Physical and chemical limnology of 59 lakes located between the southern Yukon and the Tuktoyaktuk Peninsula, Northwest Territories (Canada)

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

Abstract: Water chemistry and other limnological data gathered for 59 lakes in the Yukon and the adjacent Northwest Territories (Canada) were interpreted using linear regression and principal components analysis. The study sites represent lakes from a wide range of ecoclimatic regions, spanning large latitudinal (60°37′–69°35′N) and altitudinal gradients (15–1387 m above sea level). Water samples collected from each lake were analysed for concentrations of major ions, trace metals, nutrients, and chlorophyll *a*. Most of the lakes were dilute (mean conductivity = 160 $\mu S \cdot cm^{-1}$) and slightly acidic to alkaline (pH range = 5.9–9.3). Their ionic composition varied from Ca–Cl–Na waters near the Arctic Ocean to Ca–HCO_3 waters further inland, reflecting differences in local drainage basins and proximity to the sea. Arctic and alpine sites generally showed many similarities, but considerable differences in water chemistry were observed among sites in the interior of the Yukon Territory. These can be related mainly to differences in bedrock geology and catchment vegetation.

Résumé : Des données sur les caractéristiques limnologiques et chimiques obtenues pour 59 lacs dans le Yukon et la partie adjacente des Territoires du Nord-Ouest (Canada) ont été interprétées à l'aide de l'analyse de régression linéaire et de l'analyse des composantes principales. Les sites d'étude sont des lacs qui représentent une grande variété de régions écoclimatiques, échelonnées sur de longs gradients de latitude (60°37′–69°35′N) et d'altitude (15 à 1387 m au-dessus du niveau de la mer). Les échantillons d'eau prélevés dans chacun des lacs ont été analysés pour déterminer la concentration des ions traces, des métaux traces, des éléments nutritifs et de la chlorophylle *a*. La plupart des lacs étaient pauvres en solutés (conductivité moyenne de 160 $\mu S \cdot cm^{-1}$) et leur pH variait de légèrement acide à alcalin (étendue de pH = 5,9 à 9,3). La composition ionique a varié de Ca–Cl–Na près de l'océan Arctique à Ca–HCO_3 vers l'intérieur des terres, ce qui reflète des différences dans les bassins hydrographiques locaux et la proximité de la mer. De manière générale, les sites arctiques et alpins ont présenté de nombreuses similitudes, mais des différences considérables en ce qui a trait à la chimie de l'eau ont été observées entre les sites situés à l'intérieur du Territoire du Yukon. Ces différences peuvent être liées aux différences touchant les caractéristiques du substrat rocheux et de la végétation du bassin versant.
[Traduit par la Rédaction]

Introduction

Current general circulation models predict increased global temperatures, with projected greenhouse warming greater in northern latitudes (e.g., Luckman 1989; Roots 1989; Boer et al. 1990). For example, the CO_2-doubling scenarios of Manabe and Wetherald (1986) show summertime temperature increases of 7°C and soil moisture decreases of 50% for the subarctic area bordering on the west coast of Hudson Bay. The latter estimate represents the most extreme change in North America (Bello and Smith 1990). Ecosystems in high-latitude regions are expected to be particularly sensitive to a given change in magnitude and timing of available energy and to changes in physical and geochemical conditions (Roots 1989; Maxwell 1992). Climatic changes of this order would therefore have serious implications for energy-balance processes and hydrological budgets of northern lakes.

If greenhouse warming occurs, the chemistry of freshwater ecosystems will be greatly affected through, for example, changes in precipitation/evaporation ratios and runoff, duration of ice cover, thickness of snow cover, and forest fires in the catchments (Schindler et al. 1990). Physical and chemical cycles of lakes would be altered in fundamental ways, which in turn govern lake productivity and decomposition processes. Some preliminary work considers the consequences for individual aspects of lakes, such as the effect of flooding on the nutrients of lakes in the Mackenzie Delta (Lesack et al. 1991). However, effects on the entire ecosystem are unknown and unpredictable at present. The greatest limitation to previous studies is that they focused on single problems or issues, including a very limited number of environmental variables.

Received October 11, 1995. Accepted July 31, 1996.
J13105

R. Pienitz.[1] Centre d'études nordiques et département de géographie, Université Laval, Québec, QC G1K 7P4, Canada.
J.P. Smol. Paleoecological Environmental Assessment and Research Laboratory (PEARL), Department of Biology, Queen's University, Kingston, ON K7L 3N6, Canada.
D.R.S. Lean. Canada Centre for Inland Waters, National Water Research Institute, Box 5050, Burlington, ON L7R 4A6, Canada.

[1] Author to whom all correspondence should be addressed. e-mail: reinhard.pienitz@cen.ulaval.ca

Variable by variable investigations, in which each gradient is treated separately, effectively represent the data, but do not show interrelationships either between gradients or between species (Neilson and Stevens 1987). Thus, they fail to integrate factors that structure freshwater ecosystems.

Northern lakes have traditionally received less attention from climatologists than the vegetated landscape, perhaps because they are ecosystems in which it is difficult to set up and maintain sensitive equipment. In addition, lakes in many northern regions are shallow and typically surrounded by permafrost, like those in the Yellowknife area and on the Tuktoyaktuk Peninsula. This will enhance the role of lakes in regional water balances of northern landscapes, since these water bodies are more likely to become ephemeral, which carries biotic as well as hydrologic and climatologic implications (Bello and Smith 1990; Kling et al. 1991). In the context of climate change, improved understanding of processes related to lake evaporation will become increasingly important in subarctic and arctic regions.

The most recent general reviews of arctic limnology are by Hobbie (1980, 1984), Hammar (1989), and Vincent and Ellis-Evans (1989). Since then, a number of agencies and research groups carried out surveys or reviews on water chemistry of freshwater lakes and ponds in high-latitude regions, including the Yukon Territory, adjacent Alaska, and the Northwest Territories (e.g., Lindsey et al. 1981; Ennis et al. 1982; Horler et al. 1983; Shortreed and Stockner 1986; Welch and Legault 1986; Fee et al. 1988; Anema et al. 1990*a*, 1990*b*; Kling et al. 1992; Eilers et al. 1993). Among these investigations, several were targeted at specific questions such as assessments of fisheries resources. The latter were therefore usually limited to relatively small geographic areas and could not address the effects of climatic and vegetational changes over large environmental gradients. In addition, large areas in the western Arctic of North America remain unexplored limnologically.

In this paper, we interpret the data we have gathered from a limnological survey of 59 lakes located between Whitehorse in the Yukon and Tuktoyaktuk in the Northwest Territories (Fig. 1). Our study sites cross several ecoclimatic regions from boreal forest in the south to arctic tundra in the north. This investigation is part of a more extensive study of algal distributions (diatoms and chrysophytes) and their relationship to environmental gradients from a large number of sites in northern Canada and Scandinavia (Pienitz 1993; Pienitz et al. 1995*a*, 1995*b*).

The objectives of the present study are to describe the physical and chemical characteristics of our study sites and to compare our results with previously reported data on lakes from subarctic regions. Despite the recognized environmental and ecological importance of freshwater ecosystems in high-latitude regions, very little or no baseline data exist for many sites. Thus, another goal of this study is to collect data that will allow us to define the natural state of the present systems, thereby serving as reference data for future monitoring programs. Such data should be useful as baseline data for the management of freshwater ecosystems in these remote northern areas.

Description of study area

No previous limnological information was available for most of the 59 study lakes. Likewise, many of these lakes are unnamed, and so we numbered them in consecutive order of sampling. Samples were collected during the month of July 1990. The lakes are distributed along a south–north transect between Whitehorse and Tuktoyaktuk (Fig. 1). Between Whitehorse and Inuvik, all lakes were sampled from an inflatable boat whereas sampling of lakes on the Tuktoyaktuk Peninsula (26–55) (Fig. 1, inset) was carried out from a helicopter equipped with pontoons. All lakes studied are natural, with the exception of lake 4, which is artificially dammed.

Regional climate and hydrology

The study region comprises four major ecoclimatic provinces (Cordilleran, Subarctic Cordilleran, Subarctic, Arctic) as recognized by the Ecoregions Working Group (1989). The climate of different regions within the study area is summarized in Table 1. The steep climatic (and altitudinal) gradients along the sampling transect are particularly strong in the treeline region between Inuvik and Tuktoyaktuk, only 130 km apart, where marked physiographic changes (transition from forested to treeless areas) account for drastic changes in surface albedo (Ritchie 1977, 1984). As a result, spring breakup on small lakes (5–50 ha) near Tuktoyaktuk is more than a month later (late June to mid-July) and freeze-up in the fall comes earlier (end of August to early September) (Fee et al. 1988) than at Inuvik. In the northern forest zone, small lakes are ice free by June 15 and freeze over by October 15 whereas large (>50 ha) lakes become ice free roughly 2 weeks later than small ones.

Lakes in the southern part of the Yukon are mostly dimictic with protracted periods of ice cover, usually extending from October–November to May–June (Environment Canada 1985–1990). According to Allen (1964), the mean number of days between the clearing of ice from lakes and initial ice formation is about 90–100 days in the Inuvik area whereas the ice-free period lasts considerably longer (about 150 days) in the Whitehorse area.

Tuktoyaktuk lakes

In the Northwest Territories, we restricted our sampling to upland sites in the Inuvik area and on the Tuktoyaktuk Peninsula. The hydrological regime of these arctic lakes is largely controlled by a combination of low precipitation and permafrost, with snowmelt runoff in the spring being the dominant hydrologic event (Anema et al. 1990*a*). Water balance studies have shown that, in summer, evaporation from lake surfaces (about 230 mm) is generally greater than precipitation (10 mm) (e.g., Sheath and Hellebust 1978; Hobbie 1984; Sheath 1986; Marsh and Bigras 1988; Marsh 1989; Bigras 1990). Seasonal variations in surface water chemistry of arctic lakes are thus related mainly to dilution by snowmelt and runoff and to concentration by evaporation and exclusion from ice and (or) permafrost (cryoconcentration) (e.g., Hobbie 1984; Kling et al. 1992). These processes can cause considerable fluctuations in the chemical concentrations of major ions in arctic lakes (e.g., Howard and Prescott 1973; Schindler et al. 1974; Prentki et al. 1980; Welch and Legault 1986; Cornwell 1992). It is unlikely, however, that such seasonal variations strongly affected the major chemical groupings described below, given that all lakes were sampled during a short time span in July 1990. However, it should be noted that the water

Table 1. Climate data from the study area.

	Whitehorse (60°43′N, 135°04′W)	Mayo (63°36′N, 135°53′W)	Dawson City (64°04′N, 139°26′W)	Inuvik (68°21′N, 133°43′W)	Tuktoyaktuk (69°27′N, 133°02′W)
January mean daily air temperature (°C)	−20.0	−27.0	−29.0	−28.0	−27.0
July mean daily air temperature (°C)	16.0	15.0	16.0	13.0	10.0
Mean annual daily temperature (°C)	−1.3	−4.0	−5.0	−10.0	−11.0
Mean annual precipitation (mm)	268.9	293.0	325.1	266.0	137.6
Snow depth (mm)	145.8	144.4	151.8	175.0	56.0
Growing degree-days above 5°C	897.1	983.0	996.5	654.0	372.0
Mean annual global solar radiation ($kly \cdot yr^{-1}$)[a]	na	na	85.0	78.0	77.0
Mean annual net radiation ($kly \cdot yr^{-1}$)	na	na	20.0	14.0	10.0
Mean maximum lake ice thickness (cm)	na	na	150.0	170.0	180.0

Note: na, not available.

[a] $1\ ly = 0.70\ kW \cdot m^{-2}$.

chemistry data we recorded for our 59 lakes represent summer concentrations rather than annual averages.

Vegetation

The major vegetation zones of the study area include boreal forest in the south and arctic tundra in the north, with transitional forest–tundra or woodland in between, and alpine tundra in mountainous and high-elevation areas. Trees cover most of the plateaus and valleys in the south and form closed-canopy forests, depending on site conditions. Tree species include white spruce (*Picea glauca*), black spruce (*Picea mariana*), larch (*Larix laricina* var. *alaskensis*), alpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), and paper birch (*Betula papyrifera* ssp. *humilis*) (Oswald and Senyk 1977). Several species occur near the arctic treeline, but white and black spruce are the most prevalent. Alpine tundra consists of several communities ranging from sedge meadows or tussock fields to lichens growing on rocks.

The vegetation of the forest–tundra zone shows abundant evidence of the effects of natural fires, with upland sites usually dominated by white spruce with an understory of lichens (*Cladina* spp. and *Stereocaulon* spp.) and ericoid shrubs (*Vaccinium uliginosum, Vaccinium vitis-idaea, Ledum decumbens*, and *Oxycoccus* spp.). Poorly drained sites are occupied by *Picea mariana* stands with varied ground cover dominated by *Cladina* spp., *Sphagnum* spp., and *Betula glandulosa*. Upland sites in the tundra zone are dominated by dwarf shrubs and lichens whereas poorly drained peaty areas show ice-wedge polygon and frost hummock development with dominance by *Eriophorum vaginatum* and *Carex* stands (Koivo and Ritchie 1978).

Materials and methods

The lakes were chosen to minimize differences in basin morphometry, and therefore are usually isolated, small- to medium-sized basins (see below), circular in shape, and exceed 1 m in water depth. Almost all the study lakes are located in primary watersheds, receiving no significant drainage from rivers or from other lakes. Because of logistic constraints when sampling from a helicopter, the amount and type of information collected from each lake varied slightly from area to area. Hence, concentrations of oxygen and profiles of temperature were not recorded for all 59 lakes. Epilimnion and thermocline depths could only be measured when sampling from an inflatable boat.

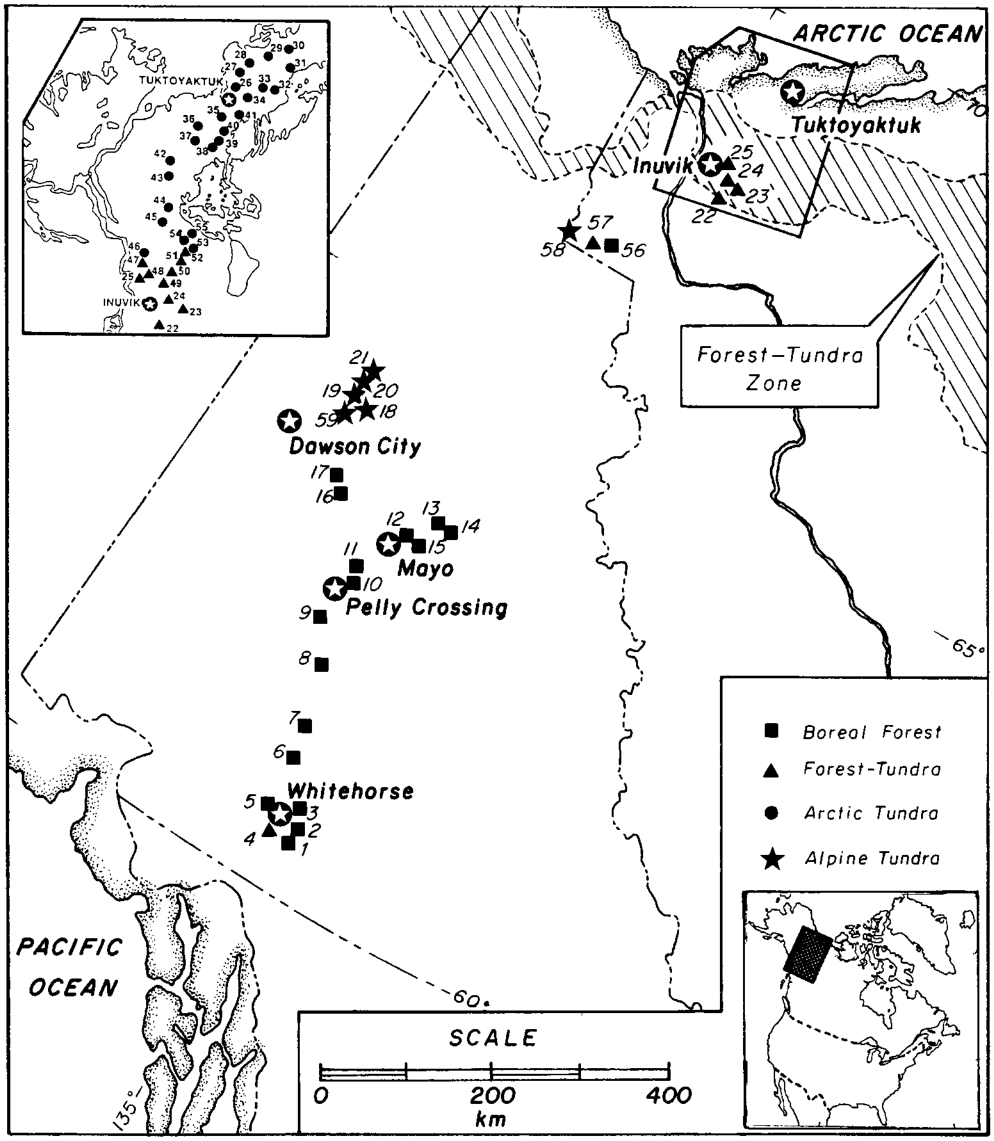
Elevations were taken from topographic maps. The surface areas of all lakes were determined by digitizing from 1 : 50 000 scale maps. Maximum depths were generally recorded during repeated sampling of lake surface sediments and were, in a few cases, based on exploratory sounding transects using a Ray Jeff MX2550 echo sounder. Other general features of the lakes, such as drainage patterns, extent of emergent vegetation, shore characteristics, and catchment vegetation, were determined from on the ground observations and are summarized in Pienitz (1993).

Several statistical approaches were used to describe the patterns observed in the physical, chemical, and environmental variables (see below). The abbreviations in parentheses correspond to the labels used in the figures and tables.

Physical and chemical variables

Limnological field measurements were usually made at one station near the deepest part of the lake, which, because of the simple circular morphometry of most basins, was generally near the centre. A

Fig. 1. Location of the 59 study sites and major towns in the Yukon and Northwest Territories.



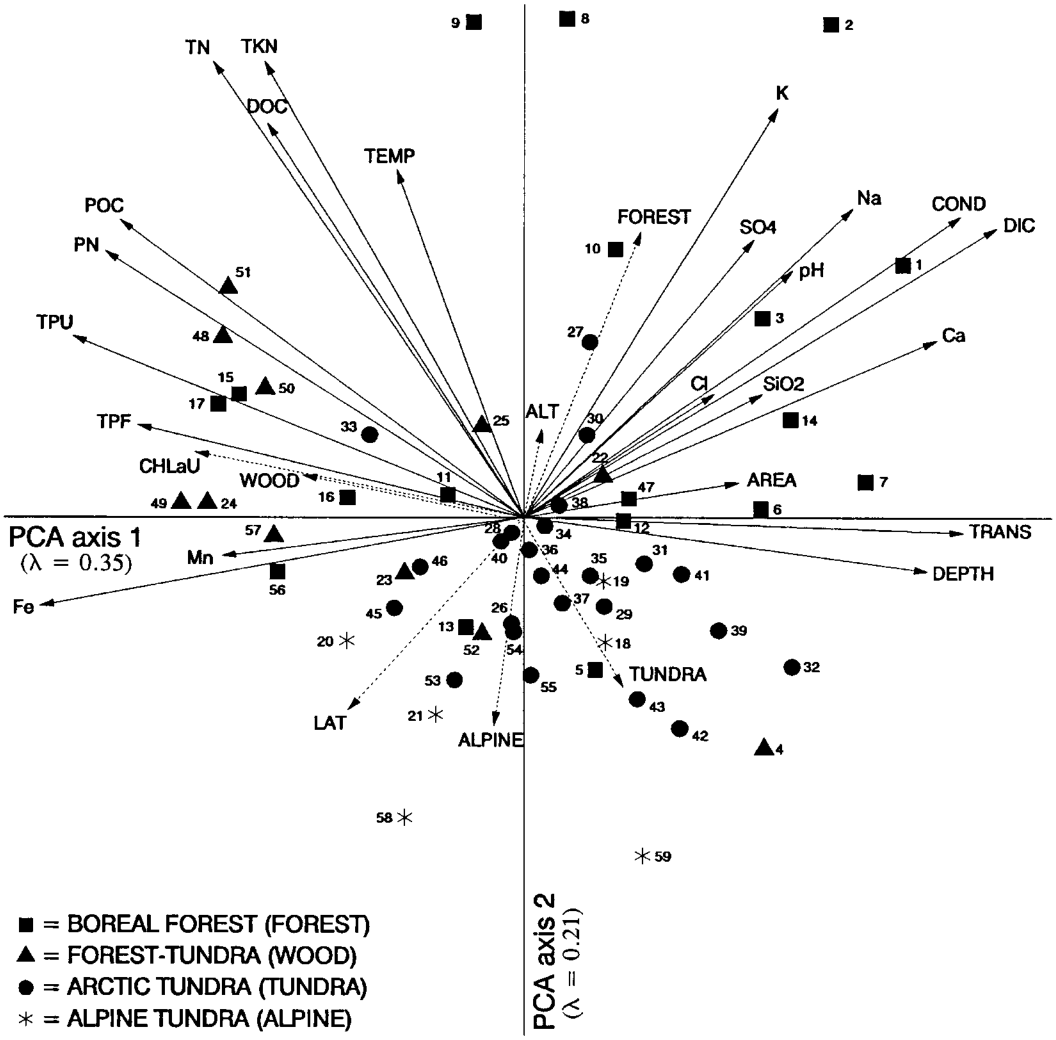
standard 22-cm Secchi disk was used to measure water transparency (TRANS). Profile measurements of salinity, conductivity (COND), and water temperature (TEMP) were recorded with a YSI model 33 SCT meter. Salinity measurements were continuously below detection levels, except for two lakes in the vicinity of Whitehorse (1, 2), and are therefore not included in the analyses. The dissolved oxygen content (DO) and pH of the surface water were measured with a YSI model 54 oxygen meter and Hanna field pH meter, respectively.

Water samples for chemical analyses were taken from approximately 0.5 m water depth using polyethylene bottles. Samples were immediately treated in the field according to sampling procedures outlined in the *Analytical Methods Manual* (Environment Canada 1979). All samples were kept cold and in the dark before being shipped to the National Water Research Institute (Burlington, Ont.) for additional analyses.

Twenty-three chemical variables were measured on each water sample using standard procedures. Water for nutrient analyses (nitrite (NO_2), nitrate (NO_3), ammonia (NH_3), soluble reactive phosphate–phosphorus (SRP), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and total Kjeldahl nitrogen (TKN)) was filtered through 47 mm diameter cellulose acetate filters (pore size = 0.45 μm) and placed in rinsed 100-mL glass bottles. The same filtration was used to obtain water for analyses of total “dissolved” phosphorus (TFP). One millilitre of 30% H_2SO_4 was added to both the filtered and the unfiltered phosphorus fractions (TPU, including phosphorus in particulate and dissolved phase) and placed in 100-mL glass bottles.

Depending on lake productivity, between 100 and 500 mL of water was filtered through ashed 47 mm diameter Whatman GF/F glass microfibre filters (particle retention = 0.7 μm). These filters were stored in plastic petri dishes, wrapped in aluminum foil, and later analysed for particulate organic carbon (POC) and particulate nitrogen (PN). About 1 mL of saturated $MgCO_3$ solution was added to a second 500-mL sample of lake water, which was then also filtered through glass microfibre filters for analyses of total chlorophyll (CHLAU and CHLAC (uncorrected and corrected for phaeophytin)). These filters were folded once, placed in a plastic petri dish, and then wrapped in aluminum foil. Major ions (sodium (Na), potassium (K), calcium (Ca), chloride (Cl), sulphate (SO_4)), dissolved silica (SiO_2) as well as the trace metals iron (Fe) and man-

Fig. 2. PCA of the physical, chemical, and environmental variables in the 59-lake data set. Passive variables are represented by arrows with broken lines.



ganese (Mn) were determined from samples stored in 100-mL plastic bottles. Water samples for analyses of Fe and Mn were preserved with 1 mL of concentrated HNO_3. The *Analytical Methods Manual* (Environment Canada 1979) provides further details concerning analytical methods and sample treatment.

Morphometric and geographic–environmental variables

Lake surface area (AREA), altitude (ALT), maximum depth (DEPTH), latitude (LAT), and longitude (LONG) were determined for each site whereas shortest distance from northern treeline (DIST) was determined for a subset of 31 sites located in the Inuvik and Tuktoyaktuk areas. In addition, the lakes were classified according to the four main vegetation zones: boreal forest (FOREST, including some lakes in peatlands), subarctic woodland (WOOD, includes both forest–tundra and lichen–woodland), arctic tundra (TUNDRA), and alpine tundra (ALPINE) (Fig. 1).

Statistical analyses

Canonical ordination combines the simplicity of regression models with the power of ordination models to detect the internal structure in a data set, including a relatively large number of interrelated variables (Van Tongeren et al. 1992). We therefore chose to use principal components analysis (PCA) to study the trends and the relationships between sites and environmental variables and to help decipher which processes may govern the observed patterns. PCA was also used to screen the data to detect any unusual or outlier sampling sites, which were excluded from further statistical analyses. The variables were tested for skewedness and, if necessary, their data were $\ln(x + 1)$ transformed (Zar 1984) to approximate a normal distribution. PCA analyses were conducted on the $\ln(x + 1)$ transformed data files. All analyses were computed using the program CANOCO, version 3.1 (Ter Braak 1990*a*, 1990*b*).

Groups of significantly ($P \leq 0.05$) correlated variables were identified from a Pearson correlation matrix with Bonferroni-adjusted probabilities (Wilkinson 1988). The correlation matrix, which is based on the $\ln(x + 1)$ transformed data and includes all available data, shows patterns of correlation between variables that are discussed below.

Results and discussion

Physical and geographic–environmental variables

Lakes sampled in the Yukon varied considerably in elevation, ranging from 15 to 1387 m above sea level (asl) (Table 2). Lakes of the Yukon Plateau in the southern Yukon generally ranged in elevation from 580 to 1020 m asl. The five alpine sites in the South Ogilvie Mountains (18–21, 59) occurred roughly between 1000 and 1400 m asl whereas the alpine site in the Richardson Mountains (58) was located only at 550 m asl, thereby indicating the progressive drop in alpine treeline elevation with increasing latitude. Low-elevation sites, where lakes were generally below 150 m asl, were predominantly regions of forest–tundra and arctic tundra. Lakes on coastal lowlands of the Tuktoyaktuk Peninsula (sites 26–41) were generally <25 m asl.

Most of the lakes were of small to intermediate size. Surface areas ranged from 1.1 (25) to 1262.1 ha (4) (equivalent to 0.011–12.62 km^2), with an average size of 91.4 ha (Table 2). The artificially dammed Fish Lake (4) was eliminated from the PCA because of its relatively large size (1262 ha) and its use as a drinking water reservoir for the Whitehorse area. Thirty-four of the study sites (60%) ranged between 20 and 100 ha whereas 13 (23%) were smaller than 20 ha and only 10 (17%) exceeded 100 ha in size.

The information on maximum depth may not always be adequate and in some cases was only the maximum depth observed during repeated sediment sampling or exploratory soundings. Lake depth ranged from 1.2 (57) to 49 m (6), with a mean of 7.4 m. Most of the deeper lakes ($Z_{max} > 5.0$ m) were found in the southern Yukon, in particular within the Yukon Plateau area, where lakes were generally confined within valleys. It is not surprising that the forest–tundra and arctic tundra lakes of the Arctic Coastal Plains were relatively shallow, with mean depths of 2.8 and 5.8 m, respectively. This is because these lakes usually occurred in thermokarst depressions. Among those arctic lakes with water depths ≤2.0 m, some may freeze to the bottom during winter, since ice covers ranging in thickness from 1.1 to 2 m have been observed to occur on the Tuktoyaktuk Peninsula (R. Pienitz, unpublished observations).

Lake surface water temperature generally showed a consistent latitudinal gradient of decreasing temperatures from south to north (along with air temperature), with the exception of lakes located in the central part of the Yukon Territory (sites 6–17) where the highest temperatures were recorded. The lowest surface water temperatures were recorded in alpine and arctic tundra lakes, with mean values of 15.5 and 17.1°C, respectively.

Because of their usually small sizes and shallow depths, the average summer surface water temperatures of the lakes surveyed were considerably higher than those reported from previous investigations in the Yukon and on the Tuktoyaktuk Peninsula (see Lindsey et al. 1981; Patalas 1984; Shortreed and Stockner 1986; Anema et al. 1990*a*, 1990*b*). The midsummer temperatures in our lake survey ranged from 12.0 to 23.0°C (Table 2), compared with 8.0–19.8°C (Lindsey et al. 1981), 8.9–14.8°C (Shortreed and Stockner 1986), and 12.5–17.5°C (Patalas 1984). The discrepancy in midsummer surface water temperatures is particularly evident when comparing temperature ranges obtained from lakes on the Tuktoyaktuk Peninsula, with temperatures ranging from 12.0 to 19.0°C, whereas Anema et al. (1990*a*) reported temperatures between 6.8 and 11.7°C in 1985.

Temperature profiles revealed that, in July 1990, complete thermal stratification was established in almost all of our southern Yukon lakes (1–14, 16). Epilimnion depths in these presumably dimictic lakes ranged from 1 to 6 m, usually increasing with lake size and depth (some of the deeper lakes (6, 10) had two thermoclines). Some of the lakes in the forest–tundra near Inuvik (22, 24) were also weakly stratified; however, because of their shallow depths and relatively cool water temperature, a stratification did not develop. Isothermal conditions were observed in our alpine tundra sites (18–21, 58), as well as in some of the smaller and shallower lakes in the boreal forest (15, 17, 56) and forest–tundra (23, 25, 57).

DO concentrations in epilimnetic waters were generally high and ranged from 11.1 to 14.6 $mg \cdot L^{-1}$ (Table 2). DO exhibited an even distribution in most of the lakes, with O_2-saturated waters occurring throughout the water column. In many of these lakes, we recorded a positive heterograde oxygen curve, with higher DO in the metalimnion most likely resulting from photosynthetic activity. Clinograde O_2 curves were observed only in some of the very deep lakes (1, 6), as well as lakes of the Pelly River – Stewart River area (8–11, 13–16) located between Carmacks and Dawson City, where DO levels were greatly reduced in hypolimnetic waters.

Temperature and oxygen profiles could not be measured when sampling from the helicopter, and are therefore not available for the tundra lakes (26–55). In any event, oxygen measurements seem to be redundant in shallow arctic tundra lakes because they are usually completely saturated with oxygen during the open-water season (Hobbie 1984; Welch 1991). Welch (1991) observed that, usually with the beginning of snowmelt, sufficient photosynthesis occurred beneath the lake ice so that O_2 production greatly exceeded O_2 consumption. In addition, thorough mixing generally created well-oxygenated water bodies in tundra regions, where in the mostly shallow lake basins thermoclines were commonly absent owing to the action of strong winds (Fee et al. 1988).

Water transparency (as measured by Secchi disk readings) ranged from 0.7 to 11.5 m (Table 2), which was similar to values of 0.6–13.0 m reported by Lindsey et al. (1981) for Yukon lakes. Mean Secchi depths were highest in boreal forest (4.4 m) and alpine tundra lakes (4.1 m). The low Secchi depths observed in forest–tundra lakes (mean = 1.7 m) were due to the highly coloured (brown) waters of these mostly shallow, low-pH lakes, which were surrounded by muskeg and open spruce woodland (also see below). Secchi readings were only useful in the deeper ($Z_{max} > 2.0$ m) arctic tundra lakes (about 58%), where Secchi depths ranged from 1.0 to 7.0 m.

The variability in light transmission depends on the amount of suspended inorganic and organic material as well as dissolved organic material (Hobbie 1984) and is reflected by the significant negative correlation between TRANS and such variables as PN, POC, and TPU (Table 3). Water colour results not only from the input of organic compounds from decaying vegetation and the leaching of organic soils in the catchment, but also from natural mineral components such as Fe and Mn (McNeely et al. 1979). Our data suggest that [Fe] appears to have had a particularly strong impact on water colour, given its locally high concentrations (see below) and its significant negative correlation with TRANS ($r = -0.75$, $P < 0.01$) (Table 3).

Chemical variables

pH

Measurements of pH indicated that our study sites were

Table 2. Field data collected in 1990 for the 59 lakes.

Lake No.	LAT (°N)	LONG (°W)	ALT (m)	Z_{max} (m)	AREA (ha)	pH	TEMP (°C)	COND ($\mu S \cdot cm^{-1}$)	O_2 ($mg \cdot L^{-1}$)	TRANS (m)	DIST (km)
Boreal forest											
1	60.39	134.57	671	32.0	181.2	8.7	17.5	700	13.7	9.1	na
2	60.40	134.59	671	10.5	56.9	8.8	19.0	1500	14.2	8.5	na
3	60.44	135.02	625	17.5	21.2	8.5	20.0	490	13.7	5.0	na
5	60.42	135.17	1021	12.0	52.5	7.8	17.0	73	13.3	2.3	na
6	61.21	135.39	823	49.0	89.0	8.3	20.0	179	13.3	3.2	na
7	61.42	135.56	634	27.0	163.0	8.3	20.8	230	12.9	10.8	na
8	62.11	136.15	686	5.5	23.7	8.7	23.0	339	14.3	2.7	na
9	62.43	136.41	579	3.0	331.5	8.7	20.7	220	14.4	1.9	na
10	63.01	136.28	655	8.0	88.6	8.6	22.0	242	13.7	4.4	na
11	63.09	136.30	732	5.0	8.6	8.5	23.0	49	11.6	3.3	na
12	63.39	135.54	579	9.2	23.4	8.4	22.0	149	12.2	6.0	na
13	63.59	135.24	701	10.1	10.1	7.8	20.8	45	11.8	3.6	na
14	63.59	135.22	701	16.5	23.1	8.3	21.5	260	13.0	11.5	na
15	63.39	135.51	594	3.0	24.1	7.5	19.4	46	11.8	1.5	na
16	63.45	137.43	610	5.0	80.3	7.6	22.0	42	11.6	2.8	na
17	63.51	138.02	610	4.0	18.9	8.2	19.4	24	12.1	1.7	na
56	67.14	135.26	366	4.0	35.0	7.5	18.0	35	11.4	1.4	na
Forest–tundra											
4	60.37	135.14	1113	7.0	1262.1	8.1	14.0	87	14.6	6.5	na
22	68.11	133.27	76	5.5	8.2	7.9	18.0	153	12.1	4.1	−21.25
23	68.18	133.16	30	2.5	6.8	7.2	18.1	72	12.1	1.8	−7.50
24	68.19	133.22	91	2.8	15.1	6.9	18.0	35	11.1	1.1	−6.25
25	68.24	133.42	122	3.0	1.1	7.8	20.0	140	13.4	**3.0**	0.00
47	68.28	133.38	122	1.5	21.1	8.3	19.5	220	na	**1.5**	7.50
48	68.25	133.35	114	1.5	96.2	8.6	20.5	71	na	1.0	2.50
49	68.23	133.25	84	3.5	5.3	6.6	19.0	41	na	0.7	0.00
50	68.25	133.22	76	2.0	21.7	7.0	20.3	71	na	1.6	5.00
51	68.29	133.22	128	1.5	87.3	8.5	19.5	72	na	1.0	12.50
52	68.34	133.20	145	6.0	19.5	7.0	18.0	116	na	1.8	21.25
57	67.13	135.36	396	1.2	7.2	7.4	18.0	140	13.3	1.0	na
Arctic tundra											
26	69.28	132.49	18	2.0	85.1	8.1	17.0	100	na	**2.0**	125.00
27	69.32	132.47	15	2.0	94.6	8.0	17.0	343	na	1.0	132.50
28	69.33	132.45	15	2.0	170.3	7.8	17.0	145	na	1.2	135.00
29	69.33	132.25	15	2.0	547.4	8.1	17.0	152	na	**2.0**	135.00
30	69.35	132.04	21	4.0	195.8	8.0	16.0	179	na	3.2	137.50
31	69.32	132.04	21	3.0	57.6	8.1	16.0	165	na	2.8	133.75
32	69.28	132.12	21	9.0	73.8	8.0	12.0	198	na	6.0	126.25
33	69.29	132.19	15	2.0	5.4	7.3	19.0	87	na	1.0	126.25
34	69.25	132.40	24	2.5	116.2	7.9	17.0	159	na	**2.5**	118.75
35	69.19	132.59	24	7.0	86.3	8.2	17.0	128	na	2.7	107.50
36	69.10	133.16	21	4.0	103.2	8.4	17.0	105	na	3.2	87.50
37	69.08	133.17	21	6.5	69.0	8.1	17.0	98	na	4.0	83.75
38	69.07	133.11	21	3.0	49.7	8.2	18.0	139	na	**3.0**	82.50
39	69.12	133.02	24	12.0	104.9	8.2	15.5	141	na	6.0	91.25
40	69.13	133.00	24	3.0	81.9	8.2	17.5	104	na	2.5	92.50
41	69.20	132.44	24	7.0	85.5	8.1	16.0	167	na	2.5	108.75
42	69.03	133.27	46	15.0	84.8	7.8	16.0	150	na	7.0	72.50
43	68.59	133.28	30	14.0	36.0	7.5	17.0	105	na	7.0	66.25
44	68.50	133.33	30	4.0	61.2	8.2	18.5	129	na	2.8	47.50
45	68.46	133.39	76	2.0	65.4	6.9	19.0	65	na	1.5	41.25
46	68.29	133.39	122	2.5	63.1	7.1	19.0	81	na	**2.5**	10.00
53	68.36	133.15	152	3.5	25.7	7.2	18.2	48	na	2.3	25.00

Table 2 (*concluded*).

Lake No.	LAT (°N)	LONG (°W)	ALT (m)	$Z_{\max}$ (m)	AREA (ha)	pH	TEMP (°C)	COND ($\mu S \cdot cm^{-1}$)	O_2 ($mg \cdot L^{-1}$)	TRANS (m)	DIST (km)
54	68.38	133.17	91	10.0	40.0	7.3	18.0	85	na	1.9	30.00
55	68.42	133.15	30	18.5	87.9	7.7	18.0	70	na	3.5	37.50
Alpine tundra											
18	64.35	138.18	1173	7.5	18.1	8.6	17.0	113	12.7	4.6	na
19	64.39	138.23	1128	3.8	20.4	8.7	16.0	111	13.2	3.2	na
20	64.44	138.22	1097	1.9	13.7	9.3	14.3	39	12.8	**1.9**	na
21	64.51	138.21	1006	3.8	144.0	7.5	17.5	32	11.7	3.7	na
58	67.06	136.00	549	5.5	19.3	5.9	16.2	77	12.9	1.9	na
59	64.29	138.17	1387	15.5	4.2	7.9	13.5	65	na	9.5	na
Minimum	60.37	132.04	15	1.2	1.1	5.9	12.0	24	11.1	0.7	−21.25
Maximum	69.35	138.23	1387	49.0	1262.1	9.3	23.0	1500	14.6	11.5	137.50
Median			122	4.0	56.9	8.1	18.0	111	12.9	2.7	66.25
Mean			355.9	7.4	91.4	7.9	18.2	159.7	12.8	3.4	63.75

Note: na, not available; TRANS, Secchi disk transparency (bold numbers = readings where TRANS = $Z_{\max}$); DIST, shortest distance from northern treeline (defined as 80% tree cover).

slightly acidic to alkaline, ranging from a pH of 5.9 (58) to 9.3 (20) (Table 2). The lowest pH values were recorded in the forest–tundra and tundra near Inuvik, where most of the surface waters were circumneutral to slightly acidic (e.g., sites 22–25, 45, 46, 49, 50, 52–54). The highest pH values were recorded in the southern Yukon, particularly in the Whitehorse area. PCA ordination and the Pearson correlation matrix showed a strong positive correlation between pH and DIC ($r = 0.71$, $P < 0.01$), as opposed to a strong negative correlation between pH and Fe ($r = -0.54$, $P < 0.01$) (Table 3; Fig. 2).

Conductivity and major ions

Patterns in the conductivity data follow those observed in most of the major ions. For example, the major ions Na, Cl, K, Ca, and SO_4, as well as DIC, are highly correlated with conductivity ($P < 0.01$) (Table 3; Fig. 2). A PCA of ion data with COND demonstrated that all of these variables are significantly negatively correlated with latitude and related climatic variables.

Ca levels were usually high and ranged from 3.5 (17) to 50.3 $mg \cdot L^{-1}$ (7), with an average of 19.6 $mg \cdot L^{-1}$ (Table 4). About 50% of the lakes had concentrations exceeding this average, indicating that most Yukon lakes are alkaline, Ca-rich waters. Not surprisingly, [Ca] is significantly correlated with [DIC] and pH (Table 3, $P < 0.05$).

High SO_4 concentrations are generally due to weathering of sedimentary bedrock and are particularly evident in lakes of the Whitehorse area (e.g., sites 1–3), where rocks composed of limestone–dolomite, sandstone, siltstone, and conglomerate prevail (Oswald and Senyk 1977). Slightly elevated concentrations of SO_4 were also observed in the vicinity of Inuvik.

Except for lakes 1 and 2 in the Whitehorse area, Cl levels were generally low in boreal forest (mean = 5.0 $mg \cdot L^{-1}$), forest–tundra (mean = 2.7 $mg \cdot L^{-1}$), and alpine tundra (mean = 0.4 $mg \cdot L^{-1}$) lakes. In contrast, [Cl] was appreciably higher in most of the arctic tundra lakes with a mean of 12.2 $mg \cdot L^{-1}$. Within this subset of lakes, [Cl] clearly varied as a function of distance from the Arctic Ocean (Fig. 3), with highest concentrations occurring in lakes located on coastal plains in the vicinity of Tuktoyaktuk (in particular, lakes 26–41). This trend is also reflected in the significant correlation between [Cl] and TUNDRA ($r = 0.61$, $P < 0.01$) (Table 3).

A similarly strong relationship between [Cl] and distance from the coast has been observed in lakes of the Kenai Peninsula (Eilers et al. 1993) and the North Slope of Alaska (Livingstone 1966; Kalff 1968; Kling et al. 1992). Sea salt in precipitation is likely to be the main source of Cl in lakes of these maritime arctic regions. However, it is possible that edaphic factors, related to the emergence of the coastal lowlands from postglacial marine waters may also play an important role in the distribution of Cl^- (see Welch and Legault 1986).

Na concentrations were highly correlated with those of Cl (Fig. 4) and decreased with distance from the coast in a pattern similar to that observed for Cl.

Nutrients and carbon

Concentrations of SiO_2 were low to moderate and ranged from 0.1 to 12.5 $mg \cdot L^{-1}$, with a mean of 2.1 $mg \cdot L^{-1}$ for all lakes. Average concentrations calculated for boreal forest, forest–tundra, and arctic tundra lakes showed a latitudinal gradient, with values decreasing with increasing latitude from 4.7 to 1.5 and 0.7 $mg \cdot L^{-1}$, respectively. This trend was corroborated by the significant negative correlation between SiO_2 and LAT ($r = -0.62$, $P < 0.01$) (Table 3; Fig. 2). SiO_2 is most easily leached from sedimentary and volcanic rocks (McNeely et al. 1979; Prentki et al. 1980) that predominate in the southern Yukon, and where the highest SiO_2 concentrations were recorded in lakes 3–10 (Table 4).

The concentrations of DIC showed considerable variation among lakes and ranged from 0.3 (58) to 134.2 $mg \cdot L^{-1}$ (2)

Table 3. Pearson correlation matrix for environmental variables (following transformations) measured in the 59 lakes included in the PCA.

	LAT	LONG	ALT	DEPTH	AREA	TEMP	TRANS	COND	pH	CHLAU	CHLAC	TPU	TPF	SRP	NO_2	NO_3	NH_3
LONG	−0.73**																
ALT	−0.88	0.88**															
DEPTH	−0.52	0.22	0.35														
AREA	−0.04	−0.20	−0.20	0.13													
TEMP	−0.35	0.20	0.32	0.00	−0.21												
TRANS	−0.44	0.22	0.30	0.74**	0.13	−0.08											
COND	−0.21	−0.21	−0.07	0.34	0.26	0.05	0.46										
pH	−0.39	0.26	0.21	0.20	0.28	0.08	0.33	0.46									
CHLAU	0.10	0.05	0.05	−0.36	−0.10	0.22	−0.36	−0.37	−0.02								
CHLAC	0.14	0.05	0.04	−0.40	−0.16	0.18	−0.37	−0.28	0.05	0.87**							
TPU	0.17	−0.04	0.00	−0.54**	−0.19	0.23	−0.53**	−0.36	−0.16	0.62**	0.64**						
TPF	0.15	−0.08	−0.02	−0.41	−0.35	0.16	−0.40	−0.37	−0.35	0.24	0.24	0.77**					
SRP	−0.21	0.06	0.18	0.01	−0.16	0.16	0.04	0.08	0.01	−0.02	−0.02	0.37	0.58**				
NO_2	0.12	−0.10	−0.13	0.14	−0.07	−0.09	0.17	−0.07	−0.14	−0.06	−0.02	−0.06	−0.02	0.04			
NO_3	−0.19	−0.04	0.08	0.31	0.16	−0.06	0.31	0.32	0.12	−0.19	−0.12	−0.00	0.10	0.13	0.07		
NH_3	0.30	−0.41	−0.37	−0.36	0.03	−0.02	−0.20	0.19	−0.06	−0.11	−0.07	0.15	0.19	0.08	−0.01	0.01	
TKN	−0.16	0.13	0.11	−0.39	−0.20	0.58**	−0.36	−0.01	0.13	0.22	0.20	0.44	0.35	0.30	−0.11	−0.09	0.36
TN	−0.16	0.15	0.14	−0.41	−0.13	0.56**	−0.39	−0.06	0.15	0.39	0.39	0.58**	0.37	0.27	−0.09	−0.02	0.31
PN	0.01	0.17	0.10	−0.50*	−0.06	0.41	−0.53**	−0.32	0.01	0.69**	0.68**	0.74**	0.36	0.05	−0.08	−0.16	0.10
POC	−0.06	0.20	0.15	−0.45	−0.06	0.45	−0.50*	−0.28	0.02	0.67**	0.64**	0.74**	0.36	0.10	−0.09	−0.14	0.11
DOC	−0.19	0.12	0.19	−0.26	−0.25	0.61**	−0.28	−0.08	−0.02	0.17	0.08	0.44	0.42	0.33	−0.09	−0.05	0.31
DIC	−0.33	−0.08	0.00	0.44	0.39	0.04	0.54**	0.86**	0.71**	−0.36	−0.33	−0.42	−0.43	0.09	−0.06	0.27	0.09
SiO_2	−0.62**	0.30	0.51*	0.55**	0.09	0.24	0.42	0.32	0.14	−0.16	−0.20	−0.20	−0.22	0.09	−0.06	0.09	−0.28
Cl	0.43	−0.68**	−0.71**	−0.11	0.33	−0.27	0.00	0.51*	0.15	−0.30	−0.21	−0.12	−0.04	0.01	0.02	0.36	0.49
SO_4	−0.37	0.06	0.32	0.27	−0.10	0.13	0.32	0.68**	0.07	−0.26	−0.17	−0.09	−0.02	0.29	−0.18	0.30	0.12
Na	−0.02	−0.41	−0.28	0.15	0.33	−0.02	0.24	0.86**	0.35	−0.40	−0.33	−0.21	−0.17	0.14	−0.08	0.31	0.44
K	−0.32	−0.13	0.05	0.22	0.22	0.27	0.32	0.78**	0.37	−0.20	−0.12	−0.05	0.01	0.34	−0.09	0.41	0.29
Ca	−0.18	−0.06	−0.02	0.37	0.25	0.05	0.42	0.69**	0.51*	−0.30	−0.27	−0.46	−0.53*	−0.10	−0.13	0.00	−0.03
Fe	0.53**	−0.22	−0.30	−0.66	−0.29	−0.07	−0.75**	−0.59**	−0.54**	0.38	0.36	0.70**	0.68**	0.11	−0.08	−0.19	0.26
Mn	0.36	−0.04	−0.10	−0.32	−0.12	−0.02	−0.36	−0.23	−0.46	0.20	0.25	0.45	0.34	0.09	0.10	−0.07	0.14
FOREST	−0.80**	0.49*	0.63**	0.46	0.01	0.62**	0.31	0.20	0.33	0.07	0.02	−0.07	−0.10	0.18	−0.12	0.15	−0.20
WOOD	0.18	−0.20	−0.03	−0.35	−0.30	0.09	−0.28	−0.15	−0.26	0.27	0.32	0.52*	0.50*	0.23	0.00	−0.04	0.01
TUNDRA	0.70**	−0.69**	−0.83**	−0.14	0.37	−0.41	−0.12	0.08	−0.11	−0.17	−0.20	−0.28	−0.25	−0.32	0.14	−0.06	0.30
ALPINE	−0.17	0.64**	0.43	0.00	−0.21	−0.37	0.09	−0.24	0.03	−0.18	−0.12	−0.13	−0.10	−0.06	−0.05	−0.08	−0.20

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

(Table 4). This corresponds to an alkalinity range of approximately 0–2.5 mequiv. $\cdot L^{-1}$, as calculated from [DIC] and pH using the carbonate species relations in Stumm and Morgan (1981). The highest DIC concentrations were observed in boreal forest lakes near Whitehorse, where values often exceeded 30 mg $\cdot L^{-1}$. They were generally lowest in forest–tundra and alpine tundra lakes.

The discrepancy between DOC concentrations in lakes with forested and unforested watersheds was evident (Table 4; Fig. 5). The lowest average [DOC] was observed in alpine (7.9 mg $\cdot L^{-1}$) and arctic tundra (9.4 mg $\cdot L^{-1}$) sites whereas concentrations were considerably higher in boreal forest and forest–tundra lakes (15.9 mg $\cdot L^{-1}$). This strong relationship between [DOC] and catchment vegetation is represented by the significant negative correlation ($r = -0.49$, $P < 0.05$, Table 3) and the PCA ordination plot (Fig. 2). Despite the relatively high concentrations of DOC in some of the study lakes, none was strongly acidic (minimum measured pH = 5.9, lake 58). Most of the high-DOC lakes received organic inputs from bog vegetation and *Sphagnum* mosses in their watersheds. However, the production of organic acids from these sources seemed to be insufficient to overcome the alkalinity produced from weathering processes in the watershed and in-lake processes.

Of the four nitrogen species analysed, TKN (dissolved organic nitrogen, measured on the filtered fraction) was the most variable, with highest mean concentrations in boreal forest (563 $\mu g \cdot L^{-1}$) and forest–tundra lakes (557 $\mu g \cdot L^{-1}$). Values for arctic and alpine tundra lakes were considerably lower, with 350 and 263 $\mu g \cdot L^{-1}$, respectively. Values ranged from a low of 72 $\mu g \cdot L^{-1}$ (59) to 1293 $\mu g \cdot L^{-1}$ (8) and averaged 439 $\mu g \cdot L^{-1}$ for all lakes (Table 4). As expected, TKN was highly correlated with TN ($r = 0.96$, $P < 0.01$) (Table 3), which was calculated as the sum of PN, TKN, NO_3, and NO_2.

[TN] ranged from a low of 123 $\mu g \cdot L^{-1}$ (59) to 1585 $\mu g \cdot L^{-1}$ (9), this range being typical of oligotrophic waters according to Wetzel (1983). Average summer surface water concentrations were almost equally high in forest–tundra and boreal forest lakes (730 and 722 $\mu g \cdot L^{-1}$, respectively) whereas they were substantially lower in arctic (435 $\mu g \cdot L^{-1}$) and alpine tundra lakes (343 $\mu g \cdot L^{-1}$).

The concentrations for the three species of inorganic nitrogen (NO_3, NO_2, and NH_3) were below or near the analytical detection limit in many lakes. NO_3 values ranged from 9 to 208 $\mu g \cdot L^{-1}$, NO_2 from 0.2 to 29 $\mu g \cdot L$, and NH_3 from 5 to 51 $\mu g \cdot L^{-1}$. The highest NO_3 concentration was recorded in lake 1 (208 $\mu g \cdot L^{-1}$) (Table 4).

Among the phosphorus variables SRP, TPU, and TPF, [TPU] and [TPF] were highly correlated ($r = 0.77$, $P < 0.01$)

Table 3 (*continued*).

TKN	TN	PN	POC	DOC	DIC	SiO_2	Cl	SO_4	Na	K	Ca	Fe	Mn	FOREST	WOOD	TUNDRA
0.96**																
0.58**	0.76**															
0.63**	0.79**	0.99**														
0.89**	0.84**	0.46	0.52*													
0.03	−0.03	−0.34	−0.30	−0.04												
0.02	−0.01	−0.20	−0.14	0.08	0.38											
−0.03	−0.07	−0.22	−0.22	−0.11	0.43	−0.41										
0.13	0.09	−0.15	−0.11	0.17	0.41	0.42	0.09									
0.10	0.03	−0.26	−0.23	0.01	0.75**	0.07	0.72**	0.55**								
0.24	0.24	0.02	0.05	0.15	0.66**	0.13	0.50*	0.62**	0.80**							
−0.03	−0.11	−0.36	−0.34	−0.04	0.77**	0.50*	0.21	0.34	0.45	0.28						
0.18	0.23	0.43	0.41	0.22	−0.72**	−0.48	−0.02	−0.30	−0.32	−0.38	−0.60**					
0.10	0.17	0.35	0.33	0.11	−0.46	−0.12	−0.18	−0.05	−0.18	−0.22	−0.33	0.53*				
0.34	0.34	0.20	0.27	0.37	0.31	0.46	−0.26	0.24	0.05	0.42	0.20	−0.46	−0.36			
0.17	0.21	0.15	0.12	0.21	−0.31	0.06	−0.16	0.18	−0.14	−0.12	−0.16	0.37	0.28	−0.32		
−0.30	−0.34	−0.24	−0.28	−0.37	0.09	−0.45	0.61**	−0.37	0.26	−0.05	0.02	0.08	−0.02	−0.53*	−0.42	
−0.24	−0.24	−0.10	−0.11	−0.49*	−0.20	−0.03	−0.38	0.00	−0.33	−0.38	−0.12	0.05	0.19	−0.21	−0.17	−0.28

(Table 3). [TPU] ranged from 3.0 μg · L (32) to 55.1 μg · L^{-1} (51) and averaged 15.5 μg · L^{-1} for all lakes (Table 4). Interestingly, the average TPU value obtained for lakes in the forest–tundra near Inuvik (29.5 μg · L^{-1}) was more than double that recorded for boreal forest lakes (14.2 μg · L^{-1}). North of and above the treeline, average TPU concentrations were almost equally low in arctic (11.6 μg · L^{-1}) and alpine tundra lakes (11.0 μg · L^{-1}).

On the basis of the general relationship between lake productivity and average concentrations of epilimnetic TP established by Vollenweider (1968, 1976), we conclude that most of our study lakes (52%) fall within the mesoeutrophic and oligomesotrophic range (24%). These results are unexpected, considering that TP concentrations in arctic lakes are usually low (Wetzel 1983; Hobbie 1984). Locally high TP concentrations within our study area may be related to the diverse geological and edaphic conditions (i.e., soil development) in the Yukon, where sedimentary rock deposits (e.g., siltstones, sandstones, and shales of Mesozoic age; limestones and dolomites of Devonian and Ordovician age) are widespread.

Concentrations of SRP were generally low (≤3.3 μg · L^{-1}), with an average concentration of 1.5 μg · L^{-1} for all lakes. Values were especially low in arctic tundra lakes (mean = 0.9 μg · L^{-1}), where concentrations frequently decreased to less than detectable levels (0.5 μg · L^{-1}). [SRP] was also low in Barrow (Alaska) lakes, where concentrations ranged between 0.5 and 3.0 μg · L^{-1} (Prentki et al. 1980; Hobbie 1984).

TN:TP ratios ranged from 13:1 to 103:1 (mean = 45:1), which was comparable to ratios reported by Shortreed and Stockner (1986) for 19 lakes in the Yukon. The highest TN:TP ratios were generally observed in boreal forest lakes of the southern Yukon (mean = 60:1), with particularly high ratios recorded in lakes of the Pelly Crossing area in the central Yukon (sites 8–10) (Table 4). TN:TP ratios were considerably lower in forest–tundra, arctic tundra, and alpine tundra sites, with averages ranging from 33:1 to 42:1.

Iron and manganese

The average concentrations of Fe and Mn were 210.7 and 23.5 μg · L^{-1}, respectively (Table 4). Average [Mn] ranged from 12.1 μg · L^{-1} in the boreal forest to 42.7 μg · L^{-1} in the alpine tundra lakes. In contrast, [Fe] averaged 564.9 μg · L^{-1} in forest–tundra lakes and reached highest concentrations of 1660 (49) and 1280 μg · L^{-1} (24) in lakes near Inuvik. The Fe concentrations in this area were particularly high in strongly coloured lakes receiving drainage from highly organic soils of surrounding bogs and peatlands. As the humic and fulvic acids of such organic soils form strong soluble complexes with multivalent cations such as Fe and Mn (Schnitzer and Desjardins 1969), the high concentrations of these elements may result from increased mobilization of organometallic complexes in peaty soils. According to Hobbie (1973), high inputs of Fe are due mainly to chelation by dissolved organic matter. The strong relationship between water colour and [Fe] is reflected

Table 4. Water chemistry data (1990) for the 59 lakes.

Lake No.	TPU (μg·L^{-1})	TPF (μg·L^{-1})	SRP (μg·L^{-1})	NO$_2$ (μg·L^{-1})	NO$_3$ (μg·L^{-1})	NH$_3$ (μg·L^{-1})	DOC (mg·L^{-1})	DIC (mg·L^{-1})	TKN (μg·L^{-1})	TN (μg·L^{-1})	SiO$_2$ (mg·L^{-1})	SO$_4$ (mg·L^{-1})	Ca (mg·L^{-1})
Boreal forest													
1	14.1	11.0	2.2	0.3	208.0	12.0	10.6	88.2	309	559	2.81	300.2	21.50
2	15.8	14.1	7.5	1.0	15.0	31.0	16.3	134.2	654	734	0.78	1242.0	15.60
3	6.5	4.5	0.5	1.0	14.0	7.0	7.8	52.9	407	514	12.47	82.1	26.70
5	8.7	4.9	ADL	1.4	ADL	ADL	8.6	12.4	260	323	7.86	3.9	16.60
6	5.1	4.3	3.3	ADL	ADL	ADL	10.1	33.1	271	321	9.26	24.5	44.20
7	4.9	3.5	0.6	ADL	ADL	ADL	8.4	40.8	208	259	9.19	29.0	50.30
8	14.6	0.2	1.8	0.2	ADL	6.0	35.1	53.5	1293	1403	4.98	90.5	37.60
9	15.4	0.2	1.3	0.6	ADL	27.0	26.9	30.8	1178	1585	7.26	23.8	37.70
10	12.0	8.1	2.0	ADL	ADL	ADL	14.2	35.1	743	885	6.54	28.9	30.00
11	12.3	9.0	1.6	0.5	ADL	5.0	17.1	3.8	572	667	0.19	2.0	7.78
12	8.7	5.5	1.1	ADL	ADL	ADL	13.5	22.5	352	418	3.08	0.5	31.00
13	9.8	5.6	1.2	1.5	ADL	ADL	16.2	4.6	437	521	0.23	2.8	7.27
14	4.3	2.9	2.4	0.9	ADL	6.0	15.9	35.1	350	409	8.84	57.1	45.40
15	28.8	13.9	2.1	2.9	ADL	5.0	24.2	4.2	699	1036	0.16	4.2	8.55
16	21.6	11.4	1.3	ADL	ADL	ADL	15.3	4.9	615	769	1.00	0.5	6.84
17	25.0	13.0	1.3	ADL	ADL	5.0	18.1	2.2	904	1258	0.17	0.5	3.52
56	35.4	14.5	1.6	1.0	ADL	14.0	12.3	2.4	409	620	1.02	7.6	5.48
Forest–tundra													
4	3.7	2.9	1.4	0.9	ADL	ADL	3.8	14.4	121	158	7.84	8.8	19.00
22	10.3	7.9	1.6	0.9	ADL	ADL	17.8	14.4	532	591	3.16	38.9	39.20
23	17.5	11.3	2.3	1.6	ADL	ADL	10.6	4.6	637	717	0.94	13.2	13.90
24	44.9	34.1	10.1	4.3	27.0	11.0	22.6	4.0	700	803	2.37	5.2	6.50
25	16.1	12.1	2.0	0.8	ADL	22.0	13.1	11.5	631	710	0.57	32.6	20.20
47	9.3	6.0	ADL	ADL	15.0	ADL	9.1	18.9	334	401	0.94	42.3	33.90
48	48.8	12.7	3.2	1.4	15.0	ADL	11.6	5.5	518	1058	0.39	8.1	9.23
49	43.9	21.2	2.0	0.6	16.0	ADL	21.5	2.0	612	781	3.31	9.1	6.73
50	28.6	24.3	0.6	2.9	16.0	37.0	29.9	3.9	823	922	0.75	9.3	9.17
51	55.1	13.6	0.6	1.9	16.0	26.0	17.2	7.4	688	1114	1.73	3.8	10.20
52	9.7	6.6	0.6	1.5	14.0	16.0	11.3	1.8	316	388	1.54	49.4	12.60
57	40.5	16.8	1.4	ADL	ADL	6.0	9.8	2.1	335	545	0.51	31.9	9.49
Arctic tundra													
26	15.3	7.1	1.5	1.1	ADL	19.0	6.6	6.3	305	380	0.14	1.9	9.14
27	19.8	8.0	2.2	ADL	15.0	36.0	12.3	27.7	535	630	0.32	17.9	43.80
28	16.7	8.1	0.7	0.4	ADL	ADL	6.7	12.9	281	403	0.29	6.0	19.30
29	9.2	4.8	ADL	ADL	ADL	ADL	5.8	17.5	239	309	0.10	1.1	20.80
30	12.6	6.0	ADL	ADL	ADL	38.0	18.2	19.6	567	649	0.09	24.7	26.90
31	6.6	3.7	ADL	ADL	10.0	18.0	8.0	19.2	343	401	0.17	10.5	24.70
32	3.0	2.9	ADL	0.9	15.0	8.0	4.8	27.4	172	220	1.52	9.2	36.20
33	13.8	11.4	1.9	1.9	11.0	51.0	19.0	6.8	862	955	0.40	4.7	11.50
34	13.7	6.3	ADL	ADL	ADL	20.0	10.7	17.9	391	473	0.57	3.0	24.00
35	11.3	6.6	ADL	ADL	ADL	22.0	8.5	17.5	282	364	0.42	2.8	21.80
36	20.8	6.2	0.7	ADL	ADL	19.0	9.6	14.1	459	541	0.43	1.4	18.30
37	10.5	5.6	ADL	0.6	ADL	17.0	8.9	12.7	309	404	0.51	1.4	16.40
38	13.3	5.3	ADL	ADL	ADL	15.0	9.6	20.8	384	506	0.57	2.1	24.20
39	5.0	3.7	ADL	ADL	ADL	ADL	6.1	21.4	211	273	1.37	4.7	29.60
40	13.1	10.3	ADL	ADL	ADL	6.0	10.1	13.3	497	587	0.64	0.8	18.90
41	7.5	4.2	ADL	ADL	ADL	9.0	7.9	24.0	247	305	0.61	9.2	32.20
42	3.5	2.7	2.2	7.2	51.0	10.0	4.6	15.7	139	229	1.54	1.9	20.80
43	5.0	3.2	0.5	29.0	23.0	9.0	5.7	10.3	197	305	0.81	1.6	14.00
44	12.3	6.6	1.1	3.7	30.0	8.0	8.1	14.2	336	451	0.73	2.1	19.80
45	17.8	12.6	ADL	0.2	20.0	14.0	11.8	3.4	397	497	1.92	12.9	7.78
46	16.2	10.9	0.6	ADL	14.0	19.0	11.4	4.9	439	541	1.18	14.6	9.74
53	11.4	7.8	1.4	1.4	ADL	21.0	10.8	3.7	263	341	0.96	6.1	5.89

Table 4 (*continued*).

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
46.30	10.10	63.6	0.3	ADL	321	42	8.4	5.0	40	8
187.00	29.90	24.5	0.1	ADL	493	64	11.4	12.0	46	8
16.30	4.30	1.5	1.5	ADL	704	92	10.8	7.0	79	8
1.95	0.56	0.6	2.3	1.3	369	52	76.0	4.0	37	7
4.60	1.21	0.9	0.3	ADL	354	40	15.8	12.0	63	9
7.56	1.85	0.9	0.2	ADL	279	41	5.9	7.0	53	7
20.70	1.93	1.4	1.5	0.7	848	100	19.4	16.0	96	8
4.32	2.84	1.3	1.9	1.3	3280	396	17.4	21.0	103	8
4.36	2.94	1.5	0.9	0.7	828	132	6.3	17.0	74	6
0.73	1.57	4.2	0.9	0.7	592	84	50.2	ADL	54	7
1.32	1.45	1.0	2.8	1.0	412	56	26.5	11.0	48	7
0.39	0.46	0.5	1.7	0.7	495	72	36.5	4.0	53	7
3.69	1.60	0.4	2.7	ADL	398	48	10.0	7.0	95	8
0.53	1.10	0.9	4.9	1.1	2170	324	165.0	18.0	36	7
0.94	1.57	0.5	2.5	0.8	1060	144	124.0	21.0	36	7
0.75	1.26	0.7	4.9	2.3	2320	344	134.0	19.0	50	7
0.77	0.84	0.7	10.5	8.0	1380	200	612.0	23.0	18	7
2.80	0.77	0.3	1.7	ADL	158	26	8.6	5.0	43	6
2.26	1.04	6.1	1.8	1.3	300	48	52.7	11.0	57	6
1.60	0.65	3.7	2.0	1.4	472	68	287.0	11.0	41	7
1.32	0.80	2.0	1.1	ADL	536	72	1280.0	33.0	18	7
8.28	2.07	3.2	2.6	2.1	464	68	136.0	20.0	44	7
5.02	1.64	2.7	0.7	0.4	272	52	26.7	8.0	43	5
1.60	1.38	1.6	20.4	18.1	3480	524	272.0	39.0	22	7
1.38	0.45	1.4	1.8	0.7	1180	152	1660.0	61.0	18	8
4.93	1.10	5.2	0.6	0.2	572	80	774.0	50.0	32	7
4.21	1.22	2.0	4.9	4.0	2940	408	771.0	43.0	20	7
7.23	1.14	1.7	0.5	0.1	304	56	348.0	72.0	40	5
0.85	1.05	0.5	7.9	6.7	1340	200	607.0	44.0	13	7
8.16	1.11	15.5	1.5	0.7	416	64	170.0	14.0	25	7
33.40	3.23	75.2	1.4	0.6	544	80	754.0	16.0	32	7
9.42	1.79	18.8	1.1	0.5	780	112	376.0	13.0	24	7
10.30	0.90	18.7	0.8	0.2	444	60	65.5	11.0	34	7
10.40	1.22	21.5	1.8	ADL	504	72	80.6	11.0	52	7
8.97	1.43	16.3	0.8	0.3	364	48	44.6	7.0	61	8
7.63	1.36	13.2	0.2	ADL	204	32	15.6	6.0	73	6
6.05	1.14	10.0	0.9	0.3	572	80	297.0	13.0	69	7
9.72	1.43	17.3	1.8	0.5	492	72	153.0	46.0	35	7
6.10	1.63	10.1	1.9	1.3	440	72	143.0	11.0	32	6
4.71	1.15	7.2	1.8	1.1	480	72	92.5	18.0	26	7
4.58	1.02	6.8	1.0	0.3	548	84	58.0	13.0	38	7
7.27	1.31	8.9	1.9	1.0	616	112	38.9	16.0	38	6
5.04	1.16	7.4	1.4	0.6	320	52	24.2	7.0	55	6
4.86	1.15	8.2	2.6	1.4	496	80	165.0	18.0	45	6
7.83	1.96	12.2	1.0	0.6	304	48	51.7	9.0	41	6
3.36	0.89	5.2	1.1	0.6	228	32	21.1	160.0	65	7
3.08	0.98	5.6	1.0	0.6	352	56	19.1	14.0	61	6
3.08	1.10	3.7	1.2	0.7	456	81	72.0	19.0	37	6
2.22	0.90	1.9	1.4	0.9	508	80	348.0	23.0	28	6
2.39	1.39	1.9	1.1	0.6	588	88	235.0	33.0	33	7
3.06	0.77	1.6	1.3	0.6	468	68	110.0	14.0	30	7

Table 4 (*concluded*).

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$_4$ ($mg \cdot L^{-1}$)	Ca ($mg \cdot L^{-1}$)
54	11.7	7.5	1.4	0.8	ADL	ADL	13.0	5.1	301	364	1.26	19.0	11.90
55	9.0	7.2	0.5	ADL	ADL	ADL	8.5	7.4	237	319	0.62	3.2	10.40
Alpine tundra													
18	11.4	6.2	1.0	0.8	ADL	ADL	6.5	18.1	239	302	2.03	11.5	23.00
19	10.0	6.9	1.4	0.8	ADL	ADL	10.2	20.5	348	415	1.95	9.0	31.60
20	23.1	14.1	2.4	2.0	ADL	11.0	12.3	5.7	498	606	0.37	1.9	9.66
21	7.8	4.9	1.2	0.6	ADL	ADL	11.4	3.8	327	422	0.30	4.1	5.82
58	9.8	4.5	ADL	ADL	ADL	ADL	3.9	0.3	93	191	1.92	39.0	8.29
59	4.0	2.8	0.5	0.9	ADL	ADL	3.1	5.5	72	123	1.74	15.2	12.80
Minimum	3.0	0.2	0.5	0.2	9.0	5.0	3.1	0.3	72	123	0.09	0.5	3.52
Maximum	55.1	34.1	10.1	29.0	208.0	51.0	35.1	134.2	1293	1585	12.47	1242.0	50.30
Median	12.3	6.6	1.2	0.6	10.0	6.0	10.7	12.9	352	497	0.94	8.8	18.30
Mean	15.5	8.4	1.5	1.4	16.0	12.2	12.3	17.8	438.6	558.9	2.12	40.6	19.58

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).

Fig. 3. Plot of Cl^- concentrations versus distance from the Arctic Ocean in a subset of 31 lakes from the Inuvik area and the Tuktoyaktuk Peninsula.

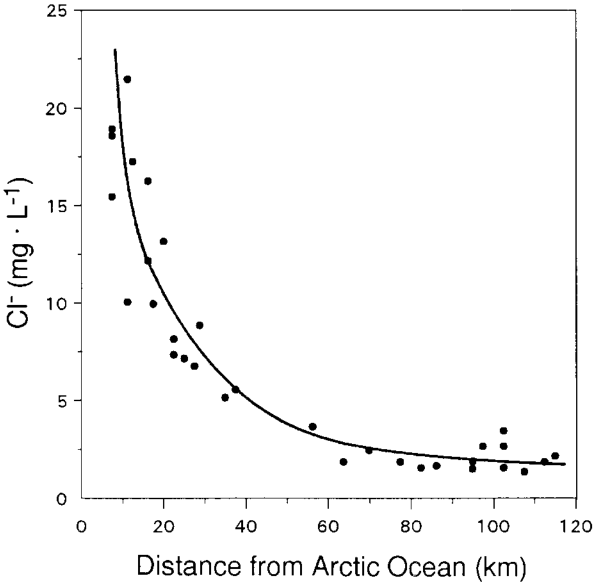
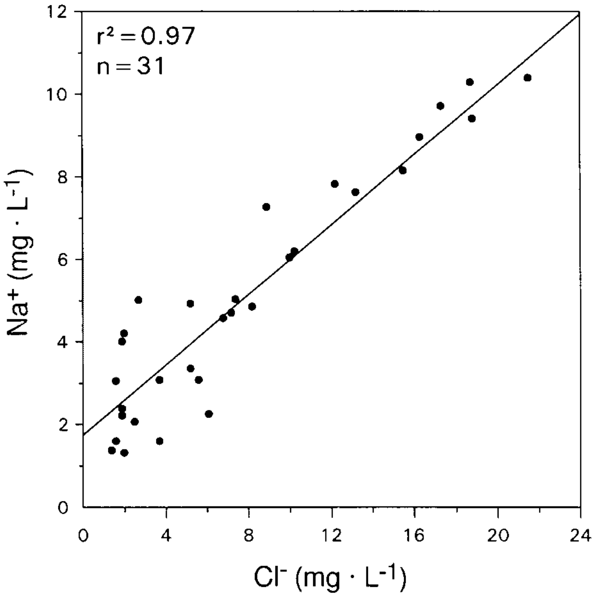


Fig. 4. Plot of Na^+ versus Cl^- concentrations in a subset of 31 lakes from the Inuvik area and the Tuktoyaktuk Peninsula. The line shows a relationship that is expected if the concentrations of both ions were derived entirely from marine aerosols.



in the significant negative correlation between Fe and TRANS (Fig. 2).

Biotic variables

Chlorophyll a

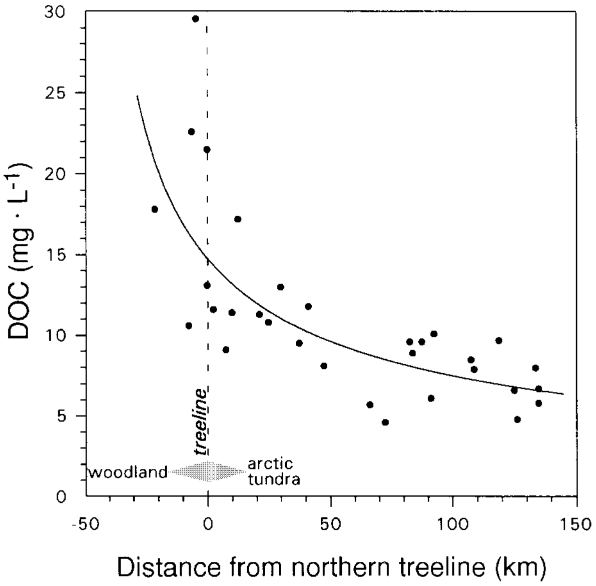
The concentration of CHLAU, which is widely used as a measure of phytoplankton biomass and trophic status (Vollenweider 1968), ranged from 0.1 to 20.4 $\mu g \cdot L^{-1}$ (Table 4). Thus, most of our study sites are oligotrophic according to Likens (1975) and Wetzel (1983). Above-average CHLAU levels were recorded in the forest–tundra (4.0 $\mu g \cdot L^{-1}$) and boreal forest lakes (2.5 $\mu g \cdot L^{-1}$) whereas average concentrations were considerably lower in arctic (1.4 $\mu g \cdot L^{-1}$) and alpine tundra (0.9 $\mu g \cdot L^{-1}$) lakes, reflecting both a latitudinal and altitudinal gradient in lake trophic status. This pattern is most likely associated with changing climatic and vegetational conditions and subsequent differences in nutrient input, length of growing season, and light regime (length of photoperiod), as well as other factors.

A significant CHLAU:TP relationship could be observed in our study lakes (r = 0.62–0.64, P < 0.01) (Table 3; Fig. 2), which corresponds to results of previous investigations of

Table 4 (*concluded*).

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
4.01	1.01	1.9	2.0	ADL	360	52	265.0	14.0	31	7
2.07	0.98	2.5	1.5	ADL	480	72	160.0	20.0	35	7
3.71	0.39	0.3	0.8	ADL	308	52	56.9	35.0	26	6
3.40	0.58	0.4	1.1	0.8	396	56	35.2	11.0	42	7
0.34	0.10	0.4	0.9	0.6	664	96	664.0	22.0	26	7
0.34	0.39	0.6	1.1	ADL	608	84	127.0	17.0	54	7
0.70	0.45	0.3	0.8	0.6	616	88	196.0	160.0	19	7
0.24	0.14	0.2	0.9	0.7	252	40	37.4	11.0	31	6
0.24	0.10	0.2	0.1	0.1	158	26	5.9	2.0	13	5
187.00	29.90	75.2	20.4	18.1	3480	524	1660.0	160.0	103	9
4.01	1.15	2.0	1.4	0.6	492	72	80.6	14.0	40	7
8.82	1.90	7.3	2.1	1.2	714.1	102.9	210.7	23.5	45	7

Fig. 5. Plot of DOC concentrations versus distance from the northern treeline in a subset of 31 lakes from the Inuvik area and the Tuktoyaktuk Peninsula.



Yukon lakes (Shortreed and Stockner 1986). These results are not unexpected, given the large number of studies that document the strong correlation between chlorophyll *a* and TP in many North American lakes (e.g., Dillon and Rigler 1974; Kerekes 1975; Vollenweider 1976; Edmondson and Lehman 1981; Prepas and Trew 1983; Stockner and Shortreed 1985; Ostrofsky and Rigler 1987).

Principal components analysis

Because not all variables were measured in all study sites, a data set of 59 sample sites with 18 chemical (pH, COND, TPU, TPF, DOC, DIC, TKN, TN, SiO_2, SO_4, Ca, Na, K, Cl, POC, PN, Fe, Mn) and 4 physical variables (TEMP, TRANS, DEPTH, AREA) was used in the PCA (Fig. 2). Those variables with concentrations below or near the analytical limit of detection (i.e., NO_2, NO_3, NH_3, SRP) or variables that were not available for many of the lakes (i.e., DO) were excluded from the analysis. The biological variable CHLAU was given zero weight and included as a passive variable. The same was done with some of the geographic–environmental variables (i.e., LAT, ALT, FOREST, WOOD, TUNDRA, ALPINE), as the main purpose of this study was to illustrate and interpret the major patterns of variation within the physical and chemical characteristics of lakes. All passive variables were nevertheless included in the PCA ordination biplot (Fig. 2).

The total percentage of variation explained by the first two PCA axes was 56%, with eigenvalues of $\lambda_1 = 0.35$ and $\lambda_2 = 0.21$, respectively. Because the eigenvalues for the third and fourth PCA axes (0.11 and 0.08) were relatively low, they were not elaborated upon. The length of the solid arrows and their proximity to the axes show the relative weight of each variable in determining each axis (Ter Braak 1987). Thus, such variables as TRANS, DEPTH, AREA, Fe, Mn, TPF, and TPU are significantly correlated ($P < 0.05$) with axis 1 whereas the physical variables TEMP, LAT, and ALT are most strongly correlated with axis 2. The highly negative correlation between DEPTH and nutrient variables (including the trophic proxy CHLAU), as well as the strong positive correlation between DEPTH and TRANS, reflects the commonly observed inverse relationship between lake productivity and lake water depth – water transparency.

Two major groups of variables with high positive correlations (generally recognizable by the small angles between their biplot arrows) could be identified from the biplot, namely nutrient-related variables (i.e., TPU, POC, PN, TN, TKN, DOC) in the upper left quadrant of the ordination and those associated with ionic concentrations (i.e., COND, DIC, K, Na, Ca, SO_4), positioned in the upper right quadrant. Some of these variables were mutually redundant (e.g., TN and TKN) as demonstrated by their highly significant correlations (Table 3) and extremely small angles between their biplot arrows. Most variables were negatively correlated between these two major sets.

From the relative positioning of the sample scores, we infer that arctic and alpine tundra sites are physically and chemically very similar. Arctic and alpine tundra sites form a dense cloud of points in the central part of the lower two quadrants of the biplot, thereby indicating narrow ranges in physical and chemical conditions (Fig. 2). Boreal forest and forest–tundra sites, however, are not as distinct limnologically. As a result, their sample scores are more widely scattered in the upper two quadrants, reflecting conditions of comparatively wide variability (Fig. 2). The inclusion of a limited range of catchment characteristics (albeit run as passive variables) suggests that lakes in conifer-forested catchments generally tend to have higher concentrations of nutrients and major ions and that lakes with unforested catchments have considerably lower concentrations.

The first PCA axis effectively separated deep oligotrophic lakes with high water transparency, such as sites 7, 14, and 32, from shallow eutrophic sites with high [Fe], such as sites 56, 57, 49, and 24. The latter were generally strongly coloured with high nutrient concentrations, and mostly occurred in the forest–tundra near Inuvik.

From the eigenvalues and the placement of arrows related to nutrient and ionic variables, it was evident that both axes were relatively complex, thereby suggesting that there were several gradients of variation in the physical and chemical data. Both axes explained large proportions of the total variance, effectively separating "forested" sites characterized by either high concentrations in nutrients or major ions (or both), positioned in the upper two quadrants, from lakes located in areas of treeless vegetation (i.e., arctic and alpine tundra sites), positioned in the lower two quadrants.

Conclusions

The lakes distributed along the Yukon – Tuktoyaktuk Peninsula transect exhibit a wide range in water chemistry, thereby not only reflecting the strong climatic and vegetational gradients (both latitudinal and altitudinal) inherent in this data set, but also the complex nature of the geological and edaphic conditions of the study area. On the basis of their limnological characteristics, the 59 lakes we sampled can be separated into several distinct groups.

As expected, one of the most prominent spatial patterns arising from the data is the strong relationship between distance from the coast and [Cl] and [Na] in the lakes. Salts from atmospheric inputs (i.e., Cl^- and Na^+) are the dominant ions determining the chemistry of arctic coastal lakes on the Tuktoyaktuk Peninsula. Because permafrost acts as a seal and prevents subsurface drainage, these lakes are similar to other coastal lakes that are isolated from groundwater inputs. The chemistry of such coastal lakes is thus determined mainly by marine aerosols (e.g., Hammar 1989; Kling et al. 1992). In contrast with the input of sea salt to lakes near the coast, atmospheric inputs seem to have relatively little influence on the chemistry of inland lakes (Kling et al. 1992).

In the interior of the Yukon, lake waters are rich in HCO_3, Ca, and SO_4, and their proportions largely reflect the chemistry of the surrounding soils and bedrock, as well as catchment vegetation type. Measurements of pH, DIC, and Ca indicate that most surface waters were characterized by relatively high alkalinity and that acidic lakes were rare in the Yukon and northwestern Northwest Territories.

The strong latitudinal gradient exhibited in the concentrations of SiO_2 may be due to local bedrock geology, as well as differences in the external input of soil-derived elements such as Ca and SiO_2, which varies greatly between high- and low-latitude lakes. For example, the presence of permafrost distinguishes high-latitude lakes from lakes at lower latitudes. Permafrost has little direct effect on a lake but profoundly alters solute runoff from the lake's drainage, and may decrease the absolute amount of solute runoff as well by reducing the area of rock surface available for weathering (Welch and Legault 1986).

In general, the productivity is likely limited by the low levels of both inorganic nitrogen and inorganic phosphorus. However, all our study sites (including lakes on the Tuktoyaktuk Peninsula) showed markedly higher ionic compositions and nutrient levels than arctic lakes on the Canadian Shield (e.g., Pienitz et al. 1997). With respect to variables commonly used as indicators of trophic status (e.g., TP, TN, chlorophyll *a*), it appears that our study lakes from the southern and central part of the Yukon were slightly more productive than the 19 lakes studied by Shortreed and Stockner (1986), most of which were oligotrophic. This discrepancy may be due mainly to differences in lake area and depth, as our study sites were generally smaller and shallower. In the present study, lakes in boreal forest and forest–tundra regions are oligo- to meso-trophic whereas arctic and alpine tundra lakes are usually oligotrophic to ultraoligotrophic.

The organically bound nutrients in our freshwater lakes appeared to be closely associated with vegetational and climatic zones, with the most striking changes (i.e., sharp decreases in nutrients) usually occurring at the transition from forested areas to those located north of the treeline. Future limnological studies in these high-latitude regions should further elucidate some of these relationships.

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 Drs. R. Hall, A. Uutala, and I. Walker for help with the fieldwork. Fieldwork was supplemented by logistic support from the Polar Continental Shelf Project and the Northern Studies Training Program.

References

Allen, W.T.R. 1964. Break-up and freeze-up dates in Canada. Department of Transport, Meteorological Branch, Ottawa, Ont.

Anema, C., Hecky, R.E., Fee, E.J., Nernberg, D., and Guildford, S.J. 1990*a*. Water chemistry of some lakes and channels in the Mackenzie Delta and on the Tuktoyaktuk Peninsula, N.W.T., 1985. Can. Data Rep. Fish. Aquat. Sci. No. 726. (Available from Department of Fisheries and Oceans, Winnipeg, MB R3T 2N6, Canada.)

Anema, C., Hecky, R.E., Himmer, S., and Guildford, S.J. 1990*b*. Water chemistry of some lakes and channels in the Mackenzie Delta and on the Tuktoyaktuk Peninsula, N.W.T., 1986. Can. Data Rep. Fish. Aquat. Sci. No. 729. (Available from Department of Fisheries and Oceans, Winnipeg, MB R3T 2N6, Canada.)

Bello, R., and Smith, J.D. 1990. The effect of weather variability on the energy balance of a lake in the Hudson Bay Lowlands, Canada. Arct. Alp. Res. **22**: 98–107.

Bigras, S.C. 1990. Hydrological regime of lakes in the Mackenzie Delta, Northwest Territories, Canada. Arct. Alp. Res. **22**: 163–174.

Boer, G.J., McFarlane, N., Blanchet, J.-P., and Lazare, M. 1990. Greenhouse gas induced climatic change simulated with the CCC second generation GCM. *In* Application of the Canadian Climate Centre general circulation model output for regional climate impact studies: guidelines for users. Canadian Climate Centre, Atmospheric Environment Service, Downsview, Ont.

Cornwell, J.C. 1992. Cation export from Alaskan arctic watersheds. Hydrobiologia, **240**: 15–22.

Dillon, P.J., and Rigler, F.H. 1974. The phosphorus – chlorophyll relationship in lakes. Limnol. Oceanogr. **19**: 767–773.

Ecoregions Working Group. 1989. Ecoclimatic regions of Canada, first approximation. Ecological land classification series No. 23. Ecoregions Working Group, Environment Canada, Ottawa, Ont.

Edmondson, W.T., and Lehman, J.T. 1981. The effect of changes in the nutrient income on the condition of Lake Washington. Limnol. Oceanogr. **26**: 1–29.

Eilers, J.M., Landers, D.H., Newell, A.D., Mitch, M.E., Morrison, M., and Ford, J. 1993. Major ion chemistry of lakes on the Kenai Peninsula, Alaska. Can. J. Fish. Aquat. Sci. **50**: 816–826.

Ennis, G.L., Cinader, A., McIndoe, S., and Munon, T. 1982. An annotated bibliography and information summary on the fisheries resources of the Yukon River Basin in Canada. Can. Manuscr. Rep. Fish. Aquat. Sci. No. 1657.

Environment Canada. 1979. Analytical methods manual. Inland Waters Directorate, Water Quality Branch, Ottawa, Ont.

Environment Canada. 1985–1990. Yukon lake ice report data. Whitehorse Airport, Yukon Territory, Canada.

Fee, E.J., Hecky, R.E., Guildford, S.J., Anema, C., Mathew, D., and Hallard, K. 1988. Phytoplankton primary production and related limnological data for lakes and channels in the Mackenzie Delta and lakes on the Tuktoyaktuk Peninsula, N.W.T. Can. Tech. Rep. Fish. Aquat. Sci. No. 1614.

Hammar, J. 1989. Freshwater ecosystems of polar regions: vulnerable resources. Ambio, **18**: 6–22.

Hobbie, J.E. 1973. Arctic limnology: a review. *In* Alaskan arctic tundra. *Edited by* M.E. Britton. Technical paper No. 25. Arctic Institute of North America, Calgary, Alta. pp. 127–168.

Hobbie, J.E. (*Editor*). 1980. Limnology of tundra ponds. Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pa.

Hobbie, J.E. 1984. Polar limnology. *In* Ecosystems of the World 23: lakes and reservoirs. *Edited by* F.B. Taub. Elsevier Science Publishers B.V., Amsterdam, The Netherlands. pp. 63–105.

Horler, A., Johnston, R.A.C., and Cronkite, G.M.W. 1983. An assessment of the fishery resource in 18 lakes within the Yukon Territory, Canada. Yukon River Basin Study Fisheries Work Group Project No. 3. Department of Fisheries and Oceans, Whitehorse, Y.T.

Howard, H.H., and Prescott, G.W. 1973. Seasonal variation of chemical parameters in Alaskan tundra lakes. Am. Midl. Nat. **90**: 154–164.

Kalff, J. 1968. Some physical and chemical characteristics of arctic fresh waters in Alaska and northwestern Canada. J. Fish. Res. Board Can. **25**: 2575–2587.

Kerekes, J.J. 1975. Limnological conditions in five small oligotrophic lakes in Terra Nova National Park, Newfoundland. J. Fish. Res. Board Can. **33**: 555–583.

Kling, G.W., Kipphut, G.W., and Miller, M.C. 1991. Arctic lakes and streams as gas conduits to the atmosphere: implications for tundra carbon budgets. Science (Washington, D.C.), **251**: 298–301.

Kling, G.W., O'Brien, W.J., Miller, M.C., and Hershey, A.E. 1992. The biogeochemistry and zoogeography of lakes and rivers in arctic Alaska. Hydrobiologia, **240**: 1–14.

Koivo, L.K., and Ritchie, J.C. 1978. Modern diatom assemblages from lake sediments in the boreal–arctic transition region near the Mackenzie Delta, N.W.T., Canada. Can. J. Bot. **56**: 1010–1020.

Lesack, L.F.W., Hecky, R.E., and Marsh, P. 1991. The influence of frequency and duration of flooding on the nutrient chemistry of Mackenzie Delta lakes. *In* Mackenzie Delta: Environmental Interactions and Implications of Development; Proceedings of the Workshop on the Mackenzie Delta, Saskatoon, Sask., October 17–18, 1989. *Edited by* P. Marsh and C.S.L. Ommanney. National Hydrology Research Institute, Environment Canada, Saskatoon, Sask. pp. 19–36.

Likens, G.E. 1975. Primary production of inland aquatic ecosystems. *In* The primary productivity of the biosphere. *Edited by* H. Lieth and R.W. Whittaker. Springer Verlag, New York. pp. 185–202.

Lindsey, C.C., Patalas, K., Bodaly, R.A., and Archibald, C.P. 1981. Glaciation and the physical, chemical, and biological limnology of Yukon lakes. Can. Tech. Rep. Fish. Aquat. Sci. No. 966.

Livingstone, D.A. 1966. Alaska, Yukon, Northwest Territories, and Greenland. *In* Limnology in North America. *Edited by* D.G. Frey. University of Wisconsin Press, Madison, Wis. pp. 559–574.

Luckman, B.H. 1989. Global change and the record of the past. GEOS, **18**: 1–8.

Manabe, S., and Wetherald, R.T. 1986. Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide. Science (Washington, D.C.), **232**: 626–628.

Marsh, P. 1989. Soil infiltration and snow-melt run-off in the Mackenzie Delta, N.W.T. *In* Proceedings of the 5th International Conference on Permafrost, Trondheim, Norway, August 2–5, 1988. Tapir Publishers, Trondheim, Norway. pp. 618–621.

Marsh, P., and Bigras, S.C. 1988. Evaporation from Mackenzie Delta lakes, N.W.T., Canada. Arct. Alp. Res. **20**: 220–229.

Maxwell, B. 1992. Arctic climate: potential for change under global warming. *In* Arctic ecosystems in a changing climate. *Edited by* F.S. Chapin, J.F. Reynolds, R.L. Jefferies, G.R. Shaver, J. Svoboda, and E.W. Chu. Academic Press, New York. pp. 11–34.

McNeely, R.N., Neimanis, V.P., and Dwyer, L. 1979. Water quality sourcebook: a guide to water quality parameters. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, Ont.

Neilson, M.A., and Stevens, R.J.J. 1987. Spatial heterogeneity of nutrients and organic matter in Lake Ontario. Can. J. Fish. Aquat. Sci. **44**: 2192–2203.

Ostrofsky, M.L., and Rigler, F.H. 1987. Chlorophyll–phosphorus relationships for subarctic lakes in western Canada. Can. J. Fish. Aquat. Sci. **44**: 775–781.

Oswald, E.T., and Senyk, J.P. 1977. Ecoregions of Yukon Territory. Canadian Forestry Service, Environment Canada, Victoria, B.C.

Patalas, K. 1984. Mid-summer mixing depths of lakes of different latitudes. Verh. Int. Ver. Theor. Angew. Limnol. **22**: 97–102.

Pienitz, R. 1993. Paleoclimate proxy data inferred from freshwater diatoms from the Yukon and the Northwest Territories. Ph.D. thesis, Queen's University, Kingston, Ont.

Pienitz, R., Douglas, M.S.V., Smol, J.P., Huttunen, P., and Meriläinen, J. 1995*a*. Diatom, chrysophyte and protozoan distributions along a latitudinal transect in Fennoscandia. Ecography, **18**: 429–439.

Pienitz, R., Smol, J.P., and Birks, H.J.B. 1995*b*. Assessment of freshwater diatoms as quantitative indicators of past climatic change in the Yukon and Northwest Territories, Canada. J. Paleolimnol. **13**: 21–49.

Pienitz, R., Smol, J.P., and Lean, D.R.S. 1997. Physical and chemical limnology of 24 lakes located between Yellowknife and Contwoyto Lake, Northwest Territories (Canada). Can. J. Fish. Aquat. Sci. **54**: 347–358.

Prentki, R.T., Miller, M.C., Barsdate, R.J., Alexander, V., Kelley, J., and Coyne, P. 1980. Chemistry. *In* Limnology of tundra ponds. *Edited by* J.E. Hobbie. Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pa. pp. 76–178.

Prepas, E.E., and Trew, D.O. 1983. Evaluation of the phosphorus-chlorophyll relationship for lakes off the Precambrian Shield in western Canada. Can. J. Fish. Aquat. Sci. **40**: 27–35.

Ritchie, J.C. 1977. The modern and late Quaternary vegetation of the Campbell–Dolomite Uplands near Inuvik, N.W.T., Canada. Ecol. Monogr. **47**: 401–423.

Ritchie, J.C. 1984. Past and present vegetation of the far northwest of Canada. University of Toronto Press, Downsview, Ont.

Roots, E.F. 1989. Climate change: high latitude regions. Clim. Change, **15**: 223–253.

Schindler, D.W., Welch, H.E., Kalff, J., Brunskill, G.J., and Kritsch, N. 1974. Physical and chemical limnology of Char Lake, Cornwallis Island (75°N lat.). J. Fish. Res. Board Can. **31**: 585–607.

Schindler, D.W., Beaty, K.G., Fee, E.J., Cruikshank, D.R., DeBruyn, E.R., Findlay, D.L., Linsey, G.A., Shearer, J.A., Stainton, M.P., and Turner, M.A. 1990. Effects of climatic warming on lakes of the central boreal forest. Science (Washington, D.C.), **250**: 967–970.

Schnitzer, M., and Desjardins, J.G. 1969. Chemical characteristics of a natural soil leachate from a humic podzol. Can. J. Soil Sci. **49**: 151–158.

Sheath, R.G. 1986. Seasonality of phytoplankton in northern tundra ponds. Hydrobiologia, **138**: 75–83.

Sheath, R.G., and Hellebust, J.A. 1978. Comparison of algae in the euplankton, tychoplankton, and periphyton of a tundra pond. Can. J. Bot. **56**: 1472–1483.

Shortreed, K.S., and Stockner, J.G. 1986. Trophic status of 19 subarctic lakes in the Yukon Territory. Can. J. Fish. Aquat. Sci. **43**: 797–805.

Stockner, J.G., and Shortreed, K.S. 1985. Whole-lake fertilization experiments in coastal British Columbia lakes: empirical relationships between nutrient inputs and phytoplankton biomass and production. Can. J. Fish. Aquat. Sci. **42**: 649–658.

Stumm, W., and Morgan, J.J. 1981. Aquatic chemistry. 2nd ed. John Wiley & Sons, New York.

Ter Braak, C.J.F. 1987. Unimodal models to relate species to environment. Agricultural Mathematics Group, Wageningen, The Netherlands.

Ter Braak, C.J.F. 1990*a*. CANOCO: a FORTRAN program for CANOnical Community Ordination. Microcomputer Power, Ithaca, N.Y.

Ter Braak, C.J.F. 1990*b*. Update notes: CANOCO version 3.10. Agricultural Mathematics Group, Wageningen, The Netherlands.

Van Tongeren, O.F.R., Van Liere, L., Gulati, R.D., Postema, G., and Boesewinkel-De Bruyn, P.J. 1992. Multivariate analysis of the plankton communities in the Loosdrecht lakes: relationship with the chemical and physical environment. Hydrobiologia, **233**: 105–117.

Vincent, W.F., and Ellis-Evans, J.C. (*Editors*). 1989. High latitude limnology. Hydrobiologia, **172**: 1–323.

Vollenweider, R.A. 1968. The scientific basis of lake and stream eutrophication, with particular reference to phosphorus and nitrogen as eutrophication factors. Techical report DAS/CSI/68. No. 27. Organisation for Economic Co-operation and Development, Paris. pp. 1–182.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol. Dott Marco Marchi, **33**: 53–83.

Welch, H.E. 1991. Comparisons between lakes and seas during the arctic winter. Arct. Alp. Res. **23**: 11–23.

Welch, H.E., and Legault, J.A. 1986. Precipitation chemistry and chemical limnology of fertilized and natural lakes at Saqvaqjuac, N.W.T. Can. J. Fish. Aquat. Sci. **43**: 1104–1134.

Wetzel, R.G. 1983. Limnology. 2nd ed. Saunders College Publishing, Philadelphia, Pa.

Wilkinson, L. 1988. SYSTAT: the system for statistics. SYSTAT Inc., Evanston, Ill.

Zar, J.H. 1984. Biostatistical analysis. 2nd ed. Prentice-Hall Inc., Englewood Cliffs, N.J.