMP ($P < 0.01$) and DOC ($P < 0.05$) (Table 4; Fig. 2), thereby reflecting the strong climatic and vegetational gradients of the study area. Because the lakes were visited along a northeast-trending sampling transect (i.e., at a right angle to the northern treeline), LAT and LONG were highly negatively correlated ($r = -20.96$, $P < 0.01$) (Table 4).

Conclusions

The physical and chemical data gathered for the 24 study lakes reveal comparatively homogeneous conditions, with consistently low nutrient and ion concentrations and relatively little variability among sites. The dilute nature of the study lakes is typical for Shield regions, as the lakes drain bedrock that is highly resistant to chemical weathering. Our results also confirm that, as has been determined elsewhere, watersheds with predominantly granitic parent materials possess lakes with low surface water alkalinities that are potentially sensitive to the effects of acid deposition.

Inputs of materials from terrestrial ecosystems strongly regulate the functioning of arctic lakes (Kling 1995) and are controlled to a great extent by vegetation that influences the composition and fluxes of elements in watersheds (Likens et al. 1977; Cornwell 1992). This is partly related to the storage and release of ions in living and dead organic matter and enhanced weathering owing to plant-derived organic acids. Plants also influence the thaw depth of arctic tundra soils, with unvegetated sites generally having a greater active zone (Brown and Berg 1980).

The concentration of DOC seemed to be strongly related to catchment vegetation (Table 4; Fig. 2). The discrepancy between DOC concentrations of lakes in forested and unforested watersheds may be attributed largely to differences in the production and sequestering of humic compounds in the vegetation and soils of the drainage basin (e.g., Engstrom 1987; Driscoll et al. 1987). Although humus loading to surface waters from sparsely vegetated woodlands is generally lower than that from forested catchments (Engstrom 1987), the elevated concentrations of DOC were most apparent in forest–tundra sites, where most lakes were tea-coloured and exhibited the lowest water transparencies. The latter may be explained by the shallowness of these lakes as well as inhibition of downward percolation of humic materials to deeper soil horizons owing to the presence of more extensive permafrost in the area.

The significant differences in ionic concentrations observed between lakes in the Yellowknife area and those along the Yukon–Tuktoyaktuk transect most likely reflect the differences between freshwater systems located on different types of bedrock. Ionic concentrations in lakes depend largely on the soil characteristics and, ultimately, on the parent bedrock of the drainage basin (Hobbie 1984).

Besides bedrock geology, vegetation type, and climate, surface water chemistry may also be influenced by the age of glacial drift in a drainage basin and thus the extent of primary rock exposure, soil development, and weathering (Kling et al. 1992). Lakes lying in younger glacial drift usually have higher conductivities and are strongly enriched in major ions when compared with lakes surrounded by older and more weathered drift (Kling et al. 1992). This relationship between lake water chemistry and the age and amount of unconsolidated sediments covering the land surface seems to be an important factor in determining nutrient availability and ionic concentrations in our study sites. Likewise, soil nutrient deficiencies imposed upon terrestrial vegetation by the shallow, sandy brunisols of the Canadian Shield have been reported by Larsen (1989) and Timoney et al. (1992).

In general, the narrow ranges in almost all of the chemical and physical variables indicate that limnological conditions were relatively homogeneous as compared with those reported from Yukon lakes (Pienitz et al. 1997).

Acknowledgements

This study was financed by the Natural Sciences and Engineering Research Council of Canada via a grant to J.P.S., a Canadian Government Scholarship to R.P., and Green Plan support on aquatic impacts of ultraviolet light to D.R.S.L. We thank Dr. B. Zeeb for help with the field work, which was supplemented by a grant from the Northern Studies Training Program.

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