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The Influence of Thermokarst Disturbance on the Water Quality of Small Upland Lakes, Mackenzie Delta Region, Northwest Territories, Canada

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ABSTRACT

Chemical data are presented for water from 22 lakes in small upland catchments (<20 ha) between Inuvik and Richards Island, Northwest Territories, Canada. Eleven of the basins appear pristine and 11 are affected by thermokarst slumping. The mean dissolved organic carbon (DOC) concentration of the pristine lakes (16.3 mg/l) is greater than the mean concentration of lakes disturbed by thermokarst slumping (10.5 mg/l). In pristine lakes, mean concentrations of Ca, Mg and SO_4 are 9.6, 3.6 and 11.1 mg/l, but in lakes affected by thermokarst, mean concentrations are 72.6, 26.8 and 208.2 mg/l, respectively. Soluble materials released from degrading permafrost are transported to lakes by surface runoff, elevating concentrations in lake water. The percentage of total basin area influenced by thermokarst is positively associated with ionic concentrations in lake water and inversely related to DOC. Thermokarst occupying as little as 2% of catchment area may modify the chemistry of lake water, and water quality may remain affected for several decades after slump development has ceased. Aerial photographs indicate that 5 to 15% of all lakes and ponds in four 49 km^2 areas between Inuvik and Richards Island are small (median size <2 ha) with catchments affected by thermokarst. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: tundra lakes; water chemistry; permafrost degradation; thermokarst; climate change; western Arctic

INTRODUCTION

The rolling tundra east of the Mackenzie Delta has thousands of small lakes and ponds connected by poorly-defined, ephemeral drainage channels (Rampton, 1988; Mackay, 1992; Burn, 2002). Permafrost is several hundred metres thick and near-surface sediments are ice-rich (Mackay, 1971; Judge, 1973; Rampton, 1988; Taylor *et al.*, 2000). Surface or subsurface runoff through the active layer transports snowmelt and rainfall from slopes to numerous lakes and streams (Quinton and Marsh, 1999). Characteristically low solute concentrations in these aquatic systems can be attributed to minimal interaction between runoff and a shallow, nutrient-poor active layer (Cross, 1980; Pienitz *et al.*, 1997; Kokelj and Burn, 2003).

Massive bodies of tabular ice underlie extensive areas of western Arctic Canada (Mackay, 1963, 1971; Rampton, 1988). This ice and the enclosing sediments may be ion-rich (Mackay, 1979; Kokelj *et al.*, 2002). Entrapment of soluble materials by a rising permafrost table, in conjunction with downward migration of ions along thermally-induced suction gradients may result in solute enrichment of near-surface permafrost (Kokelj and Burn, 2005).

Thermokarst may liberate soluble materials sequestered in permafrost, affecting the chemistry of soils and surface runoff (Leibman and Streletskaya, 1997;

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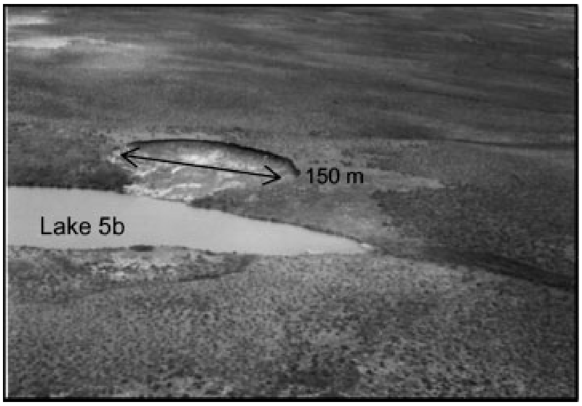

Figure 1 A large active retrogressive thaw slump in catchment of a small tundra lake (lake 5b) near Noell Lake, August 2000.

Kokelj and Lewkowicz, 1999; Kokelj *et al*., 2002). Retrogressive thaw slumps are common along lakeshores and at the coast, where individual disturbances may affect several hectares of terrain (Mackay, 1963; Rampton, 1988; Aylsworth, 2000) (Figure 1). This raises the possibility that thaw slumping may affect the water quality of small tundra lakes. To test this hypothesis, the physical and chemical characteristics of water in 11 pristine and 11 disturbed lakes (<20 ha) between Inuvik and Richards Island were evaluated in late summer 2004 (Figure 2; Table 1). In addition, the chemical composition of slump soils and runoff derived from the thaw slumps were examined. Aerial photographic analysis of catchments, lakes and disturbance in four 49 km^2 study areas east of the Mackenzie Delta place the lake survey results into a broader spatial context. The principal objectives of this paper are: (1) to demonstrate an association between thermokarst disturbance and variation in the chemical composition of waters in tundra lakes; and (2) to examine the regional significance of permafrost degradation on the chemistry of upland lakes in the western Arctic.

STUDY AREA

A total of 22 lakes were surveyed on the uplands east of the Mackenzie Delta between Inuvik and Richards Island (Figure 2). The surficial materials consist of till, ice contact deposits and outwash derived predominantly from carbonate and shale bedrock of the Mackenzie Basin (Rampton, 1988). Polygonal peatlands have developed in low-lying areas (Rampton, 1988). Near-surface sediments are characteristically

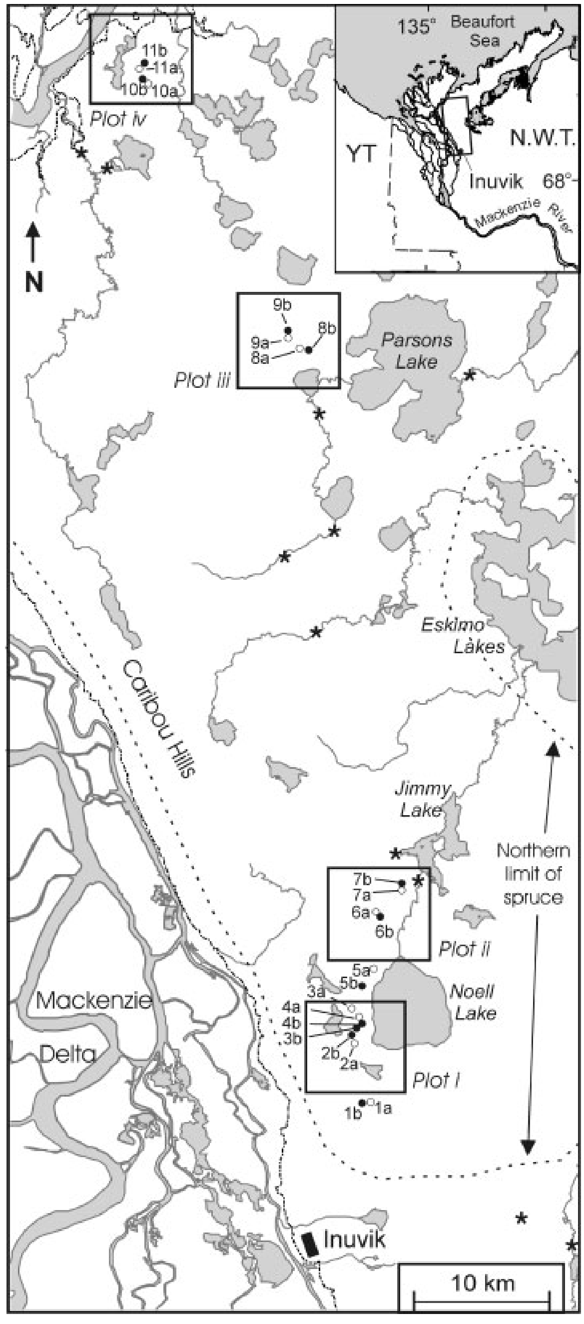

Figure 2 The tundra uplands east of the Mackenzie River Delta. Undisturbed lakes labelled 1a to 11a are indicated with (○), and disturbed lakes labelled 1b to 11b are indicated with (●). The (*) indicates stream sampling locations. The remote sensing plots are outlined and labelled from south (*plot i*) to north (*plot iv*).

Table 1 Location, basin and catchment characteristics of 22 study lakes in upland terrain east of the Mackenzie Delta.

Lake No.	LAT (°N)	LONG (°W)	Z_{max} (m)	Lake area (ha)	Catchment area (ha)	Disturbance area (ha)	Slump (Active—AS; Old—OS)
Undisturbed							
1a	68 27′ 27.5″	133 38′ 24.6″	2.8	0.9	8.0	—	—
2a	68 30′ 09″	133 39′ 54.1″	4.7	1.7	14.8	—	—
3a	68 31′ 14.3″	133 40′ 15.4″	10.3	1.1	16.4	—	—
4a	68 30′ 58.2″	133 39′ 36.1″	1.6	1.2	11.9	—	—
5a	68 33′ 04.2″	133 38′ 24.4″	5.2	2.7	23.7	—	—
6a	68 35′ 26.7″	133 38′ 37.4″	1.6	3.1	37.5	—	—
7a	68 36′ 17.7″	133 35′ 25.8″	1.9	1.1	37.9	—	—
8a	68 57′ 30.3″	133 52′ 10.5″	1.6	2.0	15.3	—	—
9a	68 58′ 8.7″	133 53′ 50.3″	1.9	2.9	28.0	—	—
10a	69 07′ 6.8″	134 10′ 06.9″	2.8	2.2	15.6	—	—
11a	69 07′ 42.1″	134 11′ 26.5″	1.6	9.5	44.6	—	—
Disturbed							
1b	68 27′ 27.6″	133 38′ 24.2″	2.8	17.1	63.8	2.9	OS
2b	68 30′ 26.5″	133 40′ 04.9″	3.4	4.0	14.3	0.8	OS
3b	68 30′ 41.5″	133 39′ 53″	11.3	3.3	17.9	3.3	OS
4b	68 30′ 51.6″	133 39′ 08.1″	8.1	4.4	21.5	1.6	OS
5b	68 32′ 15.1″	133 39′ 28″	5.6	2.5	28.9	1.9	AS
6b	68 35′ 17.5″	133 38′ 16.3″	2.0	0.9	6.1	0.3	OS
7b	68 36′ 31″	133 35′ 13.4″	4.1	2.7	28.8	0.6	AS-OS
8b	68 57′ 23″	133 50′ 24.2″	2.5	5.3	29.9	3.4	AS-OS
9b	68 58′ 13.5″	133 53′ 56.5″	3.0	3.7	8.8	1.7	AS-OS
10b	69 7′ 12.7″	134 10′ 48.6″	5.0	8.0	27.5	7.1	AS-OS
11b	69 08′ 12″	134 08′ 12″	2.8	9.2	27.4	2.5	AS-OS

ice-rich (Mackay, 1971; Pollard and French, 1980; Rampton, 1988). Massive segregated ice, pingo ice, wedge ice and near-surface aggradational ice are common in near-surface ground (Mackay, 1971, 1985; Kokelj and Burn, 2003).

Steep gradients in precipitation amounts and early summer temperatures exist between Inuvik and the Beaufort Sea coast. In winter, mean snowfall at Inuvik is about 160 cm, but less than 100 cm falls near the coast (Dyke, 2000a). In spring and early summer, persistence of sea ice lowers the air temperature near the coast (Burn, 1997). The ecological expression of these environmental gradients is the transition from subarctic boreal forest near Inuvik to shrub tundra less than 30 km north of town (Figure 2) (Ritchie, 1984; Timoney *et al.*, 1993).

An extensive area around Inuvik, and north to Noell Lake, was burned by wildfire in 1968 (Figure 2) (Landhäusser and Wein, 1993). The fire destroyed surface organic materials causing active-layer deepening and thawing of ice-rich permafrost (Heginbottom, 1971; Mackay, 1995). Degradation of near-surface permafrost may also have released water and nutrients to the base of the active layer (Kokelj and Burn, 2003).

STUDY LAKES

Water quality was evaluated in 22 upland lakes along a transect east of the Mackenzie River Delta, from Inuvik to Richards Island (Figure 2; Table 1). The lakes are in shrub tundra and tundra environments with catchment relief of 10 to 30 m. Eleven of the lakes have basins containing retrogressive thaw slumps and 11 are in undisturbed terrain. The study lakes were selected following analysis of aerial photographs and field reconnaissance between 2001 and 2003. The catchments, lakes and disturbances were delineated on 1:30,000 scale aerial photographs and digitized to calculate their areas.

The small study lakes (1 to 17 ha) are within headwater catchments that range from 6 to 64 ha (Table 1). Eleven of the catchments (lakes 1b to 11b) contain retrogressive thaw slumps. A combination of old and active thaw-slump scars, which occur on slopes surrounding the study lakes, occupy from 2 to 26% of the respective watershed areas (Table 1). In the vicinity of each disturbed lake, a small pristine lake was identified for comparison (lakes 1a to 11a; Figure 2).

Lake depth, determined at the centre of each lake, ranged from 11.3 m at Lake 3b to 1.6 m at Lake 8a (Table 1). However, bathymetric surveys of tundra lakes show that, commonly, the deepest parts of small lakes and ponds may be located away from the centre (Marsh and Neumann, 2001). Maximum late-winter ice thicknesses in 2003 and 2004 did not exceed 1.5 m and therefore, even the shallowest lakes did not freeze to the bottom.

The southern portion of the study area was burned by wildfire in 1968, which affected the catchments of lakes 1a, 1b, 2a, 2b, 3a, 3b, 4a and 4b (Landhäusser and Wein, 1993; Mackay, 1995). In the vicinity of Noell Lake, the landscape has revegetated with dense alder and willow bush (Landhäusser and Wein, 1993). Active-layer deepening and thawing of near-surface ground ice following the fire resulted in thaw slumping around lakes 1b, 2b, 3b and 4b. These slumps have now been stable for at least two decades and the scar zones are presently colonized by luxuriant growth of alder and willow. All lakes north of the area burned in 1968 occur in a shrub tundra environment and the disturbed lakes, with the exception of lake 6b, are affected by at least one area of active slumping (Table 1).

METHODOLOGY

In early September 2004, water samples were obtained from a helicopter positioned in the centre of the respective lakes. Lake temperature and specific conductivity profiles were obtained at each lake using a Hydrolab DataSonde 4. Water samples were obtained from a depth of about 30 cm in 1 L polyethylene bottles rinsed three times with sample site water prior to collection. In late summer 2004, samples of surface runoff were collected from thaw slumps and, if possible, from undisturbed slopes. Water samples were also collected from several streams between Inuvik and Richards Island. Following collection, sample bottles were placed in a cooler with ice packs and returned to the laboratory for analysis.

Water samples were analysed following standard methods taken from Clesceri *et al*. (1998). Specific conductivity, total alkalinity, and pH were measured on unfiltered samples in the laboratory using a Titralab radiometer. Apparent colour was determined using a Hellige Aqua Tester. Turbidity in nephelometric units was evaluated with a Hach Model 2100AN turbidity meter. Total dissolved solids (TDS) concentrations were determined by evaporating the filtrate of water samples. Dissolved organic carbon (DOC) was determined with a Shimadzu TOC-5050A carbon analyser. Anions and cations were evaluated by ion chromatography.

In summer 2004, the surface mineral horizon was collected from disturbed and undisturbed terrain in the respective catchments. Samples were placed in a cool, dark place until analysed 1 week after collection. Soil samples were analysed for gravimetric moisture content, pH and water soluble ions following McKeague (1978). Soil pH was determined on saturated paste extractions. Pore water samples extracted from the soil samples were analysed by ion chromatography.

The lake-water quality of undisturbed and disturbed lakes was compared using the *t*-test (Zar, 1999). Correlations between respective water quality parameters for all lakes were tested using Pearson's product-moment correlation (Zar, 1999). To account for the possibility of Type 1 error which may arise from multiple comparisons, Bonferroni adjusted probabilities ($P<0.05$) identified statistically significant differences. To perform the *t*-tests and Pearson's product-moment correlations, most of the lake-water quality parameters were logarithmically transformed so that the data fit the assumptions of parametric testing (Zar, 1999).

Lakes, catchment characteristics and permafrost disturbances were assessed in four 49 km^2 sample areas between the southern end of Noell Lake and Richards Island using 1:30,000 scale aerial photographs taken in summer 2004 (Figure 2). All small first-order catchments and thermokarst disturbances were identified in the four study areas. Lake areas for the respective units were determined using digital data from 1:50,000 scale topographic maps.

RESULTS AND DISCUSSION

Temperature and Specific Conductivity Profiles

In early September 2004, temperature profiles at 2-m depth resolution were obtained from the respective lakes. Surface waters ranged from 7.1 to 9.3°C. There was a northward trend towards colder surface temperatures, but the three coldest lakes (1a, 8a and 11a) were shallow (<3 m), possessing a relatively low heat capacity (Table 1). Lakes greater than 5 m deep (3a, 5a, 3b, 4b, 5b) were thermally stratified at the time of survey (Figure 3A). Thermal stratification was not observed at any of the tundra lakes north of 5a, but the lakes were less than 5 m deep.

Lake-water conductivity profiles indicated that the top 3 to 5 m of lakes were well mixed. Specific conductivity increased with depth in the thermally-stratified lakes (Figure 3B). For example, near-surface

Table 2. Water chemistry data for the undisturbed and disturbed study lakes, uplands east of the Mackenzie Delta, September 2004. A *t*-test was used to compare means amongst the two populations. Note that we report unadjusted *P*-values. STD indicates standard deviation. Key for abbreviated column headings: dissolved organic carbon (DOC), total dissolved solids (TDS) and specific conductivity (Cond).

	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	SO_4 mg/l	Cl mg/l	DOC mg/l	Colour	pH	Turbidity mg/l	TDS mg/l	Cond µS/cm
Undisturbed												
1a	19.9	7.0	2.0	1.3	14.0	1.8	14.0	30.0	7.5	1.6	114.0	158.0
2a	13.1	5.1	2.6	1.7	21.0	1.9	13.2	30.0	7.3	2.6	132.0	123.0
3a	17.7	6.7	3.2	2.4	47.0	2.1	13.0	30.0	7.2	2.0	114.0	174.0
4a	8.0	3.4	1.9	1.5	10.0	1.3	12.9	40.0	7.1	1.4	65.0	78.2
5a	6.5	2.2	1.6	0.9	7.0	1.3	12.7	40.0	6.9	1.4	50.0	58.4
6a	5.4	1.9	2.5	0.9	8.0	1.7	16.0	80.0	6.8	2.7	60.0	56.6
7a	3.4	1.3	1.3	0.7	5.0	0.6	9.8	80.0	6.6	2.5	36.0	35.1
8a	12.6	4.4	5.2	0.9	1.0	8.7	30.0	60.0	7.4	2.8	114.0	111.0
9a	3.5	1.7	2.1	0.5	1.0	3.8	14.5	80.0	6.6	1.7	46.0	38.9
10a	6.2	2.6	3.1	0.8	3.0	4.4	23.4	100.0	6.8	5.7	78.0	63.1
11a	9.1	3.3	3.8	1.0	5.0	6.1	19.3	200.0	7.0	11.0	92.0	85.7
Mean	9.6	3.6	2.7	1.1	11.1	3.1	16.3	70.0	7.0	3.2	81.9	89.3
Median	8.0	3.3	2.5	0.9	7.0	1.9	14.0	60.0	7.0	2.5	78.0	78.2
STD	5.6	2.0	1.1	0.5	13.3	2.5	5.9	49.8	0.3	2.8	33.0	46.7
Maximum	19.9	7.0	5.2	2.4	47.0	8.7	30.0	200.0	7.5	11.0	132.0	174.0
Minimum	3.4	1.3	1.3	0.5	1.0	0.6	9.8	30.0	6.6	1.4	36.0	35.1
Disturbed												
1b	33.5	10.8	4.7	2.0	43.0	2.5	8.8	20.0	8.1	2.2	166.0	274.0
2b	38.6	22.8	21.9	3.2	106.0	4.8	12.3	20.0	8.0	3.2	290.0	463.0
3b	88.1	30.9	11.8	3.4	274.0	3.2	7.2	10.0	7.9	1.2	502.0	715.0
4b	103.0	44.3	24.2	3.7	396.0	3.8	7.8	10.0	7.8	1.4	654.0	910.0
5b	78.5	23.3	16.6	2.6	265.0	2.0	13.0	20.0	7.6	1.9	458.0	643.0
6b	38.4	11.9	14.5	2.2	35.0	5.4	17.2	30.0	7.8	1.8	214.0	338.0
7b	26.8	11.4	13.4	1.9	72.0	3.6	15.8	20.0	7.6	3.5	196.0	294.0
8b	47.2	13.1	6.3	2.1	67.0	10.3	9.0	10.0	8.1	1.2	224.0	369.0
9b	56.9	21.7	9.3	3.8	120.0	11.0	6.8	10.0	8.0	3.9	306.0	494.0
10b	237.0	86.4	34.0	12.0	836.0	15.8	7.5	10.0	8.1	1.4	1430.0	1680.0
11b	50.8	18.6	7.3	4.3	76.0	14.3	10.2	10.0	8.1	1.5	258.0	429.0
Mean	72.6	26.8	14.9	3.7	208.2	7.0	10.5	15.5	7.9	2.1	427.1	600.8
Median	50.8	21.7	13.4	3.2	106.0	4.8	9.0	10.0	8.0	1.8	290.0	463.0
STD	59.6	22.1	8.8	2.9	238.4	5.0	3.6	6.9	0.2	1.0	365.3	407.3
Maximum	237.0	86.4	34.0	12.0	836.0	15.8	17.2	30.0	8.1	3.9	1430.0	1680.0
Minimum	26.8	10.8	4.7	1.9	35.0	2.0	6.8	10.0	7.6	1.2	166.0	274.0
P-values for *t*-test	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P = 0.014$	$P = 0.005$	$P < 0.0001$	$P < 0.0001$	$P = 0.20$	$P < 0.0001$	$P < 0.0001$

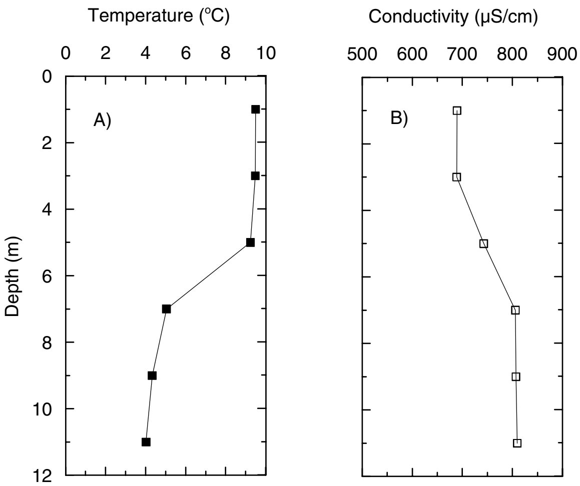

Figure 3. (A) Temperature and (B) conductivity profiles for lake 3b, Mackenzie Delta region.

conductivity of lake 3b was 689 µS/cm. An increase in conductivity was observed between the 3 and 7-m depths with maximum conductivity of 810.0 μS/cm measured at 11-m depth (Figure 3B).

Physical and Chemical Characteristics of Lake-Water Samples

The pH of pristine and disturbed lakes ranged from 6.6 to 7.5 and 7.6 to 8.1, respectively, and the means of the two populations are significantly different (Table 2). The pH measurements in given Table 2 are within the range of values reported by Pienitz *et al*. (1997) for upland lakes in the forest-tundra and tundra environments between Inuvik and Tuktoyaktuk. Lake-water pH was correlated with conductivity and major ions, but was negatively correlated with colour (Table 3).

Specific conductivity was significantly correlated with total dissolved solids and all major ions with the exception of Cl (Table 3). Conductivity was negatively correlated with DOC and colour (Table 3). Specific conductivity of samples from undisturbed lakes ranged from 35 to 174 µS/cm with a mean of 89 µS/cm. Conductivities for pristine lakes are within the range of values reported by Pienitz *et al*. (1997). In contrast, the conductivity of waters from disturbed lakes ranged from 274 to 1680 µS/cm with a mean of 601 µS/cm (Table 2). The ranges of surface water conductivity for pristine and disturbed lakes did not overlap and means of the two populations are significantly different (Table 2).

All major cations measured (Ca, Mg, Na, K) were significantly correlated (Table 3). The relative proportion of cations for undisturbed lakes was Ca > Mg > Na > K with means of 9.6, 3.6, 2.7 and 1.1 mg/l, respectively (Table 2). The relative importance of major cations in disturbed lakes is similar to pristine lakes, but absolute amounts are significantly greater (Table 2). The mean Ca, Mg, Na and K concentrations in lakes with catchments affected by thermokarst were 72.6, 26.8, 14.9 and 3.7 mg/l, respectively (Table 2).

Sulphate was the dominant anion measured (Table 2). This anion is derived from the weathering of the shale component of local till (James, 1979). In undisturbed lakes, concentrations ranged from 1 to 47 mg/l, but in disturbed lakes the range was 35 to 836 mg/l (Table 2). Mean SO_4 concentrations between the two populations were significantly different

Table 3 Pearson's product-moment correlations between different water quality parameters, 22 study lakes, uplands east of the Mackenzie Delta. Bonferroni-corrected *P*-values <0.5 are indicated in bold. Keys for abbreviated column headings: specific conductivity (Cond), total dissolved solids (TDS), dissolved organic carbon (DOC), turbidity (Turb) and colour (Col).

	Cond	TDS	DOC	Turb	Col	pH	Ca	Mg	Na	K	SO_4	Cl
Cond	X											
TDS	**0.982**	X										
DOC	−0.567	−0.524	X									
Turb	−0.335	−0.287	0.495	X								
Col	**−0.862**	**0.800**	**0.745**	0.602	X							
pH	**0.899**	**0.834**	−0.518	−0.322	**−0.853**	X						
Ca	**0.996**	**0.980**	−0.576	−0.358	**−0.864**	**0.907**	X					
Mg	**0.996**	**0.984**	−0.578	−0.332	**−0.861**	**0.890**	**0.990**	X				
Na	**0.909**	**0.920**	−0.329	−0.127	−0.662	**0.747**	**0.880**	**0.904**	X			
K	**0.934**	**0.919**	−0.637	−0.332	**−0.842**	**0.833**	**0.931**	**0.941**	**0.803**	X		
SO_4	**0.926**	**0.896**	**−0.722**	−0.370	**−0.858**	**0.775**	**0.916**	**0.919**	**0.793**	**0.923**	X	
Cl	0.559	0.583	−0.079	0.089	−0.400	0.609	0.563	0.566	0.606	0.526	0.304	X

(Table 2). Absolute amounts of Cl were relatively low, but concentrations increased with proximity to the coast (Pienitz *et al*., 1997) (Table 2). In pristine lakes north of Parsons Lake, Cl was present in greater relative abundance than SO_4 (Table 2).

The dominance of Ca, Mg and SO_4 in lake water can be attributed to runoff over local till derived from the carbonate and shale bedrock of the Mackenzie Basin (Table 2). The strong correlations between individual cations and similarity in the relative abundance of ions amongst pristine and disturbed study lakes reflect the homogeneity of the surficial materials throughout the study region (Tables 2 and 3). Highly significant differences in the mean concentrations of major ions between pristine and disturbed lakes indicate that thermokarst slumping leads to an increase in lake-water ionic concentrations (Table 2).

The water in most pristine lakes was brown in colour, but the water from disturbed lakes was clear (Table 2). Water colour was correlated with turbidity, but suspended sediment concentrations were below detection limits in all lakes except lake 11a. At the time of sampling, slumps were not actively degrading due to cool air temperatures, and therefore elevated suspended sediment concentrations were not detected in lakes affected by thermokarst (Table 2). Data collected in September 2004 indicate that most of the variation in water colour and turbidity can be attributed to inputs of organic compounds from decaying vegetation and leaching of organic soils, rather than from inorganic sediment (Hobbie, 1984).

DOC was positively correlated with colour and turbidity, but was inversely correlated with pH, conductivity and major ions (Table 3). Only the correlations with colour and SO_4 were highly significant (Table 3). Adsorption of DOC to mineral soils exposed by thermokarst may result in low DOC concentrations in surface runoff, and contribute to lower concentrations in disturbed lakes (Table 2) (Moore, 1989; Carey, 2003). In contrast, shallow, organic soils characteristic of undisturbed permafrost basins promote the export of DOC, by runoff, from the terrestrial to the aquatic environment (MacLean *et al*., 1999; Carey, 2003).

The elevated concentrations of dominant ions in undisturbed lakes within the area burned in 1968 (lakes 1a, 2a, 3a and 4a) suggest an association between wildfire and ionic loading of lakes in permafrost terrain. The effects of fire, particularly destruction of organic soils and active-layer deepening, may increase the interaction between runoff and mineral soils, explaining the elevated solute concentrations, relatively clear waters and low DOC concentrations in 'pristine' lakes 1a, 2a, 3a and 4a.

Chemical Composition of Soils and Runoff from Slopes and Disturbed Terrain

Soil and runoff samples from thaw-slump scars were collected and analysed for their chemical composition in order to demonstrate that thermokarst areas are important solute sources in permafrost catchments. In undisturbed terrain, the dominant soil soluble ions were Ca, Mg and SO_4 with mean concentrations of 0.16, 0.13 and 0.13 meq/100 g dry soil, respectively (Figure 4). Soil soluble ion concentrations in active and old slump scars were up to one order of magnitude greater than the concentrations in undisturbed soils (Figure 4) (Kokelj and Lewkowicz, 1999; Kokelj *et al*., 2002). Ionic concentrations in old slump soils were lower than in scar soils of active slumps, suggesting progressive leaching with time (Figure 4). The wide range of soil-soluble ion concentrations in old slumps may reflect the varying age of disturbances that were sampled (Figure 4).

The concentrations of major ions in runoff from undisturbed slopes and in local streams were similar to those of pristine lake waters. Calcium concentrations ranged from 2.9 to 11.7 mg/l and SO_4 concentrations ranged from 1.4 to 17.9 mg/l. Ionic concentrations in runoff from disturbed areas were at least one order of magnitude greater than concentrations in the runoff from undisturbed slopes and stream water (Table 4). For example, the mean Ca and SO_4 concentrations in runoff from thaw slumps were 265.0 and 1234.1 mg/l, respectively (Table 4).

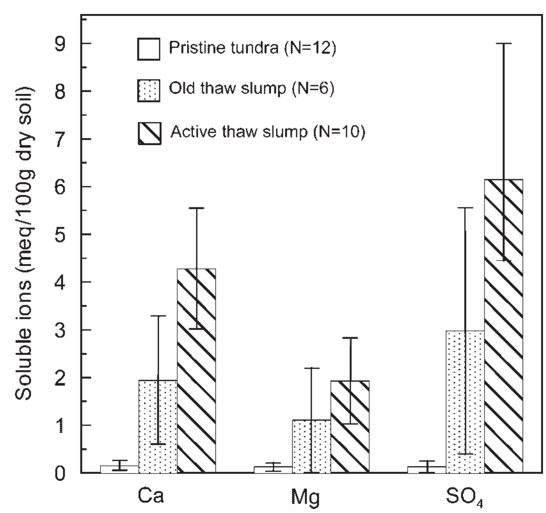

Figure 4 Mean and standard deviation of soil-soluble Ca, Mg and SO_4 concentrations of the top mineral horizon for samples from pristine tundra, old thaw slump disturbances, and active thaw-slump scars.

Table 4 Mean ionic concentrations in surface water from undisturbed slopes, local streams and thaw slump scars, tundra uplands east of the Mackenzie Delta. Standard deviations are in brackets.

	N	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	SO_4 (mg/l)	Cl (mg/l)
Slope runoff-undisturbed	3	3.5 (0.9)	1.5 (0.5)	1.1 (0.5)	0.2 (0.1)	12.3 (5.7)	1.9 (1.5)
Local streams	11	8.4 (2.4)	2.9 (0.7)	2.4 (0.9)	0.7 (0.4)	7.3 (5.0)	2.5 (1.7)
Slope runoff–disturbed	13	265.0 (1083)	88.3 (71.8)	79.8 (121.5)	8.1 (3.6)	1234.1 (692.5)	16.3 (3.6)

These values also exceed the concentrations measured in the disturbed lakes, indicating the effects of dilution by catchment runoff (Table 4) (Kokelj and Lewkowicz, 1999; Lewkowicz and Kokelj, 2002).

Surface runoff removes soluble materials from disturbed areas (Table 4), but the high ionic concentrations in old slump soils indicate that decades are required to reduce concentrations to those observed in mineral soils of undisturbed terrain (Figure 4) (Kokelj and Lewkowicz, 1999; Kokelj *et al*., 2002). Therefore, ionic concentrations in disturbed lakes may remain elevated several decades after a slump becomes inactive (Tables 1 and 2).

Variation in Chemical Characteristics between Lakes influenced by Disturbance

Thermokarst disturbance may affect the chemistry of small tundra lakes, but there is a significant range of ionic and DOC concentrations amongst the disturbed lakes (Table 2). Figure 5 suggests that ionic concentrations in the disturbed lakes are related to the percentage of catchment area influenced by disturbance. Pearson's product-moment correlation indicates a significant positive association between these variables ($r = 0.68$, $N = 11$, $P < 0.05$). The lowest conductivities of 274.0 and 294.0 μS/cm were measured in lakes with less than 5% of watershed area influenced by disturbance, whereas the highest conductivity (1680.0 μS/cm) was measured in a lake with over 25% of total catchment area influenced by disturbance (Figure 5).

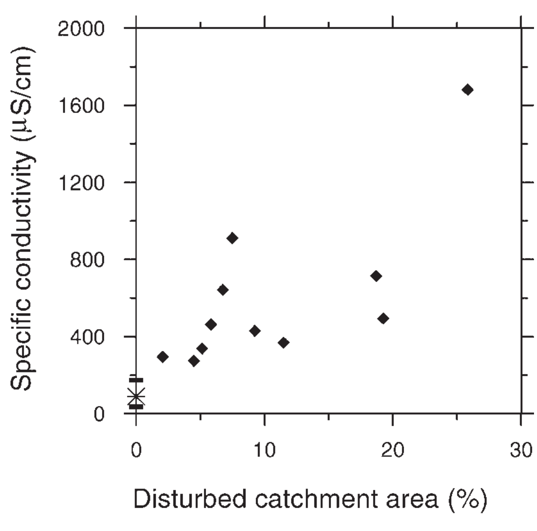

Figure 5 Percentage of catchment area influenced by slumping and specific conductivity of lake water, upland lakes, Mackenzie Delta region. The (*) indicates the mean specific conductivity of the 11 pristine lakes measured in this study. The (–) indicates maximum and minimum values for pristine lakes.

Figure 5 also shows that slumping can lead to ionic enrichment of lake water, even where disturbance comprises only a few per cent of total catchment area. Considerable scatter in Figure 5 may be attributed to differences in the chemical composition of degrading permafrost and to the varying proportion of runoff derived from the disturbed areas.

Percentage of catchment area affected by disturbance and DOC concentrations are presented in Figure 6. The Pearson's product-moment correlation indicates a significant negative relation between the two variables ($r = -0.69$, $N = 11$, $P < 0.05$). This relation is expected because slope runoff over and through a shallow organic active layer promotes the export of DOC from the terrestrial to the aquatic environment, but runoff derived from recently disturbed areas with exposed mineral soils is typically low in DOC (MacLean *et al*., 1999; Carey, 2003).

Permafrost Slumping and Small Tundra Lakes: Regional Analysis

Lake size, catchment and disturbance characteristics were investigated in four 49 km^2 areas (plots i to iv) between Noell Lake and Richards Island (Figure 2). Each area is lake-rich, with 54 (plot i) to 99 (plot ii) lakes and ponds entirely within the respective regions (Table 5A). Water occupies between 10 and 20% of the plot surfaces. The mean area of the lakes and ponds ranges from 4.4 ha in plot ii to 10.8 ha in plot iii.

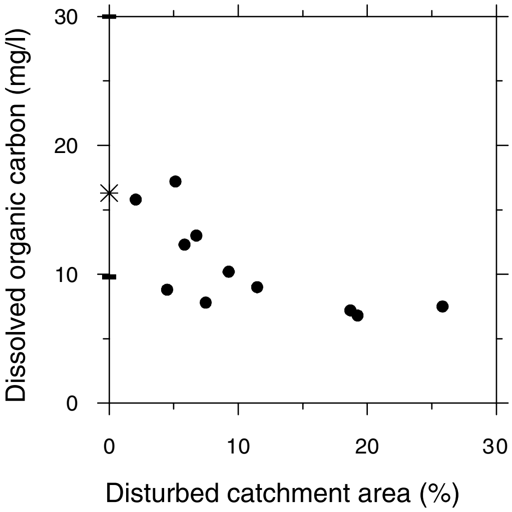

Figure 6 Percentage of catchment area influenced by slumping and dissolved organic carbon (DOC) concentration of lake water, upland lakes, Mackenzie Delta region. The (*) indicates the mean DOC concentration of the 11 pristine lakes measured in this study. The (–) indicates maximum and minimum values for pristine lakes.

Large population standard deviations indicate a wide variation in lake size (Table 5A). The median lake areas range from 1.3 to 2.3 ha, showing that the populations are positively skewed and that the majority of water bodies are less than a few hectares in area (Table 5A).

Table 5 Summary statistics for lake areas in four 49 km^2 plots (*i to iv)* between Noell Lake and Richards Island. Statistics are provided for the following populations of lakes which are completely within each plot: (A) all lakes; (B) lakes where disturbance occupies at least 5% of the catchment area; and (C) all first- and second-order lakes in upland catchments. STD indicates standard deviation.

Plot	N	Mean (STD) (ha)	Median (ha)
(A) All lakes			
i	54	9.4 ± 29.7	1.4
ii	99	4.4 ± 9.7	1.4
iii	56	10.8 ± 21.2	2.3
iv	89	9.3 ± 28.6	1.3
(B) Lakes with >5% disturbed catchment area			
i	8	3.7 ± 2.1	3.5
ii	5	3.3 ± 2.9	2.7
iii	4	7.6 ± 3.7	7.3
iv	5	6.6 ± 3.7	8.0
(C) Lakes with small upland catchments			
i	31	2.4 ± 2.4	1.6
ii	29	2.0 ± 1.8	1.2
iii	21	7.3 ± 15.4	3.0
iv	19	5.5 ± 7.4	2.8

All active and stable thermokarst areas identified on 2004 aerial photographs of the four respective plots occur on sloping terrain surrounding lakes and ponds. In the study plots, between 8 and 17% of the lakes were influenced by thermokarst slumping. Few of the thermokarst-affected lakes were situated in large catchments where disturbance comprised only a negligible portion of total watershed area. Five to 15% of all lakes in the four plots had catchments with more than 5% total area occupied by disturbance (Table 5B). On the basis of the relations between disturbance area and water quality (Figure 5), it is reasonable to suggest that solute concentrations in these lakes are significantly different from pristine lakes.

The greatest total number and percentage of lakes affected by thermokarst disturbance was in plot i, an area that was burned in 1968 (Landhäusser and Wein, 1993; Mackay, 1995) (Figure 4; Table 5B). Only one of the mapped disturbances in plot i was active, while the rest have been stable for at least a decade. In contrast, the majority of lakes affected by thermokarst activity in plots ii, iii and iv were characterized by at least one zone of active slumping.

All small, first-order catchment lakes surrounded by sloping topography in the four study plots were identified (Table 5C). Lakes and ponds of this nature constitute 21% (plot iii) to 57% (plot i) of the water bodies in the study areas. It is probable that thermokarst activity of a magnitude comparable to disturbances in the study catchments (1b to 11b) would significantly affect the water quality of these lakes (Table 5C).

This analysis suggests that in the lake-rich tundra uplands east of the Mackenzie River Delta, up to one tenth of the lakes possess elevated ionic concentrations associated with thaw slumping (Table 5A). The frequency and magnitude of thermokarst may increase under warmer climate conditions (Lewkowicz, 1990; Dyke, 2000b). Small, first-order catchments surrounded by sloping topography constitute between 20 and 60% of freshwater bodies within four 49 km^2 study plots, and the geochemistry of these lakes has potential to be modified by thermokarst (Table 2).

CONCLUSIONS

1. In small upland lakes between Inuvik and Richards Island, Ca, Mg and SO_4 are major ionic constituents of lake water. Measured mean concentrations of these ions in lakes located within

undisturbed catchments were 9.6, 3.6 and 11.1 mg/l, respectively. The low ionic concentrations in lake water reflect runoff derived from slopes with shallow, nutrient-poor organic soils underlain by permafrost.

2. In lakes located within catchments affected by thermokarst slumping, mean concentrations of Ca, Mg and SO_4 were 72.6, 26.8 and 208.2 mg/l, respectively. Soluble materials released by permafrost degradation are transported by surface runoff from the ion-rich slump soils into the aquatic systems, elevating ionic concentrations in lake water.
3. DOC concentrations were lower in lakes affected by thaw slumping and the water was clearer than in undisturbed lakes.
4. Thermokarst had a detectable effect on lake-water chemistry where slumping occupied only a few per cent of total catchment area. There was a positive association between ionic concentrations and the proportion of catchment area influenced by disturbance. DOC concentration in lake water was inversely related to the percentage of disturbed area.
5. High soil solute concentrations in old thaw slumps and elevated lake-water ionic concentrations in catchments with stabilized slumps indicate that thermokarst disturbance can affect lake chemistry for at least several decades.
6. It is estimated that 5 to 15% of all lakes in the four 49 km^2 study areas, and, by extension, the lakes of the tundra uplands east of Inuvik, have elevated ionic concentrations due to thaw slumping.
7. Fire had a discernable impact on the water chemistry in small lakes in the study area. The highest density of old slumps, and total lakes affected by disturbance were mapped in the study area within zone burned by the 1968 forest-tundra fire. Undisturbed lakes in the burned area have high ionic and low DOC concentrations with respect to the other undisturbed lakes studied.

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