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Connections between River Runoff and Limnological Conditions in Adjacent High Arctic Lakes: Cape Bounty, Melville Island, Nunavut

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ABSTRACT. Hydrological and hydrochemical monitoring of paired watersheds in the High Arctic was conducted in 2003–04 to investigate the influence of seasonal runoff on lake water chemistry and productivity. Despite similar limnological conditions overall between the two lakes, marked differences in aquatic productivity were attributed to watershed and basin morphology and the resultant influences on lake ice deterioration and growing season length. A switch from allochthonous to autochthonous sources of carbon late in the season reflected the simultaneous decline in river runoff and increase in aquatic productivity as the growing season progressed. However, low air temperatures and protracted snowmelt and ponding in the deeply incised channel of one river in 2003 led to greater solute accumulation in runoff that was discernable in hydrochemical profiles of that lake, even though runoff was greater in 2004. Notwithstanding, calculated nutrient fluxes were greater during the higher-flow year (2004), but mixing was impeded by underflow conditions in the lakes. Despite these differences, connections between river and lake water chemistry appeared weak even with marked seasonal changes in the volume of runoff. Our results highlight the interconnection between site-specific features and hydroclimatic factors like snowmelt and lake ice conditions in influencing limnological conditions and suggest that similar systems may respond differently to the same hydroclimatic conditions.

Key words: climate change, hydroclimate, snowmelt, runoff, limnology, water chemistry, aquatic productivity, freshwater, lake, ice cover

RÉSUMÉ. La surveillance hydrologique et hydrochimique de bassins versants jumelés de l'Extrême-Arctique a été effectuée en 2003 et 2004 dans le but de mieux connaître l'influence du ruissellement saisonnier sur la chimie et la productivité des eaux lacustres. Malgré des conditions limnologiques généralement similaires entre les deux lacs, les différences marquées en matière de productivité aquatique étaient attribuables à la morphologie du bassin versant et du bassin de réception de même qu'aux influences résultantes sur la détérioration de la glace lacustre et la longueur de la saison qui se prolonge sans cesse. La commutation de sources de carbone allochtones à des sources de carbone autochtones vers la fin de la saison reflète le déclin simultané du ruissellement des rivières et l'augmentation de la productivité aquatique au fur et à mesure que la saison de croissance avançait. Toutefois, les basses températures de l'air ainsi que la fonte des neiges prolongée et l'engorgement dans l'un des chenaux profondément incisé d'une rivière en 2003 se sont traduits par une plus grande accumulation de soluté dans le ruissellement que ce que l'on pouvait discerner dans les profils hydrochimiques de ce lac et ce, même si le ruissellement était plus important en 2004. Néanmoins, les flux de nutriments calculés étaient plus élevés au cours de l'année ayant enregistré un plus grand débit (2004), mais le mélange était gêné par les conditions caractérisant le courant de fond des lacs. Malgré ces différences, les connexions entre la chimie de l'eau des rivières et des lacs semblait faible même en présence de changements saisonniers marqués sur le plan du volume du ruissellement. Nos résultats mettent en évidence l'interconnexion qui existe entre les caractéristiques spécifiques aux emplacements et les facteurs hydroclimatiques comme la fonte des neiges et les conditions de la glace lacustre pour influencer les conditions limnologiques, et laissent entendre que des systèmes semblables peuvent réagir différemment aux mêmes conditions hydroclimatiques.

Mots clés : changement climatique, hydroclimat, fonte de neige, ruissellement, limnologie, chimie de l'eau, productivité aquatique, eau douce, lac, couverture de glace

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INTRODUCTION

Knowledge about the potential impacts of climate change on northern freshwaters is insufficient, despite the fact that the Arctic is warming faster than anywhere else (ACIA, 2004; White et al., 2007). In particular, the sensitivity of Arctic aquatic ecosystems to changing hydroclimatic conditions is uncertain, which makes it difficult to anticipate the response

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of these systems to continued climate change. Yet evidence of changing hydrologic conditions with direct implications for northern aquatic ecosystems is mounting. Changes have been noted in permafrost and active-layer temperature and depth (Frauenfeld et al., 2004); glacial thickness and extent (Abdalati et al., 2004; Burgess and Sharp, 2004); the areal extent of lakes, ponds, and wetlands (Smith et al., 2005; Walter et al., 2006; Smol and Douglas, 2007); precipitation and winter snow cover (Serreze et al., 2002; Peterson et al., 2006); the timing of snowmelt and subsequent discharge patterns (Déry and Wood, 2005; McClelland et al., 2006); and aquatic algal and invertebrate assemblages (Smol et al., 2005). Such changes, particularly in combination, are likely to change water quality fundamentally and alter the structure and function of Arctic aquatic ecosystems.

Although long-term monitoring of Arctic freshwaters is generally lacking, recent efforts to document baseline physical and chemical limnology across the Canadian Arctic have been significant, particularly for small lakes and ponds (e.g., Keatley et al., 2007). Seasonal changes in limnology and hydrochemistry may be crucial to understanding how aquatic ecosystems are likely to respond to future hydroclimatic change, but our understanding of these changes remains limited (Forsström et al., 2007).

The importance of intra- and interannual changes in limnology may be especially relevant to high-latitude systems, where extreme seasonality subjects aquatic ecosystems to a wide range of hydroclimatic conditions over a relatively short growing season. An intense spring runoff period caused by rapid melting of winter snowpack characterizes the Arctic hydrological cycle. In summer, precipitation is typically low, and greater soil storage reduces hydrologic connectivity, which means that the bulk of runoff occurs during a brief spring freshet. Changes in catchment hydrology and the subsequent delivery of nutrients and other constituents to lake basins could affect aquatic ecosystems significantly, particularly in systems characterized by low productivity and oligotrophic conditions.

This paper aims to help fill these knowledge gaps by 1) documenting the physical and chemical limnology of two relatively large lakes and their major sources of inflow in the Canadian High Arctic; 2) identifying the influence of site-specific factors and the range of hydrochemical responses generated by the same hydroclimatic conditions through comparison of two physiographically similar and adjacent catchments; and 3) assessing the limnological response to intra- and interannual hydroclimatic variability to help shed light on the sensitivity of High Arctic lake ecosystems to future hydroclimatic scenarios.

MATERIALS AND METHODS

Site Description

Cape Bounty is situated on the south-central coast of Melville Island in the Canadian High Arctic (74˚55′ N, 109˚35′ W; Fig. 1). Bedrock geology consists of weathered Palaeozoic sand and siltstones overlain by Holocene marine and glacial sediments (Hodgson et al., 1984). The study site lies in the area of continuous permafrost, with a maximum summer active (thawed) layer of less than 1 m. The catchments are composed of low-relief hills (< 120 m a.s.l.) with sparse vegetation cover characterized by dwarf shrub tundra. Wet sedge meadow, consisting primarily of bryophytes, cotton grass, and sedges, is found in moist, low-lying areas (Atkinson and Treitz, 2007).

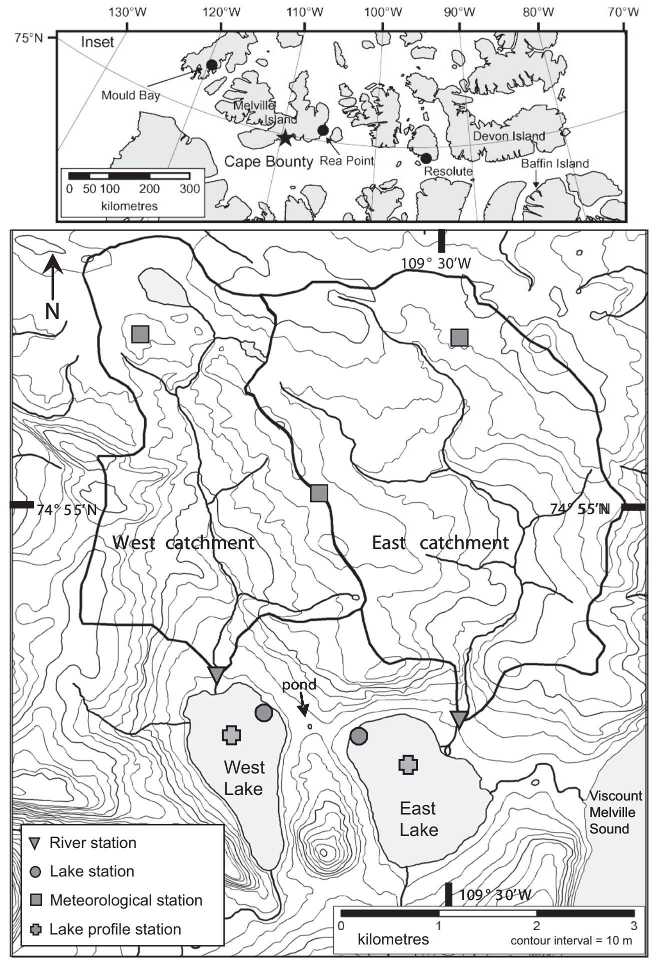

FIG. 1. Inset shows location of the Cape Bounty field site on Melville Island in the western Canadian Arctic Archipelago (★) and locations of Environment Canada meteorological stations at Mould Bay on Prince Patrick Island and Rea Point on Melville Island (●). The main map shows the delineation of the two catchments and locations where meteorological, river, and lake data were collected (see legend).

Climate conditions consist of long, cold winters and short growing seasons with limited precipitation. Mean annual precipitation (1971–2000) at Mould Bay, Prince Patrick Island (Fig. 1), approximately 200 km west of Melville Island, is 111 mm (Meteorological Service of Canada, 2002) and falls predominantly as snow (October–May). At Cape Bounty, snow surveys indicated snow water equivalences of 43 mm in 2003 and 82 mm in 2004 for the West catchment, and 20 mm (2003) and 41 mm (2004) for the East catchment (Cockburn and Lamoureux, 2008a). The greater snowpack

TABLE 1. Physical and chemical attributes of the Cape Bounty lakes (2003–04).

	West Lake	East Lake
Catchment area (km^2)	8	11.6
Lake area (km^2)	1.4	1.6
Lake volume (km^3)	.0214	.0209
Surface area/volume	.065	.076
Maximum depth (m)	35	32
Mean depth (m)	15.3	13.1
Mean water temp (˚C)	1.1	2.7
Littoral zone (km^2)[1]	.32	.44
Mean TN-F (mg l^{-1})	.26	.17
Mean TP-F (mg l^{-1})	.011	.008
Mean Chl-a (µg l^{-1})	1.0	1.85
Mean pH	7.3	7.3
Conductivity (µS cm^{-1})	38	52
Ice off	Persistent ice-pan	Mid-August

[1] Littoral zone is defined as the surface area corresponding to a lake depth of 5 m or less (i.e., area of the 0–5 m bathymetric contour interval).

in the West catchment is attributed to the steeper gradient, which results in deeper gullies and channels where drifting snow collects disproportionately (Cockburn and Lamoureux, 2008a; McDonald and Lamoureux, 2009). Summer precipitation at Cape Bounty is limited to occasional low-intensity events, typically less than 10 mm·day^{-1}. At Mould Bay, mean daily temperatures range from –34˚C in February to 4˚C in July (Meteorological Service of Canada, 2002). At Cape Bounty, mean July air temperature was 4˚C in 2003 and 2.5˚C in 2004.

The study site consists of two adjacent and physiographically similar watersheds, unofficially named "West" and "East" (Fig. 1; Table 1). The West catchment is smaller than the East catchment and has a slightly steeper gradient, with deeper channels and greater vegetative coverage (Atkinson and Treitz, 2007). Both have tributaries that feed a principal stream flowing into the north end of the lake. While the lakes are morphologically quite similar, East Lake is shallower than West Lake and has a greater surface area, resulting in a higher surface area–to–volume ratio (Table 1).

Sample Collection

Water samples were systematically collected from the river gauging stations and moats of both lakes (Fig. 1) every 5 or 6 days from snowmelt to early August in 2003 and 2004. Lake water samples were collected from moats rather than more centrally to capture conditions representing the most productive part of the lake. Moat widths increased through the season as lake ice diminished, from approximately 3 m to over 20 m by the end of the sampling period, but samples were consistently collected from 30 cm below the surface in approximately 1.5 m of water. River samples were collected at or just below the water surface, depending on stream depth. Samples were immediately partitioned and filtered following standard procedures outlined by Environment Canada (1994). We measured temperature in the field, as well as pH (Orion 290A pH meter) and conductivity (YSI 30M EC meter). However, because of instrumentation problems, electrical conductivity (EC) measurements are not available for 2003. Analysis of major and minor ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}), and trace metals (Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, P, Pb, S, Sb, Se, Si, Sn, Sr, Ti, Tl, U, V, Zn) were conducted by the Analytical Services Unit at Queen's University in Kingston, Ontario. Nutrient analyses, conducted by the National Water Research Institute in Burlington, Ontario, included nitrate-nitrite ($NO_3^- + NO_2^-$), nitrite (NO_2^-), ammonia (NH_3), total Kjeldahl nitrogen (TKN), total dissolved nitrogen (TN-F), particulate organic nitrogen (PON), soluble reactive phosphorus (SRP), total dissolved phosphorus (TP-F), total phosphorus (TP), particulate organic carbon (POC), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC). Analysis for chlorophyll-a (Chl-a; uncorrected) was conducted at the Canadian Museum of Nature, Gatineau, Quebec. Subsequent calculations based on water chemistry results included dissolved organic nitrogen (DON) = TKN - NH_3, dissolved inorganic nitrogen (DIN) = $NO_3NO_2 + NH_3$, total nitrogen (TN) = PN + NO_3NO_2 + TKN, and ratios of TN:TP (mg l^{-1}), TN:TP (molar ratios), POC:PON (mg l^{-l}) and POC:Chla (mg l^{-1}).

Lake profiles of electrical conductivity were conducted on samples drawn at 1.5 m depth intervals from approximately the middle of the ice pan of both lakes using a Kemmerer sampler and methods described above. Throughout the 2003 and 2004 hydrologic seasons, streamflow characteristics (e.g., discharge and water temperature) were monitored for both rivers, and three meteorological stations recorded weather conditions (e.g., air temperature and precipitation). Hydrological and meteorological details are reported in Cockburn and Lamoureux (2008a).

RESULTS

Seasonal Hydroclimatic Variability

Hydrographs for both seasons show the characteristic Arctic nival pattern: most runoff occurs at the beginning of the season with the onset of snowmelt, and discharge recedes rapidly as the snowpack is exhausted. In 2003, initial flow and peak discharge occurred on 19 June and 27 June in East River, and on 25 June and 30 June in West River, with baseflow conditions being met in both rivers by the second week in July (Fig. 2). In 2004, discharge peaked on 25 June in East River and on 28 June in West River, receding to baseflow conditions by mid-July (Fig. 2). Maximum discharge was higher in both rivers in 2004, particularly in East River (1.8 m^3 s^{-1} versus 0.9 m^3 s^{-1} in 2003, compared to 1.6 m^3 s^{-1} versus 1.2 m^3 s^{-1} in 2003 for West River). In both years, summer precipitation was limited to several low-intensity rainfall events that produced moderate discharge responses (Fig. 2).

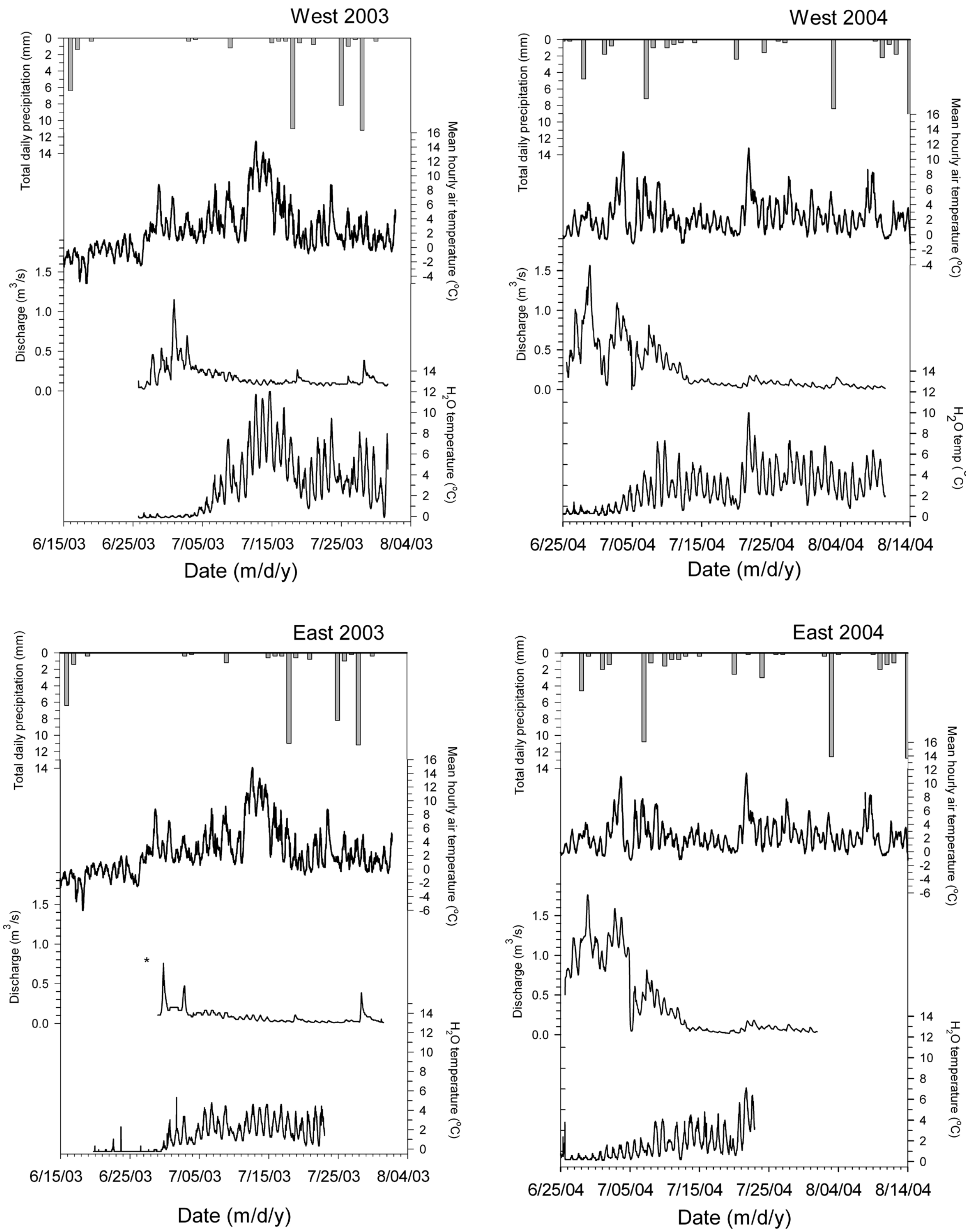

FIG. 2. Seasonal streamflow (discharge and temperature) and meteorological data for West and East rivers in 2003 and 2004. Note that for East Lake in 2003, hourly discharge before 29 June has been omitted because of the initial location of the stilling well, but manual rating curves indicate that peak discharge occurred on June 27 (*).

East River exhibited lower water temperatures than West River in both study years, but both rivers demonstrated a gradual increase to maximum values by mid-season (Fig. 2). The maximum water temperatures recorded in 2003 were 5.3˚C for East River and 12.1˚C for West River. In 2004, the maximum recorded water temperatures were

TABLE 2. A summary of key differences between the two years studied. Plus signs (+) indicate the year in which the variable has a higher value.

	2003	2004
Mean June air temperature[1]	-	+
Mean July air temperature	+	-
Snow water equivalence	-	+
Snowmelt rate	-	+
Maximum discharge	-	+
Total runoff	-	+
River solute concentrations	+	-
Nutrient fluxes	-	+
Mean river temperature	+	-
Mean lake Chl-a	-	+
Mean lake TN-F	+	-
Mean lake TP-F	+	-
Mean lake DOC	+	-

[1] Represents snowmelt period.

7.1˚C for East River and 10.0˚C for West River. Note that the recording period for East River is shorter than that for West River, but likely still captures the maximum temperature period, as observed in the West River data. Air temperatures recorded at meteorological stations in both catchments indicate a seasonal maximum of 12.4˚C in 2003 and 7.3˚C in 2004, while mean daily July air temperatures were 4.0˚C for 2003 and 2.5˚C for 2004. Air temperatures correlate well with data from the closest Meteorological Service of Canada stations at Rea Point, Nunavut, to the east and Mould Bay, Northwest Territories, to the northwest (Cockburn and Lamoureux, 2008a). Table 2 summarizes some of the key climatic and limnological differences between the two study years.

Prior to the melt season, both lakes had ice cover more than 2 m thick, but open-water moats formed with the onset of the melt season in both years. A satellite image taken in mid-August 2003 revealed that East Lake was completely ice-free, whereas West Lake remained ~30% ice covered, despite a thicker initial ice-pan on East Lake (2.3 m versus 2.0 m). Field observations from 2004 suggest a similar pattern of faster ice deterioration and earlier ice-free conditions on East Lake.

Hydrochemistry

Since few records of seasonal hydrochemical variability in Arctic lakes exist, a comprehensive suite of measured variables is presented in Table 3. Both lakes and rivers were circumneutral during the study period; the mean pH value was 7.4, with a range from 6.4 to 7.9 (Table 3). River and lake values in each catchment were similar, and there was little evidence of seasonal variability in pH, but mean values in both lakes and rivers were higher in 2004 than in 2003. Electrical conductivity was higher in the lakes (mean = 45 µS cm^{-1}, n = 14) than in the rivers (mean = 27 µS cm^{-1}, n = 14), and both East River and East Lake had higher values than their western counterparts (Table 3). A seasonal pattern of high EC in early to mid July, followed by a sharp decline and then gradual increase, is apparent in both lakes, whereas river profiles are less variable, tending toward higher values as the season progresses (Fig. 3). Water column profiles of electrical conductivity, taken in the middle of the lakes (Fig. 1) in early July, were stable; mean values were 55.7 µS cm^{-1} (SD = 2.4 µS cm^{-1}) for West Lake and 75.7 µS cm^{-1} (SD = 1.4 µS cm^{-1}) for East Lake (Fig. 3).

Ions and Metals: In order of importance, mean concentrations of major cations and anions, respectively, were $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > DIC > SO_4^{2-}$ (Table 3). Ions were marginally more concentrated in the lakes than in the rivers, with the exception of DIC in the East catchment in 2003 (Table 3). Interannual variability was limited, except that mean lake Cl^- and SO_4^{2-} concentrations were higher in 2004 than in 2003 (Table 3). River solute concentrations for the peak discharge period in 2003 are not available, but 2004 concentrations were stable despite marked changes in river discharge (Fig. 4).

Of the 27 trace (dissolved) metals analyzed, those below detection levels in the majority of samples are not reported, leaving a subset of Al, Ba, Cu, Fe, Mn, Sr, and Zn (Table 3). All values were within the range for Canadian surface waters (McNeely et al., 1979) and were relatively stable both within and between years (Table 3).

Major Nutrients: Nutrient data indicate generally higher concentrations in West Lake than in East Lake. Conversely, East River was more nutrient-rich than West River, and overall, higher concentrations were found in the rivers than in the lakes (Table 3). With respect to nitrogen, TKN (a measure of reduced forms of nitrogen, principally ammonia and amino forms of organic nitrogen) was most abundant, followed by PON, NO_3NO_2, and NH_3 (Table 3). While concentrations of NO_3NO_2 were higher in West Lake than in East Lake, this pattern was not reflected in the rivers, where concentrations in East River exceeded those in West River. In 2003, high early-season PON concentrations in West River coincided with the peak flow period, and lake concentrations also appeared to be elevated during this time (Fig. 5). A similar early-season increase in PON was not apparent in the East River, where sampling was initiated more than two weeks after peak flow. However, sampling in East Lake in 2003 did capture the peak runoff period, and PON concentrations remain stable during this period. In 2004, seasonal profiles of nitrogen species revealed higher N concentrations (especially PON) in both rivers that coincided with the peak discharge period. However, there is no evidence of this pattern in the corresponding lake profiles (Fig. 5). In both years, DIN, which includes the most readily assimilated nitrogen forms (ammonia and nitrate) necessary for periphytic and macrophytic growth, was higher in West Lake than in East Lake or either river (Table 3). Overall, a general trend toward declining TN-F concentrations throughout the season is apparent in the lake profiles of both years (Fig. 6a). No data are available for the peak discharge period in 2003; in 2004, however, TN-F concentrations in both rivers increased during the peak discharge

TABLE 3. Summary of 2003 and 2004 water chemistry results for Cape Bounty. All units are mg l^{-1}, unless otherwise noted.

	pH	EC µS cm^{-1}	$CaCO_3$	Cl	SO_4	Ca	K	Mg	Na	Al	Ba	Cu	Fe	Mn	Si
2003 West R.															
mean	7.3		8.8	1.41	1.22	1.45	0.316	0.96	1.45	0.097	0.033	0.002	0.147	0.004	
min	7.1		7.6	1.15	0.91	0.89	0.278	0.65	1.37	0.056	0.029	0.002	0.053	0.002	
max	7.5		10.4	1.85	1.60	2.25	0.339	1.33	1.57	0.141	0.035	0.002	0.249	0.006	
2003 West L.															
mean	7.1		9.7	3.48	1.89	2.18	0.653	1.67	3.73	0.121	0.034	0.007	0.166	0.006	
min	6.8		5.6	1.01	0.31	2.06	0.462	1.50	2.21	0.037	0.022	0.003	0.046	0.002	
max	7.5		14.8	7.34	3.40	2.34	0.924	2.00	4.49	0.323	0.062	0.015	0.387	0.015	
2003 East R.															
mean	7.5		15.3	2.51	1.02	2.71	0.654	1.86	2.06	0.102	0.038	0.002	0.167	0.004	
min	7.3		11.2	2.10	0.33	1.68	0.417	1.17	1.39	0.042	0.033	0.002	0.054	0.003	
max	7.6		24.4	3.10	1.77	4.29	1.003	2.94	2.73	0.144	0.047	0.002	0.260	0.006	
2003 East L.															
mean	7.3		12.5	2.75	1.05	3.39	0.733	2.35	5.85	0.050	0.033	0.007	0.060	0.026	
min	7.2		6.4	1.35	0.33	2.86	0.633	2.23	4.12	0.028	0.014	0.002	0.027	0.001	
max	7.5		19.2	8.18	3.88	4.31	0.827	2.54	6.77	0.092	0.046	0.010	0.126	0.119	
2004 West R.															
mean	7.3	24.5	5.8	2.02	2.25	1.42	0.359	0.95	1.58	0.085	0.036	0.006	0.076	0.041	0.438
min	6.4	20.6	4.0	1.73	1.88	1.00	0.293	0.73	1.34	0.047	0.002	0.001	0.026	0.001	0.291
max	7.9	34.9	8.8	2.68	2.75	2.17	0.451	1.17	2.31	0.178	0.096	0.010	0.268	0.164	0.805
2004 West L.															
mean	7.4	38.0	5.5	6.72	3.21	1.75	0.583	1.41	3.98	0.046	0.032	0.009	0.022	0.002	0.261
min	7.4	23.8	3.2	4.30	2.28	1.04	0.486	0.98	2.74	0.008	0.028	0.001	0.003	0.001	0.079
max	7.5	56.6	8.4	9.50	4.09	2.10	0.659	1.52	4.33	0.076	0.043	0.024	0.039	0.004	0.341
2004 East R.															
mean	7.5	29.1	5.4	2.45	2.23	2.04	0.533	1.56	2.01	0.073	0.036	0.011	0.041	0.003	0.370
min	7.3	23.3	4.0	2.00	2.00	1.30	0.404	1.22	1.61	0.014	0.011	0.001	0.004	0.001	0.281
max	7.9	31.7	7.2	3.15	2.75	2.70	0.714	2.09	2.65	0.113	0.053	0.038	0.065	0.009	0.532
2004 East L.															
mean	7.4	52.1	6.9	8.52	3.77	2.64	0.717	2.07	5.47	0.032	0.037	0.005	0.014	0.001	0.192
min	6.6	31.8	4.0	6.74	3.26	2.11	0.565	1.70	4.49	0.004	0.029	0.001	0.006	0.001	0.056
max	7.7	83.7	12.4	9.74	4.16	3.11	0.931	2.25	5.89	0.043	0.048	0.009	0.018	0.003	0.234
All															
mean	**7.4**	**35.9**	**8.3**	**4.16**	**2.31**	**2.17**	**0.577**	**1.60**	**3.40**	**0.071**	**0.035**	**0.007**	**0.071**	**0.012**	**0.315**
min	**6.4**	**20.6**	**3.2**	**1.01**	**0.31**	**0.89**	**0.278**	**0.65**	**1.34**	**0.004**	**0.002**	**0.001**	**0.003**	**0.001**	**0.056**
max	**7.9**	**83.7**	**24.4**	**9.74**	**4.16**	**4.31**	**1.003**	**2.94**	**6.77**	**0.323**	**0.096**	**0.038**	**0.387**	**0.164**	**0.805**

period before tapering off through the remainder of the season (Fig. 6a).

The majority of phosphorus was in particulate form, with higher concentrations in the river samples than in the lake samples (Table 3). Since most particulate phosphorus is unavailable for biological activity, SRP and dissolved P (TP-F) are more relevant when considering nutrient availability (Hamilton et al., 2001; EMAN-North, 2005). The majority of SRP concentrations were at or below the detection level of .002 mg l^{-1}. The mean TP-F concentration was .009 mg l^{-1} and differed only marginally between sites. However, both lakes and rivers had higher TP-F means in 2003 than in 2004. Seasonal profiles are inconsistent, and except for West Lake in 2003, they do not appear to be influenced by river discharge (Fig. 6b). Overall, TP-F concentrations span a range similar to those found in a suite of 46 ponds and lakes sampled elsewhere on Melville Island (Keatley et al., 2007).

The most abundant carbon fraction for both rivers and lakes was DIC (mean = 3.2 mg l^{-1}), followed by DOC (mean = 1.6 mg l^{-1}) and POC (mean = 0.77 mg l^{-1}; Table 3). Mean DIC and DOC concentrations in the lakes and their respective rivers were similar for both years, whereas POC was consistently higher in the rivers than in the lakes. Carbon fractions are generally highest in early season, with greater seasonal variability in 2003 than in 2004 (Fig. 6c, d).

Aquatic Productivity: Lake Chl-a concentrations ranged from 0.48 to 1.91 µg l^{-1} (mean = 1.12 µg l^{-1}) and were substantially higher in East Lake (mean = 1.9 µg l^{-1}) than in West Lake (mean = 1.0 µg l^{-1}). Chl-a levels were also higher for both lakes in 2004 (mean = 1.8 µg l^{-1}) than in 2003 (mean = 1.1 µg l^{-1}). In all cases, there was a gradual increase in lake Chl-a concentrations during the season, and except for West Lake in 2004, all seasonal trends appeared to be declining by the end of the sampling period (Fig. 6e). River Chl-a has been omitted because of the high error associated with the abundant detrital matter in river runoff.

Nutrient ratios were calculated to provide insight into the potential controls on aquatic productivity. Mass TN:TP ratios greater than 17 suggest the system may be P-limited, whereas ratios below 14 suggest that N is the limiting nutrient (Downing and McCauley, 1992). For Cape Bounty, TN:TP ratios ranged from 6 to 55, with a mean of 19 (Table 3). While 34% of samples suggested that productivity would be limited by P, the greatest proportion (39%) of samples fell between 14 and 17, suggesting that both P and N are in limited supply in these systems. When TN:TP molar ratios are considered (Guildford and Hecky, 2000), over 70% of samples were either N- or P-limited, with a further 20% suggesting P limitation (< 20 = N limited, 20–50 = either N or P limited, > 50 = P limited; Table 3).

TABLE 3 continued: Summary of 2003 and 2004 water chemistry results for Cape Bounty. All units are mg l^{-1}, unless otherwise noted.

	Sr	Zn	POC	DOC	DIC	NO_3NO_2	NO_2	NH_3	TKN	TN-F	DIN	DON	PON	TN	SRP
2003 West R.															
mean	0.006	0.029	1.237	1.583	2.633	0.010	0.002	0.024	0.178	0.186	0.025	0.158	0.129	0.313	0.000
min	0.004	0.028	0.336	1.200	2.000	0.005	0.001	0.007	0.134	0.153	0.003	0.109	0.032	0.174	0.000
max	0.008	0.031	4.300	2.000	3.600	0.019	0.003	0.055	0.246	0.252	0.061	0.191	0.392	0.545	0.000
2003 West L.															
mean	0.009	0.035	0.739	1.775	3.013	0.110	0.004	0.018	0.184	0.296	0.128	0.166	0.062	0.357	0.000
min	0.008	0.028	0.264	1.000	2.600	0.019	0.001	0.005	0.121	0.223	0.040	0.110	0.016	0.224	0.000
max	0.010	0.045	2.500	4.200	4.100	0.241	0.009	0.039	0.309	0.446	0.280	0.294	0.224	0.670	0.002
2003 East R.															
mean	0.008	0.030	0.960	1.533	4.300	0.042	0.004	0.025	0.221	0.267	0.067	0.196	0.124	0.387	0.000
min	0.005	0.024	0.632	0.800	2.900	0.009	0.002	0.010	0.156	0.188	0.038	0.122	0.048	0.327	0.000
max	0.012	0.037	1.700	3.200	6.500	0.077	0.005	0.046	0.334	0.378	0.092	0.300	0.224	0.498	0.001
2003 East L.															
mean	0.013	0.027	0.479	1.688	3.713	0.010	0.002	0.016	0.170	0.180	0.021	0.156	0.042	0.219	0.000
min	0.009	0.015	0.352	1.000	3.300	0.005	0.001	0.008	0.115	0.139	0.003	0.107	0.024	0.158	0.000
max	0.019	0.035	0.680	2.500	4.200	0.024	0.003	0.020	0.204	0.214	0.043	0.189	0.056	0.262	0.002
2004 West R.															
mean	0.007	0.031	0.764	1.700	2.386	0.034	0.002	0.017	0.210	0.203	0.039	0.176	0.083	0.318	0.001
min	0.005	0.004	0.296	1.400	1.700	0.020	0.001	0.006	0.140	0.121	0.006	0.005	0.040	0.186	0.000
max	0.008	0.057	1.520	2.200	3.300	0.061	0.003	0.029	0.313	0.301	0.080	0.295	0.192	0.531	0.004
2004 West L.															
mean	0.009	0.021	0.358	1.386	2.486	0.094	0.002	0.009	0.171	0.231	0.100	0.117	0.032	0.296	0.000
min	0.005	0.001	0.152	1.100	1.900	0.038	0.001	0.005	0.115	0.182	0.044	0.005	0.012	0.228	0.000
max	0.010	0.031	0.784	2.300	3.800	0.117	0.003	0.013	0.216	0.280	0.129	0.209	0.072	0.360	0.001
2004 East R.															
mean	0.007	0.028	1.208	1.771	3.357	0.044	0.002	0.027	0.246	0.242	0.049	0.234	0.146	0.430	0.001
min	0.005	0.002	0.464	1.100	2.800	0.012	0.001	0.016	0.127	0.144	0.012	0.127	0.056	0.267	0.000
max	0.010	0.039	2.230	2.700	4.100	0.157	0.003	0.046	0.414	0.366	0.173	0.368	0.221	0.650	0.004
2004 East L.															
mean	0.010	0.022	0.518	1.343	3.386	0.023	0.003	0.009	0.158	0.152	0.022	0.151	0.050	0.225	0.002
min	0.008	0.014	0.228	1.100	2.900	0.018	0.001	0.005	0.110	0.110	0.005	0.105	0.020	0.169	0.000
max	0.011	0.028	0.620	1.700	3.700	0.035	0.008	0.014	0.177	0.179	0.035	0.169	0.068	0.263	0.007
All															
mean	**0.009**	**0.027**	**0.766**	**1.604**	**3.155**	**0.054**	**0.002**	**0.018**	**0.191**	**0.220**	**0.057**	**0.169**	**0.081**	**0.230**	**0.001**
min	**0.004**	**0.001**	**0.152**	**0.800**	**1.700**	**0.005**	**0.001**	**0.005**	**0.110**	**0.110**	**0.003**	**0.005**	**0.012**	**0.000**	**0.000**
max	**0.019**	**0.057**	**4.300**	**4.200**	**6.500**	**0.241**	**0.009**	**0.055**	**0.414**	**0.446**	**0.280**	**0.368**	**0.392**	**0.670**	**0.007**

DISCUSSION

Regional Controls on Limnology

Chemical analyses of the lakes indicate generally similar limnological conditions. The Cape Bounty lakes are less alkaline than many Arctic lakes because the carbonate bedrock that predominates through much of the region is absent. In addition, conductivity measurements indicate that the Cape Bounty lakes are dilute (mean = 37 $\mu S \cdot cm^{-1}$) compared to lakes elsewhere in the region (e.g., Hamilton et al., 2001; Lim et al., 2001; Antoniades et al., 2003a), including 46 shallow lakes and ponds from Melville Island (Keatley et al., 2007). This dilution is likely due to the combined effect of relatively large catchments, which drain more sparsely vegetated upland areas, and rapid runoff, which limits the contact time of dilute snowmelt with potential solutes (Schindler et al., 1974a; Lim et al., 2001). Relatively sparse catchment vegetation is also suggested by low DOC values (Pienitz et al., 1997): those at Cape Bounty (1.6 mg l^{-1}) are considerably lower than the mean for small lakes and ponds across Melville Island (5.45 mg l^{-1}; Keatley et al., 2007) and on other islands in the Canadian Arctic Archipelago (Hamilton et al., 2001; Lim et al., 2001, 2005; Antoniades et al., 2003a). In addition, lower DOC values are often reported for areas that are larger or more sparsely vegetated or both (Lim et al., 2001; Michelutti et al., 2002; Antoniades et al., 2003b; Lim and Douglas, 2003; Keatley et al., 2007). A significantly higher DOC value (10.4 mg l^{-1}) obtained from a pond situated on a more densely vegetated plateau between the lakes (K.A. Stewart and S.F. Lamoureux, unpubl. data, Fig. 1) further supports this conclusion. Low dissolved organic carbon concentrations at Cape Bounty suggest an increased susceptibility to UV-B penetration (Pienitz and Vincent, 2000) than is typically found in Arctic lakes and ponds (Hamilton et al., 2001; Michelutti et al., 2002; Antoniades et al., 2003b; Lim and Douglas, 2003), although there are exceptions associated with sparsely vegetated catchments and deeper basins, where DOC is more dilute (Lim et al., 2001, 2005; Keatley et al., 2007).

The prominence of Cl^- and Na^+ in lakes and ponds across Melville Island (Keatley et al., 2007) extends to Cape Bounty and may reflect the proximity of sites to the coast and the resulting influence of sea spray (Wetzel, 2001). Alternatively, as the Cape Bounty watersheds contain widespread ground ice, late summer melt of the ice may have mobilized water with high solute levels (M. Lafrenière and S.F. Lamoureux, unpubl. data) which could be derived from the widespread marine sediments at elevations below c. 100 m a.s.l.

TABLE 3 continued: Summary of 2003 and 2004 water chemistry results for Cape Bounty. All units are mg l^{-1}, unless otherwise noted.

	TP-F	TP	Chl-a µg l^{-1}	TN:TP	TN:TP mol	POC:PON	POC:Chla
2003 West R.							
Mean	0.010	0.028		11	24	9	
min	0.008	0.021		8	18	7	
max	0.013	0.039		14	31	11	
2003 West L.							
mean	0.013	0.022	0.85	19	42	13	1208
min	0.009	0.011	0.49	11	25	8	285
max	0.030	0.060	1.42	26	56	19	5086
2003 East R.							
mean	0.012	0.029		15	33	8	
min	0.009	0.019		7	16	7	
max	0.017	0.053		19	41	13	
2003 East L.							
mean	0.011	0.014	1.32	16	35	12	418
min	0.009	0.011	0.58	12	27	10	184
max	0.013	0.022	1.91	20	43	15	821
2004 West R.							
mean	0.009	0.034		13	30	9	
min	0.003	0.013		6	13	7	
max	0.015	0.074		27	59	11	
2004 West L.							
mean	0.008	0.011	1.15	30	66	11	373
min	0.002	0.006	0.48	13	30	9	82
max	0.015	0.017	1.86	44	97	13	769
2004 East R.							
mean	0.006	0.032		12	27	8	
min	0.003	0.018		6	14	6	
max	0.014	0.047		16	35	10	
2004 East L.							
mean	0.005	0.008	2.38	32	72	11	221
min	0.004	0.005	1.74	16	35	7	93
max	0.007	0.015	3.02	55	121	13	272
All							
mean	**0.009**	**0.021**	**1.12**	**19**	**42**	**10**	**555**
min	**0.002**	**0.005**	**0.48**	**6**	**13**	**6**	**82**
max	**0.030**	**0.074**	**1.91**	**55**	**121**	**19**	**5086**

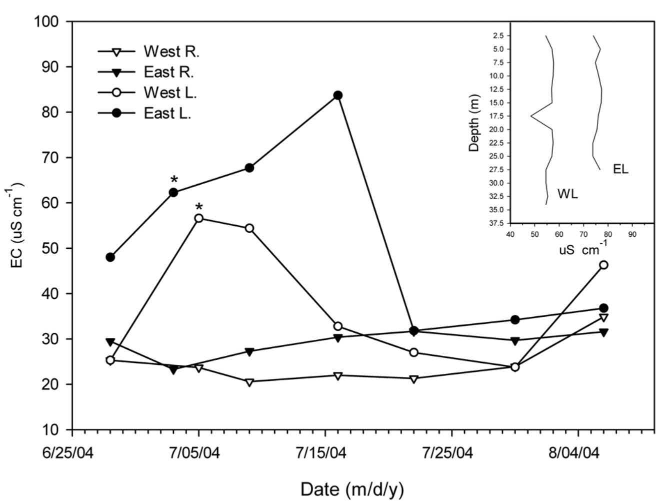

FIG. 3. Seasonal trends of specific conductance for West and East rivers and lakes for 2004. Asterisks indicate when depth profiles of electrical conductivity (inset) were collected for East Lake (July 3) and West Lake (July 4).

While larger Arctic lake systems tend to be more nutrient-limited and have lower productivity than smaller aquatic systems (Hamilton et al., 2001), this is not exclusively the case at Cape Bounty. For example, the mean concentration of TKN (generally the most abundant biologically available nitrogen species) was lower (0.171 mg l^{-1}) in the Cape Bounty lakes than in small lakes and ponds surveyed across Melville Island, Banks Island, Bathurst Island, and elsewhere in the eastern Arctic Archipelago (Hamilton et al., 2001; Lim et al., 2001, 2005; Keatley et al., 2007), but higher than mean values from small lakes and ponds from Victoria Island, Ellef Ringnes Island, and Devon Island (Michelutti et al., 2002; Antoniades et al., 2003b; Lim and Douglas, 2003). Phosphorus is more difficult to compare because of its extremely low soluble concentrations and susceptibility to contamination, but mean total dissolved phosphorus concentrations (9.25 µg l^{-1}) in the Cape Bounty lakes were comparable to those in smaller lakes and ponds from Melville Island (Keatley et al., 2007) and Victoria Island (Michelutti et al., 2002), but higher than mean concentrations from other Arctic island sites (e.g., Hamilton et al., 2001; Lim et al., 2001, 2005; Antoniades et al., 2003a; Lim and Douglas, 2003).

Allochthonous and Autochthonous Sources of Particulate Nutrients

The high particulate nutrient concentrations indicated in PN, POC, and TP fractions were within the range reported

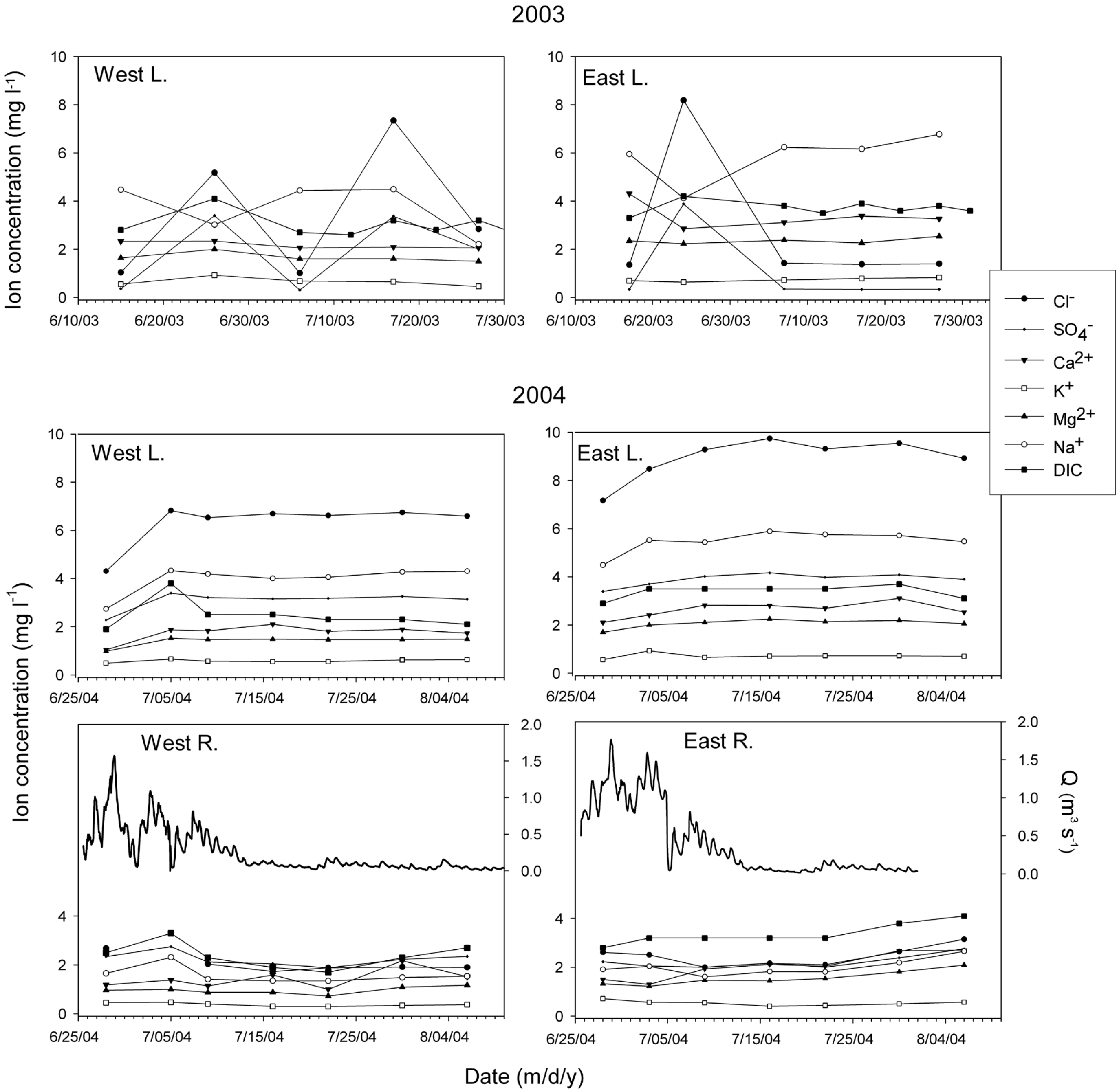

FIG. 4. Seasonal trends of major ions for West and East Lake in 2003 and 2004, and West and East River in 2004. The bold lines in the river profiles represent discharge (Q).

for other Arctic sites, but likely reflect the greater potential for nutrient transport associated with the high-energy spring runoff in large systems (whereas in smaller systems, autochthonous productivity plays a larger role). This interpretation is also suggested by higher particulate concentrations in the river than in the lake samples. In addition, POC:Chl-a ratios (mean = 555) suggest a predominantly allochthonous carbon source (i.e., a ratio greater than 100; Eppley et al., 1977), with the exception of the last sample in East and West Lake in 2004 (i.e., the only samples with ratios less than 100). A higher proportion of allochthonous organic carbon is commonly found in Arctic freshwater systems with low productivity (e.g., Hamilton et al., 2001; Lim et al., 2001; Keatley et al., 2007).

The shift to a predominantly autochthonous carbon source at the end of the 2004 sampling period is attributed to minimal runoff inputs and increased lake productivity with diminished ice cover. Generally lower ratios of POC:Chl-a in East Lake compared to West Lake might be a response to the earlier deterioration of lake ice and larger littoral zone in East Lake, which expose the most productive area of the lake sooner. The late-season change to

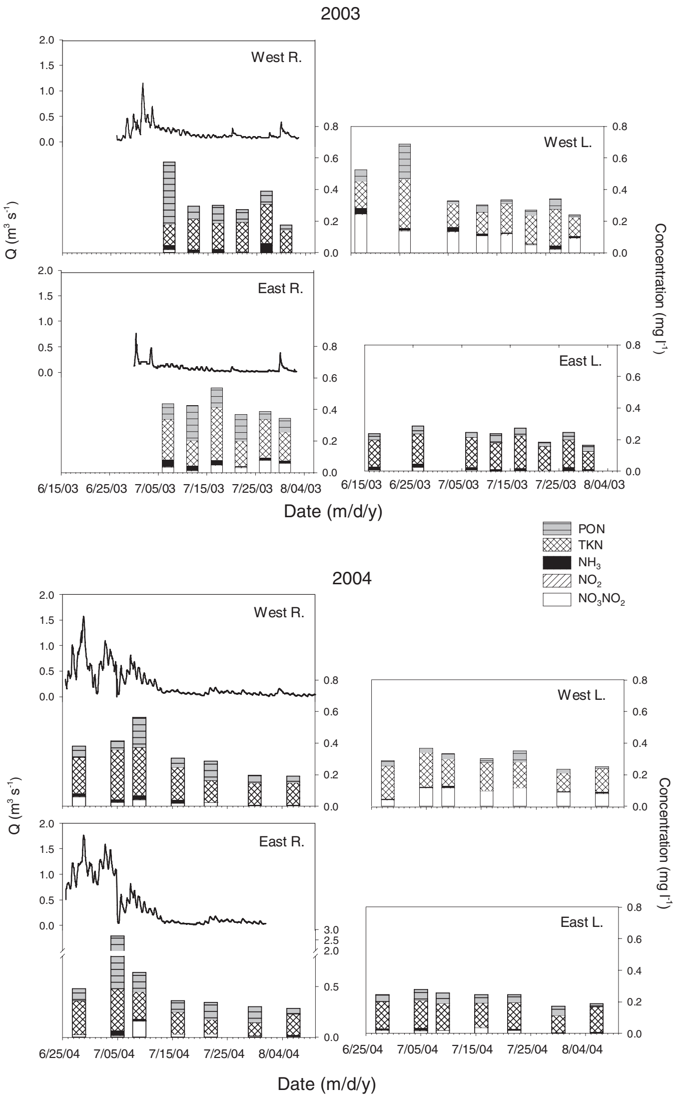

FIG. 5. Seasonal distribution of nitrogen species in East and West lakes and rivers for 2003 (upper panels) and 2004 (lower panels). Note the scale is different for East River in 2004. Solid line plots represent river discharge (Q).

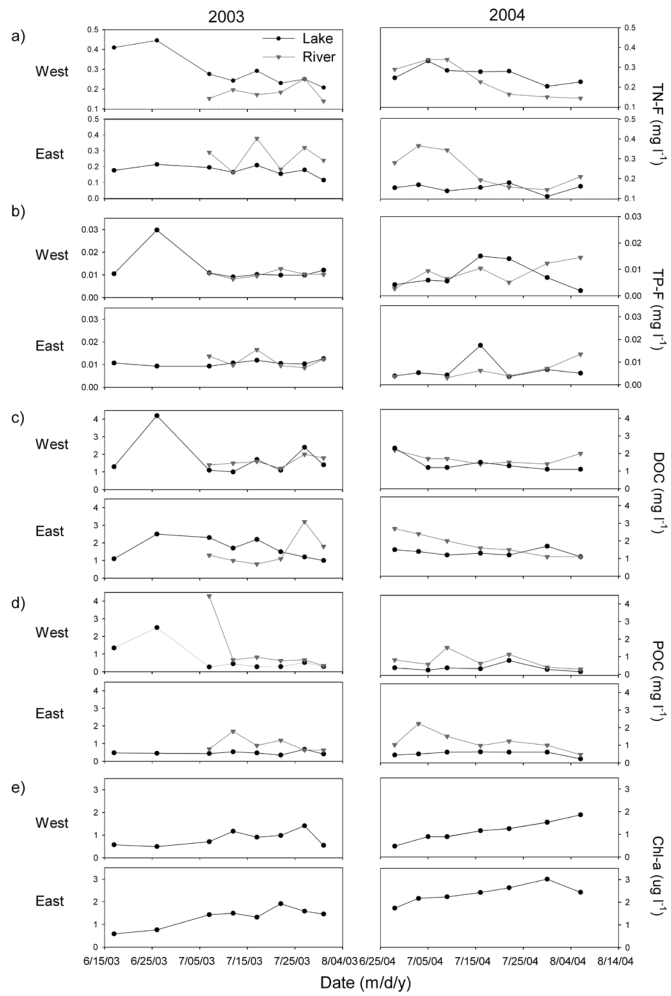

FIG. 6. Seasonal trends of major nutrients and Chl-a in lakes (darker dotted lines) and rivers (lighter dotted lines) in 2003 (left) and 2004 (right). Note that river Chl-a measurements are not included because abundant particulate mineral and organic matter on filters during high-flow periods precluded accurate Chl-a measurements.

predominantly autochthonous carbon is not apparent in the 2003 samples, but in that year sampling concluded approximately one week earlier and ice cover persisted longer than in 2004. However, a trend toward lower POC:Chl-a ratios is apparent through the 2003 season.

Controls on Aquatic Productivity

Calculated TN:TP ratios did not conclusively point to either N or P as limiting, and they suggest that an increase in one or the other would not be sufficient to boost productivity. The relatively high TN:TP ratios at Cape Bounty are common in oligotrophic systems and reflect the nutrient sources of undisturbed watersheds, which export more N than P (Downing and McCauley, 1992). Poor correlations between N or P and Chl-a in lakes and ponds across the High Arctic are common and point to factors other than nutrient limitation as controls on primary productivity (e.g., Lim et al., 2001; Michelutti et al., 2002; Antoniades et al., 2003a; Keatley et al., 2007). At Cape Bounty, higher nutrient concentrations and lower Chl-a levels in West Lake than in East Lake suggest the same interpretation. Although parallel increases in Chl-a and air temperature further suggest temperature may be controlling productivity, Chl-a concentrations were higher in 2004, when mean air and water temperatures for the sampling period were lower (air 2.3˚C and water 1.9˚C) than in 2003 (4.1˚C and 2.5˚C). Hence, we propose that greater inflow and the consequent earlier ice breakup in 2004 advanced and prolonged the lake growing season, resulting in greater aquatic productivity. In addition, greater turbulence due to higher discharge likewise produced a more favourable environment for planktonic productivity.

Chl-a levels from East Lake were almost twice those of West Lake in both years. Field observations indicate the presence of a late-lying snowbank that drains through a densely vegetated slope on the north shore of East Lake, and more frequent observations of fish along this shore area provide anecdotal support that East Lake is more productive. However, nutrient concentrations are higher in West Lake, a fact that might be attributed to a more vegetated West catchment (Atkinson and Treitz, 2007) and the associated potential for greater nutrient transport. However, this explanation is not supported by our data, which indicate higher nutrient concentrations in East River than in West River. Instead, higher Chl-a levels and lower nutrient concentrations in East Lake suggest nutrients were more readily sequestered for primary production there than in West Lake (Wetzel, 2001). This idea is further supported by West Lake's higher levels of DIN, the most readily assimilated forms of nitrogen ($NO_3NO_2 + NH_3$), in both years.

Basin morphology might account for the difference in lake productivity, as East Lake is slightly shallower and has a greater surface area than West Lake. As a result, water temperatures are higher and the littoral zone notably broader than in West Lake. In addition, East Lake experienced greater inflow and earlier lake-ice deterioration and breakup, thus gaining pelagic habitat sooner and for longer each growing season than West Lake. Hence, the hypothesis that higher discharge and earlier ice breakup in 2004 resulted in greater primary productivity (Chl-a) than in 2003 is further supported by the fact that productivity was higher in East Lake than in West Lake in both years.

Our observations support the strong influence of lake ice on Arctic aquatic productivity proposed by Brylinski and Mann (1973) and advanced by Smol (1983). Climate amelioration and associated changes in the length of the growing season are considered the primary cause of recent changes in algal and invertebrate assemblages across the circumpolar Arctic (Smol et al., 2005). Aquatic ecosystem changes associated with other factors, such as elevated atmospheric nitrogen deposition, have also been attributed to a synergistic effect with warmer climatic conditions (Wolfe et al., 2006). However, distinct responses to nutrient enrichment without apparent changes in ice cover have also been observed (e.g., Schindler et al., 1974a; Douglas et al., 2004), suggesting that although lake ice conditions limit productivity, they do not exclusively control it.

The Influence of River Runoff on Lake Water Chemistry

An influx of dilute runoff during the peak flow period did not dilute the lake water, which was more solute-rich than the river water. The gradual increase in river solute concentrations through the 2004 season, despite a decline in discharge, revealed an inverse relationship commonly observed in Arctic catchments (e.g., Stewart et al., 2005). This pattern implies that the spring freshet is not an important mechanism for solute delivery. However, gradual increases in solute concentrations over the season were offset by higher spring discharge; as a result, the highest flux rates of solutes occurred early in the season. In other systems, the limited impact of inflow on lake solute concentrations has been attributed to the fact that dilute runoff does not mix readily with the denser, solute-rich lake water below; instead, the dilute inflow travels over or just under the lake ice and is eventually lost as outflow (Schindler et al., 1974b; Bergmann and Welch, 1985). At Cape Bounty, density differences likewise inhibited mixing, but in this case high spring discharge and suspended sediment concentrations generated underflow conditions (Cockburn and Lamoureux, 2008b). The impact of subsequent increases in solute concentrations in runoff as the melt season progressed were mitigated by a decline in discharge (i.e., reduced solute fluxes), thus minimizing the impact of increased mixing on lake concentrations as the lake ice disappeared.

The dilute nature of snowmelt captured in the 2004 seasonal trend of electrical conductivity in river runoff was likewise not reflected in the lake water chemistry. Whereas seasonal trends in ion concentrations were more subtle and gradual, lake-specific conductance indicated a distinct early-season peak. The subsequent melting of dilute lake ice and influx of dilute runoff might account for the sharp decline in lake conductivities at mid-season. A trend toward higher conductivities late in the season likely reflected greater exposure to melting channels and slopes, combined with mixing and loss to outflow of dilute lake ice. The absence in the lake profiles of higher conductivity in water at depth than at the surface may be the result of collecting profiles early in the season, while the lakes were still largely ice-covered.

Nutrient flux calculations for 2004 demonstrate a strong seasonal pattern that paralleled discharge, but as was the case with ions and electrical conductivity, fluxes were not reflected in lake concentration changes (Fig. 7). In addition, seasonal changes in river particulates (PON, POC, TP) did not translate to the lakes. These findings were consistent with the relatively large existing stocks of nutrients in the lakes compared to the seasonal river influxes. However, we know that allochthonous contributions were the primary source of organic carbon to the lakes, and evidence of the hydrologic inflows can be seen in nutrient trends from 2003, particularly for West Lake (Fig. 6).

Melt Intensity and Lake Water Chemistry

The apparent connection with river runoff in 2003 and disconnection in 2004 may be a response to the damming and ponding of snowmelt that delayed streamflow in West River in 2003. Flow began almost one week later in West River in 2003 because lower melt temperatures resulted in greater ponding behind snow dams in the more deeply incised channel of West River (Cockburn and Lamoureux, 2008a). In contrast, higher melt temperatures in 2004 produced a rapid melt that initiated streamflow without significant ponding, thus overriding differences in channel morphology. As a result, the timing of initial streamflow, peak discharge, and return to baseflow conditions were similar in the East and West rivers in 2004.

Slower melting and subsequent ponding due to low melting temperatures in 2003 increased the contact time with solutes, while maintaining hydrological connectivity over a

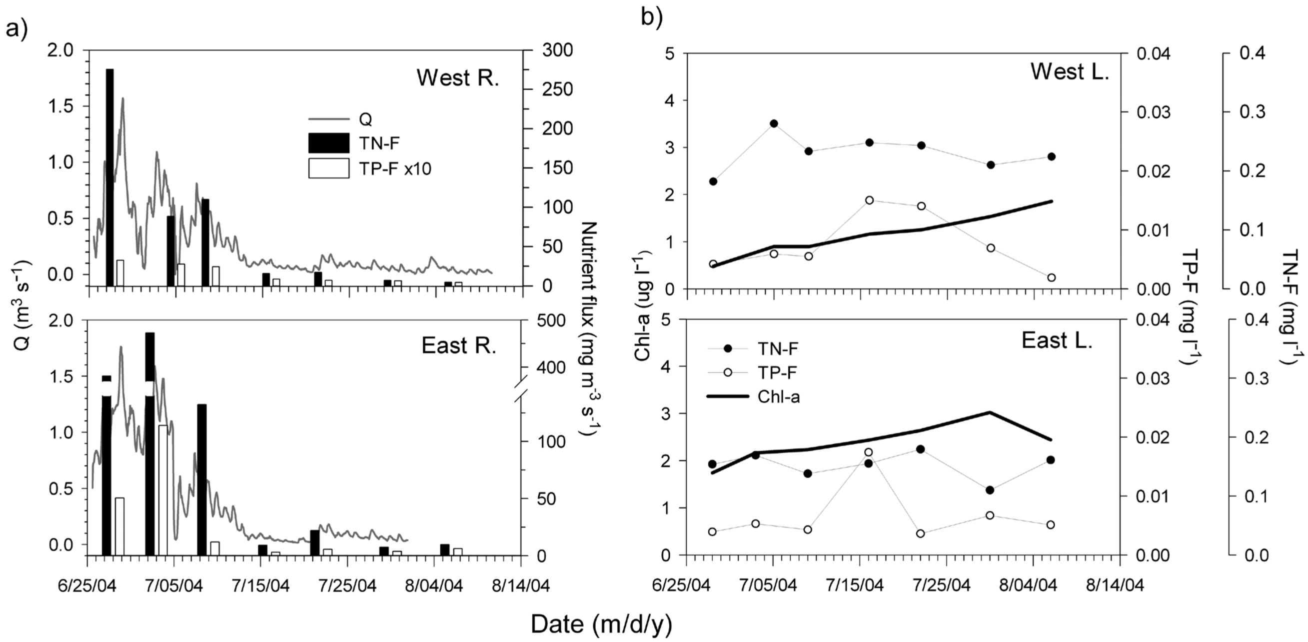

FIG. 7. Seasonal trends of (a) river discharge and nutrient fluxes and (b) lake nutrient and Chl-a concentrations for 2004. Total nitrogen (TN-F) and phosphorus (TP-F) nutrient fluxes were calculated with mean daily river discharge (Q). Note that TP-F concentrations in panel a) were multiplied by a factor of 10 for the purpose of figure clarity.

greater proportion of the catchment for a longer time, thus producing a more solute-rich runoff. The important role of melt intensity is also evident in higher particulate nutrient (POC, PON) concentrations in West River and Lake samples in 2003 compared to 2004, while particulate nutrient concentrations in the East catchment samples remained stable between the two years, despite notably higher discharge in 2004.

The differential response in lake water chemistry in the two years suggests that melt intensity is an important mechanism for the delivery of nutrients to the basin. Nevertheless, calculated turnover rates of water and nutrients demonstrate a strong sensitivity to annual discharge, whereby replacement times based on 2003 data are approximately twice as long as those based on 2004 data (Table 4). Hence, slower melt and ponding in the channel had a discernable impact on the surface water chemistry, but overall nutrient fluxes were higher with increased discharge, albeit as underflows and not immediately available in the photic zone. Thus, the implications of hydroclimatic change for the aquatic ecosystems may be different over different timescales.

Evidence suggests that the character of spring runoff has changed in recent decades (Serreze et al., 2002; Déry and Wood, 2005). Advances in the timing of streamflow may be accompanied by a less intense melt due to lower early-season melt temperatures, resulting in greater nutrient fluxes. Conversely, higher temperatures and a more rapid melt may lead to a fragmented snowpack, thus diminishing the spatial extent and connectivity of runoff and reducing the potential for nutrient transport. These hydrological factors will be balanced against a greater availability of

TABLE 4. Replacement time for lake water and total dissolved nitrogen (TN-F) and phosphorus (TN-P) stocks. Calculations were based on mean fluxes of water and nutrients from the principal streams relative to measured lake volume and nutrient concentrations in 2003 and 2004.

	West Lake		East Lake	
	2003	2004	2003	2004
Lake water (yrs)	38.6	22.4	28.0	16.7
TN-F (yrs)	61.5	25.5	18.9	10.5
TP-F (yrs)	50.2	19.9	25.7	13.9

nutrients due to enhanced terrestrial productivity and a deeper active layer, changes in soil storage, and enhanced snow ablation and melt-season evapotranspiration. Opposing trends in nutrient delivery, suspended-sediment concentrations, and lake turbidity hold additional implications for the lake ecosystem through changes in allochthonous nutrient contributions, lake mixing and nutrient re-suspension, and light regimes and UVB exposure.

CONCLUSIONS

The relatively dilute character and low nutrient concentrations in both East and West Lake may be due to the combined effect of two factors: first, the majority of runoff occurs while the ground is still frozen, and second, the relatively short growing season and lake-ice cover limit nutrient recycling and productivity. Differences between the Cape Bounty lakes and other Arctic sites are largely explained by geological setting and basin and catchment morphology.

Though the East Lake and West Lake systems are similar, they have important differences that may lead them to respond differently to changing hydroclimatic conditions. The influence of channel morphology on the timing and intensity of runoff appears to be dependent on melt conditions. Whereas a less intense melt season in 2003 resulted in more meltwater ponding in the deeper channels of West River and a delay in spring runoff compared to East River, a more intense melt in 2004 initiated streamflow rapidly and produced very similar discharge patterns in both catchments. In addition, slower melt conditions and subsequent ponding in 2003 (which increased nutrient accumulation in stream water) had a discernable impact on seasonal lake nutrient trends, particularly in West Lake. Despite this impact, overall nutrient fluxes were higher in 2004, when discharge was greater but underflow conditions prevented immediate mixing with surface waters. Hence, the importance to discharge of melt conditions and site-specific controls (i.e., channel morphology) differs in the two basins over the short and the long term, with uncertain implications for the aquatic ecosystem.

Differences in basin morphology dictated the timing of ice breakup and revealed the greater potential for primary productivity in East Lake. A longer ice-free season may elevate the importance of nutrient availability and shift greater productivity to West Lake. Furthermore, a trend toward earlier, more protracted melt seasons that result in greater channel ponding might further enhance productivity in West Lake compared to East Lake.

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