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Research Paper

Impact of Geese on the Limnology of Lakes and Ponds from Bylot Island (Nunavut, Canada)

key words: water birds, arctic, nutrients, multivariate approach, freshwater ecosystems

Abstract

Arctic freshwater ecosystems are important habitats for northern wildlife. Arctic climate impact studies suggest that global change could result in major modifications and perturbations of lakes, ponds and wildlife. Most studies focus either on freshwater ecosystems or on animal populations, but few have investigated the links that exist between them. Animal populations have the potential to alter the nutrient inputs in lakes and ponds via faeces. The present study is the first to reveal the impact of an expanding Greater Snow Goose (*Chen caerulescens atlantica*) population on the limnology of arctic lakes and ponds. A survey of 27 freshwater ecosystems was performed on Bylot Island (Nunavut, Canada) in order to identify patterns in limnological conditions. Using a multivariate statistical approach, our study shows that the presence of birds in the catchment of lakes and ponds has an impact on their nutrient status. Concentrations of major ions that were related to the distance from the sea were the main environmental variable explaining the limnological differences observed among lakes and ponds. Nutrient variables that were mostly related to the presence of Snow Geese played a secondary but significant role. N and P concentrations were different among impacted and non-impacted sites, underlining the impact of animal populations on northern freshwater ecosystems.

1. Introduction

Despite growing interest in the ecology of northern freshwater environments, baseline knowledge on their structure and dynamics is still sparse. The reason for this lack of information is due, in part, to the remoteness and the immensity of polar landscapes. Since the late 1990s, several freshwater surveys have provided baseline information and distributional patterns with emphasis on basic limnological characteristics (*e.g.*, Pienitz *et al.*, 1997a, b; Rühland *et al.*, 1998; Antoniades *et al.*, 2003b), but relatively little is known about the diversity of these ecosystems in their remote environments. In the context of rapid environmental changes (climate change and disturbances), these ecosystems are experiencing important changes, enhancing the importance of getting data on baseline conditions.

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Arctic freshwater ecosystems are important habitats for northern wildlife (Vincent and Pienitz, 1996) and accelerated warming leads to increased stress caused by wildlife migration and expansion in their watershed (Acia, 2004), thus altering inputs of naturally sparse nutrients in tundra lakes and ponds. Moreover, changes in farming practices in southern areas likely contributed to the increase, providing plenty of food to the birds, which would compensate for limitations during the summer season (Gauthier *et al.*, 2004) and thus decrease the mortality rate of young geese (Abraham and Jefferies, 1997).

Animal populations that use freshwater environments such as rivers, lakes or ponds can have a significant impact on their trophic status (*e.g.*, Laing *et al.*, 2002; Gregory-Eaves *et al.*, 2004; Lim *et al.*, 2005; Liu *et al.*, 2006a, b; Van Geesr *et al.*, 2007). This is especially so in the Arctic where inland waters are relatively pristine and thus generally nutrient-poor when compared with sites in the South. Northern lakes are sensitive to small-scale catchment changes, including vegetation, precipitation regimes, hydrology and watershed use (Vincent and Laybourn-Parry, 2008; Smol, 2008), and because remote aquatic environments are logistically difficult to monitor, there is a need for more information from lake surveys to provide the necessary reference data for the assessment and management of the impacts of global climate change on the limnological conditions of northern lakes and ponds.

The scenario of expanding wildlife can already be observed on Bylot Island (Nunavut, Canada), where an increasing Greater Snow Geese (*Chen caerulescens atlantica*) population nests and feeds throughout the arctic summer before migrating south to overwinter along the United States Atlantic coast. The known spring population of the Greater Snow Geese has increased dramatically, from less than 5 000 birds at the beginning of the 20th century (Lemieux, 1959) to more than 1 000 000 in 1999 (Menu *et al.*, 2002). Bylot Island, with its tundra landscape dotted by numerous lakes and ponds, is the main nesting site for the species in the Arctic. Therefore, geese have a significant impact on the region as grazers and fertilizers. It has been proven that the population has presently reached *ca*. 50% of the carrying capacity of terrestrial environments (Massé *et al.*, 2001), but so far the impact on the numerous freshwater ecosystems has not been studied. Since waterfowl-derived nutrients have been shown to contribute up to 30–75% of nutrient loading rates in certain habitats (Manny *et al.*, 1975; Bildstein *et al.*, 1992; Manny *et al.*, 1994; Marion, 1994; Kitchell *et al.*, 1999; Olson *et al.*, 2005), this recent increase could have significant impacts on the trophic status of Bylot Island lakes and ponds. Therefore, this situation gives us a natural simulation of possible future wildlife migration and expansion effect due to global warming.

Moreover, according to general circulation models (GCMs), northern environments will experience accelerated and amplified warming in the next century compared to lower latitudes (Acia, 2004; Rühland *et al.*, 2008). To this day, trends of increasing temperatures and decreasing snow and ice cover have already been observed in both marine and terrestrial ecosystems (Acia, 2004). Arctic lakes and ponds will likely be severely affected by unprecedented physical, chemical and biological changes (Pienitz *et al.*, 2004). Even a small rise in Arctic annual average temperatures has the potential to profoundly change their physical structure (duration and extent of ice cover, thermal stratification, *etc.*), the catchment hydrology and vegetation with increasing external inputs to the lakes, thus enhancing the aquatic productivity of these naturally oligotrophic to ultraoligotrophic systems (Vincent and Laybourn-Parry, 2008). The increased geese impact has the potential to assess the resilience of freshwater ecosystems to increased lake productivity and eutrophication due to climate change.

The objective of this study is to describe the basic physical and chemical characteristics of 27 lakes and ponds located within the Migratory Bird Territory in the south-western part of Bylot Island, and to provide a more holistic picture of the state of present-day knowledge of freshwater conditions. We attempt to identify patterns in limnological conditions and compare the results obtained through our survey with those available from other studies completed across arctic Canada. Finally, we compare the data from "impacted" sites with those of "unimpacted" sites to determine whether the presence/absence of birds in the catchment of these freshwater ecosystems has an impact on their nutrient status and subsequently on their long-term evolution on Bylot Island.

2. Site Location and Description

Bylot Island (72–74° N, 75–82° W) is part of the Canadian Arctic Archipelago (Fig. 1). The island is occupied by the Byam Martin Mountain range which is part of Canada's Arctic Cordillera. These mountains run southeast-northwest and belong to the Davis Highlands physiographic region (BOSTOCK, 1970). Glaciers feed multiple plains on either side of the Cordillera, which are part of the Arctic Lowlands physiographic region (BOSTOCK, 1970). The southern plain is essentially composed of poorly consolidated sandstone and shale (MIALL *et al.*, 1980). The study sites are located on the southwestern plain in glacial valleys C-79 and C-93 (unofficial names) (Fig. 1) (KLASSEN, 1993).

Valley C-79 (Qarlikturvik), which runs southwest-northeast, has a surface area of approximately 65 km^2 and is surrounded by plateaus with an average elevation of 400 m a.s.l. (FORTIER and ALLARD, 2004). It is approximately 15 km long and 4 to 5 km wide. A proglacial river runs through braided channels in the glaciofluvial outwash plain which is mainly composed of eolian deposits (KLASSEN, 1993).

Valley C-93 (Qunguliqtut) also runs southwest-northeast and is about 30 km long and 4 to 5 km wide. Plateaus of an average 400 m a.s.l. surround this valley which is approximately 130 km^2. The plain is composed of a muddy to sandy diamicton (KLASSEN, 1993) and includes a proglacial river.

In both valleys, the landscape is typical of an Arctic tundra region with continuous permafrost, polygon networks in the vicinity of the rivers and an abundance of lakes and ponds which developed after a marine transgression that followed glacial retreat *ca*. 6000 yr BP (ALLARD, 1996). The polygon networks are fed by rain and by meltwater originating from the hills on each side of the plain.

2.1. Regional Climate and Vegetation

Data collected by the meteorological station in Pond Inlet (72°40′ N, 77°58′ W), an Inuit community situated about 85 km to the S-E of our study sites, show that the area is characterized by a polar climate with slight marine influence (ENVIRONMENT CANADA, 2006). Mean annual temperature for 1971–2005 was –15.1 °C, with a January mean temperature of –32,4 °C and a July mean of 6,0 °C (ENVIRONMENT CANADA, 2006). Mean annual precipitation was 190.8 mm for the same period, of which 76% (144.3 mm) consisted of snow (FORTIER and ALLARD, 2004). The region has an average of 400 thawing degree-days and 5800 freezing degree-days. Winter (mean daily temperature under 0) starts at the beginning of September and ends in mid-June, for a total of about 285 days/year (FORTIER and ALLARD, 2004).

The study valleys are mainly occupied by wetlands with graminoid-moss tundra typically dominated by sedges (*e.g.*, *Carex aquatilis* var. *stans*, *Eriophorum scheuchzeri*), grasses (*e.g.*, *Arctagrostis latifolium*, *Dupontia fischeri*, *Pleuropogon sabinei*) and fen mosses (*e.g.*, *Drepanocladus* spp., *Aulocomnium* spp.) (ELLIS and ROCHEFORT, 2004).

3. Materials and Methods

All lakes and ponds were unnamed, and therefore are referred to as sites BI-01 through BI-29 according to the order of sampling in the field. Samples from sites BI-01 to BI-10 were collected between

Figure 1. Map showing the location of the sampling sites on Bylot Island.

14–19 July 2005, lakes BI-11 to BI-19 were sampled between 13–21 August 2005, and sites BI-20 to BI-29 between 26 July and 5 August 2006. Considering that there may be intra- and interannual fluctuations in limnological conditions, we are conscious that our data may not be representative of stable conditions. However, these measured values represent a "snapshot" of typical summer concentrations appropriate for this kind of survey. All limnological field measurements were made from an inflatable boat at one station near the deepest part of the lake or pond. The deepest point was determined by a short helicopter survey over each study site and by exploratory bathymetric mapping using an echosounder. Surface water samples were taken prior to the limnological measurements.

3.1. Physical and Chemical Variables

A Quanta Hydrolab water quality profiler was used to measure water temperature (TEMP), pH (pH), dissolved oxygen content (DO) and specific conductance (COND) at 0.5 m depth in the lake water column. A 22 cm Secchi disk was used to determine water transparency (TRANS) from each lake. At each site, pre-cleaned Nalgene bottles were rinsed three times with lake/pond water prior to water collection. Two litres of water were sampled at 0.5 m depth and were filtered in the field. For total phosphorus and total nitrogen analyses, water was filtered using 0.45 µm cellulose acetate filters. Total phosphorus (TP) samples, both filtered (TP-F) and unfiltered (TP-U), were acidified by adding 1 ml of 30% H_2SO_4. Chlorophyll-*a* samples were obtained by filtering 1 L of lake water on 47 mm diameter GF/C filter paper. These filters were folded, placed in plastic Petri dishes and wrapped in aluminum foil. All samples were kept cold and in the dark prior to shipping to the National Water Research Institute (NWRI) in Burlington, Ontario. At NWRI, analyses were performed for major ions and nutrients (ammonia [NH_3], calcium [Ca], chloride [Cl], dissolved silica [SiO_2], nitrate + nitrite [$NO_3 + NO_2$], magnesium [Mg], nitrite [NO_2], potassium [K], sodium [Na], sulphate [SO_4]), phosphorus (total phosphorus [TP], soluble reactive phosphate-phosphorus [SRP]), nitrogen (total nitrogen [TN], total Kjeldahl nitrogen [TKN]), carbon (dissolved inorganic carbon [DIC], dissolved organic carbon [DOC] and chlorophyll-*a* (chlorophyll-*a* uncorrected [CHLA] and corrected [CHLA-COR] for pheophytin) according to standard protocols of the National Laboratory for Environmental Testing (NLET) (Environment Canada, 1994).

Figure 2. Example of a non-impacted lake (Lake BI-26).

Figure 3. Example of an impacted lake (Lake BI-24).

Figure 4. Close-up view of the shoreline of an impacted lake (Lake BI-24).

Analyses were both performed on filtered (-F) and unfiltered (-U) samples. Two bottles were broken during transportation. Therefore, those 2 sites (BI-12 and BI-15) will not be considered due to lack of data.

Ten nitrogen variables were measured at each site, including $NO_3 + NO_2$-F, $NO_3 + NO_2$-U, NH_3-F, NH_3-U, NO_2-F, NO_2-U, TKN-F, TKN-U, TN-F and TN-U. Concentrations of $NO_3 + NO_2$-F, $NO_3 + NO_2$-U, NH_3-U, NO_2-U, TKN-U, TN-F and TN-U were not available and/or below detection limit in more than half the sites (Table 1). Because TN values were not available for the majority of sites, we used the TKN + NO_3 + NO_2 equation to calculate TN concentrations for all other sites. Filtered values were used, except where lack of data obliged us to use the non-filtered data (lake BI-11, BI-13, BI-14, BI-17, BI-18 and BI-19).

General lake catchment features like drainage patterns, catchment vegetation and presence/absence of geese feces (GEESE) were also taken into consideration (Table 2). Presence or absence of geese was determined in the field (survey of the shore) and based on multi-year survey data of lake utilization by geese (Figs. 2, 3; Gilles Gauthier, pers. comm.). Passage and occupation of lake catchments by geese was determined based on the quantity of feces present along the shorelines (Fig. 4).

3.2. Morphometric and Geographic-Environmental Variables

Coordinates of lakes, including surface area (AREA), perimeter (PERI), latitude (LAT), longitude (LONG) and altitude (ALT) were determined in the field using a handheld global positioning system (GPS). The dataset was completed for missing data and distance from the sea (DIST_SEA) was measured by incorporating a topographic map in a Geographic Information System (ArcGIS). The distance from the sea (DIST_SEA) values were obtained by measuring the distance from the center of the lake to the nearest shore. Maximum depth (DEPTH) represents the maximum depth observed by sounding.

3.3. Statistical Analysis

The dataset was screened so that all variables including values that were below detection limits or not available in more than half of the sites were removed prior to statistical analyses (*i.e.*, CHLA-COR, $NO_3 + NO_2$-F, $NO_3 + NO_2$-U, NH_3-U, NO_2-U, SRP-P-F, SRP-P-U, TKN-U, TN-F, TN-U). For the remaining variables, when the values fell below detection limits, they were replaced with that of one half the detection limits. In all other instances where data was missing, the median was used, as done in previous studies (*e.g.*, Antoniades *et al.*, 2003b). The variables were tested for skewness and

Table 1. Water chemistry data for the Bylot Island study sites.

Lake	NA-U (mg/L)	K-U (mg/L)	CA-U (mg/L)	MG-U (mg/L)	CL-U (mg/L)	SO_4-U (mg/L)	CHLA (µg/L)	CHLA-COR (µg/L)	DOC (mg/L)	DIC (mg/L)	SIO_2-U (mg/L)
BI-01	5.61	1.24	5.59	2.30	10.10	9.92	2.4	1.9	1.1	3.5	0.06
BI-02	4.72	0.58	1.86	1.51	9.37	0.42	<0.1	<0.1	2.2	2.5	0.07
BI-03	2.50	2.19	13.50	5.02	1.93	2.05	<0.1	<0.1	2.7	14.1	0.27
BI-04	3.78	1.21	8.16	3.58	0.99	2.76	<0.1	<0.1	4.4	10.2	0.66
BI-05	4.94	1.77	9.51	4.75	1.57	11.50	1.8	<0.1	5.3	10.3	1.44
BI-06	4.36	1.61	8.45	3.91	1.52	8.73	<0.1	<0.1	3.6	9.6	1.02
BI-07	4.68	0.87	2.92	1.95	6.04	3.65	<0.1	<0.1	3.2	4.2	0.19
BI-08	3.63	0.68	2.38	1.51	5.44	2.24	<0.1	<0.1	5.0	2.7	0.56
BI-09	4.65	0.85	2.82	1.81	7.22	3.21	<0.1	<0.1	4.5	3.0	0.43
BI-10	0.97	0.27	0.99	0.55	1.00	0.60	1.2	N/A	3.2	1.7	1.55
BI-11	2.62	0.62	4.65	1.59	2.34	1.91	N/A	N/A	8.2	4.2	2.32
BI-13	2.81	0.44	2.74	1.79	2.08	0.71	N/A	N/A	15.2	4.3	0.72
BI-14	2.67	0.49	4.27	2.35	2.02	0.63	N/A	N/A	7.3	5.5	0.69
BI-16	2.92	0.45	3.02	1.99	3.16	0.71	N/A	N/A	6.3	4.0	0.59
BI-17	0.57	0.51	1.09	0.46	0.24	0.70	1.9	0.8	2.9	1.9	0.87
BI-18	0.68	0.31	1.19	0.58	0.45	0.77	N/A	N/A	5.1	1.7	0.55
BI-19	0.99	0.25	1.30	0.64	0.30	0.70	N/A	N/A	5.5	1.9	1.07
BI-20	0.76	0.55	1.24	0.53	0.70	0.77	3.1	2.6	1.1	2.0	0.70
BI-21	0.52	0.35	0.73	0.27	0.16	0.25	0.5	<0.1	2.1	1.5	1.39
BI-22	1.10	0.58	1.03	0.56	1.13	0.31	2.8	2.2	3.6	2.1	0.08
BI-23	1.52	0.64	1.69	1.08	3.18	0.66	0.8	0.4	1.5	2.5	0.63
BI-24	2.22	2.08	2.67	2.01	3.72	0.08	3.3	1.5	11.3	4.8	1.90
BI-25	1.90	0.66	4.52	2.27	2.09	0.51	1.0	0.4	5.8	5.6	0.73
BI-26	1.05	0.50	0.99	0.55	1.32	0.38	0.9	0.4	4.3	1.8	0.63
BI-27	6.08	1.53	5.53	3.72	8.00	14.80	0.6	0.3	9.6	4.5	0.04
BI-28	2.78	0.56	17.00	7.24	2.34	1.07	1.9	1.5	7.2	19.5	0.71
BI-29	2.09	0.79	3.72	1.92	2.16	1.88	1.4	0.7	8.4	4.8	0.44
Min	0.52	0.25	0.73	0.27	0.16	0.08	<0.1	<0.1	1.1	1.5	0.04
Max	6.08	2.19	17.00	7.24	10.10	14.80	3.3	2.6	15.2	19.5	2.32
Median	2.62	0.62	2.82	1.81	2.08	0.77	0.9	0.4	4.5	4.0	0.66
Mean	2.71	0.84	4.21	2.09	2.98	2.66	1.1	0.7	5.2	5.0	0.75

N/A = Not available

Table 1. (continued)

Lake	NO_3 + NO_2-F (µg/L)	NO_3+NO_2-U (µg/L)	NH_3-F (µg/L)	NH_3-U (µg/L)	NO_2-F (µg/L)	NO_2-U (µg/L)	TKN-F (mg/L)	TKN-U (mg/L)	TN-F (mg/L)	TN-U (mg/L)	TP-F (µg/L)	TP-U (µg/L)	SRP-F (µg/L)	SRP-U (µg/L)	TN : TP[1,2]
BI-01	13	N/A	15	N/A	2	N/A	0.126	N/A	0.123	N/A	4.0	8.1	1.9	N/A	35
BI-02	9	N/A	12	N/A	2	N/A	0.249	N/A	0.208	N/A	8.0	21.8	1.6	N/A	32
BI-03	9	N/A	16	N/A	2	N/A	0.236	N/A	0.238	N/A	3.3	5.7	1.2	N/A	74
BI-04	9	N/A	13	N/A	2	N/A	0.311	N/A	0.272	N/A	5.8	18.5	1.4	N/A	55
BI-05	7	N/A	9	N/A	2	N/A	0.319	N/A	0.299	N/A	6.4	13.0	1.5	N/A	51
BI-06	7	N/A	9	N/A	2	N/A	0.231	N/A	0.227	N/A	4.8	10.8	1.4	N/A	50
BI-07	8	N/A	10	N/A	2	N/A	0.232	N/A	0.214	N/A	4.1	8.7	1.2	N/A	59
BI-08	8	N/A	9	N/A	2	N/A	0.234	N/A	0.218	N/A	5.4	23.3	1.5	N/A	45
BI-09	8	N/A	9	N/A	2	N/A	0.319	N/A	0.279	N/A	6.8	16.4	1.4	N/A	48
BI-10	9	N/A	14	N/A	2	N/A	0.207	N/A	0.192	N/A	3.9	5.3	1.4	N/A	55
BI-11	N/A	11	N/A	16	N/A	3	N/A	0.301	N/A	0.336	N/A	9.6	N/A	1.1	33[2]
BI-13	N/A	8	N/A	18	N/A	3	N/A	0.383	N/A	0.375	N/A	9.6	N/A	1.5	41[2]
BI-14	N/A	7	N/A	10	N/A	3	N/A	0.429	N/A	0.490	N/A	19.7	N/A	1.3	22[2]
BI-16	N/A	8	N/A	13	N/A	3	N/A	0.393	N/A	0.362	N/A	N/A	N/A	1.4	N/A
BI-17	<5	8	6	12	6	2	0.157	0.188	N/A	0.174	2.9	9.8	N/A	0.7	55
BI-18	N/A	8	N/A	52	N/A	2	N/A	0.265	N/A	0.224	N/A	5.3	N/A	12.6	52[2]
BI-19	N/A	10	N/A	30	N/A	3	N/A	0.332	N/A	0.309	N/A	7.4	N/A	1.5	46[2]
BI-20	<5	N/A	8	N/A	2	N/A	0.103	N/A	N/A	N/A	2.0	N/A	N/A	N/A	53
BI-21	<5	N/A	8	N/A	2	N/A	0.120	N/A	N/A	N/A	2.0	3.9	N/A	N/A	61
BI-22	<5	N/A	17	N/A	2	N/A	0.302	N/A	N/A	N/A	3.5	8.5	N/A	N/A	87
BI-23	<5	N/A	6	N/A	1	N/A	0.093	N/A	N/A	N/A	2.3	6.9	N/A	N/A	42
BI-24	<5	N/A	81	N/A	3	N/A	1.330	N/A	N/A	N/A	21.3	37.4	N/A	N/A	63
BI-25	<5	N/A	8	N/A	3	N/A	0.392	N/A	N/A	N/A	18.1	29.4	N/A	N/A	22
BI-26	<5	N/A	5	N/A	2	N/A	0.277	N/A	N/A	N/A	5.8	12.7	N/A	N/A	48
BI-27	<5	N/A	10	N/A	4	N/A	0.599	N/A	N/A	N/A	13.2	18.1	N/A	N/A	46
BI-28	<5	N/A	15	N/A	2	N/A	0.538	N/A	N/A	N/A	9.5	19.4	N/A	N/A	57
BI-29	<5	N/A	15	N/A	3	N/A	0.529	N/A	N/A	N/A	9.0	16.6	N/A	N/A	59
Min	<5	7	5	10	1	2	0.093	0.188	0.123	0.174	2.0	3.9	1.2	0.7	22
Max	13	11	81	52	6	3	1.330	0.429	0.299	0.490	21.3	37.4	1.9	12.6	87
Median	2.5	8	10	16	2	3	0.249	0.332	0.223	0.336	5.4	10.8	1.4	1.4	50
Mean	5.5	9	13	22	2	3	0.311	0.327	0.227	0.324	6.8	13.8	1.5	2.9	50

N/A = Not available

[1] TN = TKN + NO_3 + NO_2

[2] Filtered values were used where available and unfiltered values were used to complete the dataset (sites BI-11, BI-13, BI-14, BI-17, BI-18 and BI-19)

transformed, when required, to approximate normal distribution. Log (x) transformation was used to normalize depth, transparency, DIC and Ca, log ($x + 1$) was used for altitude, perimeter, distance to sea, pH, Cl, DOC and Mg, while square root transformation was used for area, water temperature, conductivity, chlorophyll-*a*, SO_4, K, Na, SiO_2, NH_3-F, NO_2-F, TKN-F, TP-F and TP-U. The distribution of DO-values was normal and required no transformation. All analyses were performed on the transformed dataset.

Principal components analysis (PCA) was used to explore the patterns of variation in the limnological dataset and to help interpret which processes may govern the observed trends. The ordinations were performed using the program Canoco, version 4.53 (Ter Braak and Smilauer, 1998). Inter-set correlations were also determined to assess the strength of every variable in explaining the variation within the dataset. A Pearson correlation matrix with Bonferroni-adjusted probabilities was developed to identify groups of significantly ($P < 0.05$) and highly significantly ($P < 0.01$) correlated variables (Wilkinson, 1988). The inter-set correlations and the Pearson correlation matrix were obtained using Systat, version 12.00.08. Unpaired t-tests were used to evaluate whether mean values for each variable differed significantly among sites with and without evidence of snow goose activity. The t-test was performed using SigmaStat version 3.5.

4. Results and Discussion

4.1. *Physical Variables*

The lakes and ponds selected for this study reflect the variety of the landscape in the area, with a gradient in depth and temperature from the glaciers (central Bylot Island) to the shores of Navy Board Inlet (Fig. 1). Therefore, distance from sea is highly variable, with a minimum of 0.6 km, a maximum of 28.7 km and an average of 9.1 km (Table 2). Among the 27 sites, two were defined as ponds (*i.e.*, <2 m depth), while the others were defined as lakes (*i.e.*, >2 m depth). Depth ranged from 1.5 m to 21.0 m with an average of 6.2 m, which exceeds mean depths found in comparable studies (Table 2, Antoniades *et al.*, 2003b; Mallory *et al.*, 2006) because our study sites were chosen to minimize the possibility of sediment disturbance associated with wind mixing or ice scour events, for paleolimnological purposes. Sites of varying sizes were sampled, ranging from 1 182 m^2 to 319 159 m^2, with an average of 62 774 m^2 (Table 2). The lake perimeter also varied with a minimum value of 134 m, a maximum at 2 503 m and an average of 921 m (Table 2).

High water transparency (measured as Secchi depth) reflects the naturally oligotrophic state of arctic tundra lakes, with a mean value of 6.2 m and a range from 1.5 m to 10.0 m (Table 2). Observed Secchi depth corresponded to the bottom in seven of the lakes. The mean value for transparency also equals mean depth.

Sites varied in altitude according to their distance from the sea, with a range of 8 m to 350 m above sea level (asl) and a mean of 107 m (Table 2). Altitude was negatively correlated to pH ($P < 0.05$), conductivity ($P < 0.01$), Cl ($P < 0.05$), SO_4 ($P < 0.05$), Ca ($P < 0.05$), Mg ($P < 0.05$), K ($P < 0.05$) and Na ($P < 0.01$), underscoring the importance of sea spray in the ionic composition of lake and pond waters on Bylot Island (see also specific conductivity section below). There was no significant correlation between altitude and temperature, suggesting that the difference between sites is not the result of elevation. In general, the difference between the means of altitude of sites frequented by geese and those not frequented is greater than what could be attributed to random sampling (Table 3). Unexpectedly, distance to sea is not correlated to altitude (Table 4). However, there is a strong negative relation between distance to sea and, Cl ($P < 0.01$) and Na ($P < 0.05$), enhancing the importance of sea spray as mentioned above. According to the t-test, the great difference between the means of distance to sea cannot be explained by ramdom sampling. Therefore, we can say that sites that are more heavily frequented by the avian population are located near the shore at low elevation within the bird's migration pathway. Sites not frequented by geese are

Table 2. Field data collected in 2005-2006 for the 27 lakes and ponds study sites on Bylot Island.

Lake	LAT (°N)	LONG (°W)	ALT (m)	AREA (km^2)	PERI (m)	DIST_SEA (km)	DEPTH (m)	TRANS (m)	pH	TEMP (°C)	COND (µS/cm)	DO (mg/L)	GEESE
BI-01	73.08	80.06	8	0.084491	1163	1.14	2.8	**2.8**	6.7	10.0	86	9.8	1
BI-02	73.03	80.08	10	0.018265	621	0.59	2.1	**2.1**	6.3	6.7	50	11.0	1
BI-03	73.11	79.52	10	0.017916	580	9.68	10.0	**10.0**	7.0	7.5	121	10.4	0
BI-04	73.11	79.52	10	0.030113	737	8.75	4.0	**4.0**	7.0	9.2	87	9.9	0
BI-05	73.12	79.51	10	0.047481	828	10.24	9.5	3.1	7.0	7.4	112	10.1	0
BI-06	73.12	79.51	10	0.070546	1173	9.12	10.5	3.7	6.7	4.1	97	10.0	0
BI-07	73.09	80.01	10	0.048202	840	4.68	3.0	2.8	6.8	7.4	57	10.9	1
BI-08	73.09	79.60	18	0.155844	1714	5.30	4.4	3.0	6.7	6.1	46	10.1	0
BI-09			10	0.058555	904	5.52	3.0	2.4	6.9	7.8	57	9.6	0
BI-10	73.00	79.51	210	0.029680	657	9.61	12.0	3.5	6.1	3.6	15	9.9	0
BI-11			13	0.319159	2503	6.48	9.8	1.8	6.5	9.6	48	8.5	0
BI-13	72.54	79.56	77	0.029983	714	2.94	2.0	1.5	6.3	6.5	40	10.6	0
BI-14	72.56	79.55	130	0.035872	734	2.70	3.3	2.0	6.3	6.1	50	10.7	0
BI-16	72.54	79.56	72	0.207210	1944	2.08	10.0	2.0	6.3	8.6	45	8.6	1
BI-17	73.04	79.25	317	0.048374	857	28.72	7.5	4.0	6.5	6.4	13	9.1	0
BI-18	73.03	79.29	350	0.010334	403	25.79	5.0	4.0	6.5	7.2	15	9.0	0
BI-19	73.01	79.34	250	0.009114	369	20.44	3.0	**3.0**	6.5	6.9	16	8.9	0
BI-20	73.02	79.33	300	0.027071	648	21.62	9.3	4.8	6.4	12.8	14	1.8	0
BI-21	73.02	79.33	300	0.045408	839	21.91	8.5	N/A	6.1	14.6	N/A	N/A	0
BI-22	72.59	79.45	170	0.064329	1041	12.05	3.0	N/A	6.4	15.4	14	1.1	0
BI-23	72.59	79.44	170	0.103553	1306	12.39	21.0	N/A	6.4	11.5	25	1.8	0
BI-24	72.53	79.52	75	0.001182	134	5.73	3.0	N/A	6.6	13.7	40	13.2	1
BI-25	72.53	79.50	55	0.025057	611	5.40	4.4	N/A	6.8	13.3	4	12.9	1
BI-26			160	0.023913	586	5.16	8.0	N/A	6.0	10.8	14	6.0	0
BI-27	73.09	80.03	10	0.022321	568	2.99	1.5	**1.5**	7.0	13.2	85	2.8	1
BI-28	72.51	79.48	70	0.147450	1955	2.51	N/A	N/A	N/A	N/A	N/A	N/A	1
BI-29	73.08	80.02	77	0.013481	440	3.29	1.5	**1.5**	6.6	12.4	41	4.9	1
Min			8	0.001182	134	0.59	1.5	1.5	6.0	3.6	4	1.1	
Max			350	0.319159	2503	28.72	21.0	10.0	7.0	15.4	121	13.2	
Median			72	0.035872	737	5.73	4.4	2.9	6.5	8.2	45	9.8	
Mean			107	0.062774	921	9.14	6.2	3.2	6.6	9.2	48	8.5	

Bold values indicate that water transparency = lake depth
N/A = Not available

Table 3. Student *t*-test results

Variable	Mean 1 (absence of Geese)	Mean 2 (presence of Geese)	*P*
Altitude	140	43	**0.028**
Area	0.0626	0.0631	0.988
Perimeter	922	920	0.992
Dist. sea	12 140	3 163	**0.002**
Depth	7.4	3.6	**0.028**
Transp	3.5	2.4	0.088
pH	6.5	6.6	0.413
Temp	8.5	10.4	0.155
Cond	46	50	0.741
DO	8.2	9.3	0.389
CHLA	1.0	1.3	0.433
Cl	1.9	5.2	**0.001**
SO4	2.16	3.67	0.326
DOC	4.8	6.1	0.295
DIC	4.5	5.9	0.404
Ca	3.71	5.20	0.353
Mg	1.75	2.77	0.124
K	0.77	0.97	0.353
Na	2.23	3.67	**0.026**
SiO2	0.87	0.53	0.129
NH3-F	10	20	0.074
NO_2-F	2	3	0.289
TKN-N-F	0.231	0.472	**0.007**
TP-F	4.6	10.3	**<0.001**
TP-U	11.0	18.9	**0.008**

Bold values indicate that the mean value is statistically significantly different between the two groups (<0.05).

found outside the bird's pathway, which means farther inland, which generally corresponds to higher elevation.

Water temperatures were relatively high, reflecting the general air temperatures that prevailed in the two valleys during the field seasons (Table 2). The mean water temperature was 8.2 °C, with a range from 3.6 °C to 15.4 °C. These temperature measurements should be viewed with caution, especially within the smaller and shallower ponds, as water temperatures have been shown to closely track ambient air temperature (DOUGLAS and SMOL, 1994), often with great diurnal variability.

4.2. Chemical Variables

4.2.1. pH

The mean pH of the lakes and ponds of Bylot Island is 6.6, which is lower than what was found in other arctic lake surveys where more alkaline/basic waters were observed (Table 5, mean of 7.7). It is the lowest average value reported to date in a limnological survey from the Canadian Arctic, with values ranging from acidic to circumneutral (6.0 to 7.0). The mean pH value is just above that of the acceptable limit (6.5), with 10 lakes below the limit as set by the Canadian Water Quality Branch (MCNEELY *et al.*, 1979). The polygon-patterned

Table 4. Pearson correlation matrix for environmental variables (following transformations) measured in the 27 lakes included in the PCA.

	ALT	AREA	PERI	DIST SEA	DEPTH	TRANS	PH	TEMP	COND	DO	CHLA	CL
ALT	1.000											
AREA	–0.227	1.000										
PERI	–0.245	0.928**	1.000									
DIST SEA	0.539	–0.189	–0.178	1.000								
DEPTH	0.232	0.377	0.366	0.495	1.000							
TRANSP	0.070	–0.209	–0.126	0.566	0.522	1.000						
PH	–0.677*	–0.081	–0.068	–0.007	–0.199	0.247	1.000					
TEMP	0.178	–0.092	–0.184	0.051	–0.164	–0.163	–0.005	1.000				
COND	–0.799**	0.140	0.177	–0.356	–0.084	0.051	0.572	–0.207	1.000			
DO	–0.294	–0.087	–0.144	–0.228	–0.095	0.099	0.173	–0.469	0.230	1.000		
CHLA	0.527	–0.072	–0.195	0.149	0.013	–0.079	–0.274	0.427	–0.423	–0.290	1.000	
CL	–0.699*	0.201	0.159	–0.796**	–0.423	–0.399	0.292	0.015	0.427	0.099	–0.264	1.000
SO_4	–0.703*	0.122	0.198	–0.215	–0.139	–0.082	0.658	–0.135	0.711**	–0.053	–0.197	0.418
DOC	–0.053	–0.028	–0.191	–0.283	–0.442	–0.546	0.099	–0.020	0.040	0.246	0.059	0.044
DIC	–0.578	0.134	0.157	–0.350	–0.052	0.123	0.607	–0.133	0.655	0.322	–0.164	0.198
CA	–0.703*	0.217	0.234	–0.435	–0.101	0.058	0.682*	–0.152	0.728**	0.299	–0.201	0.351
MG	–0.700*	0.148	0.175	–0.491	–0.155	0.012	0.659	–0.156	0.736**	0.303	–0.224	0.412
K	–0.681*	–0.151	–0.204	–0.179	–0.066	0.258	0.734**	0.112	0.734**	0.149	–0.107	0.381
NA	–0.918**	0.203	0.229	–0.701*	–0.383	–0.307	0.584	–0.195	0.769**	0.246	–0.407	–0.807**
SiO_2	0.296	0.146	–0.046	0.413	0.499	0.061	–0.195	–0.145	–0.166	0.322	0.212	–0.523
NH_3-F	–0.058	–0.302	–0.543	–0.161	–0.280	0.032	0.121	0.233	0.116	0.281	0.353	0.180
NO_2-F	0.081	–0.253	–0.285	0.097	–0.305	–0.084	0.217	0.100	–0.140	0.077	0.237	–0.092
TKN-N-F	–0.155	–0.302	–0.508	–0.295	–0.479	–0.258	0.278	0.275	0.098	0.222	0.223	0.233
TP-F	–0.235	–0.273	–0.438	–0.428	–0.497	–0.351	0.316	0.247	–0.005	0.344	0.124	0.355
TP-U	–0.287	–0.134	–0.249	–0.479	–0.448	–0.294	0.287	0.184	0.035	0.297	0.038	0.422

Table 4. (continued)

	SO_4	DOC	DIC	CA	MG	K	NA	SiO_2	NH_3-F	NO_2-F	TKN-N-F	TP-F	TP-U
ALT													
AREA													
PERI													
DIST SEA													
DEPTH													
TRANSP													
PH													
TEMP													
COND													
DO													
CHLA													
CL													
SO_4	1.000												
DOC	–0.014	1.000											
DIC	0.408	0.328	1.000										
CA	0.569	0.279	0.961**	1.000									
MG	0.563	0.321	0.958**	0.977**	1.000								
K	0.603	0.061	0.640	0.663*	0.679*	1.000							
NA	0.737**	0.172	0.558	0.687*	0.730**	0.594	1.000						
SiO_2	–0.273	0.268	0.012	–0.080	–0.133	–0.112	–0.382	1.000					
NH_3-F	–0.161	0.317	0.209	0.137	0.184	0.460	0.073	0.185	1.000				
NO_2-F	0.101	0.250	–0.041	–0.038	–0.033	0.133	–0.081	–0.025	0.119	1.000			
TKN-N-F	0.015	0.692*	0.380	0.313	0.397	0.443	0.225	0.121	0.768**	0.340	1.000		
TP-F	0.056	0.640	0.344	0.336	0.405	0.342	0.315	0.056	0.553	0.349	0.879**	1.000	
TP-U	–0.013	0.456	0.351	0.328	0.395	0.327	0.381	–0.002	0.453	0.286	0.711**	0.824**	1.000

Note: Significant correlations based on Bonferroni-adjusted probabilities: * $p < 0.05$; ** $p < 0.01$.

Table 5. Mean selected water chemistry characteristics as recently reported from Arctic Canada (modified from Mallory *et al.*, 2006).

Location	*n*	Area (ha)	Depth (m)	pH	Cond (µS/cm)	Ca (mg/L)	Na (mg/L)	Cl (mg/L)	DOC (mg/L)	DIC (mg/L)
Across Nunavut[1]	204	N/A	N/A	7.7	293	25.4	25.4	28.0	3.9	21.7
Axel Heiberg Island[2]	38	N/A	N/A	7.9	373	25.6	52.9	86.0	5.1	13.3
Banks Island[3]	46	N/A	N/A	8.1	180	19.0	15.3	28.8	6.1	17.8
Bathurst Island[4]	38	N/A	N/A	8.3	160	30.8	3.1	5.6	4.1	20.1
Central Nunavut[5]	56	9.0	4.6	7.2	69	6.8	2.6	3.1	29.9	6.5
Northwest Territories[6]	13	252.4	8.0	7.6	9	0.7	0.4	0.6	2.5	0.3
Devon Island[7]	22	N/A	N/A	8.3	97	21.6	1.7	4.0	2.2	16.7
Ellef Rignes Island[8]	25	N/A	1.0	6.8	405	49.0	71.6	47.4	2.1	6.2
Ellesmere Island[9]	30	N/A	N/A	8.4	331	39.1	29.5	52.0	2.7	28.6
Prince Patrick Island[9]	35	N/A	N/A	7.9	115	13.2	12.9	25.0	6.7	9.4
Southampton Island[10]	32	6.0	2.0	7.9	272	31.5	22.0	45.5	6.2	19.8
Yukon[11]	24	99.6	N/A	7.9	131	19.9	7.0	12.2	9.4	14.3
Victoria Island[12]	34	N/A	N/A	7.7	96	22.2	0.4	1.0	1.5	18.3
Bylot Island[13]	27	6.3	6.2	6.6	48	4.2	2.7	3.0	5.2	5.0
Min	13	6	1	6.6	9	0.7	0.4	0.6	1.5	0.3
Max	204	252	8.0	8.4	405	49.0	71.6	86.0	29.9	28.6
Mean	45	N/A	N/A	7.7	184	22.1	17.7	24.4	6.3	14.1

TP values are for filtered analyses, except for Rühland *et al.*, 2003.
1 – Hamilton *et al.*, 2001; 2 – Michelutti *et al.*, 2002a; 3 – Lim *et al.*, 2005; 4 – Lim *et al.*, 2001; 5 – Rühland *et al.*, 2003; 6 – Pienitz *et al.*, 1997b (only arctic tundra sites); 7 – Lim and Douglas, 2003; 8 – Antoniades *et al.*, 2003b; 9 – Antoniades *et al.*, 2003a; 10 – Mallory *et al.*, 2006; 11 – Pienitz *et al.*, 1997a (only arctic tundra sites); 12 – Michelutti *et al.*, 2002b; 13 – this study.
N/A = Not available

Table 5. (continued)

Location	SO_4 (mg/L)	Mg (mg/L)	K (mg/L)	NH_3 (mg/L)	SiO_2 (mg/L)	CHLA-U (µg/L)	TKN (µg/L)	TN-U (µg/L)	TP-F (µg/L)
Across Nunavut[1]	29.9	8.6	2.4	0.008	1.1	0.6	279	344	12.0
Axel Heiberg Island[2]	54.2	13.7	4.6	N/A	1.7	0.9	N/A	383	5.1
Banks Island[3]	14.8	12.4	1.4	N/A	1.3	1.6	435	499	8.6
Bathurst Island[4]	6.3	5.6	0.4	0.006	0.8	0.8	334	577	6.1
Central Nunavut[5]	3.4	N/A	1.7	N/A	0.7	2.5	605	601	12.1[a]
Northwest Territories[6]	0.9	N/A	0.4	0.008	0.2	1.0	116	197	4.1
Devon Island[7]	5.0	6.1	N/A	N/A	0.6	0.8	127	148	4.1
Ellef Rignes Island[8]	303.2	35.6	4.3	0.016	1.4	1.4	148	295	6.1
Ellesmere Island[9]	13.4	11.8	1.6	0.026	1.2	1.1	344	465	4.5
Prince Patrick Island[9]	7.7	5.2	1.0	0.035	0.4	0.8	515	616	8.5
Southampton Island[10]	9.3	7.5	1.5	N/A	1.1	N/A	N/A	716	25.2[b]
Yukon[11]	6.8	N/A	1.3	0.019	0.7	1.4	350	435	6.6
Victoria Island[12]	2.7	6.1	0.2	0.020	1.2	0.4	152	192	1.4
Bylot Island[13]	2.7	2.1	0.8	0.013	0.8	1.1	311	324	6.8
Min	0.9	2.1	0.2	0.006	0.2	0.4	116	148	1.4
Max	303.2	35.6	4.6	0.035	1.7	2.5	605	716	25.2
Mean	32.9	10.4	1.7	0.017	0.9	1.1	310	414	6.5[c]

1 – Hamilton *et al.*, 2001; 2 – Michelutti *et al.*, 2002a; 3 – Lim *et al.*, 2005; 4 – Lim *et al.*, 2001; 5 – Rühland *et al.*, 2003; 6 – Pienitz *et al.*, 1997b; 7 – Lim and Douglas, 2003 ; 8 – Antoniades *et al.*, 2003b; 9 – Antoniades *et al.*, 2003a; 10 – Mallory *et al.*, 2006; 11 – Pienitz *et al.*, 1997a; 12 – Michelutti *et al.*, 2002b; 13 – this study.
a Unfiltered TP value
b Includes one valid outlier; mean 4.6 µg/L if excluded
c Mean without outlier value described in b (mean of 4.6 µg/L was used)
N/A = Not available

tundra that prevails in valley 1 and 2 is suitable for the development of ombrotrophic bogs which are characterized by low pH ranging between 4 and 5 (ELLIS and ROCHEFORT, 2004). These acidic soils in the watershed in lakes and ponds drain into the freshwater ecosystems, thus having an important impact on the lake chemistry. pH was also negatively correlated with altitude ($P < 0.05$) and positively correlated with Ca ($P < 0.05$) and K ($P < 0.01$) concentrations.

4.2.2. Dissolved Oxygen

DO concentrations in epilimnetic waters were generally high, with a few exceptions. The mean value was 8.5 mg/L with a minimum of 1.1 mg/L and a maximum of 13.2 mg/L. Concentrations varied less in valley C-79 (from 9.6 to 11 mg/L, mean = 10.2 mg/L) relative to valley C-93 (from 1.1 to 13.2 mg/L, mean = 7.3 mg/L). There was no evidence for anoxia based on DO profiling throughout the water column in any of our study sites.

4.2.3. Specific Conductivity

The specific conductivity values were all low, with a mean (48 µS/cm) which is outside the natural range for surface water bodies (50 to 1500 µS/cm; MCNEELY *et al.*, 1979). There was little variation, with values ranging from 4 to 121 µS/cm. These values are low when compared to standards for Arctic water bodies (Table 5). The mean value was the second lowest recorded in all arctic surveys and was below that for all studies combined (mean = 184 µS/cm, Table 5). Conductivity and elevation were significantly negatively correlated ($P < 0.01$, Table 4), indicating that marine aerosols have an influence on the ionic composition of the water bodies at low altitude. This may also be related to snow accumulation as less snow accumulates at higher altitudes resulting in reduced runoff entering the freshwater ecosystems (MICHELUTTI *et al.*, 2002b). The relatively small difference in altitude between sites may be compensated by the local topography and wind. This could lead to greater snow accumulation at the foothills, whereas higher elevated sites are more exposed to winds that transport the snow away.

4.2.4. Major Ions

All major ion (Na, K, Ca, Mg, Cl and SO_4) concentrations were at the lower end of the natural ranges reported for Canadian inland surface waters (MCNEELY *et al.*, 1979). Na, K, Ca, Cl and SO_4 mean values were also at the lower end of the range when compared to previous studies, with mean Mg values being the lowest recorded to date (Table 5).

As expected, conductivity was positively correlated with SO_4 ($P < 0.01$), Ca ($P < 0.01$), Mg ($P < 0.01$), K ($P < 0.01$) and Na ($P < 0.01$), all of which influence the ionic composition of water and, indeed the conductivity (WETZEL, 2001).

The Na : K ratio was outside the natural limit (between 2–3 : 1) ranging from 1.1 : 1 to 8.1 : 1, and with a mean ratio of 3.5 : 1. This may indicate higher alkali metal concentrations in the water column for some of the lakes (MCNEELY *et al.*, 1979), probably influenced by the proximity to ocean waters.

The *t*-test suggests that average Na and Cl concentrations were different between the group of lakes and ponds with and without Greater Snow Goose influence (Table 3). As seen above, this may be caused by the co-varying effect of proximity to the sea as the migratory pathway used by the birds follows the coastline. Less impacted sites are situated more inland and with limited input of Na and Cl from the sea when compared to the impacted lakes.

Hence, the relationship between Na, Cl and geese can be explained by the proximity of the impacted lakes to the sea, and not by a direct geese impact.

In terms of mean concentrations, major cations were Ca > Na > Mg > K, with values of 4.21, 2.71, 2.09 and 0.84 mg/L, respectively. This differs from the Ca > Mg > Na > K pattern most often observed in the Arctic (Rühland and Smol, 1998; Gregory-Eaves *et al.*, 2000; Lim *et al.*, 2001; Michelutti *et al.*, 2002b), but corresponds to patterns observed on Axel Heiberg Island (Michelutti *et al.*, 2002a) and Southampton Island (Mallory *et al.*, 2006). However, great variability exists between sites. For example, fourteen sites correspond to this pattern, while no site presents the pattern normally found in the Arctic (*i.e.*, Ca > Mg > Na > K). In the other lakes, cation concentrations were Na > Ca > Mg > K for 8 sites, Ca > Na > K > Mg for 4 sites and Na > Ca > K > Mg for 1 site. As proximity to the ocean seems to be an important factor explaining the limnology of the lakes and ponds in our study region, the importance of sea spray could potentially explain the high Na concentrations.

Relative mean concentrations of major anions were CO_3 (DIC) > Cl > SO_4 with values of 5.0, 2.98 and 2.66 mg/L, respectively, which differs from results reported elsewhere in the Arctic (Rühland and Smol, 1998; Gregory-Eaves *et al.*, 2000; Lim *et al.*, 2001; Michelutti *et al.*, 2002a; b). Again, the proximity to the sea could explain the importance of Cl in our data.

4.2.5. Carbon

The mean DIC concentration was 5.0 mg/L, with a range between 1.5 mg/L and 19.5 mg/L. These concentrations are lower than what was reported from comparable arctic surveys with a maximum value up to 28.6 mg/L (Antoniades *et al.*, 2003a) and a mean at 14.1 mg/L (Table 5). DIC was highly correlated with Ca ($P < 0.01$) and Mg ($P < 0.01$). Increased DIC content, caused by more important CO_2 inputs, leads to water acidification. This process affects the $CaCO_3$ in the lake, thus releasing Ca in the water column.

DOC concentrations ranged from 1.1 mg/L to 15.2 mg/L, with a mean of 5.2 mg/L. DOC varied greatly between sites (variance of 10.3), but no clear association with vegetation patterns could be detected. The values are in the same range as those found in other arctic water bodies, but the mean value is lower than observed elsewhere (mean = 6.3 mg/L, Table 5). The presence of geese in the catchment of some of our study sites and the associated relatively lush, nutrient-rich vegetation can explain higher DOC values. DOC is correlated with TKN-N-F ($P < 0.05$) which could be linked to droppings from the avian population, thus enhancing the probability of bird influence on DOC content.

Low DOC concentrations are typical of arctic regions since vegetation cover is sparse in the catchment of arctic lakes (*e.g.*, Pienitz and Smol, 1993). This makes aquatic biota generally more vulnerable to damage caused by incoming UV radiation, because DOC plays a crucial role controlling UV radiation penetration (Vincent and Pienitz, 1996; Laurion *et al.*, 1997).

4.3. Nutrients

4.3.1. Phosphorus

Since Bylot Island supports a large population of Greater Snow Geese which migrate each summer into the sampling area and defecate in water bodies and their watersheds, we expected TP values to be higher than in other Arctic surveys and similar to those reported from Southampton Island (mean = 25.2 μg/L; Mallory *et al.*, 2006). However, a comparatively small range of total phosphorus concentrations was recorded. TP-F concentrations varied from 2.0 to 21.3 μg/L. The mean value for TP-F was 6.8, which is below the range for natural lakes (<10.0 μg/L; McNeely *et al.*, 1979) and would be indicative of oligotrophic conditions (Wetzel, 2001). These concentrations were in the same range as those found in other arctic sites, which showed mean values of 6.5 μg/L (Table 5). The epilimnetic total phosphorus concentrations, TP-U, were slightly higher, varying from 3.9 to 37.4 μg/L. The mean TP-U was 13.8 μg/L, which slightly exceeds the range for natural lakes (<10.0 μg/L; McNeely *et al.*, 1979). These concentrations were much lower than those found in other arctic sites but similar to those found by Hamilton *et al.* (2001) and Michelutti *et al.* (2002b). However, the mean TP-F and TP-U values for the two groups of lakes and ponds in our dataset (based on the presence/absence of birds in the watershed) showed that the difference in the concentrations was statistically significant (Table 3). This suggests that the presence of birds in the vicinity of the water bodies has an impact on their chemistry. Though this impact is presently relatively small, it nevertheless enhances the concentrations in the lakes without yet having a major impact on the trophic state of the systems. This is likely due to the snow geese feeding near or within the watershed of the water bodies, thus having an impact on the nutrient inputs, but not being a major source of inputs originating from outside the watersheds. In the latter case, impacts have been reported to be even more pronounced through external nutrient loading from marine bird populations into the lakes (*e.g.*, Michelutti *et al.*, 2008). It is the short-term impact of birds on these freshwater ecosystems that could explain why concentrations remain relatively low. However, long-term sustained inputs during consecutive summers should eventually result in significant nutrient increases. TP-F and TP-U were strongly correlated ($P < 0.01$) and also with TKN-N-F ($P < 0.01$), enhancing the possibility of a bird-induced influence.

4.3.2. Nitrogen

Total Kjeldahl Nitrogen (TKN-F) was highly variable among sites, with a mean of 311 μg/L. The concentrations in five sites were outside of the natural range (between 100 to 500 μg/L; McNeely *et al.*, 1979), one below and four above. Sites BI-23 and BI-24 had the lowest (93 μg/L) and highest (1330 μg/L) concentrations, respectively. Those values were similar to those reported from other arctic regions (mean = 310 μg/L). TKN-F was positively correlated with DOC ($P < 0.05$), NH_3-F ($P < 0.01$), TP-F ($P < 0.01$) and TP-U ($P < 0.01$) (Table 4). The TKN-F mean value was also statistically different between the groups of lakes with presence/absence of birds (Table 3). Again, bird presence seems to have an impact on the water chemistry, yet this relatively small but statistically significant difference could be explained by the low amount of external materials brought into the ecosystem by the birds and the natural buffering capacity of the lakes.

NH_3-F did not vary greatly among lakes, generally ranging between 5 and 17 μg/L, with a mean of 13 μg/L. However, site BI-24 showed an elevated value of 81 μg/L. All water bodies were below the natural limit of 100 μg/L (McNeely *et al.*, 1979) and within the range of other arctic sites (Table 5), but below their mean value (17 μg/L). NH_3 can be generated through decomposition of organic matter, thus it is interesting to note that the majority of sites with highest NH_3 concentrations (including BI-24) coincided with Greater Snow Geese activity within the catchment of water bodies (Tables 1 and 2). NH_3-F was correlated with TKN-F ($P < 0.01$) (Table 4). NO_2-F concentrations did not vary much either, with values from 1 μg/L to 6 μg/L, and a mean value of 2 μg/L.

4.3.3. Nitrogen and Phosphorus Ratios

Ratios above 17 : 1 usually suggest P-limitation (SAKAMOTO, 1966), while those below 14 : 1 suggest N-limitation (DOWNING and MCCAULEY, 1992). However, it has also been suggested that ratios between 10 : 1 and 20 : 1 reflect limitation by either nutrient (SCHANZ and JUON, 1983). The mean TN : TP ratio of our sites was 50 : 1, with a minimum of 22 : 1 and a maximum of 87 : 1. In all sites, ratios were over 20 : 1, suggesting *P*-limitation, which corresponds to the results of several other arctic surveys (*e.g.*, HAMILTON *et al.*, 2001; LIM *et al.*, 2001; MICHELUTTI *et al.*, 2002a, b).

4.4. Biotic Variables (Chlorophyll-a)

The mean concentrations of CHLAU were 1.1 μg/L. The highest value was 3.3 μg/L, while 7 of the lakes had concentrations that fell below the detection limit of 0.1 μg/L. The site with the highest value (BI-24) coincided with intense utilization of the watershed by geese (Table 2). In general, low CHLA values were expected considering the generally low nutrient levels in these tundra regions, except for lakes impacted by bird activity. However, no clear relationship can be detected between bird presence and CHLA concentrations within our dataset. The mean value of CHLAU for all arctic studies is 1.1 μg/L, suggesting that our sites are within the same range as other arctic freshwater ecosystems (Table 5).

For CHLA-CORR, the mean value was 0.7 μg/L, with a maximum of 3.3 μg/L and nine lakes having concentrations below the detection limit. According to these values, all systems can be considered as oligotrophic or ultra-oligotrophic (WETZEL, 2001).

No significant correlation was found between CHLAU and any other variable, suggesting that phytoplankton productivity was controlled either by variables not measured or, more likely, by a multitude of variables (GREGORY-EAVES *et al.*, 2000; HAMILTON *et al.*, 2001; LIM *et al.*, 2001; MICHELUTTI *et al.*, 2002a, b; ANTONIADES *et al.*, 2003a). It is also possible that the small gradients of TP and TKN reduce the potential to identify strong relationships with our CHLA values.

Moreover, even if TP-F, TP-U and TKN-F values seemed to be influenced by the presence or absence of geese in the watershed, CHLA concentrations did not differ between the two groups as anticipated (Table 3). This highlights the fact that even if the chemistry of lakes is affected, the trophic status remains unaffected. The buffering capacity of lakes coupled with a recent increase in the bird population may explain why the CHLA concentrations are not different among impacted and unimpacted sites. Moreover, it has been suggested that in high latitude lakes, increased nutrient levels do not necessarily influence phytoplankton due to low water temperatures (FLANAGAN *et al.*, 2003), low photosynthetic rates (MARKAGER *et al.*, 1999) and intense grazing by zooplankton in "two-level" food webs (HANSON *et al.*, 1992; VAN GEEST *et al.*, 2007). It has also been suggested that the loading rate is at least as important as the total amount of nutrients added to the system (BUTZLER and CHASE, 2009). A single pulse of nutrient may result in nutrients remaining in the water column for a short period of time before being incorporated into the sediments. A consistent nutrient availability through time would more likely favour algal growth. An important wind event, mixing and resuspending the sediments into the water column could also have an impact on the productivity of lakes (OLSON *et al.*, 2005). Also, benthic organisms may be responsible for most of the primary production in arctic lakes and ponds (WELCH and KALFF, 1974), while our CHLA values reflect chemical concentrations in the water column.

4.5. Multivariate Analysis (PCA)

Principal components analysis (PCA; Fig. 5) was used to explore the primary patterns of water chemistry variation among all sites.

PCA axes 1 and 2 had eigenvalues (λ) of 0.312 and 0.186, respectively, explaining a total of 49.8% of the variation in the dataset. As axes 3 and 4 accounted for smaller portions of the variation ($\lambda = 0.111$ and 0.082, respectively), they were not examined further. Inter-set correlations (Table 6) were calculated to determine which variables were most closely related to the two major axes of variation.

PCA axis 1 was controlled by the conductivity-related variables altitude and alkalinity (DIC) (Fig. 5). The variables with the strongest correlation to axis 1 were, in descending order, Na, Mg, Altitude, Ca, DIC, Conductivity and K (Table 6). These variables, with the exception of DIC, were also all strongly positively correlated ($P < 0.05$; Table 4), while altitude was negatively correlated (Fig. 5).

The second PCA axis was mostly controlled by major nutrients. The variable most strongly correlated with PCA axis 2 was TKN-F, followed by Perimeter and TP-F (Table 6). TKN-F and TP-F were strongly correlated ($P < 0.01$; Table 4).

The results of the PCA confirm patterns observed within the water chemistry data (see above). Lakes with presence of birds in their catchments (crosses; Fig. 5) are located to the left of axis 1, while unimpacted sites (circles) are found on both sides. Indirectly, the first axis is linked to the impact of the ocean. As explained previously, the geese migration

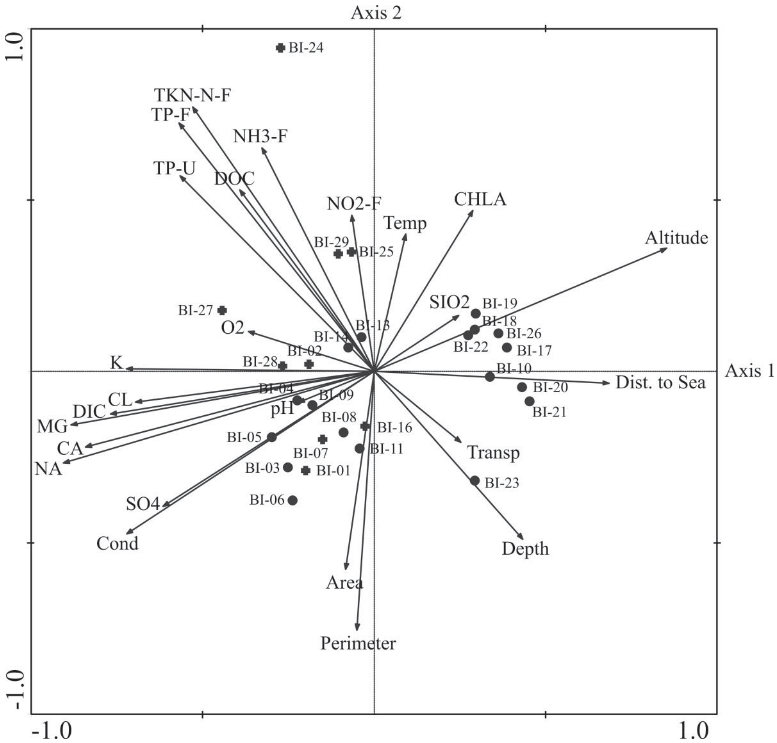

Figure 5. Principal components analysis (PCA) biplot of sites *vs*. environmental variables. ✚ = sites impacted by geese, ● = sites with no sign of goose activity

Table 6. PCA Inter-set correlations

Variable	PCA Axis 1	PCA Axis 2
Altitude	**−0.862**	−0.356
Area	0.058	0.558
Perimeter	0.030	0.739
Dist. To sea	−0.638	0.052
Depth	−0.417	0.499
Transp	−0.183	0.278
pH	0.712	0.112
Temp	−0.082	−0.397
Cond	**0.760**	0.419
DO	0.353	−0.123
CHLA	−0.296	−0.471
Cl	0.672	0.075
SO_4	0.641	0.394
DOC	0.373	−0.547
DIC	**0.781**	0.122
Ca	**0.854**	0.218
Mg	**0.891**	0.152
K	**0.756**	0.000
Na	**0.898**	0.257
SiO_2	−0.250	−0.169
NH_3-F	0.318	−0.656
NO_2-F	0.082	−0.452
TKN-N-F	0.525	**−0.778**
TP-F	0.563	−0.730
TP-U	0.556	−0.576
Eigenvalue	0.312	0.186

Bold values: correlations >75%.

pathway is located near the shore. Therefore, impacted lakes and ponds are situated at low altitude near the coastline where water bodies receive inputs from the sea.

The majority of the impacted lakes are found on the upper side of PCA axis 2, showing that the presence of geese tends to result in higher major nutrient concentrations. Three lakes seem to be more strongly linked to axis 2, which are all impacted sites.

These two major gradients of variation, one related to ionic and another to nutrient concentrations, were also identified in other arctic limnological surveys (Rühland and Smol, 1998; Lim *et al.*, 2001; Michelutti *et al.*, 2002b; Antoniades *et al.*, 2003b).

About half of the variation is unaccounted for by the ordination analysis. Hence, the chemical characteristics of the ponds and lakes in our study area are driven by several variables, including some that were not measured. A more extensive dataset including variables such as water residence time, water body volume, distance to the sea and macrophyte cover would be interesting to analyze in order to verify their impact on the water bodies. Moreover, a multi-year dataset would exclude any stochastic variation, thus probably increasing the explanatory power of the PCA. The variation explained by the ordination axes underscores the importance of proximity to the sea and the bird impact on the water chemistry of Bylot Island lakes and ponds.

5. Conclusions

Despite a large increase in the Greater Snow Goose population over the past 30 years, our study suggests that the population so far has not had a significant impact on lakes and ponds on Bylot Island. Variables associated with ionic concentration explained the main environmental gradient and limnological variation among the study sites, whereas feces-related variables (*i.e.*, P and N) played a subdominant role. Even though the concentrations of N and P are different among impacted and non-impacted sites, the trophic status of these freshwater ecosystems has not been profoundly affected. All sites can still be classified as oligotrophic to ultra-oligotrophic.

This could suggest that the freshwater ecosystems of Bylot Island are still limnologically stable and have a higher buffering capacity than previously thought. As proposed for terrestrial ecosystems, their "carrying capacity" may not yet have been reached (Massé *et al.*, 2001). The short-lived disturbances associated with the seasonal passage of the birds are likely too transitory to perturb the systems outside their range of natural variability (Butzler and Chase, 2009). This suggests that the Greater Snow Goose population will likely not profoundly alter the water quality in Sirmilik National Park unless a continuously growing population is kept in proximity to a single site for an extended period of time, which is a likely scenario according to the Acia (2004) report. Periodic measurements (regular lake and pond monitoring) of the water chemistry would be beneficial to identify the magnitude and duration of short-term and long-term impacts. Nonetheless, any future perturbation of these high-latitude freshwater ecosystems may be related to a combination of impacts from a growing bird population and from rapid warming in the Arctic. Hence, there is a need for establishing baseline limnological data in arctic regions to allow the monitoring of the impacts of future environmental change. In particular, there is a need to generate information on whether the systems are more stable than previously thought, as well as develop a better knowledge of their carrying capacity and impact thresholds.

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