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The Physical and Chemical Limnology of 24 Ponds and One Lake from Isachsen, Ellef Ringnes Island, Canadian High Arctic

key words: limnology, high arctic, phosphorus, chlorophyll-*a*, nutrients

Abstract

The limnology of freshwaters surrounding Isachsen, Ellef Ringnes Island, Nunavut was examined to determine the baseline physical and chemical limnological conditions present in the region. Sites were found to be circumneutral to slightly acidic, and were oligotrophic. Concentrations of most measured chemical variables were highly variable, with broad ranges that greatly exceeded those found in previous surveys conducted in the High Arctic. Ratios of nitrogen to phosphorus suggest that nitrogen may be the limiting nutrient for algal growth at the majority of sites. Principal Components Analysis (PCA) indicated that the major controls on water chemistry variability between sites were conductivity and related variables, and nutrients, explaining 36.5% and 26.5% of the variation in the dataset, respectively.

1. Introduction

Surface waters are a dominant feature of arctic landscapes, however high arctic lakes and ponds remain some of the least studied and poorest understood limnological systems in the world (Schindler, 2001). Despite their geographical isolation, these systems are subject to environmental stressors, many of which can be linked to human activities originating at much lower latitudes. For example, these sites may be subjected to the effects of long-range transport of pollutants (AMAP, 1998) and, in rare cases, cultural eutrophication (Douglas and Smol, 2000). Polar systems may also be highly sensitive to changes in incident UV radiation (Vincent and Pienitz, 1996) and to changes in annual temperature (Smol *et al.,* 1991). As climate models suggest that the High Arctic will experience a disproportionately larger warming due to increased concentrations of greenhouse gases in the next century (Rouse *et al.,* 1997), arctic lakes and ponds will likely experience dramatic future physical, chemical, and biological changes during that period. Despite the need to understand and monitor these systems, even the most basic limnological surveys have yet to be completed in many areas of the High Arctic.

Ellef Ringnes Island, located in the Sverdrup Islands of the Canadian Arctic Archipelago, has numerous lakes and shallow ponds; however, no previous limnological research has been conducted in this area, likely due to its inaccessibility and extreme climate. Limnological surveys have been completed from several neighbouring high arctic regions, including Bathurst Island (Lim *et al.,* 2001), Axel Heiberg Island (Michelutti *et al.,* 2002b), Elles-

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mere Island (ANTONIADES *et al.,* 2000; DOUGLAS and SMOL, 1994), Baffin Island (JOYNT and WOLFE, 2001), Victoria Island (MICHELUTTI *et al.*, 2002a), and from a series of high arctic islands (HAMILTON *et al.,* 2001). However, Ellef Ringnes Island is located in the centre of what is currently a large gap in the geographical coverage of high arctic limnological surveys. The current study is an examination of the physical and chemical limnology of 25 lakes and ponds near Isachsen, a former meteorological station on Ellef Ringnes Island.

In addition to uncommon bedrock and surficial geology (as discussed below), Ellef Ringnes Island is subject to perhaps the most severe climate found in the Canadian High Arctic. Despite the relatively narrow geographic range of our study area (maximum distance between sites = 15 km), the lakes and ponds sampled contain astonishing variability in their limnological characteristics, far in excess of previous arctic surveys. The 25 sites sampled encompass ranges of conductivity and nutrient related variables that are similar to, and often exceed, the ranges of variability seen to date from the entire Canadian Arctic Archipelago (HAMILTON *et al.*, 2001; LIM *et al.*, 2001; MICHELUTTI *et al.*, 2002a; MICHELUTTI *et al.*, 2002b; ANTONIADES *et al.*, 2000; DOUGLAS and SMOL, 1994).

Our main objective for this study is to provide baseline limnological data for the Isachsen region of Ellef Ringnes Island, a previously uninvestigated area of the High Arctic, and to compare these limnological conditions to those found in other arctic regions. This study shows that the limnological characteristics of the lakes and ponds surrounding Isachsen reflect the distinct geology and extreme climate characterizing the region. The data from Ellef Ringnes thus provide an important opportunity to increase our understanding of high arctic limnological characteristics.

2. Material and Methods

2.1. Site Location and Description

Ellef Ringnes Island is a member of the Sverdrup Island group of the Queen Elizabeth Islands in the Canadian Arctic Archipelago (Fig. 1). Isachsen (78°47′ N, 103°32′ W) is located on the west coast in Deer Bay, at an elevation of 25 m asl. Isachsen was first established in April 1948 as one of the Joint US-Canada High Arctic Weather Stations (NAHIR, 1996). It operated under Environment Canada until its closing in September 1978, but a Meteorological Service of Canada automated weather station continues to collect data. Isachsen is considered to be part of the polar desert, as it receives an average precipitation of only 102 mm per year (MAXWELL, 1982). The average annual temperature is –19.0 °C, while monthly averages range from a low of –36.4 °C in February to a high of 3.3 °C in July (MAXWELL, 1982). The region is characterized by perhaps the coldest and most overcast and cloudy conditions in the Canadian Arctic, and is dominated by fog and cloud during much of the year. During the eleven days of the 1996 sampling season, only two periods longer than 6 hours in duration were observed that had less than 60% cloud cover (J. GLEW, pers. comm.). From 1953 to 1972, the cloud ceiling was below 300 m or visibility below 4.8 km an average of 30% of the year (MAXWELL, 1982).

Bedrock in the immediate area is composed of two predominant types: the black shales of the lower Cretaceous Deer Bay Formation, and by outcrops of gabbro (HEYWOOD, 1957; ST.-ONGE, 1965). Large gypsum deposits are present to the south and east of Isachsen (BLACKADAR, 1964; HEYWOOD, 1957). The differences between the erosional properties of gabbro and the other rock types are largely responsible for changes in local topography, with ridges in the area being composed of gabbro (HEYWOOD, 1957). Low-lying hills are present to the northwest of Isachsen, and several sharply rising promontories are present to the south and west. Maximum local elevation reaches approximately 150 m asl. Farther inland, the maximum elevation is approximately 300 m.

The soils of Ellef Ringnes Island are very poorly developed and are generally poorly drained (EVERETT, 1968; HODGSON, 1977). Oxidation of pyrite from the underlying shale has led to the development of acid sulfate soils, with soil pH in the area ranging from 3.0 to 7.2 (FOSCOLOS and KODAMA, 1981; ROSS and IVARSON, 1980; EVERETT, 1968). Isachsen also averages 338 days per year of frost. Due

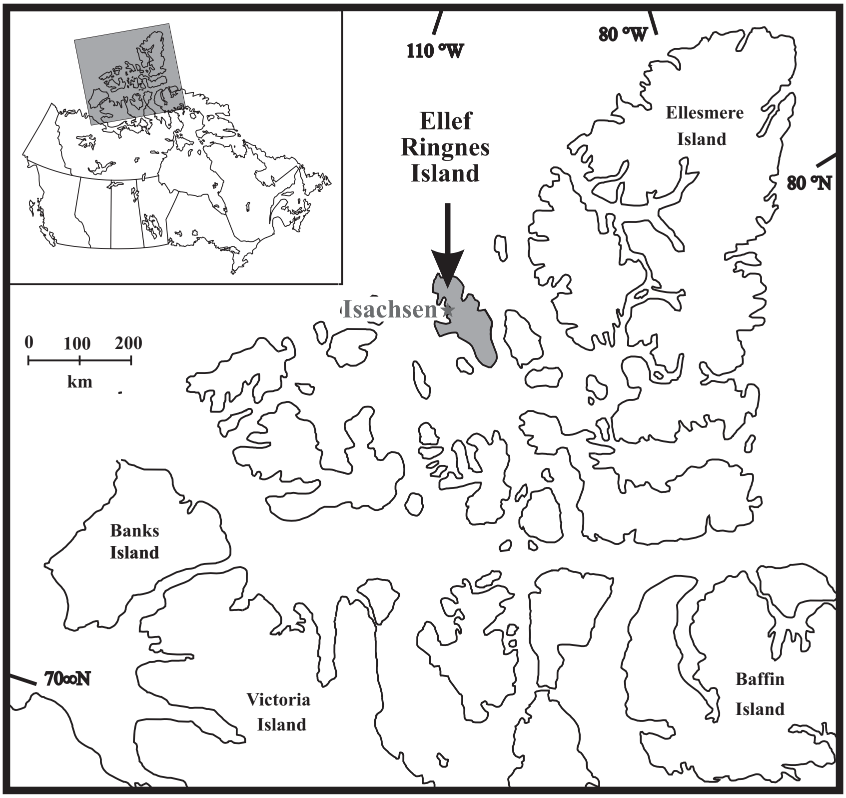

Figure 1. Location map of Isachsen in the Canadian Arctic Archipelago.

to the extremely dry and cold climate coupled with the poor soil conditions, vegetation is almost entirely absent. Vegetative cover is estimated to be below 10%, restricted to herbaceous plants, and largely limited to grasses and mosses (NAHIR, 1996; EDLUND and ALT, 1989).

2.2. Sampling Methods

Twenty-five lakes and ponds were sampled within a 7.5 km radius of the abandoned Isachsen weather station between July 21–31, 1996. Sampling sites were selected to encompass the maximum available range of physiographic and limnological characteristics in this region. Studies of tundra ponds at similar latitudes have shown them to be frozen for approximately 10 months of the year (DOUGLAS and SMOL, 1994). Because values of many limnological variables may fluctuate during the brief summer, our data are not necessarily representative of stable conditions in each site. However, due to the short open-water period we feel confident that these measured values represent a reasonable estimate of typical concentrations for the water bodies.

Despite the relative proximity of the sites, diverse limnological conditions were present. Sampling methods followed those that were used in our other high arctic studies (e.g. LIM *et al.,* 2001; ANTONIADES *et al.,* 2000; DOUGLAS and SMOL, 1994; MICHELUTTI *et al.,* 2002b; MICHELUTTI *et al.,* 2002a). Water temperature (T) was measured immediately below the water surface using a handheld thermometer, pH using a handheld Hannah pH meter, and electrical conductivity (COND) with a YSI model 33 conductivity meter. Samples were prepared for subsequent analysis of 37 water chemistry variables, carried out according to standard protocols at the National Laboratory for Environmental Testing (NLET) of the National Water Research Institute (NWRI) in Burlington, Ontario, (Environment Canada 1994). Unfiltered water was used for measurement of metals: silver (Ag), aluminum (Al), barium (Ba), beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), strontium (Sr), vanadium (V) and zinc (Zn); major ions: calcium (Ca), chloride (Cl), magnesium (Mg), potassium (K), silica (SiO_2), sodium (Na), and sulfate (SO_4); and total phosphorus (TPU). Water was filtered through 0.45 μm polytetrafluoroethylene (PTFE) filters for analysis of total Kjeldahl nitrogen (TKN), ammonia (NH_3), nitrite (NO_2), nitrate-nitrite ($NO_3 + NO_2$), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), soluble reactive phosphorus (SRP) and total dissolved phosphorus (TPF). Water was filtered using pre-ignited 0.7 μm glass microfiber filters for analysis of particulate organic carbon (POC) and particulate organic nitrogen (PON), and chlorophyll-*a*, both uncorrected (CHLAU) and corrected for phaeophytin (CHLAC). These filters were stored frozen and in the dark between sampling and analysis. Total nitrogen (TN) was calculated as the sum of TKN, $NO_3 + NO_2$ and PON, and particulate organic phosphorus (POP) calculated as TPU-TPF. (See Table 1). Measurements of nitrogen, phosphorus, and chlorophyll *a*, including ratios, are presented in mass units (i.e. mg or μg/L), to allow comparisons with earlier published literature (e.g. SAKAMOTO, 1966; DILLON and RIGLER, 1974; SMITH, 1982; SCHANZ and JUON, 1983; DOWNING and MCCAULEY, 1992; RÜHLAND and SMOL, 1998; GREGORY-EAVES *et al.,* 2000; HAMILTON *et al*., 2001; LIM *et al*., 2001; MICHELUTTI *et al*., 2002a, b). Conversions to molar ratios can be made by multiplying the N:P ratio by 2.21 (DOWNING and MCCAULEY, 1992). Latitude and longitude were measured using a handheld GPS receiver. Depth and diameter were measured in the field, with the exception of larger sites where diameter was measured from 1:50,000 NTS topographic map sheets 69 F/12 and 69 F/13. Elevation (ELEV) was also estimated from these maps.

2.3. Statistical Analysis

The dataset was screened prior to statistical analysis, so that all variables that were below detection limits in at least half of the sites were removed (i.e. Ag, Be, Cd, Co, Cr, Mo, NO_2, $NO_3 + NO_2$, NH_3, Pb, V, Zn, and CHLAC). In all other instances where a measured value fell below detection limits, the value was replaced with that of one half the detection limit. The data were transformed, where required, to attain a normal distribution of each variable. Log(x) transformation was used to normalize Al, CHLAU, Cl, COND, Cu, Diameter, DIC, DOC, Fe, K, Li, Mg, Mn, Na, POC, PON, SO_4, Sr, TPU, TPF and TN, log (x + 1) with Ca, log (x + 0.5) with depth, and square root transformation with Ba, ELEV, SiO_2 and TKN. The distributions of T and pH values were normal, and required no transformation, while the distributions of soluble reactive phosphorus (SRP), Ni, and Zn could not be normalized, and so were excluded from further statistical analyses.

Covariation between limnological variables in the dataset was identified by generating a Pearson correlation matrix with Bonferroni adjustment of probabilities (Table 2). Outlier sites in the dataset were identified with Principal Components Analysis (PCA) (HALL and SMOL, 1992). Two sites (i.e. I-N, I-Q) had site scores that exceeded the 95% confidence limit of the mean scores, and were thus considered outliers. These two sites were run passively in further PCA runs. Subsequently, the primary gradients controlling water chemistry were investigated by PCA using CANOCO version 4 (ter BRAAK and ŠMILAUER, 1998). PCA was performed using the transformed dataset as described above. To examine the effect of underlying bedrock on water chemistry, bedrock was added to the dataset as a "dummy" variable. Sites were given a value of 1 or 0 for presence/absence of either gabbro or shale. These variables were included passively in the PCA analysis, to explore their relationship with other limnological variables. The effect of bedrock types on water chemistry was then further investigated using Canonical Variates Analysis (CVA).

3. Results and Discussion

3.1. Physical Variables

The sites that were sampled for this study (Fig. 2) were generally small, shallow, tundra ponds, reflecting the nature of typical water bodies in the area. Of the 25 sites included in this study, all were defined as ponds (i.e. < 2 m depth), except for one lake (i.e. >2 m depth; site I-U). Average depth was 1.0 m; mean diameter of the sites was ~70 m, with a range from 3 to ~460 m. Sites were relatively restricted in elevation, ranging from 6 to 69 m asl, with a mean of 37 m asl. Water temperatures were low, reaching a maximum of 5.5 °C, a minimum of 0 °C, and a mean of 3 °C. Despite the small size and thus low thermal capacities of these sites, water temperatures remained low because warming by solar radiation was reduced due to the persistent cloud cover and cold air temperatures at Isachsen.

3.2. pH, Conductivity

The mean pH (6.9) of the lake and ponds of the Isachsen region was the lowest reported to date in a high arctic limnological survey (HAMILTON *et al.,* 2001; LIM *et al.,* 2001; ANTONIADES *et al.,* 2000; DOUGLAS and SMOL, 1994; MICHELUTTI *et al.,* 2002b; MICHELUTTI *et al.,* 2002a). Despite the close proximity of the sites, pH values ranged from acidic to slightly alkaline (5.1 to 7.9), reflecting differences in bedrock and soil types (Table 1). Those sites with a pH of 7.5 or higher (i.e. I-A, I-D, I-E, I-M, I-Q, I-S) were located on the broad, flat, outwash plain immediately surrounding the Isachsen weather station. Sites that had pH values of 6.0 or lower (i.e. I-F, I-G, I-I, I-J) were also found to the east of the Isachsen station. However, sites within several hundred metres of each other and with apparently similar characteristics were found to have values that differed by as much as 1.5 pH units. We have never recorded such differences in any of our previous high arctic surveys.

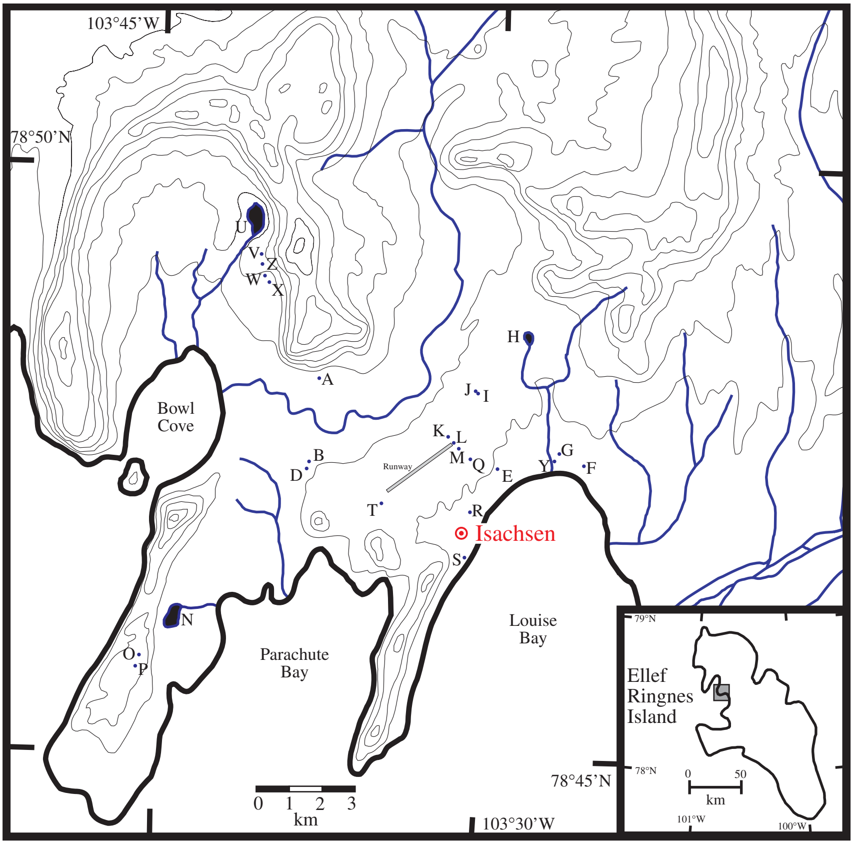

Figure 2. Location map of sites sampled in the Isachsen region.

Table 1. Measured limnological variables from Isachsen, Ellef Ringnes Island. All values are mg/L, unless noted. A list of abbreviations can be found in Methods section and in Figure 2. D.L. = below detection limit, N/A = not available

	SO_4	Cl	DIC	SiO_2	Na	Ca	Mg	K	Ag	Al	Ba	Be	Cd
I-A	6.1	12.7	2.2	1.07	6.9	1.9	1.6	1.1	0.001	0.92	0.0105	<0.0002	<0.001
I-B	62.6	22.7	1.6	0.07	18.4	10.9	5.6	1.8	<0.001	0.59	0.0226	<0.0002	<0.001
I-D	472	667	3.0	0.01	546	59	66	24.7	<0.001	0.10	0.0538	<0.0002	<0.001
I-E	125	115	4.2	0.30	77.6	21.3	15.4	4.8	<0.001	0.26	0.0285	<0.0002	<0.001
I-F	107	3.4	0.9	2.92	9.4	18.1	10.1	1.6	<0.001	0.18	0.0127	<0.0002	<0.001
I-G	159	3.7	1.3	3.70	11.9	25.4	14.7	2.0	<0.001	0.10	0.0123	<0.0002	<0.001
I-H	40.7	1.7	2.2	0.33	3.7	8.3	5.4	1.3	<0.001	1.13	0.0120	<0.0002	<0.001
I-I	241	3.2	1.7	4.05	13.5	38.3	23.9	2.1	<0.001	0.62	0.0123	0.0003	<0.001
I-J	695	18.1	1.1	1.56	84.1	90.7	80.2	3.0	<0.001	0.35	0.0083	<0.0002	<0.001
I-K	896	17.0	6.4	0.72	83.8	128	122	8.8	<0.001	0.01	0.0248	<0.0002	<0.001
I-L	230	3.6	10.6	0.51	20.1	42.6	33.3	3.2	<0.001	0.05	0.0159	<0.0002	<0.001
I-M	332	7.3	24.3	0.16	41.4	59.6	50.8	6.7	0.001	0.06	0.0211	<0.0002	<0.001
I-N	14.0	10.1	4.1	2.28	7.0	2.6	3.1	2.0	<0.001	2.55	0.0401	0.0002	0.001
I-O	2.1	3.4	1.8	2.33	1.1	1.5	1.4	0.3	<0.001	0.95	0.0051	<0.0002	<0.001
I-P	2.9	2.2	1.3	1.45	1.0	1.2	0.9	0.3	<0.001	0.49	0.0032	<0.0002	<0.001
I-Q	2100	93.5	45.9	0.54	501	264	273	19.4	<0.001	0.03	0.0217	<0.0002	<0.001
I-R	370	23.9	4.6	2.36	52.4	61.4	46.0	4.7	<0.001	0.06	0.0220	<0.0002	<0.001
I-S	796	64.4	19.4	0.32	196	122	85.8	8.3	<0.001	0.07	0.0188	<0.0002	<0.001
I-T	131	7.7	3.3	1.37	18.6	19.8	12.4	2.9	<0.001	0.22	0.0143	<0.0002	<0.001
I-U	17.3	0.9	2.4	1.56	1.6	4.5	2.3	0.5	<0.001	0.15	0.0050	<0.0002	<0.001
I-V	181	1.1	6.0	0.49	6.1	64.1	6.3	1.2	<0.001	0.06	0.0139	<0.0002	<0.001
I-W	6.9	0.4	1.0	1.18	0.5	1.7	0.5	0.2	<0.001	0.10	0.0015	<0.0002	<0.001
I-X	2.9	0.3	1.7	2.64	0.7	1.2	0.5	0.2	<0.001	0.10	0.0009	<0.0002	<0.001
I-Y	66.9	98.9	2.8	0.51	71.1	9.3	7.1	3.3	<0.001	0.61	0.0123	<0.0002	<0.001
I-Z	522	2.0	1.6	3.13	17.0	169	22.6	2.1	<0.001	0.22	0.0152	<0.0002	<0.001
Mean	303.2	47.4	6.2	1.42	71.6	49.0	35.6	4.3	0.000	0.40	0.0164	0.0000	0.000
Median	131	7.3	2.4	1.18	17.0	21.3	12.4	2.1	0.001	0.18	0.0139	0.0003	0.001
Max	2100	667	45.9	4.05	546	264	273	24.7	0.001	2.55	0.0538	0.0003	0.001
Min	2.1	0.33	0.9	0.01	0.5	1.2	0.5	0.2	D. L.	0.01	0.0009	D. L.	D. L.
Std Dev	456.3	133.4	10.0	1.20	143.0	63.9	59.0	5.90	N/A	0.55	0.0119	N/A	N/A

Table 1. Continued

	Co	Cr	Cu	Fe	Li	Mn	Mo	Ni	Pb	Sr	V	Zn	TPU
I-A	<0.001	0.001	0.002	0.344	0.003	0.0018	<0.001	<0.002	<0.005	0.0146	0.002	0.002	0.1620
I-B	<0.001	0.001	0.001	0.773	0.013	0.0164	<0.001	0.004	<0.005	0.0524	0.001	0.003	0.0317
I-D	0.001	<0.001	0.001	0.177	0.090	0.0180	<0.001	<0.002	<0.005	0.4040	<0.001	0.001	0.0141
I-E	<0.001	<0.001	0.001	0.288	0.033	0.0164	<0.001	0.003	<0.005	0.1160	<0.001	0.002	0.0162
I-F	0.004	<0.001	<0.001	0.093	0.025	0.3310	<0.001	0.009	<0.005	0.0591	<0.001	0.007	0.0102
I-G	<0.001	<0.001	0.001	0.092	0.036	0.0300	<0.001	0.010	<0.005	0.0680	<0.001	0.006	0.0120
I-H	0.001	0.001	0.004	1.620	0.015	0.0140	<0.001	0.003	<0.005	0.0234	0.002	0.006	0.1202
I-I	0.015	<0.001	<0.001	0.058	0.066	1.0200	<0.001	0.033	<0.005	0.0707	<0.001	0.022	0.0056
I-J	0.026	0.001	<0.001	0.268	0.113	2.7900	<0.001	0.040	<0.005	0.1500	<0.001	0.014	0.0200
I-K	0.001	<0.001	<0.001	0.118	0.159	0.0738	<0.001	0.004	<0.005	0.2640	<0.001	0.001	0.0109
I-L	<0.001	<0.001	<0.001	0.139	0.039	0.0334	<0.001	0.002	<0.005	0.0830	<0.001	0.003	0.0450
I-M	<0.001	<0.001	0.001	0.121	0.046	0.0107	<0.001	0.002	<0.005	0.1320	<0.001	0.001	0.0214
I-N	0.002	0.005	0.008	6.420	0.013	0.0884	<0.001	0.009	0.005	0.0225	0.006	0.026	0.2569
I-O	0.002	0.001	0.008	3.070	0.002	0.0381	<0.001	0.002	<0.005	0.0046	0.003	0.010	0.1091
I-P	<0.001	0.001	0.005	0.813	0.001	0.0121	<0.001	<0.002	<0.005	0.0040	0.001	0.004	0.0292
I-Q	0.001	<0.001	0.001	0.386	0.341	0.2120	<0.001	0.004	<0.005	0.7170	<0.001	0.001	0.0233
I-R	<0.001	<0.001	0.001	0.141	0.058	0.0250	<0.001	0.006	<0.005	0.1450	<0.001	0.004	0.0101
I-S	0.001	<0.001	<0.001	0.229	0.102	0.0482	<0.001	0.002	<0.005	0.2010	<0.001	0.002	0.0226
I-T	<0.001	<0.001	0.001	0.319	0.021	0.0130	<0.001	0.003	<0.005	0.0776	<0.001	0.002	0.0169
I-U	<0.001	<0.001	0.001	0.148	0.004	0.0048	<0.001	0.003	<0.005	0.0139	<0.001	0.002	0.0063
I-V	<0.001	<0.001	0.001	0.117	0.004	0.0063	<0.001	0.006	<0.005	0.1330	<0.001	0.002	0.0123
I-W	<0.001	<0.001	0.001	0.103	0.001	0.0091	<0.001	0.002	<0.005	0.0046	<0.001	0.002	0.0045
I-X	<0.001	<0.001	0.004	0.216	0.001	0.0032	<0.001	<0.002	<0.005	0.0034	<0.001	0.001	0.0092
I-Y	0.001	0.001	0.002	0.893	0.016	0.0150	<0.001	0.004	<0.005	0.0472	0.001	0.004	0.0705
I-Z	0.004	<0.001	0.001	0.062	0.029	0.2990	<0.001	0.036	<0.005	0.3410	<0.001	0.018	0.0070
Mean	0.002	0.000	0.002	0.680	0.049	0.2052	<0.001	0.007	0.000	0.1261	0.001	0.006	0.0419
Median	0.002	0.001	0.001	0.216	0.025	0.0180	<0.001	0.004	0.005	0.0707	0.002	0.003	0.0169
Max	0.026	0.005	0.008	6.420	0.341	2.7900	D. L.	0.040	0.005	0.7170	0.006	0.026	0.2569
Min	D. L.	D. L.	D. L.	0.058	0.001	0.0018	D. L.	D. L.	D. L.	0.0034	D. L.	0.001	0.0045
Std Dev	0.008	0.001	0.002	1.362	0.073	0.5787	N/A	0.012	N/A	0.1621	0.002	0.007	0.0602

Table 1. Continued

	TPF	SRP	TKN	NO_2	$NO_{3+}NO_2$	NH_3	PON	TN	POC	DOC	CHLAU (µg/L)	CHLAC (µg/L)	T (°C)
I-A	0.0073	0.0006	0.184	0.002	<0.010	0.005	0.410	0.604	4.670	1.9	4.7	2.9	3.0
I-B	0.0030	0.0002	0.055	<0.002	<0.010	<0.005	0.088	0.153	0.730	1.0	1.7	1.0	2.5
I-D	0.0085	0.0011	0.147	<0.002	<0.010	0.009	0.042	0.199	0.398	1.4	<0.1	<0.1	3.5
I-E	0.0058	0.0003	0.178	<0.002	<0.010	0.013	0.038	0.226	0.430	1.9	1.5	<0.1	5.0
I-F	0.0038	0.0004	0.078	<0.002	<0.010	<0.005	0.029	0.117	0.357	1.3	0.2	<0.1	2.5
I-G	0.0066	0.0003	0.092	<0.002	<0.010	<0.005	0.038	0.140	0.459	2.2	0.8	<0.1	3.5
I-H	0.0176	0.0003	0.151	<0.002	<0.010	<0.005	0.278	0.439	2.630	2.8	1.2	<0.1	0.0
I-I	0.0032	0.0002	0.040	<0.002	0.011	0.005	0.023	0.074	0.258	1.4	<0.1	<0.1	3.0
I-J	0.0034	0.0005	0.049	<0.002	<0.010	0.012	0.106	0.165	0.872	0.9	3.7	1.4	1.5
I-K	0.0073	0.0009	0.200	<0.002	0.015	0.009	0.043	0.258	0.512	2.6	0.4	<0.1	3.5
I-L	0.0071	0.0003	0.148	<0.002	<0.010	<0.005	0.172	0.330	1.300	2.6	4.8	1.2	3.5
I-M	0.0067	0.0004	0.136	<0.002	<0.010	0.007	0.094	0.240	0.788	2.6	0.9	<0.1	3.0
I-N	0.0065	0.0005	0.453	0.004	0.091	0.250	0.981	1.525	9.890	2.0	5.3	4.3	4.0
I-O	0.0069	0.0002	0.108	<0.002	<0.010	<0.005	0.258	0.376	2.780	1.7	0.7	<0.1	2.5
I-P	0.0063	<0.0002	0.141	0.002	<0.010	0.012	0.081	0.232	0.841	2.1	0.3	<0.1	5.5
I-Q	0.0087	0.0024	0.252	<0.002	<0.010	0.013	0.104	0.366	0.916	4.6	1.4	1.2	4.5
I-R	0.0053	0.0004	0.161	<0.002	<0.010	<0.005	0.026	0.197	0.360	2.8	0.3	<0.1	2.0
I-S	0.0072	0.0006	0.234	<0.002	<0.010	<0.005	0.098	0.342	0.884	4.1	1.7	1.0	2.0
I-T	0.0053	<0.0002	0.172	<0.002	0.015	0.057	0.049	0.236	0.543	2.1	1.8	1.1	4.0
I-U	0.0033	<0.0002	0.044	<0.002	<0.010	<0.005	0.023	0.077	0.356	1.0	1.3	<0.1	0.0
I-V	0.0041	<0.0002	0.109	0.002	0.027	<0.005	0.062	0.198	0.609	1.4	0.3	<0.1	2.5
I-W	0.0037	<0.0002	0.073	0.003	0.013	0.006	0.015	0.101	0.256	1.1	0.4	<0.1	4.0
I-X	0.0044	<0.0002	0.094	<0.002	<0.010	<0.005	0.025	0.129	0.338	1.4	0.3	<0.1	4.0
I-Y	0.0068	0.0002	0.190	<0.002	<0.010	<0.005	0.132	0.332	1.480	3.7	1.5	1.2	3.5
I-Z	0.0030	0.0002	0.203	0.002	0.072	0.006	0.032	0.307	0.466	1.4	0.4	<0.1	2.0
Mean	0.0061	0.0004	0.148	0.001	0.010	0.016	0.130	0.295	1.325	2.1	1.4	0.6	3.0
Median	0.0063	0.0004	0.147	0.002	0.015	0.009	0.062	0.232	0.609	1.9	1.2	1.2	3.0
Max	0.0176	0.0024	0.453	0.004	0.091	0.250	0.981	1.525	9.890	4.6	5.3	4.3	5.5
Min	0.0030	D. L.	0.040	D. L.	D. L.	D. L.	0.015	0.074	0.256	0.9	D. L.	D. L.	0.0
Std Dev	0.0030	0.0005	0.087	0.001	0.033	0.067	0.201	0.285	2.050	1.0	1.6	1.1	1.3

Table 1. Continued

	pH	Cond	Depth (m)	Diam (m)	ELEV (m)	POC : PN	PN : PP	POC : PP	POC : CHLAU	TN : TPU	TN : TPF	Latitude	Longitude
I-A	7.5	36	0.25	200	23	11:1	3:1	30:1	994:1	4:1	83:1	78°48.141′ N	103°38.165′ W
I-B	7.1	122	0.50	30	12	8:1	3:1	25:1	429:1	5:1	51:1	78°47.521′ N	103°38.118′ W
I-D	7.5	1380	0.30	15	12	9:1	8:1	71:1	N/A	14:1	23:1	78°47.482′ N	103°38.227′ W
I-E	7.7	353	0.25	60	34	11:1	4:1	41:1	287:1	14:1	39:1	78°47.402′ N	103°30.025′ W
I-F	5.9	158	0.25	25	12	12:1	5:1	56:1	1785:1	11:1	31:1	78°47.516′ N	103°26.158′ W
I-G	6.0	201	0.45	12	6	12:1	7:1	85:1	574:1	12:1	21:1	78°47.689′ N	103°27.303′ W
I-H	6.8	66	0.30	140	38	9:1	3:1	26:1	2192:1	4:1	25:1	78°48.561′ N	103°28.478′ W
I-I	5.1	273	0.30	27	53	11:1	10:1	108:1	N/A	13:1	23:1	78°48.069′ N	103°30.827′ W
I-J	5.6	740	1.00	27	53	8:1	6:1	53:1	236:1	8:1	49:1	78°48.069′ N	103°30.827′ W
I-K	7.0	900	0.30	16	53	12:1	12:1	142:1	1280:1	24:1	35:1	78°47.727′ N	103°32.475′ W
I-L	7.2	331	0.30	22	53	8:1	5:1	34:1	271:1	7:1	46:1	78°47.697′ N	103°32.411′ W
I-M	7.7	459	1.00	25	53	8:1	6:1	54:1	876:1	11:1	36:1	78°47.647′ N	103°32.063′ W
I-N	7.1	49	0.25	337	12	10:1	4:1	39:1	1866:1	6:1	235:1	78°46.271′ N	103°43.858′ W
I-O	6.9	17	0.25	92	69	11:1	3:1	27:1	3971:1	3:1	54:1	78°45.795′ N	103°45.721′ W
I-P	6.7	12	0.25	50	69	10:1	4:1	37:1	2803:1	8:1	37:1	78°45.700′ N	103°45.814′ W
I-Q	7.9	2130	0.75	12	43	9:1	7:1	63:1	654:1	16:1	42:1	78°47.545′ N	103°31.292′ W
I-R	6.7	510	0.30	7	23	14:1	5:1	75:1	1200:1	20:1	37:1	78°47.044′ N	103°31.292′ W
I-S	7.6	1000	0.70	5	15	9:1	6:1	57:1	520:1	15:1	48:1	78°46.589′ N	103°31.264′ W
I-T	6.8	207	0.40	29	46	11:1	4:1	47:1	302:1	14:1	45:1	78°47.174′ N	103°35.275′ W
I-U	6.8	32	15	460	53	15:1	8:1	119:1	274:1	12:1	23:1	78°49.474′ N	103°39.768′ W
I-V	7.1	228	0.30	3	69	10:1	8:1	74:1	2030:1	16:1	48:1	78°49.233′ N	103°39.712′ W
I-W	6.5	19	0.25	30	46	17:1	19:1	320:1	640:1	22:1	27:1	78°49.054′ N	103°39.604′ W
I-X	6.7	10	0.50	112	43	14:1	5:1	70:1	1127:1	14:1	29:1	78°48.991′ N	103°39.355′ W
I-Y	6.7	295	0.35	18	8	11:1	2:1	23:1	987:1	5:1	49:1	78°47.516′ N	103°27.288′ W
I-Z	6.4	600	0.35	4	61	15:1	8:1	117:1	1165:1	44:1	102:1	78°49.170′ N	103°39.669′ W
Mean	6.8	405	0.99	70	38	11:1	6:1	72:1	1150:1	13:1	50:1		
Median	6.8	228	0.30	27	43	11:1	5:1	56:1	987:1	12:1	39:1		
Max	7.9	2130	15	460	69	17:1	19:1	320:1	3971:1	44:1	235:1		
Min	5.1	10	0.25	3	6	8:1	2:1	23:1	236:1	3:1	21:1		
Std Dev	0.7	504	2.93	111	21	2	4	61	934	9	43		

Table 2. Pearson Correlation Matrix with Bonferroni Adjusted Probabilities
Bold denotes $p < 0.01$; Italics denote $p < 0.05$

	Cl	SO4	SiO2	POC	PON	DOC	DIC	TKN	Al	Ba	Fe	Li	Mn	Sr
Cl	1.00													
SO_4	0.53	1.00												
SiO_2	−0.52	−0.25	1.00											
POC	0.13	−0.30	−0.14	1.00										
PON	0.21	−0.20	−0.24	**0.98**	1.00									
DOC	0.40	0.31	−0.25	0.32	0.35	1.00								
DIC	0.41	0.53	−0.50	0.16	0.24	*0.70*	1.00							
TKN	0.40	0.14	−0.18	0.58	0.55	0.66	0.52	1.00						
Al	−0.07	−0.56	0.21	0.57	0.52	−0.25	−0.52	0.03	1.00					
Ba	**0.76**	0.60	−0.44	0.17	0.24	0.28	0.45	0.53	−0.11	1.00				
Fe	0.16	−0.48	−0.16	**0.80**	**0.78**	0.20	−0.02	0.44	0.66	0.08	1.00			
Li	0.66	**0.93**	−0.20	−0.12	−0.02	0.40	0.52	0.24	−0.40	0.68	−0.27	1.00		
Mn	0.18	0.54	0.36	−0.09	−0.04	−0.08	−0.05	−0.05	0.02	0.19	−0.14	0.61	1.00	
Sr	0.63	**0.97**	−0.31	−0.21	−0.11	0.31	0.54	0.26	−0.49	*0.72*	−0.39	**0.90**	0.47	1.00
Ca	0.45	**0.98**	−0.21	−0.31	−0.21	0.30	0.55	0.14	−0.60	0.53	−0.51	**0.87**	0.53	**0.95**
Mg	0.63	**0.96**	−0.27	−0.17	−0.06	0.41	0.60	0.22	−0.52	0.64	−0.34	**0.97**	0.56	**0.94**
Na	**0.88**	**0.86**	−0.45	−0.06	0.04	0.44	0.57	0.34	−0.37	**0.76**	−0.17	**0.90**	0.38	**0.90**
K	**0.82**	**0.87**	−0.46	−0.03	0.07	0.49	0.64	0.41	−0.40	**0.84**	−0.17	**0.92**	0.34	**0.91**
TPU	0.23	−0.32	−0.24	**0.97**	**0.97**	0.36	0.13	0.53	0.60	0.19	**0.84**	−0.12	−0.16	−0.23
TPF	0.33	0.03	−0.42	0.52	0.54	*0.73*	0.42	0.54	0.00	0.29	0.44	0.19	−0.25	0.07
T	0.21	−0.12	−0.03	−0.04	−0.03	0.23	0.13	0.33	−0.12	0.10	0.07	−0.08	−0.10	−0.07
pH	0.43	0.06	**−0.73**	0.33	0.37	0.47	*0.70*	0.57	−0.24	0.42	0.28	0.06	−0.53	0.19
COND	0.68	**0.98**	−0.33	−0.22	−0.11	0.37	0.55	0.23	−0.50	0.68	−0.38	**0.93**	0.50	**0.98**
TN	0.31	−0.06	−0.21	**0.88**	**0.87**	0.53	0.37	**0.87**	0.32	0.41	0.67	0.08	−0.06	0.07
CHLAU	0.10	−0.07	−0.21	0.65	0.65	0.24	0.25	0.36	0.24	0.02	0.46	0.02	−0.11	−0.06
POP	0.23	−0.29	−0.23	**0.94**	**0.96**	0.34	0.14	0.49	0.61	0.18	**0.82**	−0.10	−0.12	−0.19
ELEV	−0.50	−0.11	0.10	−0.14	−0.14	−0.18	0.08	−0.22	−0.18	−0.44	−0.15	−0.24	0.05	−0.15
Depth	−0.20	−0.09	0.03	−0.19	−0.22	−0.27	0.01	−0.33	−0.08	−0.21	−0.13	−0.11	−0.18	−0.12
DIAM	−0.28	−0.63	0.14	0.45	0.36	−0.24	−0.21	0.06	0.51	−0.18	0.48	−0.46	−0.33	−0.58

The mean value of specific conductivity (393 µS/cm) was also high by arctic standards, and again a large range was present (10 to 2130 µS/cm), which was primarily dependent on bedrock geology and localized physiographic factors (Table 1). Values fell outside natural ranges for surface waters at both the high and low ends of the spectrum (50 to 1500 µS/cm, MCNEELY *et al.,* 1979). Conductivity was significantly correlated ($p \leq 0.01$) with [Ca], [K], [Li], [Mg], [Na], [SO_4] and [Sr]. Those sites with the lowest conductivity values (i.e. I-X, I-P, I-O, I-W) were located on areas of exposed gabbroic bedrock, reflecting the resistance of this substrate to chemical decomposition. The sites with the highest conductivity values (i.e. I-Q, I-D, I-S, I-K) were amongst the smallest ponds closest to the weather station. However, interspersed between these high conductivity sites were ponds with conductivity values that were lower by nearly an order of magnitude (i.e. I-B, I-T), and differences did not appear to be consistently related to changes in size, depth, or other observed physical characteristics. Conductivity and elevation were not correlated ($p \leq 0.05$, Table 2), indicating that marine aerosols were not a major influence on the ionic composition of the ponds.

3.3. Major Ions

Many elements (including Ca, Mg, Na, and SO_4) are typically found in elevated concentrations in waters draining acid sulfate soils (ASTROM and BJORKLUND, 1995), similar to those found near Isachsen (FOSCOLOS and KODAMA, 1981). Accordingly, the concentrations of the major cations (Ca^{2+}, mean = 49.0 mg/L, Mg^{2+}, mean = 35.6 mg/L, Na^{+}, mean = 71.6 mg/L; see Table 1) from Isachsen were among the highest yet recorded from our high arctic sur-

Ca	Mg	Na	K	TPU	TPF	T	pH	COND	TN	CHLAU	POP	ELEV	Depth	DIAM
1.00														
0.94	1.00													
0.80	**0.91**	1.00												
0.81	**0.92**	**0.97**	1.00											
−0.35	−0.18	−0.02	0.00	1.00										
0.00	0.18	0.24	0.32	0.60	1.00									
−0.13	−0.08	0.07	0.06	0.01	0.07	1.00								
0.08	0.14	0.32	0.36	0.37	0.51	0.23	1.00							
0.95	**0.96**	**0.94**	**0.93**	−0.22	0.11	−0.04	0.16	1.00						
−0.05	0.06	0.18	0.23	**0.84**	0.60	0.14	0.52	0.05	1.00					
−0.12	−0.02	0.05	0.02	0.61	0.21	−0.08	0.35	−0.05	0.56	1.00				
−0.31	−0.14	0.00	0.01	**0.98**	0.53	−0.02	0.34	−0.18	**0.81**	0.63	1.00			
0.04	−0.10	−0.34	−0.33	−0.23	−0.17	−0.03	−0.06	−0.18	−0.16	−0.11	−0.20	1.00		
−0.10	−0.10	−0.17	−0.17	−0.25	−0.26	−0.49	0.01	−0.15	−0.36	0.13	−0.22	0.16	1.00	
−0.67	−0.55	−0.50	−0.45	0.40	0.07	−0.23	0.09	−0.63	0.22	0.36	0.37	0.01	0.56	1.00

veys. Two of the major anions (Cl^-, SO_4^-) were also found in elevated concentrations relative to our other arctic studies, while values for HCO_3^- (i.e., dissolved inorganic carbon, (DIC), mean = 6.1 mg/L) were much lower than those found in other High Arctic studies.

Values for Ca^{2+}, while above normal freshwater ranges, were not atypical for sites influenced by gypsum (McNeely *et al.,* 1979). High levels of Na^+ and Mg^{2+} mobilized from local soils are largely derived from the evaporitic sulfate-rich local bedrock (Everett, 1968).

Concentrations of Cl^- comparable to those from Ellef Ringnes were found only from Axel Heiberg Island (Michelutti *et al.,* 2002b). Again, the primary source of chloride to the lakes and ponds at Isachsen is evaporitic rock. The correlation between elevation and Cl^- concentration was not significant ($p \leq 0.05$, Table 2), suggesting that sea spray was not a major contributor to these high Cl^- levels.

SO_4 levels (mean = 293.9 mg/L) were one to two orders of magnitude greater than those found at other high arctic sites. Sites that were situated on exposed basaltic bedrock (i.e. I-A, I-O, I-P, I-W, I-X) had concentrations of Ca, Mg, Na, and SO_4 that were an order of magnitude lower than the mean value, reinforcing the importance of soil leachate in influencing the chemistry of these small ponds. At these exposed basaltic sites, the mean [DIC] was also less than one third of the overall mean DIC value. The high DIC concentrations found elsewhere in the High Arctic (e.g. Hamilton *et al.*, 2001; Lim *et al.,* 2001; Michelutti *et al.,* 2002b; Michelutti *et al.,* 2002a) reflect the influence of calcium carbonate bedrock at each of these locations. By comparison, Isachsen's bedrock is predominantly shale and gabbro, resulting in these relatively low DIC concentrations.

In terms of mean concentrations, major cations were Na > Ca > Mg > K, with values of 71.6, 49.0, 35.6, and 4.3 mg/L, respectively. However, great variability existed between sites. Twelve sites at Isachsen had concentrations Ca > Mg > Na > K, the pattern consistently observed in most previous arctic limnological studies (LIM *et al.,* 2001; GREGORY-EAVES *et al.,* 2000; RÜHLAND and SMOL, 1998; MICHELUTTI *et al.,* 2002a). In these previous studies, few if any sites deviated from this order of cation concentrations. However, in five Isachsen sites, cation concentrations were Ca > Na > Mg > K, similar to those observed from Axel Heiberg Island (MICHELUTTI *et al.,* 2002b). A further seven sites had Na as the dominant cation, with five following Na > Ca > Mg > K, and two Na > Mg > Ca > K. One site (I-Q) had concentrations Mg > Ca > Na > K, a pattern not previously reported from arctic sites. At Isachsen, the order of cation concentrations from individual sites did not correlate to elevation, distance from the ocean, pH, or conductivity. The likely cause for these differences is local variability in the availability of soil minerals.

Relative mean concentrations of major anions at Isachsen were $SO_4 > Cl > CO_3$, while elsewhere in the Arctic, concentrations were found to be $CO_3 > SO_4 > Cl$. At Isachsen, 14 sites followed $SO_4 > Cl > CO_3$, seven sites followed $SO_4 > CO_3 > Cl$, and four sites were $Cl > SO_4 > CO_3$. The relatively high concentrations of SO_4 and Na and the correspondingly low relative concentrations of Ca in our study reflect both the importance of evaporitic deposits and the lack of carbonate rock on Ellef Ringnes Island.

3.4. Metals

Concentrations of the metals analyzed from each site (i.e. Ag, Al, Ba, Be, Cd, Co, Cr, Cu, Fe, Li, Mn, Mo, Ni, Pb, Sr, V, Zn) were typically low, but only three metals (Al, Fe and Mn) were present in sufficient concentrations to be included in the dataset after our initial data screening. Concentrations were higher in comparison to our other arctic collections, but the average concentration of Al (0.40 mg/L) was within normal limits for Canadian fresh waters (<1 mg/L; MCNEELY *et al.,* 1979), whereas the average concentrations of Fe and Mn (0.77 mg/L, 0.20 mg/L) were at or above levels that are considered normal for Canadian surface waters (MCNEELY *et al.,* 1979). Two extreme values greatly increased the mean values for Fe and Mn. Sites I-N and I-O, the two most exposed and turbid sites in the dataset, had Fe concentrations of 6.42 and 3.07 mg/L, respectively. Sites I-I and I-J had Mn concentrations of 1.02 and 2.79 mg/L, but had no apparent characteristics distinguishing them from nearby similar ponds with much lower [Mn]. However, by removing these extreme values from the calculations, the average values of both metals were greatly reduced, to within normal ranges (Fe = 0.35 mg/L, Mn = 0.06 mg/L) (MCNEELY *et al.,* 1979). Regardless, the average values of each of these three metals were the highest yet recorded in the High Arctic, even exceeding the concentrations from extreme sites in other high arctic limnological datasets to date. The pyrite-rich shales in the area contribute to high Fe levels. Also, metals including Al, Fe and Mn are mobilized in acid sulfate soils (RITSEMA and GROENENBERG, 1993), thus the high levels in the small ponds sampled are likely the result of accumulation of metals leached from local soils.

3.5. Nutrients

3.5.1. Phosphorus

A broad range of total phosphorus (TPU) concentrations was recorded at Isachsen, with values between 0.0045 mg/L and 0.2569 mg/L. The mean concentration of TPU was 0.0418 mg/L, a value exceeding the range for uncontaminated lakes (MCNEELY *et al.,* 1979), and which would be indicative of eutrophic conditions (WETZEL, 1983). Both the mean and median concentrations from Isachsen exceed the average TPU concentrations measured in other high arctic regions (i.e. HAMILTON *et al.*, 2001; LIM *et al.,* 2001; MICHELUTTI *et al.,* 2002b; MICHELUTTI *et al.,* 2002a,). Concentrations of total dissolved phosphorus (TPF) were not similarly elevated (mean = 0.0066 mg/L), and were within typical ranges for the High Arctic.

Two factors were responsible for this elevated average TPU concentration. Extremely high values at five sites that were observed to have very turbid water (i.e. I-A, I-H, I-N, I-O and I-Y) greatly increased the average [TPU]. At these sites, TN:TP ratios were considerably lower than the mean (3:1–6:1, overall mean = 13:1), and closely approximated the TN:TP ratios reported from oligotrophic lake sediment (3:1, DOWNING and MCCAULEY, 1992), suggesting that the source of the majority of TPU may be resuspended sediment.

Furthermore, the majority of Isachsen sites (n = 17) were underlain by phosphorus-rich shale. The contribution of this shale to TPU concentrations is supported by the strong correlation between high concentrations of TPU and Fe ($p \le 0.01$, Table 2), a correlation that has been observed elsewhere in the High Arctic in freshwaters influenced by phosphorus-rich shales (HAMILTON *et al.*, 2001).

The extreme TPU values that result from sediment resuspension were due to wind-induced mixing in this extreme environment. As our sampling regime consisted of a single measurement, it is unclear whether such conditions were persistent, or the result of episodic mixing. As such, some of the TPU figures in our dataset must be viewed with caution. As noted above, TPF values were not elevated. Soluble reactive phosphorus (SRP) concentrations ranged from below detection limits to 0.0024 mg/L, with a mean value of 0.0006 mg/L, similar to the mean values reported from Bathurst (LIM *et al.,* 2001) and Victoria islands (MICHELUTTI *et al.,* 2002a).

3.5.2. Nitrogen

Five nitrogen species were measured from each site sampled – TKN, NH_3, NO_2, $NO_3 + NO_2$, and PON. Concentrations of NH_3, NO_2 and $NO_3 + NO_2$ were below detection limits in the majority of the sites (Table 1), which is common in arctic regions. Site I-N was a notable exception, having the highest concentration of these three variables (0.25 mg/L NH_3, 0.004 mg/L NO_2, and 0.091 mg/L $NO_3 + NO_2$), as well as the highest values of the other nitrogen variables (0.453 mg/L TKN and 0.981 mg/L PON). These concentrations were likely high because I-N drained an area of mosses and grasses – one of the few vegetated locations in the study site, and also was turbid with resuspended sediment. Overall, TKN values were highly variable, with a range from 0.030 mg/L to 0.453 mg/L. The mean TKN concentration (0.143 mg/L) was the lowest found to date in high arctic limnological surveys, likely due to the paucity of nitrogenous detrital material in the watersheds of the area. Conversely, PON concentrations at Isachsen were the highest high arctic values yet measured. Whereas in other high arctic surveys, mean concentrations of TKN exceeded PON by a factor of between 4 and 9 (HAMILTON *et al.,* 2001; LIM *et al.*, 2001; MICHELUTTI *et al.*, 2002b, MICHELUTTI *et al.*, 2002a), at Isachsen the mean concentrations of TKN and PON were roughly equal. This increased PON value can again be attributed to sediment resuspension at several exposed sites.

As such, total nitrogen (TN) values from Isachsen (mean = 0.289 mg/L) fell within normal ranges for high arctic sites despite atypical contributions from the two major constituents of [TN]. According to these TN concentrations, ten of our sites are classified as oligotrophic, while the remaining 15 are classified as ultra-oligotrophic (LIKENS, 1975). However, N availability to phytoplankton may be even lower than TN values indicate, due to the larger proportional presence of PON.

3.6. CHL-a and Carbon

Dissolved organic carbon (DOC) concentrations were at the low end of the ranges recorded in previous limnological studies conducted north of treeline (LIM *et al.,* 2001; ANTONIADES *et al.,* 2000; DOUGLAS and SMOL, 1994; MICHELUTTI *et al.,* 2002b; MICHELUTTI *et al.,* 2002a). Isachsen DOC concentrations ranged from 0.6 to 4.6 mg/L, with a mean of 2.0 mg/L. Similarly low or lower values have been observed on Victoria (MICHELUTTI *et al.,* 2002a) and northern Ellesmere islands (ANTONIADES *et al.,* 2000). The low values and restricted range are related to the near complete absence of vegetation and poorly drained soils in the Isachsen area, coupled with prolonged frozen conditions. Such low DOC concentrations make arctic lakes especially vulnerable to damage from incoming UV radiation (LAURION *et al.,* 1997; VINCENT and PIENITZ, 1996).

Ratios of particulate organic carbon (POC) to CHLAU were calculated to determine the source of POC. The mean ratio was 1116:1, with a range from 236:1 to 3971:1. Values in excess of 100:1 imply elevated deposition of allochthonous, detrital or sedimentary POC (EPPLEY *et al.,* 1977). As N:P ratios (See section 3.5.1) suggested that the source of much of the nitrogen and phosphorus was resuspended sediment, in our dataset the majority of POC is likely also derived from sedimentary sources. These POC:CHLA ratios are similar to those reported elsewhere in high arctic ponds (HAMILTON *et al.*, 2001; LIM *et al.*, 2001; MICHELUTTI *et al.,* 2002a; MICHELUTTI *et al.,* 2002b).

The mean concentration of CHLAU was 1.4 μg/L. [CHLAU] reached a maximum of 5.30 μg/L, again at the nitrogen-enriched site I-N, while at two sites in the dataset (i.e. I-D, I-I) [CHLAU] was below the detection limit of 0.1 μg/L. The concentrations of nitrogen species at site I-I were among the lowest in the dataset. The cause of the low [CHLAU] at site I-D is uncertain, as it had typical N and P concentrations, and was notable among other sites only for its extremely high concentrations of Cl, Na, and SO_4. The average [CHLAU] was slightly higher than those reported in other High Arctic studies (HAMILTON *et al.*, 2001; LIM *et al.*, 2001; MICHELUTTI *et al.*, 2002a; MICHELUTTI *et al.,* 2002b). However, according to Chl-*a* values, all sites would be considered oligotrophic (WETZEL, 1983).

In previous arctic and high arctic studies, no significant relationships existed between N, P, or C variables and CHLAU, from which it was concluded that other variables were controlling phytoplankton productivity (HAMILTON *et al.*, 2001; LIM *et al.*, 2001; MICHELUTTI *et al.,* 2002a; MICHELUTTI *et al.*, 2002b; GREGORY-EAVES *et al.*, 2000). However, in this study, weak linear relationships were present between PON and CHLAU ($r^2 = 0.43$), POC and CHLAU ($r^2 = 0.42$), and TPU and CHLAU ($r^2 = 0.38$).

3.7. Nitrogen and Phosphorus Ratios

Ratios of nitrogen to phosphorus provide information about the degree of N or P limitation. At Isachsen, the mean TN:TPU ratio was 13:1, with values ranging from 3:1 to 44:1. TN:TP ratios above 17:1 generally suggest P-limitation (SAKAMOTO, 1966), while those below 14:1 suggest N-limitation (DOWNING and MCCAULEY, 1992), although ratios between 10 and 20:1 may suggest limitation by either nutrient (SCHANZ and JUON, 1983). In 18 sites, ratios indicated that N may be limiting (i.e. ≤14; I-A, I-B, I-D, I-E, I-F, I-G, I-H, I-I, I-J, I-L, I-M, I-N, I-O, I-P, I-T, I-U, I-X, I-Y), the ratios of four sites suggested P-limitation (i.e. ≥20; I-K, I-R, I-W, I-Z), and the remaining three sites (I-Q, I-S, I-V) had ratios between 14:1 and 20:1, indicating limitation by either or both of these nutrients. These ratios were significantly lower than those found in other high arctic surveys. According to TN:TP ratios, P is the limiting nutrient at a majority of sites in the High Arctic (e.g. HAMILTON *et al.,* 2001; LIM *et al.*, 2001; MICHELUTTI *et al.*, 2002b; MICHELUTTI *et al.*, 2002a). However, based on these ratios, N appears to be the limiting nutrient for algal communities at some of the sites in the Isachsen region.

TN : TP ratios at the five turbid sites (i.e. I-A, I-H, I-N, I-O, I-Y) were the lowest in the dataset (Table 1), and all suggested strong N-limitation. Site I-N also had the highest concentrations of TPU, TKN, NH_3, $NO_3 + NO_2$, and CHLAU. While sites I-H, I-O, and I-Y also had elevated TPU levels, non-particulate nitrogen species at these sites were similar to the mean concentration, and CHLAU values were below the mean for the dataset. This response of CHLAU to increases in nitrogen, but not to increases in phosphorus, may support the hypothesis of nitrogen limitation at these sites. However, site I-A had both the third highest CHLAU and the second highest high TPU concentration in the dataset, despite typical TKN values and values of NH_3 and $NO_3 + NO_2$ at or near the detection limit. Ultimately, the relationship between elevated levels of N and P variables at these turbid sites remains unclear.

To further explore the nature of nutrient limitation on productivity, the Isachsen data were compared to the DILLON-RIGLER (1974) equation, which models the relationship between chlorophyll-*a* and TPU. P-limited sites are expected to fall along or near the slope of this regression line, while N-limited sites fall below it. The DILLON-RIGLER model overestimated the Chl-*a* at all 25 Isachsen sites, although site I-U, the only lake in the dataset (the rest are shallow ponds), fell almost exactly along the regression line (Figure 3a). This suggests that phytoplankton production at the sites was not limited by phosphorus. SMITH (1982) hypothesized that as N : P decreases, the importance of N as a limiting nutrient may increase, and developed a model incorporating both TP and TN values to infer Chl-*a* concentrations to account for this increased importance of N. However, when plotted with the Isachsen data, these regressions fail to segregate sites according to their N : P ratio. Despite 16 sites with N : P > 10, only one set of measured values (Lake I-U, TN : TP = 12) is situated above the TN : TP = 10 regression line from SMITH's (1982) model. The remaining sites all fall below the TN : TP = 10 regression line on the plot, despite a TN : TP range of 3 : 1 to 44 : 1 (Figure 3b). This may suggest some degree of N-limitation.

It may be noteworthy that the only site to conform to the TP : Chl-*a* regression equations is also the sole lake in the dataset (i.e. depth >2 m, site I-U). The remaining sites are tundra ponds, generally less than 1m deep, and only tens of metres in diameter. Although such sites

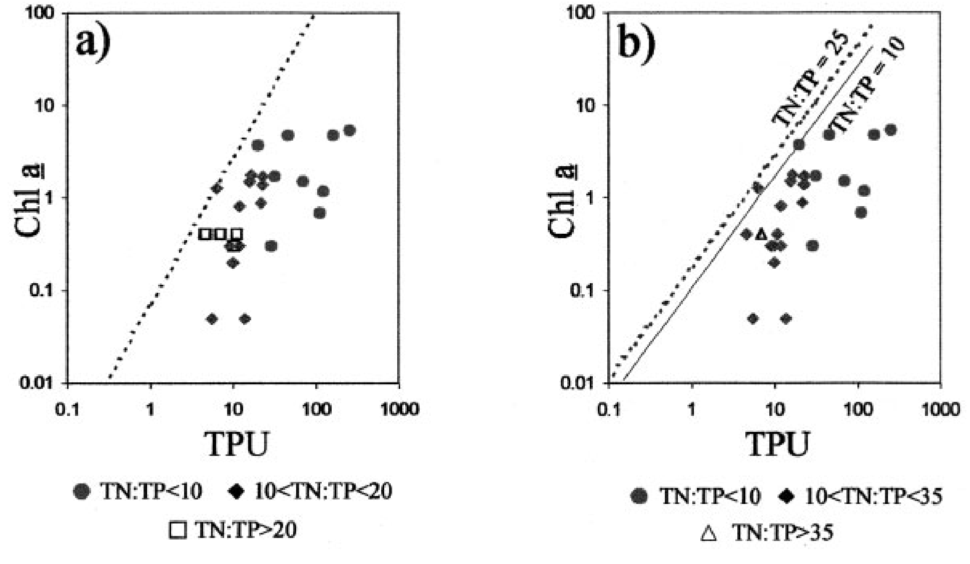

Figure 3. Isachsen TPU:Chl-*a vs*. regression models. Fig. 3a) Isachsen sites *vs*. DILLON and RIGLER (1974) equation. Fig. 3b) Isachsen sites *vs*. SMITH (1982) equation.

are present in great abundance in arctic landscapes, they are rare in temperate regions, where sampling is concentrated on larger, deeper bodies of water. Tundra ponds have extremely low volumes relative to lakes, and are thus highly sensitive to any changes in nutrient inputs, and are more closely tied to their catchments. These models were developed using temperate lakes, and often underestimate the importance of nitrogen as a limiting nutrient in arctic and oligotrophic lakes (LEVINE and WHALEN, 2001; ELSER *et al.,* 1990). As such it may not be appropriate to apply models developed for much larger temperate bodies of water to these high arctic ponds.

3.8. Multivariate Analysis

Principal components analysis (PCA; Figure 4) was used to further explore the primary patterns of water chemistry variation across all sites. The first two axes of the PCA explained a total of 63.0% of the variation in the dataset. Axis 1 and 2 had eigenvalues (λ) of 0.365 and 0.265, respectively. As axis 3 and 4 accounted for smaller portions of the variation ($\lambda = 0.089$ and 0.075, respectively) they were not examined further. Inter-set correlations (Table 3) were calculated to determine which variables were most closely related to the two major axes of variation.

Table 3. PCA Interset correlations

Variable	PCA Axis 1	PCA Axis 2
Cl	–0.67	–0.40
SO_4	**–0.96**	0.14
SiO_2	0.32	0.56
POC	0.23	**–0.89**
PON	0.12	**–0.89**
DOC	–0.33	–0.62
DIC	–0.56	–0.39
TKN	–0.37	–0.63
Al	0.51	–0.31
Ba	**–0.85**	–0.23
Cu	0.72	–0.42
Fe	0.45	–0.72
Li	**–0.93**	0.02
Mn	–0.41	0.38
Sr	**–0.96**	0.04
Ca	**–0.93**	0.15
Mg	**–0.96**	–0.01
Na	**–0.93**	–0.20
K	**–0.96**	–0.20
TPU	0.21	**–0.93**
TPF	–0.09	**–0.77**
T	0.03	0.00
pH	–0.15	–0.64
Cond	**–0.98**	0.00
TN	–0.11	**–0.90**
Chl*a*-U	0.08	–0.54
POP	0.19	**–0.90**
Elevation	0.31	0.15
Depth	0.20	0.27
Diameter	0.64	–0.11
Eigenvalue	0.3729	0.2361

The broad ranges of conductivity and major nutrients present in the dataset controlled the distribution of sites in the PCA ordination. PCA axis 1 was controlled by conductivity-related variables (Fig. 4). The variables with the strongest correlation to axis 1 were, in descending order: COND, Sr, SO_4, K, Mg, Na, Li, and Ca (Table 3). These variables were all strongly correlated ($p \leq 0.01$) with each other (Table 2). Accordingly, they are represented in the cluster of arrows along the left side of the first PCA axis (Fig. 4). The second PCA axis was controlled by concentrations of major nutrients. The variable most strongly correlated with PCA axis 2 was TPU, followed by TN, POP, PON, and POC (Table 3). Again, these variables were all strongly correlated ($p \leq 0.01$) with each other (Table 2). These two major directions of variation – an ionic gradient and a nutrient gradient – are the same as those identified in other high arctic limnological surveys (LIM *et al.,* 2001; ANTONIADES *et al.,* 2000; MICHELUTTI *et al.,* 2002b; MICHELUTTI *et al.,* 2002a).

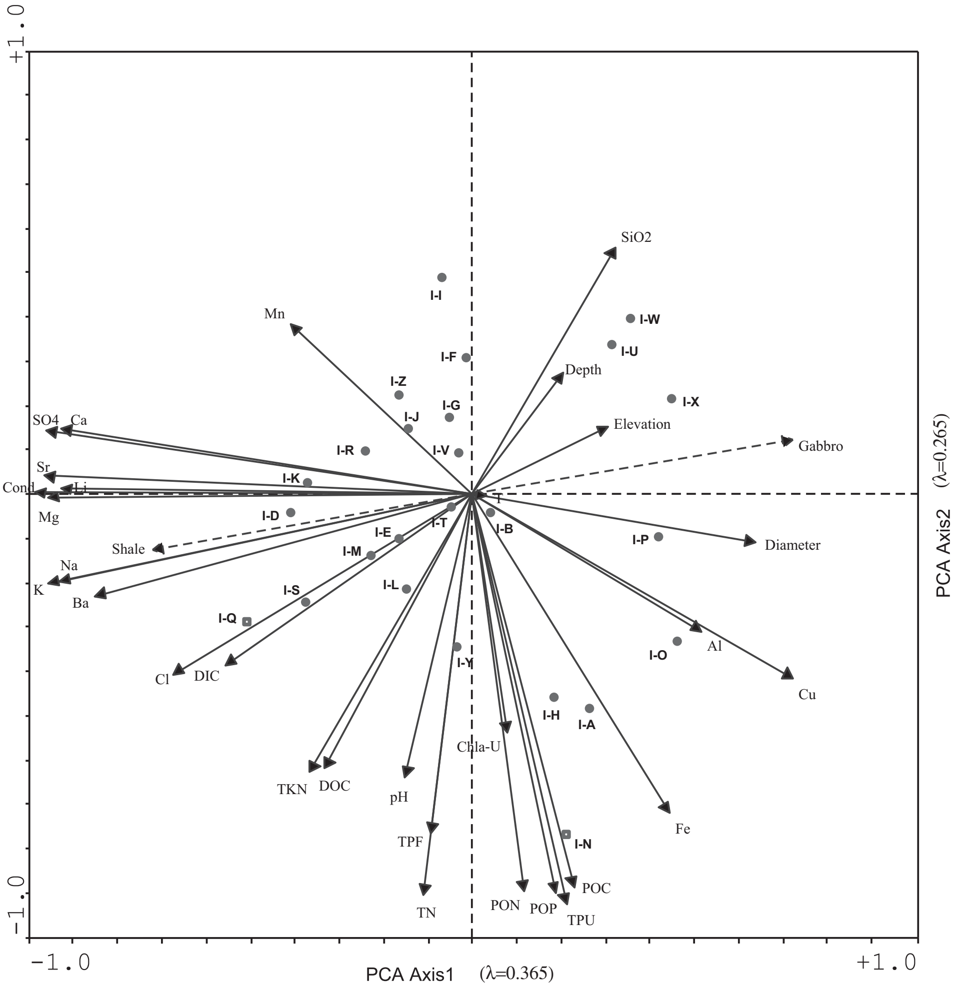

Figure 4. PCA biplot of sites *vs.* environmental variables. Denotes passive sites, dashed lines denote passive environmental variables.

Due to the differences in the two types of bedrock present in the Isachsen area (i.e. gabbro and shale), canonical variates analysis (CVA) was used to investigate the differences between the water chemistry of sites on the respective bedrock types. There were clear groupings of sites based on their bedrock, and CVA indicated that Li, Ca, and SO_4 explained 87.5% of the variance in water chemistry between sites located on gabbro and shale. Those sites found on or associated with gabbro were at the low end of the ionic gradient generated by the CVA, reflecting both the resistance of gabbro to weathering and the contribution of the weathering of shale to high levels of sulfate, Li, and Ca.

4. Conclusions

The ponds sampled in the region surrounding Isachsen were relatively similar in morphology, yet showed a large diversity in their chemical limnological characteristics. Although the sites were located within 15 km of each other, nutrient and dissolved ion concentrations varied greatly between sites, some by up to three orders of magnitude. Several limnological variables were present in concentrations that were unusually high (i.e. Ca, Cl, COND, TPU, SO_4) or unusually low (i.e. TKN) for high arctic sites.

Ionic concentrations were very high relative to those recorded in other arctic sites, reflecting the distinctive bedrock geology and acid soil characteristics of the Isachsen area. Nutrient concentrations were also atypical of high arctic freshwaters. Concentrations of nitrogen species were among the lowest levels found thus far in the High Arctic; conversely, mean total phosphorus concentrations were the highest measured to date in high arctic surveys. However, the high mean TPU concentration at some sites was related to large amounts of resuspended sediment and thus was not indicative of eutrophic conditions.

PCA indicated that the first two axes explained 63% of the variation in the limnological dataset, with the dominant influence on the first axis (36.5%) being conductivity and related variables, while the second axis (26.5%) reflected a nutrient gradient.

Isachsen's regional limnological characteristics were unique among high arctic studies completed thus far, due to the severity of the climate and unusual geology of Ellef Ringnes Island. Given the complexity of the distributions of water chemistry variables and the rarity of acid sulfate soils in the Canadian High Arctic, further research into the relationships between surface waters and soil processes at Isachsen are merited. This dataset encompasses enormous variability in measured chemical concentrations over short geographical distances, and thus represents an expansion of High Arctic limnological conditions observed to date. The proximity of such divergent sites may allow for the observation of parallel changes across wide limnological gradients in response to identical local climate patterns.

These data represent baseline information about the limnological characteristics of Ellef Ringnes Island, and form the foundation for our future research into diatom biogeography and autecology in the region. Paleolimnological research may also benefit from the diversity of limnological conditions. Widely divergent diatom communities are present across these sites, an expected response to their diverse water chemistries (unpubl. data). The possibility that any down-core community responses may occur simultaneously in distinct diatom assemblages can only serve to strengthen paleolimnological reconstructions of environmental change.

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