Thawing Permafrost and Temporal Variation in the Electrical Conductivity of Water in Small Tundra Lakes, Mackenzie Delta Region, N.W.T., Canada

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Abstract

Temporal variation in the late summer water quality of 21 small tundra lakes in the Mackenzie Delta region was investigated from 2003 to 2007. Ten lakes were undisturbed, eight had thaw slump scars in their catchments, and three were impacted by highly active thaw slumps. The electrical conductivities (EC) of lake waters from 2003–2007 varied significantly between most lakes. The greatest differences were between the disturbed lakes with elevated EC and undisturbed lakes with relatively low EC. Over the study period, the lowest and highest late-summer lake water EC were recorded in 14 of 21 lakes in association with the wettest preceding year (2006), and driest preceding winter (2003), respectively. This suggests that the chemistry of small tundra lakes is sensitive to variations in the annual water balance. Over time, the greatest relative variation in EC within lakes was associated with undisturbed lakes with unique catchment characteristics and lakes with large active thaw slumps. Intense slumping caused lake water EC to increase, and stabilization was associated with a decreasing trend.

Keywords: climate change; lake chemistry; Mackenzie Delta region; retrogressive thaw slumping; tundra lakes.

Introduction

Impacts to northern aquatic systems are anticipated with climate warming due to the modification of hydrological processes, increases in water temperature and terrestrial biomass, and intensification of disturbance regimes (Rouse et al. 1997, Jorgenson et al. 2006, Lantz & Kokelj, 2008). It is well documented that water in small tundra lakes is generally low in ionic concentration because runoff derived from snowmelt and rainfall is rapidly transported through a thin nutrient-poor active layer (Quinton & Marsh 1999, Kokelj & Burn 2005). Interannual variations in precipitation and catchment runoff should then influence the chemistry of these lakes (Rouse et al. 1997). Furthermore, there is a geochemical contrast between the leached active layer soils and the underlying ion-rich permafrost so that degradation of near-surface permafrost due to -active layer deepening or thaw slumping (Fig. 1) may modify the chemistry of soils, slope runoff, and waters in adjacent lakes and ponds (Kokelj & Lewkowicz 1999, Kokelj et al. 2002, Kokelj et al. 2005, Keller et al. 2007).

The physical and chemical characteristics of small lakes affected by retrogressive thaw slumps and adjacent undisturbed tundra lakes were described by Kokelj et al. (2005), and here we examine temporal variations in the electrical conductivity (EC) of water in these lakes from 2003 to 2007. Since runoff from areas affected by thawing permafrost is solute-rich (Kokelj & Lewkowicz 1999), we hypothesized that the ionic concentrations as indicated by EC would increase with time in lakes affected by active thaw slumps, whereas the stabilization of a slump may cause lake water ionic concentration to stabilize or decrease. It is reported that solute concentrations in lakes with stable thaw slumps are elevated with respect to undisturbed lakes (Kokelj et al. 2005), but relative interannual variability of the two populations may be similar due to the influence of regional climate conditions. To test these hypotheses, the chemical characteristics of water in the ten undisturbed lakes and the 11 lakes affected by recently stabilized and active slumps between Inuvik and Richards Island were evaluated in late summer from 2003 to 2007 (Fig. 2). Temporal patterns in EC are examined with respect to precipitation patterns and disturbance status. The implications of climate-induced permafrost degradation on lake chemistry are discussed and variability in water quality conditions is considered with respect to defining baseline water quality conditions for assessing environmental impacts of northern development.

Environmental Setting

The study lakes are in upland terrain east of the Mackenzie River Delta between Inuvik and the Beaufort Sea coast (Fig. 2). Kokelj et al. (2005) described the study area so that only a brief overview is provided here. The region is characterized by thousands of small lakes and ponds, most of which occur in glaciogenic deposits derived from carbonate and shale bedrock of the Mackenzie Basin (Rampton 1988, Mackay 1992, Burn 2002). As a result, calcium and sulphate are dominant ionic constituents of lake water (Kokelj et al. 2005).

Figure 1. Large, recently stabilized retrogressive thaw slump, Lake 10B. The thaw slump scar is about 7 ha in area. Note active slumps are developing in the scar zone in the upper part of photograph.

Lakes occupy between 10 and 20% of the landscape in the vicinity of the study lakes and median lake areas are on the order of a few hectares (Kokelj et al. 2005). Terrain is underlain by ice-rich permafrost and thaw slumps are common throughout the region (Fig. 1) (Mackay 1963, Rampton 1988). From 8 to 17% of water bodies in the vicinity of the study lakes are influenced by thermokarst slumping (Kokelj et al. 2005).

Study Lakes

Twenty-one study lakes between Inuvik and Richards Island were selected following analysis of aerial photographs and field reconnaissance in 2002 (Fig. 2). Small lakes with first-order catchments were selected (Table 1). Catchment, lake. and thaw slump disturbance areas were estimated by digitizing respective parameters on georeferenced, orthorectified, 1:30,000 scale, colour aerial photographs from 2004. Field reconnaissance and re-correction of aerial photographs has resulted in minor modifications to the aerial estimates of catchment and disturbance areas reported in Kokelj et al. (2005) (Table 1).

The lakes are in shrub and low shrub tundra environments in rolling terrain (Ritchie 1984). The small lakes (1 to 18 ha) are within headwater catchments that range from 7 to 92 ha. Eleven of the catchments (Lakes 1B to 11B) contain retrogressive thaw slumps, which occur on slopes surrounding the study lakes and occupy from 4 to 35% of the respective watershed areas (Fig. 1, Table 1). Lakes 5B, 9B and 10B were impacted by highly active slumping for at least a portion of the five-year study period. Slumping at 5B and 10B stabilized in 2004 and 2003, respectively, with activity at 10B increasing again in 2007. Lake 9B had a large and highly active slump for the first three years of study, but as the slump grew upslope, the headwall diminished and activity decreased in 2006 and 2007. Ten undisturbed lakes (Lakes 1A to 11A) are situated near disturbed catchments (Fig. 2). Time series data were not available for Lake 7A. The southern portion of the study area was burned by wildfire in 1968, affecting catchments 1A, 1B, 2A, 2B, 3A, 3B, 4A, and 4B (Landhäuser & Wein 1993, Mackay 1995). Burned areas are colonized by dense alder and willow bush and active-layeractive layer thicknesses are generally greater than in the nearby tundra (Landhäuser & Wein 1993). Lake depth, determined at the centre of each lake, ranged from 11.3 m at Lake 3B to 1.6 m at Lake 8A, but the deepest parts of

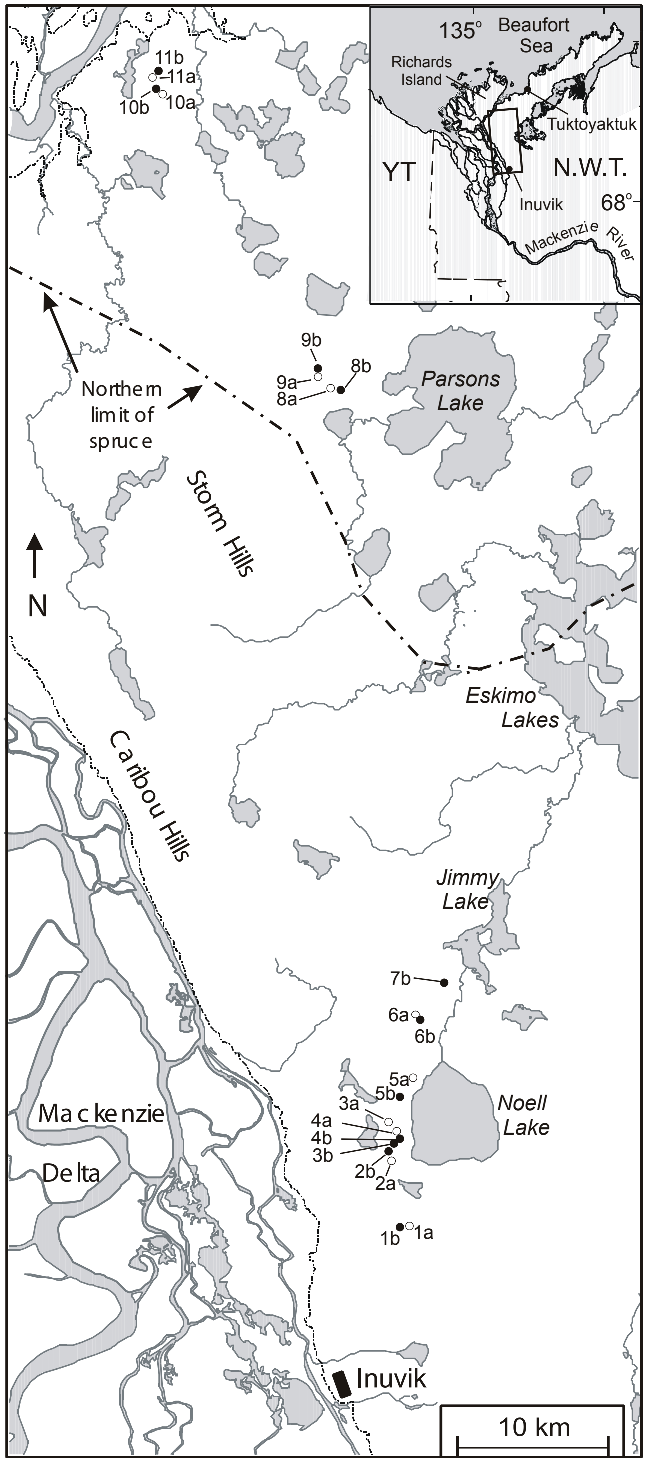

Figure 2. Map of tundra upland study lakes east of Mackenzie Delta, NWT.

small lakes and ponds may be located away from the centre. Maximum late winter ice thickness in 2003 and 2007 did not exceed 1.5 m, and therefore, even the shallowest lakes did not freeze to the bottom. Profiles obtained during late summer surveys suggest that portions of lakes over about 6 m deep may be thermally and chemically stratified in late summer (Kokelj et al. 2005, Fig. 3).

Methods

From 2003 to 2007, during late August or the first week of September, surface water samples were obtained from the centre of each lake using a helicopter equipped with floats. Water samples were collected in 1 L polyethylene bottles rinsed three times with sample site water prior to collection. Sampling depth was about 50 cm. Following collection, sample bottles were placed in a cooler with ice packs and returned to the laboratory for analysis. Water samples were analyzed following standard methods taken from Clesceri et al. (1998). Specific EC and total alkalinity were measured on unfiltered samples in the laboratory using a Titralab radiometer. Anions and cations were evaluated by ion chromatography and hardness was calculated as the sum of inorganic calcium and magnesium using:

$$\text{Hardness (mg/L)} = 2.497 \times \text{Ca(mg/L)} + 4.117 \times \text{Mg(mg/L)}$$

Potential effects of lake and year on EC in undisturbed and disturbed lakes were tested using a randomized complete block design with years as blocks (Sokal & Rohlf 1995) followed by *post hoc* multiple comparisons using Tukey's test to control the experiment-wise Type 1 error rate. As lakes were not replicated, the interaction between year and lake could not be tested. Since multiple comparisons of means among lakes collapse data over years, the assumption of no year-lake interaction must be met if there is a significant effect. Although this assumption could not be tested, time series graphics of EC by lake provide no evidence of lake-year interaction. Residual diagnostics including Shapiro-Wilk's test of normality, visual assessment of leverage, plot residuals versus observed values, and a plot of fitted versus observed values indicate no concerns with assumptions of the statistical model (Sokal & Rohlf 1995). Relative variation in the conductivity of individual lakes over time was described by the coefficient of variation (CV) (Sokal & Rohlf 1995). Relations between water quality parameters and temporal variation in EC between lakes were explored using Spearman's rank correlations (Sokal & Rohlf 1995). Interpretation of the correlation results were regarded as tentative due to the likely low power of the between-lake EC tests because of small sample size and the large number of tests which adversely affect Type 1 error rate. Statistical analyses were conducted in R (R Development Core Team, 2007).

Results

Lake water ionic concentrations, 2003–2007

Electrical conductivity (EC) in late summer surface water samples collected from 2003–2007 was strongly correlated with major ions (Ca, Mg, K, Na, and SO_4; $P < 0.0001$) (also, see Kokelj et al. 2005; Table 3). This indicates that EC is a good descriptor of ionic strength in the water of the study lakes. In the undisturbed lakes, the highest late summer conductivities from 2003–2007 were observed in Lake 3A (160 to 185 µS/cm), which is one of the more southerly catchments and was burned in 1968 (Fig. 3). The lowest conductivities over this period were observed in Lake 9A (38.9 to 44.2 µS/cm), located in hilly upland tundra on the eastern slope of the Storm Hills (Fig. 2). The mean EC of undisturbed lakes from 2003 to 2007 was 104.5, 94.7, 93.2, 87.2, and 96.7 µS/cm, respectively. Analysis of variance shows that EC in undisturbed lakes varies significantly with year and lake, with the largest variation being associated with between lake differences (Table 2a, Fig. 3). Tukey's honest significant difference procedure indicates that, with four exceptions, the disturbed lakes, across years, are significantly different from one another. The *post hoc* testing also showed that in 2003, the mean EC of undisturbed lakes was significantly higher than in 2004 through 2006, but not 2007, and that EC in 2006 was significantly lower than that in 2007.

Table 1. Lake area and catchment characteristics and coefficients of variation (CV) of late summer EC, 2003–2007, for ten undisturbed lakes and 11 lakes affected by retrogressive thaw slumping, tundra uplands, Mackenzie Delta region.

Lake No.	Lake area (ha)	Catchment area (ha)	Slump area (ha)	Slump status Active - A Stable - S	CV
Undisturbed					
1A	1.1	10.9	-	-	0.0737
2A	2.0	17.2	-	-	0.1007
3A	1.3	13.1	-	-	0.0669
4A	1.2	15.5	-	-	0.0979
5A	2.9	20.9	-	-	0.0799
6A	3.6	19.7	-	-	0.1144
8A	2.1	24.4	-	-	0.0947
9A	3.1	29.3	-	-	0.0547
10A	2.3	26.3	-	-	0.0475
11A	9.8	70.1	-	-	0.1034
Disturbed					
1B	18.0	91.6	3.3	A/S	0.0644
2B	4.9	15.9	0.9	S	0.0397
3B	4.0	15.3	3.6	S	0.0499
4B	5.0	17.8	2.5	S	0.0495
5B	2.8	27.7	2.0	A	0.1418
6B	1.2	7.5	0.8	S	0.0349
7B	3.1	34.7	1.0	A/S	0.0600
8B	6.5	32.7	4.0	A/S	0.0482
9B	3.6	7.2	2.5	A	0.0650
10B	11.4	23.3	7.2	A/S	0.0318
11B	10.5	39.4	2.5	A/S	0.0378

Ionic concentrations in lakes affected by retrogressive thaw slumping were always elevated with respect to undisturbed lakes (Figs. 3 & 4) (Kokelj et al. 2005). Lake 10B, had the highest lake water EC of any disturbed lake

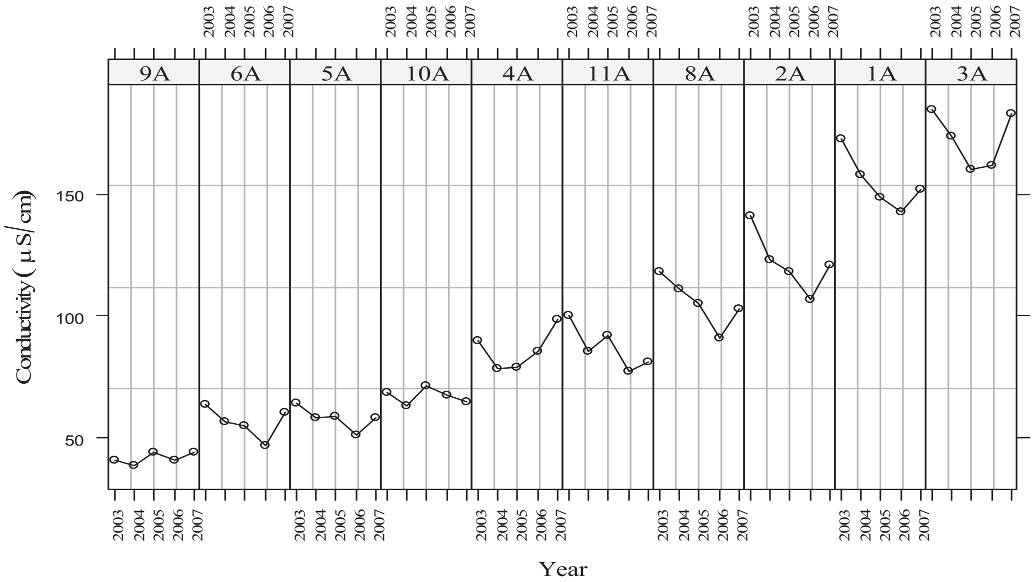

Figure 3. Electrical conductivity of lake water, undisturbed lakes 2003–2007, Mackenzie Delta region.

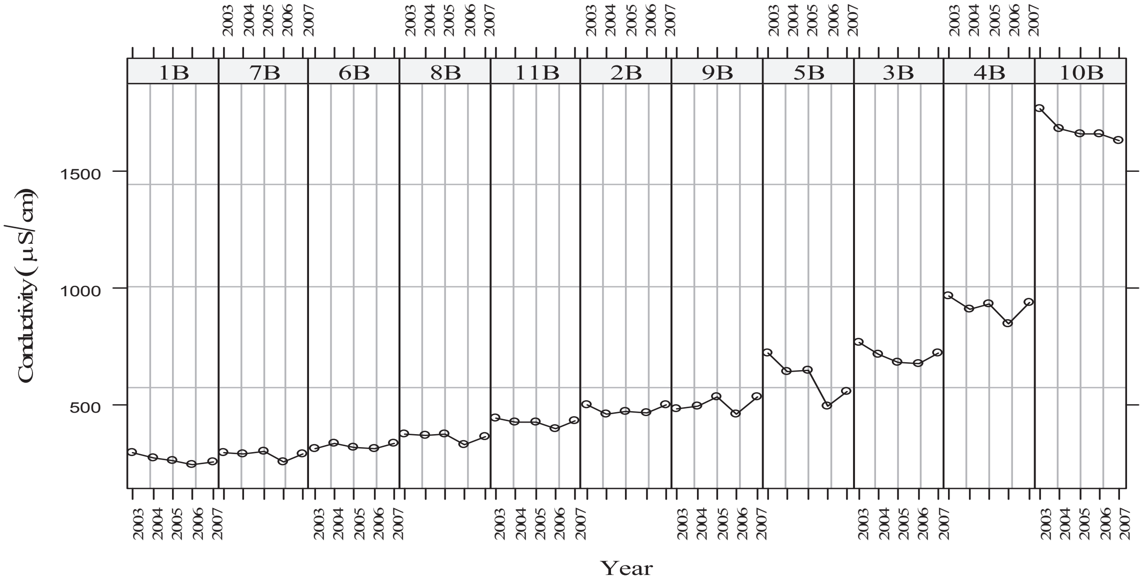

Figure 4. Electrical conductivity of lake water, lakes affected by slumping 2003–2007, Mackenzie Delta region.

and the greatest proportion of catchment area affected by slumping (Fig. 4, Table 1). The most southerly lake, 1B, had the smallest proportion of catchment area influenced by slumping and the lowest EC values. Yearly mean EC of the 11 lakes impacted by slumping from 2003 to 2007 was 631.7, 600.8, 602.5, 561.0, and 597.0 µS/cm, respectively. Table 2b shows that both lake and year are significant factors describing conductivity in the disturbed lakes and as expected the effect of lake (Kokelj et al. 2005) is much larger than that of year. The *post hoc* testing indicated that most lakes are significantly different from one another and that conductivity in 2006 is significantly lower than in 2003 through 2005.

Spearman's rank correlations of late summer lake water EC from 2003 to 2007 indicated significant positive associations between 36 pairs of lakes (Figs. 3, 4). It is also interesting to note the highest late summer EC was measured in 2003 for 14 of the 21 lakes, and the lowest lake water EC was also measured in 14 of 21 lakes in summer 2006 (Figs. 3, 4). Variability in late summer EC over years was described for each of the 21 lakes by calculating their CV (Table 1). Electrical conductivities of lakes 6A and 11A had the highest CV for the undisturbed population. The EC of lakes affected by retrogressive thaw slumping appear to be less variable than the undisturbed lakes, but this is due to the much higher ionic concentrations in disturbed lakes (Figs. 3, 4, Table 1) (Kokelj et al. 2005). Among the disturbed lakes, the highest CV for EC occurred in lakes 5B, 9B, and 1B. The first two lakes were characterized by large areas of highly-active slumping, and Lake 1B is in the largest study catchment and has a relatively large slump that reactivated in 2006 (Table 1).

Table 2. ANOVA table for conductivity in a) undisturbed lakes and b) lakes affected by thaw slumping.

Source	Degrees of freedom	Mean square	F-statistic	P-value
a)Undisturbed lakes				
Lake	9	9488	9.8968	<0.0001
Year	4	391	240.0757	<0.0001
Error	36	40		
b)Disturbed lakes				
Lake	10	836065	874.3637	<0.0002
Year	4	6964	7.2826	<0.0001
Error	40	956		

Discussion

In the study region, tundra lakes are characterized by low ionic concentrations typically less than 100 µS/cm (Pienitz et al. 1997, Kokelj et al. 2005). Local variations in terrain and catchment conditions contribute to between lake differences in the EC of lake water (Figs. 3, 4, Table 2). For example, amongst undisturbed lakes, the highest lake water EC (1A, 2A, 3A) was associated with catchments that were burned in 1968 (Kokelj et al. 2005). Active layer deepening and thawing of near-surface permafrost can release soluble materials which may be transported to the lakes by surface runoff. Amongst the undisturbed lakes, the greatest relative variation in late summer EC (Table 1) was associated with lakes that possess unique catchment characteristics, including the influence of periodic icings and flooding by a nearby stream (6A), and large catchment areas which may experience interannual variation in contributory areas (11A).

End of summer EC from 2003–2007 covaried between many disturbed and undisturbed lakes (Figs. 3, 4). Although we interpret these results cautiously, the correlations suggest the influence of a regional driver. Mean conductivities of both disturbed and undisturbed lakes were notably high in 2003 and low in 2006. The minimum end of summer EC occurred in 14 of 21 lakes in August 2006, which was preceded by the wettest summer and year (Fig. 5). In contrast, EC highs in 14 of 21 individual lakes were recorded in August 2003, which was preceded by the driest winter. These observations suggest that the ionic chemistry of these lakes is sensitive to annual variations in the seasonal water balance.

Regardless, Table 2 emphasizes that between-lake differences have a greater relative influence over EC than does year. Figures 3 and 4 highlight the importance of permafrost degradation on between lake differences in EC as well as on the temporal variations in the chemistry of disturbed lakes. Lakes affected by retrogressive thaw slumping possess elevated ionic concentrations and EC with respect to undisturbed lakes because soluble materials released from thawing permafrost are transported to the lakes by surface runoff (Figs. 3, 4) (Kokelj et al. 2005). The intensity of ionic effects on lake water is positively associated with the proportion of catchment area affected by disturbance (Kokelj et al. 2005). Slumping also appeared to influence temporal variability in lake water EC. The highest coefficients of variation in late summer EC of disturbed lakes were associated with lakes affected by active slumping (Table 1). As hypothesized, intense slumping activity was associated with increasing EC (9B, 2003–2005) because thaw slumping exposes soluble materials that may be transported from disturbed slopes to the lake by surface runoff (Kokelj & Lewkowicz 1999). Stabilization of large active slumps was associated with a decreasing trend in EC, likely because the source of soluble materials is diminished with time (5B, 2005–2007; 10B, 2003–2007) (Fig. 4). It should be pointed out that temporal variation in ionic strength of water in the lakes 9B and 10B did not correlate with any of the other study lakes. In these lakes, effects of slumping subsumed the effects of a regional driver which appears to be influencing the EC of many other study lakes.

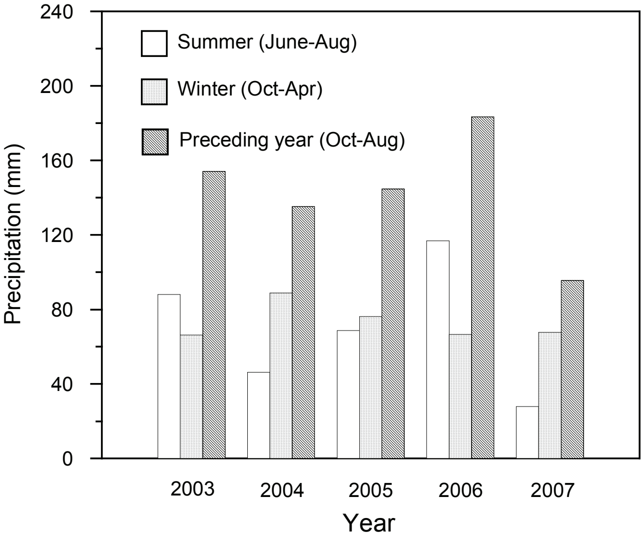

Figure 5. Precipitation for preceding summer, winter and year, Tuktoyaktuk, NWT (Environment Canada 2007).

Permafrost temperatures are rising in response to 20th Century climate warming in Alaska and northwestern Canada and the frequency and magnitude of terrain disturbances associated with thawing permafrost is increasing (Serreze et al. 2000, Jorgenson et al. 2006, Lantz & Kokelj, 2008). An acceleration of thermokarst activity in conjunction with the geochemical response of lakes to slump growth (Fig. 4) suggests that permafrost disturbance could grow in importance as a driver of lake water chemistry.

In addition to anticipating impacts of climate change on tundra lakes, understanding factors that influence temporal variation in water chemistry is critical to establishing baseline water quality conditions for aquatic effects-monitoring programs. These programs are becoming regulatory requirements for assessing impacts and determining effectiveness of mitigations associated with resource development projects in Canada’s North. The study lakes highlight the importance of considering catchment characteristics such as thaw slumping and lake sensitivity to interannual variations in the water balance when selecting reference lakes for the establishment of baseline conditions.

Conclusions

From these results the following conclusions are drawn:

1. Small lakes affected by thermokarst slumping have elevated EC relative to undisturbed lakes.
2. The largest degree of temporal variation in ionic strength of undisturbed tundra lakes occurred in association with unique catchment characteristics.
3. Patterns of variation in late summer EC appeared to be similar amongst many small tundra lakes. End of summer lake water EC may be sensitive to the annual water budget.
4. Amongst the disturbed lakes, those influenced by active slumping showed the greatest degree of variability in lake water EC. Increasing lake water EC was observed in a lake with a large rapidly growing slump and a decline in lake water EC was observed in lakes where large slumps have recently stabilized.

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