ORIGINAL PAPER

# Impacts of settlement, damming, and hydromanagement in two boreal lakes: a comparative paleolimnological study

C. A. Serieyssol · M. B. Edlund · L. W. Kallemeyn

**Abstract**   Namakan Lake, located in shared border waters in northeastern Minnesota and northwestern Ontario, was subjected to several anthropogenic impacts including logging, damming, water-level manipulations, and perhaps climate change. We used paleolimnology to determine how these stressors impacted Namakan Lake in comparison to a control lake (Lac La Croix) that was not subject to damming and hydromanagement. One core was retrieved from each lake for $^{210}$Pb dating and analysis of loss-on-ignition and diatom composition. $^{210}$Pb-derived chronologies from the cores indicated that sediment accumulation increased after logging and damming in Namakan Lake; Lac La Croix showed no significant change. Loss-on-ignition analysis also showed an increase in concentration and accumulation of inorganic material after damming in Namakan Lake; again, minimal changes were observed in Lac La Croix. Diatom communities in both lakes displayed community shifts at the peak of logging. Simultaneous, post-1970s diatom community changes may reflect regional climate warming. Taxonomic richness in Namakan Lake decreased sharply after damming and the peak of logging, and was followed by a slow recovery to taxonomic richness similar to that prior to damming. Ecological variability among post-damming diatom communities, however, was greater in Namakan Lake than in Lac La Croix. A diatom calibration set was used to reconstruct historical conductivity and total phosphorus (TP). Lac La Croix showed little historical change in conductivity and TP. In contrast, conductivity increased for several decades in Namakan Lake after damming, possibly in relation to several large fires and flooding. Total phosphorus also increased in Namakan Lake after damming, with a possible decrease in the last decade to pre-damming TP levels.

**Keywords**   Diatoms · Human impacts · BACI · Climate change · Minnesota · Ontario

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## Introduction

Humans change the landscape to facilitate their way of life. One major landscape change has been the

construction of dams to control waterways. Over 45,000 large dams were built in the last century (World Commission on Dams (WCD) 2000) and an estimated 800,000 small dams exist in the world (McCully 1996; Rosenberg et al. 2000). In the twentieth century, dams were at first seen as a tool for economic development. Dams provide a source of energy, flood control, water supply, jobs and industrial development, and can therefore be an asset for regional economies. Even though dams can generate social benefits, dams also have impacts on the natural environment. Studies have shown that dams have detrimental effects on aquatic ecosystem properties and processes including sediment transport (Vörösmarty et al. 2003), habitat fragmentation (Rood and Mahoney 1990), downstream geomorphology (Ligon et al. 1995), water quality (Petts 1984), biodiversity (Rosenberg et al. 1997; Kingsford 2000), biotic homogenization (Marchetti et al. 2001), food web interactions (Power et al. 1996), accumulation of methyl mercury (Tremblay et al. 1996; Sorensen et al. 2005), nutrient cycling and primary productivity (Rosenberg et al. 1997), and emission of greenhouse gases (St. Louis et al. 2000).

In the United States, the construction and operation of over 75,000 dams has had great impacts on the hydrology and ecology of American rivers, beyond the expected impacts of climate change (Graf 1999; Doyle et al. 2003). Most of these dams were built in the golden era of dams (1950–1970s). An early increase in dam building, however, occurred in the late 1800s and early 1900s, with small-and medium-sized dam construction (Doyle et al. 2003). Several of these dams were built in northern Minnesota in the Rainy River watershed to develop hydropower for the timber industry (UM and TCPT 2005).

The lower Rainy River watershed is controlled by three dams, which were built at the beginning of the twentieth century. Two are located on Namakan Lake and one on Rainy Lake. The dams on Namakan Lake were constructed to regulate water flow into Rainy Lake. Thus, Namakan Lake became the back-up source of water for the power-generating dam on Rainy Lake at International Falls, Minnesota-Fort Frances, Ontario. All three dams were owned and regulated first by the Minnesota and Ontario Paper Company (IJC 1934), and later were controlled by the International Joint Commission (IJC) under the 1938 Convention that provided emergency regulation of

water level (CUSA 1940). The IJC implemented additional water-level manipulations (rule curves, minimum and maximum water levels in between which actual water level should fall) between 1949 and 2000. The impacts of damming and the impact of the IJC rule curves have not been determined comprehensively. To date, the effects of these various water-level manipulations have not been fully explored (Kallemeyn et al. 2003).

Determining the many impacts of damming may involve cost/benefit analysis, biological monitoring, social interactions, or paleolimnology. Paleolimnological techniques have been used to determine the impacts of artificial dams on water bodies or the paleoecological history of reservoirs (Prat and Daroca 1983; Donar et al. 1996; Quinlan and Smol 2002; Benett and Dunbar 2003; Teodoru et al. 2006). These studies were limited in scope because they could only determine environmental changes that occurred as a result of damming and reservoir development—a cause-effect reconstruction design. However, because Namakan Lake is part of a "chain-of-lakes system," we approached our research with a more robust design, a "Before–After, Control-Impact" approach (BACI; Stewart-Oaten et al. 1986). We used a paleolimnological approach that included sediment biogeochemistry, biological proxies, and quantitative reconstructions of water quality in Namakan Lake (impacted) and Lac La Croix (control), to identify pre-European settlement conditions and variability (before), and changes due to post-settlement activities such as logging, damming and hydromanagement (after).

## Study site

Namakan Lake and Lac La Croix are shared border waters located in northeastern Minnesota (USA) and northwestern Ontario, Canada (Fig. 1). They are located in a Precambrian crystalline rock formation overlain with schist (Boerboom 1994). Both lakes are part of the Rainy River watershed and are in the Northern Lakes and Forests ecoregion (Omerick 1987). Lac La Croix is <25 km up-gradient from Namakan Lake and has a surface area of 10,170 ha with a maximum depth of 51 m. Namakan Lake, the Minnesota portion of which is located in Voyageurs National Park (USA), has a surface area of 13,788 ha

**Fig. 1** Namakan Lake and Lac La Croix and their respective coring sites (×). Dam sites indicated by *black bars*
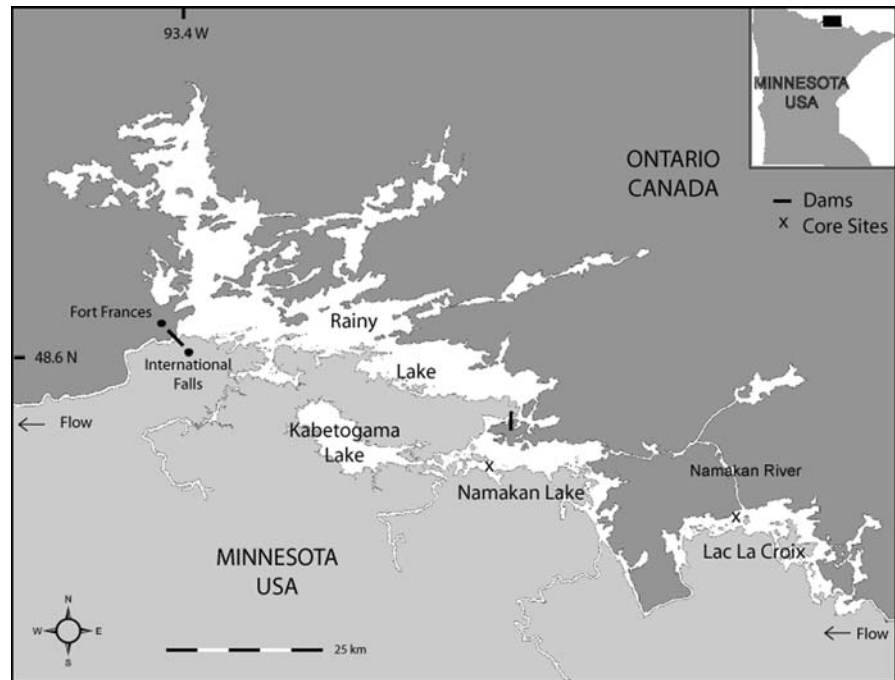


and a maximum depth of 45 m. Both lakes have complex basin morphometry and several depositional basins. The lakes are normally connected by drainage through the Namakan River, but under high water conditions by additional drainage via the Loon River. Namakan Lake and Lac La Croix had similar histories until dams were completed in 1914 on the outlets of Namakan Lake into Rainy Lake to control the water-level of Namakan Lake (Fig. 1). Lac La Croix was not impacted by these hydrological changes.

History

Cree, Monsoni, and Assiniboin tribes were the primary inhabitants of the area now included in Voyageurs National Park when European voyageurs came to explore the area for fur potential in the early 1700s (Catton and Montgomery 2000; VNP 2007). By the 1730s, however, they were replaced by the Ojibwe (Warren 1957). The era of the fur trade ended in 1870 (Birks and Richner 2004), at the same time Europeans first settled in the region (HBCIFM 1983). Extensive logging followed European settlement, with a peak at the beginning of the twentieth century (VNP 2007). As a result, Namakan Lake and nearby lakes were also points of interest for power

generation at the turn of the twentieth century (UM and TCPT 2005). In 1914, two dams were completed at Squirrel and Kettle Falls in the northern outlets leading from Namakan Lake into Rainy Lake (Fig. 1). These dams were constructed to regulate outflow from Namakan Lake into Rainy Lake and are not power-generating dams (Chandler and Koop 1995). Both dams control water storage capacity of Namakan and four other lake basins and secondarily control 51% of the supply of water used to generate power at the dam located at the outlet of Rainy Lake between Fort Frances, Ontario and International Falls, Minnesota (BLI 2007). Boise Cascade Paper Mill in Minnesota and Abitibi-Consolidated, Inc., in Ontario (formerly the Minnesota and Ontario Paper Company) have owned all the dams since their construction (IJC 1934; BLI 2007). The companies have utilized the water as a means for producing power, pulp, paper, and building products (Chandler and Koop 1995).

Namakan Lake and Rainy Lake are currently under the jurisdiction of the International Joint Commission (IJC), which was formed in 1909 by the Boundary Waters Treaty as a means of preventing and resolving disputes regarding the use and quality of Canadian/American boundary waters (IJC 2005). Although the

dams were initially under the control of their owners, both the USA and Canada have strong interest in Namakan Lake and therefore have relied on the IJC since 1925 to oversee regulation of the lake system. In 1940, the IJC became actively involved in the regulation of Namakan Lake when Canada and the United States ratified the 1938 Convention Prescribing Method Regulating the Levels of the Boundary Waters (IRLBC 1999; CUSA 1940). The Convention only allowed for IJC management of the lake under emergency regulation. Following multiple hearings and studies in the 1940s, the first actual regulating order was established in 1949. This prevented extreme flow conditions and gave the commission greater flexibility in regulating the water level of Namakan Lake with a single rule curve, which denotes where the water level of the lake shall be maintained throughout the year. After severe floods in 1950 and 1954, the single rule curve was modified in 1957 by stipulating that the curve include both minimum and maximum water-level bands. The rule curve was further amended in 1970 after high and low water events occurred between 1957 and 1968 (BLI 2007). Throughout these manipulations, lake depth variation resulting from drawdown was increased over what would have occurred naturally (IRLBC 1999).

Recently, in a report compiled and submitted by the Rainy Lake and Namakan Reservoir Water Level International Steering Committee to the IJC, it was recommended that Namakan Lake should have an earlier and greater band width during the spring refill period (i.e. high and low water level differential), a reduced overall annual fluctuation, and a modest summer drawdown (IRLBC 1999). This would allow more management control to optimize overall habitat conditions and to simulate more "natural" conditions, thereby increasing species diversity or minimizing diversity loss in the Namakan system. Under past regulations, Namakan Lake had retained water for a longer period after spring peak; discharge of these waters takes a longer time than would occur under natural conditions. Based on the recommendations of the IRLBC, the IJC adopted the recommended regulatory modifications in 2000 with the stipulation that biotic communities and habitats be monitored to determine if they respond to the new regulations. The new regulation retains water for a shorter period than previous regulations by discharging water during the summer months.

To determine if the regulations have had an impact on biotic communities, it is important to establish what the natural ecological condition was prior to dams or water regulations. Monitoring efforts have been sporadic or only recently implemented. To extend the environmental history of these aquatic systems beyond the limited monitoring data available, we used paleolimnological techniques to establish baseline conditions and to examine the timing, nature and magnitude of change over the recent past (Smol 2008). Using diatoms and geochemical indicators preserved in lake sediments, we compared the pre-damming/pre-logging condition to the post-damming condition.

## Materials and methods

### Core collection

Sediment cores were collected in the summer of 2005 from Namakan Lake and Lac La Croix (Fig. 1) using a drive-rod piston corer equipped with a 1.5-m-long and a 7.5-cm-diameter polycarbonate barrel (Wright 1991). The Namakan Lake core was recovered from Junction Bay, south of Namakan Island (48°26.028′N, 92°52.136′W); 1.31 m of sediment was recovered at a water depth of 24.07 m. The Lac La Croix core site was located just west of 27 Island and east of 41 Island (48°21.485′N, 92°10.943′W) and away from the outlet of the Namakan River; 1.82 m of sediment was recovered at a water depth of 14.9 m. Cores showed no signs of sediment disturbance. Cores were sectioned in the field into 1-cm increments, stored in air-tight containers and transported to 4°C storage.

### Sediment geochemistry and dating

For loss-on-ignition (LOI) analysis, approximately 1 g of a homogenized subsample was dried at 105°C for 24 h to determine dry density, then heated at 550 and 1,000°C to determine organic, carbonate, and inorganic matter, respectively, from post-ignition weight loss (Heiri et al. 2001). Cores were dated using $^{210}$Pb to determine age and sediment accumulation rates over approximately the last 150 years. The activity of $^{210}$Pb was determined by the activity

of its daughter [210]Po through distillation and alpha spectrometry. Dates were calculated using the constant rate of supply model (Appleby and Oldfield 1978). Dating and sedimentation errors were determined by first-order propagation of counting uncertainty (Binford 1990). Downcore dates were extrapolated to 300–400 years ago using averaged pre-settlement sedimentation rates. Twenty samples were analyzed for Namakan Lake and 16 for Lac La Croix.

### Hydrological and climate analysis

Historical water-level data for both lakes were available through Water Survey Canada (2007). Water levels were reported as monthly means above Kettle Falls (05PA003) in Namakan Lake and at Campbell's Camp (05PA011) in Lac La Croix. Data for Namakan Lake were available from 1912 to 2007 and data for Lac La Croix from 1921 to 2007 with the exception of a few data missing in the early 1920s and in the mid-1960s to early 1970s. Temperature data (1899–2006) were from Environment Canada (http://www.cccma.ec.gc.ca/hccd/) for Kenora, Ontario, Canada, located about 175 km northwest of Namakan Lake.

### Diatom analysis

Homogenized subsamples of sediment were prepared for diatom microfossil analysis using 10% hydrochloric acid to remove carbonates and 30% hydrogen peroxide to digest organic material (Renberg 1990). Subsamples were digested in an 85°C water bath for 1 h (Reavie et al. 2006). After cooling, cleaned sediments were rinsed six times with deionized water, alternating with centrifugation (3,500 rpm, 6 min), to achieve neutral pH. Cleaned material was dried onto coverslips and the coverslips mounted on microslides using Zrax® (r.i. = 1.74). Four hundred diatom valves were counted along a random transect(s) using an Olympus BX51 outfitted with full immersion DIC optics (N.A. 1.4) capable of 1,000× magnification. Identification was made to the lowest possible taxonomic category using standard floras (e.g. Krammer and Lange-Bertalot 1986–1991; Patrick and Reimer 1966, 1975), regional floras (e.g. Edlund 1994; Reavie and Smol 1998), and monographs (e.g. Camburn and Charles 2000; Fallu et al. 2000). Forty-seven samples were processed for diatoms from Namakan Lake and 36 from Lac La Croix.

### Statistical analysis

Taxonomic richness ($S$) was calculated as the sum of all taxa found in the first 400 counts from each sample (McIntosh 1967). Species turnover ($t$) was calculated using the Diamond and May (1977) calculation $t = (l + g)/(S \times \mathrm{ci})$ where $l =$ the number of species lost, $g =$ the number of species gained, $S =$ the total number of species present, and $\mathrm{ci} =$ the time interval between samples (Magurran 2004). Non-metric multidimensional scaling (NMS) using Manhattan distance was used to explore similarities of diatom communities and stratigraphic zonations among core samples (McCune and Grace 2002). In addition, diatom-based biostratigraphic zones were determined by cluster analysis using constrained incremental sum of squares (CONISS) and ZONE software (Juggins 1996). All ecological analyses except turnover should be viewed with caution, as the time intervals within each sample near the bottom of the core are greater than the intervals near the core top.

A transfer function was applied to historical diatom communities to reconstruct total phosphorus concentrations. We used a 71-lake calibration set developed by Paterson et al. (2007) that combines 16 surface sediment samples from Lake of the Woods (LOW; Ontario, Canada) and 55 surface samples (Edlund 2005) from the Northern Lakes and Forests ecoregion (NLF) of Minnesota (Omerick 1987). It is important to note that even though the samples from LOW are all from the same lake, water-chemistry varies greatly within this large morphometrically complex lake and thus, samples are considered to be independent. Four water-chemistry variables were common between these two surface sediment data sets: total phosphorus (TP), total nitrogen (TN), pH and conductivity (Cond). Total phosphorus, TN and Cond were log-transformed to approximate normal distributions. The training set included taxa that occurred in two or more lakes at an abundance >1% and taxa that occurred once at >5% abundance. We used constrained canonical correspondence analysis (CCA) to test the significance of each environmental variable on the first axis using Monte Carlo tests with 200 permutations. Forward selection and backward elimination were used to determine if each variable
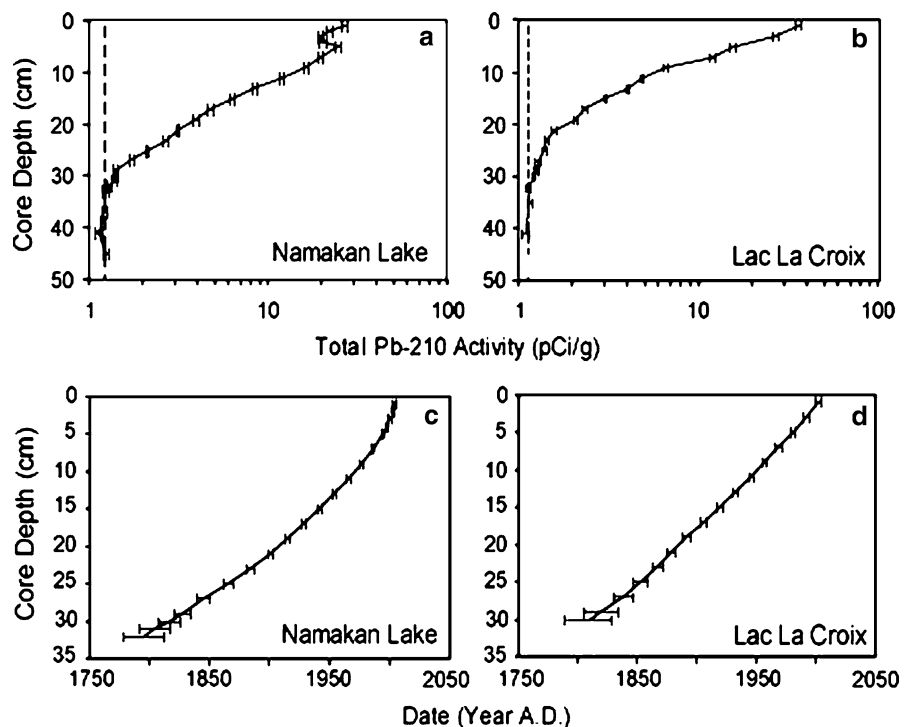
**Table 1** Summary statistics for weighted averaging model performance

| Environmental variable | $R^2$ | RMSE | RMSEP$_{boot}$ |
|---|---|---|---|
| log Cond | 0.73 | 0.14 | 0.18 |
| pH | 0.60 | 0.22 | 0.32 |
| log TP | 0.42 | 0.14 | 0.17 |
| log TN | 0.19 | 0.12 | 0.15 |

The strength of the transfer function is reported for each environmental variable in terms of $R^2$, RMSE and RMSEP$_{bootstrapped}$

was significant. Weighted averaging (WA) regression with inverse deshrinking and bootstrapping (100 permutations) cross-validation was used to develop transfer functions for TP and Cond. The WA reconstructions were performed using the program C2 (Juggins 2003). We estimated the strength of the transfer functions (Table 1) by calculating the square correlation coefficient ($R^2$) of the observed versus diatom-inferred environmental variable, the root mean square error (RMSE), and the RMSE of prediction (RMSEP) as described by Ramstack et al. (2003) and Reavie et al. (2006).
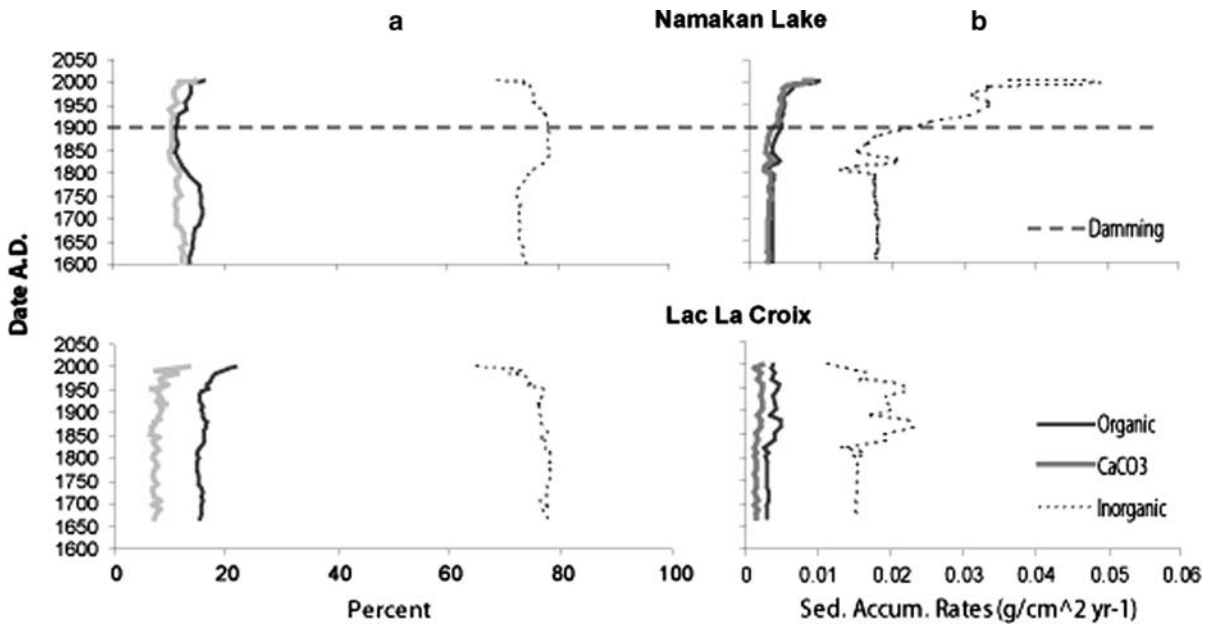
## Results

### Sediment dating and geochemistry

Radioisotopic inventories show monotonic declines in unsupported $^{210}$Pb activity in both lakes (Fig. 2). Namakan Lake and Lac La Croix sediments are similar in that they are primarily made up of inorganic matter (Fig. 3). Organic and carbonate content are 14 and 11%, respectively, in Namakan Lake with a slight increase in both after damming. Lac La Croix sediments are more organic than Namakan with 15% organic matter and only 7% carbonate content throughout the core. The sedimentation rate in Lac La Croix fluctuates around 0.02 g cm$^{-2}$ yr$^{-1}$ (Fig. 4). The sedimentation rate in Namakan Lake is similar to Lac La Croix prior to damming, but shows a threefold increase in sedimentation after damming and during water-level manipulations (Fig. 3). This increase is mostly attributed to the increase in flux of inorganic matter (Fig. 3).

### Hydrograph

It is clear that since damming, variations in water level of Namakan Lake have been greater than natural



**Fig. 2** Total $^{210}$Pb inventory in sediment cores from Namakan Lake (**a**) and Lac La Croix (**b**) as a function of core depth and core chronology (**c**, **d**) based on the CRS model (Appleby and Oldfield 1978). *Error bars* represent ±1 SD propagated from counting uncertainty

**Fig. 3** **a** Inorganic, organic and carbonate content of Namakan Lake and Lac La Croix sediments determined by loss on ignition. **b** Sediment flux of inorganics, organics, and carbonates in Namakan Lake and Lac La Croix

variations seen in Lac La Croix (Fig. 5). Water levels varied seasonally in Lac La Croix with high spring-time levels; the increases and decreases of water-level in Namakan Lake were also very regular. However, water level fluctuations in Namakan Lake have decreased in bandwidth through time from almost 4 m after damming to 1.5 m in 2000.

Diatoms

*Taxonomic richness and diversity*

Four hundred and ninety-one taxa were found in both lakes, with 367 taxa from Namakan Lake, 389 from Lac La Croix, and 270 taxa common to both lakes. Species richness in Lac La Croix samples fluctuated around 85 taxa through time, with a slight downward trend possibly related to shorter temporal increments in upcore samples (Fig. 5). In contrast, species richness in Namakan sediments fluctuated around 70 taxa prior to damming, but at the time of damming there was a sharp decrease in richness to a low of 54 taxa. Taxonomic richness in Namakan Lake slowly recovered thereafter.

Species turnover was stable during pre-European settlement in both lakes (>0.1; Fig. 5). However, the
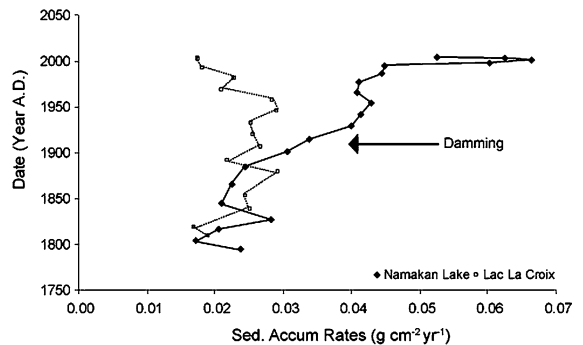


**Fig. 4** Sediment accumulation rate through time in Namakan Lake and Lac La Croix. Note increased sediment accumulation rates in Namakan Lake after damming

species turnover increased in Namakan Lake at the time of European settlement, and damming, and increased sharply at the end of the twentieth century. In Lac La Croix, few changes occurred in species turnover during European settlement and logging; however, species turnover increased in the middle and late twentieth century.

Dominant taxa in both lakes are tychoplanktonic species: *Aulacoseira ambigua*, *A. granulata*, *A. islandica*, and *A. subarctica* (Figs. 6, 7). Other major taxa found in both lakes are the planktonic species *Asterionella formosa*, *Cyclotella bodanica* var. *lemanica*,
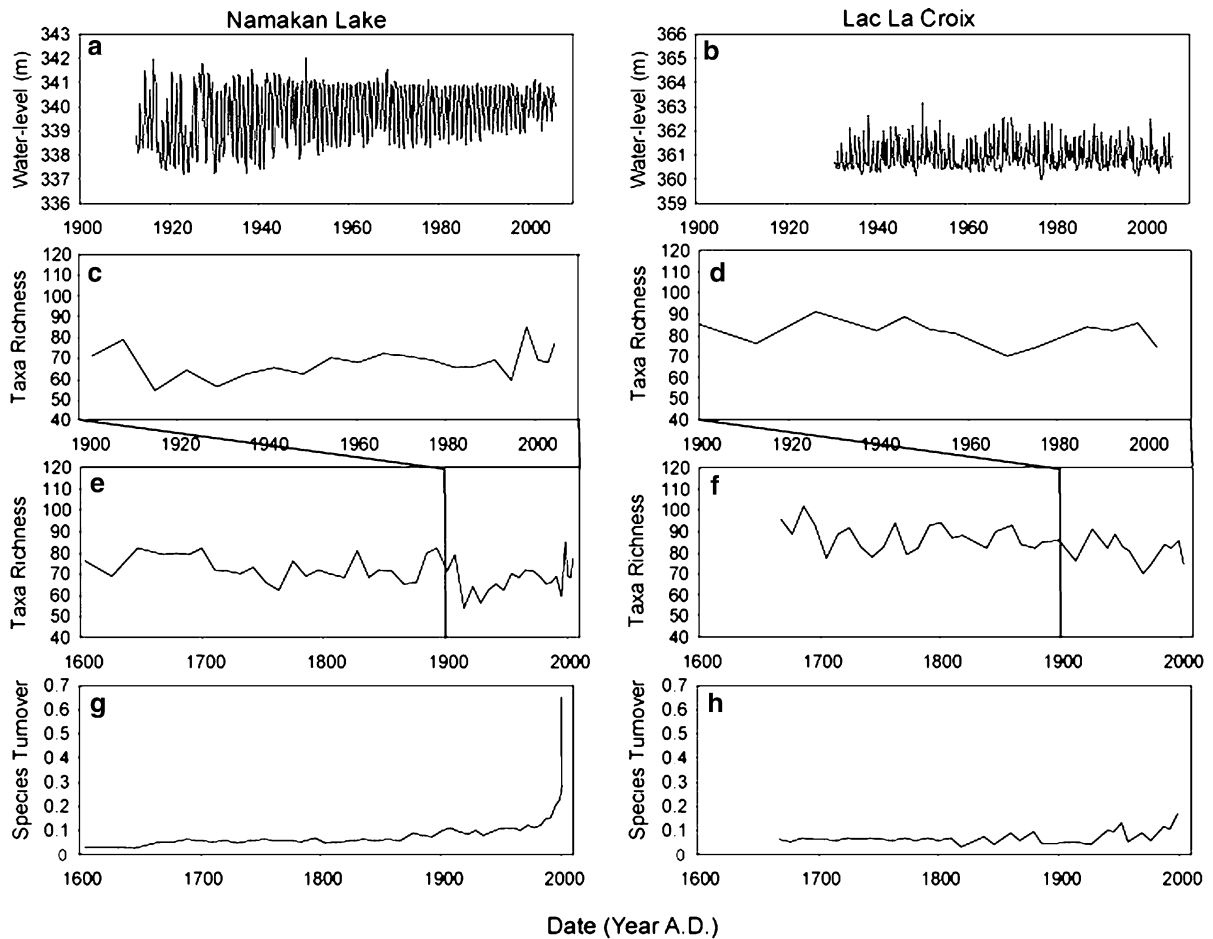
**Fig. 5** Water-level, taxa richness and species turnover in Namakan Lake and Lac La Croix through time. **a, b** Hydrograph of Namakan Lake at Kettle Falls (1912–2007) and Lac La Croix at Campbell's Camp from (1921–2007; Water Survey Canada). **c–f** Taxonomic richness (*S*) of diatoms. **g, h** Species turnover (*t*) of diatoms

*C. stelligera*, *C. pseudostelligera*, *C. stelligeroides*, and *Tabellaria flocculosa* group II. Several taxa vary in abundance between lakes. For example, Namakan Lake has the planktonic species *Cyclostephanos* sp. 1 (Reavie and Smol 1998), *Cyclostephanos invisitatus*, *C. tholiformis*, *Fragilaria capucina*, *Stephanodiscus medius*, *S. minutulus*, *S. niagarae* and *S. parvus* (Fig. 6), whereas the benthic taxa *Eolimna minima*, *Navicula aboensis*, *N. farta*, *N. submuralis*, and *Pseudostaurosira microstriata* are more abundant in Lac La Croix (Fig. 7).

*Community analysis*

An NMS analysis separated the two cores along axis 1 (Fig. 8). Each core was differentiated into three

stratigraphic zones. Zone I (1604–1901) in Namakan Lake represents samples deposited before European arrival and during early logging and European settlement. Within that zone is a sub-zone, zone Ia, which contains diatoms deposited immediately after European settlement (1856–1901). This zone is characterized by an increase in *Cyclotella pseudostelligera* and *Fragilaria capucina*, and a slight decrease in *Aulacoseira granulata* (Fig. 5). Zone II (1908–1972) has greater ecological variability, as samples become more distant from one another in ordination space. This time period represents the peak of the logging era in the region, the impacts of damming, and early water-level regulations. In zone II, several dominant taxa fluctuate in abundance: *Aulacoseira islandica*, *Aulacoseira subarctica*, *Fragilaria*
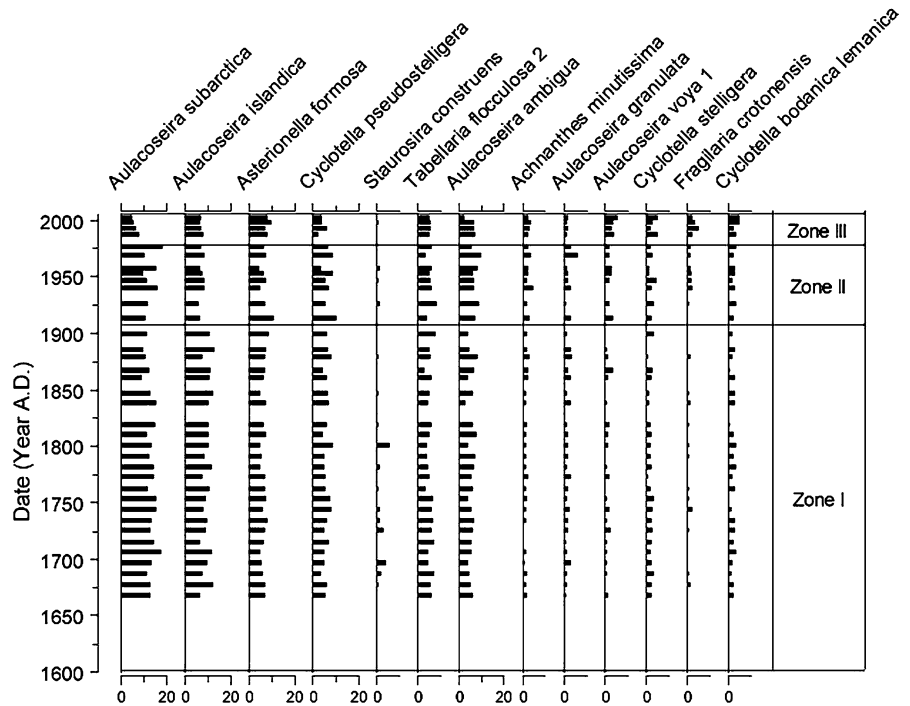
Fig. 6 Relative abundance of dominant diatom taxa from Namakan Lake core, 1600–2005 AD. Biostratigraphic zones denoted in *right panel*. Taxa occurred in at least one sample at ≥2% relative abundance
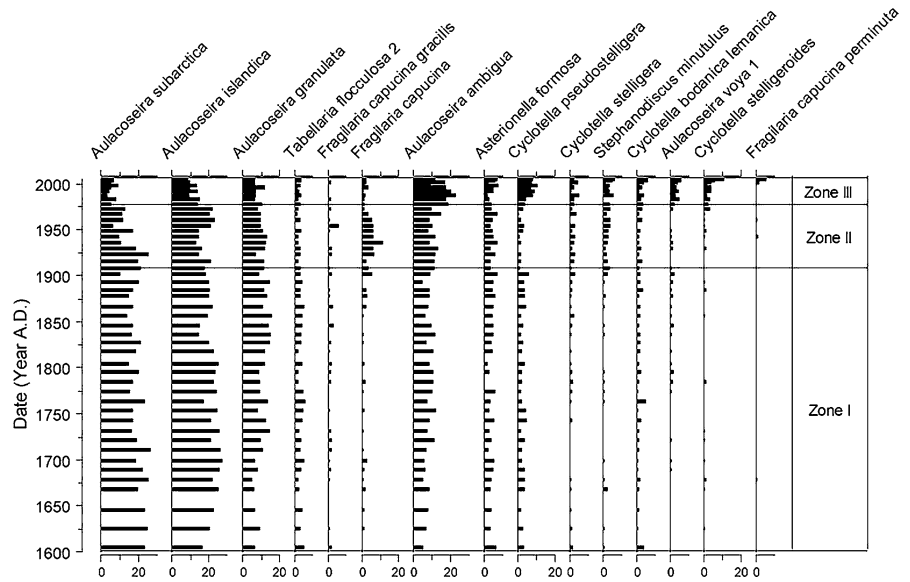


Fig. 7 Relative abundance of dominant diatom taxa from Lac La Croix, 1668–2005 AD. See Fig. 6 for details

*capucina*. There is also a gradual increase in eutrophic indicators (*Stephanodiscus minutulus* and *S. parvus*). Zone III includes post-1970s samples where again there is large ecological variability among the diatom assemblages, and a new diatom community trajectory. This zone is characterized by an increase in *Aulacoseira ambigua*, *Cyclotella*

*stelligera*, *C. pseudostelligera* and *C. stelligeroides*, and a decrease in *A. granulata*, *A. islandica*, and *A. subarctica*. These zones were confirmed using CONISS. CONISS identified two-first-order diatom biostratigraphic zones (zone I and II together, and zone III) and two-second-order subzones (zone I and II) for Namakan Lake.
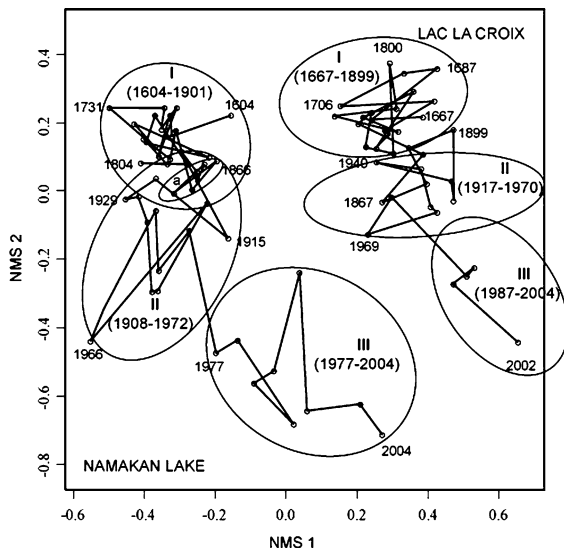
**Fig. 8** Non-metric multidimensional scaling (NMS) analysis displaying dated samples from Namakan Lake and Lac La Croix (stress 11.7%). Line segments connect samples in each core in chronological order. *Circled clusters* of samples represent diatom biostratigraphic zones in each core identified using CONISS as first order and second order zones. Shifts between clusters represent periods of significant change in diatom communities

In Lac La Croix, zone I identifies samples from before European settlement to early logging (1668–1899). Zone II represents the shift into post-European settlement and peak logging (1913–1976). No significant changes occurred in the dominant taxa between zones I and II; it is the abundance of minor taxa that separate the zones. Zone III comprises post-1980 samples. In this zone, we see shifts in abundance of several dominant taxa. *Aulacoseira subarctica* decreases, whereas *Cyclotella stelligera* and *C. stelligeroides* increase. Similar biostratigraphic zones were identified with CONISS. There were two first-order zones (zones I and II together, and zone III). Zones I and II were recognized as second-order subzones for Lac La Croix.

Diatom communities in both lakes show a clear directional shift from the 1970s onward, suggesting that both lakes responded to a broad regional change. Furthermore, these clusters are converging in multivariate space, which indicates the diatom communities in the lakes became more similar in the late twentieth century than in the past (Fig. 8). They are similar because downcore taxa, such as

*Navicula aboensis* in Lac La Croix, are no longer present at the top of the core and *Aulacoseira* spp. in Namakan Lake decreased in abundance, similar to percentages in Lac La Croix (Figs. 6, 7).

*Calibration set*

Canonical correspondence analysis indicates that conductivity, pH, TP and TN account for 20% of the variance in the modern diatom calibration set. Using constrained CCAs, all four variables had a statistically significant ($P < 0.005$) influence on the diatom distribution. Conductivity was the strongest explanatory variable (8.3%) followed by pH (6.9%), TP (4.5%) and then TN (3.5%). Axis 1 accounts for 8.7% of the explained variation in the diatom data and is most closely related to Cond and pH. Axis 2 explains 5.5% of the variance and is closely related to TP and TN.

*Reconstructions*

Transfer functions were used to reconstruct two environmental variables, Cond and TP. Even though the diatom communities in Lac La Croix have changed through time, diatom-inferred TP and Cond showed little variation over time. Diatom-inferred conductivity in Lac La Croix has fluctuated around 72 µS cm$^{-1}$ (Fig. 9). Namakan Lake conductivity fluctuated around 95 µS cm$^{-1}$ before settlement, increased sharply to 130 µS cm$^{-1}$ after damming, and then decreased after the 1960s. This post-damming increase was greater than our model error, suggesting a significant change in conductivity followed damming. Reconstructed conductivity measures in Namakan Lake are slightly higher than the modern measured conductivity levels in both lakes: 50 µS cm$^{-1}$ in Namakan Lake and 42 µS cm$^{-1}$ in Lac La Croix (Table 2).

Diatom-inferred TP in Lac La Croix remained constant around 14 µg l$^{-1}$ throughout the length of the core, whereas TP increased in Namakan Lake after damming. Namakan Lake increased to 22 µg l$^{-1}$ TP compared to around 17 µg l$^{-1}$ TP prior to damming. This increase is slightly beyond our model's error of prediction. Modern TP also appears to be slightly overestimated compared to direct measurements in the lake (Table 2).

**Fig. 9** Diatom-inferred conductivity (*Cond*) and total phosphorus (*TP*) reconstructions for Namakan Lake (*NAM*) and Lac La Croix (*LLC*). Damming and hydromanagement periods impacting Namakan Lake are displayed in the *right panel*
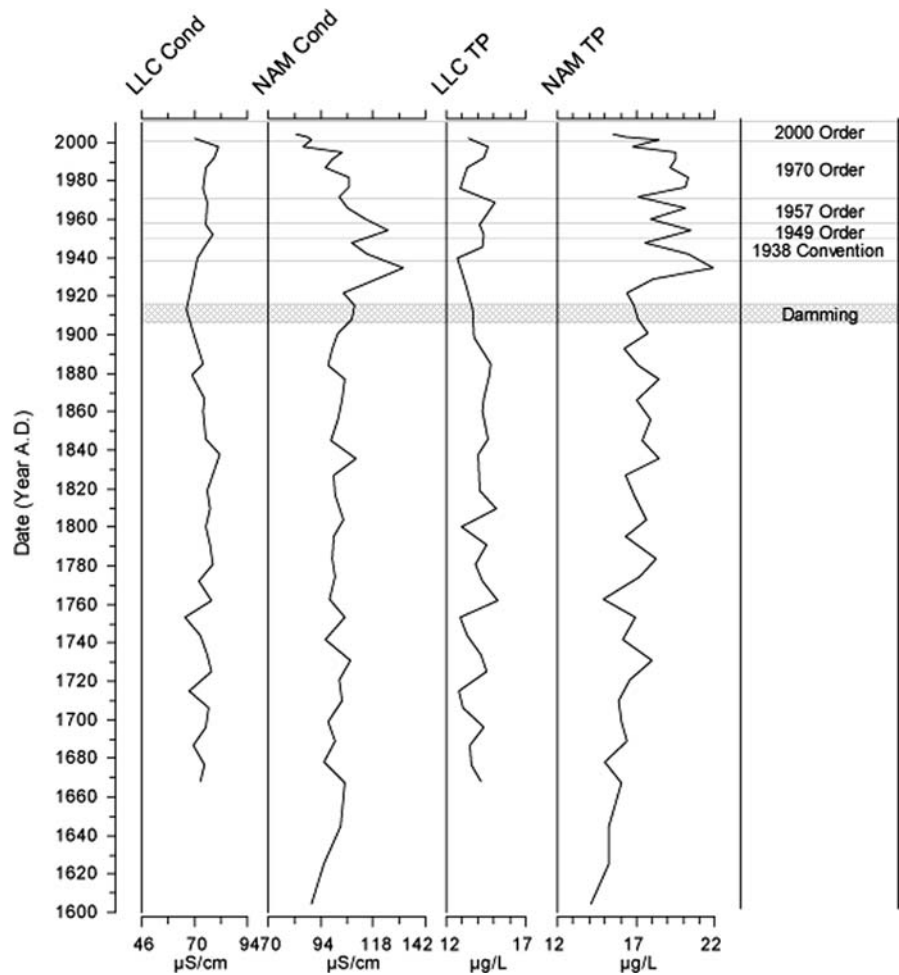


## Discussion

Damming impacted Namakan Lake with respect to sediment accumulation, geochemistry, species diversity, community composition and water quality. However, other stressors have also impacted both Namakan Lake and control Lac La Croix, notably European settlement and possibly climate warming. The different periods in the lakes' histories can be defined as follows: pre-European settlement, European settlement and logging, damming (Namakan Lake only), water-level regulation (Namakan Lake only), and post-1970s regional change.

During pre-European settlement (1600–1860 AD), Namakan Lake and Lac La Croix showed no distinct changes. Sediment accumulation, geochemistry, species diversity, community composition and water quality displayed only minor variation. Namakan Lake and Lac La Croix were slightly different biologically in that the sediments of Namakan Lake had a less diverse diatom community than Lac La Croix. Differences between the lakes are also evident in their water chemistry reconstructions. Lac La Croix has slightly lower conductance and TP than Namakan Lake.

Early logging, ca. 1880–1900 AD, likely had little impact on Namakan and Lac La Croix. Inorganic matter accumulation increased slightly in both lakes. This limited response is likely related to early logging techniques. Logs were cut only in winter and stored and transported via waterways (UM and TCPT 2005) although records are limited as to the extent of logging near and around Lac La Croix. Toward the end of the early logging period, however, changes occurred in the diatom communities of both lakes.

**Table 2** Water chemistry variables for Namakan Lake and Lac La Croix

| Environmental variable | Namakan Lake | Lac La Croix |
|---|---|---|
| Alkalinity (mg l$^{-1}$ as CaCO$_3$) | 14[a] | 12[b] |
| Lake area (ha) | 13,760[d] | 10,118[d] |
| Littoral area (ha) | 3,440[d] | 2,034[d] |
| pH | 7.2[a] | 6.5[b] |
| Secchi (m) | 2.3[c] | 3.3[b] |
| Specific conductance (μS cm$^{-1}$) | 50[a] | 42[b] |
| | 0.008–0.028 | |
| TP (mg l$^{-1}$) | 0.013[a] | 0.017[b] |
| Z max (m) | 51[d] | 45[d] |

[a] Data found in Christensen et al. (2004); data represent one observation each from May 16, 2001 except TP which represents the range and mean of 12 samples taken from May to October in 2002

[b] Data collected by the Minnesota Pollution Control Agency (2007) from observation on 10 October 1985 found on http://www.pca.state.mn.us/data/eda/

[c] Data collected during the Summer 2005 field season

[d] Data found on the Minnesota Department of Natural Resources Lake Finder website http://www.dnr.state.mn.us/lakefind/index.html

The first significant changes in the sediment record coincided with damming of Namakan Lake. After damming, Namakan Lake differed from Lac La Croix in terms of sediment geochemistry and accumulation. The increase in inorganic matter may be related to increased trapping of sediment in Namakan Lake. Dams can create a new or amplify an existing sediment sink (Anselmetti et al. 2007). The change in sedimentation rate was coincident with the building of the dams and not with a broader regional impact, as Lac La Croix showed no significant changes in sediment accumulation.

Diatom species richness declined and species turnover increased in Namakan Lake after damming. In a study modeling the effects of dams on shoreline vegetation of lakes and reservoirs, shoreline vegetation was less diverse in a dammed system (Hill et al. 1998). Wilcox and Meeker (1991) determined that macrophyte communities in Namakan Lake were less diverse than in Lac La Croix and concluded that Namakan Lake would benefit from a hydrological regime similar to Lac La Croix (Wilcox and Meeker

1991; Kallemeyn et al. 2003). Although untested with diatom communities, following the Hill et al. (1998) hypothesis that a broader water-level bandwidth led to loss of herbaceous species richness, it is possible that the recovery in diatom species richness after the 1950s is related to the change in bandwidth through time (Fig. 5). Because our core samples do not represent equal time intervals (with shorter time periods upcore), further study is needed to confirm this relationship.

Non-metric multidimensional scaling indicates that logging and damming impacted ecological variability among samples in Namakan Lake (shift from Zone I to Zone II; Fig. 8). Sample-to-sample variation (Fig. 8) and species turnover (Fig. 5) increased in Namakan Lake after damming. This pattern is not as evident in Lac La Croix; the shift in communities from zone I to zone II is more likely attributable to logging. It is not possible to differentiate the impact of damming from logging in Namakan Lake as they occurred simultaneously. Nevertheless, logging impact on control Lac La Croix seems to have resulted in less ecological variability than the combined impacts of damming and logging on Namakan Lake.

After inferring the water quality variables, it was evident that damming, rather than logging, played a greater role in the history of Namakan Lake. Lac La Croix did not display fluctuations beyond "natural" variations in water quality following logging. Thus, logging may not have played a major role in water quality changes in Namakan Lake. Namakan Lake showed post-damming increases in conductivity, with a recovery in the 1960s. Similarly, TP may be recovering in the last decade. The first peak in conductivity in Namakan Lake may be related to inundation after damming or a fire that occurred in Voyageurs National Park. A total of 16,000 ha burned in 1936 (Coffman et al. 1980). Carignan et al. (2000) attributed higher major ion concentrations in lakes that had their surroundings burned compared to lakes with unburned watersheds. Recovery in the lakes with burned watersheds seemed to occur within a few years. Thus, the first peak in conductivity may be related to the fire that occurred near Namakan Lake. The second peak occurred about 1954, after two severe floods. We believe the floods washed out the ions that remained on top of the soil after the fire.

Hambright et al. (2004), in a study linking historic lake level and land use with phosphorus accumulation in Lake Kinneret (Israel), identified an increase in P accumulation after the lake was dammed and after land-use changes. They stated that damming and hydro-management may have changed the lake's discharge regime and increased the transport of littoral materials into the lake. This would have caused a net reduction in P export from the lake because most discharge occurred during months with low epilimnetic P concentrations, thus increasing nutrient retention and P accumulation. They also reported that when the water level of natural lakes is managed, nutrient flux to sediments increases when lake volume and water level are more variable.

Perhaps the most puzzling result we found is the shift in diatom communities after the 1970s. Both lakes display higher variability and their diatom communities are increasingly similar in zone III (Figs. 6, 7, 8), which indicates a broad regional change. A history of the region indicates that regional land-use changes in the 1970s were protective and not expected to impact aquatic resources negatively. For example, the area surrounding Namakan Lake and Lac La Croix actually decreased in population (UVL 2007), parks were established, and legislation was created to provide greater protection around the lakes. Voyageurs National Park was established in 1975 (VNP 2007) and the Boundary Water Canoe Area Wilderness Act of 1978 protected a large wilderness area (including Lac La Croix) within the Superior National Forest, established earlier in 1909 (SNF 2007). On the Canadian side of the border, the Quetico Provincial Park, established in 1913, put in place the 1971 Cease of Logging Act (TQF 2007). As such, the shift in post-1970s diatom communities and greater species turnover in the sediment cores may be associated with other factors, including atmospheric deposition or climate change.

In 1982, the Minnesota state legislature passed the Acid Deposition Control Act (Minn. Statutes 116.42–116.45). This act required the Minnesota Pollution Control Agency (MPCA) to identify areas sensitive to acid deposition and develop standards to protect both terrestrial and aquatic ecosystems (MPCA 2002). In order to comply with the legislation, the MPCA conducted several studies and determined that "there is no evidence that any of Minnesota's lakes … have been acidified by acid rain" (MPCA 2002).

Alternatively, nitrate and sulfate deposition may have impacted the lakes. Whereas, the National Atmospheric Deposition Program (NADP) reports no change in nitrate concentrations since 1978 at the Marcell Experimental Forest (MN16), located 65 km south of Namakan Lake (NAD 2007), this trend is not true for sulfate deposition. Kallemeyn et al. (2003) show a decline in sulfate concentrations in interior lakes of Voyageurs National Park and the NAD (2007) shows a decrease in atmospheric sulfate deposition at the Marcell Experimental Forest since 1978. Although these decreases are coincident with the post-1970s community shifts in our cores, in a recent study on acid deposition in the northeastern United States, Driscoll et al. (2001) used a model to estimate past and predict future sulfate deposition. In the model, three peaks in post-industrialization sulfate deposition were identified (1925, 1940, and 1970s; Driscoll et al. 2001). If we attribute the high ecological variability found in zones III in Fig. 7 to changes in sulfate concentration, we might expect to see high ecological variability throughout the period when sulfate deposition varied greatly; this clearly is not the case in undammed Lac La Croix. Thus, we believe that the post-1970s shifts in diatom communities and greater ecological variability in both Namakan Lake and Lac La Croix are not linked directly to atmospheric deposition.
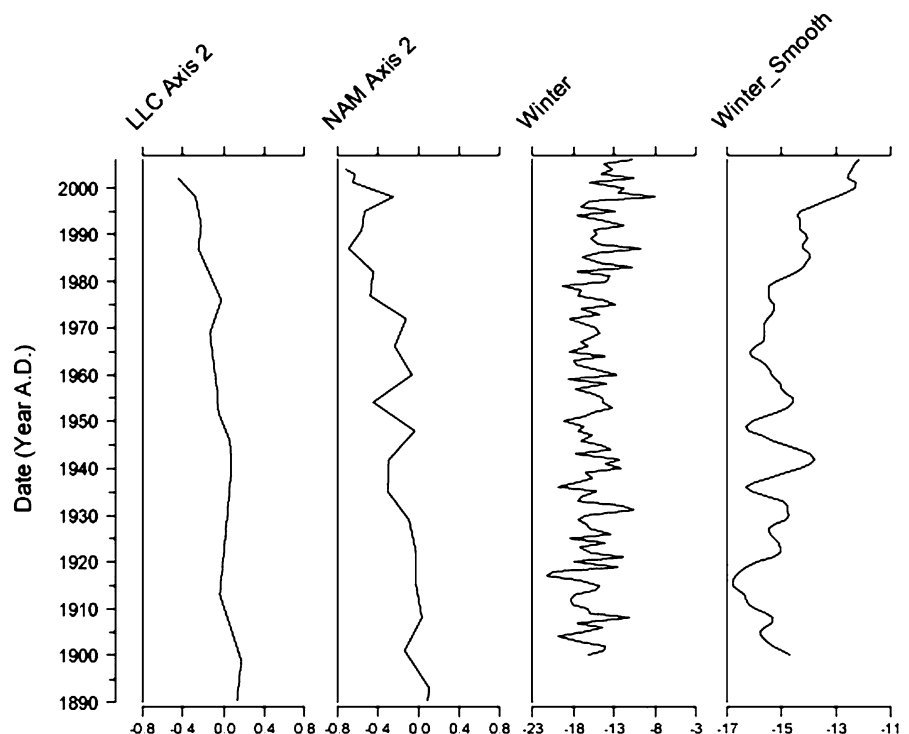
These community shifts do seem to correlate well with several indicators of climate change. Shifts in biological communities have been linked to climate change in arctic lakes (Smol et al. 2005), the northern Canadian Cordillera (Karst-Riddoch et al. 2005), the Canadian Subarctic (Rühland and Smol 2005), and in Svalbard (Birks et al. 2004). Climatic warming in the Arctic lengthens the growing season for diatoms, and therefore allows the development of more complex and diverse diatom communities (Douglas et al. 1994). Specifically, as temperature increases, the ice-free season increases, which promotes earlier stratification in lakes, which can lead to lower oxygen levels in the hypolimnion, increased nutrient supply, and enhanced light for primary producers (Rouse et al. 1997).

In a recent study on indicators of climate warming, Johnson and Stefan (2006) suggest that climate warming has also occurred in Minnesota. They determined that ice-out dates have shifted earlier from 1965 to 2002 and ice-in dates have been delayed

from 1979 to 2002 (Johnson and Stefan 2006). Long-term ice-out records for Rainy Lake (1930–2000) and Kabetogama Lake (1952–2000) in Voyageurs National Park suggested that ice-out has been occurring earlier in recent years (Kallemeyn et al. 2003). Jensen et al. (2007) support these findings with a study on the Laurentian Great Lakes. This trend to longer ice-free seasons occurs at the same time that we see community shifts and increased ecological variability in our cores.

Rising average winter temperature records can be correlated to the post-1970s community shifts. Mean winter air temperature records from Kenora, Ontario, Canada (Fig. 10), about 175 km northwest of Namakan Lake, show two post-1970s trends, increased interannual variability and increased winter annual temperature. To explore the correlation between climate change and diatom community changes, we plotted the axis 2 scores from each core based on a paired NMS analysis against annual winter average temperatures from Kenora (Fig. 10). We used axis 2 scores as they capture the major direction of within-core variation (axis 1 separates the two cores based on overall diatom community differences). Trends in temperature variation mirror the ecological variation explained by axis 2 through time in both lakes.

Furthermore, Sorvari et al. (2002) and Rühland and Smol (2005) attribute increases in *Cyclotella* spp. and sharp decreases of *Aulacoseira* spp. to longer ice-free seasons. Karst-Riddoch et al. (2005) also associate the decrease in small benthic *Fragilaria* taxa to climate warming. Similar patterns were found in the Namakan Lake sediment record, but were less obvious in Lac La Croix (Figs. 6, 7). Thus, evidence suggests that post-1970s diatom community shifts in Namakan Lake and Lac La Croix are strongly correlated to climate warming.

## Conclusion

European settlement and activities such as damming, hydro-management, and logging, impacted Namakan Lake. Coincident with logging, diatom assemblages changed and became different from the diatom communities that characterized the lake before European settlement. This change also occurred in the un-dammed, control lake, Lac La Croix. Damming and water-level manipulations on Namakan Lake created physical (increased sedimentation), ecological (decreased species richness and greater inter-sample variability) and water quality (increased



**Fig. 10** Stratigraphic diagram comparing Axis 2 scores (Fig. 8) based on Non-metric multidimensional scaling of downcore diatom communities from Namakan Lake (*NAM*) and Lac La Croix (*LLC*) against mean winter air temperature (°C) from Kenora, Ontario, Canada and a LOWESS smoothed line of same with a span of 0.8. Note scale difference in two right panels

TP and conductivity) changes. None of these changes occurred in the control lake, Lac La Croix. However, potential impacts from post-1970s climate warming were identified in both Namakan Lake and Lac La Croix based on diatom community response. Further studies are needed to test a mechanistic link between changes in the diatom community and temperature trends.

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