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Natural Resource Stewardship and Science

Determining the Historical Impact of Water-level Management on Lakes in Voyageurs National Park

Natural Resource Technical Report NPS/VOYA/NRTR—2014/920

ON THE COVER
Larry Kallemeyn steadies the ladder as Mark Edlund sections the long sediment core from Kabetogama Lake, Voyageurs National Park.
Photograph by: Claire Serieyssol Bleser

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Project Summary

^{210}Pb-dated sediment cores from four lakes along the Ontario–Minnesota (Canada–USA) border were analyzed for diatom and biogeochemical records to determine historical diatom communities, inferred water quality, core geochemistry, and sedimentation rates. Analyses targeted sediments deposited from before Euro-American settlement through the subsequent ecological impacts of post-19th century land use (logging, human population growth, beaver), climate change, damming, and water-level management (a high priority regional resource concern). The drainage basins of all lakes were heavily logged in the late 19th to early 20th century. Three lakes were dammed ca. 1914 (Rainy, Namakan, Kabetogama), whereas one lake (Lac La Croix) remained undammed. During the 20th century, pulpwood cutting continued around the dammed lakes, human population rose, beaver recolonized the region after the 1940s, and regional climate warmed after the 1970s. The dammed lakes were also subject to a series of modified “rule curves” to control water level and discharge in response to mill demands, emergency response to flooding, and mitigation of ecological impacts associated with water-level variation. Except for Rainy Lake, all border lakes had shifts in their diatom communities coincident with heavy logging in the early 20th century. Two lakes—Namakan and Kabetogama—that were dammed during the peak of logging had larger changes in their diatom communities and increased sedimentation rates. Diatom-based transfer functions were used to reconstruct historical total phosphorus and specific conductivity in all lakes. Two lakes—Lac La Croix (undammed) and Rainy Lake (the largest lake)—showed little variability in inferred water quality during the last 300 years. In contrast, Namakan Lake increased in total phosphorus and conductivity following damming while Kabetogama Lake increased in conductivity and had a slight decrease in total phosphorus. Lastly, variance partitioning analysis was used to determine the unique and interactive effects of water-level management, regional land use, and climate on diatom communities during two 20th century periods, pre- and post-1959. Whereas the interactive effects of climate, water-level and/or land use were large and highly significant, land use generally explained the greatest portion of variance in diatom communities from most lakes during both time periods. Although water-level management has been the primary resource concern in these border waters, water-level was never a dominant variable explaining historical changes in diatom communities. Based on variance partitioning results, other environmental stressors including landscape changes and climate variation and their interactions with each other and water level regulation must be recognized as significant drivers of recent change in the Ontario–Minnesota border lakes region.

List of Acronyms

BACI	Before-After, Control-Impact Approach
BP	Before Present
BWCA, BWCAW	Boundary Waters Canoe Area, Boundary Waters Canoe Area Wilderness
CCA	Canonical Correspondence Analysis
CONISS	Constrained Incremental Sum of Squares
CWD	Coarse woody debris
FIA	Forest Inventory and Analysis
GLO	General Land Office
IDH	Intermediate Disturbance Hypothesis
IJC	International Joint Commission
IRLBC	International Rainy Lake Board of Control
LOI	Loss-on-ignition
MANDO	Minnesota and Ontario Paper Co
MPCA	Minnesota Pollution Control Agency
NADP	National Atmospheric Deposition Program
NLF	Northern Lakes and Forests (ecoregion)
NLFLOW	Northern Lakes and Forest and Lake of the Woods
NMS	Non-metric Multidimensional Scaling
OMOE	Ontario Ministry of the Environment
PP	Provincial Park
PWQMN	Provincial Water Quality Monitoring Network
RMSE	Root Mean Square Error
RMSEP	Root Mean Square Error of Prediction
TN	Total Nitrogen

TP	Total Phosphorous
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VOYA, VNP	Voyageurs National Park
VRL	Virginia and Rainy Lake Company
WA	Weight Averaging

Project Rationale and Objectives

Recent changes in the International Joint Commission's water management plan for the Rainy Lake-Namakan Reservoir system in Voyageurs National Park (VOYA) will hopefully return the system to more "natural" hydrologic variation and are projected to reduce phosphorus loading and phytoplankton biomass. Planned monitoring efforts will attempt to document the benefits and impacts of these management changes; however, understanding the impacts requires knowledge of the environmental history of water level management and knowledge of the pre-damming conditions and natural variability of the lake system.

The most important water resource issue for Voyageurs National Park (VOYA) has been and continues to be water-level management for Rainy Lake and the Namakan Reservoir, which encompasses five lake basins. Together, these water bodies cover 40% or 32,388 ha (ca. 80,000 acres) of VOYA. Water levels in these large lakes have been controlled by a hydroelectric dam at the outlet of Rainy Lake and by regulatory dams on the two outlets of upstream Namakan Lake since the early 1900s. Whereas all of these lakes existed as natural water bodies before damming, the present-day reservoirs are larger and regulated to satisfy a variety of water users.

Because these are international waters shared by Canada and the United States, the lakes are regulated by the International Joint Commission (IJC). While the dams are regulated by the IJC, they have always been owned and operated by private industry. The IJC uses "rule curves," which are bands of permitted high- and low-water levels throughout the year, to regulate this system of lakes. The "rule curves" use larger-than-natural fluctuations in lake levels on Namakan Reservoir to maintain less-than-natural-fluctuations on Rainy Lake. The timing of the fluctuations is also different from natural cycles under the regulated system.

In the 1980s, the National Park Service (NPS), because of its concern about the effects of the regulated lakes on the aquatic ecosystem, initiated a research program to 1) assess the effects of regulation on the aquatic ecosystem, and 2) to develop alternatives to the water management program. The species and biological communities that were investigated were generally found to be adversely affected by the existing water management programs (1970 rule curves), and in particular, by the greater-than-natural fluctuations in water levels on the Namakan Reservoir (Kallemeyn et al. 1993).

In 1993, a steering committee consisting of U.S. and Canadian representatives from private industry (dam owners), the public, and government agencies submitted a final report and updated water management recommendations to the IJC. The IJC, through its International Rainy Lake Board of Control (IRLBC), evaluated these recommendations, particularly as to their potential effect on the reservoir and downstream interests, and recommended that "rule curve" modifications should occur. The recommendations were accepted by the IJC and went into effect on 6 January 2000. They will provide a hydrologic regime more closely approximating that with which the species and communities in these waters evolved.

Especially pertinent to the proponents of rule curve change, was the section of the 2000 Order in which the IJC stated that it was subject to review after 15 years and that "the review shall, at minimum, consider monitoring information collected by natural resource management agencies and others during the interim that may indicate the effect of the changes contained in this Supplementary Order." During this period, it is incumbent on the natural resource agencies, including the National Park Service, to document if the rule curve changes have produced the anticipated biological benefits. Although benefits are not a given, if they are not documented it is conceivable the IJC could return to rule curves that maximize hydropower production.

A model suggests that a water management program that more closely approximates natural conditions, like the 2000 rule curves, may lower phosphorus loadings in Namakan Reservoir (Kepner and Stottlemyer 1988). This was attributed to (1) a reduction in bottom areas exposed by drawdown and accompanying sediment-water interactions, (2) reduced nutrient inputs resulting from die-off of littoral vegetation, and (3) reduced nutrient concentrations because of volume changes. The authors, stressing the model was uncalibrated, concluded a return to a more natural hydrological system could reduce phytoplankton biomass and accompanying primary production. These changes, in turn, could have ramifications throughout the food web.

In accordance with the IJC ruling and to test the Kepner and Stottlemyer (1988) model, the USGS monitored water quality in the Rainy-Namakan Reservoir system from 2001 to 2003 to determine if the changes in reservoir operation (2000 rule curves) affected algal primary production (chl-*a*), nutrient enrichment (total phosphorus), and major ion chemistry (Christensen et al. 2004). Sampling was conducted every two weeks during the open water season at three sites in Kabetogama Lake, in Black Bay, the main basin of Rainy Lake, and at one reference site in both Sand Point and Namakan Lakes. Monitoring of chl-*a* and total phosphorus has been continued in subsequent years. Also in 2004, a 3-year interdisciplinary monitoring program was initiated to assess the effects of the 2000 rule curves on the fish communities, benthic communities, muskrats, loons, grebes, and wetland vegetation.

While the water quality monitoring program may document the potential nutrient reductions, lack of historical data on the Namakan-Rainy system prevents understanding the context of changes resulting from the 2000 rule curves in relation to the natural variation and pre-damming conditions in the lakes. Water quality and phytoplankton information that exists from these lakes is sporadic and dates from well after the establishment of the dams. Herein we report on a paleolimnological reconstruction of environmental conditions from multiple lakes of varying management history and catchment size within and near the reservoir system to obtain the long-term and quantitative historical information that resource managers need to determine (1) the environmental impacts of damming and management and (2) whether the 2000 rule curves produce the changes and benefits expected by returning the system to a more natural hydrologic state. Analysis of the sediment cores provides historical background on pre-European lake conditions and variability, and also provides a temporal record of changes that have occurred in each of the lakes as a result of natural and anthropogenic perturbations resulting from damming, management, and land use changes (Charles et al. 1994).

Information gained from sediment records from multiple lake systems, in addition to providing an assessment of the effects of impoundment and water regulation, will be further used to assess the timing, magnitude, and extent of natural lake response due to land use changes such as logging, fire history, population growth, climate change, and beaver activity in the surrounding catchments over the last 500 years (Swain 1973, Coffman et al. 1980, Naiman et al. 1988, Davis et al. 1998, 2000).

Earlier investigations on sediment cores from smaller, unmanaged lake systems in Voyageurs National Park show historical changes in water chemistry and sedimentation rates. For example, changes and magnitude of diatom-inferred water color from environmental reconstructions on dated sediment cores from Tooth and Locator Lakes closely track one another in both timing and magnitude (Ramstack unpublished) despite the lakes being separated by 25 km. The inferred decrease in water color in the 1930s (hence, decreased DOC) is consistent with the measured response of similar lake systems in boreal Canada to recent climatic warming (Schindler et al. 1990, 1996a,b). Increased color in both Tooth and Locator Lakes in recent decades may also be a response to the reestablishment of beaver in VOYA since the 1940s (Naiman et al. 1988) due to modified hydrologies from flooding and wetland establishment (Engstrom 1987). Winkler and Sanford (1998) documented historical lake response in the early 20th century to logging in Voyageurs' Cayou Lake basin; increased abundance of diatom species preferring nutrient-enriched waters followed the onset of logging in 1917. From these data, it is clear that the current paleolimnologic investigation of the Rainy-Namakan system can provide a model of natural lake variability and their differential responses to hydrologic management, climate, and land use at regional and catchment size-dependent levels (George et al. 2000).

The primary objectives of this paleolimnological study are: 1) a historical quantitative reconstruction of the ecological impacts of damming and water level manipulation on the Rainy Lake-Namakan Reservoir system over the last 100 years, 2) a historical reconstruction of coincident environmental changes in an upstream "control" large lake system, Lac La Croix, 3) the determination of regional and scale-dependent pre-damming/pre-European "natural" lake conditions and historical lake response variability during the last 500 years due to catchment history, lake ontogeny, and climate change, and 4) assemblage of an annotated bibliography on the land use, water management, and resource management of the Rainy River region.

Part I: Impacts Of Settlement, Damming, And Hydromanagement In Two Boreal Lakes: A Comparative Paleolimnological Study

Abstract

Namakan Lake, located in shared border waters in northeastern Minnesota and northwestern Ontario, has been subject to several anthropogenic impacts including logging, damming, various water-level manipulations and potential 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 analysis of ^{210}Pb inventory, loss-on-ignition, and diatom composition. ^{210}Pb isotope analysis of the sediment 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 percentage 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 and simultaneous post-1970s diatom community change that may reflect patterns of regional environmental climate warming. Taxonomic richness in Namakan Lake sharply decreased after damming and the peak of logging, and was followed by a slow recovery similar to taxonomic richness prior to damming. However, ecological variability among post-damming diatom communities 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 in Namakan Lake after damming for several decades possibly in relation to inundation and several large fires. Total phosphorus also increased in Namakan Lake after damming with a possible decrease in the last decade back to pre-damming TP levels.

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I. Introduction

Humans change the landscape in order 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 (WCDC 2000) and an estimated 800,000 small dams exist in the world (McCully 1996, Rosenberg et al. 2000). In the 20th century, dams were at first widely seen as a tool to economic development. Dams provide a source of energy, flood control, water supply, job creation, and industrial development and therefore can be an asset for regional economies. Even though dams can have social benefits, it is also vital to understand the impacts that dams have 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 1997, Kingsford 2000), biotic homogenization (Marchetti et al. 2001), food web interactions (Power et al. 1996), the accumulation of methyl mercury (Tremblay et al. 1996, Sorensen et al. 2005), nutrient cycling and primary productivity (Rosenberg 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 American rivers hydrologically and ecologically, 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); however, an early increase in dam building 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 that were built at the turn of the 20th century. Two are located on Namakan Lake and one on Rainy Lake. The dams on Namakan Lake were put into place 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) by 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-level at which actual water-level should fall in between) between 1949 and 2000; however, the impacts of damming and the impact of the IJC rule curves have not been comprehensively determined. 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. Several studies have used paleolimnological techniques to determine the impacts of artificial dams on water bodies or the paleoecological history of a reservoir (Prat and Daroca 1983, Donar et al. 1996, Quinlan and Smol 2002, Benett and Dunbar 2003, Teodoru et al. 2006). These studies have been limited in their scope because they could only determine environmental changes that occurred as a result of damming and reservoir development—a cause-and-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 use a paleolimnological approach including sediment biogeochemistry, biological proxies, and quantitative reconstructions of water quality targeting 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).

Site Description and Background

Study site

Namakan Lake and Lac La Croix are shared border waters located in northeastern Minnesota (USA.) and northwestern Ontario (Canada) (Figure I-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 less than 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 and 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 by 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 (Figure 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); however, by the 1730s 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 20th century (VNP 2007). As a result, Namakan Lake and nearby lakes were also points of interest for power generation at the turn of the 20th 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 (Figure 1). These dams were constructed as a means 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).

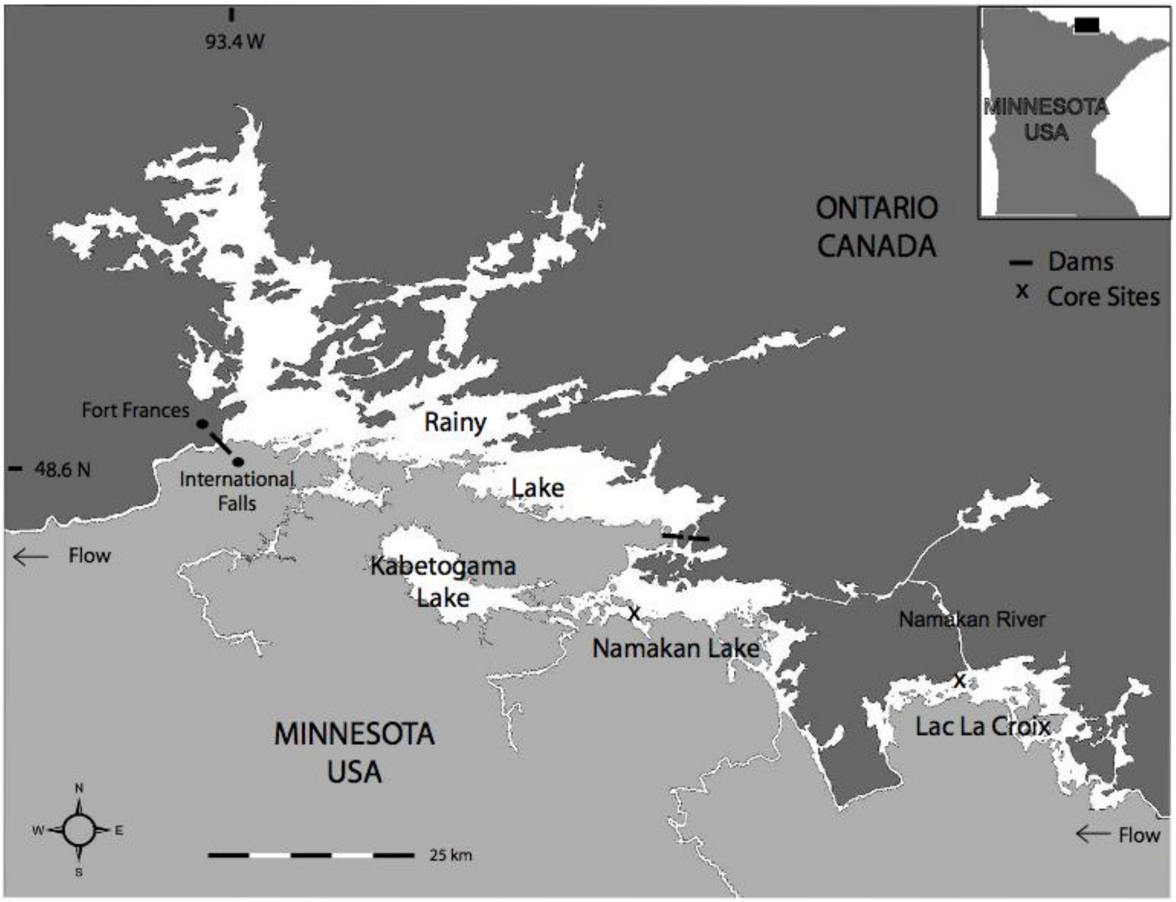

Figure I-1. Namakan Lake and Lac La Croix and their respective coring sites (x). Dam sites are indicated by black bars.

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 in regards to the use and quality of Canadian/American boundary waters (IJC 2005). Although the dams were initially under the control of their owners, both the U.S.A. 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 band. The rule curve was further amended in 1970 after high and low water events occurred between 1957 and 1968 (BLI 2007). Throughout these manipulations, the amount of 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 & 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.

However, in order to determine if the regulations have had an impact on biotic communities, it is important to establish what the natural ecological condition was (i.e. with no 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 available monitoring data, 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 determine what the pre-damming/pre-logging condition was compared to post-damming condition.

I. Material and Methods

Core Collection

Sediment cores were collected in the summer of 2005 from Namakan Lake and Lac La Croix (see Figure I-1) using a drive-rod piston corer equipped with a 1.5-m-long and 7.5-cm-diameter polycarbonate barrel (Wright 1991). The Namakan Lake core—1.31 m of sediment collected at a water depth of 24.07 m—was recovered from Junction Bay, south of Namakan Island (N48º26.028', W92º52.136'). The Lac La Croix core site was located just west of Twentyseven Island and east of Fortyone Island (N 48º21.485', W92º10.943') and away from the outlet of the Namakan River. Here, we recovered 1.82 m of sediment at a water depth of 14.9 m. Cores showed no signs of sedimentary 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 one gram of a homogenized subsample was dried at 105˚C for 24 hours to determine dry density, then heated at 550˚C and 1000˚C to determine organic, carbonate, and inorganic matter, respectively, from post-ignition weight loss (Heiri et al. 2001). Cores were dated using ^{210}Pb, in order 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 product ^{210}Po through distillation and alpha spectrometry methods. Dates were calculated using a constant rate of supply model (Appleby and Oldfield 1978). Dating and sedimentation errors were determined by first-order propagation of counting uncertainty (Binford 1990). Down-core dates were extrapolated to 300–400 years B.P. 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 and 30% hydrogen peroxide to digest organic material (Renberg 1990). Sub-samples were digested in an 85ºC water bath for 1 hour (Reavie et al. 2006). After cooling, cleaned sediments were rinsed six times with deionized water, alternating with centrifugation (3500 RPM, 6 min) to achieve a 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 random transects using an Olympus BX51 outfitted with full immersion DIC optics (N.A. 1.4) capable of 1000x 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 iconographs (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:

$$t = (1 + g)/(S \times ci)$$

Where l = the number of species lost, g= the number of species gained, S= the total number of species present, and 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 interval within each sample at the bottom of the core is greater than the intervals at 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 greater than 1% and taxa that occurred once at greater than 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 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 I-1) by calculating square correlation coefficient (r^2) of 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).

Table I-1. Summary statistics for weighted averaging model performance. The strength of the transfer function is reported for each environmental variable in terms of r^2, RMSE and $\text{RMSEP}_{\text{bootstrapped}}$

Environmental variable	r^2	RMSE	$\text{RMSEP}_{\text{boot}}$
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

I. Results

Sediment Dating and Geochemistry

Radioisotopic inventories show monotonic declines in unsupported ^{210}Pb activity in both lakes (Figure I-2). Namakan Lake and Lac La Croix sediments are similar in that they are primarily made up of inorganic matter (Figure I-3). Organic and carbonate content are 14% and 11%, respectively, in Namakan Lake, with a slight increase of 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 (Figure I-4). The sedimentation rate in Namakan Lake is similar to Lac La Croix prior to damming, but shows a three-fold increase in sedimentation after damming and during water-level manipulations (Figure I-3). This increase is mostly attributed to the increase in flux of inorganic matter (Figure I-3).

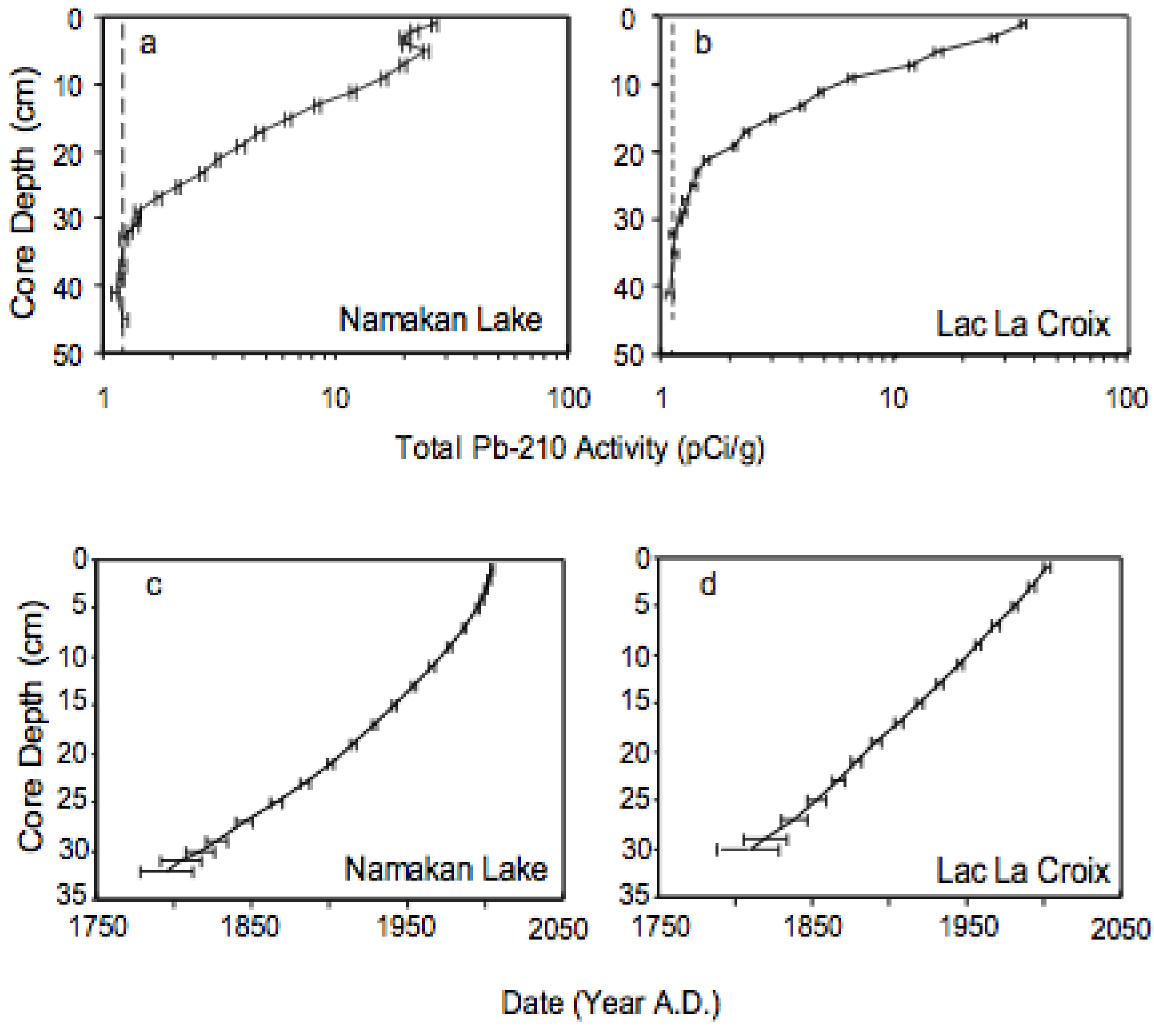

Figure I-2. Total ^{210}Pb inventory in sediment cores from Namakan Lake (a) and Lac La Croix (b) as a function of core depth (c) and core chronology (d). Based on the CRS model (Appleby and Oldfield 1978). Error bars represent ±1 s.d. propagated from counting uncertainty.

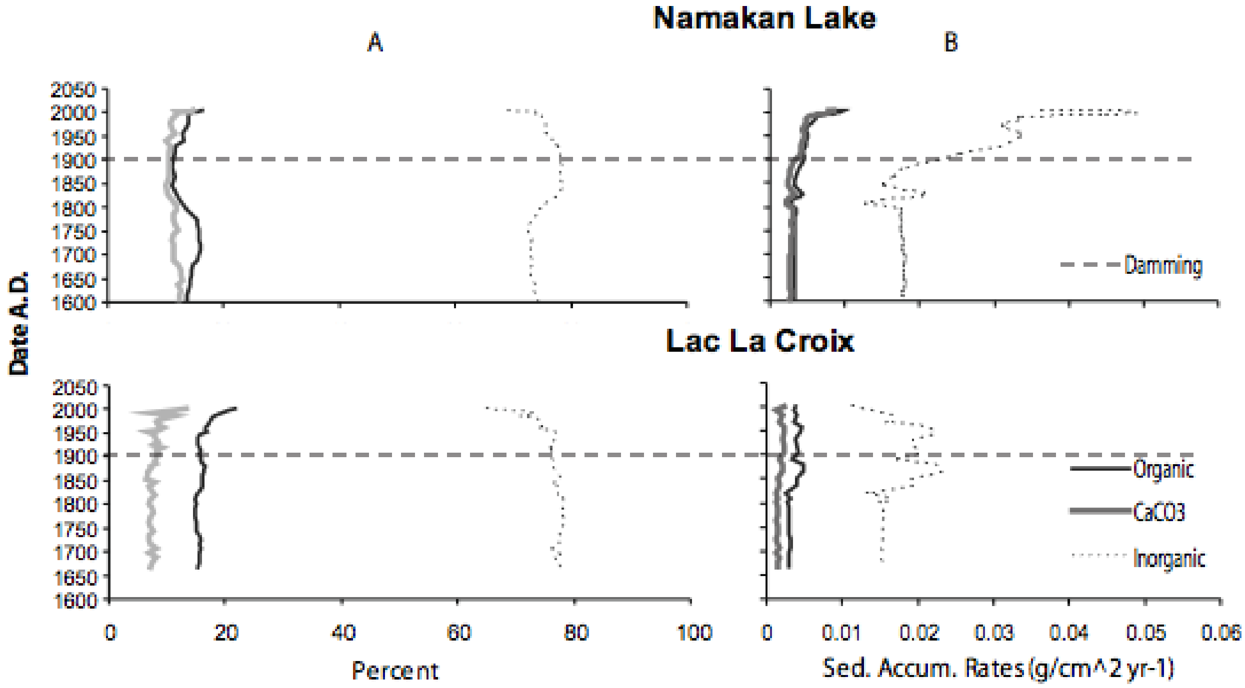

Figure I-3. Inorganic, organic, and calcium carbonate content of Namakan Lake and Lac La Croix sediments determined by loss on ignition (**A**), and sediment flux of inorganics, organics, and carbonated in Namakan Lake and Lac La Croix (**B**).

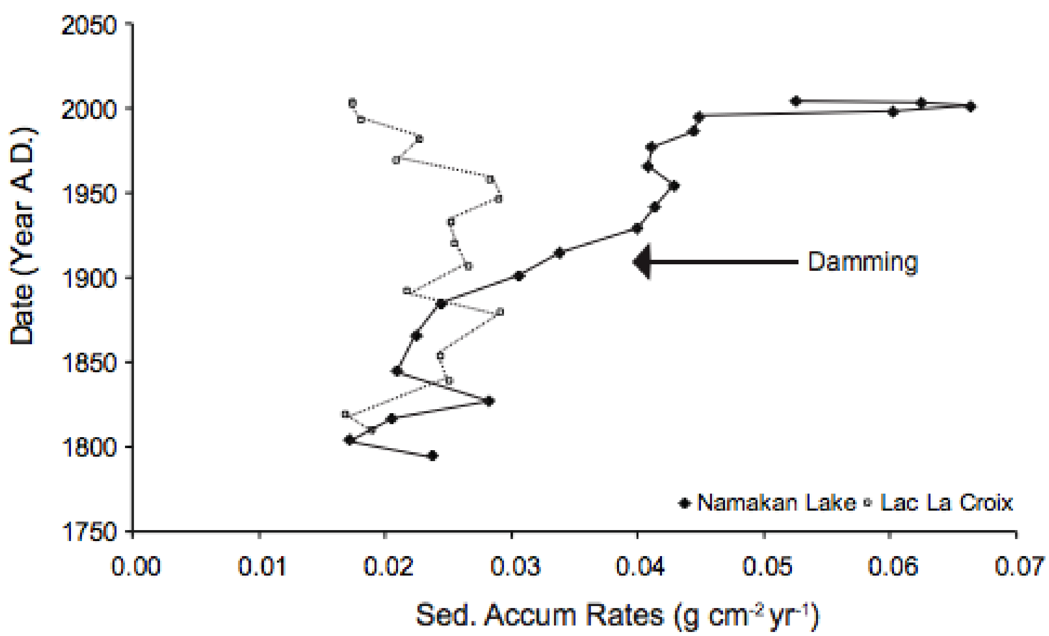

Figure I-4. Sediment accumulation rate through time in Namakan Lake and Lac La Croix. Note increased sediment accumulation rates in Namakan Lake after damming.

Hydrograph

Since damming, it is clear that the variations in water-level of Namakan Lake have been greater than natural variation seen in Lac La Croix (Figure I-5). Water levels vary seasonally in Lac La Croix with high spring-time levels; in contrast, the increases and decreases of water-level in Namakan Lake are 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.

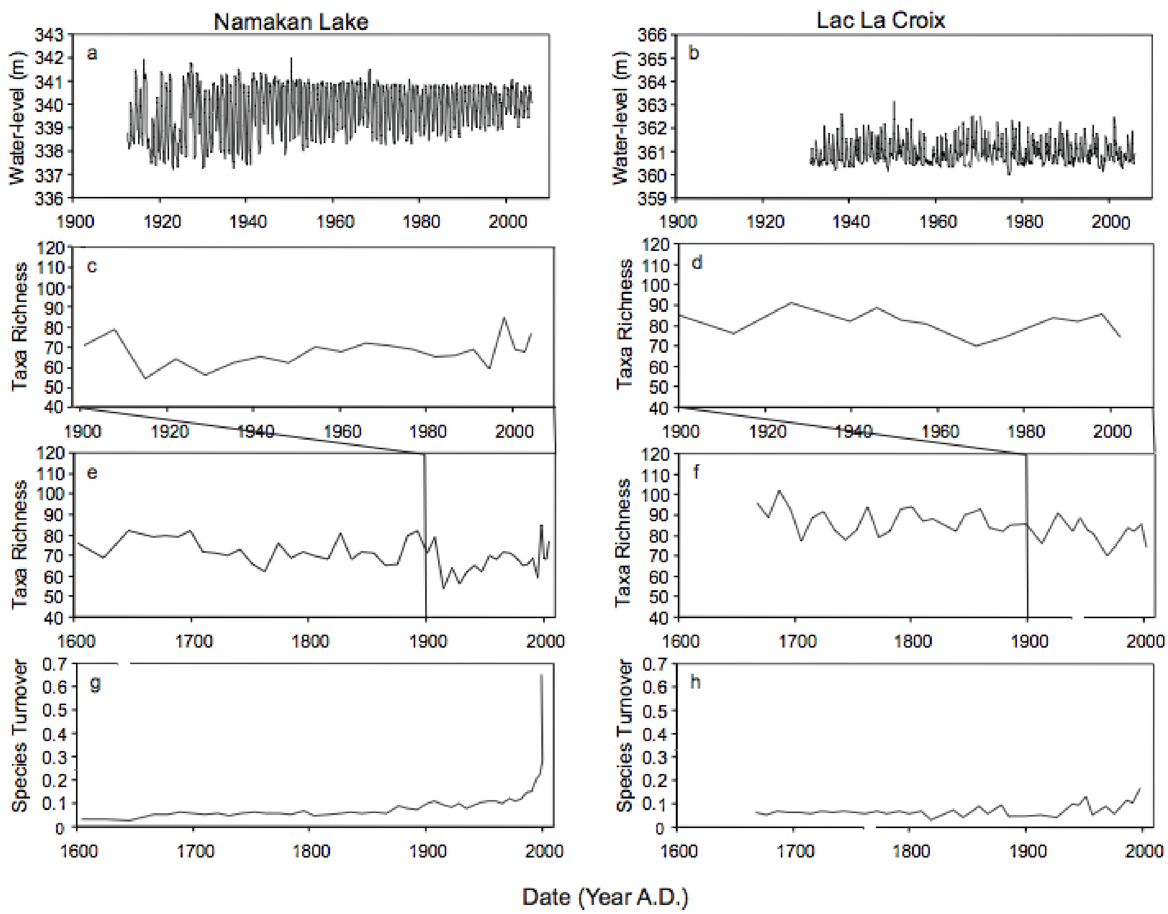

Figure I-5. (**a**) Hydrograph of Namakan Lake at Kettle Falls (1912–2007) and (**b**) Lac La Croix at Campbell's Camp (1921–2007). Data from Water Survey Canada (2007). (**c–f**) Taxonomic richness (S) of diatoms. (**g, h**) Species turnover (t) of diatoms.

Diatoms

Taxonomic richness and diversity

A total of 491 taxa was 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 up-core samples (see Figure I-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) (see Figure I-5). However, the species turnover increases in Namakan Lake at time of European settlement, damming and sharply increases at the end of the 20th century. In Lac La Croix, few changes occur in species turnover during European settlement and logging; however, species turnover increases in the mid and late 20th century.

Dominant taxa in both lakes are tychoplanktonic species: *Aulacoseira ambigua*, *A. granulata*, *A. islandica*, and *A. subarctica* (Figures I-6 and I-7). Other major taxa found in both lakes are the planktonic species *Asterionella formosa*, *Cyclotella bodanica* var. *lemanica*, *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* (Figure I-6), whereas the benthic taxa *Eolimna minima*, *Navicula aboensis*, *N. farta*, *N. submuralis*, and *Pseudostaurosira microstriata* are more abundant in Lac La Croix (Figure I-7).

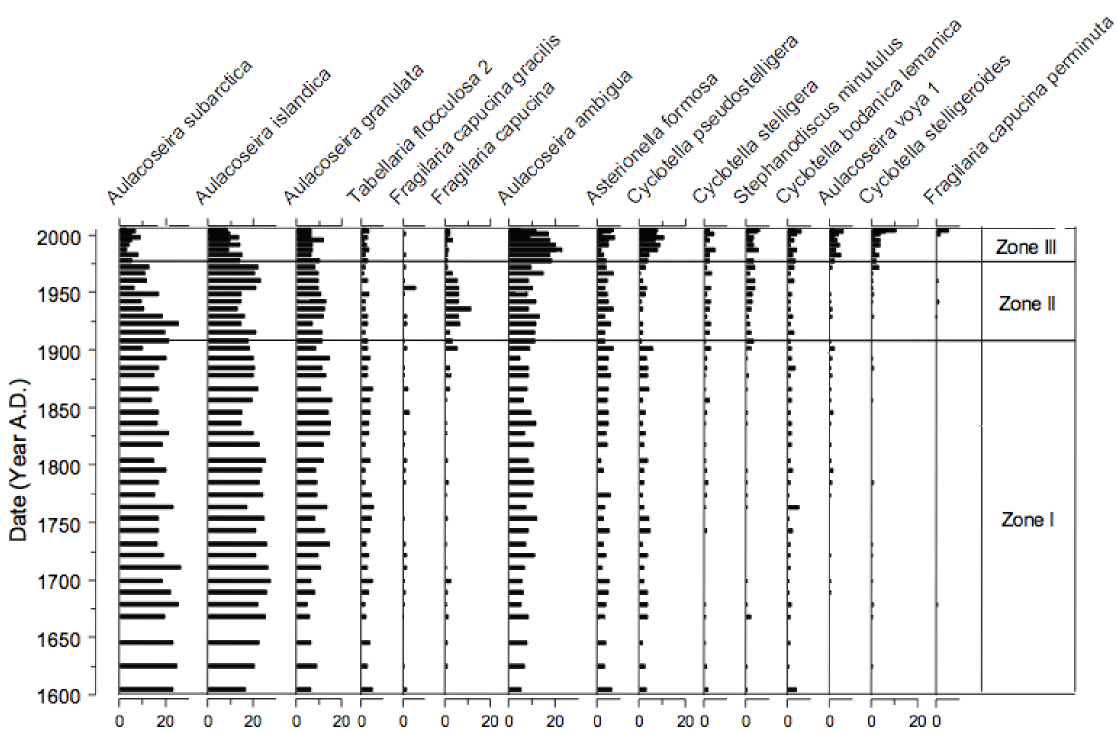

Figure I-6. Relative abundance of dominant diatom taxa from Namakan Lake core, 1600–2005 A.D. Biostratigraphic zones denoted in right panel. Taxa occurred in at least one sample at ≤2 % relative abundance.

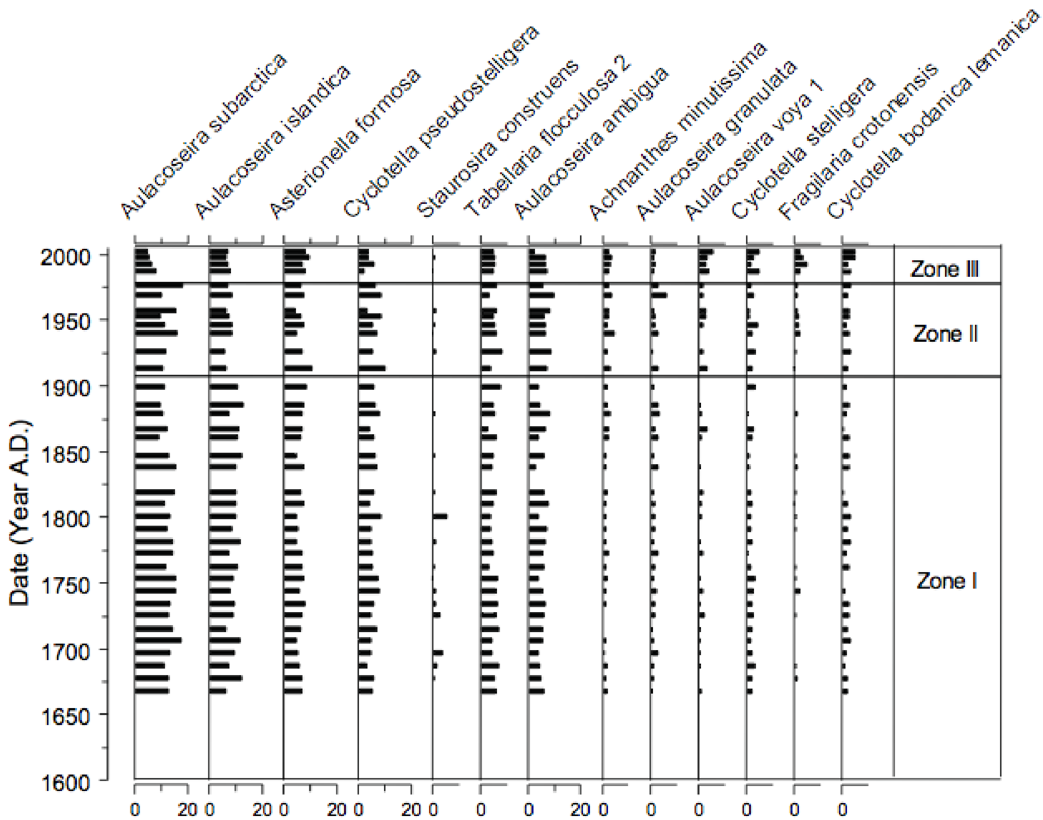

Figure I-7. Relative abundance of dominant diatom taxa from Lac La Croix, 1668–2005 A.D. See Figure I-6 for details.

Community analysis

An NMS analysis separated the two cores along axis 1 (Figure I-8). Each core was differentiated into three stratigraphic zones. Zone I (1604–1901) in Namakan Lake represents samples deposited pre-European and during early logging and European settlement. Within that zone is a sub-zone (zone Ia), which represents 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* (see Figure I-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 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.

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 of 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 in several dominant taxa. *Aulacoseira subarctica* decreases, whereas *Cyclotella stelligera* and *C. stelligeroides* increase. Similar biostratigraphical zones were identified with CONISS. There were two first order zones (Zones I and II together, and Zone III). Zone I and Zone II were recognized as second order subzones for Lac La Croix.

Diatom communities in both lakes show a clear directional shift in their community assemblages from the 1970s onward, suggesting that both lakes are responding to a broad regional change. Furthermore, these clusters are converging in multivariate space which indicates the diatom communities in the lakes have become more similar in the late 20th century than in the past (Figure I-8). They are similar because down-core 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 decrease in abundance similar to percentages in Lac La Croix (see Figures I-6 and I-7).

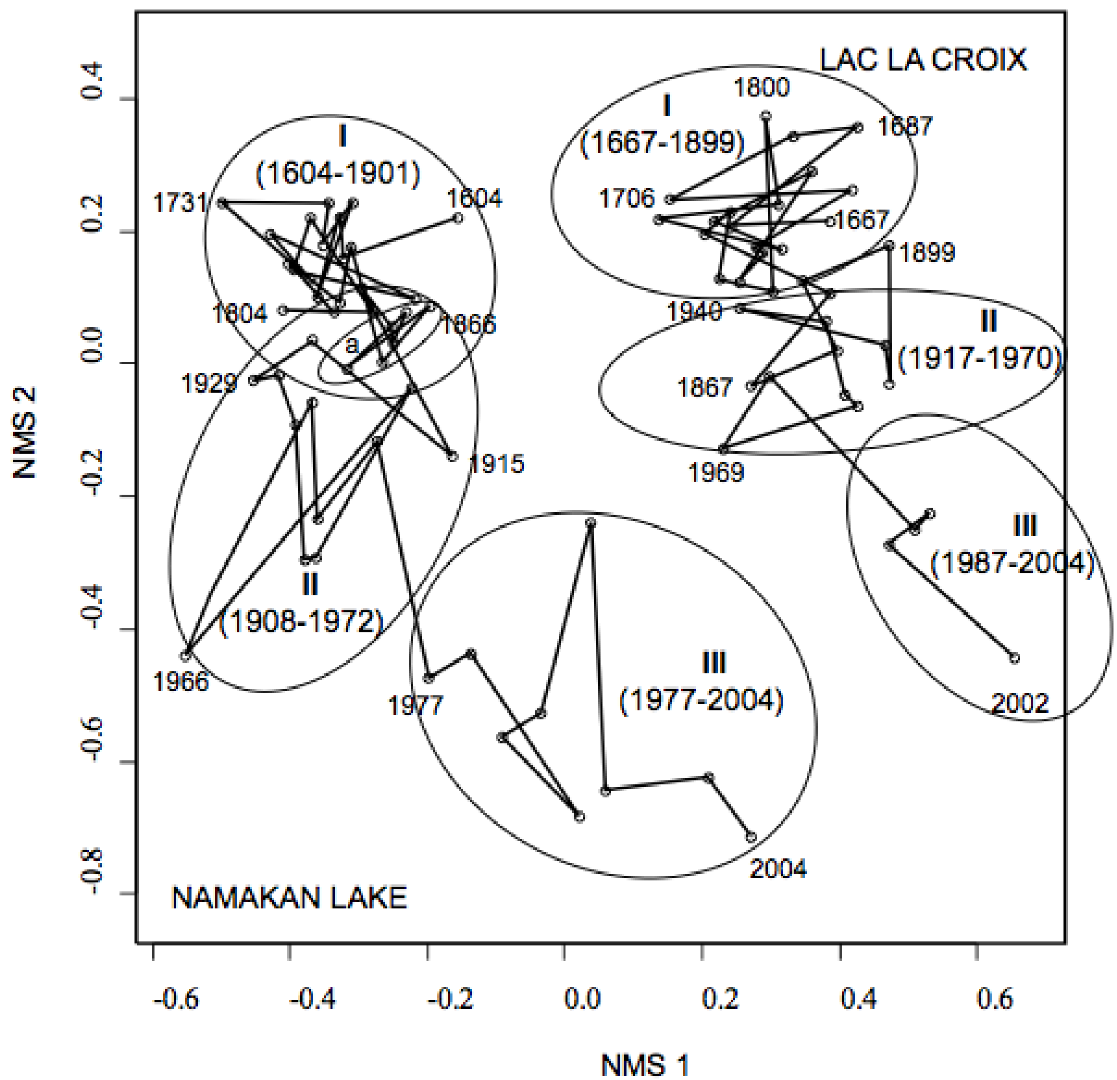

Figure I-8. Non-metric Multidimensional Scaling (NMS) analysis displaying dated samples from Namakan Lake and Lac La Croix. Line segments connect samples in each core in chronological order. Circled clusters of samples represent diatom biostratigraphic zones in each core identified using CONISS as first order and second order zones. Shifts between clusters represent periods of significant change in diatom communities.

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. In a CCA biplot, LOW samples are clustered together. One reason the LOW samples are separate from the NLF samples is that a dominant taxon (*Aulacoseira islandica*) is not present in the NLF calibration set.

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} (Figure I-9). Namakan Lake conductivity fluctuates around 95 µS cm^{-1} before settlement, increases sharply to 130 µS cm^{-1} after damming and then decreases after the 1960s. This post-damming increase is 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 I-2).

Table I-2. Water chemistry parameters 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 depth (m)	2.3 [c]	3.3 [b]
Specific conductance (µS cm^{-1})	50 [a]	42 [b]
TP (mg L^{-1})	0.008–0.028 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 16 May 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 Environmental Data Access (2007) from observation on 10 October 1985.

[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

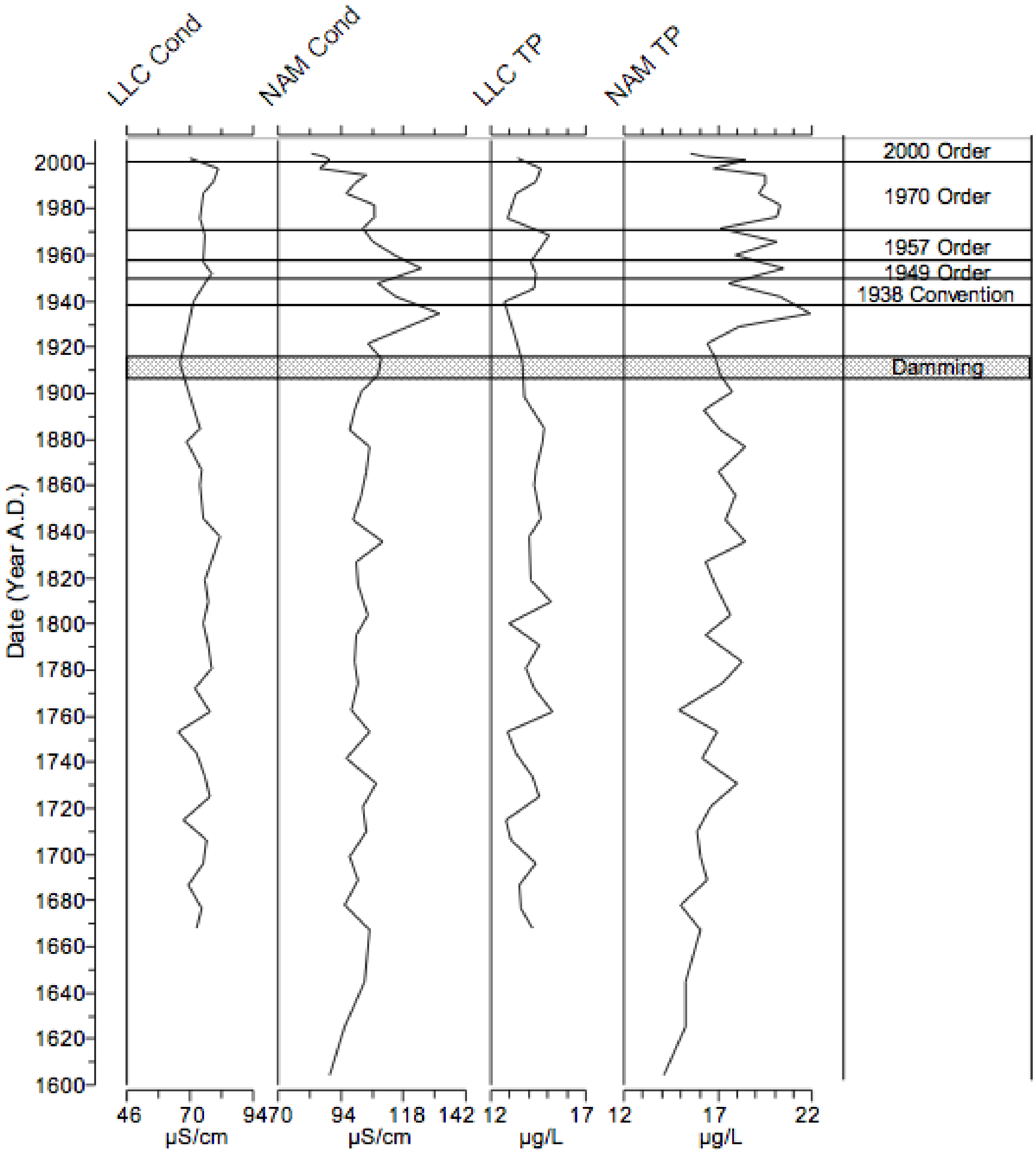

Figure I-9. Diatom-inferred conductivity (Cond) and total phosphorus (TP) reconstructions for Namakan Lake (NAM) and Lac La Croix (LLC). Damming and hydromanagement periods impacting Namakan Lake are displayed in the right panel.

Diatom-inferred TP in Lac La Croix remains constant around 14 µg L^{-1} throughout the length of the core, whereas TP increases in Namakan Lake after damming. Namakan Lake increases 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 known measurements of this system (see Table I-2).

I. Discussion

It is clear that damming impacted Namakan Lake in terms of sediment accumulation, geochemistry, species diversity, community composition, and water quality. However, other stressors have also impacted Namakan Lake and the control lake, Lac La Croix, notably European settlement and possibly climate warming. The different periods in the lakes' history can be defined as the following: pre-European settlement, European settlement and logging, damming (Namakan Lake only), different water-level regulations (Namakan Lake only), and a post-1970s broader regional change.

During pre-European settlement (1600–1860 A.D.), Namakan Lake and Lac La Croix showed no distinct changes; sediment accumulation, geochemistry, species diversity, community composition and water quality had only minor variation. Namakan Lake and Lac La Croix were slightly different biologically in that the sediments of Namakan Lake preserve a less diverse diatom community than Lac La Croix. Differences in 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 A.D.) 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. However, toward the end of early logging period, changes occur in the diatom communities of both lakes.

Damming of Namakan Lake coincided with the first significant changes in the sediment record. 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 2007). The change in sedimentation rate was coincident with the building of the dams and not to 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 in 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 (see Figure I-5). However, because our core samples do not represent equal time intervals (with shorter time periods up-core), further study is needed in order 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; see Figure I-8). Sample-to-sample variation (see Figure I-8) and species turnover (see Figure I-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 versus logging in Namakan Lake as they occurred simultaneously. Nevertheless, logging impact in our control lake, Lac La Croix, seems to have resulted in less ecological variability than the combined impacts of damming and logging had on Namakan Lake.

After reconstructing the various water quality parameters, it was evident that damming and not logging played a greater role in the history of Namakan Lake. Lac La Croix did not dissociate from its “natural” variation in water quality and thus logging may not have been a leading factor in changing water quality parameters in Namakan Lake. Namakan Lake showed post-damming increases in conductivity with a recovery in the 1960s; TP may similarly 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 was 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 burned lakes 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 ca. 1954 after two severe floods. We believe that the floods created a washout of 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 phosphorus after it was dammed and after other land use changes. They stated that damming and hydromanagement likely changed the lake’s discharge regime and increased the transport of littoral materials and inputs of phosphorus to the lake. Oddly, this resulted in a net reduction of phosphorus export from the lake because most of the discharge occurred during months with low epilimnetic phosphorous concentrations and there was an increase in nutrient retention. They also reported that water-level management of natural lakes increases sedimentary nutrient flux when lake volume and water level are more variable.

Perhaps the most confounding result we found is the ecological shift in diatom communities after the 1970s. Both lakes have higher ecological variability and their diatom communities are increasingly more similar in Zone III (Figures I-6, I-7, I-8), which is indicative of broad regional change. A history of the region indicates that while there was land use change in the region in the 1970s, the changes were protective and not expected to negatively impact aquatic resources. For example, the population surrounding Namakan Lake and Lac La Croix actually decreased (UVL 2007), various parks were established, and legislation was created to provide greater protection surrounding 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, earlier established 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 (Minnesota 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 (Minnesota Pollution Control Agency 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" (Minnesota Pollution Control Agency 2002).

Alternatively, nitrate and sulfate deposition may have impacted the lakes. Whereas, the National Atmospheric Deposition Program (NADP) presents no change in nitrate concentrations since 1978 at the Marcell Experimental Forest (MN16) located 65 km south of Namakan Lake (NADP 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 NADP (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, 1940s, and 1970s (Driscoll et al. 2001). If we attribute the high ecological variability found in Zone III in Figure I-7 to changes in sulfate concentration, we might expect to see high ecological variability throughout the period that sulfate deposition has 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 directly linked to atmospheric deposition.

However, these community shifts 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 climate 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 been occurring 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 winter average temperature records can be correlated to the post-1970s community shifts. Mean winter air temperature records from Kenora, Ontario, Canada (about 175 km northwest of

Namakan Lake show two post-1970s trends: increased interannual variability and increased winter annual temperature (Figure I-10). 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 (Figure I-10). We use 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 (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 (see Figures I-6 and I-7). Thus, evidence suggests that post-1970s diatom community shifts in Namakan Lake and Lac La Croix are strongly correlated to climate warming.

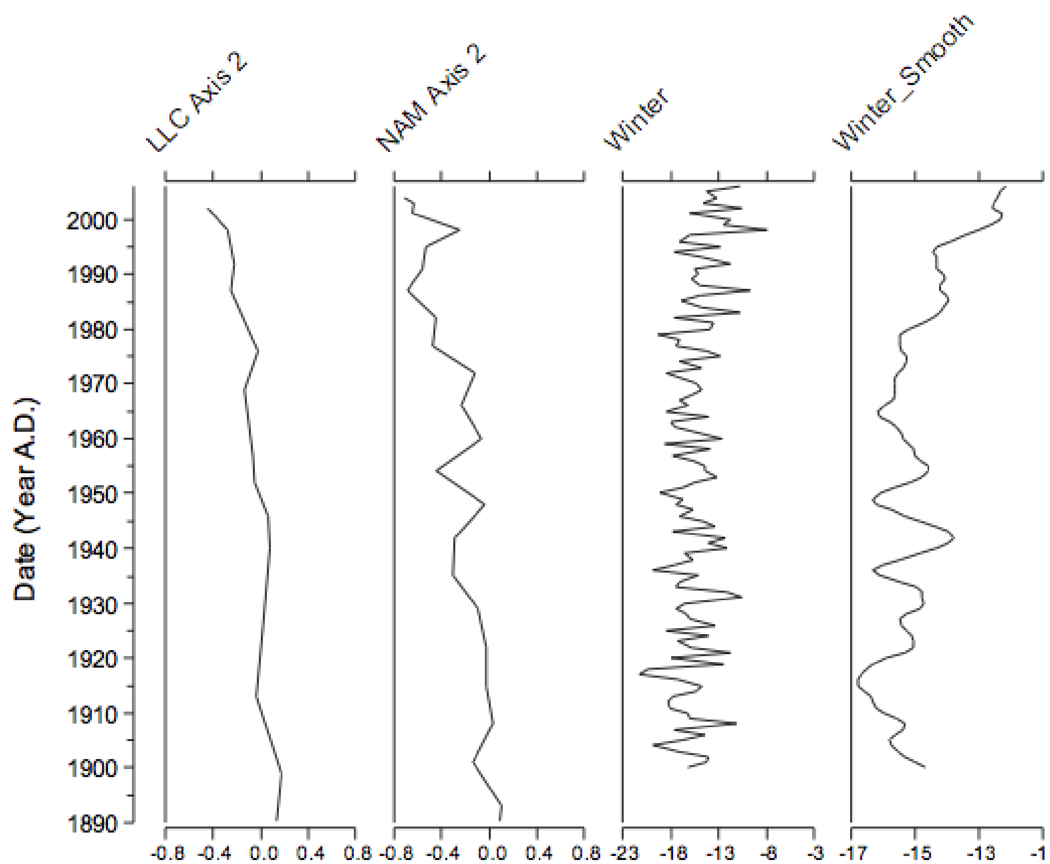

Figure I-10. Stratigraphic diagram comparing Axis 2 scores (see Figure I-8) based on Non-metric Multidimensional Scaling of down-core diatom communities from Namakan Lake (NAM) and Lac La Croix (LLC) against mean winter air temperature (°C) from Kenora, Ontario, Canada, and a locally weighted scatterplot smoothed (LOWESS) line of same with a span of 0.8. Note scale difference in two right panels.

I. Conclusion

European settlement (particularly logging), damming, and hydromanagement impacted Namakan Lake. At logging, diatom assemblages shifted away from pre-settlement communities. This also occurred in our control lake, Lac La Croix. Nevertheless, damming and water-level manipulations on Namakan Lake clearly created changes physically (increased sedimentation), ecologically (decreased species richness and greater intersample variability), and in water quality (increased TP and conductivity). None of these changes took place in the control lake, Lac La Croix. However, a potential signal of impacts from post-1970s climate warming can be identified in both Namakan Lake and Lac La Croix based on diatom community response. Further studies need to be developed to test a mechanistic link between changes in the diatom community and temperature trends.

Part II: Interactive Effects of Hydromanagement, Land Use, and Climate Change on Water Quality of US–Canada Border Waters

Abstract

Ontario–Minnesota border lakes have been subject to anthropogenic and natural impacts including logging, damming, hydromanagement, population growth, and climate change. To determine how stressors affected the lakes, we developed a before-after control-impact paleolimnological study. Sites include Namakan, Rainy, and Kabetogama Lakes, which are dammed and largely within Voyageurs National Park, and undammed Lac La Croix, which is upgradient in protected wilderness lands. One core was retrieved from each lake for analysis of ^{210}Pb, loss-on-ignition, and diatoms. Species richness and turnover, cluster analysis, multivariate ordination, diatom-inferred water quality, and variance partitioning were used to determine how and when lakes responded and the unique and interactive effects of major stressors. Most lakes showed impacts from logging; two dammed lakes also had increased sedimentation following logging and damming. Variance partitioning showed that among stressors, land use generally explained greatest variance in diatom communities. However, interactive effects among land use, climate, and hydromanagement were also highly significant. Results suggest that although hydromanagement is a primary resource concern, multiple environmental stressors and their interactions must be considered in the management of the border lakes.

Acknowledgements

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II. Introduction

Human alterations of the landscape are substantial and growing (Vitousek et al. 1997). Other landscape change can be attributed to natural processes (e.g., fire, beaver, dry versus wet years); however, most recent changes can be credited to human-influenced stressors (e.g., agriculture, urbanization, water manipulations). Human alterations of the landscape also have wide-ranging effects on lake ecosystems (Ramstack et al. 2004). Many paleoecological studies have documented the impacts of both natural and human stresses on water quality in lakes (e.g., Hall and Smol 1996, Hall et al. 1999b, Quinlan et al. 2002, Ramstack et al. 2004, Pienitz et al. 2006, Smol 2008). However, these studies focused mainly on changes driven by modifications to the surrounding landscape, nutrient sources and dynamics, and climate change, rather than water-level regulation.

Water-level manipulations have been identified as a significant factor in controlling and structuring biological communities. Wilcox and Meeker (1991) found that water-level regulations had a significant effect on the macrophyte communities. Lake-level manipulations influence year-class strength of fishes and spawning time of walleyes (Chevalier 1977, Kallemeyn 1987, Kallemeyn et al. 2003). Distributions and numbers of clams and mussels are also affected by water-level manipulations (Kraft 1988, Kallemeyn et al. 2003). Clearly, water-level manipulation is a major control for various biological communities in lake systems and must be considered in conjunction with other significant forcing factors of lake ecosystems such as landscape and climate changes.

To attribute historical changes in biological communities to various environmental and human stressors, recent studies (e.g., Hall et al. 1999b, Quinlan et al. 2002, Galbraith et al. 2008) have used variance partitioning (Borcard et al. 1992) to determine whether potential explanatory variables have had significant unique and/or interactive effects on structuring the historical biological communities. For example, Hall et al. (1999b) were able to show that resource use (agriculture and fisheries) and urbanization (population and TP/TN loads) were the dominant drivers of change in historical algae and invertebrate composition of Pasqua Lake in Saskatchewan, Canada.

In Minnesota, lakes in the lower Rainy River watershed have been subjected to simultaneous human (e.g., European settlement, logging, damming and water-level manipulation) and natural (e.g., beaver, fire, length of ice cover) stressors; one of the major human impacts to these systems has been the damming of lakes and subsequent control of their water-levels. In order to understand how these various stressors have impacted the lakes, a before-after, control-impact paleolimnological study was undertaken. Cores were collected from four lakes located within the same watershed, including three dammed (Kabetogama, Namakan and Rainy Lakes) and one undammed lake (Lac La Croix). The cores were analyzed for geochemical and biological proxies specifically to: 1) determine the background or pre-damming lake conditions, 2) determine the historical response of sedimentation rates and diatoms to damming, and 3) to determine the unique and interactive effects of water level management, land use, and climate on post-damming diatom communities using variance partitioning analysis in each lake.

II. Material and Methods

Study Sites

Kabetogama, Namakan, and Rainy Lakes along with Lac La Croix are part of the lower Rainy River drainage basin. They form much of the international boundary between northern Minnesota (U.S.A.) and northwestern Ontario (Canada) (Figure II-1). All lakes lie on Precambrian crystalline rock overlain with schist (Boerboom 1994). The lakes vary in size, depth, chemistry and hydrological histories. Kabetogama Lake is the shallowest (maximum depth 24.3 m), Lac La Croix is undammed and its water levels unmanipulated, Namakan Lake has the greatest hydrological variation, and Rainy Lake is the largest (92,000 ha) (Table II-1). Regional climate is continental, characterized by moderately warm summers and long cold winters; however, 17 out of 23 years between 1980 and 2002 have exceeded mean annual temperatures (1948–2002) (Kallemeyn et al. 2003). Ice-in typically occurs on these large lakes in late November to early December and ice-out in late April to mid-May.

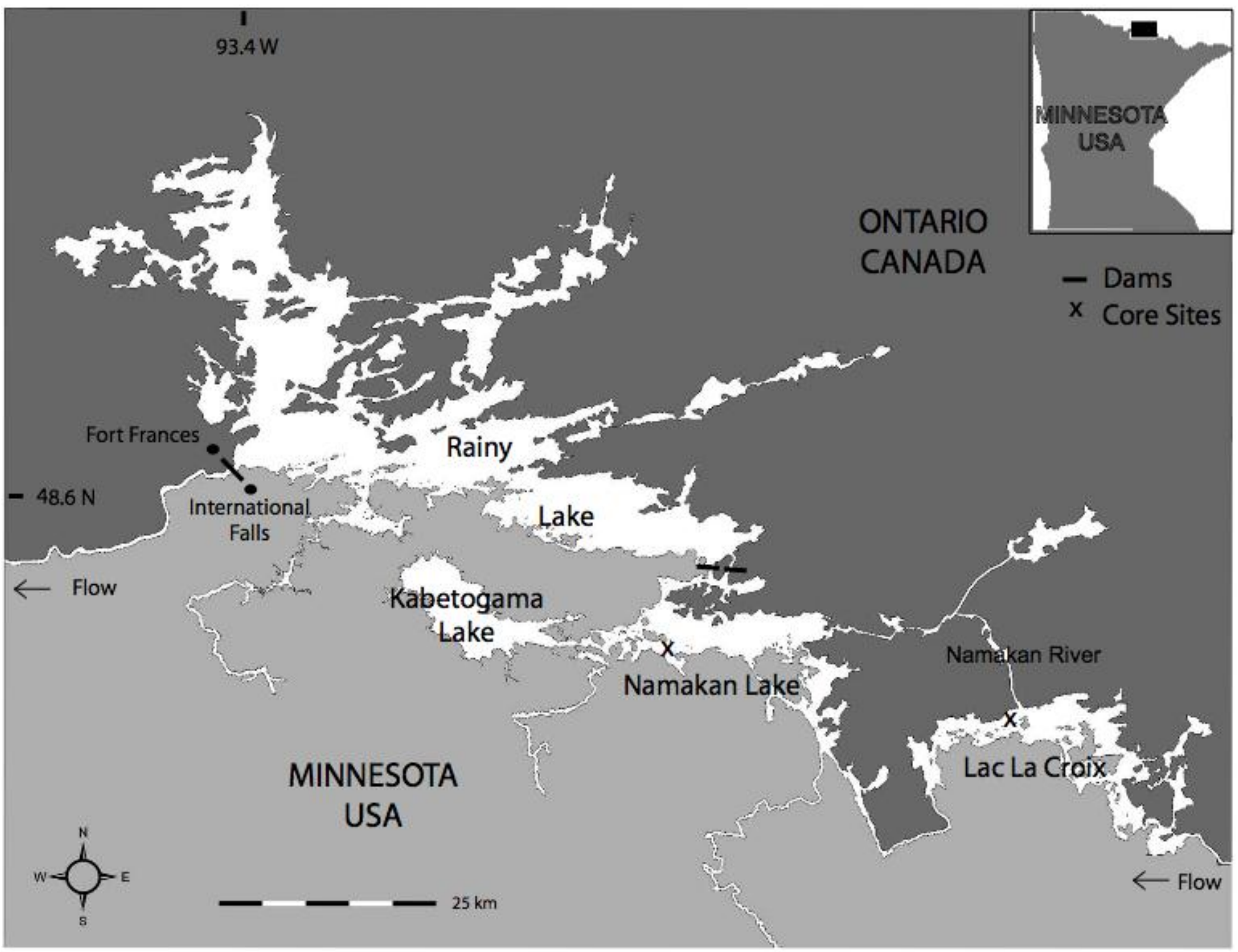

Figure II-1. Kabetogama Lake, Namakan Lake, Rainy Lake, and Lac La Croix and their respective coring sites (x). Dam sites indicated by black bars.

The International Falls region was first settled by Europeans in the latter part of the 19th century, and lumber processing mills became an active industry. Extensive logging followed with a peak in the early 1900s (Perala 1967). Damming of Rainy Lake and Namakan Lake soon followed and was completed in 1914. The dams were put in to secure enough water throughout the year for wood processing and electrical generation (Chandler and Koop 1995). At first, the dams were operated at the owners' discretion, but soon after the United States and Canadian governments requested that the International Joint Commission (IJC) make recommendations on the water regulation of Rainy Lake and nearby boundary waters. The IJC became actively involved in water-level manipulation in 1938 and produced their first regulation in 1949; subsequent regulations were issued in 1956, 1970, and in 2000. The 2000 order suggested that the spring refill period occur earlier and have a wider water-level bandwidth (acceptable levels between the minimum and maximum levels in a given period) between the beginning and end of the filling period. Therefore, less of an annual fluctuation developed and a more moderate drawdown occurred during the summer (International Rainy Lake Board of Control 1999). Besides regulating water levels, the IJC further stipulated that the biological communities and their habitats be monitored to determine their response to the new water-level manipulations. Additional details on the history of the region and water regulations can be found in Serieyssol et al. (2009).

Historical Data

Environmental and anthropogenic data were gathered from literature and agency records to determine their impacts on historical diatom communities and water quality. The following categories were explored: temperature, precipitation, water levels, human population, logging, and beaver activity. Climate records of seasonal and annual precipitation (in mm; 1912–1959) and temperature (in ºC; 1912–2005) were obtained from the Environment Canada weather station in Fort Frances, Ontario. Precipitation data from 1959 to 2005 were obtained from the NOAA weather station in International Falls, Minnesota (see Figure II-1).

Monthly water-level data were available through Water Survey Canada (2007) for Lac La Croix (05PA011, Campbell's Camp; 1921–2007), Namakan Lake (05PA003, above Kettle Falls; 1912–2007), and Rainy Lake (05PB007, Fort Frances; 1912–2007). Water-level differentials, annual and seasonal minima, and annual and seasonal maxima were calculated for each lake.

The third category—landscape—includes both anthropogenic and wildlife changes in the region: human population size, logging, and beaver population size. Human census data were obtained for both Koochiching and Itasca Counties (Minnesota) from the Historical Census Browser website of the University of Virginia, Geospatial and Statistical Center (UVL 2007). Even though our lakes are primarily in Koochiching and St. Louis Counties, we also acquired earlier censuses for Itasca County because they included what are now known as Koochiching and Itasca Counties. Thus, census numbers of both counties were combined to form one variable (Human Population Size). Canadian census records are compiled by district (e.g., Thunder Bay, Kenora, Rainy River) (Lorch and Phillips 1991). Because population trends for the Rainy River district were similar to trends in Itasca and Koochiching Counties, which is expected because this region encompasses similar industries,

Table II-1. Lake and watershed characteristics. Missing data (n.d.) for Lac La Croix were not available at the time of this study.

Lake	Lake Area (ha)	Watershed to Lake Area Ratio	Shoreline Development	Maximum Depth (m)	Mean Depth (m)	Littoral Area (%)	Volume (m^3x10^6)	Renewal Time (years)
Kabetogama	10,425	196.7	9	24.3	9.1	30	948.7	*
Namakan	10,170	192.7	6.5	45.7	13.6	20	1,383.1	0.6*
Rainy	92,100	41.9	14.4	49.1	9.9	35	9,117.9	1
Lac La Croix	13,788	n.d.	n.d.	51.2	n.d.	25	n.d.	n.d.

*Renewal time for Namakan Reservoir includes Kabetogama Lake.

landscape, and climate, we used only population data from Itasca and Koochiching Counties in our analyses.

Logging is the dominant industry in the region and has played an important role in modifying the landscape in the Lower Rainy River Drainage Basin. A record of the initial cut of virgin forest was assembled using records of the Virginia Rainy Lake Lumber Company (Perala 1967) and extrapolated to 1936, when the lumber mills in International Falls closed. Subsequent logging in the region was primarily for pulpwood production. Long-term pulpwood trends from the counties were lacking for the watershed prior to 1959, so we used pulpwood production data for the Lake States (Minnesota, Wisconsin and Michigan) spanning various time intervals between 1910–1959 (Demmon 1946, Horn 1960); annual intervals were extrapolated using linear regression. From 1959 to 2005, annual total pulpwood production data for Koochiching, Lake, and St. Louis Counties were used (North Central Forest Experiment Station 1960–2005).

Beaver were extirpated from Voyageurs National Park in the 1800s (Naiman et al. 1986), but they have recolonized the region since the 1940s (Broschart et al. 1989). Beaver can significantly alter hydrologic regimes by cutting wood and building dams (Naiman et al. 1994), so they are relevant as a landscape change variable. Long-term beaver data for the Kabetogama Peninsula were gathered from two sources: Broschart et al. (1989) and Steve Windels (National Park Service Terrestrial Ecologist, personal communication).

Field and Laboratory Methods

One core was retrieved from a depositional basin in each lake (see Figure II-1) during summer 2005 using a drive-rod piston corer equipped with a 1.5-m-long and 6.5-cm-diameter polycarbonate barrel (Wright 1991). None of the cores showed signs of sedimentary disturbance. The cores varied in length and were retrieved at various water depths (Table II-2). Cores were sectioned in the field at 1-cm increments and were stored in air tight containers at 4ºC.

Sediment geochemistry was determined by loss-on-ignition analysis following Heiri et al. (2001). Analysis of ^{210}Pb was performed using alpha spectrometry methods. Sediment age and accumulation rates were calculated using a constant rate of supply model (Appleby and Oldfield 1978), and errors were determined using the first-order propagation of counting uncertainty (Binford 1990).

Diatoms were prepared using standard techniques (Serieyssol et al. 2009). Coverslips were mounted onto glass microscope slides using Zrax®. At minimum, 400 diatom valves were identified using an Olympus BX51 outfitted with full immersion DIC optics (N.A. 1.4) capable of 1000x magnification. Diatom taxonomy followed Krammer and Lange-Bertalot (1986–1991), Patrick and Reimer (1966, 1975), Edlund (1994), Reavie and Smol (1998), Camburn and Charles (2000) and Fallu et al. (2000). All species and provisionally named taxa are illustrated in Serieyssol Bleser (2010). Diatom data were converted to percent abundance by taxon relative to total number of valves counted in the sample. Fifty-seven samples were processed for diatom analysis from Kabetogama Lake, 36 from Lac La Croix, 47 from Namakan Lake, and 27 from Rainy Lake.

Table II-2. Basins cored June 2005–September 2006, depth (Z) at coring site, length of core recovered, and results of field sectioning.

Basin Name	Coring Date	Coring Location	County	Z (m)	Core length (cm)	Sectioned (cm)	Core name
Namakan	28 June 2005	48°26.028'N 92°42.136W	St. Louis (MN)	24.07	131	0–50	Nam
Kabetogama	28 June 2005	48°27.346'N 92°57.177W	St. Louis (MN)	16.71	140	0–80	Kab
Rainy	12 Sept 2005	48°32.351'N 92°49.751'W	St. Louis (MN)	21.09	190	0–45	RA2
Lac La Croix	13 Sept 2005	44°55.521'N 93°31.975W	Rainy R. District, Ontario, Canada	14.90	207	0–49	LLC

Numerical Analysis

Diatom species richness was calculated for each sample using McIntosh's (1967) calculation for S (taxonomic richness). This measure should be used with caution, as time intervals within samples can increase down core due to sediment compaction (Rühland and Smol 2005). Species turnover (t; Magurran 2004), the rate of change in community composition through time, was calculated and plotted for all four lakes. Planktonic to benthic (P/B) ratios were calculated to determine major changes in diatom communities. Non-metric Multidimensional Scaling (NMS) using Manhattan scaling (McCune and Grace 2002) was used to evaluate changes in fossil assemblages in all lakes through time. Manhattan scaling was used because large sample differences are weighted less heavily than Euclidean scaling. In addition, cluster analysis using constrained incremental sum of squares (CONISS) and ZONE software (Juggins 1996) determined diatom-based biostratigraphic zones.

Transfer functions were applied to all four cores to reconstruct historical records of total phosphorus and conductivity. A modification of the Northern Lakes and Forest and Lake of the Woods (NLFLOW) calibration dataset was used for all lakes. The NLFLOW was developed by Paterson et al. (2007) and includes 16 samples from Lake of the Woods (Ontario, Canada) and 55 surface sediment samples from lakes in the Northern Lakes and Forest ecoregion (Omerick 1987) of Minnesota (Serieyssol et al. 2009). We further included surface sediments of Namakan Lake, Kabetogama Lake, and Rainy Lake in the training set. Associated chemical data for Voyageurs lakes were provided by the U.S. Geological Survey for conductivity, TP, pH (Payne 1991), and total nitrogen (Christensen et al. 2004). Model performance and summary statistics are presented in Table II-3.

Table II-3. Summary and performance statistics for weighted averaging models. The strength of the transfer function is reported for each environmental variable in terms of r^2, RMSE, and RMSEP $_{bootstrapped}$.

Environmental Variable	R^2	RMSE	RMSEP $_{bootstrapped}$
log Cond	0.8	0.15	0.18
pH	0.77	0.23	0.33
log TP	0.63	0.13	0.16
log TN	0.3	0.21	0.27

Potential drivers of diatom community change were investigated for all lakes using variance partitioning on two time periods: pre-1959 and post-1959. The separation at 1959 was based on the different sources of pulpwood data before and after that year. This date also allows us to isolate the major ecological stressors in each time period (pre-1959: logging, beaver recolonization, and discretionary hydromanagement; post-1959: climate warming, population, pulpwood, and rule curves). Potential explanatory sub-variables (e.g., summer temperature, beaver colonies) from each of three variable categories (climate, landscape, and water level) were gathered from literature and agency sources (see Historical Data above). An un-weighted five-point moving average was used to smooth all sub-variables prior to analysis; a five-point average was chosen based on the average chronology of the biological data from all cores. Sub-variables for each category were selected for variance partitioning based on percent variance explained and the ANOVA test with a significance level of $P<0.005$. Within each variable category, manual forward selection was used to select a suite of sub-variables that explain significant and unique variance and to eliminate highly correlated sub-variables. The number of sub-variables selected from each variable category for a specific lake or time period varied by no more than one in comparison to the other variable categories. Human population and pulpwood during post-1959 were not included in the analysis of Lac La Croix because the region near and upstream of Lac La Croix has long been protected by the Wilderness Act of 1964. Finally, constrained and partial canonical ordinations (ter Braak 1988) were used for variance partitioning to explore the relationship between change in diatom communities and potential explanatory variable categories (climate, landscape change, and water-level manipulation) by determining the unique effects of each category and their interactive effects with other explanatory variables (Borcard et al. 1992, Hall et al. 1999b, Galbraith et al. 2008).

II. Results

Historical Data

Temperature trends in Fort Frances, Ontario, were relatively constant prior to the 1970s (Figure II-2). Post-1970s, winter temperatures increased. Spring temperatures increased slightly, while autumn temperatures have increased only in the last decade. As a result, annual temperatures have increased in the past two decades. Precipitation trends vary throughout the 20th century except for the past decade when the region experienced wetter autumns (Figure II-2).

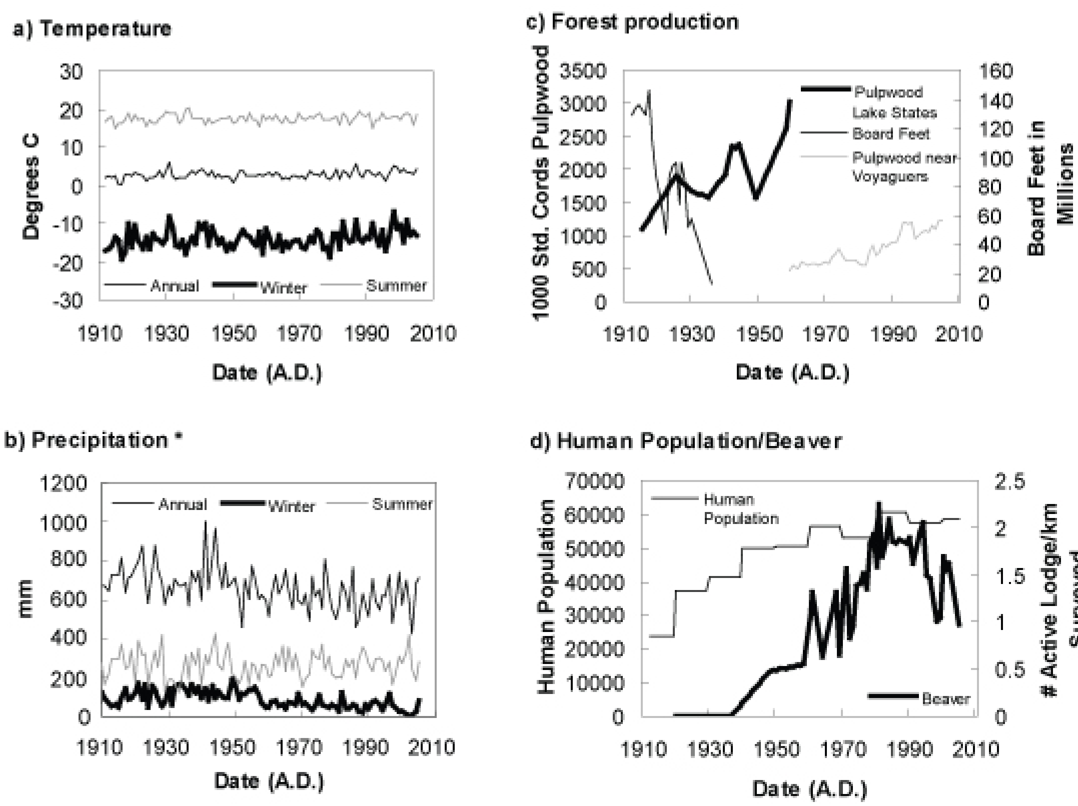

Figure II-2. Long-term data for the Voyageurs National Park region. Climate variables include (a) temperature and (b) precipitation records from Fort Frances, Ontario, and International Falls, Minnesota. Resource use variables include (c) forest production and (d) human population and beaver index.

Water-levels in the managed lakes were distinctively different than in Lac La Croix (Figure II-3). Namakan Lake and Rainy Lake had large water level differentials pre-1940, followed by structured water-levels with consistent yearly minima and maxima with slight variations related to changes in management plans. These structured water-levels consist of high water-levels during summer months with slow drawdown throughout the fall and winter months followed by gradual increases during spring. The water-level differential post-1940s in Rainy Lake was less than what would occur naturally, while in Namakan Lake the differential was greater than what would occur naturally. The natural water-level pattern was exemplified by our control lake, Lac La Croix, and clearly denotes a winter low followed by a spring peak (Figure II-3).

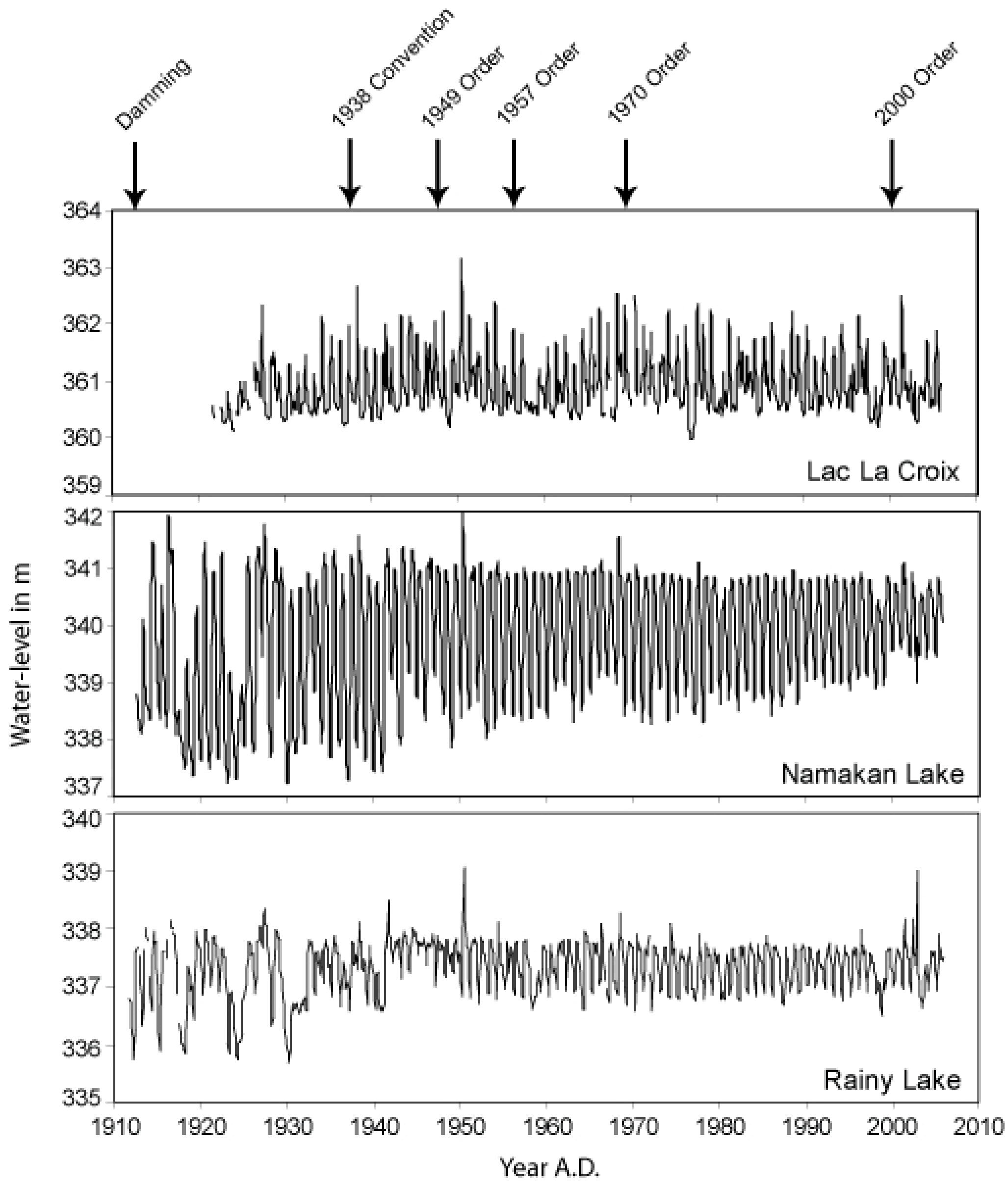

Figure II-3. Hydrograph of Namakan Lake at Kettle Falls (1912–2007), Rainy Lake at Fort Frances (1912–2007), and Lac La Croix at Campbell's Camp (1921–2007). From Water Survey Canada (2007).

Human population trends are similar to a log function graph in that the number of inhabitants greatly increased at the start of the 20th century (going from mid-4,000s in 1900 to 23,000 in 1910 to around 50,000 in 1940) (see Figure II-2). Population has recently begun to level off at around 58,000.

Two distinct activities emerged in the logging data (see Figure II-2). The first relates to the number of board-feet cut by sawmills. Even though the overall number of board-feet cut decreased from 1910 to 1936, the number of board-feet cut increased from 1910 to 1914 and in the mid-1920s. Logging decreased during World War I and decreased from the mid-1920s until 1936 when large saw mills stopped operating in the region. The second logging trend relates to pulpwood production, with a general increase through time (see Figure II-2). Four dips in pulpwood production occurred during this time frame (late 1920s to mid-1930s, from 1944 to 1949, mid-to-late 1970s and late 1990s).

The Kabetogama Peninsula beaver population increased from 1936 until 1986 and then decreased (see Figure II-2). The number of active colonies per kilometer surveyed steadily increased from none in 1936 to approximately one in the 1970s. The rate of increase then became higher from the 1970s into the mid-1980s. Thereafter, the number of active colonies declined to almost one colony per kilometer in 2005.

Sediment Dating and Geochemistry

All cores showed a general decline in unsupported ^{210}Pb activity (Figure II-4). The Euro-American settlement horizon (1870) was identified at 38 cm in Kabetogama Lake, 25 cm in Namakan Lake, 24 cm in Lac La Croix, and 11 cm in Rainy Lake. Sediment composition in all lakes was mainly inorganic, ranging from 68% in Kabetogama to 84% in Rainy Lake, whereas organic matter followed the opposite trend with Rainy Lake at 12% and Kabetogama at 21% (Figure II-5). Calcium carbonate content was low in all lakes, ranging from 4–11% by weight. Sediment composition was stable through time with the exception of Namakan Lake where organic matter increased and inorganic matter decreased at the time of damming (Figure II-5). Sediment accumulation patterns varied among lake cores (Figure II-5). All dammed lakes showed an increase in sediment accumulation beginning either at the time of damming (Namakan and Kabetogama Lakes) or later (Rainy Lake) (Figure II-6). No change in accumulation rate was apparent in Lac La Croix.

Taxonomic Richness and Species Turnover

A combined total of 587 diatom taxa were found in all lakes. The taxonomic richness patterns vary depending on the core (Figure II-7). Lac La Croix and Rainy Lake have similar patterns in taxonomic richness; richness fluctuates between 85 and 60 taxa, respectively. Prior to damming and logging, taxonomic richness fluctuated around 70 taxa in Namakan Lake. After damming, the richness decreased to 48 taxa and has since gradually recovered (Figure II-7). Taxonomic richness in Kabetogama Lake has a similar trend as Namakan Lake but showed no sign of recovery.

Species turnover— the number of taxa gained and lost through time—was fairly stable in all lakes prior to European settlement (Figure II-7). However, diatoms in Lac La Croix and Kabetogama Lake seem to have responded to the beginning of the logging era, as their species turnover rates increase. Lac La Croix seems to recover shortly after (1880), but then species turnover starts increasing again in the 1930s. In Kabetogama Lake, species turnover decreased in the 1930s then stabilized through the 1970s during the rule curve manipulations, and then turnover increased post-1970s. Namakan Lake also showed a similar pattern in turnover. Lac La Croix and Rainy Lake, which showed no changes in species turnover with damming (Rainy only) through the 1970s, had a rapid increase in turnover post-1970s (Figure II-7).

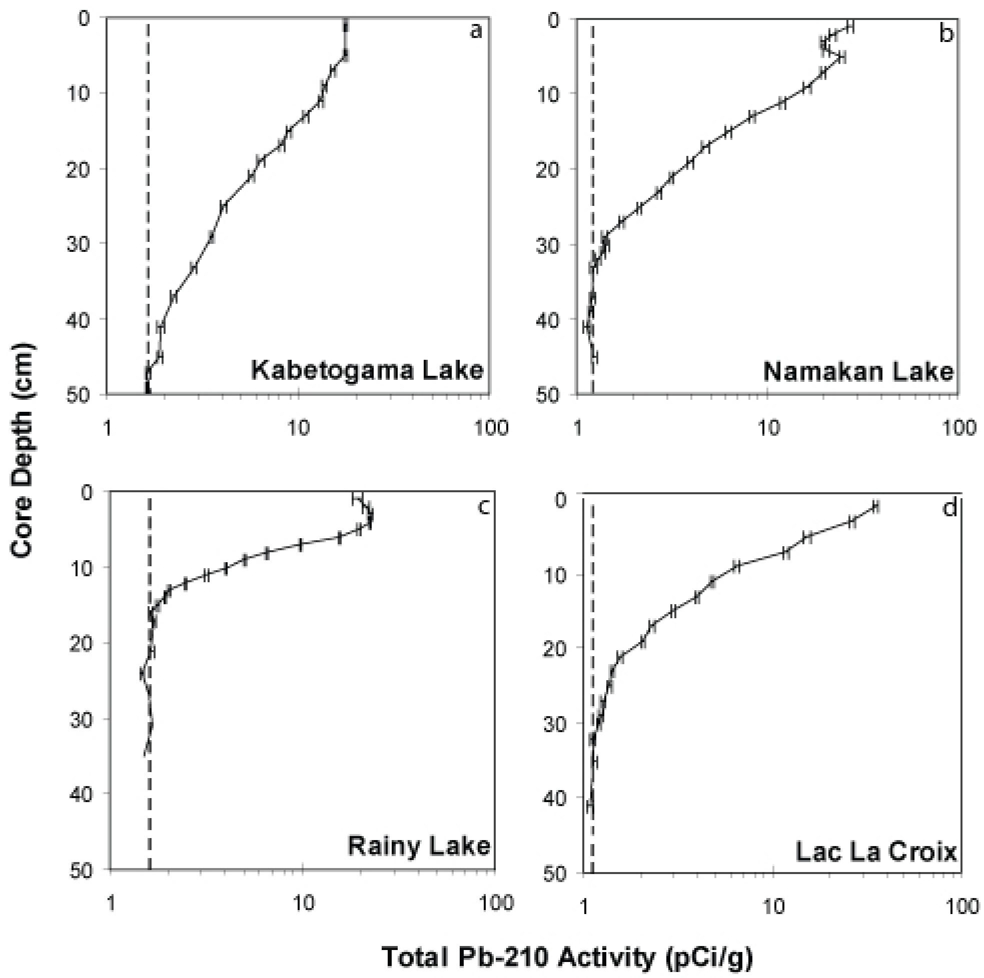

Figure II-4. Total ^{210}Pb inventory in sediment cores from Kabetogama Lake (a), Namakan Lake (b), Rainy Lake (c), and Lac La Croix (d) as a function of core depth based on the CRS model (Appleby and Oldfield 1978). Error bars represent ±1 s.d. propagated from counting uncertainty.

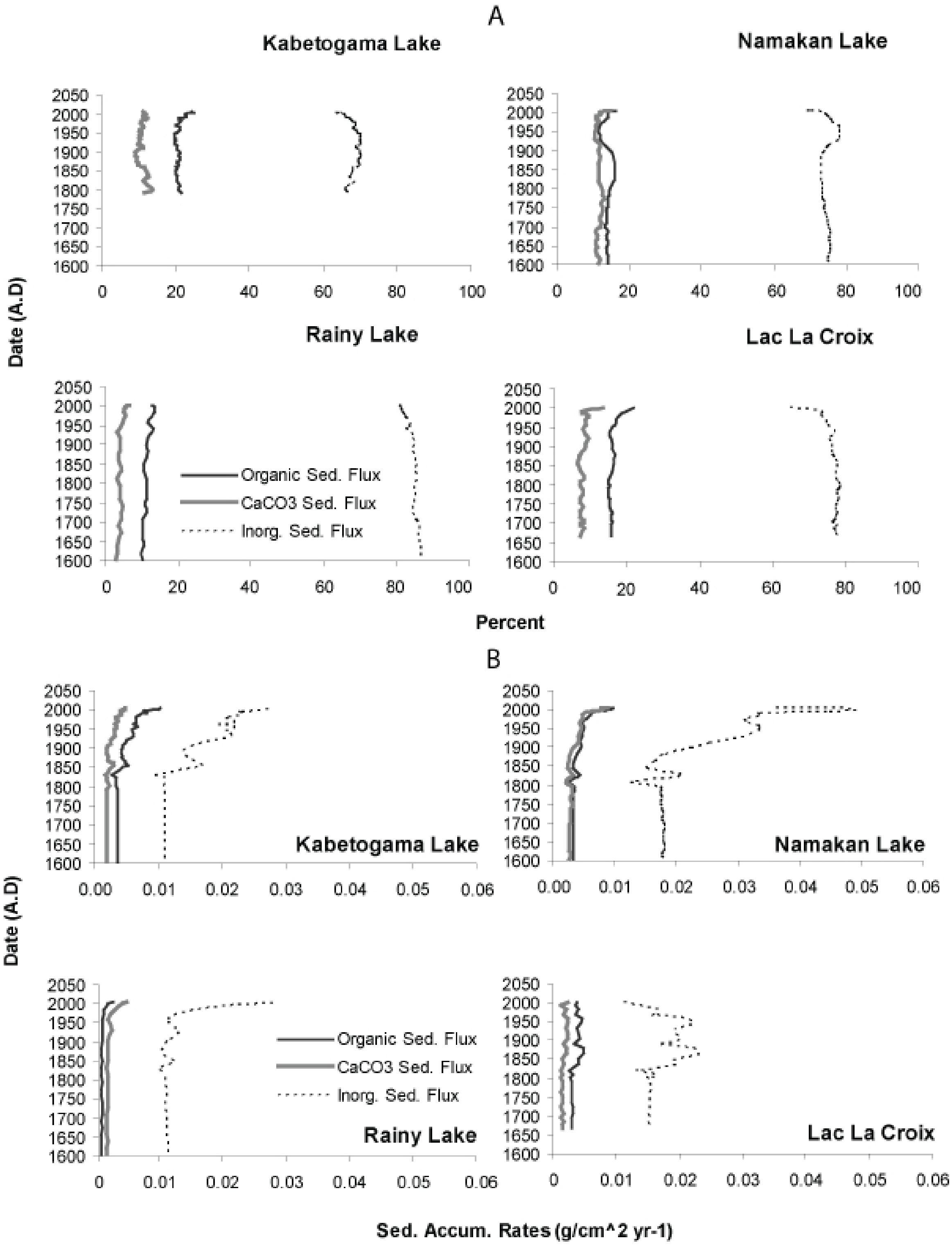

Figure II-5. (**A**) Inorganic, organic, and calcium carbonate content (dry weight percent) of Kabetogama Lake, Namakan Lake, Rainy Lake, and Lac La Croix sediments determined by loss-on-ignition. (**B**) Sediment flux of inorganics, organics, and carbonates (g cm^{-2} yr^{-1}) in Kabetogama Lake, Namakan Lake, Rainy Lake, and Lac La Croix.

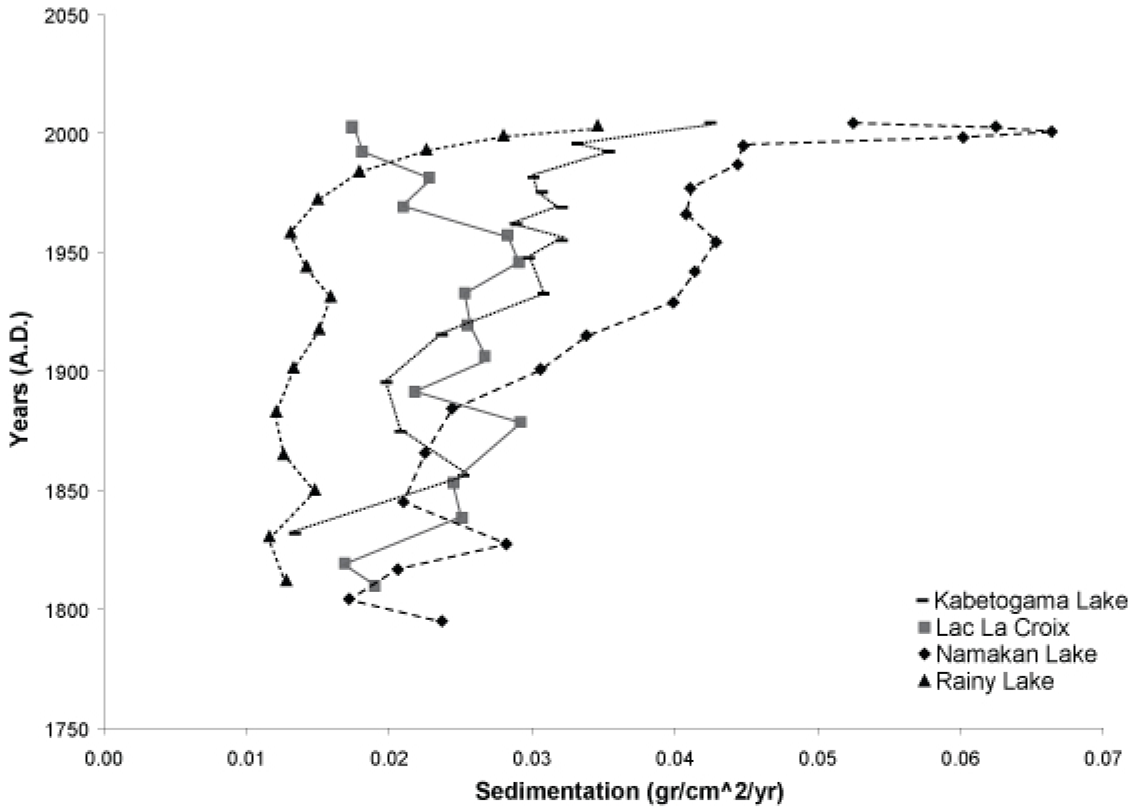

Figure II-6. Sediment accumulation rate (g cm^{-2} yr^{-1}) through time in Kabetogama Lake, Namakan Lake, Rainy Lake, and Lac La Croix. Note the increased sediment accumulation rates in Kabetogama Lake and Namakan Lake following damming, and post-1950s increases in Rainy Lake.

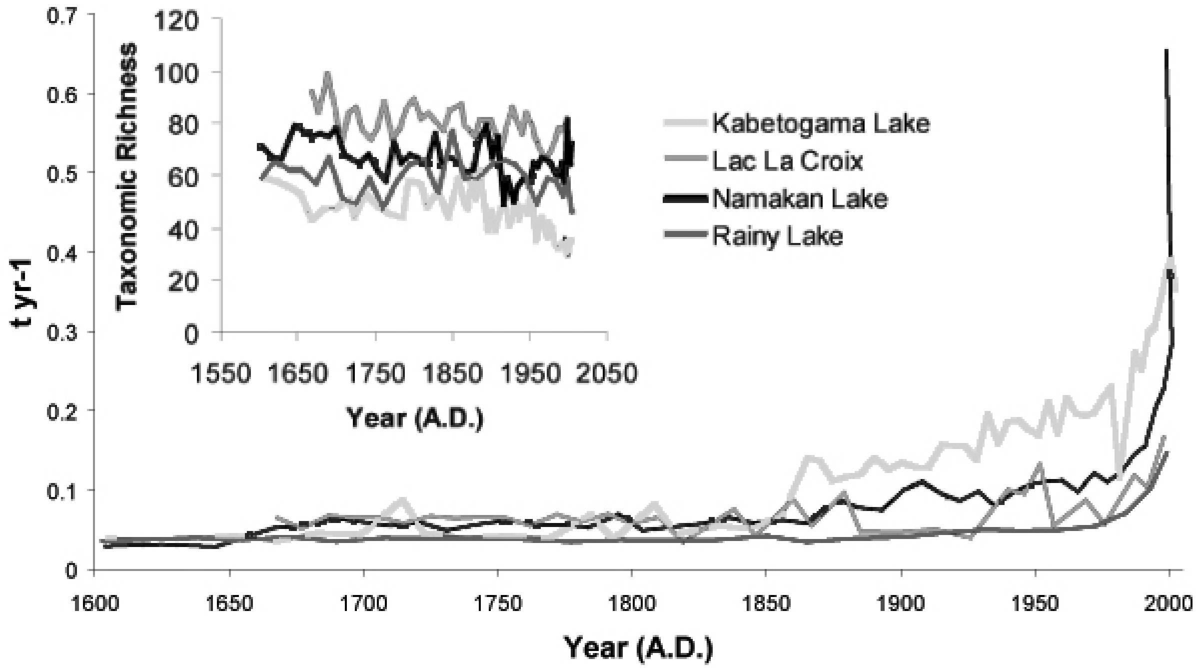

Figure II-7. Taxonomic richness (S) and species turnover (t) of diatoms in Kabetogama Lake, Namakan Lake, Rainy Lake, and Lac La Croix through time.

Diatom Stratigraphies

Diatoms were well preserved in all four lakes. Dominant taxa were planktonic species. Each lake had a distinct association and showed community shifts within their cores. For Kabetogama Lake, CONISS identified two first order zones: pre-1900 (Zone 1) (Figure II-8) and post-1900s. Two sub-zones were identified in the post-1900s zone: pre- and post-1978 (Zones 2 and 3, respectively) (Figure II-8). The pre-damming assemblages (Zone 1, 1605–1905) were composed mostly of *Aulacoseira granulata* (reaching 52 % in one sample); however, a small decreasing trend in abundance was noted up-core. Other sub-dominant taxa include *Stephanodiscus niagarae*, *A. ambigua*, and other planktonic taxa (*S. minutulus/parvus*, *A. subarctica*, *S. "parvus"*). Zone 2, dated 1905–1977, is characterized by a sharp increase in *S. "parvus,"* a slight decrease in *A. granulata* and *A. ambiqua*, a decrease of *A. subarctica* towards the top of the zone, and *S. minutulus/parvus* almost disappears. Within Zone 3, dated 1977–2005, *S. "parvus"* further increased, *S. niagarae* and *A. ambigua* decreased, and *A. subarctica* almost disappeared.

CONISS identified similar temporal zones for Namakan Lake as for Kabetogama Lake (Figure II-9). Pre-damming assemblages (Zone 1, 1604–1907) include *Aulacoseira subarctica*, *A. islandica*, *A. granulate*, and *A. ambigua* as dominant taxa. Zone 2 (1908–1972) has a slight decrease in most of the *Aulacoseira* species and an increase in *Fragilaria capucina*. Zone 3 (post-1970s) shows a decline in *A. subarctica*, *A. islandica*, *A. granulata*, and *F. capucina*, while *A. ambigua* and *Cyclotella pseudostelligera* increased in abundance along with other common taxa (*Stephanodiscus minutulus*, *Cyclotella bodanica* var. *lemanica*, *Aulacoseira voya* 1, and *Cyclotella stelligeroides*). In both lakes, the ratio of planktonic-to-benthic diatom species (P/B) increased following damming. In Namakan

Lake the increase in P/B was short-lived and returned to pre-damming values and variability by the 1950s, whereas P/B values in Kabetogama Lake generally increased throughout the 20th century.

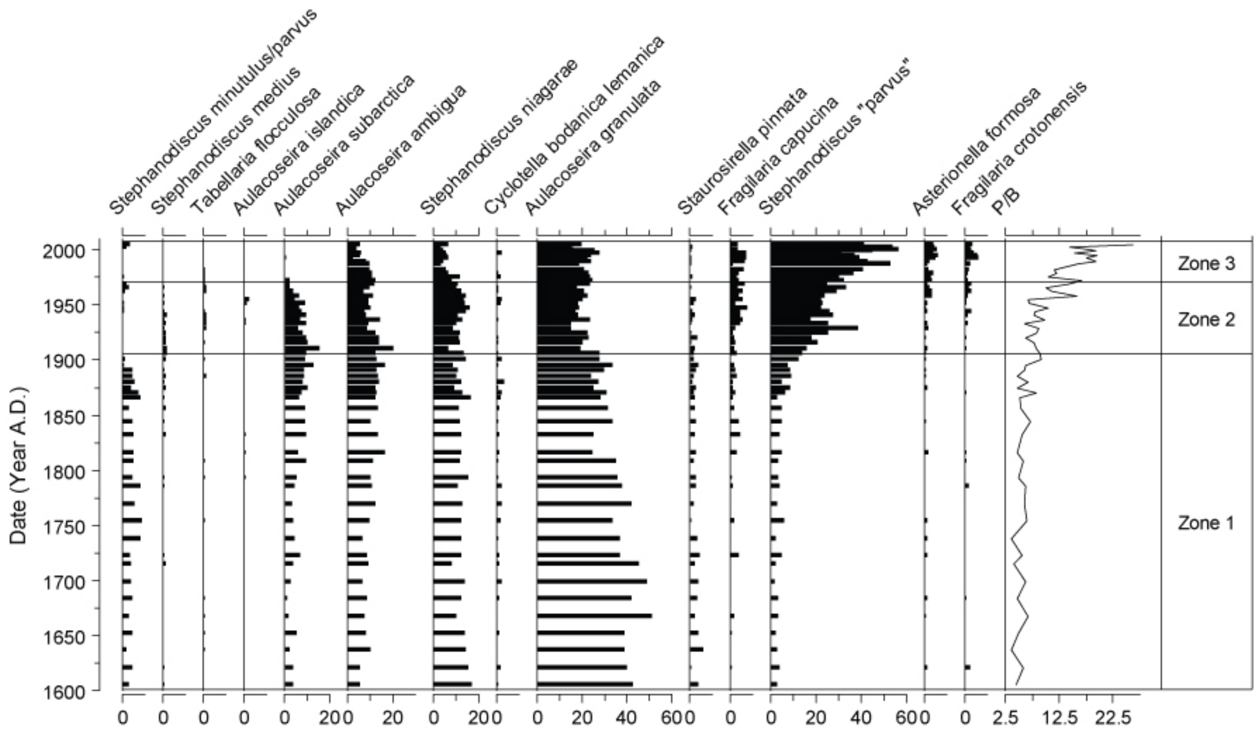

Figure II-8. Relative abundance of dominant diatom taxa and planktonic-to-benthic (P/B) ratio from Kabetogama Lake core, 1600–2005 A.D. Biostratigraphic zones as determined by CONISS denoted in right panel. Taxa occurred in at least one sample at ≥2 % relative abundance.

Rainy Lake did not have the same temporal zones as Kabetogama and Namakan Lakes. CONISS identified a first order break at 1850 to delineate Zone 1 (1600–1850) (Figure II-10). The second order zones were identified in the upper core as Zone 2 (1850–1983) and Zone 3 (1983–2005). The separation between Zone 1 and Zone 2 is very distinct because certain minor taxa (*Staurosirella lapponica*, *Pulchella kriegeriana*, and *Tabellaria flocculosa* IV) are present in Zone 1 but absent in the other zones, whereas other minor taxa appear or increase in importance in Zone 2, (*Cyclotella stelligera*, *T. flocculosa* II, *Achnanthes minutissima*, *C. bodanica* v. *lemanica*, *Asterionella formosa*, *F. capucina*, and *F. crotonensis*). Zone 3 (1983–2005) is characterized by the increase of the planktonic species *Asterionella formosa* and *Cyclotella stelligera*.

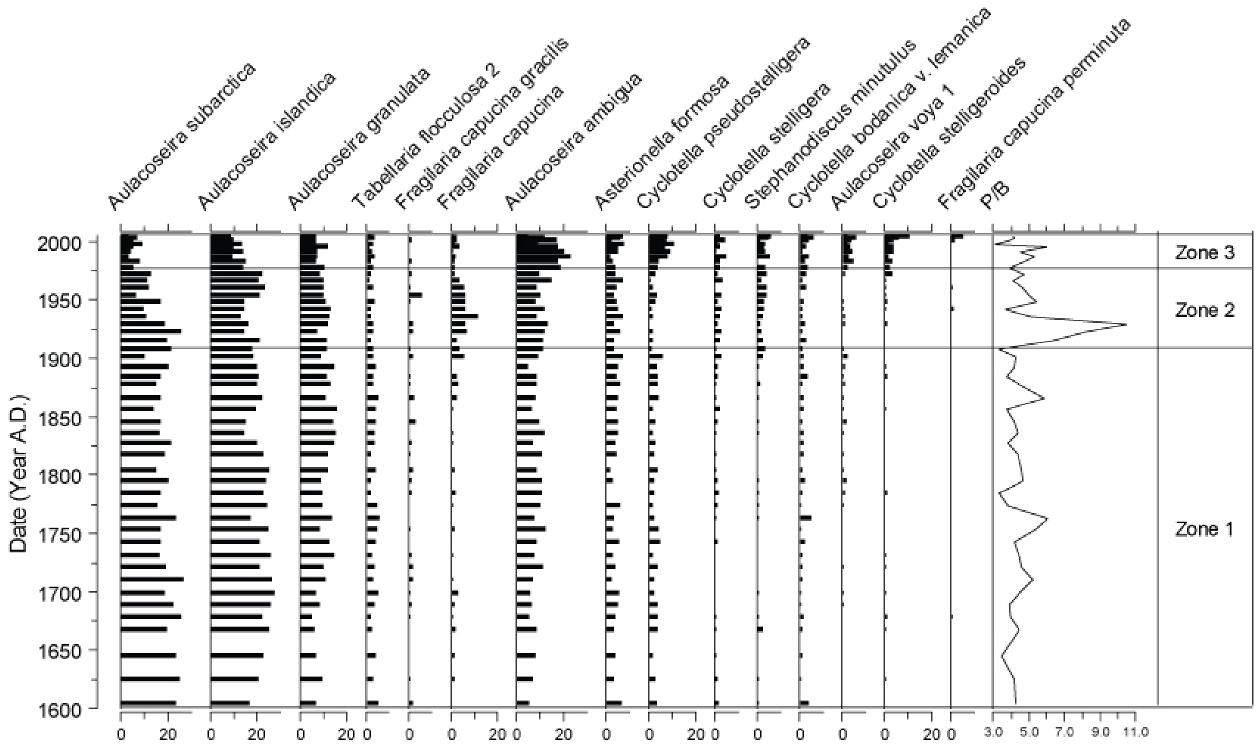

Figure II-9. Relative abundance of diatom taxa and P/B ratio from Namakan Lake core, 1600–2005 A.D. See Figure II-8 for details.

Similar to Kabetogama and Namakan Lakes, the diatom assemblages in Lac La Croix were also divided into three zones (Figure II-11): Zone 1 (pre-1900s), Zone 2 (post-1900s to pre-1970s), and Zone 3 (post-1970s). However, in this case the separation between the Zones 2 and 3 was of first order, while the division between Zones 1 and 2 was second order. It is the abundance of the minor taxa that differentiate Zone 1 (1668–1899) from Zone 2 (1913–1976). In contrast, Zone 3 (post-1970s) has an increase in *Aulacoseira voya* 1, *C. stelligera*, *F. crotonensis*, and *C. bodanica* v. *lemanica*, and a decrease in *A. subarctica* and *Cyclotella pseudostelligera*.

Non-metric multidimensional scaling analysis of all four lake cores grouped samples from each lake together (Figure II-12). Kabetogama Lake samples were separated from the other samples along axis 1. The diatom stratigraphies identified with CONISS can also be recognized as sample zones in this analysis. Earlier zones can be identified by their tight chronological sample groupings. The post-1970s–1980s zones in all lakes show much greater ecological variability.

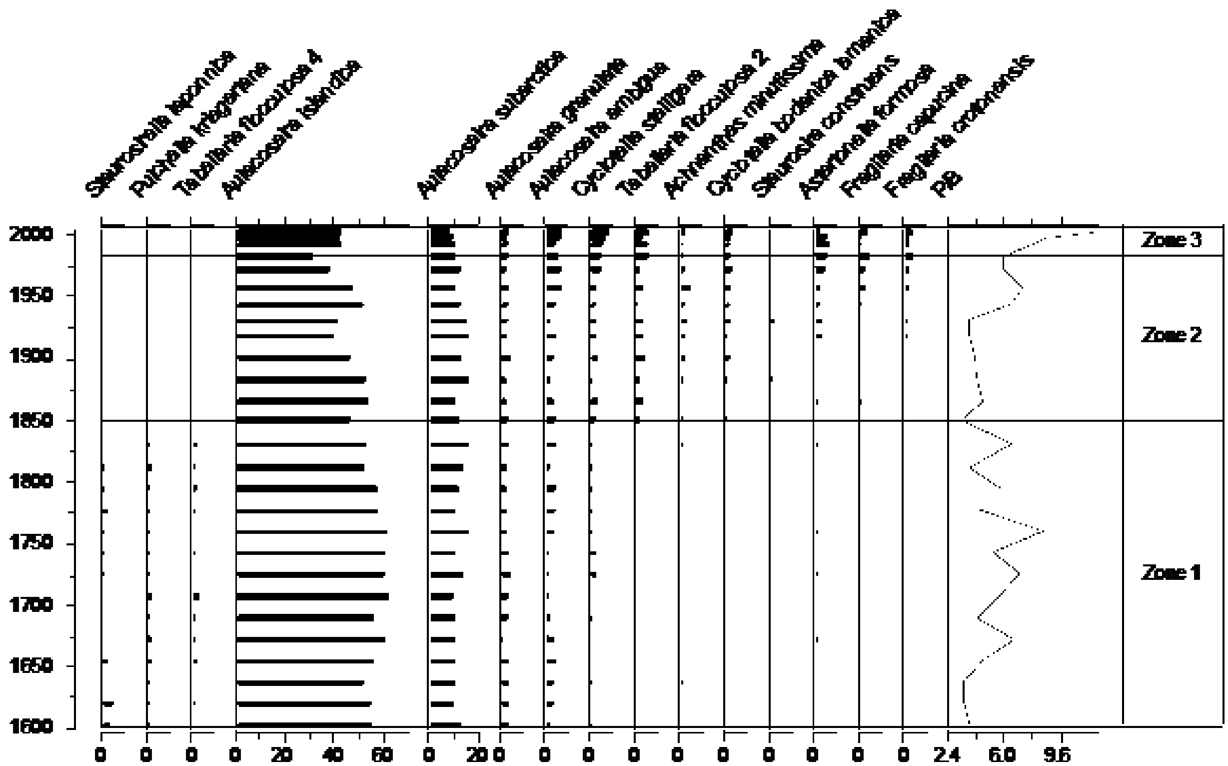

Figure II-10. Relative abundance of diatom taxa and P/B ratio from Rainy Lake core, 1600–2005 A.D. See Figure II-8 for details.

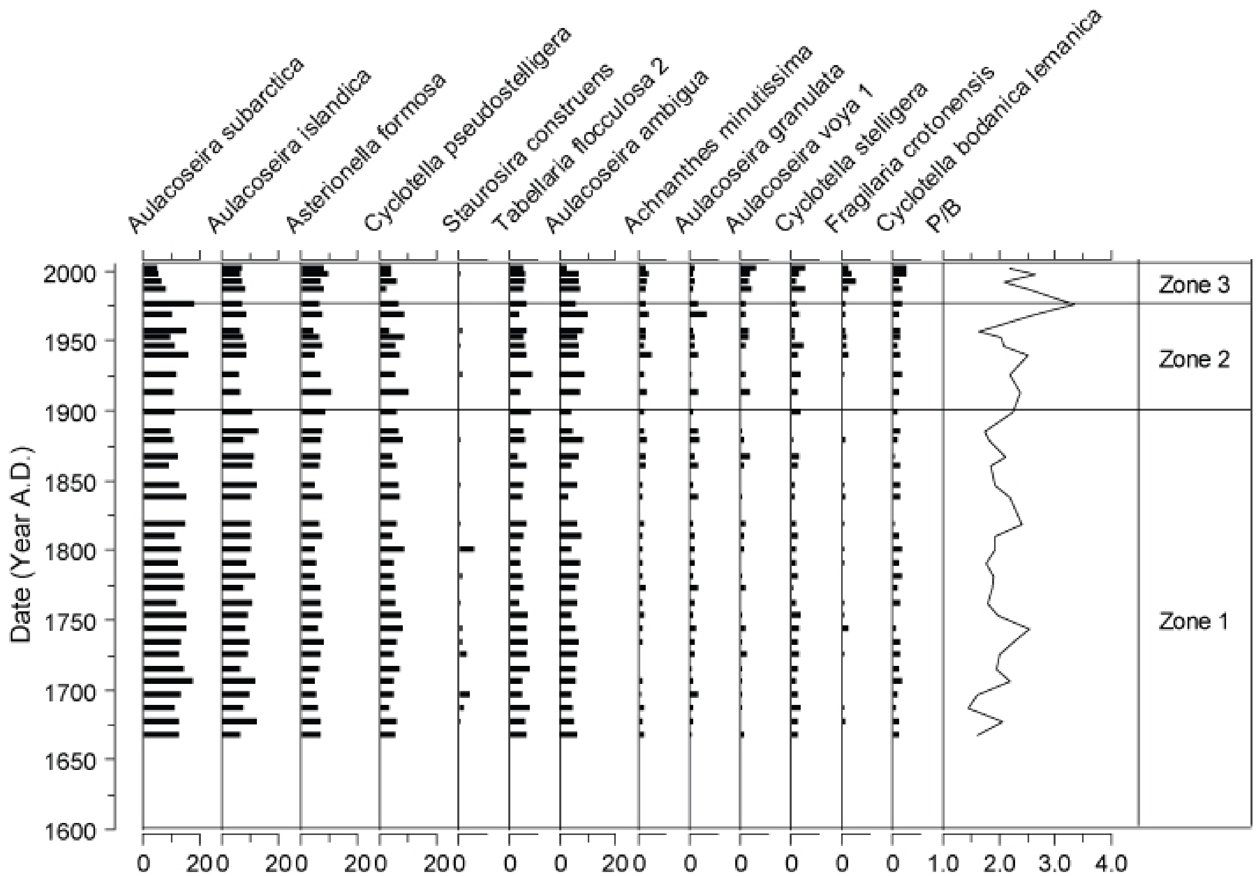

Figure II-11. Relative abundance of diatom taxa and P/B ratio from Lac La Croix, 1668–2005 A.D. See Figure II-8 for details.

Variance Partitioning

Many sub-variables selected for climate, landscape and water-level were significant (P<0.05) in explaining diatom assemblage composition. No individual climate sub-variables were significant in post-1959 Rainy Lake, and no individual water-level sub-variables were significant in post-1959 Rainy Lake and Lac La Croix. However, when sub-variables were combined into their representative categories (climate, landscape, or water-level) the unique variance explained by each major variable was usually significant, but not always (Table II-4). For example, the variable category water-level was not uniquely significant in pre-1959 Kabetogama Lake (Table II-4). The interaction among climate, landscape, and water-level variables generally explained a significant amount of variance in past diatom assemblages at all sites except for post-1959 Rainy Lake and Lac La Croix because no water-level sub-variables (or climate sub-variables in Rainy Lake) were significant.

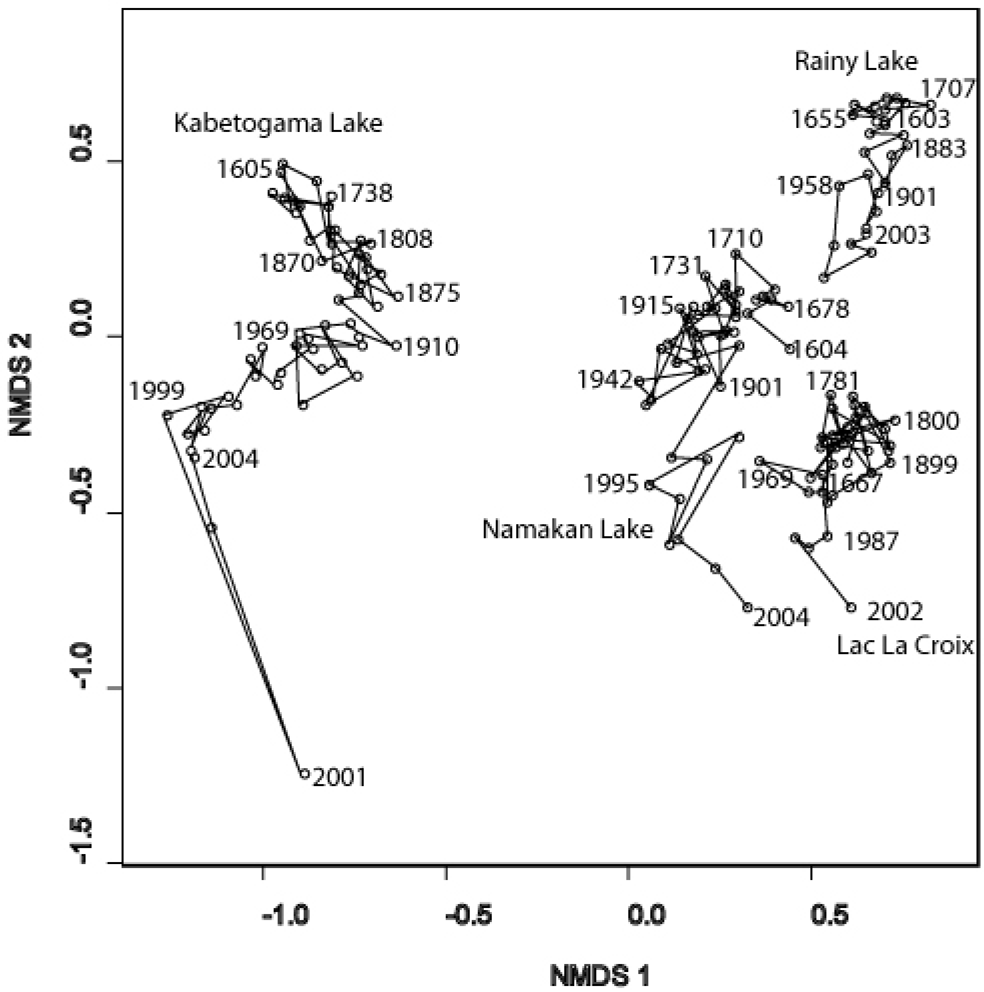

Figure II-12. Non-metric Multidimensional Scaling (NMS) analysis displaying dated samples from Kabetogama Lake, Namakan Lake, Rainy Lake, and Lac La Croix. Line segments connect samples in each core in chronological order.

Overall, landscape was the strongest explanatory category in all four lakes (Table II-4). Landscape uniquely explained up to 25% of the variation in past diatom assemblages. Pre-1959 human population size was the most common landscape sub-variable retained in variance partitioning (4 of 4 lakes). Beaver and board-feet processed were also important and retained in three of four lakes. For post-1959, the size of the beaver population was retained in all four lakes; human population and pulpwood processing were also selected for Kabetogama and Namakan Lakes.

Table II-4. Total variance explained (accounting for overlapping or interactive effects of other variables), unique variance explained (variance which remains when other significant variables are used as conditional co-variables), and significance for major variable categories. Individually significant sub-variables within each variable category are listed parenthetically for each lake and time period (pre- and post-1959). (A= Aspen or pulpwood, AP= Annual Precipitation, AT= Annual Temperature, AuT=Autumn Temperature, B= Beaver, BF= Board-feet, Dif= Water-level differential, HP= Human Population, Min= Water-level Minimum, Max= Water-level Maximum, NS= not significant, P= Pulpwood, SP= Spring Precipitation, SuP= Summer Precipitation, ST= Spring Temperature, SuT= Summer Temperature, WP= Winter Precipitation, WT= Winter Temperature).

Pre-1959

Kabetogama Lake	Variance	% Var. Explained	Signif. for Major Variable Categories
Climate (AT, AP)	total	35%	p<0.005
	unique	9%	p<0.005
Landscape (HP, A)	total	49%	p<0.005
	unique	21%	p<0.005
Water-Level (Max)	total	14%	p<0.005
	unique	1%	NS

Namakan Lake	Variance	% Var. Explained	Signif. for Major Variable Categories
Climate (AP, SP, SuP)	total	38%	p<0.005
	unique	3%	p<0.05
Landscape (BF, HP, B)	total	75%	p<0.005
	unique	23%	p<0.005
Water-Level (Max, Min, Dif)	total	47%	p<0.005
	unique	7%	p<0.005

Post-1959

Kabetogama Lake	Variance	% Var. Explained	Signif. for Major Variable Categories
Climate (ST, WT, AT)	total	61%	p<0.005
	unique	4%	p<0.01
Landscape (HP, B, P)	total	82%	p<0.005
	unique	13%	p<0.005
Water-Level (Dif, Min, Max)	total	55%	p<0.005
	unique	4%	p<0.005

Namakan Lake	Variance	% Var. Explained	Signif. for Major Variable Categories
Climate (ST, WT, AT)	total	60%	p<0.005
	unique	5%	p<0.005
Landscape (B, P, HP)	total	77%	p<0.005
	unique	25%	p<0.005
Water-Level (Dif, Max, Min)	total	56%	p<0.005
	unique	4%	p<0.005

Table II-4 (continued). Total variance explained (accounting for overlapping or interactive effects of other variables), unique variance explained (variance which remains when other significant variables are used as conditional co-variables), and significance for major variable categories. Individually significant sub-variables within each variable category are listed parenthetically for each lake and time period (pre- and post-1959). (A= Aspen or pulpwood, AP= Annual Precipitation, AT= Annual Temperature, AuT=Autumn Temperature, B= Beaver, BF= Board-feet, Dif= Water-level differential, HP= Human Population, Min= Water-level Minimum, Max= Water-level Maximum, NS= not significant, P= Pulpwood, SP= Spring Precipitation, SuP= Summer Precipitation, ST= Spring Temperature, SuT= Summer Temperature, WP= Winter Precipitation, WT= Winter Temperature).

Pre-1959				**Post-1959**			
Rainy Lake	**Variance**	**% Var. Explained**	**Signif. for Major Variable Categories**	**Rainy Lake**	**Variance**	**% Var. Explained**	**Signif. for Major Variable Categories**
Climate (AP, SP, SuP)	total	35%	p<0.005	Climate (WP, WT)	total	34%	p<0.005
	unique	3%	p<0.005		unique	27%	p<0.005
Landscape (B, BF, HP)	total	86%	p<0.005	Landscape (B)	total	18%	p<0.005
	unique	23%	p<0.005		unique	18%	p<0.005
Water-Level (Min, Dif)	total	68%	p<0.005	Water-Level (Min)	total	15%	p<0.02
	unique	3%	p<0.005		unique	3%	p<0.005
Lac La Croix				**Lac La Croix**			
Climate (SP, AP, AuT)	total	32%	p<0.005	Climate (WT, AT)	total	39%	p<0.005
	unique	5%	p<0.02		unique	19%	p<0.005
Landscape (B, HP, BF)	total	66%	p<0.005	Landscape (B)	total	24%	p<0.005
	unique	14%	p<0.005		unique	11%	p<0.005
Water-Level	total	51%	p<0.005	Water-Level (Dif, Max)	total	25%	p<0.005
(Min, Max, Dif)	unique	16%	p<0.005		unique	14%	p<0.005

Climate was the second-most significant variable category to explain changes in diatom assemblages. Even though the combined and unique effect of climate variables were generally less than landscape, climate still played an important role in explaining variance in diatom assemblages (at most 61% total and 27% uniquely). Generally, a precipitation variable was selected as the most explanatory climate sub-variable for the pre-1959 period and a temperature sub-variable for post-1959.

Historical water-level also significantly explained diatom assemblage changes, except for Lac La Croix and Rainy Lake in the post-1959 analysis. Water-level and its interactions with the other categories accounted for between 14% and 68% of the variance explained. But for the unique influence, water-level explained from less than 2% to a maximum of 16% of the variance. Generally, the differential between and the minimum and maximum water-levels was equally likely to be selected as significant sub-variables.

Diatom-inferred Water Quality

Diatom-inferred total phosphorus reconstructions in Lac La Croix and Rainy Lake showed no significant changes throughout the core. Kabetogama Lake displayed a slight decrease in total phosphorus (3–4 ug/L) after damming, which preceded an increase; total phosphorus in Namakan Lake increased with a possible recovery within the last decade.

Diatom-inferred conductivity showed that conductivity in Lac La Croix and Rainy Lake had varied slightly over time, but no clear trends were evident (Figure II-13). Both Namakan and Kabetogama Lakes had diatom reconstructions showing an increase in conductivity after damming. Namakan Lake had two peaks in conductivity, one in 1935 the other in 1954, reaching 115 $\mu S\ cm^{-1}$ and 105 $\mu S\ cm^{-1}$, respectively. In Kabetogama Lake, conductivity increased from 142 $\mu S\ cm^{-1}$ in 1910 to 169 $\mu S\ cm^{-1}$ in 1992 followed by a slight decrease. Both Namakan and Kabetogama Lakes show recent decreases in conductivity. The changes in conductivity noted in Namakan and Kabetogama Lakes are less than model error and although they suggest some trends in the environmental history of these lakes, the magnitude of change would not be considered significant.

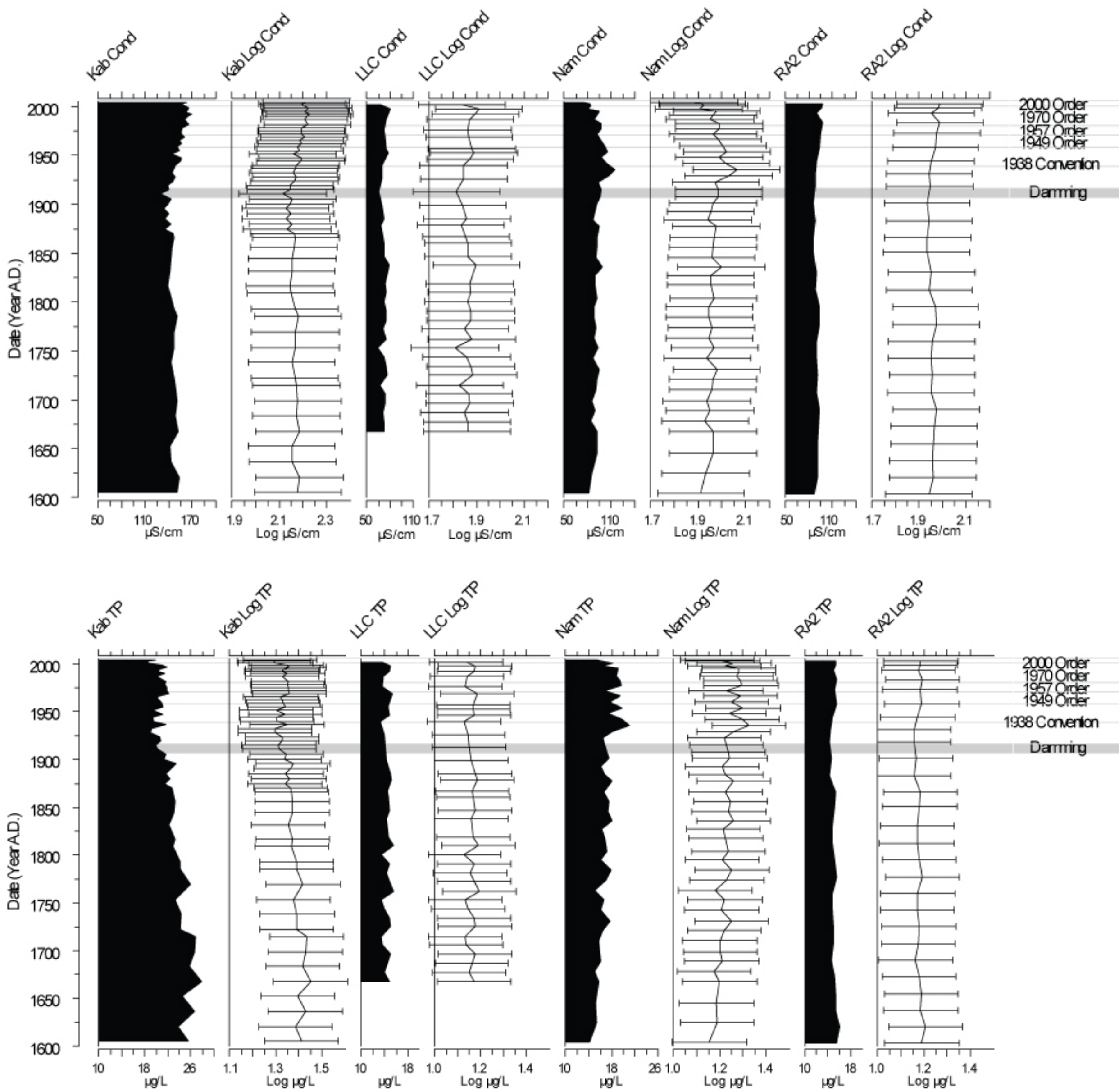

Figure II-13. Diatom-inferred conductivity (Cond) and total phosphorus (TP) reconstructions and model error estimates for Kabetogama Lake (KAB), Namakan Lake (NAM), Rainy Lake (RA2), and Lac La Croix (LLC). Damming and hydromanagement periods impacting Kabetogama Lake, Namakan Lake, and Rainy Lake are displayed in the right panel.

II. Discussion

Although the impacts of damming and hydromanagement are the main management concern in this boundary region (Kallemeyn et al. 2003), it is clear from our analyses that damming and hydromanagement are not the only drivers of change in Ontario–Minnesota border lakes. Additional stressors including landscape variables and climate were identified as impacting these lakes regardless of whether they were hydrologically manipulated. Changes in diatom communities and physico-chemical characteristics of sediments varied among all regulated lakes despite similar water level regulation, geology, land use, and climate change. However, shifts in diatom communities also occurred in an unregulated lake, Lac La Croix, coincident with regional logging and climate patterns (Serieyssol et al. 2009). To put historical human and environmental factors that have influenced the border lakes into context, we explored how initial damming and logging impacted these border lakes in the early 20th century. We then used variance partitioning analysis to determine the unique and interactive effects of landscape, hydromanagement, and climate variables on diatom communities after damming. We will first describe the initial impacts of logging and damming on lakes in this region and follow with a discussion of lake response and the environmental variables that have likely driven post-damming changes.

Impacts of Logging and Damming

The Minnesota–Ontario boundary region was first settled by Euro-Americans in the late 1800s. Logging began first for local development and later for commercial purposes. Logging peaked at the beginning of the 20th century (Perala 1967) and mills were constructed in the region. Construction of dams also occurred during that same time period; they were completed in 1914. Because logging and damming occurred simultaneously, we can use the ecological response of the undammed control, Lac La Croix, to separate the impacts of logging and damming.

Conditions in all lakes before Euro-American settlement were mostly stable. Sedimentation rates showed only slight fluctuations (Figure II-6). Although each lake had a unique diatom assemblage, species turnover was also fairly stable. Small shifts within the diatom assemblages were not reflected in any significant water quality trends before 1900. The first major change in sediment accumulation and diatom communities occurred simultaneously with logging and the constructions of dams. These changes are evident in sedimentation rates, taxonomic richness, and diatom community shifts.

Lac La Croix, the undammed lake, should have been primarily affected by land use changes from logging; however, sediment accumulation, taxonomic richness, and water quality parameters showed no variations from background conditions before or after initial logging. The changes in diatom communities that were identified with CONISS (see Zone 2 in Figure II-11) were mostly in minor taxa. Species turnover rates also had only minor fluctuations (see Figure II-7). Studies on Finnish (Rasanen et al. 2007) and Canadian (Laird and Cumming 2001, Laird et al. 2001) lakes have shown similar minor changes in relative abundance of diatom species rather than large diatom community shifts in response to logging and clear-cutting within their watersheds.

Diatom communities also show minor changes in Rainy Lake in the 1850s, which is prior to the peak of logging and damming. Several minor species were lost and other species either appeared or increase in abundance (see Figure II-10). Dating errors at this depth in the Rainy Lake core are relatively small, so we can only speculate that these changes in diatom assemblages may be related to very early nearshore lumbering or climate. Logs were cut during the winter months and then transported through waterways after ice-out (UM and TCPT 2005), which may have impacted spring lake conditions. Alternatively, this time period marks the end of the Little Ice Age, and the changes in diatom communities in Rainy Lake may be due to a limnological response to climate. If this were the case, however, we might expect to see changes on a similar time scale in the other lakes, but such changes are not apparent.

Logging and damming mark the beginning of significant changes in the sediment records in the other regulated lakes. Namakan Lake and Kabetogama Lake responded to damming with an increase in sediment accumulation (see Figure II-6). Dams create artificial sediment traps where sediment accumulates at higher rates (Anselmetti et al. 2007). However, a similar increase in sediment accumulation was delayed in Rainy Lake until after the 1960s and may have been in response to rule curve changes.

The biological communities in Kabetogama and Namakan Lakes also responded to damming and logging. Taxonomic richness sharply decreased and species turnover began to increase following logging and damming. Namakan Lake had an increase of planktonic-to-benthic (P/B) ratios at the time of damming with a recovery following, whereas Kabetogama Lake had an increase in the P/B ratio at the time of logging and damming that continued to increase up-core, tracking the abundance pattern of *Stephanodiscus* “*parvus*.” Small *Stephanodiscus* species are commonly associated with increased nutrient levels (Stoermer et al. 1985). Increases in the P/B ratio of diatom communities are a typical response to increased nutrient levels or changes in lake morphometry if lake levels rise and/or relative littoral extent decreases. In the context of an ecological disturbance, logging and damming in combination may have gone beyond an intermediate disturbance level, which can lead to lower diversity. The Intermediate Disturbance Hypothesis (IDH) predicts that lower diversity will result after a high magnitude disturbance and or increased frequency of disturbances (Connell 1978). Changes in taxonomic richness and species turnover were not apparent in Rainy Lake or undammed Lac La Croix during this same time period. The initial impacts of damming are highly dependent on characteristics of reservoir formation. Hall et al. (1999a) compared the ontogenetic history of two reservoir types—river valley impoundment and lake inundation—and showed the initial responses of the two reservoirs differed. River valley inundation resulted in an initial period of eutrophication, whereas lake inundation resulted in a decrease in productivity. The impacts of damming on biological communities similarly span a wide range. Little and Smol (2000) and Karst and Smol (2000) showed the impact of canal construction and damming on the chironomid and diatom communities of an inundated lake was minimal, whereas Hübener and Dörfler (2002) report dramatic changes in diatom communities in response to 13th century damming of Lake Krakower Obersee.

Post-damming Drivers of Change

Many environmental drivers could have worked individually and in concert to change diatom communities after damming in the Minnesota–Ontario border lakes. Water levels in Kabetogama, Namakan, and Rainy Lakes were regulated (Kallemeyn et al. 2003). Logging and increased pulpwood harvest became a foundation for the regional economy; wood processing increased throughout the 20th century (North Central Forest Research Station 1960–2005). Population in the region increased and finally steadied by the end of the 20th century (Historical Census Browser 2004). Beaver recolonized the region in the 1940s (Broschart et al. 1989, Naiman et al. 1994). Regional climate also changed. Temperature trends indicate warmer winters within the past three decades (Johnson and Stefan 2006).

After the initial response to logging, Lac La Croix's diatom communities changed again at the end of the 20th century, including an increase in species turnover and a slight increase in the P/B ratio. Sediment accumulation, water quality parameters, and taxonomic richness showed no significant changes. The change in diatom community was identified by CONISS as a first order change indicating a more important shift than the early 1900s shift that was linked to logging.

The regulated lakes also incurred changes in the 20th century. Taxonomic richness in Namakan Lake seemed to recover to pre-damming/logging levels. In contrast, taxonomic richness in Kabetogama Lake showed no sign of recovery, but instead decreased further. Rainy Lake's taxonomic richness did not vary significantly during the 20th century. The changes in taxonomic richness are not mirrored by species turnover patterns because all lakes have an increase in turnover in the latter part of the 20th century. Post-damming changes in diatom communities are also reflected in CONISS zonations and in our NMS analysis; all lakes have notably higher ecological variability in the 20th century and a diatom community shift post-1970s. Serieyssol et al. (2009) suggested the post-1970s shift in Namakan Lake and Lac La Croix was possibly linked to climate change. Similar temporal shifts in diatom communities have been identified in north temperate, boreal, and arctic lake systems, with multiple lines of evidence that suggest climate as a primary forcing factor (Rühland and Smol 2005, Smol et al. 2005, Rühland et al. 2008).

Diatom-inferred water quality parameters changed during the 20th century in Kabetogama and Namakan Lakes (see Figure II-13), but not in Rainy Lake or Lac La Croix. Total phosphorus concentrations decreased in Kabetogama Lake after damming, while TP concentrations increased in Namakan Lake. The decrease in TP in Kabetogama Lake could be a post-damming dilution effect because of the increased volume of the lake. Hall et al. (1999a) report a similar post-damming decrease in primary productivity following inundation of Buffalo Pound Lake in Saskatchewan (Canada). For Namakan Lake, inundation at the time of damming likely led to higher TP concentrations. Although mixing patterns between Namakan and Kabetogama Lakes are not well resolved, a potential for increased inflows or mixing from the more nutrient-rich Kabetogama may have also contributed to increased nutrient concentrations in Namakan Lake. The strength of our phosphorus reconstructions was evaluated using comparison of down-core assemblages to modern analogues and by comparing up-core reconstructions to recent TP concentrations in the lakes. Down-core samples were well represented in the modern training set, and diatom-inferred TP values for samples near the core tops were close to or within the range of modern TP measurements (Namakan 8–28 µg/L and Kabetogama 8–16 µg/L) (Payne 1991, Christensen et al. 2004).

Diatom-inferred conductivity increased in both Kabetogama Lake and Namakan Lake after damming. In Kabetogama Lake, inferred conductivity increased from damming until the 1980s, whereas in Namakan Lake, conductivity increased to a peak in the mid-1930s. Conductivity peaks in Namakan Lake might have been enhanced by known forest fires followed by floods (Serieyssol et al. 2009). Davis et al. (2006) showed that increases in diatom-inferred chloride in Hatch Pond reflected changes in catchment biogeochemical cycles largely due to logging. Similarly, Carignan et al. (2000) studied the impacts of fire and logging on boreal lakes and showed that K^+ and Cl^- concentrations were much higher in cut and burned lakes than in reference lakes. Diatom-inferred reconstructions for Rainy Lake were close to modern data (98 µS/cm). However, reconstructed values for Kabetogama and Namakan Lakes were higher than modern data (76 µS/cm compared to measured 45 µS/cm for Namakan Lake, 166 µS/cm compared to 93 µS/cm measured for Kabetogama Lake) (Payne 1991, Christensen et al. 2004). Although down-core assemblages did have good modern analogues in the training set, we note that the error bars associated with reconstructed values errors do encompass modern conductivity values for Namakan and Kabetogama Lakes.

Many paleoecological studies have attributed changes in sediment records to a single environmental variable. However, advances in statistical methods have allowed scientists to quantify the unique and interactive effects of multiple environmental stressors using methods such as variance partitioning analysis (Borcard et al. 1992). To understand potential ecological drivers of change in the border lakes, we determined the unique and interactive effects of climate, landscape and water-level changes on the diatom communities.

Overall, variance partitioning identified landscape as the strongest correlate of change in fossil diatom assemblages. Hall et al. (1999b), in their study of historical water quality in Canadian prairie lakes, also identified resource use and urban activities (landscape changes) as the strongest correlate to historical diatom and pigment changes. Logging in the border lakes region has been and still is a major industry (except around Lac La Croix), and therefore it was not a surprise that logging plays an important role in explaining pre and post-1959 variations in diatom communities. Beaver were also an important regional element in landscape change. Naiman et al. (1994) determined that beaver in the Kabetogama Peninsula altered the hydrologic regime and affected biogeochemical cycles, chemical distribution, and sediment accumulation over time and space. For example, small beaver dams can retain 2,000–6,500 m^3 of sediment (Naiman et al 1986), and export rates of dissolved ions, nutrients, and fine particulate organic matter are greater in beaver-influenced streams than in similar-sized streams without beaver (Naiman 1982). Beaver presence was significant in all post-1959 analyses and was the single significant landscape sub-variable identified for Rainy Lake and Lac La Croix; logging did not significantly explain post-1959 variation in diatom communities in these lakes. Human population was another landscape variable that significantly explained changes in fossil assemblages although never as a primary sub-variable in any lake. Generally, the interactive effects of landscape with climate and water-level explained more variation in diatom communities than the unique variance explained by landscape variables.

Climate did not play as dominant of a role as landscape in explaining variation in diatom assemblages. In pre-1959 samples, climate uniquely and interactively explained significant variance. For example, the interactive effect of climate explained between 32%–38% of total variance in pre-1959 samples. Serieyssol et al. (2009) suggested climate as possible explanation for the changes in the post-1970s fossil diatom assemblages in Namakan Lake and Lac La Croix. However, variance partitioning analysis of post-1959 samples indicated that the unique influence of climate was less than landscape, except in Rainy Lake. In post-1959 samples, climate uniquely explained 27% of the variance in Rainy Lake and 19% in Lac La Croix. In contrast, climate only explained 5% of unique variation in Namakan Lake, and climate variables were only weakly significant in Kabetogama Lake. However, in both Kabetogama and Namakan Lakes, the interactive effect of climate played an important role in explaining assemblage changes, at 61% and 60%, respectively. A similar pattern was noted by Hall et al. (1999b) in Saskatchewan lakes where landscape, climate, and their interactions with other stressors played an important role in explaining changes in historical diatom assemblages and pigment records.

Surprisingly, water-level as a unique influence on diatom communities was not as significant as originally expected. The unique influence of pre-1959 water-level ranged from 16% in Lac La Croix to not significant in Kabetogama Lake. There was significant “natural” hydrologic variation in Lac La Croix during this time period, and its strong interactive effect with climate and land use variables in influencing diatom communities supports the strong connection among these variables in natural settings. Water-level had a greater influence in pre-1959 samples compared to post-1959 water-levels in Rainy Lake and Lac La Croix. In post-1959 samples, the interaction of water level with other environmental drivers was highly significant in Namakan and Kabetogama Lakes, at 55% and 56%, respectively. Other studies have indicated that water-level manipulation impacts biological communities within Voyageurs National Park (Chevalier 1977, Kallemeyn 1987, Kraft 1988, Wilcox and Meeker 1991) and diatom communities in general (Wolin and Duthie 1999).

Although water-level management has been the primary resource concern in these border waters, water-level was never a dominant variable explaining historical changes in diatom communities. Based on variance partitioning results, other environmental stressors including landscape changes and climate variation (and their interactions with each other) and water level regulations must be recognized as significant drivers of recent change in the Ontario–Minnesota border lakes region.

II. Conclusions

Analysis of geochemical and biological proxies preserved in sediment cores from four large lakes in the Minnesota–Ontario border region was used to determine the impacts of Euro-American settlement, logging, damming, and subsequent land use and climate change on the water quality, sedimentation rates, and diatom communities. Damming and first cut logging impacted lakes along the Minnesota–Ontario border region based on temporal coherence of changes in sedimentation and diatom communities with historical records of logging and/or damming. After damming, land use, climate, and hydromanagement have been important drivers of change in border lakes. All three drivers generally contributed significant interactive effects and often explained unique variance in post-damming diatom communities among regulated lakes. Lac La Croix, an undammed control lake, responded primarily to landscape and climate factors over the same time period. More important, interactions among environmental drivers were the largest contributor to changes in diatom communities preserved in sediment core from these lakes.

Additional Information Needs

1. Based on these findings, particularly those relative to the effects of land use, attempts to evaluate the effects of rule curve changes need to take these watershed scale effects into consideration. This is also important to the National Park Service as they try to fulfill their mandates relative to natural areas.

2. Additional analyses are needed to incorporate the possible historical effects of forest fires on this region's lakes. Available historical data are not detailed enough to reconstruct fire extent and frequency in VOYA and the potential impact on lakes. Analysis of charcoal remains in sediment cores would be one method to reconstruct historical fire records and their impacts on each lake.

3. Given the size and complex nature of these lake basins, additional cores should be collected and analyzed. Of particular interest would be cores from the western end of Rainy Lake, the Canadian waters of Rainy Lake, and Black Bay. Additional cores would also allow assessment of whole basin impacts, thereby eliminating single core artifacts (e.g. post-damming sediment focusing). See also recommendation 5.

4. Flow patterns need to be determined, particularly between Kabetogama and Namakan Lakes, to better understand interannual and seasonal mixing patterns.

5. Similar paleoecological analyses, including assessment for fire effects, should be done on Sand Point and Crane Lakes so there would be a complete picture for the Namakan Reservoir.

6. Additional biological and geochemical analyses could be used to fine tune the ecological histories of the VOYA lakes. Suggested analyses include biogenic silica (proxy for algal/diatom productivity), fossil pigments (would provide historical record of

cyanobacteria), and invertebrate remains (zooplankton and chironomids) to understand higher trophic level responses and anoxia.

Part III. An Annotated History of the Rainy Basin Watershed

This section includes timelines and historical information gathered for this project. Significant dates are in **bold** within the text. Much of this information was gathered by Kallemeyn.

Brief Historiography of Voyageurs National Park

1688	Jacques de Noyon explores Rainy River
1780	Ojibwe primary residents
1800	Rainy Lake and Rainy River main transit way for fur trade
1865	Prospectors started coming to search for gold
1870	First registered settlers
1880s–1890s	Initial logging frenzy
1892	Development of commercial fisheries
1893	George Davis finds gold
1898	Gold boom is over
1901	Train in Fort Frances, ON
1907	Train in Ranier and International Falls, MN
1905–1909	Koochiching Falls at Rainy Lake outlet are being dammed
1914	Dam completion of Kettle Falls and Squirrel Falls on Namakan Lake
1918	Cloquet fires (770,000 acres) evidence in Voyageurs National Park
1923	Fire on Kabetogama Peninsula (11,000 acres)
1925	First investigation to regulate lake levels in the Rainy watershed lakes
1926	Kabetogama Lake bans commercial fishing
1936	Fire in VNP (14,000 ha or 35,594 acres)
1940	IJC Takes Over, Rainy Lake Convention, IJC only manages the lake under emergency regulations
1949	IJC changes the regulation in order to prevent extreme flow conditions

1957 IJC modifies the regulation due to extreme floods

1970 IJC modifies regulations due to high water levels

1975 Voyageurs National Park established

2000 New order to bring the Rainy Watershed back to natural variations

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Administrative Origin and Structure Timeline for Water Management in the Rainy Lake Basin

1909 United States and Canada established the Boundary Waters Treaty which established the International Joint Commission and defined its role.

1909 International dam at International Falls/Fort Frances completed.

1914 Canadian Dam and International Dam at Kettle Falls completed.

1925 U. S. and Canada issued the Rainy Lake Reference requesting the IJC to make recommendations as to the regulation of Rainy Lake and other boundary waters.

1934 IJC submitted the final report for the reference to the U.S. and Canadian governments.

1940 Governments ratified the report (1940 Convention). The 1940 Convention did not actually define any specifics for regulation but assigned the power to the IJC to determine when emergency conditions exist in the Rainy Lake basin and to adopt control measures as necessary.

1941 IJC established International Rainy Lake Board of Control and directed it to examine and report on the issue of emergency issues.

1949 IJC integrated the IRLBC findings into its Order of June 8, 1949. Order had a single rule curve (one line) for both Rainy Lake and Namakan Reservoir.

1957 IJC issued a supplementary Order on October 1, 1957, in response to excessive spring runoff in 1950 and 1954. No change was made in the Rainy Lake rule curve but a maximum rule curve was added for Namakan Reservoir.

1970 IJC issued a new supplementary Order on July 29, 1970. It established a rule curve band on Rainy Lake and amended the rule curves on Namakan Reservoir.

1987 U. S. Federal Regulatory Commission license issued for the U.S. portion of the dam at International Falls for 40 years. License required Rainy Lake water levels to be at the top of the 1970 Rule Curve for two weeks following ice-out.

1995 U. S. Congress passes and President signs an act requiring the dam operators utilize the Rainy Lake and Namakan Reservoir Water Level International Steering Committees proposed rule curves in conjunction with the 1970 rule curves. In each instance in which an existing rule curve coincided with a proposed rule curve, the water level was to be maintained within the range of coincidence. When the existing rule curve and proposed rule curve did not coincide the water level was to be maintained at the limit of the existing rule curve that was closest to the proposed rule curve. The amendment, which was sponsored by Senator Wellstone, had a sunset provision that said the amendment was to remain in effect until the IJC reviewed and made a decision on the Steering Committee’s recommendations.

2000 IJC issued a new supplementary Order on January 5, 2000 which implemented new rule curves for both Rainy Lake and Namakan Reservoir, directed the Companies to target the middle of the rule curves, and gave the IRLBC authority to direct the Companies to target elsewhere in the band.

2001 IJC adopted a consolidation as the authoritative text of the Commission’s Order of June 8, 1949, as amended, and replaced the individual Order and the Supplementary Orders of 1957, 1970, and 2000. The rule curves in the 2000 supplementary Order were not changed.

Beaver Population Trends

Johnston and Naiman (1990a) used aerial photographs taken in 1940, 1948, 1961, 1972, 1981, and 1986 from the Kabetogama Peninsula to determine size and growth rates of individual patches along with the numbers, area, density, and established rate of the patch population. It was determined that the total number of pond sites had increased from 71 in 1940 to 835 in 1986 but with a decrease in rate after 1961. Also, the colony counts were lower since 1981. More information on the methodology can be found in Johnston and Naiman (1990b).

Steve Windels, Terrestrial Ecologist at Voyageurs National Park, is currently compiling a report on the beaver population in Voyageurs National Park from 1927–1970. Like Johnston and Naiman, Windels found the same increase–decrease pattern; beaver population increased from 1936 to 1986 and then decreased from 1986 to 2006 (Table III-1).

Table III-1. Annual beaver population estimates on the Kabetogama Peninsula, 1936–2005. Data represent number of active colonies per km of transect surveyed. Data were collected in 1936, 1940, 1948, 1958, 1961, 1964, 1968–2005. Data points between those sampling years are estimated based on linear interpolation.

Year	Active Beaver Colonies per Transect km	Year	Active Beaver Colonies per Transect km	Year	Active Beaver Colonies per Transect km	Year	Active Beaver Colonies per Transect km
1936	0.000	1954	0.520	1972	0.835	1990	1.896
1937	0.036	1955	0.528	1973	0.948	1991	1.625
1938	0.072	1956	0.536	1974	1.377	1992	1.783
1939	0.108	1957	0.545	1975	1.400	1993	1.941
1940	0.144	1958	0.553	1976	1.512	1994	2.054
1941	0.180	1959	0.809	1977	1.354	1995	1.490
1942	0.221	1960	1.065	1978	1.840	1996	1.456
1943	0.263	1961	1.321	1979	1.930	1997	1.230
1944	0.304	1962	1.091	1980	1.591	1998	1.005
1945	0.346	1963	0.862	1981	2.250	1999	1.050
1946	0.387	1964	0.632	1982	1.682	2000	1.693
1947	0.429	1965	0.801	1983	1.828	2001	1.546
1948	0.470	1966	0.971	1984	2.088	2002	1.625
1949	0.478	1967	1.140	1985	1.851	2003	1.410
1950	0.487	1968	1.309	1986	1.828	2004	1.190
1951	0.495	1969	0.643	1987	1.874	2005	0.971
1952	0.503	1970	1.163	1988	1.851		
1953	0.512	1971	1.569	1989	1.828		

Forest Fires

Fire histories for the Quetico Provincial Park (Woods and Day 1977), Boundary Waters Canoe Area Wilderness (BWCAW) (Heinselman 1996), and Voyageurs National Park (Coffman et al. 1980) have much in common. Table III-2 presents the major fire periods identified by these investigators for these protected areas, which in total cover 10,058 km^2 (26%) of the Rainy Lake watershed. For the BWCAW, Heinselman defined major fire years as those when over 100 mi^2 (25,900 ha) were burned. Heinselman's research was much more intensive than that in Voyageurs and the Quetico, and Heinselman looked back much further.

Table III-2. Years of significant fire events in Voyageurs National Park, Boundary Waters Canoe Area Wilderness, and Quetico Provincial Park, 1681–1971. Acreage estimates in parentheses.

Voyageurs National Park	BWCAW	Quetico PP
1863–1864	1681 (39,887 ha)	1860–1869 (4,913 ha)
1869	1692 (26,677 ha)	1870–1879 (10,417 ha)
1875	1727 (53,614 ha)	1880–1889 (18,033 ha)
1894	1755 and 1759 (80,809 ha)	1890–1899 (7,964 ha)
1910	1801 (41,959 ha)	1900–1909 (10,409 ha)
1917–1918	1824 (33,930 ha)	1910–1919 (20,016 ha)
1923	1863–1864 (180,267 ha)	1920–1929 (241 ha)
1925	1875 (90,652 ha)	1930–1939 (16,397 ha)
1936 (14,000 ha)	1894 (67,636 ha)	1940–1949 (16 ha)
	1910 (20,720 ha)	1950–1959 (12 ha)
	1936 (4,144 ha)	1960–1969 (1,880 ha)
	1971 (6,216 ha)	1970–1976 (1,974 ha)

Additional historical commentary on forest fires

Ahlgren and Ahlgren (1984)

The authors express concerns about fires that may have occurred in the BWCAW that were not detected by Heinselman (1996) and others. As an example, they use 1871, which was a major fire year in Michigan and Wisconsin, and was identified by a U. S. Signal Corps meteorologist as having been a year with "unparalleled fires in northeastern Minnesota."

Ayer (1902)

Timber cruiser who in 1902 cruised most of the land north and east of Rainy Lake. In nearly all his notes, Ayer referred to a huge burn area that occupied much of this area. Based on Ayer's description most of the area was probably burned in 1894. "Burnt as far as eye can reach N.E. and west so recently that the brush has not grown to any extent." "Indians tell me this last fire was about eight years ago."

Beatty (1962–1968)

Commented on fires in the area now in Voyageurs National Park in **1923**, **1926**, and **1936**. The 1923 fire burned from Nashata Point on the north shore of Kabetogama Lake east to Squaw Narrows on the east end of the Kabetogama Peninsula. The 1926 fire started south of the Park but moved north and jumped the lake at Kabetogama Narrows before being stopped on the Kabetogama Peninsula.

Dawson, S. J. 1857. Unpublished letter from Fort Frances.

"From the Grand Lakes on the Kaministigua to this place, the whole country seems at no very distant period to have been overrun by fire."

Drache (1992)

In **1938**, a fire started after the first killing frost, ultimately burning at least 150,000 acres in northern Minnesota and an even greater area in Ontario.

Cameron, J. D., director of the Hudson Bay Company Lac La Pluie (Rainy Lake) post, 1824–1832. Unpublished copies of post records at Voyageurs National Park.

1 June 1820 – "The weather very warm, and the woods around us on fire."

27 September 1829 – "as I am apprehensive the fire which is running all over may destroy the hay." After a further look Cameron determined "the fire is in the Islands and across the lake.

2 October 1830 – fires were around the fort for several days but Cameron didn't comment whether they were just local or more widespread.

Ontario Ministry of Natural Resources (1980)

The Fort Frances District doesn't include that portion of the Rainy Lake basin in Quetico Provincial Park and a little of the NE portion of the basin. It extends west to Lake of the Woods and has a total area of 12,600 km^2 or 4,865 mi^2.

"The entire southern part of the District is traversed by the Quetico Fault. Typically, this major east–west trending fault zone is highly fractured and sheared…. The Quetico Fault can be traced westerly from Bennett Lake to Stratton. Parts of the Turtle River, as well as Crowrock, Halfway, and MacDonald's inlets of Rainy Lake occupy valleys within the fault zone."

Assuming an average runoff of 20 cm/year, the District would produce 550,000 hectare-meters of water per year.

The three tertiary watersheds in the District are the Middle Rainy River (66%), Lower Rainy River (17%), and the Lake of the Woods (17%).

Canadian Northern Railway to Fort Frances in **1902**.

Water accessible locations were logged for saw timber in the last quarter of the 19th Century.

The Fort Frances Pulp and Paper Mill was established in **1914** and the company got its first Crown Timber Limit in **1927**.

As early as the **1890s** fish and game of the District were attracting a tourist trade. Most present day resorts were established in the 1930s, 1940s, and 1950s.

Population of the District has remained relatively stable for the last two decades.

Substantial portion of the District subjected to fires in the past 6 decades, with the largest burns occurring prior to **1941**.

1923 was a particularly severe fire year. There were extensive fires west of Otukamamoan Lake, northeast of Redgut Bay as well as in the area of Manion and Pettit Lakes.

1929: There was a large fire between Rainy and Loonhaunt Lakes.

1930s: Large fires east of Entwine Lake (**1933**), East of Rat River Bay (**1936**), and north from Buriss to Loonhaunt Lake and northeast of Namakan Lake (**1938**).

Soil depths around Rainy and Namakan Lakes are shallow.

The Turtle River, Little Turtle River, and Seine River, all of which flow into Rainy Lake, were used for pulpwood logging drives.

Gold mining occurred in the District in the late **1890s** and early **1900s**.

Copper mining was done five miles west of Mine Centre, with 11,565 kg of copper being produced during World War I.

1978: The Rainy River census subdivision had a total population of 24,257 or 1.7 people/km^2 (=sparse). The most rapid growth last occurred from 1921–1931 with only moderate growth from 1931 to 1961.

Bertrand (1997)

A little information about Backus's development activities but mostly deals with the area east of the Rainy Lake watershed, including along Lake Superior.

The author does mention that while traveling in the fall of 1938 from Kenora to Fort Frances then to Duluth on Highway 53 that there were large intense fires both in the Emo, ON area and south of International Falls along Highway 53.

Ontario Department of Lands and Forest (1963)

Page 1: Farms on the Canadian side of the Rainy River in 1873. Treaty ceding land between Lake of the Woods to Lake Superior to the Dominion in 1873. There were 600 farms located on the Canadian side of the Rainy River by 1893.

Page 3: The first sawmill in the area [Fort Frances Forest District] appears to have been erected at Fort Frances by H. S. Fowler in 1873. During 1900–1920 sawmills were erected and operated at Mine Centre, Rocky Inlet on Rainy Lake and at Fort Frances. "Gold locations…lying immediately to the east of Bad Vermillion Lake, two stamp mills erected in the region." Vol VIII of the Annual Report for 1895 of the Geological Survey, Department of Canada, Harold Lake had five stamp mills.

Page 4: Almost all land between Shoal and Bad Vermillion Lakes…gold locations.

Page 7: A 1934 letter stated that in May there was a large infestation of tent caterpillars attacking aspen but other trees were not affected, from Ft. William to Ft. Frances and reported 10 miles north of Atikokan. The tent caterpillar infestation continued to defoliate poplar and white birch.

Page 8: 1936–1938, Severe fire seasons.

Page 11: 1951, Dr. C. E. Atwood discovered European Spruce Sawfly colonies in the Quetico area, an extension of its previously known range.

Page 12: 1954, New boundaries established for Quetico Park including a one mile buffer where no land disposition is permitted.

Page 14: 1957, First open season on moose in almost 20 years.

Page 15: 1961, Walter Kenyon of the Royal Ontario Museum staff began skin-diving operations along the old fur trade canoe route staring on the Maligne River east of Namakan Lake.

Page 15: 1961 was the most severe fire season since 1936–1938. Four thousand six hundred acres burned near Saganagons Lake in Quetico.

Fritz (1986)

The author presents description of the **1936** fire on the Kabetogama Peninsula. One portion of the fire started on July 1 near the west end of Mica Bay on Namakan Lake. It burnt east crossing at Squaw Narrows into Ontario. Another fire started near Cruiser Lake. The fires burned until September 28, 1936, when four inches of rain put them out.

Gates (1965)

From the diary of Hugh Faries who was stationed at the post at the outlet of Rainy Lake in 1804–1805:

28 October 1804 – "In the evening the Fort was near catching fire, the wind blowing very hard from the S.W. and the country on fire all around us."

29 October 1804 – "The fire was still going."

Kemp (1980)

1804 was a particularly dry year.

The low water levels on the Shield between Lake Superior and Lake Winnipeg caused the Red River brigade to fall well behind schedule.

Nute (1950)

Quote from Father Jean Pierre Aulneau in **1735**: “Journeyed nearly all the way from Lake Superior to Lake of the Woods through fire and a thick stifling smoke.”

The author cites J. D. Cameron: “…because of the fearful forest fires of **1803–1804**…”

“Winchell in **1887** found evidences of a much more recent conflagration.”

“Despite the great forest fires of **1734**, **1803–1804**, and later…”

Plummer (1912)

In 1910, there were 936 fires in northern Minnesota and Wisconsin, burning over 1,051,331 acres and causing a loss of $1,721,752. Approximately one-third of these fires occurred on the Lake of the Woods watershed. The cause was drought.

Human Settlement and Population

The main focus was on identifying historic structures, but Sanford and Graves-Budak (1999) provide some good information on the timing of development and the type and number of units that were developed in various periods.

- The Dawson Trail, completed in 1873, ran from Lake Superior to the Red River Country. It served as a stimulus to settlement, particularly along the Rainy River. “By 1873, for example, regular steamboat services were available on the larger lakes, from Kettle Falls to Lake of the Woods.” Steamboat travel remained important through the 1890s.
- Tourism and recreational development occurred from 1880s to 1950s.
- “At the time of the establishment of Voyageurs National Park in 1975, 650 summer homes, weekend cabins, hunting shacks, resorts, and state lease cabins occupied sites within the park boundaries.”
- From the 1880s into the 1920s, the focus was on wealthier tourists and outdoor adventurers who could afford extended stays. After the 1920s the types and numbers of vacationers shifted to the less wealthy and people with a wide variety of interests.
- Early development was restricted by lack of roads. Roads were developed in a piecemeal fashion, and it wasn’t until 1923 that State Highway 11 (now 53) was completely opened. Roads were not hard-surfaced until the 1940s. In the 1930s main highways were impassible from mid-March to mid-June.
- In 1922, the Superior National Forest received 12,000 visitors.
- After the railroad reached International Falls in 1907, promoters started pushing the area for tourism. Backus was involved along with many other wealthy individuals.

- By the mid-1920s, there was at least one business serving tourists at each of the major access points for the park: Watson's Lake View resort (1918) on Kabetogama Lake, Borderland Lodge on Crane Lake, Clark's Resort on Sand Point Lake, Island View on Rainy Lake, and Palmer's Frontier Lodge at Ash River.

- "...[N]orthern Minnesota did not see a significant rise in tourism until the mid-to-late 1930s." Prior to that the focus was on timber, and tourists were thought of as a detriment to logging.

- "A 1935 report on suitable land uses for northern Minnesota noted that the numbers of private cabin and cottage owners exceeded the number who stopped at commercial resorts."

- 1931—11 of 26 private property owners on Kabetogama Lake owned resorts or worked as fishing guides. The two property owners on Rainy Lake were both resort owners. Resorts were also owned by three of four property owners on Namakan Lake and two of two property owners on Sand Point Lake.

- 1930s—CCC constructed 36 campgrounds in the Kabetogama State Forest; 20 were abandoned by 1948.

- 1936—Black Bay Road extended to Island View.

- 1936—26 resorts on Kabetogama Lake.

- 1939—Highway 53 paved from Virginia to International Falls.

- 1949—Highway 11 East extended to Sha-Sha Point.

- **1949—42 camps, hotels, and resorts on Kabetogama Lake—privies are the main form of bathroom.**

- State leases began at Lake Vermilion in 1917. Gappa's Landing (Kabetogama Lake) was platted shortly thereafter, and nine lots on Sand Point by 1922. Namakan and Ash River lots were platted in the 1940s. High demand resulted in 500 lots being platted between 1958 and 1961.

- Kabetogama was most popular area, with 116 plats between 1922 and 1973. In 1931, a survey of state-owned property listed 72 summer homes and campgrounds on Kabetogama, 52 on Sand Point Lake, and 66 on Lake Vermilion.

- 1935—30 private resorts in the roadless area in the Superior National Forest.

- 1946—30 resorts and 14 private developments in the roadless area; in the La Croix and Kawishiwi Districts, there were 71 developments in a 13 lake area.

- 1949—42 camps, hotels, and lodges on Kabetogama Lake.

- 1958—Comprehensive survey of 19 northern counties by Richard O. Sielaff showed that an average resort in Koochiching and St. Louis counties had 6.2 and 10.7 cabins, respectively. There was significant resort development in Koochiching County from 1945 to 1950. "As late as 1958, the 'roughing it' tradition of the northern border lakes area continued: roughly half of resort cabins in the northern counties had indoor toilets and less than that offered both hot and cold running water."

- 1960s——greatest influx of seasonal residences in Voyageurs area where more than 200 cabins were built.
- 1964—Follow-up study by Sielaff found that in the proposed national park area (excluding east Namakan and Sand Point), there were 138 summer cabins (49 leased from the state), five resorts, seven commercial properties, and five homesteads.
- By the 1970s, the government had acquired and removed 45 resorts and 91 cabins in the Boundary Waters Canoe Area (BWCA).
- 1968—40 resorts on Kabetogama, 13 on Rainy Lake, and 19 at Ash River. There were also three year-round residences, 120 seasonal cabins, and 32 cottages in use.
- 1999—Within VOYA, there are 28 resorts on Kabetogama, nine resorts on Rainy, and four at Ash River. Also 123 recreational properties under lease or other agreement, and an additional 50 privately owned properties with cabins.
- Kabetogama Narrows became road accessible in the late 1950s.
- 1940s—38 resorts on the south shore of Kabetogama. By the mid-1960s, 62 resorts were listed in Koochiching County in the proposed park boundaries.

Oral histories

George Esslinger: He started resort on Kabetogama in 1932 —"…resort business was just opening up in the border region."

Ed Nelson: He thought first resort in Ash River (Frontier Resort) started around 1928.

Yeigh (1892)

Noted that **1891** was a good year for grains and fruits.

Population of Fort Frances in the 1891 census is 1,339 (p. 14).

A new survey of Fort Frances was directed to be done by the Hon. Arthur S. Hardy, September 1891, with talk about a lock into Rainy Lake (p. 16).

Makes reference to a fire north of Rainy Lake/Sand Island River "has been burnt over and is now grown over with small growth poplar." Also, "On the chain of water connecting Sand Island River with Rainy Lake lumber camps have been in operation in former years" (p. 22).

Ontario Department of Lands and Forests (1963)

See summary on pp. 73–74.

International Joint Commission (1934: p. 195)

First steam vessels on Rainy Lake, Rainy River, and Lake of the Woods seem to have been built in 1871 or 1872.

Nute (1950)

The tugboat era was in the 1870s. There were tugs on Lac des Mille Lacs, Kashabowie, Lac la Croix, Namakan Lake, Rainy Lake, Rainy River, and Lake of the Woods.

Minnesota Pollution Control Agency (2001)

Table III-3. Populations in the three watersheds, 1980 and 1990.

	1980	**1990**
Rainy River headwaters	8,201 (3.3 people/mi^2)	6,518 (2.6 people/mi^2)
Vermilion River	13,566 (13.1 people/mi^2)	11,415 (11.0 people/mi^2)
Rainy River/Rainy Lake	4,962 (5.5 people/mi^2)	4,263 (4.7 people/mi^2)

Table III-4. U.S. census reports for the four counties, parts of which make up the Rainy Lake basin.

Year	St. Louis	Lake	Cook	Itasca[1]	Koochiching
1860	406	248		51	
1870	4561	135		96	
1880	4,504	106	65	124	
1890	44,862	743	98	743	
1900	82,932	4,654	810	4,573	
1910	163,274	8,011	1,336	17,208	6,431
1920	206,391	8,251	1,841	23,876	13,520
1930	204,596	7,068	2,435	27,224	14,078
1940	206,917	6,956	3,030	32,996	16,930
1950	206,062	7,781	2,900	33,321	16,910
1960	231,588	13,702	3,377	38,006	18,190
1970	220,693	13,351	3,423	35,530	17,131
1980	222,229	13,043	4,092	43,069	17,571
1990	198,213	10,415	3,868	40,863	16,299
2000	200,528	11,058	5,168	43,992	14,355

[1]Prior to the 1910 census, Itasca County included what is now Koochiching County. Duluth and the Iron Range towns and communities along the North Shore that are not actually in the Rainy Basin comprise a large portion of the populations in St. Louis, Lake, and Cook counties. Most of the proportion of Itasca and Koochiching that are in the Lake of the Woods drainage actually enter the watershed below the Rainy Lake outlet.

Lorch and Phillips (1991)

Table III-5. Population densities in northwest Ontario census districts, 1901–2006. Values for 1901 to 1986 were interpolated from the figure in Lorch and Phillips (1991).

Year	Rainy River	Thunder Bay	Kenora
1901	6,500	10,000	10,000
1911	10,000	38,000	18,500
1921	13,000	49,000	18,500
1931	17,000	65,000	26,000
1941	19,000	85,000	33,000
1951	21,000	119,000	38,000
1961	27,500	138,000	51,000
1971	27,000	145,000	53,000
1981	24,000	150,000	58,000
1986	22,000	156,000	52,000
1996	23,138	157,619	63,360
2001	22,109	150,860	61,802
2006	21,564	149,063	64,419

Kallemeyn et al. (2003)

Voyageurs National Park benefits from the fact that 25% of the watershed upstream from the park is in the protected areas in the Quetico Provincial Park and the Boundary Waters Canoe Area Wilderness in the Superior National Forest.

Logging in the Rainy River Basin

Early logging chronology

Also see Quetico Provincial Park section for some more pertinent dates, particularly 1971 when it was closed to logging.

1880 Canadian railway connects eastern Ontario with Winnipeg.

1880s Illegal logging of pine and other saw logs, some in the basin upstream of International Falls, including the area now occupied by Voyageurs National Park.

1890s Continued logging of pine, particularly in the Ely/Tower area now in the BWCAW.

1893–1894 Logging to supply gold mines and building of Rainy Lake City.

1902	Morris Act shuts down movement of saw logs to Ontario mills from Minnesota.
1909	Superior National Forest and Quetico Forest and Game Reserve established.
1913	Ontario designates Quetico Provincial Park, which closed the area to hunting.
1910 to 1929	The Virginia Rainy Lake Lumber Company logged pine and other saw logs in the area now in Voyageurs National park and the area to the south and east.
1910 to 1937	The International Lumber Company, a subsidiary of the Minnesota and Ontario Paper Company, harvested pine and other saw logs on the Kabetogama Peninsula.
1910 and 1914	Pulp mills in International Falls and Fort Frances. Spruce and balsam fir were the preferred species initially, aspen increasingly became more important.
1911 to 1936/1937	Backus sawmill operated in International Falls.
Early 1900s–1942	Shevlin Clarke saw mill operated in Fort Frances.
1922–1954	J. Mathieu saw mill operated in Fort Frances.
1930	The federal Shipstead-Newton Nolan Act prohibited on federal lands the logging of lakeshores, islands, and streamsides to a breadth of 400 feet from the waterway. A similar state law that applied to state areas was passed later.

Logging in Minnesota

Nute (1950)

Nute provides an extensive description of both the illegal logging that happened prior to 1890 along the international boundary as well as the logging that occurred after that time. The movement of wood to Rat Portage (Kenora) started as early as the late 1870s in response to the Canadian intercontinental railroad opening up the prairies. While a lot of the wood that moved northward appears to have come from the Little Fork and Bigfork drainages, some also came from the Rainy Lake basin above the falls at International Falls.

- The discovery of gold created a demand for wood for the building of Rainy Lake City in 1893–1894.

- Most of the legal pine harvest occurred between 1910 and 1929. The International Lumber Company, a subsidiary of the Minnesota and Ontario Paper Company (MANDO), operated west of the eastern border of Koochiching County, while the Virginia and Rainy Lake Company (VRL) operated east of Koochiching County as far as a line drawn south of Lac La Croix. The MANDO subsidiary remained in operation through 1937 but the parent company continued to function after that. VRL closed in 1929. Nute provides a fair amount of detail about how the companies operated.

- 1910—pulp mill built in International Falls; 1911—huge sawmill in International Falls; 1914—pulp mill built in Fort Frances. There were numerous other sawmills along the Rainy River downstream from International Falls/Fort Frances.

- "During the first thirty years of operation by the MANDO pulp and paper mills, giant grinders and chippers gnawed away approximately six million cords of pulpwood, or the average yield of six hundred thousand acres of forest land. In addition, the sawmill cut slightly more than a billion board-feet of lumber in its twenty-seven years of operation, or the average yield of about half a million acres." (Unfortunately Nute doesn't tell us how much of that came from the Rainy Lake basin.)

- At the time Nute wrote her book, some wood was still being rafted to the mills. Also at that time, the International Falls mill had an operating area of 4,000,000 acres.

- Together, the Fort Frances and International Falls mills in the late 1940s required 250,000 cords annually.

Perala (1967)

Chapter IV. Early Logging in northern St. Louis County

- Prior to 1900 extensive logging north of Laurentian Divide.

- The logging was done where loggers could use waterways to move logs north to Rat Portage (=Kenora, Ontario).

- Logging was concentrated within five miles of river banks so logs could be moved to the rivers and lakes for floating out.

- The focus was on white pine—"These stands of white pine apparently grew up in areas widely burnt in 1734, 1803, and 1804."

- Quote's Nute's description of illegal logging in its entirety.

Chapter V. Lumbering in the Tower area.

- First sawmill in Tower in 1882 or 1883.

- Logs processed came from Lake Vermilion, Pine Lake, “26 area” near Ely, (1893), Bear Head Lake (1895), Lake Vermilion, Trout Lake, and the country adjacent to the Pike River (1899).

- Trout Lake Lumber Company logged as far north as Elbow and Hoodoo Lakes from 1915 to 1918.

Chapter VI. Logging in the Ely area.

- The first logging [in the Ely area] was in 1892 in the Fall Lake and Shagawa Lake area.

- St. Croix Lumber and Manufacturing Company had logging camps at Basswood Lake, Stoney River, and Burntside Lake areas (all in the Rainy basin).

- “Where dams were connected by rivers, a system of dams and sluiceways were erected to provide sufficient water to float the logs from lake to lake.”

- Logging locomotives burnt wood.

- Logging in the Basswood Lake area by Swallow and Hopkins ran from 1893–1910 and removed over 300,000,000 board-feet of lumber.

- Fall Lake dam was built in 1902–1903.

- “By the end of World War I the timber supply in the Ely and Winton area had been largely exhausted.”

Chapter VII. The Virginia Rainy Lake Lumber Company (VRL)

- Stock holders were Cook and O’Brien (33%), Hines (33%), and Weyerhaeuser (33%).

- Headquarters was in Cusson.

- Lack of water transportation forced the building of a railway system to get the logs to Virginia, Minnesota.

- They built the Duluth, Virginia, and Rainy River Railway Company. In 1905 the company was renamed the Duluth, Rainy Lake, and Winnipeg Railway Company.

- 1902–1903: Built railway from Virginia to Cook.

- 1907: Built the 67 miles to International Falls; it was opened to traffic in 1908.

- 1908: The railway was extended to Duluth.

- In 1923, the railway became part of the Canadian National system.

- The main line of the VRL logging railroad ran from Cusson northeast to Elephant Lake, then north to Black Duck Lake, and then north to Hoist Bay on Namakan Lake (latter site is in Voyageurs National Park). At Elephant Lake, the Vermilion main line branched off the Namakan line and ran east to the south end of Elephant Lake and then eastward to Echo Lake.

- In total, in the 20 years, the company operated 2,000 miles of branch railroad that were built off the main lines.

- Main line spurs were graded and blasted.

- “After the ice went out of the lakes, the logs were towed to hoists on Namakan, Kabetogama, Rainy, Elbow, Black Duck, Johnson, Club, and other lakes in the area.”

- Logging operations: The company logged in the territory extending from the international boundary south about 50 miles and then east and west from Lac La Croix, west to Range 23.

- From 1910 to 1929, they produced 1,991,556,030 board-feet of lumber.

- The acreages logged were not available for 1910–1914, but from 1915–1929 they logged 306,725 acres (Table III-6). The acres logged per year ranged from 11,520 to 32,585.

Chapter X. Conclusion

- “… the virgin white pine forests were destined for destruction. The tax laws of the time ruled out a system of logging based on sustained yield.”

- “The laws requiring that the logging slash be burned, assuming that in doing so the land was being prepared for the farmers who would follow, served to destroy whatever young pine trees and seedlings that remained.”

- “…in the Orr and Cusson area several thousand men were congregated to work in the woods…”

- “Much of northern Minnesota’s finest timber was stolen and shipped to Canada duty free.”

- “…through the destruction of the pine forests did destroy an important esthetic value which today would be of value to the tourist industry,…”

Table III-6. Board-feet produced and acres logged by the Virginia Rainy Lake Lumber Company from 1910 to 1929.

Year	Board-Feet	Acres Logged
1910	114,720,770	Not given
1911	113,631,730	Not given
1912	128,775,580	Not given
1913	134,207,180	Not given
1914	136,161,740	Not given
1915	132,162,130	32,585
1916	128,684,040	23,600
1917	145,975,420	27,160
1918	109,273,820	16,980
1919	88,047,170	11,800
1920	75,820,670	16,220
1921	62,694,170	14,320
1922	46,580,980	11,520
1923	86,550,820	14,680
1924	93,318,230	19,240
1925	96,417,545	20,840
1926	67,375,620	19,780
1927	95,695,495	23,220
1928	84,546,260	30,640
1929	50,926,660	24,140
Total	***1,991,566,630***	***306,725***

Sielaff et al. (1964)

- Report covered the part of the park west of the western one-third of Namakan Lake, so it did not include most of Namakan and Sand Point Lakes. It did include the Kabetogama Peninsula.

- Authors' explanation for the relatively low harvest (Table III-7):

    1. Area had been rather thoroughly logged by 1910 and consequently it had not had time to restock (grow back).

    2. The 1936 fire had destroyed some 20,000 acres of commercial forest land in the area.

Table III-7. Data from Minnesota state records for timber harvested from the proposed park area from 1 April 1959 to 31 March 1964.

Timber type	Harvest (cords)	Forested acres	% of acreage	Kabetogama Peninsula Forest Classification (ac)
Poplar (aspen)	3005.91	28,400.00	37.11	17,991
Balm of Gilead	142.56	1,346.92	1.76	3,963
White, black spruce	1397.25	13,201.26	17.25	3,711 (black)
Balsam	2754.81	26,027.61	34.01	9,604 (+white spruce)
Cedar	81.00	765.30	1.00	2,322
Jack pine	443.88	4,193.80	5.48	2,392
White, Norway pine	141.75	1,339.26	1.75	1,508
Ash and elm	40.50	382.65	0.50	2,210
Tamarack	40.50	382.65	0.50	368
All others	51.84	489.80	0.64	
Total	***8100.00***	***76,529.25***	***100***	***45,867***

Ahlgren and Ahlgren (1983)

- "Ecologically, no force since the glaciers has rivaled northern logging in either its immediate or long-term effects, some of which are just now becoming evident."
- Logging slash greatly increased fire incidence.
- Pine removal opened large acreages to establishment of aspen and other pioneer species, which previously had been a minor component of the forest community. Aspen accounted for about one-third of the northern forest in the mid-1970s.
- Timber harvest – Clear-cutting done mechanically – utilize the entire tree. "Complete removal of the biomass every 30 to 60 years for this rapid growing, high productivity species (aspen) may result in site depletion."

Heinselman (1996)

- Prairie Portage Dam was built in 1902. It was a wooden dam that washed out in 1968. It was rebuilt with concrete in 1975 by the U.S. Forest Service.
- Logging Little Vermilion, Loon, and Lac La Croix region.
- Rat Portage Lumber Company logged along the international boundary from Lake of the Woods east to about the Loon River between 1885 and 1915. They cut white and red pine which was then rafted to Kenora, Ontario.
- Virginia and Rainy Lake Company 1910–1929
- 1916: Dam and a sluiceway were built on the outlet of Loon Lake; remnants of the dam still existed in the 1960s.

- The last significant pine cut was done between 1924 and 1929 when 400 acres were logged at the southern tip of Lady Boot Bay on Lac La Croix. The logs were rafted across Lac La Croix, floated down the Namakan River into Namakan Lake, and then rafted to Hoist Bay where they were taken out by rail.
- When the Virginia and Rainy Lake operations were completed, there were some large slash fires.
- Ecological Effects of Early Logging—184,000 acres of upland forest were logged in the BWCAW between 1895 and 1940. Because no year-round roads were built, no tractors were used for log skidding, no mechanical ground preparation was used to prepare logged areas for planting and seeding, and no herbicides were used to control post-logging vegetation. Thus, there was little disturbance of the natural soil profile and little direct effect of logging on the ground vegetation. Developing railroad grades did leave some "permanent scars" on the landscape. Heinselman felt the dams and sluiceways built for logging had significant ecological effects on some water bodies. "The most important general effect of the early pine logging has been a major reduction from 15 percent to 5 percent of the landscape occupied by mature white and red pine forests." In the early pine operations only half the total land surface may actually have been affected.
- Ecological effects of the Pulpwood Logging Era—From 1940 to 1979, when logging in the BWCAW was terminated, mechanized logging was used to harvest primarily jack pine and black spruce. Aspen pulpwood, because of low demand, was not usually taken until 1965. "The legacy of the pulpwood logging era in the BWCAW is damage to the natural landscape and ecosystem substantially exceeding that of the early big-pine logging." It resulted in a semi-permanent shift in species composition of the forest on large areas. "The area occupied by multi-aged stands of aspen, paper birch, and balsam has increased at the expense of the boreal conifers and large old white and red pine." The extensive road system that was put in was also a major disturbance.
- The federal Shipstead-Newton Nolan Act of 1930 prohibited the logging of lakeshores, islands, and streamsides to a breadth of 400 feet from the waterway. A similar state law applies to state areas (buffer strips).

Coffman et al. (1980)

- It also covers history of Virginia and Rainy Lake Company.
- VRL started south of the area now in the park but then moved to the Kabetogama Peninsula. Their harvest volumes consisted of white pine (32.3%), Norway pine (21.2%), and other species (primarily spruce and balsam fir) (47.5%).
- Authors provide a good description of how alligator tow boats worked. Based on their description, all the anchoring that went with that type of operation could have certainly had an effect on benthic sediments.

- Logging on the north side of the Kabetogama Peninsula started by the International Lumber Company about the same time. MANDO, International's parent company, owned about 50,000 acres on the Kabetogama Peninsula.

- Boise Cascade bought out MANDO in **1964**. They continued to log on the Kabetogama Peninsula from **1949** to **1972**. Aspen was clear-cut, balsam mostly clear-cut, but the smaller trees were left; seed trees were left in the white spruce areas and in the white and red pine areas. The cut averaged about 10–12 cords per acre, so about 700 acres were logged each year, producing about 7,000 cords. From 1949–1972, a total of 154,000 cords were taken off the Kabetogama Peninsula.

- MANDO and its predecessors logged from 1907 until 1964.

- Coffman et al. compared the composition of the vegetation identified in the General Land Office survey with a survey done by Steigerwaldt in 1973. John R. Snyder (Voyageurs National Park GIS specialist) updated their comparison and added the results of the 1997 USGS vegetation survey. Direct comparisons are difficult due to the use of different classification systems and multiple other factors. John included in the mixed forest category spruce-fir-aspen association and spruce-fir-pine associations. Given all the uncertainties, it is still safe to say that there are significant differences between the early forest and what exists in the park now.

Table III-8. Comparison of forest composition by different land surveyors at different times on the Kabetogama Peninsula.

Forest type	GLO Survey	Steigerwaldt	USGS
Pine	21%	18%	9%
Aspen	3%	50%	22%
Spruce-fir	4%	12%	4%
Mixed forest	64%	??	43%
Swamp conifer	6%	3%	7%
Lowland Brush	1%	10%	5%
Other	1%	7%	10%

Fritz (1986)

- Incorporates lots of information on logging history, much of which was reported earlier by Nute (1950) and others. Fritz also provides material from interviews with people from the logging industry.

- Fritz does spend some time describing the early illegal logging that occurred.

- Virginia and Rainy Lake Company activity within the area now encompassed in the park. Thirty-one of the 143 VRL camps between Virginia, Minnesota, and Rainy Lake were in or close to the area now in the park. Of the 31, 18 were on the Kabetogama Peninsula and 13 were on the mainland. Three of the latter were not within the park. Two of the camps were construction camps, so only 29 were actually logging camps. Most camps were only used for a winter or two. Between October 1912 and September 1929, the 29 camps produced 224,935,030 board-feet of white pine logs. Wood from sixteen of the camps was hauled over the ice on Namakan Lake by sleigh to Hoist Bay, as was wood from nine camps that was hauled across Kabetogama. Some wood was towed by steamers after the ice went out. These 25 camps produced 202,734,720 board-feet of lumber. The remainder of the wood went out by sleigh from three camps on the Kabetogama Peninsula in 1928 and 1929 via Rainy Lake, and from Camp 46 on Crane Lake where wood was shipped out on a railroad spur.

- The sawmill in International Falls closed in 1936–1937.

- Fritz reports that logging for pulp on the Kabetogama Peninsula "slowed to a crawl" during the 1930s. The last significant cut of saw-timber went off the peninsula sometime in the 1930s according to Nobel Trygg.

- He provides a description of the activity associated with the 1936 fire on the Kabetogama Peninsula.

- From an interview with Ed Nelson, Fritz reports that attempts were made to salvage logs from the lake at Hoist Bay. Evidently, however, it was not very successful due to the logs disintegrating when they tried to saw them.

- Logging continued on the Kabetogama Peninsula right up until the time Voyageurs National Park was established. Logging after World War II was entirely mechanized with Caterpillars, tractors, trucks, and sleighs. From 1949 to 1955, the logs were taken out by water in the summer and over the ice in the winter. In 1956 a winter road was put in that came off Highway 53 and crossed over to the peninsula just south of Black Bay and then went eastward for about 15 to 20 miles. It came within five or six miles of Kettle Falls.

- In 1968, Boise-Cascade owned 55,509 acres of land within the proposed park boundary; 52,000 acres was on the Kabetogama Peninsula.

Friedman and Reich (2005)

- "Hence, a spatially explicit regional-scale change analysis was conducted using General Land Office Survey records from the late 1800s and the 1990 U. S. Forest Service Inventory and Analysis Survey, for a 3.2 million hectare study area in northeastern Minnesota" (Table III-9).

- Detailed study, the most pertinent part of which is the results from the border lakes area, including Voyageurs National Park.

- White pine represented 20% of the forest basal area in pre-settlement northeastern Minnesota.

Table III-9. Comparison of species composition (%) from the GLO survey and the FIA survey for the border lakes area.

Tree type	GLO	FIA
White Pine	5.8	3.0
Spruce	19.2	17.5
Larch	8.4	1.0
Red Pine	3.9	2.4
Cedar	4.0	4.4
Balsam fir	9.3	19.6
Jack pine	16.4	5.0
Pinus spp.	2.5	0.0
Paper birch	17.0	14.7
Aspen	11.9	25.7
Maple	0.4	5.0
Ash	0.5	1.6
Miscellaneous	0.5	0.2

Verry (1986)

- "Clearcutting upland hardwoods or conifers will increase annual streamflow by 9 to 20 cm (a 30- to 80-percent increase). Streamflow returns to preharvest levels in 12 to 15 years. Annual peak flows are at least doubled and snowmelt flood-peak increase may persist for 15 years."

- "…clearcutting pine forests will yield an additional 7 cm above the 9 cm increase obtained by clearcutting aspen forests."

- The author cites Schindler et al. (1980). See Ontario section about effects of wind and fire on water yield and quality in the Ontario Experimental Lakes Area.

- The author also cites Wright (1976) and McColl and Grigal (1975, 1977) about Little Sioux Fire not producing detectable changes in an adjacent lake.

Verry (2000)

- Cutting 20% of a watershed or 25% of mature basal area is necessary to measurably increase the yield of water on an annual basis.

- Cutting the whole watershed will cause the annual yield of water to be 40% higher than that from the mature forest condition; most of this comes in the growing season when water is converted from transpiration to subsurface flow; it may take 15 years to diminish.

- Heavily cut landscapes may cause real flow increases of 150%.

- "Consider emulating the early mature stage (80 to 125 years old) near water to provide a continuing supply of organic matter and CWD." (CWD=coarse woody debris.)

Pulpwood Logging in the Rainy River Watershed, U.S. side of border, 1959–2005

These data are gleaned from annual publications by the U.S. Department of Agriculture from 1959–present, which were provided by Ronald J. Piva, USDA Forest Service, North Central Research Station.

Table III-10. Pulpwood production by county and for state of Minnesota, 1959–2005. Data represent thousands of standard cords (roughwood basis).

Year	Koochiching Co	St Louis Co	Lake Co	Minnesota
1959	176	188	100	994
1960	169	265	113	1048
1961	166	246	104	968
1962	170	260	82	979
1963	201	294	93	1063
1964	194	286	89	1062
1965	205	277	60	1018
1966	206	303	73	1174
1967	205	315	54	1205
1968	199	290	58	1087
1969	212	301	61	1192
1970	227	299	66	1224
1971	237	279	65	1196
1972	295	305	71	1354
1973	277	360	77	1269
1974	356	382	71	1465
1975	292	340	74	1251
1976	251	302	79	1209
1977	243	306	76	1220
1978	257	297	68	1228
1979	263	305	57	1340
1980	224	270	71	1237
1981	204	294	60	1270
1982	196	305	58	1391
1983	261	402	75	1,816
1984	289	453	105	2,057
1985	193	412	93	1,790
1986	191	444	115	1,876
1987	182	586	115	1,965
1988	237	476	102	2,017
1989	260	491	115	2,185
1990	284	510	116	2,276
1991	313	496	83	2,306
1992	376	540	98	2,585
1993	448	665	97	2,857
1994	476	622	107	2,858
1995	461	603	112	2,810
1996	449	637	102	2,897
1997	337	520	93	2,875
1998	337	555	114	2,800

Table III-10 (continued). Pulpwood production by county and for state of Minnesota, 1959–2005. Data represent thousands of standard cords (roughwood basis).

Year	Koochiching Co	St Louis Co	Lake Co	Minnesota
1999	397	582	82	2,951
2000	390	599	92	2,937
2001	388	575	84	2,755
2002	421	636	86	2,907
2003	366	628	95	2,830
2004	373	743	99	2,876
2005	365	765	92	3,020

Pulpwood Logging in the Great Lakes States, U.S.A., 1915–1959.

These data are gleaned from annual publications by the U.S. Department of Agriculture from 1959–present, which were provided by Mr. Ronald J. Piva, USDA Forest Service, North Central Research Station.

Table III-11. Pulpwood production in the Great Lakes states, 1915–1959. Pulpwood data represent thousands of standard cords.

Year	Pulpwood (standard cords)	Year	Pulpwood (standard cords)	Year	Pulpwood (standard cords)
1915	1,100	1930	1,675	1945	2,222
1916	1,180	1931	1,655	1946	2,059
1917	1,260	1932	1,635	1947	1,895
1918	1,340	1933	1,615	1948	1,731
1919	1,420	1934	1,595	1949	1,568
1920	1,500	1935	1,575	1950	1,685
1921	1,580	1936	1,647	1951	1,801
1922	1,660	1937	1,718	1952	1,918
1923	1,740	1938	1,790	1953	2,035
1924	1,820	1939	1,862	1954	2,152
1925	1,900	1940	1,933	1955	2,268
1926	1,855	1941	2,162	1956	2,385
1927	1,810	1942	2,359	1957	2,502
1928	1,765	1943	2,317	1958	2,619
1929	1,720	1944	2,386	1959	3,034

Logging in Ontario

Ayer (1902)

- 2 September **1902**, Hale Bay, Rainy Lake, and vicinity—reported land east and south of Hale Bay "has been cut through." Also commented the timber was "valueless for future use from its extensive liability to fire in account of cutting."
- Black Sturgeon Lake area—"generally logged through"; on one point there had been a fine tract of pine but it was cut through apparently 15 years ago.
- Mentions sluice from Little Sawbill Lake that was falling apart.
- 14 June **1903**—Pine was cut along the north shore of Namakan Lake and the Namakan River.
- The author mentions that his boat was delayed because of log jams from Canadian cutting.
- 3 October **1903**—"All timber of useful size on the East Bay or arm of Redgut Bay has been cut and fire has followed cutting."

Armson (2001)

- Lumbering—there was limited large scale disturbance until the railroads came in, particularly in the Fort Frances and Rainy River area. Pulp and paper did not get going until after the railroads.
- 1881—CPR (Canadian Pacific Railroad) completed between Winnipeg and the Lakehead; "... also stimulated logging and sawmill development in northwestern Ontario, particularly in the Fort Frances, Rainy River, and Kenora areas."
- Ontario Forestry Branch conducted a forest survey in 1929. They bought an airplane to do aerial photography. Their report, published in 1931, stated that 16% of the forest in the Rainy River region was mixed wood (low proportion) and 29% was classified as recent burns.
- Provincial air service was established in 1924 to help with forest fire control.
- The effects of new logging machinery were often negative. Skidders on wet grounds caused rutting; large accumulations of slash hindered regeneration.
- "Other machines might strip the forest floor to its mineral soil, reduce fertility, and increase the possibility for erosion losses."
- "Mechanization of harvesting brought a series of developments which would affect the "new" forest significantly:
    1. A greater proportion—up to 5%—of the productive forest could now be left in roads or landings on which regeneration of commercial tree species would be slow.
    2. Mature commercial broadleaved species not utilized, such as poplar and white birch, generally died as a result of exposure, while other conifers were subjected to exposure and

windthrow. The net result was that harvested forests of predominantly spruce or jack pine, in mixtures with poplar and white birch (which are usually of fire origin), regenerated mainly to poplar and white birch, usually with a balsam fir component, some 20 to 30 years after logging.

3. Logging of jack pine on well-drained sandy soils was done in summer so that the slash with cones was well distributed; it could be expected that jack pine would regenerate. The degree of success depended on the amount of forest floor disturbance because jack pine seeds germinate best in mineral soil.

4. Generally, regeneration of black spruce stands on poorly-drained soils decreased after mechanical logging, compared to the regeneration that occurred after manual strip cutting, because machinery caused damage to advanced growth, as well as physical damage to the wet soils. This situation was largely remedied in the early 1980s with the introduction of wide tracks and wide, high flotation tires.

5. Shrub species such as mountain ("moose") maple and alders would flourish on logged upland and lowland forests until a new canopy formed above. It might take several decades for tree species to form such a canopy.

- Armson quotes Niven (1973) who surveyed the line between the districts of Thunder Bay and Rainy River in 1890: "…the country along the whole line has been burned at various times from seventy years down to seven years ago."

Bertrand (1959)

- In the early 1900s, sawmills in the Rainy Lake basin were at Savanne, Ontario, on the north shore of Lac des Mille Lacs, at Mine Centre, at Rocky Inlet on Rainy Lake, in Fort Frances, and in International Falls.

- "The demand for railway ties, timber, and lumber had been so great that practically all the islands of the Lake of the Woods had been denuded of lumber."

- 1902—Morris Act shut down movement of saw logs to Ontario mills from Minnesota.

- 1910—Backus Brooks erected sawmill at International Falls.

- Shevlin Clarke mill in Fort Frances operated until 1942, with 1,600,000,000 feet of lumber processed.

- J. A. Mathieu managed the Shevlin Clarke mill until 1921, after which Mathieu started his own; that mill processed 800,000,000 feet of lumber from 1922 to 1954.

- The population of Port Arthur in 1900 was 3,225; in Fort William there were 3,780 people. By the1950s, it was 80,000.

Carignan and Steedman (2000)

From the abstract:

> *This supplement presents data syntheses and new evidence from temperate (primarily boreal) North American studies of aquatic ecosystem response to episodic watershed deforestation and acid rain. These studies confirm the dominant role of the watershed in modulating aquatic response to terrestrial disturbance and quantify important regional differences related to physiography, vegetation, and drainage patterns. Comparisons of watershed disturbance by wildfire and logging revealed both similarities and differences in aquatic impact and underscore the need for ongoing regional evaluation of forest management models based on simulation of natural disturbance patterns. General quantitative impact models are now available but tend to be regional in scope and relevant primarily to water yield and water quality, rather than to habitat and biota.*

Burgar (1983)

- Has a figure that shows pine production in Ontario topped 125 million cubic feet annually in the 1890s but then fell, so that from the 1920s to 1970s only about 25 million cubic feet were being taken annually. The figure also shows that, starting in the 1920s, spruce and balsam became the primary species being harvested. The harvest gradually increased until more than 200 million cubic feet were being taken annually in the 1970s.

Schindler et al. (1980)

- Stream flows increased, with the result being a doubling in total yield of total nitrogen, total phosphorus, and potassium. The increased flow and nutrient concentrations were short-lived, taking only three growing seasons to return to pre-windstorm conditions. There were no detectable changes in nutrients in an adjacent lake.

Wedeles et al. (1995)

From the "Environmental Considerations" section:

Soil nutrients

- "During harvesting, nutrients are lost both directly, through the removal of the timber crop, and indirectly through hydrologic losses that occur after harvesting due to erosion, surface runoff, and leaching to groundwater (Mann et al. 1988).

- Based on the studies reviewed in this paper, the time to replace the nutrients lost by logging seems to be quite variable and dependent on the type of logging. Replacement time figures presented ranged from 8 to 10 years, and went up to 21 years.

- "Weetman and Webber (1972) concluded that weathering, atmospheric inputs, and vegetation development quickly offset nutrient losses following harvests in boreal forests. However, nutrient drain may occur after several rotations, particularly when full-tree harvesting is combined with short rotations."

- Mann et al. (1988) concluded that, “for most forest systems, hydrologic nutrient losses are much less than direct nutrient losses through timber removal.”

Water resources

- “Although the effects of harvesting on soil erosion in boreal mixed woods seem fairly limited, there are effects upon water yield and stream flow.”

- “A significant loss of forest canopy after harvesting can cause a reduction in the interception of precipitation and in evapotranspiration rates, resulting in wetter soils and increased streamflow.”

- Water yields increase after clearcutting but then diminish as revegetation occurs (Ohmann et al. 1978, Arnup et al. 1988).

- The effect of selective cutting on water yield and other harvesting techniques that maintain vegetation on site, “moderate the increases in water yields normally associated with clear cutting (Arnup et al. 1988).” Note from Kallemeyn: Based on the literature, it seems that the focus on big pine during early logging in the Rainy Basin would be considered selective logging, thus the effect on water yield might not have been all that significant, particularly when compared to the clearcutting that is pretty much the standard mode of operation in the current logging for pulp.

- “To conclude, water quality response to the application of different silvicultural systems is specific to the climate, lithology, topography, and vegetation of each watershed (Miller et al. 1988a).”

Ontario Department of Lands and Forest (1963)

See summary on pp. 73–74.

Logging History for Quetico Provincial Park

Bowes (1970)

- Two primary companies were the Shevlin-Clark Company Limited (entered early in the 20th century) and J. A. Mathieu Limited (entered 1920s).

- 1922—Shevlin-Clark applied to build a dam at Pickerel River and to make a cut at the extreme west end of Batchewaung Lake for purpose of diverting water to Fort Frances via Quetico Lake. The dam at the outlet of Pickerel Lake replaced one originally built as part of the Dawson Trail development.

- There was possibly an old dam at Wolseley Lake.

- 1925–1926—Work to develop 37,000 horsepower of hydroelectric power was begun in Calm Lake by the Backus-Brooks interests. The power was to go to Fort Frances for the paper mill. Dams and powerhouses were also begun at Moose Lake and Sturgeon Falls (=Crilly Dam).

- 1926—High water occurred at French Lake due to Shevlin-Clarke keeping it high with stop logs at Pickerel dam and at Batchewaung. The high water ruined some pines and washed out roads and docks.

- 1927—Three dams and powerhouses on the Seine River.

- 1927—Quetico Improvement Company asks permission to construct five temporary dams for lumbering in Quetico.

- "Extensive improvements have been made on Quetico and Namakan Rivers that have been in use for some years, but none on Bear Creek."

- Five new structures: (1) Outlet of Badwater Lake, to put 6 ft. on the lake; (2) Outlet of Cub and Omeme Lakes, to put 6 ft. on lakes; (3) Bear Creek; (4) [also on] Bear Creek, (5) Outlet of Wolseley Lake, to put 4 ft. on the lake.

- Log movement would be from Lake Anne (Kasakokwog) to Quetico River to Beaverhouse Lake to Namakan Lake to Rainy Lake.

- Shirley Peruniak—"most logging was in the northwest part of the park."

- 1941—Consideration given to installing 300 foot protected strips along lakes and streams in Quetico. Evidently was already being done in Superior National Forest due to Shipstead-Nolan Act.

- Pine Volume Record for Quetico Provincial Park, 1918–1946:

  Total volume of pine logs: 503,521,665 fBm (foot-board measure, or board-feet)

  Total volume of pine boom timber: 15,981,492 fBm

  Total pine harvest: 519,503,157 fBm

- 1961—Several articles and controversy came out of Jim Mathieu Lumber Company and the Ontario and Minnesota Paper Company logging in the north half of Quetico Provincial Park (PP).

- 1963—Jim Mathieu Lumber Company got cutting rights to 468 square miles of the Quetico PP while the Ontario and Minnesota Paper Company got cutting rights on 420 square miles.

- 1971—Premier Davis announced discontinuation of logging in Quetico PP.

- 1973—Hon. Leo Bernier affirmed the concept that Quetico be kept in as natural state as possible—no commercial logging.

Mining in the Rainy Lake Basin

Bruce (1925)

- Includes detailed description of the geology of the gold mines and some fairly detailed maps of mine sites, including dump sites and roads.

Mackenzie (1908)

- Includes description of iron mining at Atikokan in 1905, which was before the Steeprock Mines.

Johnston (1915)

- While the primary focus is on the area downstream from Fort Frances, there is some very useful historic information and descriptions of the area.
- Page 5 mentions Dr. J. J. Bigsby, who was the medical officer for the International Boundary Commission Survey in 1823 and 1824. Bigsby also did extensive geological surveys on Rainy Lake and Lake of the Woods, the results of which were published 30 years later in three papers in the Quarterly Journal of the Geological Society of London in 1851, 1852, and 1854.
- Pages 17–21 (Chapter III) contain a very useful discussion of till sources and lacustrine and littoral deposits by Lake Agassiz.

Alanen (1989)

- Iron mining activities began in northeast Minnesota during the **1880s** and **1890s**.
- Portion of the Iron Range that is in the Rainy Lake basin is the Vermilion Range, which stretches from Ely/Winton to Tower/Soudan.
- First ore shipped from the Vermilion Range went out in **1884**.
- Mines on the Vermilion Range shut down in the **1960s**.
- Most of the mines on the Vermilion Range were underground operations.
- Based on a figure in this chapter, it appears the Vermilion Range produced on average about 20,000–25,000 tons of ore annually, which was a relatively small proportion of what came from the whole Iron Range.
- Presents census data for 1900 to 1985. On the Vermilion Range the populations were 1900=7,690, 1910=7,430, 1920=8,105, 1930=8,180, 1940=8,855, 1950=7,955, 1960=8,740, 1970=8,130, 1980=8,020, and 1985=6,915.

Sims (1972)

- Vermilion District produced high-grade hematite ores (60% or more iron).
- From **1884 to 1967**, when the last shipment was made, 98,399,000 gross tons of direct-shipping ore and 5,354,000 gross tons of gravity concentrates were shipped from the Vermilion District.

- Sims also presents some information on the Little American gold mine on Rainy Lake, which yielded about $4,600 worth of gold in **1894** and **1895**.

- He also mentions several other sites where prospecting activity occurred: Big American Island, Bushyhead Island, and a small island 1,200 ft. southeast of Pedersons Island.

Perry (1993)

A small book on the history of the Rainy Lake gold rush and Rainy Lake City.

- Gold was discovered on Little American Island in Rainy Lake in **1893**. (The island is located just northwest of the north end of Black Bay Narrows, so the cores we collected from just west of Brule Narrows and east of Brule Narrows are many miles upstream from the gold mining that occurred not only on Little American Island but also at the other sites where prospecting and mining occurred near Rainy Lake City. The core we took from the north side of Grindstone Island could possibly have been affected by the mining activity since the outflow from Black Bay does tend to go north past the east end of Grindstone Island.)

Allan and Allan (1976)

This 3-ring binder of information is on file at the Fort Frances Cultural Centre. A Xerox copy is also available at the Voyageurs National Park library.

- Provides some very good information on the gold mining that occurred on the Canadian Seine River-Mine Centre gold field. The Seine River is one of the main tributaries flowing into the south arm of Rainy Lake.

- This mining occurred from the mid**-1890s** to the early **1990s**, and unlike the mines on the U.S. side of the border, three of these mines actually produced a decent amount of gold. The Foley mine was the only one of these mines that directly abutted Shoal Lake, the others being in the drainage but not close to the Seine River.

- The mining activity also resulted in some small settlements being developed, the most prominent being Mine Centre, which was located on the northeast end of Shoal Lake on the Seine River. As a result it was accessible by steamboat from Fort Frances and the rest of Rainy Lake. Mine Centre's population at one time exceeded 500, so conceivably domestic water and sewage probably was an issue. "The arrival of the Canadian Northern Railroad in 1903 sealed the fate of the old Mine Centre because the railroad took over the business of the steamboats and the centre of the population gradually shifted north to the present site of Mine Centre Station. Now old Mine Centre has gone the way of Rainy Lake City, Gold Rock, and Seine City."

- One portion of this material provides a detailed description of how the ore was processed in stamp mills and how mercury was used to capture the gold from the finely ground ore. (Kallemeyn note: Although it isn't specifically mentioned in this or any of the other material I've reviewed, I suspect all the fine material coming out of the stamp mills ended up in whatever lake the mill was adjacent to. [I] suspect this [because] material dealing with one of the mines says that in 1974 another company had acquired an option on one of the old mines that included "a call on adjoining water claims where about 35,000 tons of tailings were deposited during former operations.")

Nute (1950)

Contains a chapter on gold mining with a lot of emphasis on the Rainy Lake–Rainy Lake City gold rush.

- Lots of interesting information, but the most pertinent from the water quality perspective may be the following: "Sanitary conditions in Rainy Lake City left something to be desired in those gay days of the 'nineties.' When a typhoid fever epidemic broke out in the summer of **1894**, no doctor had as yet appeared in the "city." Therefore, a former Civil War army surgeon's assistant, one "Doc" Lewis, took charge, and with liberal doses of quinine and whiskey checked the spread of the disease, or so it is related."

- Rainy Lake City lasted until **1901**.

Notes and citations gathered by Kallemeyn from material at the Atikokan Centennial Museum on 13 July 2006

- The mining activity that appears to have possibly had the largest potential effect on Rainy Lake was the iron mining that occurred at Steep Rock Lake near Atikokan, Ontario, which is in the Seine River watershed.

- Iron ore body under the waters of Steep Rock Lake was discovered in 1938. Steep Rock Lake was part of the original channel of the Seine River. In 1941, diversion of the river from the lake basin started. There was a power plant and dam at the head of the Steep Rock Lake that created Lake Marmion that was about 100' above Steep Rock Lake.

- Bateman (1944) provides a detailed description of diversion process, including blasting methods.

- After the diversion was completed, the flow of the Seine River was from Marmion Lake to Raft Lake to Lake Finlayson to Barr Lake, Reed Lake, Modre Lake, then into the western arm of Steep Rock Lake, which was part of the original channel.

- Two companies involved were Steep Rock Iron Mines (1938–1979) and Caland Ore Ltd. (1946–1980).

- 9,165,000 tons of ore were shipped from **1944 to 1953**.

- Taylor (1978) discusses the expansion to a new ore body that resulted in the following situation:

  The dredging operation went along quite nicely during the first few months of ***1951****. But when the breakup came in the spring of* ***1951****, it was obvious that there was a serious problem. All the way from Steep Rock to Rainy Lake, the water of the Seine River, instead of being a sparkling blue colour, was a ribbon of muddy grey and the discolouration extended into the Rainy River near Fort Frances, a distance of ninety miles. Charges of* *pollution came fast and furious, mostly from Americans in the border waters area and tourist camp operators along the Seine River. Some discolouration had been evident in **1944** when the first small dredges had begun operation and the disclouration had increased slightly when the second 15-inch dredge "La Seine" started up. But with the commissioning of the giant "Steep Rock," the amount of the silt dumped into the river system increased twenty-fold and the problems began. The situation was studied in detail by the Ontario Research Council and the Ontario Department of Health, and a number of laboratory methods of eliminating the solids suspended in the water were devised. None of the methods, however, were practical and it was obvious that drastic steps had to be taken."*

Given where the Seine River enters Rainy Lake, the area west of the Brule Narrows and north of Grindstone Island is the most likely to have been affected.

- The drastic action was a second diversion, which was built in the winter of **1951–1952**.
- Also from Taylor: "The discolouration of the Seine River due to the suspended silt from the dredging proved to be harmless."
- A series of articles in the *International Falls Daily Journal* from May to June, 1951, dealt with the Steep Rock situation.
    - 26 May 1951 headline: "Fort Frances group protests lake contamination danger."
    - Quote from George Smith, President of the Rainy Lake commercial fishermen's association: "Conditions were first brought to government attention five years ago." Ontario biologists investigated at that time.
    - 29 May 1951: The International Falls City Council and Chamber of Commerce passed resolutions protesting the pollution. The pollution was evident within 12 miles of Fort Frances and International Falls.
    - 31 May 1951: Engineer Adolph Meyer did a two-day inspection. He said, "the silt coloring the lake a yellow shade is silica so it remains suspended." Meyer observed a river of silt extending from Seine Bay some 30 miles west along the American side to a point near Ranier. The silt wasn't in some bays on the North Arm.
    - 2 June 1951: Congressman Blatnik asked the International Joint Commission to investigate.
    - 5 June 1951: Chester Wilson, the Minnesota Conservation Commissioner, threatened to use the 1909 Boundary Waters treaty.
    - 6 June 1951: E. R. Gustafson with the Corps of Engineers was to do a survey.

- 7 June 1951: Aerial black-and-white photography showed obvious silt. There were more requests to stop the pollution.
- 11 June 1951: International Joint Commission (IJC) says they cannot act without the government(s) asking them to get involved.
- 12 June 1951: IJC said they would discuss.
- 14 June 1951: Map showing location of Rainy Lake silt feed in Seine Bay and the main lake west of Brule Narrows. Chester Wilson starts action.
- 15 June 1951: Minnesota governor Youngdahl signs letter asking State Department to intervene.

- Kemwick (1976: p. 3, "Topography and Drainage") noted that, "before 1942 Finlayson Lake drained into Marmion Lake, then south through Steeprock [*sic*] Lake to the Lower Seine waterway. With the discovery of rich iron ore bodies in Steeprock Lake, the lake was drained…the waters of the river that previously entered Steeprock Lake and the northeast corner of Falls Bay were diverted to flow around Steeprock by way of Finlayson, Bass, Reed and Madred Lakes. Diversion channels were excavated between Raft Lake and Finlayson Lake and through the end moraine at the south end of Finlayson Lake (Skillings 1946). The Finlayson Lake drain tunnel was blown through July 1943 and the lake fell." … "Flooding of Marmion Lake moved shoreline back up to 0.4 kilometers, or ¼-mile, resulting in drowning of shoreline trees causing hidden stumps and logs."

- Kemwick goes on to talk about the Fin-Lan Copper Mines Ltd. (Nic-Cop Copper occurrence) (p. 65). Worked since 1955, west shore of Finlayson Lake, 2.5 miles from the south end, known as the Cranston Copper deposit.

- Pirie (1978; p. 2): The first geological mapping was by McInnes in 1899 for the Geological Survey of Canada.

- Fumerton (1985) discusses geology of the Seine River drainage and mines. Provides a description of the Quetico Fault. Also see Fumerton (1986).

- Acres Consulting Services Ltd. (1978): Objective was to examine the degree and effect of atmospheric deposition (loading) of SO_2 and sulfate aerosols by the proposed plant. Conducted a modeling exercise in which they found an estimated increase of 7% in BWCA and 16% in Quetico Provincial Park. Emission data from the U.S. Environmental Protection Agency (USEPA) and Ontario Ministry of the Environment (OMOE) showed the sources for the BWCA would be 65.4% from the U.S., 27.2% from Canada, and 7.4% from the Atikokan station. Sources for Quetico PP were 53.8% from the U.S, 30.6% from Canada, and 15.6% from the Atikokan station.

- Acres Consulting Services Ltd. (1978) stated, “The estimated times required for depletion of the various levels of lake buffering capacity with existing background loadings of SO_4 were eight years for one, weakly buffered, shallow lake to several hundred years for deep, heavily buffered lakes. An average for all lakes in the BWCA and Quetico Park areas may be about 85 years. In the most sensitive lakes the sulphate [*sic*] emissions from the Atikokan station, added to the background levels, would decrease the periods by 7% to 8%. These calculations assume no throughflow and no capacity for neutralization within the lakes.” At the time the report was prepared, the Steep Rock and Caland iron ore mines near Atikokan were emitting 16.1 and 0.3 thousand tons of SO_2 annually. The sulfur content of ore at the Steep Rock Mine was 1%.

- All sources (background) except the Atikokan station of the annual ambient air concentration of SO_2 (ug/m^3) were 1.65 in the BWCA and 1.53 in Quetico PP. The Atikokan station would add 0.18 and 0.35 ug/m, respectively. Acres concluded the Atikokan station would not significantly add to the rate of acidification in the BWCA and Quetico PP.

Drainage Ditches—Minnesota

- On 3 June 1908, the *International Falls Press* ran the headline, “Million dollars for drainage.”

- These were state ditches in Koochiching County: #56 was 4.8 miles long, #59 was 12.5 miles long, and #60 was 18.5 miles long.

- In December 2006, Kallemeyn’s search of the archives at the Minnesota Historical Society yielded the following information: In Koochiching County, most of the ditches were in the northwest part of the county, so they would have drained to the Rainy River downstream from International Falls. A map in the file showed two ditches (#10 and #16) that would have drained into the Rat Root River, which would then empty into Black Bay and ultimately Rainy Lake.

- From Drache (1992):
    - The Minnesota Drainage League was formed in 1905.
    - Judicial ditches that may have drained to Rainy Lake include one south of International Falls (T70N, R23–24W) and one south from Ericsburg (T69N, R23–24W).
    - Ditches were dug at two-mile intervals, both north–south and east–west.
    - Most ditching was done between 1913 and 1917.
    - Project was abandoned in 1919.
    - Koochiching County issued $1,435,000 in bonds, but the state had to take over payment of the bonds in the 1930s, in exchange for land in the western part of the county.

Water Quality Records

Ontario Ministry of Natural Resources (1992)

- Pertinent sites monitored included six sites along the Rainy River, one above the toll bridge, and five others spaced along the river down to Lake of the Woods. These were sampled multiple times per year from 1968 to 1972 and from 1975 to 1989.

- In addition to the Rainy River sites, there is a list in Appendix 1.2 of discontinued and excluded Provincial Water Quality Monitoring Network (PWQMN) stations, several of which were in the Rainy Lake basin. The most pertinent were only sampled in 1971. These stations included the Quetico River Station (19000101902), Namakan River at Lac La Croix (19000102002), Maligne River upstream from Minn Lake outlet (19000102102), Namakan River at the outlet of Sheridan Lake (19000102702), and Rainy Lake at the Highway 11 Noden Causway (19000103401). Data from this last site are shown in Table III-12. Copies of the data collected from these additional sites in 1971 were obtained from another OMOE report.

Table III-12. Water quality parameters sampled and the long–term median values and sample sizes for the Rainy River site above the toll bridge ("Rainy Lake at the Highway 11 Noden Causway"), site number 19000103401, 1971.

Parameter	Long-term Median Value	Sample Size
Aluminum	0.11 mg/L	39
Ammonia nitrogen	0.02 mg/L	182
BOD5	0.7 mg/L	236
Cadmium	below detection	
Chloride	1.0 mg/L	223
Cobalt	below detection	
Colour	37 TCU	33
Conductivity	54 uhmos/cm	232
Copper	0.002 mg/L	79
Fecal coliform	1	146
Iron	0.19 mg/L	93
Kjeldahl nitrogen	0.40 mg/L	140
Manganese	0.007 mg/L	76
Nitrate nitrogen	0.02 mg/L	141
Nitrite nitrogen	0.004 mg/L	141
Particulate solids	3 mg/L	230
pH	7.3	178
Phosphate phosphorus	0.004 mg/L	228
Pseudomonas	4	1
Silicon dioxide	1.31 mg/L	56
Sodium	2.0 mg/L	62
Total alkalinity	19 mg/L	174
Total coliform	140	201
Total cyanide	0.001 mg/L	17
Total hardness	22 mg/L	153
Total phosphorus	0.018 mg/L	236
Total solids	55 mg/L	180
Turbidity	1.6 FTU	
Unfiltered reactive sulphate	6.0 mg/L	73
Zinc	0.002 mg/L	81

Climate and Meteorological Records

Johnston (1915)

While the primary focus is on the area downstream from Fort Frances, there is some very useful historic information and descriptions of the area.

- Page 5 mentions Dr. J. J. Bigsby, who was the medical officer for the International Boundary Commission Survey in 1823 and 1824. Bigsby also did extensive geological surveys on

Rainy Lake and Lake of the Woods, the results of which were published 30 years later in three papers in the Quarterly Journal of the Geological Society of London in 1851, 1852, and 1854.

- Page 9: **1910** was an exceptionally dry year, with only 11″–12″ of rain.
- Page 9: Rural population in **1911** was 4,430, while the combined town population in Fort Frances, Rainy River, Emo, and Devlin was 3,707. Total population of 8,137.
- Page 9: Area of the district (not including Indian reserves), Mathieu Township, and unsubdivided areas was 672,924 acres.
- Page 11: Average precipitation for International Falls from **1892–1914** was 25.62 inches. In **1905**, the total was 33.0 in, and in **1910**, it was 19.40 in. There were exceptionally dry summers in **1886**, **1896**, and **1910**, which resulted in considerable damage by forest fires.
- Pages 17–21 (Chapter III): Very useful discussion of till sources and lacustrine and littoral deposits by Lake Agassiz.
- Page 31: Rainy Lake in June 1913 was at 1,110 ft (high). "It is stated that water in the lake is ponded to a depth of 4' by the dam on the Rainy River at Fort Frances by which the outflow is regulated. Former low stages of lake level are suggested by the deep and flooded character of the channels of the lower portion of some of the streams entering the lake, as in the case of the stream at the southern end of Stanjikoming Bay."

Saunders (2000)

ABSTRACT

- All available stations showed temperature increase.
- Greatest warming was in the spring (>1ºC)
- Smaller increases in winter and growing season.
- Negative change in the fall.
- Warming greater for minimum than maximum, which resulted in declines in the diurnal temperature range, especially in the first half of the study period.
- Average rainfall has increased at all stations.
- An analysis of daily rain events suggests increases in frequency and amounts of individual events (>40 mm in southern locations and 30 to 39.9 mm in the northern stations).

METHODS

His analysis included 11 locales, two of which were in the Rainy Lake basin (Fort Frances, 1917–1998, and Mine Centre, 1915–1998). Other stations close to the Rainy basin were Kenora (downstream) and Dryden (north). The other sites were located east and north of the basin.

Methods for temperature:

- Monthly means were calculated if there were no more than five days of missing data.
- If there were missing temperatures for 6 to 9 days, the means were flagged as estimates.
- If there were more than nine days of data missing, no monthly mean was calculated.
- In 1961, there was a change in observation time at the principle stations, which introduced a bias of a step decrease of 0.6ºC to 0.8ºC. Saunders corrected for this when necessary.

Methods for precipitation:

- Months with missing values were entered as a minimum estimate.
- Another methodological issue was that, prior to the late 1950s, a snow/water ratio of 10 in:1 ft was assigned at most climate stations. However, this could actually be highly variable, as Saunders measured values of 35 in:1 ft for dry snow and 3.5 in:1 ft for wet or slushy snow. Starting in the late 1950s, the Nipher snow gauge, which converts snow to water, was used. No correction for this was done.
- Sampling periods were Winter (December through February), Spring (March through May), Autumn (September through November), and the growing season (May through September).

RESULTS

Temperature

When averaged, Saunders' Ontario results supported a finding from Minnesota that average annual temperatures changed by approximately 1.1ºC per degree of latitude (Table III-13).

His analysis of long-term trends in temperatures showed a warming period from 1910 to 1940, temperatures declined slightly from 1941 to 1969, and another warming period occurred from 1970 to 1998. Based on these results, Saunders used the periods 1916–1943, 1944–1970, and 1971–1998 in most of his other analyses (Tables III-14 and III-15).

Table III-13. Summary statistics for change in annual mean temperatures (°C), 1916–1998.

Station	Avg. annual change (ºC/year)	Significance level	Total change in 83 years (ºC)
Kenora	0.0141	0.001	1.2
Fort Frances	0.0108	0.05	0.9
Mine Centre	0.0168	0.001	1.4

Table III-14. Summary statistics for average annual temperature change (°C) in three time periods: 1916–1943, 1944–1970, and 1971–1998.

Station	1916–1943	1944–1970	1971–1998
Kenora	0.052	-0.012	0.019
Fort Frances	0.045	-0.010	0.035
Mine Centre	0.032	0.008	0.026

Table III-15. Comparison of seasonal mean temperatures (°C) in three time periods: 1916–1943, 1944–1970, and 1971–1998. Asterisks (*) indicate significant differences between periods.

***Period*/Station**	**1916–1943 (Period 1)**	**Sig. Diff. Periods 1/2**	**1944–1970 (Period 2)**	**Sig. Diff. Periods 2/3**	**1971–1998 (Period 3)**	**Sig. Diff. Periods 1/3**
Winter						
Kenora	-15.5		-15.6		-14.9	
Fort Frances	-14.7		-15.1		-14.1	
Mine Centre	-15.7		-14.9		-13.9	
Spring						
Kenora	1.7		1.6	*	3.2	*
Fort Frances	2.0		1.7	*	3.1	
Mine Centre	1.7		1.9	*	3.2	*
Growing season						
Kenora	15.0		14.8		15.6	
Fort Frances	14.9		14.2	*	15.1	
Mine Centre	14.9		14.6		15.0	
Autumn						
Kenora	4.0		4.4		4.0	
Fort Frances	4.3		4.5		4.3	
Mine Centre	4.0		4.8		4.2	

Increases in daily minimums made up 60% to 75% of the increase in the mean temperatures.

Largest changes in the diurnal temperature range occurred prior to the mid-1940s.

All stations showed a negative trend in the number of days with minimum temperatures of <0ºC.

Precipitation

All stations showed an increase in the number of rain days (>0.6 mm) during the growing season (Tables III-16 and III-17).

Number of rain events >40 mm increased at all stations (Table III-18).

Saunders did not present any information on snowfall for Fort Frances, Mine Centre, or several other stations.

For Kenora, there has been a significant decrease in total precipitation due to snowfall. Between 1961 and 1998, there was about a 10% decline in the amount of precipitation due to snow.

Table III-16. Growing season rainfall, 1916–1998.

Station	Avg. annual change (mm)	Sig. Level	Total Change (mm)
Kenora	0.9		71.0
Fort Frances	1.0	0.05	79.6
Mine Centre	0.8		67.1

Table III-17. Growing season rainfall (mm) in three time periods: 1916–1943, 1944–1970, and 1971–1998.

Station	1916–1943	1944–1970	1971–1998
Kenora	375.5	380.5	413.1
Fort Frances	416.6	448.3	460.7
Mine Centre	396.2	426.9	437.7

Table III-18. Percent of the average annual precipitation due to rain events >40 mm in three time periods: 1916–1943, 1944–1970, and 1971–1998.

Station	1916–1943	1944–1970	1971–1998
Kenora	8.7	9.9	10.7
Fort Frances	10.7	11.7	14.8
Mine Centre	8.6	10.7	11.3

CONCLUSION

Saunders characterized the three time periods as “An extended period of warming” (1916–1943), “A relatively benign period?” (less variability) (1944–1970), and “Warming and variability” (1971–1998).

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