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Comparative physical and chemical limnology of two Canadian High Arctic regions: Alert (Ellesmere Island, NU) and Mould Bay (Prince Patrick Island, NWT)

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With 6 figures, 2 tables and 2 appendices

Abstract: The physical and chemical limnological characteristics of 65 lakes and ponds from two areas in the Canadian High Arctic were examined to determine differences in regional limnology due to geological and vegetational characteristics, as well as other climate factors. Sites in the Alert region of northern Ellesmere Island had relatively low concentrations of total phosphorus (median TP = 9.1 $\mu g\,l^{-1}$), and total N (median = 0.465 $mg\,l^{-1}$). Dissolved organic carbon (DOC) concentrations were relatively low (median = 2.7 $mg\,l^{-1}$) reflecting the sparsity of vegetation in the region. Within the Alert dataset, there were pronounced differences in water chemistry between small tundra ponds and larger, deeper lakes. The first axis of a principal components analysis of the Alert dataset reflected conductivity and nutrient gradients (λ = 0.28), while the second axis (λ = 0.20) was related to metal concentrations. Mould Bay sites on Prince Patrick Island had relatively high concentrations of TP (mean = 16.5 $\mu g\,l^{-1}$), total N (mean = 0.616 $mg\,l^{-1}$), and DOC (mean = 6.7 $mg\,l^{-1}$). Mean total N and DOC were at the highest levels yet measured from any similar high arctic limnological survey, while mean TP was the second highest high arctic value yet recorded in our surveys. A principal components analysis of the Mould Bay data indicated that the two dominant gradients in the dataset were conductivity and related variables (λ = 0.30) and nutrients (λ = 0.19). The differences in water chemistry variables between Mould Bay and all previous high arctic surveys is attributable to the relatively dense vegetation and deep soils present at Mould Bay relative to Alert and other high arctic regions.

Key words: climate factors, polar freshwater systems, high arctic limnology.

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Introduction

The Canadian High Arctic is a region that has historically been underrepresented in limnological research (Schindler 2001). This can be attributed in large part to the logistical problems involved in sampling such remote locations. Until recently, detailed limnological studies in the North American Arctic have been restricted to those undertaken in arctic Alaska (see Hobbie 1997) and a small number of lakes from Cornwallis Island (e.g. Schindler et al. 1974, Kalff & Welch 1974). More recently, a considerable volume of literature has been developed on the limnology of lower arctic and subarctic regions of northern Canada and Alaska (e.g. Gregory-Eaves et al. 2000, Rühland & Smol 1998, Pienitz et al. 1997 a, b, Kling et al. 1992), arctic Fennoscandia (e.g. Korhola et al. 2002, Weckström & Korhola 2001, Blom et al. 2000, Weckström et al. 1997) and Siberia (Duff et al. 1999). However, research into the freshwaters of high arctic regions remains sparse.

With increasing awareness of the sensitivity of high arctic ecosystems and their vulnerability to ongoing climatic and environmental change (e.g. Rouse et al. 1997), surveys have recently been initiated to document the baseline limnological conditions from around the High Arctic (e.g. Antoniades et al. 2003, Michelutti et al. 2002 a, b, Hamilton et al. 2001, Ellis-Evans et al. 2001, Lim et al. 2001, Hamilton et al. 2000, Douglas & Smol 1994), as well as into other aspects of high arctic limnology (e.g. Van Donk et al. 2001, Villeneuve et al. 2001, Markager et al. 1999, Quesada et al. 1999, Vezina & Vincent 1997). Nonetheless, considerable additional study is required to understand the dynamics of these polar freshwater systems, as the High Arctic represents a vast and varied region with many ecological, climatic and geological gradients.

Shallow tundra ponds dominate typical high arctic landscapes. These ponds (defined as being <2 m deep, and freezing completely in winter) differ markedly from lakes in their limnological characteristics. Due to their small volumes, tundra ponds have low capacity for the dilution of solutes, and their chemical limnological characteristics are thus highly sensitive to any change in external inputs (Douglas & Smol 1999). Seasonal variations in arctic physical and chemical limnology are largely dependent on the extent and duration of ice within limnic systems, which controls interactions with the atmosphere and inputs of solar radiation (Smol 1988). High arctic lakes are generally completely frozen for over nine months of the year, and in some regions, lake ice is perennial. Ponds, by comparison, thaw and freeze earlier than lakes due to their lower thermal capacities, and are completely ice free for several months each year. As a result, while water temperatures in high arctic lakes generally remain low (i.e. below 5 °C; Schindler et al. 1974), summer water temperatures in high arctic ponds may even exceed ambient air temperature (Douglas & Smol 1994).

Alert and Mould Bay are amongst the more studied regions in the Canadian High Arctic, as logistical difficulties are eased by the presence of weather stations. However, despite the volume of scientific investigation in each area, little or no research has been undertaken on limnological questions. The only published study focusing on freshwaters near Alert was primarily concerned with paleolimnology (Doubleday et al. 1995), and no studies exist to date on the limnology or paleolimnology of the Mould Bay region.

Due to poor soil development and the inhospitable climate, highly vegetated regions are exceedingly rare in the High Arctic. In the Mould Bay region, however, the well-developed vegetation is strikingly different from the sparse vegetative cover found across most of the Canadian High Arctic. Increases in vegetation are expected to accompany predicted temperature and precipitation increases in the High Arctic during the next century (Maxwell 1997). As such, the effect of vegetation on the limnology of the Mould Bay region may provide insights into future conditions in other, less vegetated high arctic regions.

Consequently, there were two primary objectives of this study. Firstly, to establish the baseline limnological conditions in these previously uninvestigated regions; and secondly, to evaluate the effects of greater vegetation and soil depth on the limnology of high arctic lakes and ponds by contrasting the regional water chemistry variability of our two study regions.

This study forms part of a larger project by members of our research group to document the limnological conditions of the Canadian High Arctic islands (e.g. Antoniades et al. 2003, Michelutti et al. 2002 a, b, Lim et al. 2001, Douglas & Smol 1994), and will serve to augment our understanding of the freshwaters of this little studied region. In addition, these data will be used in determining diatom autecological characteristics that will form the basis for future paleoenvironmental reconstructions from these regions.

Materials and methods

Site description

Alert

Alert (80° 30′ N, 60° 20′ W), the northernmost human settlement on the planet, consists of a Canadian military installation and a Meteorological Service of Canada (MSC) climate station. Alert is situated at an elevation of 62 m a.s.l. on the northeastern tip of Ellesmere Island in the Queen Elizabeth Islands (Fig. 1). Local topography consists of low rugged mountains that reach a maximum of 550 m a.s.l. The bedrock of the Alert area is composed of Ordovician to Silurian sequences of carbonates and mudstones of the Hazen and Danish River formations (Christie 1964).

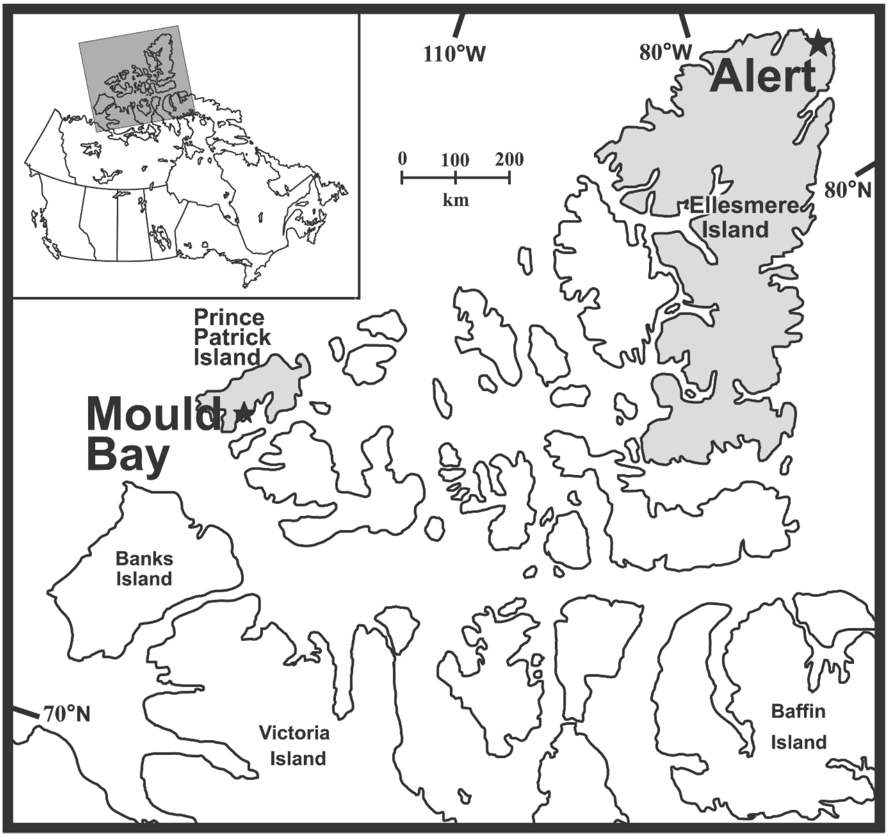

Fig. 1. Location map of Alert and Mould Bay in the Canadian Arctic Archipelago.

Alert has a cold, dry climate, with an annual mean temperature of –18.0 °C (Meteorological Service of Canada 2002). The growing season is very short, averaging 28 degree days per year above 5 °C. Alert is in the polar desert, and receives an average annual precipitation of 154 mm (Meteorological Service of Canada 2002). Vegetation in the area is sparse, and low herbaceous shrubs and mosses are the only plants capable of surviving the harsh climate, lack of moisture, and poorly developed soils (EDLUND & ALT 1989). While tundra ponds dominate most regions in the High Arctic, they are not abundant near Alert. However, equally unusual among high arctic landscapes is the concentration of large, deep lakes (i.e. 1–3 km diam., 10–50 m deep) present within a 30 km radius of the Alert base (Fig. 2).

Mould Bay

Prince Patrick Island is situated along the western fringe of the Queen Elizabeth Islands (Fig. 1), with its north coast directly in contact with the permanent polar pack of the Arctic Ocean. The MSC Mould Bay weather station (76° 14′ N, 119° 20′ W) was lo-

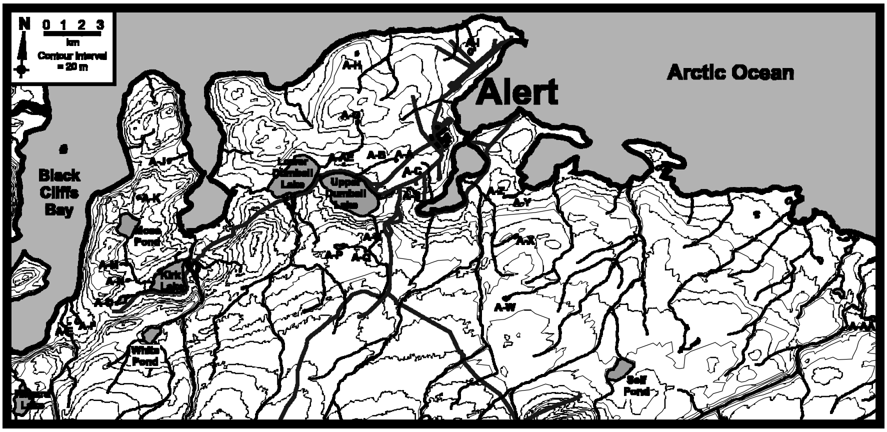

Fig. 2. Map detail of Alert sampling sites.

cated along the southern coast of Prince Patrick Island from 1948 until its closure in 1995, and an automated station continues to record climate data at the site. Mould Bay is situated in a region of low lying topography, with rolling hills that reach a maximum elevation of 150 m. It is underlain by Devonian clastic sediments of the Melville Island group as well as fine to medium-grained sandstones of the Jurassic to Cretaceous Awingak and Isachsen formations (EVERETT 1968).

Predominant winds on Prince Patrick Island are from the northwest, bringing cold, dry air from the Arctic Ocean. Mould Bay has an annual mean daily temperature of –17.5 ˚C, and a July mean daily temperature of +4.0 ˚C. Mould Bay is amongst the driest areas of the High Arctic, with average annual precipitation of 111 mm per year, and a growing season of only 27 days per year (Meteorological Service of Canada 2002).

The soils of the Mould Bay region are described as either tundra or polar desert soils (EVERETT 1968). Drainage is typically poor, with a shallow permafrost depth that prevents the drainage of surface waters. The soils are slightly acidic and extremely low in organic matter, particularly below a depth of 1–2 cm, the typical depth of the upper organic horizon (EVERETT 1968). Vegetation is extremely dense by high arctic standards, with a large percentage of lowland areas densely populated with mosses and grasses. Upland areas in the region are only sparsely vegetated due to lack of soil development caused by wind erosion and to the direct effects of wind (EVERETT 1968).

Sampling methods

Water samples were collected at 35 sites in the Mould Bay region between July 12 and 21, 1999 (Fig. 3), and at 30 sites in the Alert area between July 24 and August 7, 2000 (Fig. 2). Individual sites at Mould Bay were chosen in an effort to capture the maximum range of physical and limnological variation present in the region. At Alert, virtually every accessible site within a 25 km radius of the base was included in the sample set. The largest site in the dataset, Upper Dumbell Lake, was sampled twice on the

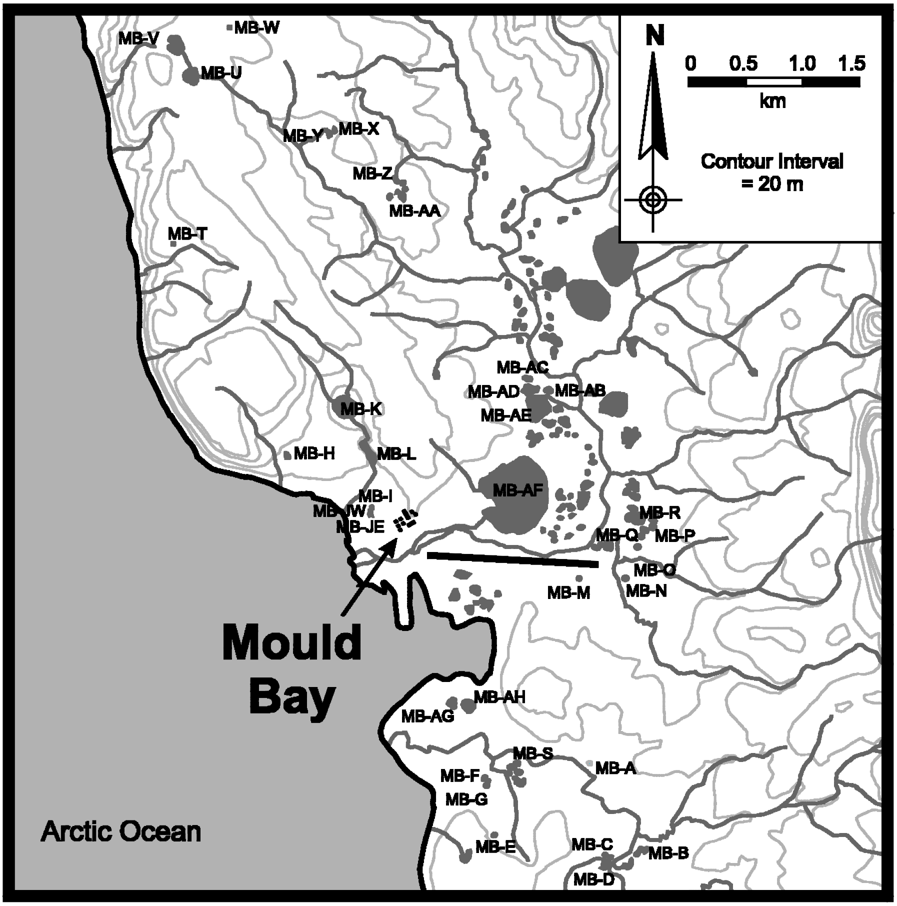

Fig. 3. Map detail of Mould Bay sampling sites.

same day at locations approximately 1.5 km apart to investigate the homogeneity of the water chemistry. Two Alert sites (i.e. Lower Dumbell L. and Kirk L.) contained land-locked char, while all other sites in the study are fishless.

Sampling methods followed those of our other high arctic studies (e.g. Antoniades et al. 2003, Michelutti et al. 2002 a, b, Lim et al. 2001, Douglas & Smol 1994), and are summarized here. For each site, water temperatures were measured using a hand held thermometer held at approximately 0.3 m depth. Conductivity (COND) and pH were measured in a field laboratory within hours of sampling, using a YSI Model 33 conductivity meter and a handheld Hanna pH meter, respectively. Latitude and longitude were measured in the field with a handheld GPS receiver, while elevation (ELEV) was estimated from 1 : 50,000 NTS topographic map sheets 89 B/4, 89 B/5 (Mould Bay), and MCE 140 (Alert).

Water samples were collected for 37 water chemistry variables, which were later analyzed at the National Water Research Institute (NWRI) in Burlington, Ontario, according to standard protocols (Environment Canada 1994). Measured concentrations were determined for silica (SiO_2), 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)); and major ions: calcium (Ca), chloride (Cl), magnesium (Mg), potassium (K), sodium (Na), sulfate (SO_4), and dissolved inorganic carbon (DIC). Measurements of nutrients were made using water that was filtered through 0.45 μm polytetrafluoroethylene (PTFE) filters, and comprised total dissolved phosphorus (TPF), soluble reactive phosphorus (SRP), total Kjeldahl nitrogen (TKN), ammonia (NH_3), nitrite (NO_2), nitrate-nitrite (NO_3+NO_2), and dissolved organic carbon (DOC). Total phosphorus (TPU) was measured from unfiltered water. For analysis of particulate organic carbon (POC) and nitrogen (PON), 150 ml of water was filtered through Whatman glass microfiber filters pre-ignited at 500 °C, while 300 ml of water was filtered for chlorophyll-a (CHLA) analysis. All filters were frozen immediately, and stored in the dark between sampling and analysis. CHLA was extracted by addition of 90 % acetone, and the extract analyzed with a Beckman DU-62 spectrophotometer. POC and PON were measured with a Perkin-Elmer 2400 CHN Elemental Analyzer. Due to a change in NWRI laboratory protocols, Mould Bay samples were filtered using Whatman GF/F filters (particle retention 0.7 μm), while Alert samples used Whatman GF/C filters (particle retention = 1.2 μm). As such, CHLA values are not directly comparable between Alert and Mould Bay sites. Total nitrogen (TN) was calculated as the sum of TKN, NO_3+NO_2 and particulate organic nitrogen (PON) (see Appendix 1).

Statistical analyses

The datasets were 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, Ni, NO_2, NO_3+NO_2, Pb, and V) from both datasets. For statistical analyses, single measurements below detection limits were replaced with a value of half the detection limit. At seven sites with no available CHLA measurement (i.e. MB-G, MB-JE, MB-O, MB-X, MB-Y, MB-AD), the median CHLA value was substituted for statistical analysis. Two sites in the Alert dataset (i.e. A-A, A-B) had extremely high concentrations of most chemical limnological variables, often two orders of magnitude greater than all other measured values. Because chemical concentrations were generally very low for most variables, these values dramatically affected the means of many variables. Thus, Alert median values are used in the discussion, as they better typify sites in the dataset.

Covariation between limnological variables in the dataset was identified using Pearson correlation matrices with Bonferroni adjustment (Tables 1 and 2). The primary gradients controlling water chemistry were investigated by redundancy analysis (RDA) and standardized principal components analysis (PCA) using CANOCO version 4 (ter Braak & Šmilauer 1998). A preliminary PCA was used to identify outliers, defined as any sites that exceeded the 95 % confidence limit of the mean sample scores in the dataset (i.e. A-A, A-B, MB-O, and MB-AF); (Birks et al. 1990). However, even when

Table 1. Alert Pearson Correlation Matrix with Bonferroni Adjusted Probabilities. Bold denotes $p < 0.01$, Italics denote $p < 0.05$.

Cl	1.00																												
SO_4	**0.89**	1.00																											
SiO_2	−0.17	−0.25	1.00																										
POC	**0.84**	**0.81**	−0.23	1.00																									
PON	0.88	0.85	−0.21	**0.98**	1.00																								
DOC	−0.02	0.06	0.60	0.02	0.06	1.00																							
DIC	0.20	0.14	0.22	0.19	0.17	0.55	1.00																						
SRP	**0.81**	**0.73**	−0.05	**0.90**	**0.89**	0.12	0.21	1.00																					
NH_3	−0.13	0.24	0.06	−0.01	0.02	0.49	0.00	−0.01	1.00																				
TKN	0.10	0.26	0.46	0.18	0.23	**0.93**	0.40	0.22	*0.65*	1.00																			
Al	**0.74**	*0.63*	−0.29	**0.86**	**0.82**	−0.21	0.09	**0.83**	−0.18	−0.10	1.00																		
Ba	**0.93**	**0.89**	−0.25	**0.85**	**0.89**	0.05	0.27	**0.80**	0.00	0.18	**0.80**	1.00																	
Cu	0.07	0.01	−0.19	0.12	0.11	−0.16	0.08	0.09	−0.22	−0.21	0.29	0.25	1.00																
Fe	**0.70**	0.60	−0.30	**0.81**	**0.77**	−0.24	0.06	**0.79**	−0.21	−0.14	**0.99**	**0.79**	0.41	1.00															
Li	**0.89**	**0.79**	−0.20	**0.88**	**0.89**	0.11	0.33	**0.86**	−0.10	0.20	**0.81**	**0.86**	0.08	**0.76**	1.00														
Mn	**0.73**	*0.64*	−0.28	**0.80**	**0.77**	−0.23	0.07	**0.80**	−0.20	−0.12	**0.91**	**0.81**	0.50	**0.94**	**0.74**	1.00													
Sr	**0.84**	**0.81**	−0.14	**0.77**	**0.77**	0.25	0.61	**0.72**	0.05	0.31	0.61	**0.83**	0.03	0.56	**0.85**	0.57	1.00												
Zn	0.53	0.43	−0.34	*0.64*	0.59	−0.17	0.14	*0.64*	−0.22	−0.14	**0.86**	**0.68**	0.50	**0.90**	*0.66*	**0.82**	0.48	1.00											
Ca	0.28	0.28	0.23	0.20	0.20	0.42	**0.88**	0.24	0.08	0.29	0.12	0.37	0.17	0.12	0.29	0.20	0.58	0.13	1.00										
Mg	**0.93**	**0.92**	−0.20	**0.85**	**0.87**	0.16	0.37	**0.79**	0.07	0.29	**0.69**	**0.90**	0.03	*0.64*	**0.90**	*0.64*	**0.94**	0.52	0.36	1.00									
Na	**1.00**	**0.88**	−0.17	**0.85**	**0.89**	−0.02	0.19	**0.82**	−0.14	0.10	**0.75**	**0.92**	0.07	**0.71**	**0.90**	**0.73**	**0.84**	0.54	0.27	**0.92**	1.00								
K	**0.98**	**0.87**	−0.23	**0.90**	**0.92**	−0.02	0.19	**0.86**	−0.13	0.11	**0.81**	**0.93**	0.08	**0.77**	**0.94**	**0.78**	**0.84**	0.61	0.22	**0.93**	**0.99**	1.00							
TPU	**0.71**	*0.64*	−0.25	**0.85**	**0.81**	−0.19	0.07	**0.79**	−0.16	−0.07	**0.79**	**0.67**	0.09	**0.75**	**0.75**	**0.79**	0.59	0.60	0.13	*0.66*	**0.72**	**0.77**	1.00						
TPF	0.48	0.50	0.25	0.47	0.53	0.61	0.57	0.39	0.20	0.63	0.17	0.50	0.11	0.13	0.48	0.23	*0.66*	0.05	0.50	0.58	0.48	0.47	0.29	1.00					
Cond	**0.99**	**0.90**	−0.15	**0.84**	**0.88**	0.06	0.30	**0.81**	−0.08	0.17	**0.72**	**0.93**	0.06	**0.67**	**0.90**	**0.70**	**0.89**	0.52	0.38	**0.95**	**0.99**	**0.97**	**0.69**	0.54	1.00				
pH	−0.20	−0.01	0.24	−0.08	−0.08	0.52	−0.04	−0.08	0.44	0.60	−0.25	−0.14	−0.15	−0.27	−0.14	−0.32	−0.09	−0.26	−0.25	0.03	−0.20	−0.17	−0.20	0.26	−0.17	1.00			
Elev	−0.14	−0.03	0.21	−0.18	−0.12	0.16	−0.23	−0.02	0.22	0.23	−0.10	0.03	0.07	−0.06	−0.26	0.00	−0.24	−0.14	−0.09	−0.19	−0.14	−0.16	−0.30	−0.02	−0.14	0.24	1.00		
Chl-a	0.39	0.61	−0.08	0.42	0.47	0.36	0.15	0.40	0.43	0.50	0.10	0.41	−0.24	0.04	0.41	0.09	0.46	0.00	0.14	0.55	0.39	0.39	0.24	0.44	0.43	0.41	0.11	1.00	
	Cl	SO_4	SiO_2	POC	PON	DOC	DIC	SRP	NH_3	TKN	Al	Ba	Cu	Fe	Li	Mn	Sr	Zn	Ca	Mg	Na	K	TPU	TPF	Cond	pH	Elev	Chl-a	

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

Cl	1.00																										
SO_4	0.23	1.00																									
SiO_2	−0.07	0.05	1.00																								
POC	−0.04	−0.07	0.49	1.00																							
PON	−0.05	−0.06	0.51	**1.00**	1.00																						
DOC	0.02	0.22	0.43	0.15	0.17	1.00																					
DIC	0.01	0.54	0.16	−0.07	−0.04	0.61	1.00																				
SRP	−0.09	0.13	0.63	0.48	0.49	**0.68**	0.22	1.00																			
NH_3	−0.14	−0.24	−0.25	−0.19	−0.18	0.35	0.19	0.17	1.00																		
TKN	0.06	0.04	0.22	0.07	0.08	**0.91**	0.58	0.52	0.56	1.00																	
Al	−0.07	−0.02	0.03	**0.67**	**0.66**	−0.26	−0.10	−0.02	−0.25	−0.21	1.00																
Ba	0.31	0.43	0.08	0.52	0.52	0.19	0.45	0.13	−0.16	0.18	0.48	1.00															
Cu	0.34	*0.63*	−0.11	−0.09	−0.08	0.11	0.42	0.01	−0.24	0.02	−0.05	0.45	1.00														
Fe	−0.02	−0.06	**0.64**	**0.94**	**0.94**	0.24	−0.07	*0.61*	−0.18	0.11	0.54	0.48	−0.06	1.00													
Li	0.42	0.28	0.47	0.33	0.35	0.43	0.40	0.19	−0.26	0.29	0.07	0.61	0.30	0.42	1.00												
Mn	0.45	0.04	0.38	**0.69**	**0.69**	0.07	−0.09	0.31	−0.18	0.01	0.43	0.46	0.09	**0.71**	0.42	1.00											
Sr	*0.63*	**0.65**	0.04	−0.10	−0.09	0.42	**0.74**	0.06	−0.01	0.41	−0.09	*0.60*	*0.60*	−0.08	0.58	0.25	1.00										
Zn	0.00	−0.03	0.20	**0.71**	**0.71**	−0.11	−0.19	0.20	−0.21	−0.14	**0.79**	0.42	−0.07	**0.64**	0.12	0.52	−0.12	1.00									
Ca	0.21	0.59	0.15	−0.12	−0.10	0.56	**0.90**	0.20	0.17	0.54	−0.12	0.47	0.43	−0.12	0.43	−0.02	**0.83**	−0.19	1.00								
Mg	**0.90**	0.44	−0.05	−0.03	−0.03	0.17	0.31	−0.05	−0.14	0.17	−0.07	0.48	0.50	0.00	0.54	0.47	**0.80**	−0.04	0.39	1.00							
Na	**0.98**	0.36	−0.06	−0.05	−0.06	0.07	0.11	−0.06	−0.16	0.07	−0.07	0.34	0.43	−0.04	0.42	0.40	**0.69**	−0.01	0.29	**0.92**	1.00						
K	**0.74**	0.25	0.25	0.20	0.21	0.31	0.40	0.11	−0.13	0.31	0.06	*0.60*	0.42	0.28	0.78	0.59	**0.76**	0.10	0.43	**0.85**	**0.73**	1.00					
TPU	0.00	−0.03	0.40	**0.98**	**0.98**	0.11	−0.06	0.40	−0.20	0.05	**0.75**	0.55	−0.07	**0.89**	0.30	**0.70**	−0.05	**0.76**	−0.09	0.01	−0.01	0.20	1.00				
TPF	0.04	0.12	*0.61*	0.55	0.56	*0.61*	0.12	**0.82**	0.12	0.47	0.06	0.17	−0.03	**0.66**	0.33	0.41	0.07	0.40	0.05	0.10	0.07	0.25	0.50	1.00			
Cond	**0.95**	0.42	−0.03	−0.08	−0.08	0.19	0.30	−0.02	−0.10	0.21	−0.09	0.43	0.46	−0.06	0.51	0.39	**0.83**	−0.06	0.48	**0.94**	**0.97**	**0.80**	−0.03	0.06	1.00		
pH	−0.06	0.51	−0.12	−0.25	−0.25	0.36	**0.86**	0.01	0.20	0.39	−0.10	0.31	0.41	−0.30	0.15	−0.25	0.59	−0.35	**0.78**	0.23	0.04	0.16	−0.20	−0.17	0.21	1.00	
Elev	−0.29	−0.10	0.10	−0.18	−0.14	0.14	0.25	−0.10	0.07	0.17	0.03	0.00	−0.09	−0.14	0.07	−0.22	0.08	0.09	0.25	−0.26	−0.30	−0.03	−0.16	−0.13	−0.20	0.03	1.00
	Cl	SO_4	SiO_2	POC	PON	DOC	DIC	SRP	NH_3	TKN	Al	Ba	Cu	Fe	Li	Mn	Sr	Zn	Ca	Mg	Na	K	TPU	TPF	Cond	pH	Elev

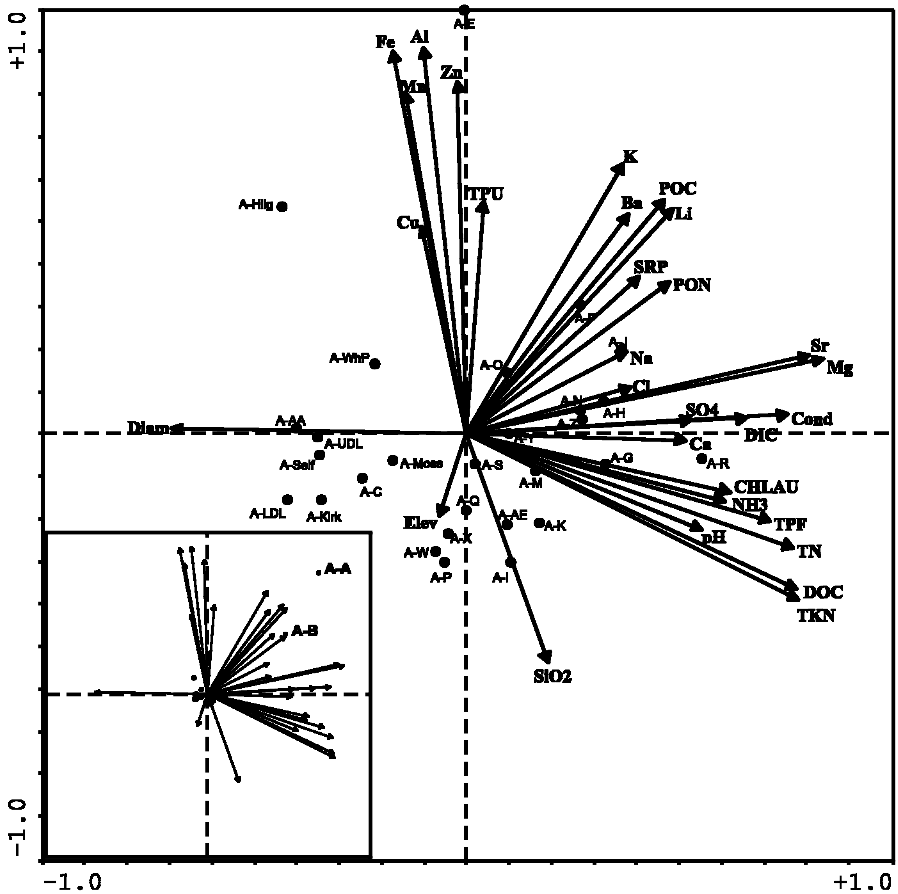

Fig. 4. Alert PCA biplot, with outlier sites removed. Inset indicates relative position of outlier sites when included passively in PCA analysis.

included as passive sites in their respective analyses, these sites influenced the ordinations to such a degree that they hampered the visualization of patterns among sites, and were thus removed from the biplots entirely. Their positions on the PCA biplots relative to the other sites are shown inset in Figs. 4 and 5.

A combined dataset from both study regions was analyzed with RDA in order to determine to what degree water chemistry variation could be explained solely by geography. Measured physical and chemical variables were analyzed using an explanatory dataset that consisted of a binary environmental variable representing either Alert or Mould Bay.

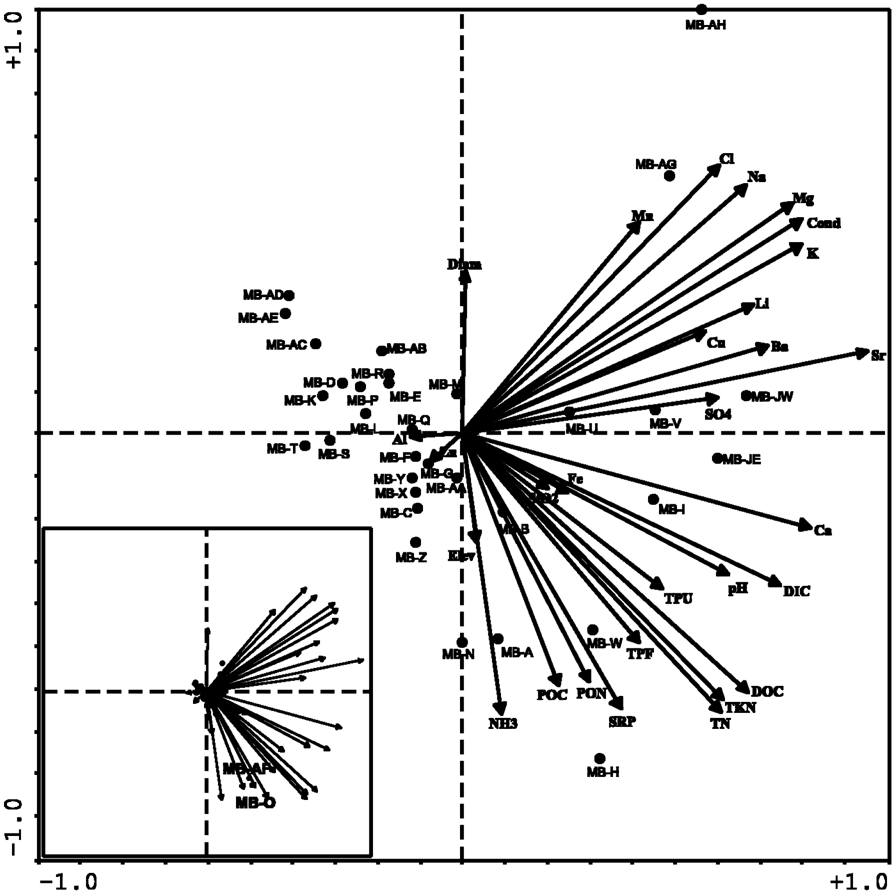

Fig. 5. Mould Bay PCA biplot, with outlier sites removed. Inset as in Figure 4.

Results

Conductivity, pH and major ions

Thirty sites with diverse physical characteristics were sampled near Alert. Sites ranged in elevation from 13 to 147 m a.s.l. (mean = 65 m a.s.l.). Seven of these sites were classified as lakes (i.e. >2 m deep) that varied from ~450 to 1400 m in diameter. Water temperatures in the Alert sites ranged from 2 to 15 °C, and conductivity varied from 121 to 2000 µS cm^{-1}. Median conductivity was 230 µS cm^{-1}, and except for two extreme sites (i.e. A-A: 2000 µS cm^{-1}, and A-B: 1650 µS cm^{-1}), Alert conductivity values fell within a more restricted range of (121–420 µS cm^{-1}). Alert sites were strongly alkaline, ranging from pH 8.1 to 8.9 (mean = 8.4).

At Mould Bay, 32 of 35 sites were classified as ponds, which were typically small (i.e. <50 m diam.) and less than 1 m deep. The majority were located on low, emergent grassy plains, with 22 sites at or below 10 m in elevation. Mould Bay water temperatures fell within the restricted range of 4 to 9.5 °C (mean = 6.4 °C), while conductivity values ranged from 25 to 530 μS cm^{-1} (mean = 115 μS cm^{-1}). Mould Bay mean pH was 7.9, with a range from 7.0 to 8.6.

Ca had the highest median concentration among major ions at Alert (37.8 mg l^{-1}, range = 18.8–67.5 mg l^{-1}). Mg, Na and K had medians of 9.3, 4.5, and 0.5 mg l^{-1}, respectively, and each had a range of at least one order of magnitude (see Appendix 1).

Median DIC was 26.3 mg l^{-1}, with a relatively restricted range from 12.1 to 45.9 mg l^{-1}. Cl had a much broader range (0.6–703 mg l^{-1}), but a lower median of 7.5 mg l^{-1}. SO_4 was typically lower (median = 3.2 mg l^{-1}), although concentrations ranged from 0.2 to 111 mg l^{-1}. Median concentrations at Alert were Ca > Mg > Na > K, and Ca was the dominant cation at 28 of 30 sites. Two sites were Na dominated (i.e. A-A, A-B) due to greatly elevated Na and Mg. Among anions, median concentrations were DIC > Cl > SO_4, and sites were generally DIC dominated. However, at sites where Cl > SO_4, often both variables had very low concentrations and differences between the two were minimal.

Mould Bay Ca and Na had similar means (13.2 mg l^{-1} and 12.9 mg l^{-1}, respectively). Ca ranged from 2.6 to 29.3 mg l^{-1}, and Na from 1.6 to 98.8 mg l^{-1}. Mean Mg was 5.2 mg l^{-1} (range = 0.8–22.8 mg l^{-1}), while mean K was 1.0 mg l^{-1} (range <0.2–4.0 mg l^{-1}). Cl had the highest mean (25.0 mg l^{-1}) among anions. However, concentrations ranged from 3.2 to 212 mg l^{-1}, and the median value of 9.32 mg l^{-1} was more typical of Mould Bay sites. DIC concentrations reached a maximum of 22.5 mg l^{-1} (mean = 9.4 mg l^{-1}). SO_4 had the lowest mean concentration among major anions (7.7 mg l^{-1}; range = 0.6–38.4 mg l^{-1}). Mean concentrations were Ca > Na > Mg > K, and Cl > DIC > SO_4, although five different relative cation and six different anion concentrations existed.

Metals

Similar to most chemical variables, metal concentrations were low in both the Alert and Mould Bay datasets, with the exception of a small number of sites with greatly elevated values. Many of the metals analyzed were below detection limits at the majority of sites and thus were removed from the datasets prior to statistical analysis. At Alert, median Fe was 0.11 mg l^{-1}, with a range from 0.008 to 3.70 mg l^{-1}. Alert Al values ranged from below the detection limit (<0.1 mg l^{-1}) to 2.15 mg l^{-1}, with a median value of 0.05 mg l^{-1}, while median Mn was 0.0057 mg l^{-1} (range = 0.0013–0.0605 mg l^{-1}).

Sites in the Mould Bay dataset had higher metal concentrations than those from Alert. Fe had a mean of 0.724 mg l^{-1} and a maximum concentration of 7.20 mg l^{-1}. Al concentrations were generally low, and although mean Al was 0.12 mg l^{-1}, the median was 0.03 mg l^{-1}. Two Mould Bay sites were below the Al detection limit of 0.1 mg l^{-1}, while the maximum was 1.49 mg l^{-1}. Mn ranged from 0.0011 to 0.1480 mg l^{-1}, with a mean of 0.0185 mg l^{-1}.

Phosphorus, nitrogen, carbon and Chl-a

TPU at Alert ranged from 3.4 to 67.6 µg l^{-1}, with a median of 9.1 µg l^{-1}. According to WETZEL's (1983) classification scheme, 17 % of Alert sites were ultra-oligotrophic by TPU concentrations, 37 % were oligotrophic, 33 % were mesotrophic, and 13 % were eutrophic. Mould Bay TPU ranged from 7.1 to 117.0 µg l^{-1}, with a mean of 16.5 µg l^{-1}. By TPU concentrations, no Mould Bay sites were ultra-oligotrophic, 28 % were oligotrophic, 66 % were mesotrophic, and 6 % were eutrophic.

Five nitrogen measurements were made from each site (i.e. TKN, NH_3, NO_2, NO_3+NO_2, and PON). NO_2 and NO_3+NO_2 were below their respective detection limit at the majority of sites in both study areas. Alert TN ranged from 0.107 to 1.631 mg l^{-1} (median = 0.465 mg l^{-1}). TKN varied from 0.086 to 0.736 mg l^{-1}, with a median of 0.350 mg l^{-1}. Alert mean PON was 0.032 mg l^{-1} (range = 0.015–0.286 mg l^{-1}), and median NH_3 was 0.022 mg l^{-1}, although NH_3 was below detection limits (i.e. 0.005 mg l^{-1}) at 14 sites.

Mean Mould Bay TN was 0.616 mg l^{-1} (range = 0.206 to 1.430 mg l^{-1}), and TKN concentrations ranged from 0.160 to 1.360 mg l^{-1} (mean = 0.515 mg l^{-1}). PON concentrations were also highly variable, ranging from 0.030 to 0.684 mg l^{-1} (mean = 0.096 mg l^{-1}), while NH_3 ranged from <0.005 to 0.122 mg l^{-1} (mean = 0.035 mg l^{-1}). TN : TPU ratios ranged from 4 : 1 to 104 : 1 at Alert sites, with a mean of 46 : 1, while at Mould Bay the mean was 49 : 1, with ratios ranging from 9 : 1 to 101 : 1.

Alert Chl-a concentrations were consistently low, ranging from below the detection limit of 0.1 µg l^{-1} to a maximum of 2.6 µg l^{-1} (median = 1.0 µg l^{-1}). POC varied from 0.108 to 3.090 mg l^{-1} (median = 0.328 mg l^{-1}), while DOC ranged from 0.6 to 6.1 mg l^{-1}, with a median of 2.7 mg l^{-1}. POC : CHLA ratios were calculated to assess the potential carbon sources, as ratios greater than 100 : 1 suggest allochthonous sources of POC (EPPLEY et al. 1977). Median POC : CHLA (348 : 1) implied that the majority of POC at Alert sites was allochthonously derived, with values ranging from 106 : 1 to 1818 : 1.

Due to analytical problems, seven Mould Bay sites have no measured Chl-a values. At a further 10 sites, Chl-a was below the detection limit of 0.1 µg l^{-1}. At the 18 sites with available Chl-a measurements, mean Chl-a was 0.8 µg l^{-1}. POC and DOC values reflected higher catchment inputs of detrital matter.

POC ranged from 0.375 to 7.090 mg l^{-1} (mean = 0.901 mg l^{-1}), while DOC ranged from 1.1 to 13.7 mg l^{-1} (mean 6.7 mg l^{-1}). POC : CHLA ratios calculated at the 18 sites in the Mould Bay dataset with available Chl-a values again suggested terrestrial sources for POC, with a large range of values from 174 : 1 to 8800 : 1 (mean = 1289 : 1).

Multivariate analyses

Several iterations of RDA and PCA were used to investigate patterns of variation in the water chemistry datasets. RDA was run to determine the degree to which a strictly geographic factor could account for differences between the Alert and Mould Bay datasets, and indicated that classification by island explained 16.4 % of the water chemistry variation. The variables most highly correlated with the first RDA axis were, as expected, those for which one of the study regions had distinctively higher concentrations. High DIC, Ca, and pH were most strongly associated with Alert. High concentrations of TPF and DOC were most strongly linked with Mould Bay.

PCA analysis indicated that there were two primary gradients in each environmental dataset. The first two axes of the Alert PCA explained 47.6 % of the water chemistry variation, with eigenvalues of 0.276 and 0.199, respectively. Conductivity-related variables and nutrients (i.e. Mg, Sr, TKN, DOC, TN, and Cond) most strongly controlled the first axis. The second axis was most strongly correlated with Al, Fe, Zn, and Mn, and thus represented a gradient of metal concentrations.

The first two axes of the Mould Bay PCA had eigenvalues of 0.302 and 0.188, respectively, and collectively explained 49.0 % of the variation in the dataset. The first axis was again controlled by conductivity-related variables (i.e. Sr, Ca, Cond, K, Mg, and DIC), while the second axis represented a nutrient gradient, and was correlated with NH_3, TN, SRP, and TPU.

Discussion

Conductivity, pH, and major ions

The majority of the sites present in the study were shallow tundra ponds, however physical characteristics (Appendixes 1, 2) differed between Alert and Mould Bay. Roughly one quarter of Alert sites were lakes, compared with fewer than one in ten at Mould Bay. Although the greater proportion of lakes in the Alert dataset may partially account for differences in nutrient and solute concentrations between Alert and Mould Bay, geology and vegetation appear to play the largest role in determining regional water chemistry. Differences in trophic status between Alert and Mould Bay sites can be attributed to vegetational regime, while differences in ionic chemistry resulted largely from bedrock differences. High arctic water bodies are typically alkaline, dilute, and oligotrophic. While Alert sites largely conformed to these trends, the trophic status and ionic chemistry of Mould Bay sites were distinct among Canadian high arctic regions.

Conductivity at both Alert and Mould Bay was within ranges found in other high arctic limnological studies (i.e. ANTONIADES et al. 2003, MICHELUTTI et al. 2002 a, b, HAMILTON et al. 2001, LIM et al. 2001, VEZINA & VINCENT 1997, DOUGLAS & SMOL 1994). No significant correlation was identified between conductivity and elevation at either Alert or Mould Bay, a correlation that previous high arctic studies have inferred represent distance from the ocean (LIM et al. 2001, MICHELUTTI et al. 2002 b). However, any relationship between conductivity and elevation at Alert may have been obscured by the fact that the four largest, most dilute lakes also had the lowest elevations. At Mould Bay, the eight sites closest to the Arctic Ocean had the eight highest conductivity values, despite a range of elevations.

The predominance of alkaline sites across the Canadian High Arctic results from the carbonate bedrock and glacial materials that dominate most of the region. In tundra ponds, pH may also be elevated by photosynthesis during the extended daylight of the arctic summer. pH typically ranges from 7 to 8.5, and values exceeding 9 have been reported (VEZINA & VINCENT 1997, HAMILTON et al. 2001). Alert sites were among the most alkaline reported from the High Arctic, while Mould Bay sites, which were situated on non-calcareous sandstones, were circumneutral to slightly alkaline due to the influence of carbonate surficial materials.

Trends in major ion concentrations at Alert were broadly similar to those observed in other high arctic surveys, however Mould Bay's major ions differed from other high arctic sites. Alert sites had the highest DIC and second highest Ca yet recorded in a limnological survey in the Canadian High Arctic, resulting from the calcium carbonate bedrock underlying the Alert area. Similar Ca concentrations were also recorded farther north on Ward Hunt Island (VILLENEUVE et al. 2001). Conversely, Mould Bay mean Ca and DIC were at or among the lowest found to date in a high arctic limnological survey, reflecting that Mould Bay is the lone study site not dominated by calcareous bedrock (ANTONIADES et al. 2003, MICHELUTTI et al. 2002 a, b, HAMILTON et al. 2001, LIM et al. 2001). Na and Cl were at the upper end of typical high arctic ranges at both Mould Bay and Alert, reflecting the greater proximity of sites in this study to the ocean. Concentrations of other major ions (Mg, K, and SO_4) were within previously identified ranges in the Canadian High Arctic and normal ranges for Canadian freshwaters (ANTONIADES et al. 2003, MICHELUTTI et al. 2002 a, b, HAMILTON et al. 2001, LIM et al. 2001, DOUGLAS & SMOL 1994, MCNEELY et al. 1979). Individual sites with elevated Na, Cl, Mg, and SO_4 were either situated within very short distances of the ocean (i.e. MB-I, MB-JE, MB-JW, MB-AG, MB-AH), or may have been impacted by anthropogenic sources (i.e. A-A, A-B).

K in tundra ponds may be increased by leaching from vascular plant litter, particularly during spring melt (Prentki et al. 1980, Cornwell 1992). High individual K concentrations have been attributed to higher catchment vegetation (Lim et al. 2001, Michelutti et al. 2002 a); however, despite vegetation levels that far exceed any observed in these studies, Mould Bay K remained low, and concentrations were similar to those from Alert.

Na : K in natural waters is typically between 2 : 1 and 3 : 1 (McNeely et al. 1979). However, median Alert Na : K was 9 : 1, while the ratio from Mould Bay was 4 : 1. The ratio of mean Na : K in previous high arctic surveys has ranged from 8 : 1 to 13 : 1, and appears to increase with decreasing vegetation levels. The highest Na : K in the High Arctic was from Isachsen, Ellef Ringnes Island, a region almost completely devoid of vegetation (Antoniades et al. 2003), while the lowest value was from Mould Bay, the most lushly vegetated region among these studies. By comparison, studies from the Canadian and Alaskan Arctic mainland had Na : K ratios ranging from 1 to 5 (Gregory-Eaves et al. 2000, Rühland & Smol 1998, Pienitz et al. 1997 a, b), and a survey from Victoria Island, the farthest south of the Canadian Arctic Islands, had a ratio of 2 : 1. High ratios from around the High Arctic relative to lower arctic sites may be indicative of extremely low K contributions resulting from the depauperate vegetation regime at these sites.

Metals

Similar to most high arctic datasets, metals in both study areas were present in low concentrations. A notable exception was the high mean Fe at Mould Bay, which was above the range considered normal for Canadian waters ($< 0.5\ mg\,l^{-1}$; McNeely et al. 1979), although a broad range of concentrations was present (0.083 to $7.200\ mg\,l^{-1}$). While extreme sites in the dataset increased this mean (median Fe = $0.267\ mg\,l^{-1}$), 12 sites still had Fe concentrations that exceeded $0.5\ mg\,l^{-1}$. Weathering of ferric minerals in the sandstones of the Mould Bay area may be responsible for these elevated Fe levels. In addition, while mean Fe at Alert was within typical high arctic and Canadian ranges, six sites in the dataset had values above $0.5\ mg\,l^{-1}$. Elevated Fe concentrations have been observed at other high arctic sites in contact with pyrite-rich shale (Antoniades et al. 2003, Hamilton et al. 2001). At Alert, crystallized pyrite was observed between bedrock joints, and provided a potential source of Fe to Alert sites.

Nutrients, Chl-a, and trophic status

Broad ranges of TPU concentrations were present in both regions, however at Alert the majority of sites was oligotrophic to meso-oligotrophic, while at Mould Bay the majority of sites were mesotrophic. Mean Mould Bay TPU exceeded those from all other Canadian High Arctic studies (Michelutti et al. 2002 a, b, Hamilton et al. 2001, Lim et al. 2001, Douglas & Smol 1994) except Isachsen, Ellef Ringnes Island, which was heavily influenced by phosphatic shale (Antoniades et al. 2003). TPU values similar to Mould Bay have also been reported from lakes on Spitsbergen (van Donk et al. 2001). The decay of organic matter from lush vegetation provides a potential source of increased phosphorus supply to Mould Bay sites not available in other, less vegetated high arctic locations.

Alert mean TKN was higher than any previously reported in a high arctic survey, but was further exceeded by mean TKN at Mould Bay. Mould Bay mean TN and NH_3 were higher than those of all previous high arctic surveys, and mean PON was only exceeded by that from Ellef Ringnes Island (Antoniades et al. 2003). TKN values greater than 0.5 mg l^{-1} generally indicate high organic inputs (McNeely et al. 1979). Although there was great between-site variability, mean TKN and concentrations at 17 of 35 Mould Bay sites exceeded this figure. The higher TPU, TKN and PON levels at Mould Bay are a reflection of high vegetation levels, which provide an abundant source of detrital organic matter.

Ninety-eight percent of the sites in this study were classified as oligotrophic by Chl-a concentrations, which is typical of high arctic water bodies. Alert Chl-a concentrations, while low, were somewhat higher than measurements from our other high arctic studies. However, recent methodological changes may hamper direct comparisons of Chl-a concentrations with earlier published figures (see Methods). Regardless, the consistently low Chl-a concentrations in both study areas are indicative of low productivity in the water column, and were similar to those reported from the Canadian High Arctic and from Spitsbergen.

TN : TPU ratios were calculated in order to investigate the degree to which phytoplankton productivity may be limited by nitrogen or phosphorus. High arctic lakes are typically dominated by benthic communities, which can account for over 95 % of a site's phototrophic productivity (Vezina & Vincent 1997, Villeneuve et al. 2001). In addition, nutrients and major ions within arctic cyanobacterial mats can be concentrated by over an order of magnitude when compared with concentrations in the overlying water column (Villeneuve et al. 2001). As such, estimates of nutrient limitation using samples taken from the water column are applicable only to phytoplankton.

TN : TP ratios suggested P-limitation (i.e. ≥17 : 1) at 93 % of Alert sites and 97 % of Mould Bay sites. Strong P-limitation was indicated at the majority of sites in the dataset, as 67 % of Alert sites and 83 % of Mould Bay sites exceeded 30 : 1. Only three sites (A-E, UDL, MB-AF) had ratios suggesting N-limitation. Of these, two sites (i.e. UDL, MB-AF) had anomalously high concentrations of particulate matter and low TN : TP ratios, which likely result from resuspended sediment and may not be reflective of N-limitation.

Phosphorus and nitrogen were present in high concentrations at Mould Bay relative to other high arctic sites, yet Chl-a concentrations remained at the low end of High Arctic ranges. The importance of nitrogen as a limiting factor is often underestimated in arctic and oligotrophic lakes (Levine & Whalen 2001, Elser et al. 1990). In our study, dissolved inorganic nitrogen species were at or below detection limits in many sites at both regions. As such, we performed a series of linear regressions to investigate the response of Chl-a to increases in TPU, TN, and TKN (Fig. 6), and compared these to published equations for CHLA : TP (i.e. Smith 1982, Dillon & Rigler 1974). Despite the suggestion of strong P-limitation by nutrient ratios, Chl-a and TPU were not significantly correlated ($p \leq 0.05$), and there was no significant relation between Chl-a and TN or TKN. The regression equations from the literature consistently overestimated Chl-a responses to increases in TPU in our sites (Fig. 6 a, b). This supports the findings of Flanagan et al. (2003), who suggested that in arctic lakes, smaller increases in algal biomass result from a given increase in phosphorus than would occur in temperate sites. However, the lack of a relationship between Chl-a and N or P suggests that other factors may be controlling phytoplankton productivity at our sites. Moreover, as the majority of the production in these sites is from the periphyton, open water Chl-a concentrations are not measuring periphytic production. The precise role of nutrients in regulating phytoplankton productivity in these and other high arctic sites is thus unclear, and warrants future investigation through bioassays and fertilization experiments.

Alert's median POC concentration was similar to those found at typical, sparsely vegetated high arctic sites, while the Mould Bay median POC concentration exceeded those reported from all high arctic regions except Ellef Ringnes Island, where resuspension of sediments was a confounding factor (Antoniades et al. 2003). POC : CHLA ratios were significantly lower at Alert than those calculated in other high arctic surveys (Antoniades et al. 2003, Michelutti et al. 2002 a, b, Lim et al. 2001), and may reflect the slightly elevated Chl-a concentrations found at Alert. Mean POC : CHLA at both study areas suggests that the majority of POC is derived from allochthonous, and thus likely terrestrial sources, a finding similar to all previous high arctic limnological surveys. POC : CHLA ratios were not calculated at Mould Bay sites with no measured CHLA concentration; however, as ten of these

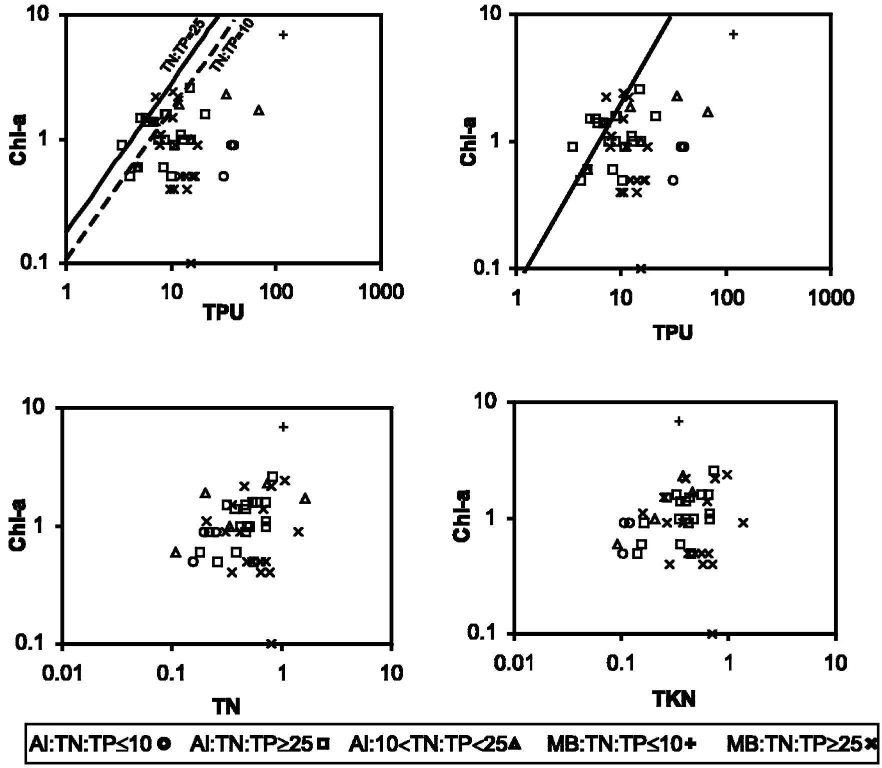

Fig. 6. Individual regressions of Chl-a against TPU, TN and TKN. **a)** sites fail to segregate according to SMITH's (1982) regression equations for TN : TP = 10 and 25. **b)** includes Chl-a : TP regression of DILLON & RIGLER (1974).

sites were below the CHLA detection limit, it is likely that our mean value under-represents the actual value for Mould Bay sites. Despite this, ratios from Mould Bay were much higher than those from Alert and elsewhere in the High Arctic, further reinforcing the sensitivity of these sites to external detrital inputs, and the influence of the relatively lush vegetation in the Mould Bay area relative to other, more sparsely vegetated high arctic regions.

Alert DOC concentrations were higher than those from Spitsbergen (ELLIS-EVANS et al. 2001) and similar to those found elsewhere in the Canadian High Arctic, with the exception of Ward Hunt Lake, where DOC exceeded the maximum found at Alert (VILLENEUVE et al. 2001). This emphasizes the importance of individual catchment characteristics in determining high arctic DOC.

Mould Bay DOC greatly exceeded all values previously reported from our high arctic surveys. Concentrations were similar to those reported at or near treeline from the subarctic Northwest Territories and arctic sites in northern

Russia (Pienitz et al. 1997 a, Duff et al. 1999); however, DOC remained far lower than values reported from Alaska and western arctic Canada (Gregory-Eaves et al. 2000, Pienitz et al. 1997 b). High arctic freshwater sites are typically low in DOC and thus highly sensitive to ultraviolet radiation (Vincent & Pienitz 1996). Predicted future increases in ultraviolet radiation are expected to further stress high arctic lakes and ponds. However, high arctic vegetation cover is also predicted to increase in response to higher temperatures and greater precipitation. High DOC at Mould Bay resulting from terrestrial organic inputs suggest that the future effects of increased UV radiation on these water bodies may be moderated by higher DOC concentrations.

Outlier sites

The water chemistry of several sites was distinct from all others in the study. A-A and A-B had water chemistry characteristics that were distinctly different from all other sites in the Alert dataset. Site A-A had the highest concentration in the dataset for 23 measured chemical variables, including Cl, SO_4, Mg, Na, and K, while A-B had the second highest concentration of these five variables. These sites were among the closest to the Alert military base, and were located short distances from roads used to service outlying components of the installation. This proximity was the only distinguishing feature of these ponds; as such their elevated concentrations likely result from the construction and maintenance of these roads.

The TPU concentration of UDL (mean = 34.6 $\mu g\,l^{-1}$) was the highest among non-impacted sites in the Alert dataset. The TPF concentration at UDL (2.6 $\mu g\,l^{-1}$) was not comparably elevated, and was, in fact, similar to that measured at other lakes in the dataset. Turbid waters resulting from high winds and large waves were observed while sampling UDL. The adjacent LDL, similar in size and general characteristics, was sampled during calm conditions, and had a TPU concentration of only 4.1 $\mu g\,l^{-1}$. In addition, the TN : TP ratio of UDL (5 : 1) closely approximates that of oligotrophic lake sediment (i.e. 3 : 1, Downing & McCauley 1992). As such, high TPU at UDL is likely reflective of the contribution of resuspended particulate phosphorus.

MB-AF TPU (117.0 $\mu g\,l^{-1}$) was the highest amongst the Mould Bay sites. It was the largest site sampled at Mould Bay, and was sampled under conditions similar to UDL. POC and PON were also elevated at MB-AF, however TPF barely exceeded the Mould Bay mean (9.3 vs. 8.5 $\mu g\,l^{-1}$). MB-AF also had the lowest TN : TP ratio among the Mould Bay sites. Classifications of MB-AF and UDL as eutrophic (by TPU) are somewhat improbable given the trophic conditions of all other sites in the region. The similarities between these sites imply that measured TPU concentrations include resuspended particulate material, and are not indicative of increased trophic levels.

Tundra ponds are more sensitive than lakes to increasing concentration of solutes from external inputs and via evaporative concentration. Because of this difference in physical characteristics, concentrations of many water chemistry variables differed greatly between lakes (n = 7) and ponds (n = 23) in the Alert dataset. A series of simple t-tests indicated that 17 limnological variables differed significantly ($p \leq 0.05$) between lakes and ponds (i.e. POC, PON, DOC, DIC, SiO_2, NH_3, TKN, TN, TPF, SO_4, Ca, Mg, Li, Sr, Cond, T, and pH). Concentrations of these limnological variables were higher in ponds than in lakes, as expected. The difference in the chemical limnology between lakes and ponds is indicative of the degree to which their concentrations are dependent on external inputs. Because of their small volumes, tundra ponds have much lower capacities for dilution of allochthonous material, and are thus highly sensitive to allochthonous deposition of solutes and nutrients. Canonical Variates Analysis (CVA) indicated that the differences in concentrations of these 17 variables accounted for 71.7 % of water chemistry differences between lakes and ponds. The variables that most strongly differentiated between lakes and ponds were, in descending order, TKN, DIC, POC, PON, and Mg. A second CVA indicated that these five variables alone explained 63.7 % of the water chemistry differences between lakes and ponds.

Multivariate analysis

Lakes and ponds were divided mainly into two groups along Alert PCA axis 1, reflecting the difference in the evaporative concentration between the two site types. Accordingly, the arrows representing site diameter and the conductivity-related variables are directly opposite to each other along the axis. The higher degree of variability in the chemical compositions of ponds was reflected in their wide distribution along both PCA axes. Lakes, which were consistently low in solute concentrations, more densely clustered than ponds, and are situated in the left-centre of the ordination.

The Mould Bay PCA illustrates the effect of distance from the ocean on the chemical composition of sites. High conductivity sites, situated near the ocean, are located in the right half of the ordination. Proximity to the ocean appears to override site size as the primary determinant of solute concentrations, however, diameter is inversely related to nutrient and particulate concentrations along PCA axis 2.

Conclusions

The data presented in this study constitute the first documentation of baseline limnological conditions for lakes and ponds in the Alert and Mould Bay region. This information is crucial, as these systems are likely to undergo dramatic changes in the future due to changing climatic conditions. The different limnology and higher DOC concentrations of the Mould Bay region relative to other, less vegetated sites may provide examples of future limnological conditions that may be expected elsewhere in the High Arctic under the warmer, wetter climate regimes and more densely vegetated ecosystems predicted within the next century.

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Appendix 1. Alert Water Chemistry. D. L. = Below detection limits; N/A = value not available.

Site	Cl mg L^{-1}	SO_4 mg L^{-1}	SiO_2 mg L^{-1}	POC mg L^{-1}	PON mg L^{-1}	DOC mg L^{-1}	DIC mg L^{-1}	SRP µg L^{-1}	NO_2 mg L^{-1}	NO_3+NO_2 mg L^{-1}	NH_3 mg L^{-1}	TKN mg L^{-1}	Al mg L^{-1}	Ba mg L^{-1}	Be mg L^{-1}
A-A	703.0	111.0	0.44	3.090	0.286	2.4	34.7	4.8	0.001	0.888	<0.005	0.457	2.15	0.0205	<0.0002
A-B	553.0	92.3	0.51	1.210	0.142	2.7	33.2	2.0	<0.001	0.220	<0.005	0.376	0.51	0.0152	<0.0002
A-C	2.2	3.5	0.23	0.247	0.029	1.1	25.0	0.6	<0.001	<0.010	<0.005	0.153	0.06	0.0022	<0.0002
Hilgard L.	0.6	1.8	0.40	0.116	0.017	0.8	21.2	0.8	<0.001	0.033	<0.005	0.086	0.84	0.0077	<0.0002
A-E	7.8	5.8	0.04	1.060	0.072	0.6	25.1	2.0	0.076	0.073	<0.005	0.106	1.07	0.0043	<0.0002
A-F	10.7	12.3	0.24	1.080	0.100	2.7	33.2	0.9	0.114	0.117	<0.005	0.327	0.24	0.0052	<0.0002
A-G	6.2	1.5	3.12	0.387	0.052	6.1	45.9	1.3	0.004	<0.010	0.049	0.669	0.12	0.0043	<0.0002
A-H	10.6	1.4	0.60	0.519	0.059	4.9	34.4	1.4	<0.001	<0.010	0.077	0.650	0.09	0.0052	<0.0002
A-I	3.3	0.9	4.11	0.333	0.043	6.0	22.5	1.3	<0.001	<0.010	0.077	0.667	0.01	0.0016	<0.0002
A-J	43.5	11.9	0.55	0.542	0.047	3.8	41.2	1.5	<0.001	<0.010	0.078	0.418	0.31	0.0048	<0.0002
A-K	21.9	8.5	1.49	0.190	0.023	3.9	24.0	1.1	<0.001	<0.010	0.083	0.602	0.02	0.0032	<0.0002
Moss P.	51.6	6.1	0.83	0.108	0.016	0.7	19.8	0.8	<0.001	<0.010	0.013	0.091	0.04	0.0025	<0.0002
A-M	19.6	2.8	2.75	0.301	0.028	3.5	41.6	1.3	0.001	<0.010	0.037	0.353	0.01	0.0034	<0.0002
A-N	13.0	8.5	0.56	0.387	0.037	4.8	29.1	1.2	0.001	<0.010	0.020	0.556	0.04	0.0032	<0.0002
A-O	37.8	9.2	0.33	0.278	0.028	1.8	32.4	0.9	0.001	0.099	<0.005	0.204	0.21	0.0032	<0.0002
A-P	1.2	0.2	4.29	0.348	0.040	3.7	24.1	1.3	<0.001	<0.010	0.006	0.471	0.04	0.0019	<0.0002
A-Q	1.0	1.0	1.81	0.220	0.028	4.0	35.2	1.2	<0.001	<0.010	0.012	0.393	0.02	0.0038	<0.0002
A-R	12.7	71.0	0.15	0.737	0.080	4.1	21.5	1.2	0.002	0.016	0.229	0.736	0.04	0.0066	<0.0002
A-S	1.3	0.7	0.37	0.407	0.047	2.2	36.3	0.7	<0.001	0.084	<0.005	0.349	0.03	0.0030	<0.0002
White P.	1.3	3.2	0.69	0.173	0.023	1.9	28.0	0.9	<0.001	0.304	<0.005	0.235	0.08	0.0054	<0.0002
Kirk L.	10.4	2.6	0.60	0.196	0.024	0.9	21.4	0.5	0.002	0.031	0.030	0.165	0.01	0.0020	<0.0002
Self P.	0.6	2.9	0.34	0.339	0.045	0.9	12.1	1.8	<0.001	0.025	<0.005	0.132	0.04	0.0022	<0.0002
A-W	2.5	10.5	1.80	0.212	0.027	2.8	26.3	0.7	0.001	0.048	0.022	0.399	<0.01	0.0033	<0.0002
A-X	0.9	3.0	1.99	0.328	0.031	3.2	25.0	0.9	<0.001	<0.010	0.016	0.435	<0.01	0.0043	<0.0002
A-Y	24.3	14.6	1.16	0.159	0.015	2.7	37.8	1.0	0.002	0.036	0.014	0.264	0.01	0.0043	<0.0002
A-Z	46.4	17.1	1.61	0.260	0.025	3.3	40.9	1.0	<0.001	<0.010	0.022	0.350	0.08	0.0037	<0.0002
A-AA	2.0	1.0	0.22	0.329	0.043	1.0	16.4	0.6	<0.001	0.021	<0.005	0.203	0.14	0.0025	<0.0002
LDL	2.5	1.3	0.59	0.224	0.032	0.7	16.6	0.5	0.001	0.083	0.016	0.141	0.02	0.0016	<0.0002
A-AE	7.5	3.5	2.05	0.291	0.027	4.2	37.3	0.9	0.083	0.086	<0.005	0.448	0.01	0.0034	<0.0002
UDL-W	6.9	2.0	0.92	0.263	0.023	0.7	23.1	1.1	<0.001	0.031	<0.005	0.102	0.05	0.0019	<0.0002
UDL-E	7.0	2.1	0.93	0.402	0.035	0.7	22.8	1.0	0.001	0.039	<0.005	0.120	0.24	0.0025	<0.0002
Mean	52.0	13.4	1.15	0.475	0.049	2.7	28.6	1.2	0.009	0.072	0.026	0.344	0.21	0.0045	<0.0002
Median	7.5	3.2	0.60	0.328	0.032	2.7	26.3	1.0	0.002	0.061	0.022	0.350	0.05	0.0034	<0.0002
Maximum	703.0	111.0	4.29	3.090	0.286	6.1	45.9	4.8	0.114	0.888	0.229	0.736	2.15	0.0205	<0.0002
Minimum	0.6	0.2	0.04	0.108	0.015	0.6	12.1	0.5	0.001	0.016	0.006	0.086	<0.01	0.0016	<0.0002

Appendix 1. Continued.

Site	Cd mg L^{-1}	Co mg L^{-1}	Cr mg L^{-1}	Cu mg L^{-1}	Fe mg L^{-1}	Li mg L^{-1}	Mn mg L^{-1}	Mo mg L^{-1}	Ni mg L^{-1}	Pb mg L^{-1}	Sr mg L^{-1}	V mg L^{-1}	Zn mg L^{-1}	Ca mg L^{-1}	Mg mg L^{-1}
A-A	<0.001	0.003	0.005	0.008	3.700	0.015	0.0605	0.003	0.007	<0.005	0.2700	0.003	0.010	50.2	56.5
A-B	<0.001	0.001	0.001	0.007	0.905	0.009	0.0266	0.002	0.002	<0.005	0.2230	<0.001	0.003	53.4	43.0
A-C	<0.001	0.001	<0.001	0.004	0.082	0.002	0.0013	<0.001	<0.002	<0.005	0.0762	<0.001	<0.001	28.9	7.3
Hilgard L.	<0.001	0.001	0.002	0.013	1.850	0.001	0.0246	<0.001	0.004	<0.005	0.0517	0.003	0.008	31.6	4.0
A-E	<0.001	0.002	0.003	0.009	1.890	0.005	0.0335	0.001	0.004	<0.005	0.0932	0.002	0.006	31.0	10.5
A-F	<0.001	<0.001	0.001	0.012	0.480	0.002	0.0090	<0.001	0.002	<0.005	0.1040	0.001	0.003	37.8	14.5
A-G	<0.001	0.001	<0.001	0.006	0.185	0.004	0.0104	0.001	<0.002	<0.005	0.1130	<0.001	0.002	67.5	7.2
A-H	<0.001	<0.001	0.001	0.006	0.184	0.004	0.0055	0.002	0.002	<0.005	0.0999	<0.001	0.003	40.2	11.4
A-I	<0.001	<0.001	<0.001	0.006	0.083	0.002	0.0022	0.001	<0.002	<0.005	0.0543	<0.001	0.001	28.8	5.9
A-J	<0.001	0.001	0.001	0.005	0.454	0.002	0.0058	<0.001	0.002	<0.005	0.1320	<0.001	0.003	54.9	16.6
A-K	<0.001	<0.001	<0.001	0.008	0.105	0.001	0.0032	<0.001	<0.002	<0.005	0.0804	<0.001	0.001	25.4	13.4
Moss P.	<0.001	<0.001	<0.001	0.002	0.088	<0.001	0.0031	<0.001	<0.002	<0.005	0.0892	<0.001	<0.001	27.8	9.3
A-M	<0.001	<0.001	<0.001	0.008	0.046	<0.001	0.0071	<0.001	<0.002	<0.005	0.1410	<0.001	0.002	61.8	9.5
A-N	<0.001	0.001	0.002	0.004	0.073	0.004	0.0033	0.002	0.003	<0.005	0.1150	<0.001	0.004	20.9	16.6
A-O	<0.001	0.001	0.001	0.005	0.330	0.004	0.0055	0.001	0.013	<0.005	0.1240	<0.001	0.002	41.1	13.9
A-P	<0.001	<0.001	<0.001	0.003	0.077	<0.001	0.0055	<0.001	<0.002	<0.005	0.0566	<0.001	<0.001	29.0	6.9
A-Q	<0.001	<0.001	<0.001	0.007	0.050	<0.001	0.0092	<0.001	<0.002	<0.005	0.0734	<0.001	<0.001	53.8	5.5
A-R	<0.001	<0.001	<0.001	0.003	0.086	0.001	0.0087	<0.001	0.002	<0.005	0.1140	<0.001	<0.001	39.8	19.4
A-S	<0.001	<0.001	<0.001	0.005	0.082	0.001	0.0059	<0.001	<0.002	<0.005	0.1090	<0.001	0.001	40.2	10.0
White P.	<0.001	0.001	<0.001	0.018	0.677	<0.001	0.0270	<0.001	0.002	<0.005	0.0713	<0.001	0.003	46.3	5.1
Kirk L.	<0.001	0.001	<0.001	0.004	0.014	0.001	0.0013	0.001	<0.002	<0.005	0.0574	<0.001	0.001	30.5	5.0
Self P.	<0.001	<0.001	0.001	0.006	0.109	<0.001	0.0095	<0.001	<0.002	<0.005	0.0263	<0.001	0.001	18.8	1.4
A-W	<0.001	<0.001	<0.001	0.004	0.008	<0.001	0.0016	<0.001	<0.002	<0.005	0.0643	<0.001	<0.001	40.7	6.5
A-X	<0.001	<0.001	<0.001	0.004	0.015	<0.001	0.0015	<0.001	<0.002	<0.005	0.0721	<0.001	0.001	32.5	7.4
A-Y	<0.001	0.001	0.002	0.008	0.151	0.002	0.0033	0.001	0.003	<0.005	0.1060	<0.001	0.004	55.0	13.3
A-Z	<0.001	0.001	0.001	0.008	0.238	0.003	0.0057	0.001	<0.002	<0.005	0.1220	<0.001	0.002	55.6	19.5
A-AA	<0.001	<0.001	<0.001	0.006	0.270	<0.001	0.0065	<0.001	0.024	<0.005	0.0362	<0.001	0.003	23.0	2.2
LDL	<0.001	<0.001	<0.001	0.008	0.084	<0.001	0.0047	<0.001	<0.002	<0.005	0.0399	<0.001	<0.001	25.1	2.9
A-AE	<0.001	<0.001	<0.001	0.003	0.029	0.001	0.0028	<0.001	<0.002	<0.005	0.1060	<0.001	<0.001	51.1	9.9
UDL-W	<0.001	0.001	<0.001	0.002	0.107	0.001	0.0055	0.001	<0.002	<0.005	0.0599	<0.001	0.001	33.1	4.8
UDL-E	<0.001	0.001	0.001	0.009	0.615	<0.001	0.0206	<0.001	0.002	<0.005	0.0644	<0.001	0.004	36.3	5.4
Mean	<0.001	0.001	0.001	0.006	0.422	0.002	0.0104	0.001	0.002	<0.005	0.0950	0.000	0.002	39.1	11.8
Median	<0.001	0.001	0.001	0.006	0.107	0.002	0.0057	0.001	0.003	<0.005	0.0892	0.003	0.003	37.8	9.3
Maximum	<0.001	0.003	0.005	0.018	3.700	0.015	0.0605	0.003	0.024	<0.005	0.2700	0.003	0.010	67.5	56.5
Minimum	<0.001	0.001	0.001	0.002	0.008	0.001	0.0013	0.001	0.002	<0.005	0.0263	0.001	0.001	18.8	1.4

Appendix 1. Continued.

Site	Na mg L^{-1}	K mg L^{-1}	Ag mg L^{-1}	TPU µg L^{-1}	TPF µg L^{-1}	TN mg L^{-1}	Chl-a µg L^{-1}	POC : CHL-a	TN : TP	Cond µS cm^{-1}	T (°C)	pH	ELEV (m asl)	Diam (m)	Latitude	Longitude
A-A	404.0	18.4	0.002	67.6	7.7	1.631	1.7	1818 : 1	24 : 1	2000	7	8.2	45	65	82°29.608′N	62°25.505′W
A-B	309.0	12.1	0.002	33.9	9.7	0.738	2.3	526 : 1	22 : 1	1650	7	8.3	45	30	82°29.605′N	62°26.933′W
A-C	4.0	0.5	0.003	4.8	3.2	0.182	0.6	412 : 1	38 : 1	152	2	8.2	40	33	82°29.171′N	62°25.546′W
Hilgard L.	0.4	0.4	0.002	4.8	1.5	0.136	<0.1	N/A	28 : 1	140	9	8.25	143	750	82°26.180′N	63°06.635′W
A-E	8.6	2.6	0.002	39.8	2.1	0.251	0.9	1178 : 1	6 : 1	190	15	8.35	23	15	82°27.137′N	63°01.152′W
A-F	6.9	1.2	0.001	21.1	8.7	0.544	1.6	675 : 1	26 : 1	260	15	8.65	25	100	82°27.137′N	63°01.152′W
A-G	2.2	0.2	0.003	12.5	7.9	0.721	1.1	352 : 1	58 : 1	311	11	8.15	95	7	82°30.196′N	62°30.121′W
A-H	6.1	1.7	0.002	9.1	5.3	0.709	1.6	324 : 1	78 : 1	259	13	8.5	72	9	82°31.208′N	62°30.634′W
A-I	3.1	<0.2	0.002	13.0	6.3	0.710	1.0	333 : 1	55 : 1	168	15	8.65	25	80	82°31.152′N	62°17.721′W
A-J	24.6	1.2	0.002	10.8	3.8	0.465	0.9	602 : 1	43 : 1	420	13	8.45	31	65	82°29.602′N	62°50.887′W
A-K	12.2	0.8	0.002	6.0	6.2	0.625	N/A	N/A	104 : 1	251	12	8.9	120	12	82°29.025′N	62°54.214′W
Moss P.	26.6	1.4	0.002	4.8	3.0	0.107	0.6	180 : 1	22 : 1	302	6	8.2	85	650	82°28.674′N	62°54.242′W
A-M	9.9	0.5	0.002	8.4	6.5	0.381	0.6	502 : 1	45 : 1	282	8	8.1	57	45	82°28.020′N	62°56.418′W
A-N	12.5	2.4	0.002	8.7	4.9	0.593	1.6	242 : 1	68 : 1	238	14	8.7	40	18	82°27.790′N	62°55.040′W
A-O	21.1	1.2	0.002	15.6	4.8	0.331	1.0	278 : 1	21 : 1	282	13	8.4	26	300	82°27.300′N	63°56.050′W
A-P	0.8	<0.2	0.002	7.6	4.6	0.511	1.0	348 : 1	67 : 1	165	6	8.7	125	225	82°28.334′N	62°32.387′W
A-Q	0.7	0.2	0.002	8.8	6.1	0.421	1.0	220 : 1	48 : 1	230	6	8.4	116	45	82°28.286′N	62°28.816′W
A-R	3.7	0.6	0.002	15.0	5.7	0.832	2.6	283 : 1	55 : 1	278	7	8.7	122	25	82°28.492′N	62°26.528′W
A-S	3.5	0.5	<0.001	15.6	5.8	0.480	1.0	407 : 1	31 : 1	215	6	8.4	45	30	82°29.226′N	62°24.291′W
White P.	0.6	0.2	<0.001	8.7	4.0	0.562	<0.1	N/A	65 : 1	185	6.5	8.3	115	450	82°27.093′N	62°52.388′W
Kirk L.	5.2	0.4	0.001	3.4	0.7	0.220	0.9	218 : 1	65 : 1	170	4	8.2	13	900	82°27.891′N	62°49.190′W
Self P.	0.4	<0.2	<0.001	12.0	1.7	0.202	1.9	178 : 1	17 : 1	135	4	8.3	137	600	82°26.552′N	62°01.618′W
A-W	0.8	0.2	<0.001	6.7	3.2	0.474	1.4	151 : 1	71 : 1	202	6	8.5	147	58	82°27.646′N	62°12.358′W
A-X	0.9	0.2	0.001	5.7	2.8	0.466	1.5	219 : 1	82 : 1	183	7	8.6	118	52	82°28.568′N	62°11.894′W
A-Y	10.2	0.4	<0.001	5.1	3.0	0.315	1.5	106 : 1	62 : 1	329	7	8.4	17	40	82°29.123′N	62°11.956′W
A-Z	21.1	0.7	<0.001	6.0	3.5	0.375	1.4	186 : 1	63 : 1	388	8	8.4	18	23	82°29.111′N	62°13.107′W
A-AA	1.0	0.2	<0.001	13.8	1.3	0.267	<0.1	N/A	19 : 1	121	4	8.1	37	80	82°27.389′N	61°31.899′W
LDL	1.6	0.2	<0.001	4.1	3.4	0.256	0.5	448 : 1	62 : 1	132	6	8.3	20	1150	82°29.066′N	62°38.411′W
A-AE	5.0	0.2	<0.001	10.1	5.4	0.561	0.5	582 : 1	56 : 1	268	9	8.45	35	14	82°29.855′N	62°23.444′W
UDL-W	4.4	0.4	0.001	37.6	2.1	0.156	0.5	526 : 1	4 : 1	179	4.5	8.35	21	1400	82°29.354′N	62°33.954′W
UDL-E	4.5	0.5	<0.001	31.6	3.1	0.194	0.9	447 : 1	6 : 1	171	4.5	8.2	21	1400	82°29.301′N	62°29.138′W
Mean	29.5	1.6	0.001	14.6	4.5	0.465	1.1	379 : 1	46 : 1	331	8.2	8.4	65	242		
Median	4.5	0.5	0.002	9.1	4.0	0.465	1.0	348 : 1	48 : 1	230	7	8.4	45	55		
Maximum	404.0	18.4	0.003	67.6	9.7	1.631	2.6	1818 : 1	104 : 1	2000	15	8.9	147	1400		
Minimum	0.4	<0.2	0.001	3.4	0.7	0.107	0.5	106 : 1	4 : 1	121	2	8.1	13	7		

Appendix 2. Mould Bay Water Chemistry. D.L. = below detection limits, N/A = value not available.

Site	Cl mg L^{-1}	SO_4 mg L^{-1}	SiO_2 mg L^{-1}	POC mg L^{-1}	PON mg L^{-1}	DOC mg L^{-1}	DIC mg L^{-1}	SRP µg L^{-1}	NO_2 mg L^{-1}	NO_3+NO_2 mg L^{-1}	NH_3 mg L^{-1}	TKN mg L^{-1}	Al mg L^{-1}	Ba mg L^{-1}
MB-A	5.92	4.0	0.31	0.880	0.083	7.5	10.7	1.1	<0.001	<0.010	0.122	0.712	0.01	0.0143
MB-B	9.32	3.8	0.57	0.552	0.054	8.0	16.8	1.2	0.002	0.019	0.054	0.572	0.09	0.0154
MB-C	14.10	3.8	0.25	0.650	0.053	6.8	7.0	1.3	0.001	<0.010	0.033	0.490	<0.01	0.0064
MB-D	11.80	5.5	0.30	0.394	0.043	5.1	2.9	1.0	0.001	<0.010	0.027	0.347	0.08	0.0057
MB-E	13.40	23.1	0.36	0.440	0.043	5.3	3.5	0.6	<0.001	<0.010	0.026	0.372	0.08	0.0147
MB-F	17.40	7.5	0.59	0.665	0.062	6.9	4.9	0.9	0.001	<0.010	0.025	0.427	0.01	0.0083
MB-G	17.70	3.2	0.17	0.621	0.068	7.2	7.6	0.9	0.001	<0.010	0.028	0.523	0.01	0.0074
MB-H	8.22	0.9	0.08	0.669	0.070	13.7	14.5	1.6	0.001	<0.010	0.105	1.360	0.01	0.0128
MB-I	57.50	25.5	1.40	0.683	0.080	10.1	21.0	1.3	0.001	<0.010	0.014	0.645	0.03	0.0033
MB-JE	60.80	38.1	0.13	0.708	0.083	9.3	20.3	1.3	0.001	<0.010	0.044	0.611	0.02	0.0358
MB-JW	61.50	38.4	0.13	0.725	0.076	9.0	20.3	1.2	0.001	<0.010	0.010	0.561	0.04	0.0345
MB-K	5.69	2.8	0.06	0.579	0.072	3.9	3.7	0.6	0.001	<0.010	0.050	0.280	0.03	0.0035
MB-L	7.03	5.2	0.28	0.568	0.070	3.0	4.7	0.9	0.001	0.146	0.025	0.212	0.58	0.0113
MB-M	7.84	12.5	0.04	0.375	0.048	4.5	11.2	1.0	0.001	<0.010	0.035	0.353	0.31	0.0247
MB-N	9.38	0.7	0.05	1.070	0.111	9.3	4.8	1.3	0.001	<0.010	0.075	0.774	0.26	0.0064
MB-O	12.70	2.8	3.54	6.140	0.620	13.5	7.3	3.0	0.001	<0.010	0.010	0.774	0.10	0.0260
MB-P	6.47	5.1	0.11	0.412	0.043	8.2	4.9	0.4	<0.001	<0.010	0.028	0.478	<0.01	0.0075
MB-Q	6.07	1.4	0.06	0.499	0.067	6.1	7.6	0.7	0.001	<0.010	0.046	0.456	0.01	0.0208
MB-R	9.12	0.6	0.09	0.560	0.052	5.5	8.1	0.5	0.001	<0.010	0.018	0.427	0.03	0.0111
MB-S	14.80	0.6	0.13	0.760	0.102	2.6	5.4	0.4	0.001	<0.010	0.056	0.253	0.01	0.0079
MB-T	3.15	4.0	0.36	0.433	0.060	4.3	1.5	0.8	0.002	<0.010	<0.005	0.221	0.24	0.0091
MB-U	11.90	11.5	1.76	0.430	0.065	6.9	17.4	0.4	<0.001	<0.010	<0.005	0.555	0.37	0.0218
MB-V	12.80	14.8	0.32	0.465	0.070	9.9	22.1	0.4	0.001	<0.010	0.016	0.743	0.02	0.0322
MB-W	3.65	1.4	0.11	0.587	0.086	11.2	22.5	1.0	0.001	<0.010	0.104	0.972	0.01	0.0250
MB-X	5.56	6.4	0.46	0.488	0.048	7.8	10.2	1.0	0.001	<0.010	0.071	0.568	0.02	0.0116
MB-Y	5.77	9.8	0.20	0.495	0.065	6.9	8.1	1.2	0.001	<0.010	0.016	0.547	0.01	0.0127
MB-Z	5.88	2.1	0.51	0.601	0.075	8.0	8.3	0.7	<0.001	<0.010	0.058	0.717	0.02	0.0073
MB-AA	7.47	6.5	1.27	0.437	0.059	7.8	12.1	1.3	0.001	<0.010	0.021	0.624	0.04	0.0134
MB-AB	10.90	4.8	0.14	0.382	0.054	5.4	8.2	0.6	<0.001	<0.010	0.010	0.399	0.02	0.0144
MB-AC	6.24	1.8	0.05	0.446	0.043	2.6	5.2	0.6	<0.001	<0.010	0.023	0.263	0.01	0.0107

Appendix 2. Continued.

Site	Cl mg L^{-1}	SO_4 mg L^{-1}	SiO_2 mg L^{-1}	POC mg L^{-1}	PON mg L^{-1}	DOC mg L^{-1}	DIC mg L^{-1}	SRP µg L^{-1}	NO_2 mg L^{-1}	NO_3+NO_2 mg L^{-1}	NH_3 mg L^{-1}	TKN mg L^{-1}	Al mg L^{-1}	Ba mg L^{-1}
MB-AD	3.95	1.2	0.08	0.413	0.030	1.9	5.1	0.2	<0.001	<0.010	<0.005	0.200	0.03	0.0119
MB-AE	3.80	1.5	0.13	0.465	0.046	1.1	3.9	0.2	0.002	<0.010	0.026	0.160	0.08	0.0091
MB-AF	23.30	6.5	0.22	7.090	0.684	3.5	7.3	0.8	<0.001	<0.010	<0.005	0.347	1.49	0.0481
MB-AG	201.00	2.9	0.16	0.423	0.046	7.8	7.0	0.6	<0.001	<0.010	0.018	0.711	0.03	0.0263
MB-AH	212.00	8.9	0.10	0.438	0.046	4.1	4.1	0.5	<0.001	<0.010	0.033	0.376	0.02	0.0223
Mean	24.98	7.7	0.41	0.901	0.096	6.7	9.4	0.9	0.001	0.005	0.035	0.515	0.12	0.0158
Median	9.32	4.0	0.17	0.552	0.065	6.9	7.6	0.9	0.001	<0.010	0.028	0.490	0.03	0.0127
Maximum	212.00	38.4	3.54	7.090	0.684	13.7	22.5	3.0	0.002	0.146	0.122	1.360	1.49	0.0481
Minimum	3.15	0.6	0.04	0.375	0.030	1.1	1.5	0.2	0.001	D.L.	D.L.	0.160	D.L.	0.0033

Site	Be mg L^{-1}	Cd mg L^{-1}	Co mg L^{-1}	Cr mg L^{-1}	Cu mg L^{-1}	Fe mg L^{-1}	Li mg L^{-1}	Mn mg L^{-1}	Mo mg L^{-1}	Ni mg L^{-1}	Pb mg L^{-1}	Sr mg L^{-1}	V mg L^{-1}	Zn mg L^{-1}	Ca mg L^{-1}
MB-A	<0.0002	<0.001	<0.001	0.001	0.005	0.623	0.004	0.0023	0.001	<0.002	<0.005	0.0373	<0.001	0.004	16.0
MB-B	<0.0002	<0.001	<0.001	<0.001	0.004	0.305	0.005	0.0056	<0.001	<0.002	<0.005	0.0568	<0.001	0.002	25.5
MB-C	<0.0002	<0.001	<0.001	<0.001	0.005	0.278	0.002	0.0012	<0.001	<0.002	<0.005	0.0287	<0.001	0.001	12.1
MB-D	<0.0002	<0.001	<0.001	<0.001	0.004	0.262	0.002	0.0051	<0.001	<0.002	<0.005	0.0181	<0.001	0.001	5.9
MB-E	<0.0002	<0.001	<0.001	<0.001	0.003	0.264	0.003	0.0151	<0.001	<0.002	<0.005	0.0323	<0.001	0.003	10.9
MB-F	<0.0002	<0.001	<0.001	<0.001	0.003	0.746	0.004	0.0080	<0.001	<0.002	<0.005	0.0301	<0.001	0.002	10.4
MB-G	<0.0002	<0.001	<0.001	0.001	0.007	0.235	0.003	0.0181	<0.001	<0.002	<0.005	0.0334	<0.001	0.001	12.5
MB-H	<0.0002	<0.001	<0.001	<0.001	0.004	0.560	0.001	0.0123	<0.001	0.003	<0.005	0.0644	<0.001	0.002	16.5
MB-I	<0.0002	<0.001	<0.001	<0.001	0.007	0.148	0.003	0.0305	<0.001	<0.002	<0.005	0.0942	<0.001	0.002	23.6
MB-JE	<0.0002	<0.001	<0.001	<0.001	0.009	0.348	0.006	0.0119	<0.001	<0.002	<0.005	0.1250	<0.001	0.002	27.9
MB-JW	<0.0002	<0.001	<0.001	<0.001	0.025	0.764	0.006	0.0131	<0.001	<0.002	<0.005	0.1260	0.001	0.002	27.8
MB-K	<0.0002	<0.001	<0.001	<0.001	0.006	0.203	0.001	0.0045	<0.001	<0.002	<0.005	0.0186	<0.001	0.001	4.3
MB-L	<0.0002	<0.001	<0.001	0.001	0.007	1.150	0.001	0.0170	<0.001	<0.002	<0.005	0.0268	0.001	0.005	5.4
MB-M	<0.0002	<0.001	<0.001	0.001	0.008	1.140	0.002	0.0141	<0.001	0.002	<0.005	0.0557	0.001	0.003	15.3
MB-N	<0.0002	<0.001	<0.001	0.001	0.004	1.150	0.004	0.0169	<0.001	0.002	<0.005	0.0104	<0.001	0.004	4.3
MB-O	<0.0002	0.002	0.002	0.001	0.004	7.200	0.011	0.1190	<0.001	0.006	<0.005	0.0257	0.001	0.007	6.9
MB-P	<0.0002	<0.001	<0.001	<0.001	0.004	0.174	0.004	0.0014	<0.001	<0.002	<0.005	0.0262	<0.001	0.001	5.7
MB-Q	<0.0002	<0.001	<0.001	<0.001	0.007	0.249	0.003	0.0044	<0.001	<0.002	<0.005	0.0273	<0.001	0.001	6.6

Appendix 2. Continued.

Site	Be mg L^{-1}	Cd mg L^{-1}	Co mg L^{-1}	Cr mg L^{-1}	Cu mg L^{-1}	Fe mg L^{-1}	Li mg L^{-1}	Mn mg L^{-1}	Mo mg L^{-1}	Ni mg L^{-1}	Pb mg L^{-1}	Sr mg L^{-1}	V mg L^{-1}	Zn mg L^{-1}	Ca mg L^{-1}
MB-R	<0.0002	<0.001	<0.001	<0.001	0.008	0.130	0.004	0.0053	<0.001	<0.002	<0.005	0.0227	<0.001	0.001	5.1
MB-S	<0.0002	<0.001	<0.001	<0.001	0.004	0.216	0.001	0.0030	<0.001	<0.002	<0.005	0.0204	<0.001	0.002	6.6
MB-T	<0.0002	<0.001	<0.001	0.001	0.005	0.236	0.001	0.0038	<0.001	0.004	<0.005	0.0093	0.001	0.012	2.6
MB-U	<0.0002	<0.001	0.001	0.001	0.005	0.858	0.010	0.0105	<0.001	0.002	<0.005	0.0864	0.001	0.003	24.9
MB-V	<0.0002	<0.001	<0.001	0.001	0.011	0.150	0.012	0.0118	<0.001	<0.002	<0.005	0.1160	<0.001	0.001	29.3
MB-W	<0.0002	<0.001	<0.001	<0.001	0.004	0.519	0.003	0.0175	<0.001	<0.002	<0.005	0.0901	<0.001	0.002	26.7
MB-X	<0.0002	<0.001	<0.001	<0.001	0.002	0.255	0.002	0.0030	<0.001	<0.002	<0.005	0.0400	<0.001	<0.001	17.7
MB-Y	<0.0002	<0.001	<0.001	<0.001	0.005	0.234	0.002	0.0018	<0.001	<0.002	<0.005	0.0404	<0.001	0.001	17.1
MB-Z	<0.0002	<0.001	<0.001	<0.001	0.005	0.144	0.001	0.0026	<0.001	<0.002	<0.005	0.0278	<0.001	0.001	14.5
MB-AA	<0.0002	<0.001	<0.001	<0.001	0.008	0.125	0.002	0.0011	<0.001	<0.002	<0.005	0.0559	<0.001	0.001	21.8
MB-AB	<0.0002	<0.001	<0.001	<0.001	0.005	0.267	0.004	0.0050	<0.001	<0.002	<0.005	0.0253	<0.001	0.001	5.7
MB-AC	<0.0002	<0.001	<0.001	<0.001	0.003	0.090	0.002	0.0031	<0.001	<0.002	<0.005	0.0155	<0.001	0.001	3.2
MB-AD	<0.0002	<0.001	<0.001	<0.001	0.004	0.083	0.001	0.0034	<0.001	<0.002	<0.005	0.0180	<0.001	0.001	4.4
MB-AE	<0.0002	<0.001	<0.001	<0.001	0.006	0.402	0.001	0.0114	<0.001	<0.002	<0.005	0.0152	<0.001	0.002	3.4
MB-AF	<0.0002	0.001	0.002	0.003	0.005	4.900	0.005	0.1130	<0.001	0.005	0.005	0.0398	0.005	0.015	10.1
MB-AG	<0.0002	<0.001	<0.001	<0.001	0.007	0.351	0.009	0.0024	<0.001	0.002	<0.005	0.1040	<0.001	0.002	15.1
MB-AH	<0.0002	<0.001	0.001	<0.001	0.010	0.596	0.007	0.1480	<0.001	0.002	<0.005	0.1280	<0.001	0.003	15.2
Mean	<0.0002	0.001	0.001	0.001	0.006	0.724	0.004	0.0185	<0.001	0.001	<0.001	0.0480	<0.001	0.003	13.2
Median	<0.0002	0.002	0.002	0.001	0.005	0.267	0.003	0.0056	0.001	0.002	0.005	0.0320	0.001	0.002	12.1
Maximum	<0.0002	0.002	0.002	0.003	0.025	7.200	0.012	0.1480	0.001	0.006	0.005	0.1280	0.005	0.015	29.3
Minimum	D.L.	D.L.	D.L.	D.L.	0.002	0.083	0.001	0.0011	D.L.	D.L.	D.L.	0.0090	D.L.	D.L.	2.6

Site	Mg mg L^{-1}	Na mg L^{-1}	K mg L^{-1}	Ag mg L^{-1}	TPU μg L^{-1}	TPF μg L^{-1}	TN mg L^{-1}	Chl-a mg L^{-1}	POC : CHL-a	TN : TP	Cond μS cm^{-1}	T (°C)	pH	Elev (m asl)	Diam (m)	Latitude (°N)	Longitude (°W)
MB-A	2.6	2.6	0.7	<0.001	15.5	11.3	0.795	0.1	8800 : 1	51 : 1	75	7.0	8.2	10	20	76° 13.345′	119° 17.677′
MB-B	2.8	4.3	1.0	0.001	9.8	9.1	0.645	0.4	1380 : 1	66 : 1	109	7.5	8.4	8	20	76° 12.915′	119° 16.920′
MB-C	2.5	6.1	0.3	<0.001	16.1	8.8	0.543	0.5	1300 : 1	34 : 1	78	8.0	8.0	8	15	76° 12.915′	119° 17.267′
MB-D	2.3	4.8	<0.2	<0.001	9.4	6.5	0.390	<0.1	N/A	41 : 1	53	8.0	7.7	8	12	76° 12.912′	119° 17.381′
MB-E	4.3	5.1	0.2	<0.001	11.1	8.5	0.415	0.9	489 : 1	37 : 1	73	8.0	7.6	6	10	76° 13.205′	119° 19.330′
MB-F	2.9	7.4	<0.2	<0.001	12.3	8.4	0.489	0.5	1330 : 1	40 : 1	83	8.0	7.7	5	8	76° 13.351′	119° 19.347′
MB-G	3.1	8.9	0.6	<0.001	11.4	8.2	0.591	N/A	N/A	52 : 1	89	8.0	7.9	5	18	76° 13.330′	119° 19.214′

Appendix 2. Continued.

Site	Mg mg L^{-1}	Na mg L^{-1}	K mg L^{-1}	Ag mg L^{-1}	TPU µg L^{-1}	TPF µg L^{-1}	TN mg L^{-1}	Chl-a mg L^{-1}	POC: CHL-a	TN: TP	Cond µS cm^{-1}	T (°C)	pH	Elev (m asl)	Diam (m)	Latitude (°N)	Longitude (°W)
MB-H	5.8	3.2	1.1	<0.001	17.9	15.8	1.430	0.9	743 : 1	80 : 1	97	6.0	8.1	31	12	76° 14.943′	119° 23.129′
MB-I	11.4	42.5	1.6	<0.001	16.9	12.5	0.725	0.5	1366 : 1	43 : 1	256	6.0	8.5	3	25	76° 14.530′	119° 22.011′
MB-JE	11.9	42.2	1.8	<0.001	13.3	11.3	0.694	N/A	N/A	52 : 1	279	6.0	8.5	3	28	76° 14.530′	119° 22.011′
MB-JW	12.1	43.1	1.8	<0.001	13.9	9.5	0.637	0.5	1450 : 1	46 : 1	278	6.0	8.6	3	35	76° 14.530′	119° 22.011′
MB-K	1.7	3.1	0.3	<0.001	10.6	8.6	0.352	0.4	1448 : 1	33 : 1	32	5.0	7.4	50	250	76° 15.001′	119° 22.517′
MB-L	2.0	5.8	0.7	<0.001	14.6	7.2	0.428	<0.1	N/A	29 : 1	47	6.0	7.5	43	100	76° 14.792′	119° 22.140′
MB-M	6.2	3.4	1.1	<0.001	10.1	7.9	0.401	<0.1	N/A	40 : 1	89	6.0	8.1	13	5	76° 14.367′	119° 17.185′
MB-N	3.1	4.1	1.3	<0.001	14.3	10.4	0.885	<0.1	N/A	62 : 1	47	6.0	7.5	8	12	76° 14.417′	119° 17.105′
MB-O	4.2	4.0	2.4	<0.001	77.9	23.9	1.394	N/A	N/A	18 : 1	60	6.0	7.0	8	3	76° 14.453′	119° 16.970′
MB-P	3.3	3.4	0.2	<0.001	10.4	7.1	0.521	<0.1	N/A	50 : 1	47	6.0	7.6	7	80	76° 14.532′	119° 16.884′
MB-Q	4.5	2.8	1.0	<0.001	11.2	7.4	0.523	<0.1	N/A	47 : 1	53	6.0	7.9	6	10	76° 14.862′	119° 17.098′
MB-R	6.2	4.1	0.9	<0.001	8.1	7.0	0.479	<0.1	N/A	59 : 1	60	6.0	8.0	6	25	76° 14.862′	119° 17.098′
MB-S	2.3	6.0	0.5	<0.001	10.5	6.1	0.355	1.5	507 : 1	34 : 1	57	4.0	7.3	7	30	76° 13.364′	119° 19.283′
MB-T	0.8	1.6	0.2	<0.001	13.8	11.6	0.281	N/A	N/A	20 : 1	25	5.0	7.0	78	10	76° 15.958′	119° 26.147′
MB-U	6.2	6.0	2.2	<0.001	11.2	7.7	0.620	<0.1	N/A	55 : 1	138	5.0	8.3	75	125	76° 16.641′	119° 25.841′
MB-V	7.5	7.0	2.7	<0.001	11.8	5.6	0.813	2.2	211 : 1	69 : 1	156	6.0	8.3	77	140	76° 16.778′	119° 26.115′
MB-W	5.8	1.9	1.5	<0.001	10.5	6.8	1.058	2.4	245 : 1	101 : 1	124	6.0	8.4	62	12	76° 16.704′	119° 25.163′
MB-X	1.1	2.8	<0.2	<0.001	8.5	6.0	0.616	N/A	N/A	72 : 1	75	8.0	7.9	62	30	76° 16.421′	119° 26.098′
MB-Y	1.1	2.6	0.2	<0.001	9.4	7.2	0.612	N/A	N/A	65 : 1	77	7.5	7.7	37	25	76° 16.418′	119° 22.982′
MB-Z	1.0	2.6	0.4	<0.001	14.1	6.4	0.792	0.4	1503 : 1	56 : 1	65	9.0	7.8	36	18	76° 16.181′	119° 21.726′
MB-AA	1.7	3.3	0.7	<0.001	7.1	4.6	0.683	1.4	312 : 1	96 : 1	96	9.5	8.1	33	38	76° 16.130′	119° 21.512′
MB-AB	6.3	4.4	1.0	<0.001	7.2	4.0	0.453	2.2	174 : 1	63 : 1	67	6.0	8.0	32	30	76° 14.760′	119° 17.655′
MB-AC	3.9	2.7	0.8	<0.001	7.8	6.8	0.306	0.9	496 : 1	39 : 1	42	6.0	7.7	3	27	76° 14.820′	119° 17.705′
MB-AD	2.7	2.1	0.6	<0.001	8.5	4.4	0.230	N/A	N/A	27 : 1	38	6.0	7.7	3	75	76° 14.758′	119° 17.734′
MB-AE	1.9	2.4	0.5	<0.001	8.1	4.3	0.206	1.1	423 : 1	25 : 1	29	4.0	7.7	4	30	76° 14.685′	119° 17.737′
MB-AF	5.0	11.7	1.3	<0.001	117.0	9.3	1.031	6.9	1028 : 1	9 : 1	99	5.5	7.8	4	700	76° 14.484′	119° 19.088′
MB-AG	17.3	98.8	3.1	<0.001	11.4	9.1	0.757	<0.1	N/A	66 : 1	510	6.0	7.5	2	60	76° 13.688′	119° 20.500′
MB-AH	22.8	96.2	4.0	<0.001	14.1	6.7	0.422	<0.1	N/A	30 : 1	530	6.0	7.5	2	110	76° 13.665′	119° 20.222′
Mean	5.2	12.9	1.0	<0.001	16.5	8.5	0.616	0.8	663 : 1	49 : 1	115	6.4	7.9	21	61		
Median	3.3	4.1	1.0	0.001	11.2	7.7	0.591	0.9	885 : 1	47 : 1	75	6.0	7.8	8	25		
Maximum	22.8	98.8	4.0	0.001	117.0	23.9	1.430	6.9	8800 : 1	101 : 1	530	9.5	8.6	78	700		
Minimum	0.8	1.6	D.L.	D.L.	7.1	4.0	0.206	0.1	174 : 1	9 : 1	25	4.0	7.0	2	3		