Determining the Impacts of Damming, Water-Level Fluctuations, Climate, and Landscape Changes in Voyageurs National Park and Vicinity

A DISSERTATION

SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL

OF THE UNIVERSITY OF MINNESOTA

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

Dr. Leonard Ferrington, Dr. Mark Edlund

June 2010

Acknowledgements

I would like to thank my advisors Dr. Mark Edlund and Dr. Leonard Ferrington for guiding me throughout my graduate degree; Dr. Rob Blair for developing my teaching skills and opening my eyes to the world of conservation biology; Dr. Euan Reavie for valuable comments; Dr. Kristen Nelson for guiding me through the social sciences; Dr. Steve Juggins for teaching me valuable statistical tools; Erin Mortensen for helping me with lab work and for dating my samples; Joy Ramstack who spent many hours helping me ID diatoms and teaching me the R language; Dr. Kat Ruhland and Dr. Andrew Patterson for reviewing my first chapter; Larry Kallemeyn for teaching me the VOYA world; Sharon Mallman, Virginia Mondry, and Suzanne Yoche for encouraging me throughout the process; Jill Wasik for helping me in the lab; my chironomid lab (Moriya Rufer, Dr. Will Bouchard, Adam Sealock, Alyssa Anderson and Brian Schuetz) for enjoyable travels, critiques and encouragements; Maria Juergens and Bonnie Anderson for helping me throughout the stumbling blocks of graduate schools; the Department of Entomology and the Department of Fisheries, Wildlife and Conservation Biology for hosting me and including me as one of their own; the Water Resources Program for providing me with funding and travel support; Dr. Karen Oberhauser and Dr. Susan Weller for opening my eyes to the GK-12 program and science education; The Saint Croix Watershed Research Station for letting me use their facilities for my research; my peers who have sparked interesting conversations; my mother and father, Karen and Alain, who have encouraged me and helped me pursue my interests; my husband, Steve, who has encouraged me and listened to me talk about diatoms and macroinvertebrates; and a special thanks to Dr. Ferrington for opening my eyes to a whole new world of organisms and the world of outreach education.

Dedication

This dissertation is dedicated to the belated Dr. John C. Kingston former friend, mentor and advisor and Mrs. Edee Rothman, a caring loving great grandmother both of whom are dearly missed.

Abstract

In the past century, the border lakes in and near Voyageurs National Park have been subject to anthropogenic and natural stressors. These stressors include logging, damming, hydromanagement, human population growth, and climate change, which can be broadly categorized into three groups: land use, hydromanagement, and climate. In order to determine how these stressors have impacted the lakes, we developed a before-after control-impact paleolimnological study.

Lakes included in the study were the dammed lakes of Namakan, Rainy, and Kabetogama, which are all in the Voyageurs National Park region, and undammed Lac La Croix, which is upgradient in protected wilderness lands. One sediment core was retrieved from each lake and analyzed for ^{210}Pb inventory, loss-on-ignition, and diatoms. Multiple statistical analyses (species richness and turnover, cluster analysis, multivariate ordination, diatom-inferred water quality, and variance partitioning) were used to provide a more comprehensive picture of how these lakes were affected uniquely and interactively by the different stressors. Among the various stressors, land use generally explained the greatest amount of variance in diatom communities. Nevertheless, it is important to note that the interactive effects among land use, climate, and hydromanagement were also highly significant. Although hydromanagement is a primary source of concern in this region, multiple stressors and their interactions were identified as drivers of change in the diatom community and therefore must be considered in the management of the border lakes.

The International Joint Commission who has been managing this system since 1940 has been mostly re-active in its decision making. However, in the late 1990s enough awareness was raised in regards to the deterioration of biological communities that they choose to modify the water-level rules in the border lakes. This step created a new decision-making process in this region; a move from being re-active to been pro-active. As part of this new rule change, the IJC required local agencies to evaluate the change in the rule curve. The ruling board located in the Rainy-Namakan System also has taken part in the new International Watershed Initiative which approaches the management of watersheds in an ecosystem approach. This step is extremely important as it promotes interactions between all stakeholders and therefore is able to fully integrate concerns in decision-making. Nevertheless, there are still concerns for the management of the resources in a sustainable way. Repeatedly, agencies in the region have raised concerns in the lack of funding from the IJC to maintain monitoring station. These stations are extremely important when making sustainable decisions especially during a time of unprecedented climate change. Thus, it is important that the IJC not only pro-active in its decision-making but also consider long-term sustainability.

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Chapter 1: Introduction

Since the time of European settlement, the landscape in the United States has been modified to facilitate the human life style. Dams were built to control waterways, trees cut to meet the demands of builders, and prairies were converted into farmland only to name a few. Even though these changes brought social and economic benefits, the resource was impacted. The Border Lakes Region on the Minnesota-Ontario border was not spared. European settlers arrived in the Rainy Lake-Namakan Reservoir region in the mid-19th century to exploit its vast forests, and dams were built to provide hydropower year round to the lumbering companies that owned the dams. At first, water levels were regulated by the owners; however, soon regulations were put in place with the controlling body being the International Joint Commission (IJC).

The International Joint Commission was created under the Boundary Waters Treaty of 1909 to prevent or resolve conflicts over shared water resources. Once the IJC took control of the dams, it sequentially implemented several water-level regulations (1949, 1957, 1970, & 2000). The overall aim of this thesis is to determine how landscape changes, predominantly in the form of damming and manipulated water-level variations, have impacted water quality in the border lakes of the Rainy Lake-Namakan Reservoir Region. In addition, the thesis will also determine if the IJC is managing water resources sustainably now and for future generations.

Study Area

The Rainy Lake - Namakan Reservoir region (also known as the lower Rainy River watershed) is located in the border region of northern Minnesota near

International Falls (USA) and northwestern Ontario (Canada). The study area not only includes Rainy Lake and Namakan Reservoir, but also Kabetogama Lake and Lac La Croix, a reference lake located 25 kilometers upstream from Namakan Reservoir (see map 1 and Table 1 for physical characteristics). They are all located on Precambrain rock formations underlain with schist (Boerboom, 1994) and are situated in the Northern Lakes and Forests ecoregion (Omernick, 1987). The lakes have complex basin morphometries and each has several depositional basins.

All lakes had fairly similar management histories until damming occurred at the start of the 20th century. Native Americans inhabited the region until Europeans came to settle in the mid to late 1800s. Extensive logging followed European settlement and lakes became points of interest for their hydro-power potentials. Soon after, dams were built at the turn of the 20th century. Two are located at the outlet of Namakan Reservoir into Rainy Lake and one at the outlet of Rainy Lake into the Rainy River (Figure 1). The dams on Namakan Reservoir were built to regulate waterflow into Rainy Lake and provide a back-up source of water for the power-generating dam on Rainy Lake. The dams were first regulated by the owners of the dam (IJC 1934) and later by the IJC (CUSA 1940). The IJC set three different water-level regulation mandates. The first, in 1949, controlled the system under extreme conditions and recommended that water-levels follow a single rule curve. The second regulation included a minimum and maximum water-level band throughout the year. This band was modified with the third regulation in 1970 after several high and low water events. These regulations imposed water-levels that were quite different from what would occur normally if the systems were natural (IRLBC 1999).

The 2000 regulation, also known as the New Order, came about when citizens came together and formed the Rainy Lake Namakan Reservoir International Steering Committee and brought to the IJC's attention that the 1970 water-level regulation were negatively impacting the biological communities (IRLBC 1999). They recommended that the water-levels should be manipulated to optimize and simulate natural habitat conditions. The IJC took those recommendations into consideration and implemented the 2000 Order. The 2000 Order differs from the other regulation in that the water is retained for a shorter period of time as the water is discharged during the summer months.

Research Design

In order to determine how damming, water-level manipulations and other landscape changes have impacted the lakes in the Lower Rainy River watershed, a Before-After, Control- Impact approach (Karr and Chu, 1999) was chosen. Paleolimnological tools were used to obtain data for this analysis. Cores were taken from the three impacted lakes (Rainy Lake, Namakan Reservoir and Kabetogama Lake) and one from our reference lake (Lac La Croix). The cores were analyzed for sediment biogeochemistry, diatom assemblages, and water chemistry. A relationship between changes in environmental variables and changes in the diatom communities were determined using variance partitioning. Furthermore, changes in water quality (biologically and chemically) were correlated to water resource management changes in order to determine if governance by the IJC was managing the resources in a sustainable way. In particular the question of whether or not the IJC was ready for the potential impacts of climate change was examined.

Research Objectives

The primary research objective was to determine if damming impacted water quality both biologically and chemically in Rainy Lake, Kabetogama Lake and Namakan Reservoir. The null hypothesis was that no changes had occurred. The second objective was to look at whether or not the different water-level manipulation impacted the system. The results from the study of the impacted lakes were then compared to changes in the reference lake to determine if broader regional changes were occurring such as climate change. For example, verification was made to insure that changes in water quality parameters that were attributed to water-level manipulation did not occur in our reference lake where damming and water-level manipulations never occurred. The third objective was to determine if the International Joint Commission can be used as a model for a sustainable transboundary water resource management organization that could be implemented in other regions of the world.

Thesis Summary

Chapters one and two provide an introduction to the impacts of damming and water regulation on Namakan Reservoir and investigate whether broader regional impacts are occurring by comparing results from Namakan Reservoir with Lac La Croix. It was discovered that logging and damming were not the only changes impacting this system. Both Lac La Croix and Namakan Reservoir had similar impacts that could only be linked to climate change in particular warmer winter months.

Chapter three investigates in addition to the impacts of damming on Rainy Lake and Kabetogama Lake, how much influence broader regional changes have impacted the diatom community in all of the investigated lakes. Variance partitioning was used to determine which environmental variable explained the most changes in the diatom assemblages identified pre 1959 and post 1959. Water-level manipulations were not only factors influencing changes in the diatom communities; landscape and climate variations were also found to be equally important factors.

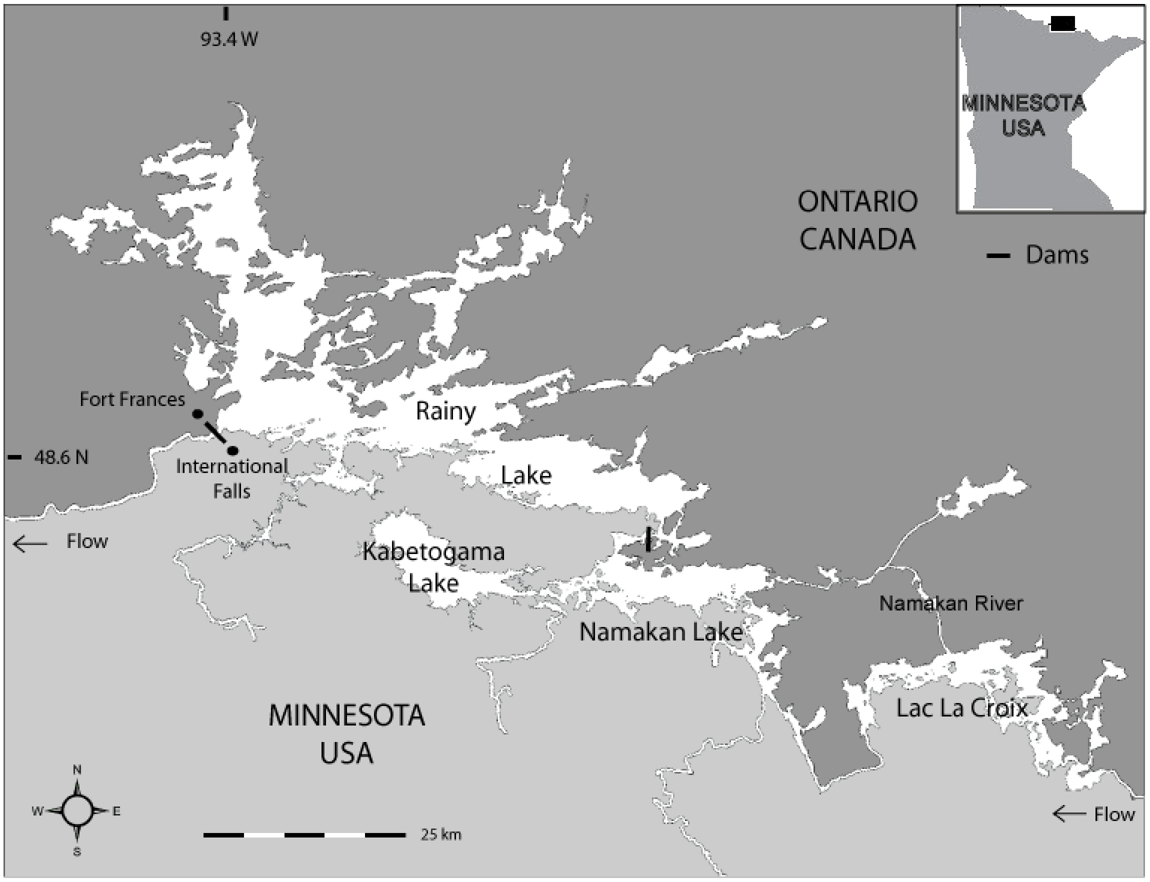
Chapter 4 discusses the relevance of the International Joint Commission as a model to be applied in other regions for water resource management, in particular, the role of governance. As governance has been identified by many scholars as the problem behind the reason why organizations are unable to manage their resources in a sustainable manner. With the stresses of climate change, governance is under more and more pressure and political instability could become a problem. The analysis showed that the IJC needs to consider a few adjustments to the way they exercise power.

Voucher Deposition

Two extra sets of diatoms slides were made for each sample. These slides will act as voucher samples. Researchers can use these slides for follow-up studies or other pertinent research. One set of slides will be deposited at the St. Croix Watershed Research Station and the original will remain in my personal collection.

Table 1. Lake and watershed characteristics. (Information for Lac La Croix was not available at the time of this study) *Renewal time is for Namakan Reservoir.

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	10425	196.7	9	24.3	9.1	30	948.7	…
Namakan	10170	192.7	6.5	45.7	13.6	20	1383.1	0.6*
Rainy	92100	41.9	14.4	49.1	9.9	35	9117.9	1
Lac La Croix	13788	…	…	51.2	…	25	…	…



Source: Voyageurs National Park

Figure 1. Kabetogama Lake, Namakan Lake, Rainy Lake and Lac La Croix. Dam sites indicated by black bars.

Chapter 2: Impacts of settlement, damming, and hydromanagement in two boreal lakes: a paleolimnological Before-After Control-Impact study

Reprinted with kind permission from Springer Science + Business Media: Journal of Paleolimnology, Impacts of settlement, damming and hydromanagement in two boreal lakes: a paleolimnological Before-After Control-Impact study, online publication, Dec 2008, CA Serieyssol, MB Edlund and LW Kallemeyn

This chapter can be cited as: Serieyssol, C.A., Edlund, M.B. and Kallemeyn, L.W. 2009. Impacts of settlement, damming, and hydromanagement in two boreal lakes: a comparative paleolimnological study. Journal of Paleolimnology 42: 497-513.

DOI:10.1007/s10933-008-9300-9

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. Pb-210 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 though conductivity only increased temporarily.

Total phosphorus also increased in Namakan Lake after damming with a possible decrease in the last decade back to pre-damming TP levels.

Keywords: diatoms, human impacts, BACI, climate change, Minnesota, Ontario

Introduction

Every day 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 (WCD 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 ecosystems properties and processes including sediment transport (Vörösmarty et al. 2003), habitat fragmentation (Rood & 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 & 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. 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 in order to determine the impacts of artificial dams on water bodies or the paleoecological history of a reservoir (Prat & Daroca 1983, Donar et al. 1996, Quinlan & Smol 2002, Benett & 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-effect reconstruction design. However, because Namakan Lake is part of a chain-of-lakes system, we approached our research with a more robust design: a Before-After, Control-Impact approach (BACI; Stewart-Oaten et al. 1986). We used a paleolimnological approach using 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), changes due to post-settlement activities such as logging, damming and hydromanagement.

Site Description and Background

The Site

Namakan Lake and Lac La Croix are shared border waters located in northeastern Minnesota and northwestern Ontario (Fig. 1). They are located in a Precambrian crystalline rock formation overlain with schist (Boerboom, 1994). Both lakes are part of the Rainy River watershed and are in the Northern Lakes and Forests ecoregion (Omerick 1987). Lac La Croix is less then 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 have had similar histories until dams were built at the outlet of Namakan Lake into Rainy Lake to control the water-level of Namakan Lake. Lac La Croix was not impacted by these hydrological changes.

History

Cree, Monsoni, and Assiniboin tribes were the primary inhabitants of Voyageurs National Park when European voyageurs came to explore the area for fur potential in the early 1700s (Catton & 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 DA 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 & TCPT 2005). In 1914, two dams were completed at Squirrel and Kettle Falls in the northern outlet leading from Namakan Lake into Rainy Lake (Fig. 1). These dams were constructed as a means to regulate outflow from Namakan Lake into Rainy Lake and are not power-generating dams (Chandler & Koop 1995). Both dams control water storage capacity of Namakan and Kabetogama Lakes and secondarily control the supply of water used for a power generating dam located at the outlet of Rainy Lake between Fort Frances and International Falls (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 inception (IJC 1934, BLI 2007). The companies have utilized the water as a means for producing power, pulp, paper, and building products (Chandler and Cook 1995).

Namakan Lake, Rainy Lake and Lac La Croix 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 by the International Steering Committee (IRLBC, 1999) for 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. 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 might be (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 biological (i.e. diatoms) and geochemical indicators preserved in lake sediments, we determine what the pre-damming/pre-logging natural condition in biological communities and water quality variation was compared to post-damming and post-logging condition.

Material and Methods

Core Collection

Sediment cores were collected in the summer of 2005 from Namakan Lake and Lac La Croix (Fig. 1) using a drive-rod piston corer equipped with a 1.5 m long and a 7.5 cm diameter polycarbonate barrel (Wright, 1991). The Namakan Lake core was recovered from Junction Bay, south of Namakan Island (N48º26.028”, W92º52.136’); 1.31 m of sediment was recovered at a water depth of 24.07 m. The Lac La Croix core site was located just west of Twentyseven Island and east of Fortyone Island (N 48º21.485”, W92º10.943’) and away from the outlet of the Namakan River; 1.82 m of sediment was recovered at a water depth of 14.9 m. Cores showed no signs of 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). Downcore 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 retrieved from Environment Canada website (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). Subsamples were digested in an 85°C water bath for 1 hour (Reavie 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 a random transect(s) 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 Diamond and May (1977) calculation $t= (l+g)/(S*ci)$ 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 detemined by cluster analysis using constrained incremental sum of squares (CONISS) and ZONE software (Juggins 1996). All ecological analyses should be viewed with caution as the time interval between samples at the bottom of the core represent longer time periods then the ones at the 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 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 (2003) and Reavie (2006).

Results

Sediment Dating and Geochemistry

Radioisotopic inventories show monotonic declines in unsupported Pb-210 activity in both lakes (Fig. 2). Namakan Lake and Lac La Croix sediments are similar in that they are primarily made up of inorganic matter (Fig 3). Organic and carbonate content are 14% and 11% respectively in Namakan Lake with a slight increase 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 $gcm^{-2}yr^{-1}$ (Fig. 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 (Fig. 3). This increase is mostly attributed to the increase in flux of inorganic matter (Fig. 3).

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

Diatoms

Taxonomic Richness and Diversity

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 sediment fluctuated around 85 taxa through time with a slight downward trend possibly related to shorter temporal increments in upcore samples (Fig. 5). In contrast, species richness in Namakan sediments fluctuated around 70 taxa prior to damming, but at the time of damming, there was a sharp decrease in richness to a low of 54 taxa. Taxonomic richness in Namakan Lake slowly recovered thereafter.

Species turnover was stable during pre-European settlement in both lakes (> 0.1; Fig. 5). However, the 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* (Fig. 6, 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* (Fig. 6), whereas the benthic taxa *Eolimna minima, Navicula aboensis, N. farta, N. submuralis*, and *Pseudostaurosira microstriata* are more abundant in Lac La Croix (Fig. 7).

Community Analysis

An NMS analysis separated the two cores along axis 1 (Fig. 8). Each core was differentiated into 3 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* (Fig. 5). Zone II (1908-1972) has greater ecological variability as samples become more distant from one another in ordination space. This time period represents the peak of the logging era in the region, the impacts of damming, and early water-level regulations. In zone II, several dominant taxa fluctuate in abundance: *Aulacoseira islandica*, *Aulacoseira subarctica*, *Fragilaria 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 drive the shift. 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 (Fig. 8). They are similar because downcore taxa, such as *Navicula aboensis* in Lac La Croix, are no longer present at the top of the core and *Aulacoseira* spp. in Namakan Lake decrease in abundance similar to percentages in Lac La Croix (Figs 6, 7).

Calibration Set

Canonical Correspondence Analysis indicates that conductivity, pH, TP and TN account for 20% of the variance in the diatom data. 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 the 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 $\mu S\ cm^{-1}$ (Fig. 9). Namakan Lake conductivity fluctuates around 95 $\mu S\ cm^{-1}$ before settlement, increases sharply to 130 $\mu S\ cm^{-1}$ 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 $\mu S\ cm^{-1}$ in Namakan Lake and 42 $\mu S\ cm^{-1}$ in Lac La Croix (Table 2).

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 which means that it was significant. Modern TP also appears to be slightly overestimated compared to known measurements of this system (Table 2).

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 biologically slightly different 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 (c. 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&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 to the buildings 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 dammings. 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 the macrophyte communities in Namakan Lake was 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). 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 species richness after the 1950s is related to the change in bandwidth through time (Fig. 5). However, because our core samples do not represent equal time intervals (with shorter timer periods upcore), 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; Fig. 8). Sample-to-sample variation (Fig. 8) and species turnover (Fig. 5) increased in Namakan Lake after damming. This pattern is not as evident in Lac La Croix; the shift in communities from Zone I to Zone II is more likely attributable to logging. It is not possible to differentiate the impact of damming vs 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 seems to have not 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 c. 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 state that damming and hydro-management may have changed the lake's discharge regime and increased the transport of littoral materials into the lake which would result in net reduction of P export from the lake because most of the discharge occurred during months with low epilimnetic P concentrations increase in nutrient retention and P inputs. They also report 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 (Figs 6,7,8), 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 impact aquatic resources. For example, the area surrounding Namakan Lake and Lac La Croix actually decreased in population (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 (Minn. Statutes 116.42-116.45). This act required the Minnesota Pollution Control Agency (MPCA) to identify areas sensitive to acid deposition and develop standards to protect both terrestrial and aquatic ecosystems (MPCA 2002). In order to comply with the legislation, the MPCA conducted several studies and determined that "there is no evidence that any of Minnesota's lakes … have been acidified by acid rain" (MPCA 2002).

Alternatively, nitrate and sulfate deposition may have impacted the lakes. Whereas, the National Atmospheric Deposition Program (NADP) 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 zones III in Fig. 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 occurred 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, Fig. 10, shows two post-1970s trends: increased interannual variability and increased winter annual temperature. To explore this correlation, we plotted the axis 2 scores of an NMS analysis from each lake with the yearly winter average temperature from Kenora (Fig. 10). We use axis 2 scores as they capture the major direction of intersample variation in each core (axis separates the two cores from each other based on overall diatom community differences). Temperature variation is similar to the ecological variation explained by axis 2 through time in both lakes in that they are mirror image of each other.

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

1970s diatom community shifts in Namakan Lake and Lac La Croix are strongly correlated to climate warming.

Conclusion

European settlement (particularly logging), damming, and hydro-management 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 physical (increased sedimentation), ecological (decreased species richness and greater intersample variability) and water quality (increased TP and conductivity) changes. 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 in order to confirm that the changes in the diatom community are related to temperature trends.

Acknowledgements

This project was funded by the United States Geological Survey (PM15-94151). Special thanks to Mary Graves, Culture Resources Specialist in International Falls, Andrew Jourdain and the Lac La Croix First Nation for technical assistance on Lac La Croix, Ryan Maki at Voyageurs National Park for collecting environmental data, Erin Mortenson for sediment dating, Rick Cousins (Lake of the Wood Control Board) and the Water Survey of Canada for providing hydrological and governance information, Kathleen Rühland, Andrew Paterson, Joy Ramstack, and Euan Reavie for sharing an

unpublished calibration set for northern Minnesota and northwestern Ontario, Steve Juggins for sharing his statistical expertise, Joy Ramstack for providing answers to many questions and Andrew Paterson, Euan Reavie and Kathleen Rühland for providing valuable comments on earlier drafts.

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

Environmental variable	r^2_{boot}	RMSE	RMSEP
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

Table 2. Water chemistry parameters for Namakan Lake and Lac La Croix. [a]Data found in Christensen et al. (2004); data represent one observation each from May 16, 2001 except TP which represents the range and mean of 12 samples taken from May to October in 2002. [b]Data collected by the Minnesota Pollution Control Agency from observation on 10 Oct 1985 found on http://www.pca.state.mn.us/data/eda/. [c]Data collected during the Summer 2005 field season. [d]Data found on the Minnesota Department of Natural Resources Lake Finder website http://www.dnr.state.mn.us/lakefind/index.html.

Environmental variable	Namakan Lake	Lac La Croix
Alkalinity (mg L^{-1} as $CaCO_3$)	14 [a]	12 [b]
Lake area (ha)	13,760 [d]	10,118 [d]
Littoral area (ha)	3,440 [d]	2,034 [d]
pH	7.2 [a]	6.5 [b]
Secchi (m)	2.3[c]	3.3[b]
Specific conductance (µS cm^{-1})	50 [a]	42 [b]
TP(mg L^{-1})	0.008-0.028 0.013[a]	0.017[b]
Z max (m)	51 [d]	45 [d]

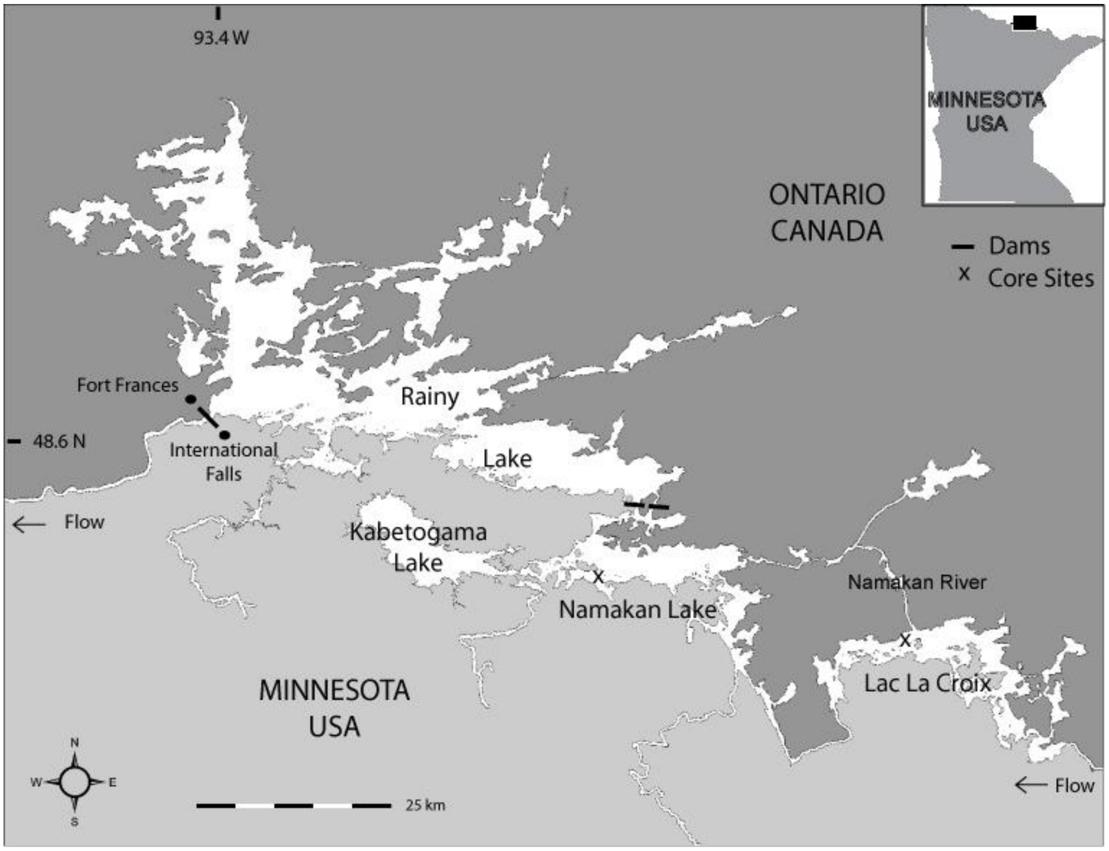


Figure 1. Location map showing Namakan Lake and Lac La Croix and their respective coring sites (x). Dam sites indicated by black bars.

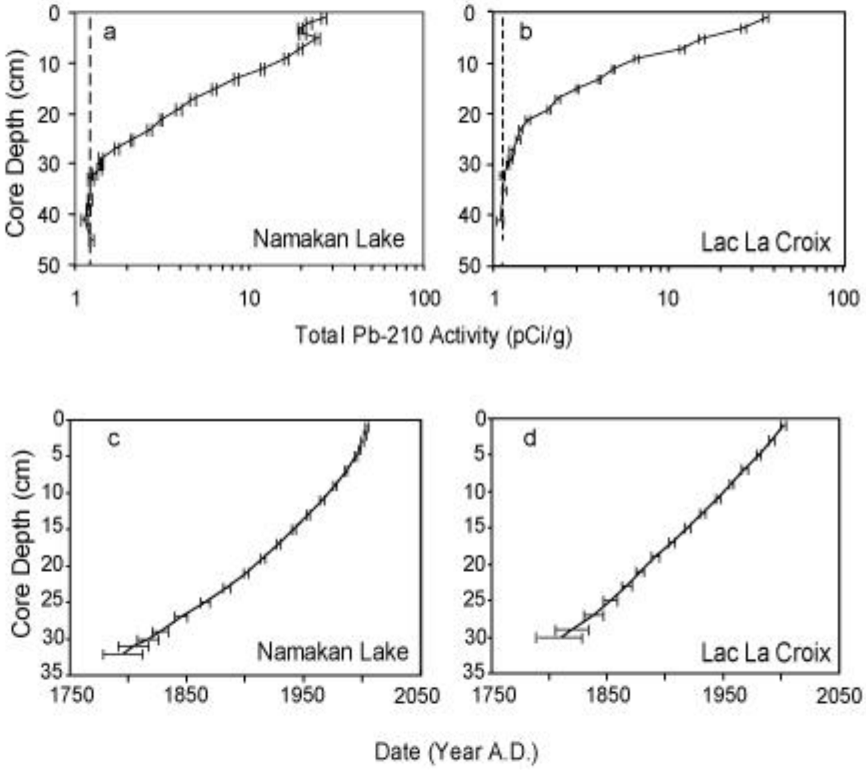


Figure 2. Total ^{210}Pb inventory in sediment cores from Namakan Lake (a) and Lac La Croix (b) as a function of depth (c,d) showing chronology based on the CRS model (Appleby and Oldfield 1978). Error bars represent ±1 s.d. propagated from counting uncertainty.

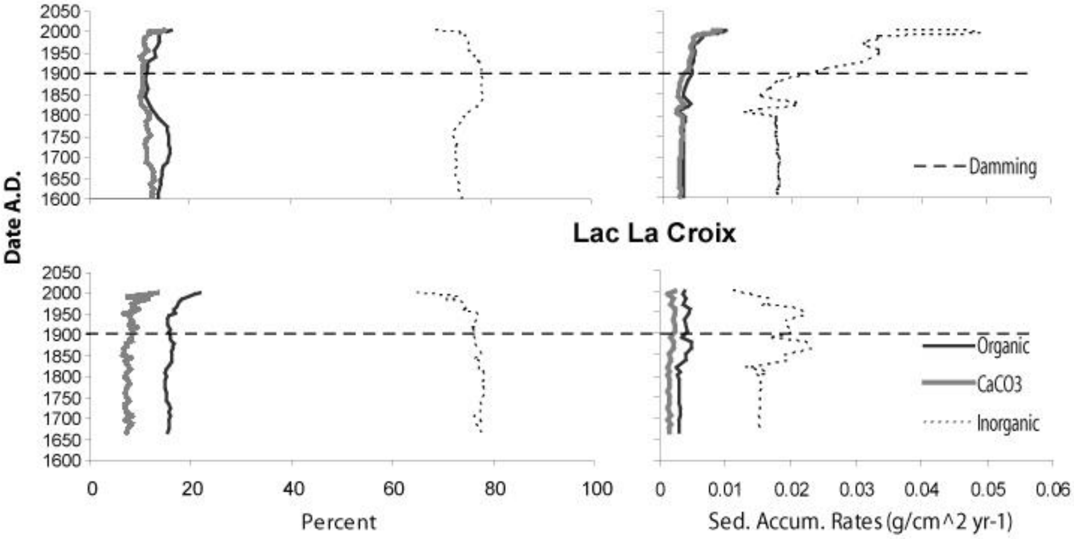


Figure 3. A. Inorganic, organic and calcium carbonate content of Namakan Lake and Lac La Croix sediments determined by loss on ignition. B. Sediment flux of inorganics, organics, and carbonated in Namakan Lake and Lac La Croix.

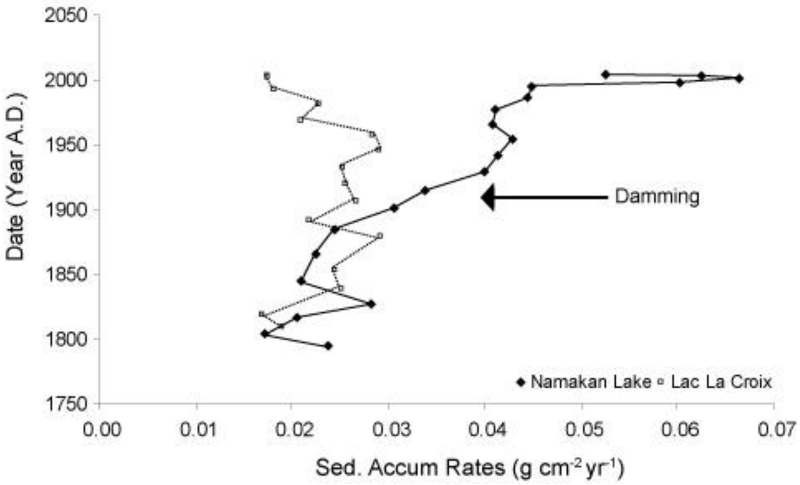


Figure 4. Sediment accumulation rate through time in Namakan Lake and Lac La Croix. Note increased sediment accumulation rates in Namakan Lake after damming.

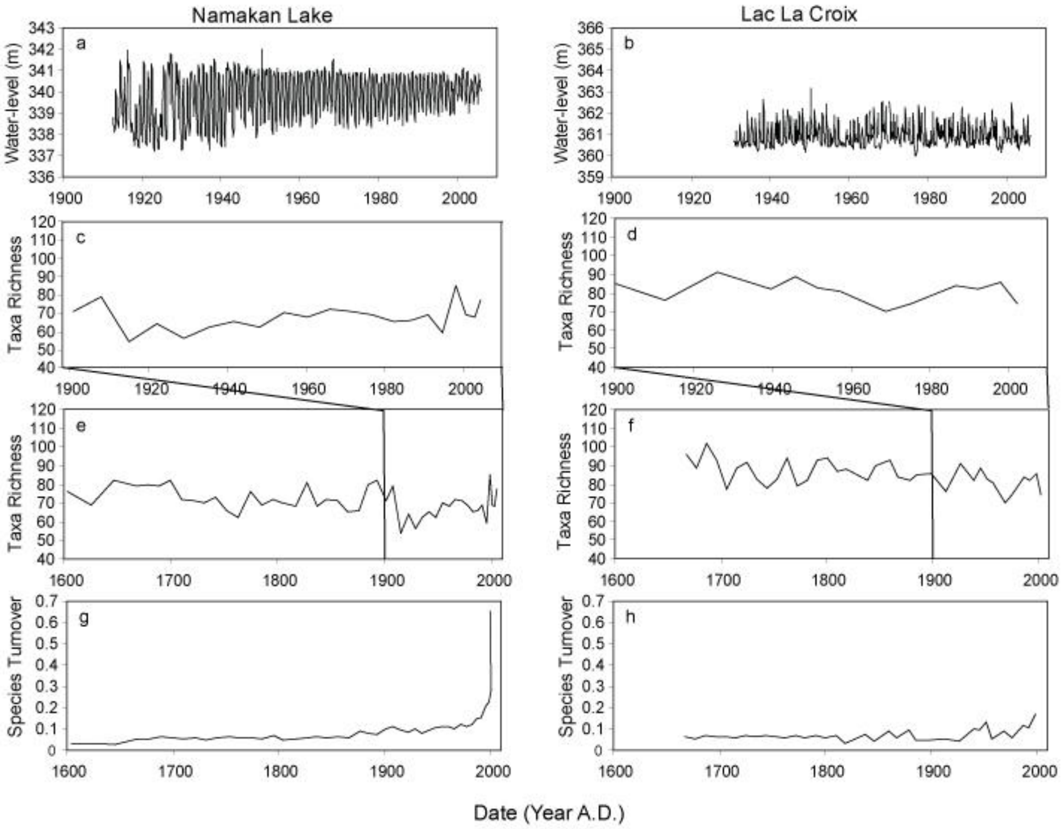


Figure 5. Water-level, taxa richness and species turnover in Namakan Lake and Lac La Croix through time. 4 a,b. Hydrograph of Namakan Lake at Kettle Falls (1912-2007) and Lac La Croix at Campbell's Camp from (1921-2007) (Water Survey Canada). 4c-f.Taxonomic richness (*S*) of diatoms (McIntosh 1967). 4 g,h. Species turnover (*t*) of diatoms (Diamond and May1977).

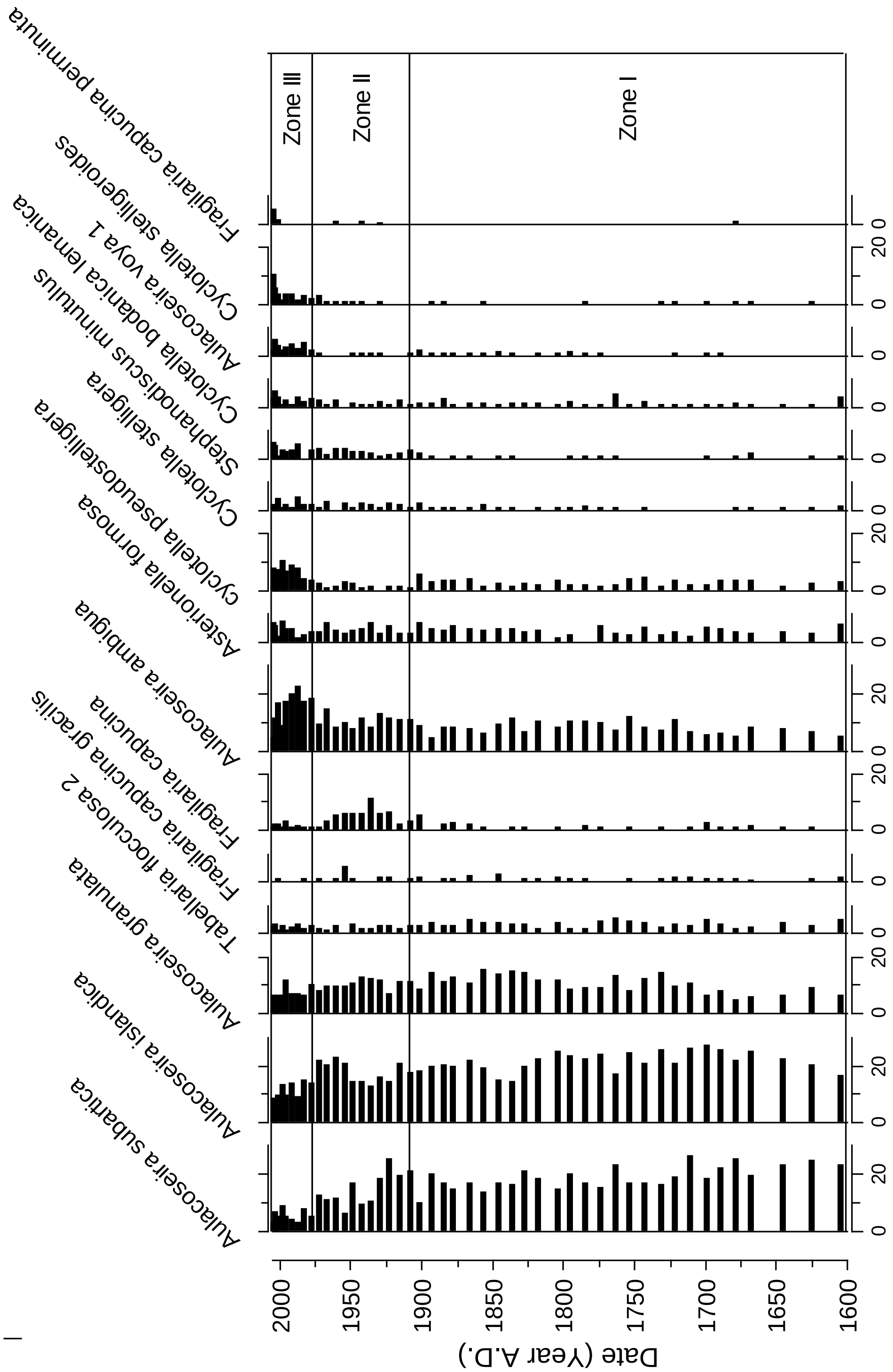


Figure 6. Relative abundance of dominant diatom taxa from Namakan Lake core, 1600-2005 A.D. The different zones denote damming and the various management plans. Taxa occurred in at least one sample at ≤5 % relative abundance.

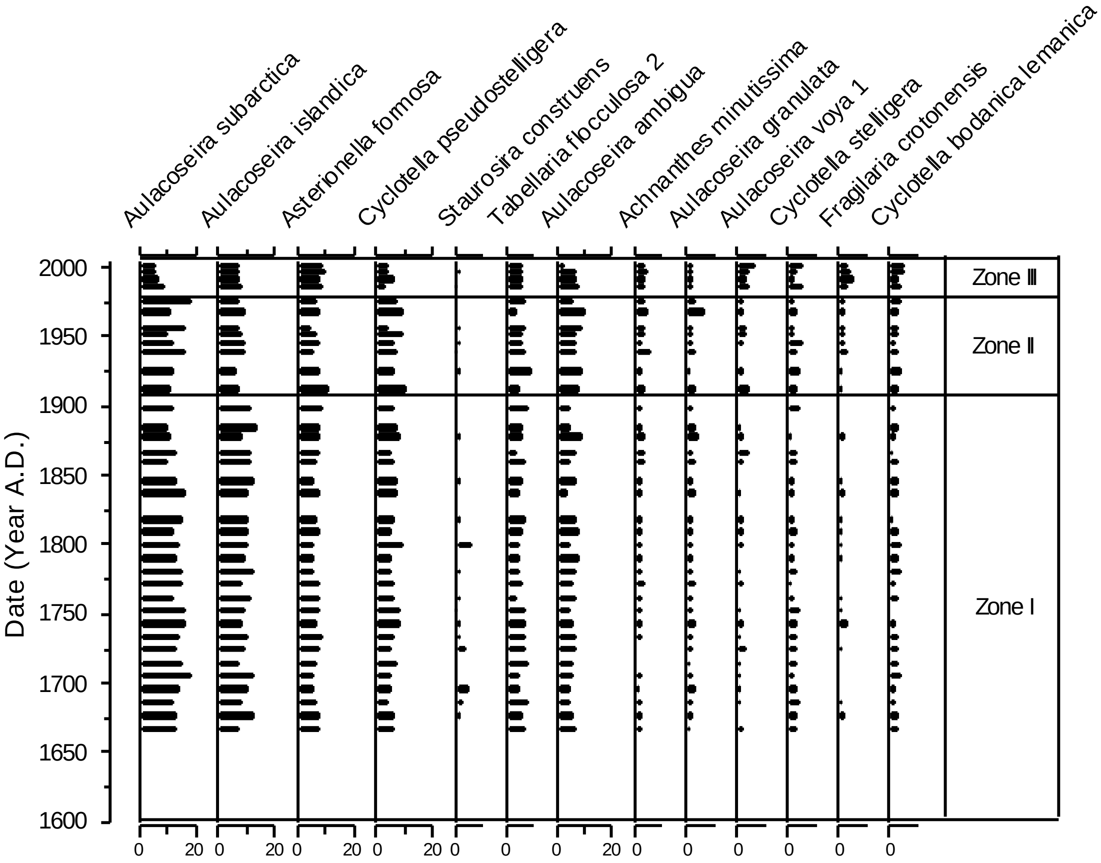


Figure 7. Relative abundance of dominant diatom taxa from Lac La Croix, 1668-2005 A.D. Taxa occurred in at least one sample at ≤5 % relative abundance.

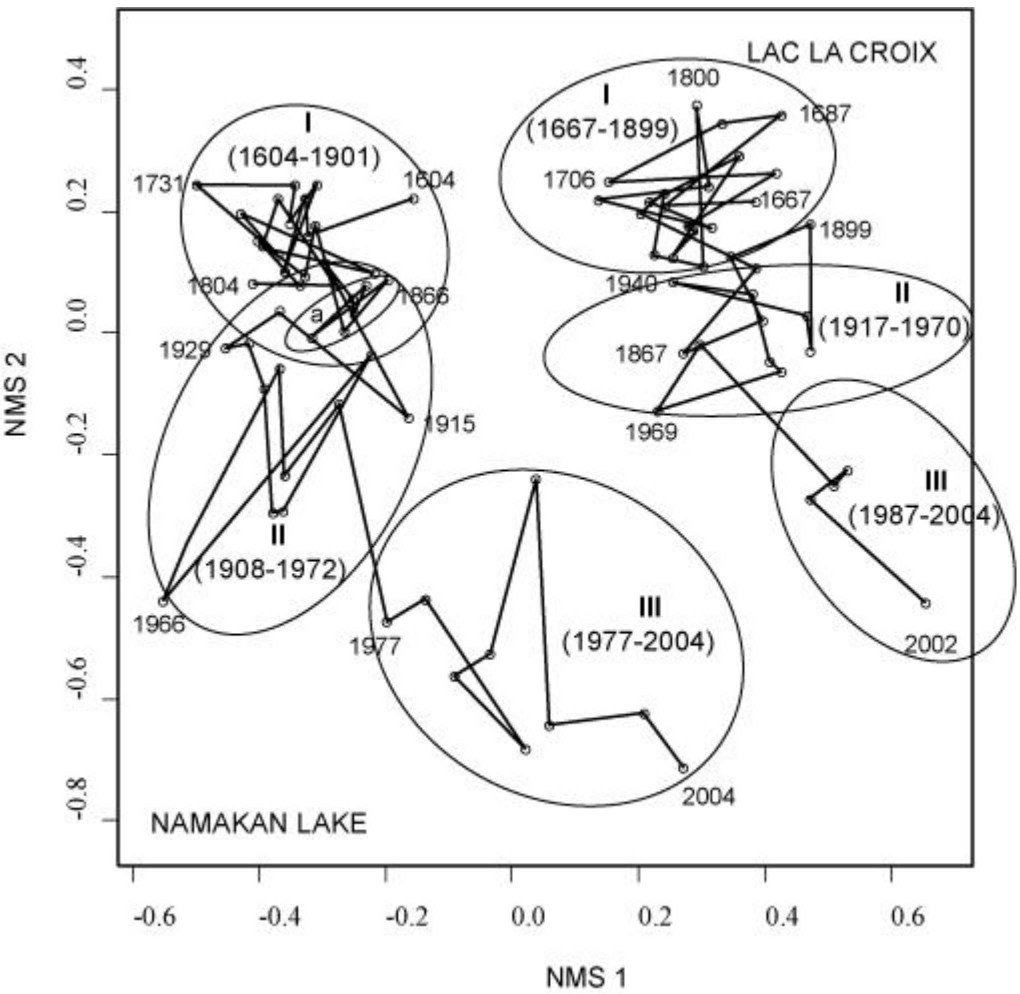


Figure 8. Non-metric Multidimensional Scaling (NMS) analysis displaying dated samples from Namakan Lake and Lac La Croix. Line segments connect samples in each core in chronological order. Circled clusters of samples represent diatom biostratigraphic zones in each core identified using CONISS as first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

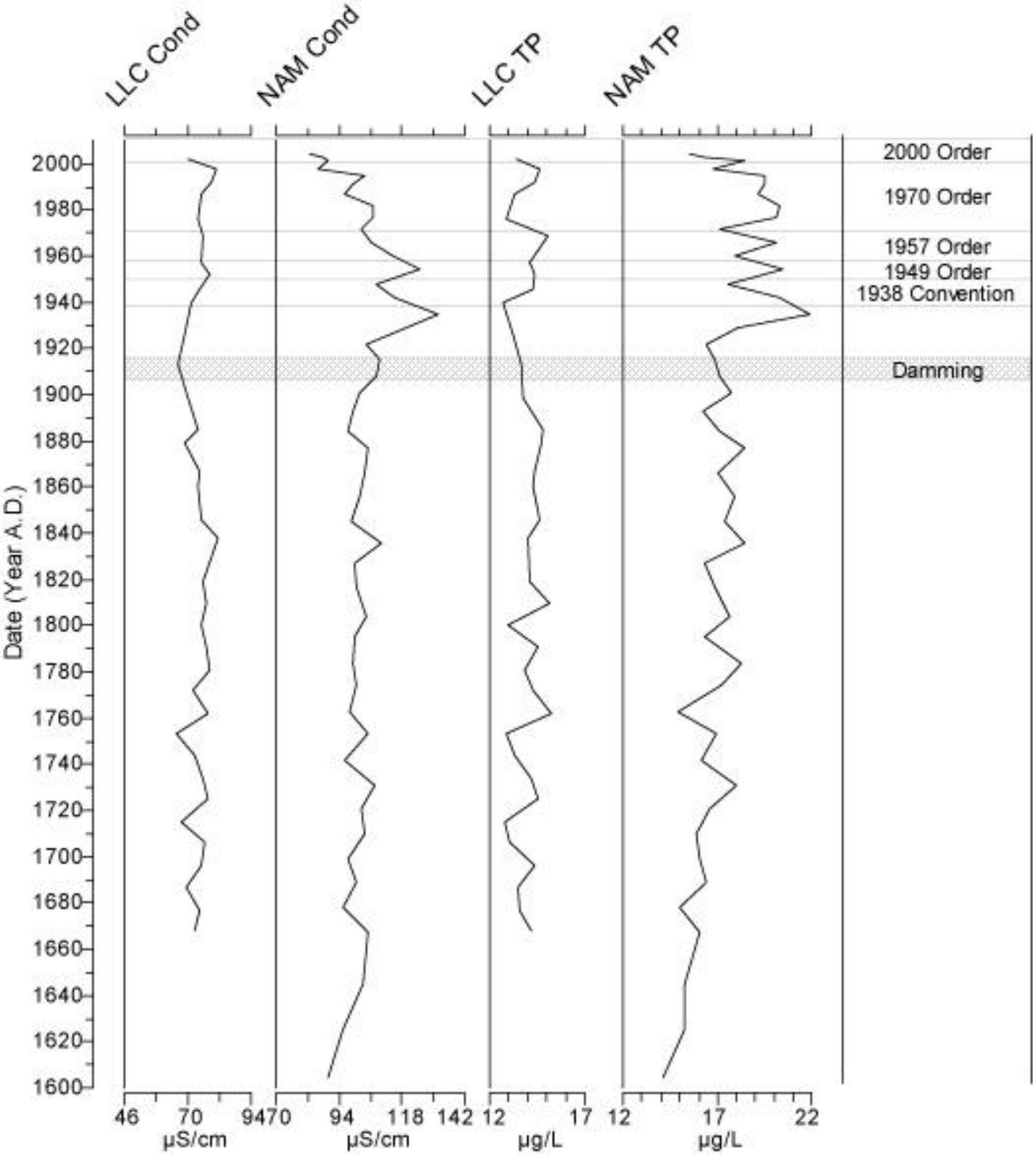


Figure 9. Diatom-inferred conductivity (Cond) and total phosphorus (TP) reconstructions for Namakan Lake (NAM) and Lac La Croix (LLC). Damming and hydromanagement periods impacting Namakan Lake are displayed in the right panel.

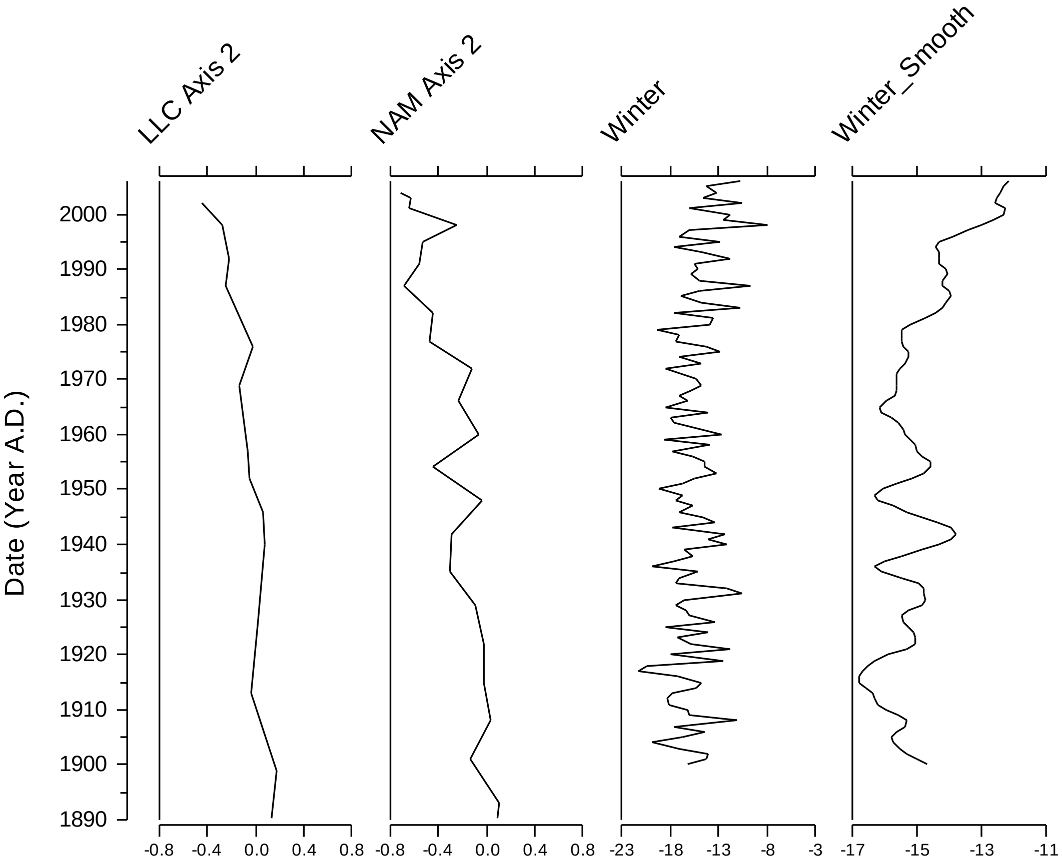


Figure 10. Stratigraphic diagram comparing Axis 2 scores based on Non-metric Multidimensional Scaling of downcore diatom communities from Namakan Lake (NAM) and Lac La Croix (LLC) against mean winter air temperature in degrees Celsius from Kenora, Ontario, Canada and Lowess smooth line with a span of 0.8.

Chapter 3: Interactive effects of hydromanagement, land use and climate change on water quality of US – Canada borders waters

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 the dammed lakes Namakan, Rainy, and Kabetogama, 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 were affected 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.

Abstrait

Les lacs entre la frontiere de l'Ontario et le Minnesota ont été le sujet de plusieurs impacts anthropogenique et naturelle qui inclus le déboisement de la forêt, la construction d'un barrage, hydro-gérance, accroissement de la population, et le changement climatique. Pour savoir comment ces differents stresseurs ont affecté ces lacs, nous avons developpé une étude avant-après control-impact paleolimnologique. Les sites inclus sont les lacs de Namakan, Rainy et Kabetogama qui ont été controllés pas des barages et Lac La Croix qui n'a pas été controllé et qui se trouve amont des autre lacs dans une région protégée. Un carotage de chaque lacs a été retiré pour faire des analyses ^{210}Pb, «loss-on-ignition», et de diatomés. La richesse des espèces et leur changement, cluster analysis, multivariate ordination, la reconstruction de la qualité d'eau avec les diatomés, et variance partitioning ont été utilisé pour déterminer comment et quand les lacs ont été affecté par ces different stresseurs et, les effets de ces stresseurs uniquement et ensemble. La pluspart des lacs ont montré des impacts envers le déboisement ; deux lacs ont augmenté dans l'accumulation des sédiments après le déboisement et la construction des barrages. Variance partitioning a montré que entre les stresseurs, la gérance des terrains expliqué le plus le changement de la communitée des diatomés. Cependant, les effets interactifs entre la gérance des terrains, climat, et l'hydro-gérance étaient aussi très important. Les résultats suggère que même si l'hydro-gérance est sujets primaire de considération, les differnt stressurs environmental et leur interactions entre eux doivent être consideré dans la gérance de ces lacs.

Keywords: diatoms, human impacts, paleolimnology, climate change, Minnesota, Ontario

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 alteration of the landscape also has 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. 1999a; 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 on 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 ecosystem change such as landscape and climate change.

To attribute historical changes in biological communities to various environmental and human stressors, recent studies (e.g., Hall et al. 1999a; Quinlan et al. 2002; Galbraith et al. 2008) have used variance partitioning (Brocard 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. (1999a) 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 the Northern Great Plains, 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 to determine background or predamming lake conditions and the historical response of sedimentation rates and diatoms to damming, water-level manipulation, land use and climate change. We applied variance partitioning analysis to determine the unique and interactive effects of water level management, land use, and climate on diatom communities in each lake.

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; Fig.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 (92000 ha; Table 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 (Kallemeyn et al. 2003). Ice-in typically occurs in these large lakes in late November to early December and ice-out in late April to mid May.

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 followed shortly and was completed in 1914. The dams were created 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 and subsequent regulations in 1956, 1970 and in 2000. The 2000 order suggested that the spring refill period occur earlier and has 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 water-level fluctuation developed and a more moderate drawdown occurred during the summer (IRLBC 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 (mm; 1912-1959) and temperature (ºC; 1912-2005) were obtained from the Environment Canada weather station in Fort Frances, Ontario. Precipitation data from 1959 till 2005 were obtained from the NOAA weather station in International Falls, Minnesota as the Fort Frances data were not complete (Fig. 1).

Monthly water-level data were available though Water Survey Canada 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). Annual water-level differentials, annual minima and maxima were recorded 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. Even though our lakes are primarily in Koochiching County, earlier censuses were included for Itasca County because it included what is 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). Tabular data were not available but graphed trends for the Rainy River district were similar to trends in Itasca and Koochiching Counties, which is expected because this region encompasses similar industries, landscape and climate. As such, 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 pulpwood production. Long-term pulpwood trends from the counties were lacking for the watershed prior to 1959, so pulpwood production data of the Lake States (Minnesota, Wisconsin and Michigan) spanning various time intervals between 1910-1959 (Demmon 1946; Horn 1960) were used; 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 (NCFES 1960-2005).

Beaver were extirpated in the 1800s (Naiman et al. 1986) in Voyageurs National Park, but 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) and therefore 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 the depositional zone of each lake (Fig. 1**)** during summer 2005 using a drive-rod piston corer equipped with a 1.5 m long and a 7.5 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 2). Cores were sectioned in the field at 1-cm increments and were stored in air tight containers at 4°C.

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). 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.

Numerical Analysis

Diatom species richness was calculated for each sample using McIntosh (1967) *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 chosen as large differences were 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) in 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 Rainy, Namakan and Kabetogama Lakes were provided by the USGS for conductivity, TP and pH (Payne 1991) and Christensen et al. (2004) for total nitrogen. Model performance and summary statistics can be found in Table 3.

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 source 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, discretionary hydromanagement; post-1959, climate warming, population, pulpwood, rule curves). Potentially explanatory subvariables (e.g., summer temperature, beaver colonies) from each of three variable categories (climate, landscape, 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 subvariables prior to analysis. Subvariables 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 subvariables that explain significant and unique variance and to eliminate highly correlated subvariables. The maximum number of subvariables selected for each category was no greater than one more than other categories by lake and time period. Human population and pulpwood during post-1959 were not included for the analysis of Lac La Croix as the region near and upstream of Lac La Croix has long been protected by the Wilderness Act (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) and to determine the effects of each category "singly" and their interactive effects with other explanatory variables (Brocard et al. 1992; Hall et al. 1999a; Galbraith et al. 2008).

Results

Historical Data

Temperature trends in Fort Frances were relatively constant prior to the 1970s (Fig. 2). Post-1970s, winter temperatures increased (Fig. 2). Spring temperatures increased slightly while autumn temperatures have increased only in the last decade (not illustrated, see Appendix 2). As a result, annual temperatures have increased in the past two decades. Precipitation trends vary throughout the 20th century (Fig. 2) except for the past decade when the region has had wetter autumns (not illustrated, see Appendix 2).

Water-levels in the managed lakes were distinctively different than in Lac La Croix (Fig. 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 (Fig. 3).

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-4000s in 1900 to 23000 in 1910 to around 50,000 in 1940, Fig. 2d). Population has recently begun to level off at around 58,000.

Two distinct patterns emerged in the logging data (Fig. 2c). The first relates to the number of board feet cut by sawmills. Even though the overall pattern is decreasing from 1910 to 1936, from 1910 to 1914 the number of board feet cut increased and then decreased during World War I (1914-1918). This decrease was followed by a brief increase in the mid-1920s and a final decrease until 1936, when the saw mills stopped operating in the region. The second logging trend relates to pulpwood production, with a general increase (Fig. 2) through time. 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).

Kabetogama Peninsula beaver population increased from 1936 until 1986 and then decreased (Fig. 2). The number of active colonies per kilometer surveyed steadily increased from 0 in 1936 to approximately 1 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 1 colony per kilometer in 2005.

Sediment Dating and Geochemistry

All cores showed generally a decline in unsupported ^{210}Pb activity (Fig. 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% (Fig. 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 (Fig. 5). Sediment accumulation patterns varied among lake cores (Fig. 5). All dammed lakes showed an increase in sediment accumulation beginning either at the time of damming (Namakan and Kabetogama

Lake) or later (Rainy Lake; Fig. 6). No change in accumulation rate was apparent in Lac La Croix.

Taxonomic Richness and Species Turnover

A combined total of 587 diatom taxa was found in all lakes. The taxonomic richness patterns vary depending on the core (Fig. 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 and has since gradually recovered (Fig. 7). Taxonomic richness in Kabetogama 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 (Fig. 7**)**. However, diatoms in Lac La Croix and Kabetogama Lake seem to respond 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 (Fig.7).

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; Fig. 8) and post-1900s. In the post-1900 zone, two sub-zones were identified pre and post 1978 (Zone 2 and 3 respectively; Fig. 8). The pre-damming assemblages (Zone 1, 1605-1905) were composed mostly of *Aulacoseira granulata* (reachings 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 (Fig. 9) as Kabetogama. Pre-damming assemblages (Zone 1; 1604-1907) include *Aulacoseira* .

subarctica, *A. islandica, A. granulata* 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-1970's) shows a decline in *A. subarctica*, *A. islandica, A. granulata* and *F. capucina*, whereas *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 predamming values and variability by the 1950s, whereas P/B values in Kabetogama Lake generally increased throughout the 20th century.

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) (Fig. 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 as 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.*

Similar to Kabetogama and Namakan Lakes, the diatom assemblages in Lac La Croix were also divided into three zones (Fig. 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 Zone 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 (Fig. 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-80s zones in all lakes show much greater ecological variability.

Variance Partitioning

Many subvariables selected for climate, landscape and water-level were significant ($P < 0.05$) in explaining diatom assemblage composition, although no climate subvariables were significant in post-1959 Rainy Lake, and no water-level subvariables were significant in post-1959 Rainy Lake and Lac La Croix (Table 4). Furthermore, when significant subvariables were combined into major variable categories (climate, landscape, water-level) the unique variance explained by each major variable was usually significant, but not always (Table 4). For example, the variable category “climate” was not uniquely significant in pre-1959 Lac La Croix (Table 4).

Overall, landscape was the strongest explanatory category in all four lakes (Table 4). Landscape uniquely explained up to 25% of the variation in past diatom assemblages. Pre-1959 human population size was the most common landscape subvariable 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.

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 subvariable for the pre-1959 period and a temperature subvariable for post-1959.

Historical water-level also significantly explained diatom assemblage changes. 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, all three water-level subvariables, i.e. the differential between the minimum and maximum water-level, the minimum, and the maximum water-level from each lake, were selected as the most significant subvariables.

Diatom-inferred Water Quality

Diatom-inferred total phosphorus reconstructions in Lac La Croix and Rainy Lake showed no significant changes throughout the core (Fig. 13). Kabetogama Lake displayed a slight decrease in total phosphorus (3-4 ug/L) after damming preceding an increase (Fig. 13). Total phosphorus in Namakan Lake increased with a possible recovery within the last decade (Fig. 13).

Diatom-inferred conductivity showed that Lac La Croix and Rainy Lake had varied slightly over time but no clear trends in conductivity were detected (Fig. 13). Both Namakan and Kabetogama Lakes had diatom reconstructions with an increase in conductivity after damming. Namakan Lake had two peaks in conductivity, one in 1935 the other in 1954, reaching 115 µS cm^{-1} and 105 µS cm^{-1}, respectively. In Kabetogama Lake, conductivity increased from 142 µS cm^{-1} in 1910 to 169 µS cm^{-1} in 1992. Both Namakan and Kabetogama lakes show recent decreases in conductivity. These changes are only trends and are not considered significant because they are not greater than the margin of error of the reconstruction.

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 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 (Fig. 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 (Zone 2, Fig. 11) were mostly in minor taxa. Species turnover rates also had only minor fluctuations (Fig. 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 (Fig. 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 initial logging 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 respond to damming with an increase in sediment accumulation (Fig. 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. Furthermore, Namakan Lake has an increase of P/B ratio at the time of damming with a recovery following. However, even though Kabetogama Lake also diplays an impact at the time of logging and damming with the increase of P/B ratio mimicking the increase in abundance of *Stephanodiscus “parvus”*, the species turnover never appears to recover and only increases till 2005. The combined impact of logging and damming may have been so great that the species turnover went beyond an intermediate disturbance level, which led 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. (1999b) 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 Krakower See.

Post-damming Drivers of Change

Many environmental drivers 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 increasingly 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. 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 underwent 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 a further decrease. Rainy Lake's taxonomic richness did not change during the 20th century but nevertheless Rainy Lake sediments contain a great proportion of planktonic diatoms from the 1950s onward. These 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).

Diatom-inferred water quality parameters changed during the 20th century in Kabetogama and Namakan Lakes (Fig. 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. The steep-sided basins of Kabetogama support this interpretation; because of its basin morphometry, Kabetogama would have had a smaller surface area to volume increase than Namakan Lake and minimal change in shoreline development. Hall et al. (1999b) report a similar post-damming decrease in primary productivity following inundation of Buffalo Pound Lake, Saskatchewan. For Namakan Lake, inundation at the time of damming likely led to higher TP concentrations. The TP values identified in the sample at the top of the cores are close or within the range of modern TP measurements collected within that time period - Namakan 8-28 ug/L and Kabetogama 8-16 ug/L.

Diatom-inferred conductivity increased in both Kabetogama Lake and Namakan Lake after damming. In Kabetogama, 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 burnt lakes than in reference lakes. Diatom-inferred conductivity reconstruction for Rainy Lake was close to modern data (97 µS/cm compared to 98 µS/cm); however, Kabetogama and Namakan Lakes reconstructed values were higher than the modern data (76 µS/cm compared to 45 µS/cm for Namakan Lake, 166 µS/cm compared to 93 µS/cm for Kabetogama Lake). It is important to note that the reconstruction errors are in the range that includes modern data.

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 (Brocard 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. (1999a), 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 2000-6500 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 was significant in all post-1959 analyses and was the single significant landscape subvariable 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 subvariable 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 variables 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 variance in Rainy Lake. In contrast, climate only explained 5% of unique variation in Namakan. Additionally, in Kabetogama Lake, climate variables were not uniquely significant. However, in both Kabetogama and Namakan Lakes, the interactive effect of climate with other variables played an important role in explaining assemblage changes, at 61% and 60% respectively. A similar pattern was noted by Hall et al. (1999a) 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 water-level ranged from not significant to 16% in pre-1959 samples from Lac La Croix. Overall, water-level had a greater influence in pre-1959 samples, except in Kabetogama and Namakan Lake. In post-1959 samples, water level was interactively significant in Namakan and Kabetogama Lakes, at 56% and 55% 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 had been the primary resource concern in these border waters, water-level was never a dominant variable explaining historical changes in diatom communities. In fact, water level was never a significant unique explanatory variable in Rainy Lake. Based on variance partitioning results, other environmental stressors including landscape changes and climate variation and their interactions with each other and with water level regulations must all be recognized as significant drivers of recent change in the Ontario-Minnesota border lakes region.

Conclusion

Clearly, 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, hydromanagement (for the dammed and regulated lakes), landscape use, and climate have also 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 in 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.

Acknowledgements

This project was funded by the United States Geological Survey (PM15-94151). Special thanks to Mary Graves, Culture Resources Specialist in International Falls, Andrew Jourdain and the Lac La Croix First Nation for technical assistance on Lac La Croix, Ryan Maki at Voyageurs National Park for collecting environmental data, Erin Mortenson (St. Croix Watershed Research Station) for sediment dating, Rick Cousins (Lake of the Wood Control Board) and the Water Survey of Canada for providing hydrological and governance information, Kathleen Rühland, Andrew Paterson, and Euan Reavie for sharing an unpublished calibration set for northern Minnesota and northwestern Ontario, Steve Juggins for sharing his statistical expertise, and Ron Piva, North Central Forest Experiment Station, for pulpwood production data.

Tables

Table 1. Lake and watershed characteristics. (Information for Lac La Croix was not available at the time of this study; conductivity measures and total phosphorus levels are available in Appendix 1) *Renewal time is for Namakan Reservoir.

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	10425	196.7	9	24.3	9.1	30	948.7	…
Namakan	10170	192.7	6.5	45.7	13.6	20	1383.1	0.6*
Rainy	92100	41.9	14.4	49.1	9.9	35	9117.9	1
Lac La Croix	13788	…	…	51.2	…	25	…	…

Table 2. Basins cored June 2005-September 2006, 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	28VI2005	48°26.028'N 92°42.136'W	St. Louis (MN)	24.07	131	0-50	Nam
Kabetogama	28VI2005	48°27.346'N 92°57.177'W	St. Louis (MN)	16.71	140	0-80	Kab
Rainy	12IX2005	48°32.351'N 92°49.751'W	St. Louis (MN)	21.09	190	0-45	RA2
Lac La Croix	13IX2005	44°55.521'N 93°31.975'W	Rainy R. District, Ontario, Canada	14.90	207	0-49	LLC

Table 3. Summary statistics for weighted averaging model performance. The strength of the transfer function is reported for each environmental variable in terms of r2, RMSE and RMSEP bootstrapped

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

Table 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 subvariables within each variable category are listed parenthetically for each lake and time period (pre- and post-1959). (A= Aspen, 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, WP= Winter Precipitation, WT= Winter Temperature)

Pre-1959				Post-1959			
Kabetogama Lake				Kabetogama Lake			
Climate (AT, AP)				Climate (ST, WT, AT)			
	total	35%	$p<0.005$		total	61%	$p<0.005$
	unique	9%	$p<0.005$		unique	4%	$p<0.01$
Landscape (HP, A)				Landscape (HP, B, P)			
	total	49%	$p<0.005$		total	82%	$p<0.005$

	unique	21%	p<0.005		unique	13%	p<0.005
Water-Level (Max)				Water-Level (Dif, Min, Max)			
	total	14%	p<0.005		total	55%	p<0.005
	unique	1%	NS		unique	4%	p<0.005
Namakan Lake				Namakan Lake			
Climate (AP, SP, SuP)				Climate (ST, WT, AT)			
	total	38%	p<0.005		total	60%	p<0.005
	unique	3%	p<0.05		unique	5%	p<0.005
Landscape (BF, HP, B)				Landscape (B, P, HP)			
	total	75%	p<0.005		total	77%	p<0.005
	unique	23%	p<0.005		unique	25%	p<0.005
Water-Level (Max, Min, Dif)				Water-Level (Dif, Max, Min)			
	total	47%	p<0.005		total	56%	p<0.005
	unique	7%	p<0.005		unique	4%	p<0.005
Rainy Lake				Rainy Lake			
Climate (AP, SP, SuP)				Climate (WP, WT)			
	total	35%	p<0.005		total	34%	p<0.005
	unique	3%	p<0.005		unique	27%	p<0.005
Landscape (B, BF, HP)				Landscape (B)			
	total	86%	p<0.005		total	18%	p<0.005
	unique	23%	p<0.005		unique	18%	p<0.005
Water-Level (Min, Dif)				Water-Level (Min)			
	total	68%	p<0.005		total	15%	p<0.02

	unique	3%	$p<0.005$
Lac La Croix			
Climate (SP, AP, AuT)			
	total	32%	$p<0.005$
	unique	5%	$p<0.02$
Landscape (B, HP, BF)			
	total	66%	$p<0.005$
	unique	14%	$p<0.005$
Water-Level (Min, Max, Dif)			
	total	51%	$p<0.005$
	unique	16%	$p<0.005$

	unique	3%	$p<0.005$
Lac La Croix			
Climate (WT, AT)			
	total	39%	$p<0.005$
	unique	19%	$p<0.005$
Landscape (B)			
	total	24%	$p<0.005$
	unique	11%	$p<0.005$
Water-Level (Dif, Max)			
	total	25%	$p<0.005$
	unique	14%	$p<0.005$

Figures

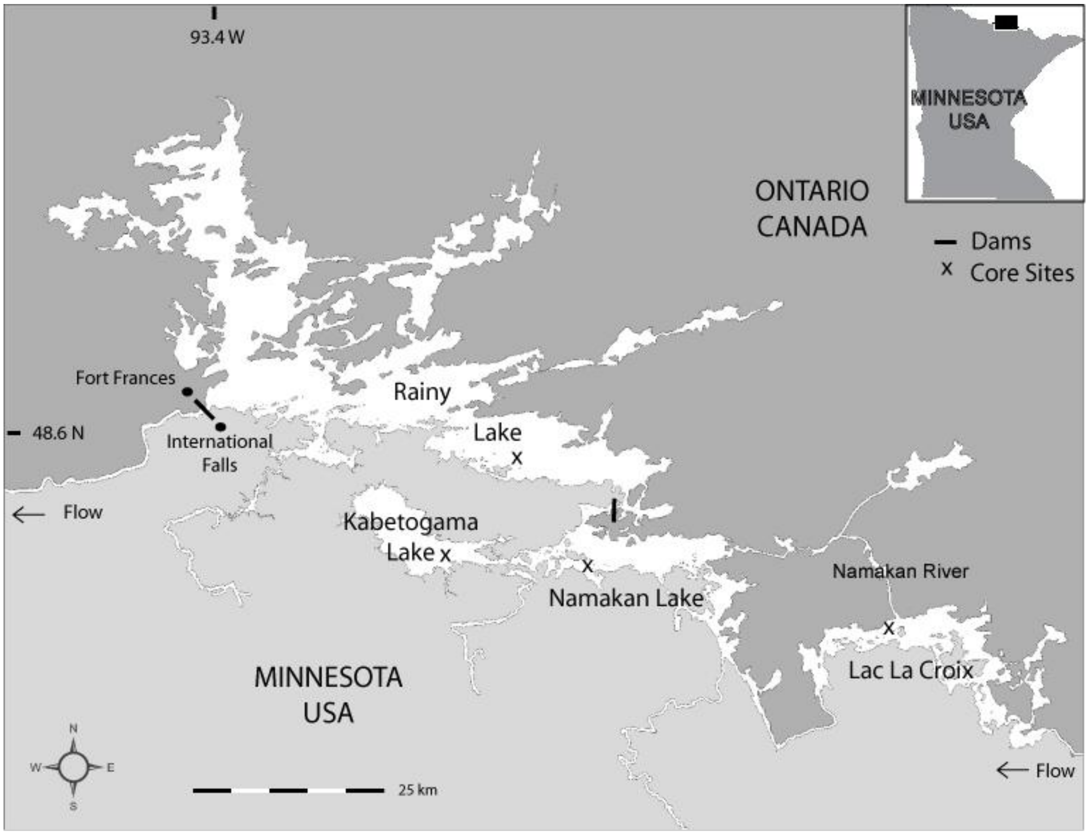


Figure 1. Kabetogama Lake, Namakan Lake, Rainy Lake and Lac La Croix and their respective coring sites (x). Dam sites indicated by black bars

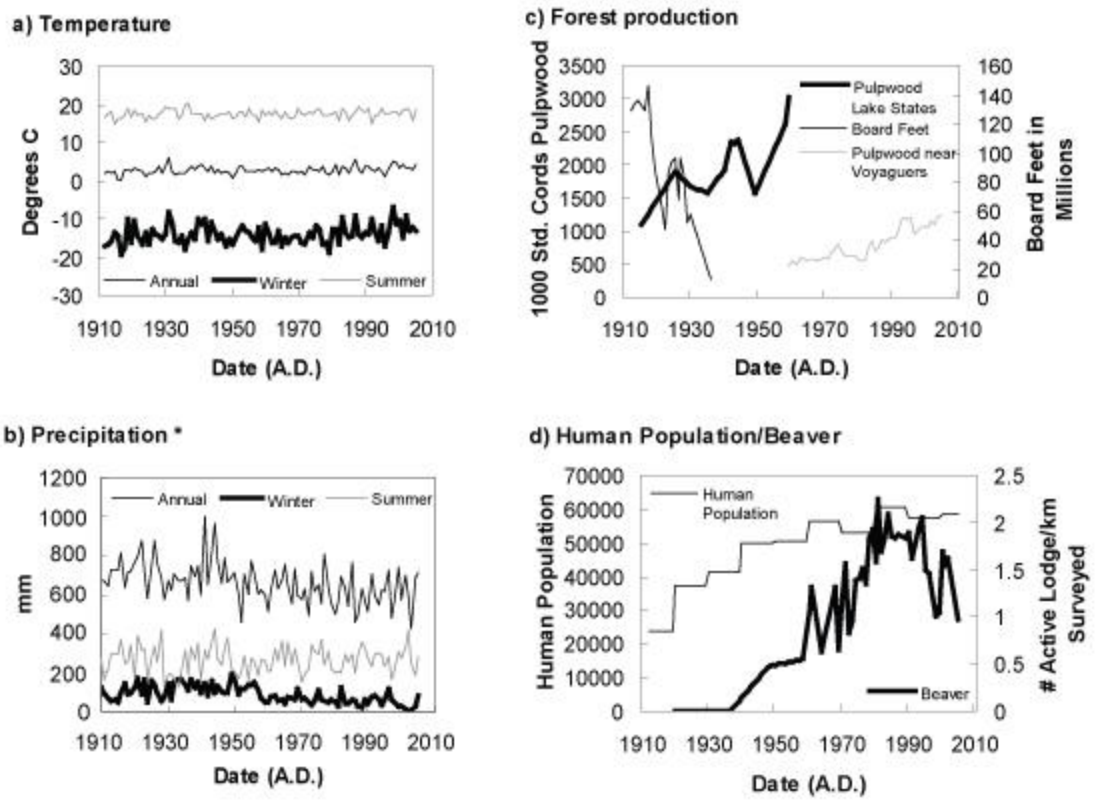


Figure 2. Long-term data for the Voyageurs National Park region. Historical records include the climatic variables of mean seasonal and annual (a) temperature and (b) preciptation records from Fort Francis, ON and International Falls, MN, and the resource use variables of (c) forest production, and (d) human population and beaver index. Further details are given in the methods section. * Data from 1910 till 1958 are from Fort Francis, ON and thereafter from International Falls, MN.

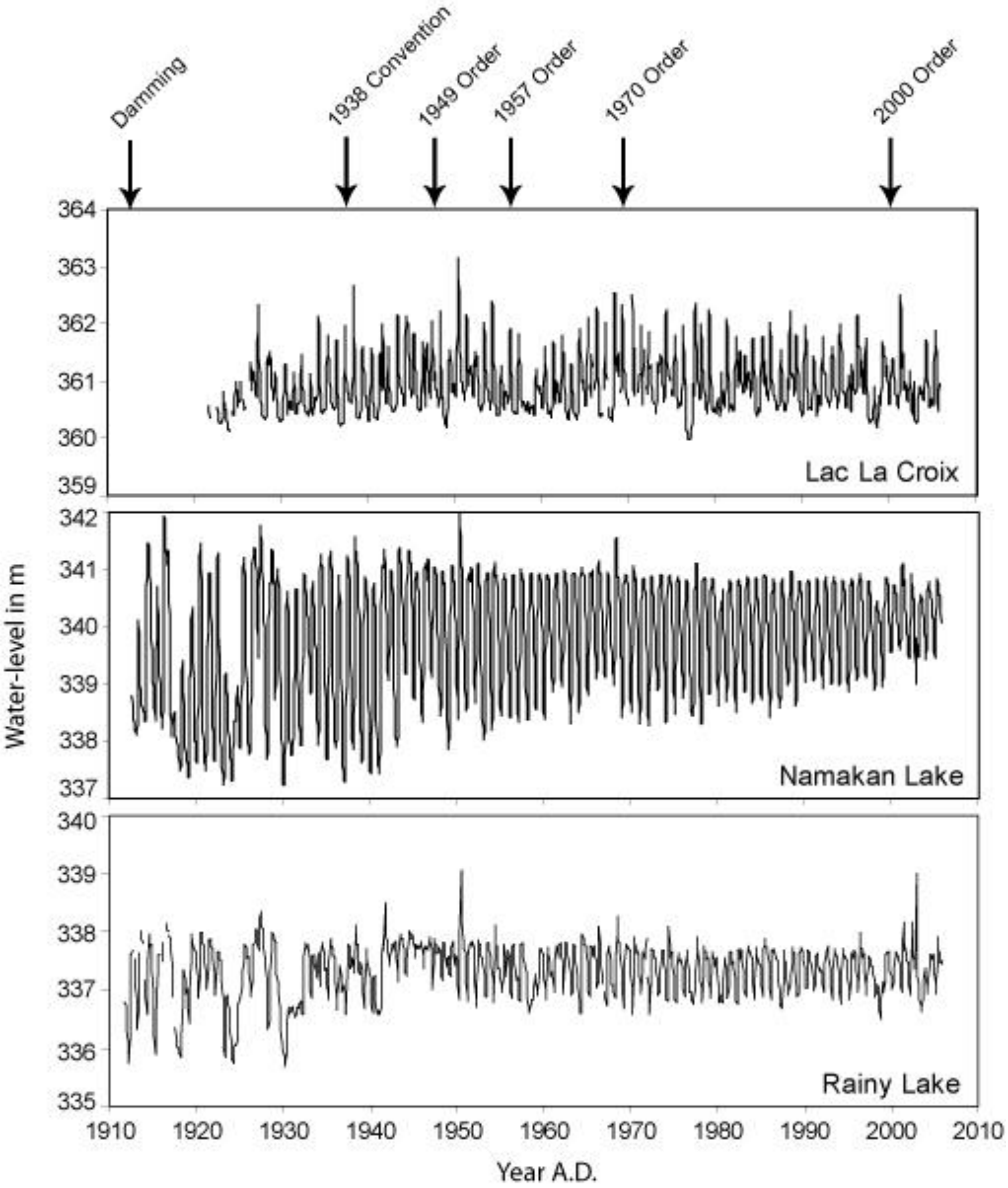


Figure 3. Hydrograph of Namakan Lake at Kettle Falls (1912-2007), Rainy Lake at Fort Frances (1912-2007) and Lac La Croix at Campbell's Camp from (1921-2007; Water Survey Canada).

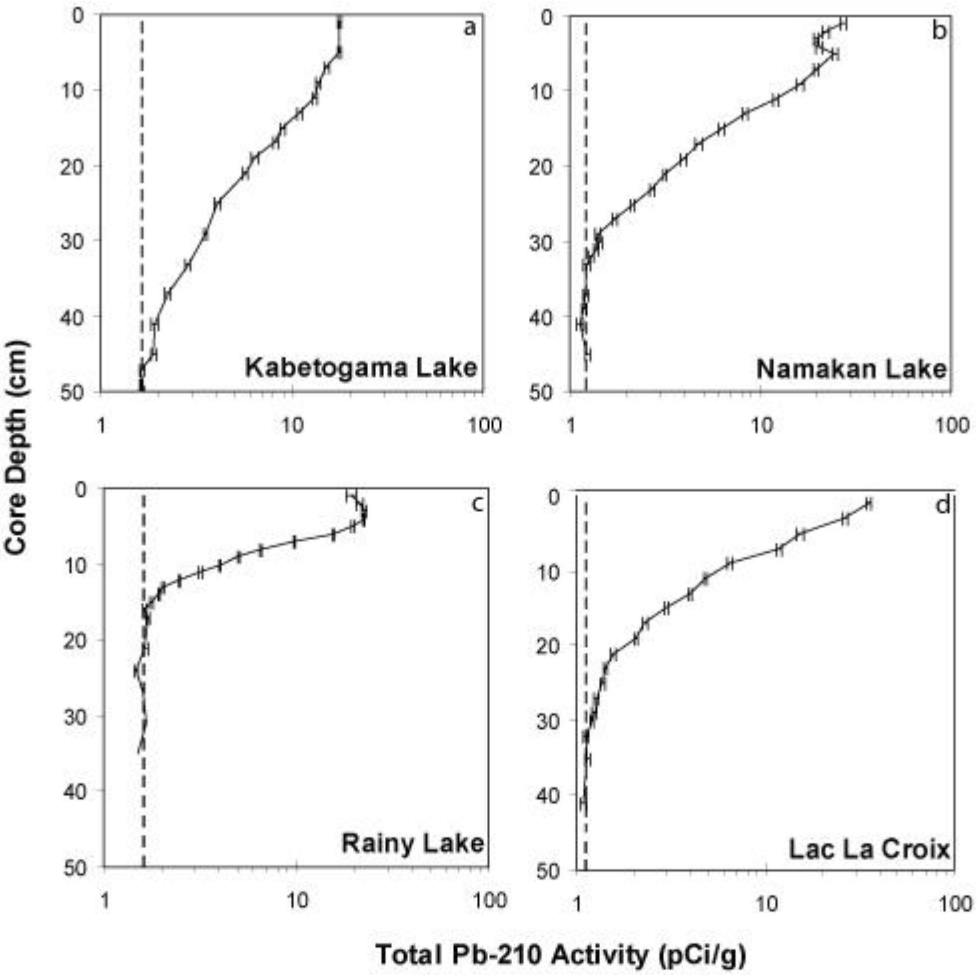


Figure 4. Total ^{210}Pb inventory in sediment cores from Kabetogama Lake (a), Namakan Lake (b), Rainy Lake (c) and Lac La Croix (d) as a function of core depth based on the CRS model (Appleby and Oldfield 1978). Error bars represent ±1 s.d. propagated from counting uncertainty.

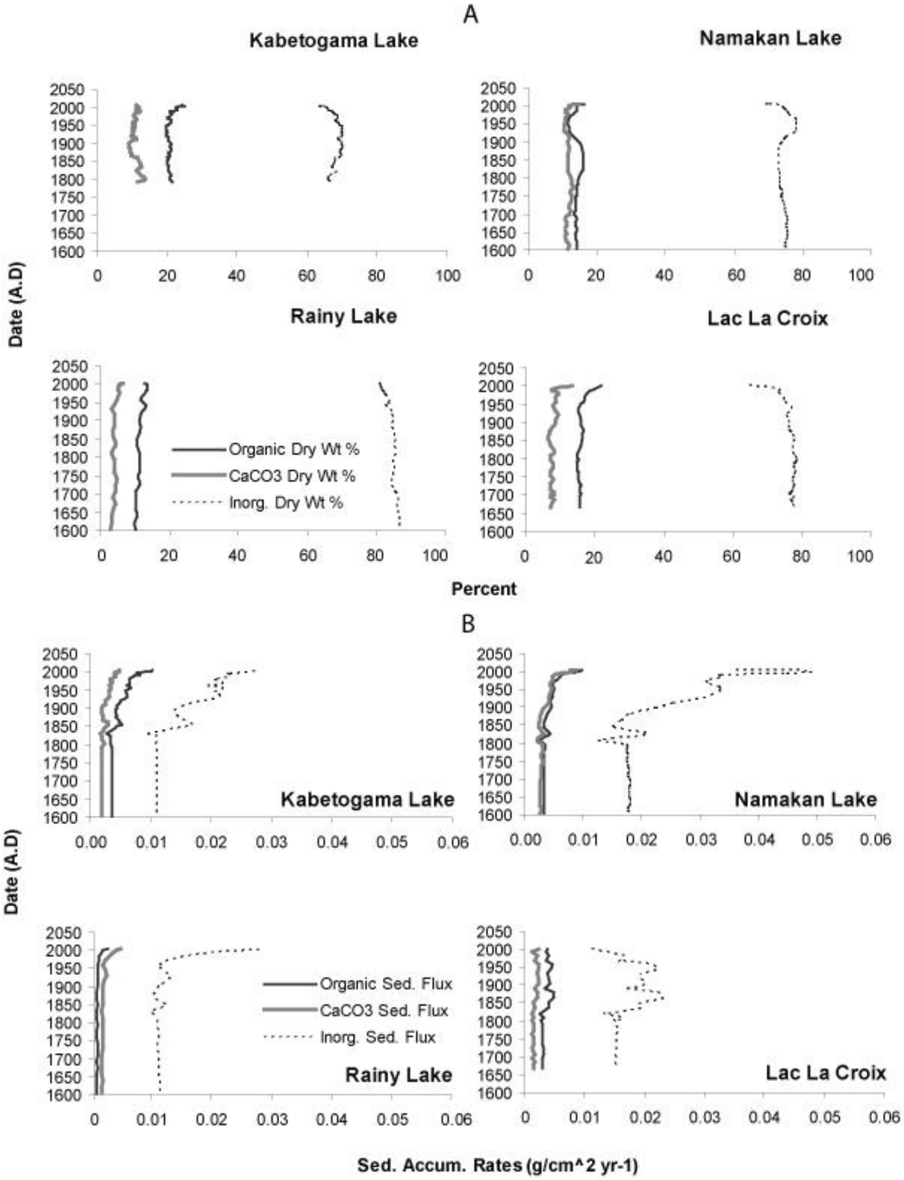


Figure 5. A. Inorganic, organic and calcium carbonate content of Kabetogama Lake Namakan Lake, Rainy Lake and Lac La Croix sediments determined by loss on ignition. B. Sediment flux of inorganics, organics, and carbonates in Kabetogama Lake, Namakan Lake, Rainy Lake and Lac La Croix.

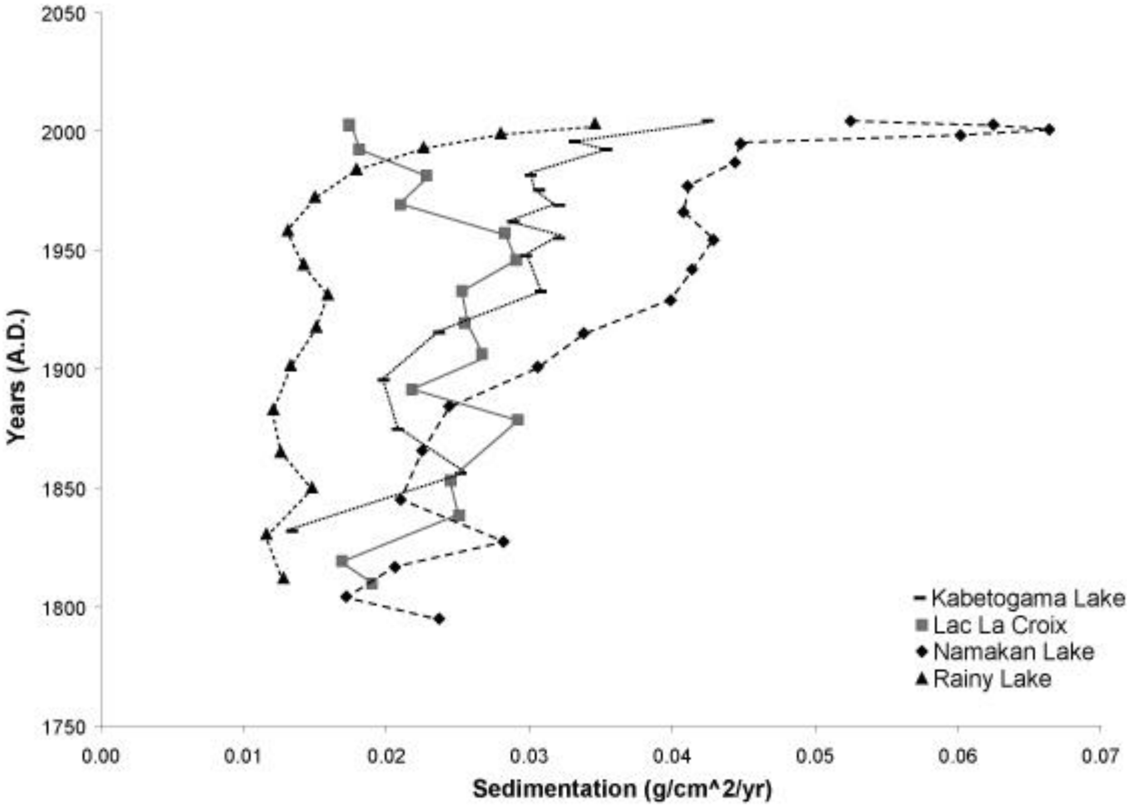


Figure 6. Sediment accumulation rate through time in Kabetogama Lake, Namakan Lake, Rainy Lake and Lac La Croix. Note increased sediment accumulation rates in Kabetogama Lake and Namakan Lake after damming and eventually Rainy Lake.

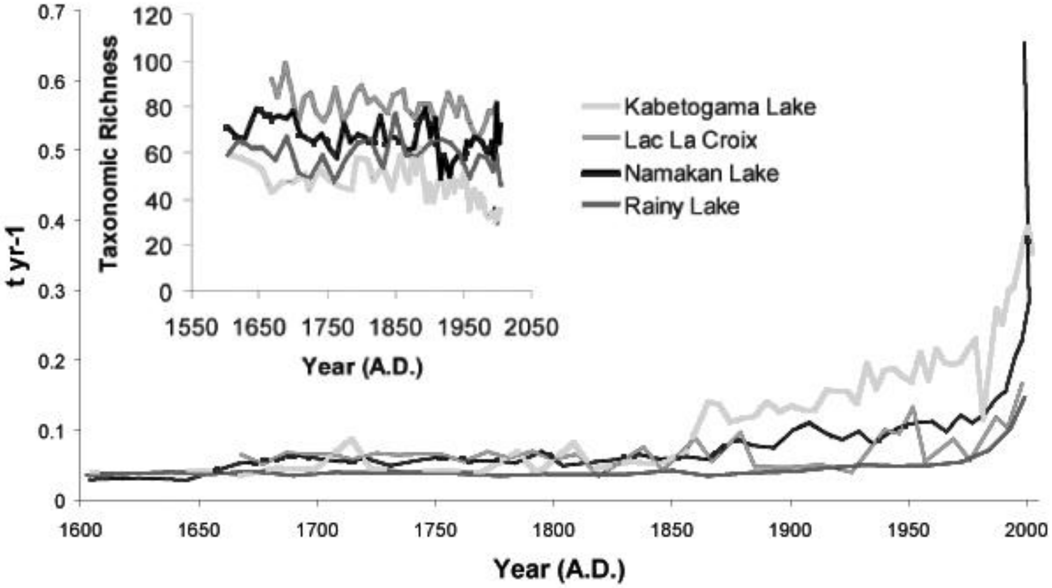


Figure 7. Taxonomic richness (S) and species turnover (t) of diatoms in Kabetogama Lake, Namakan Lake, Rainy Lake and Lac La Croix through time.

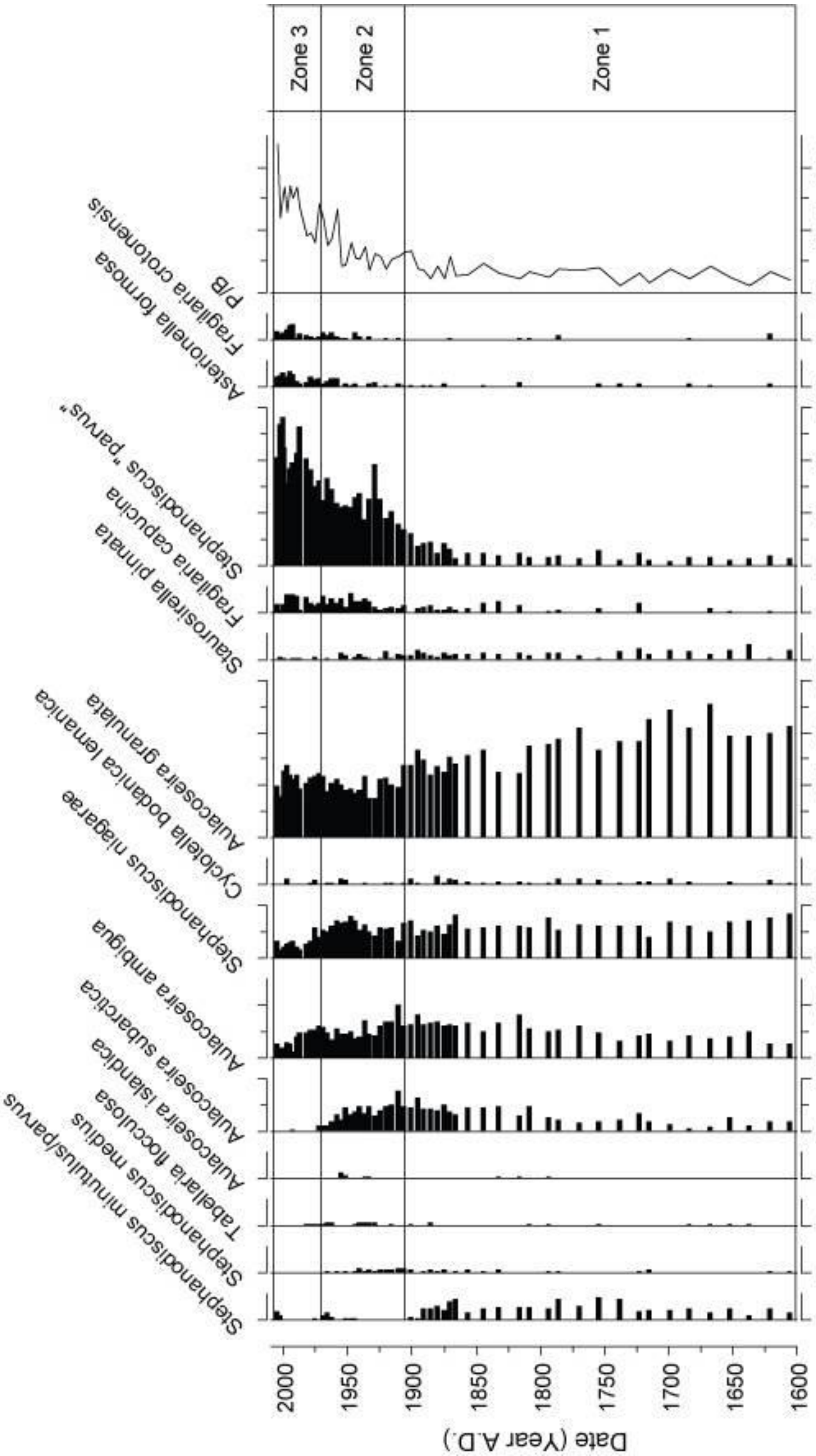


Figure 8. Relative abundance of dominant diatom taxa and planktonic to benthic (P/B) ratio from Kabetogama Lake core, 1600-2005 A.D. Biostratigraphic zones as determined by CONISS denoted in right panel. Taxa occurred in at least one sample at ≥2 % relative abundance. *Stephanodiscus "parvus"* was originally named *S. voya1*. However, while reconstructing phosphorus and conducting, we compared

our specimen to diatoms in our calibration set and determined that it was best considered *S. parvus*.

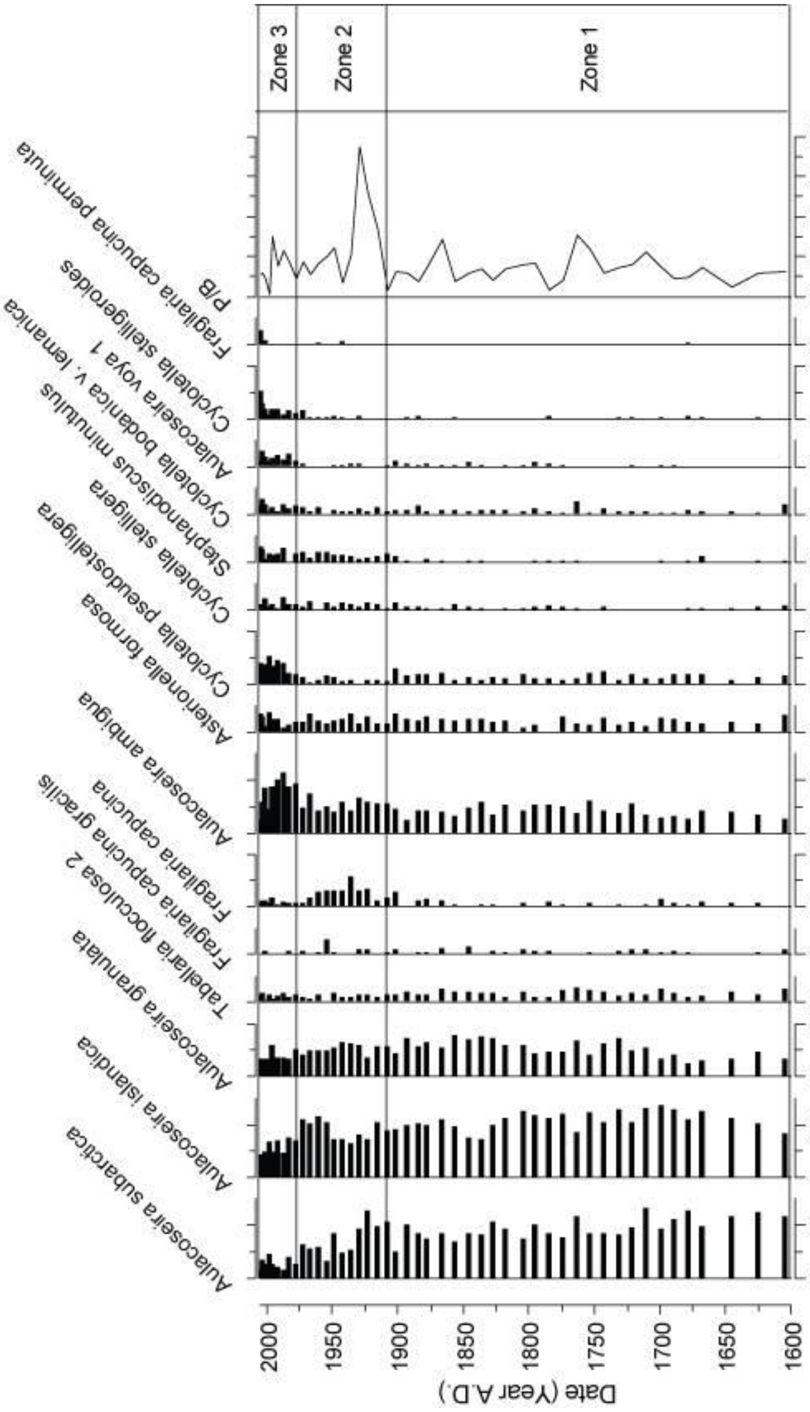


Figure 9. Relative abundance of diatom taxa and P/B ratio from Namakan Lake core, 1600-2005 A.D. See Fig. 8 for details.

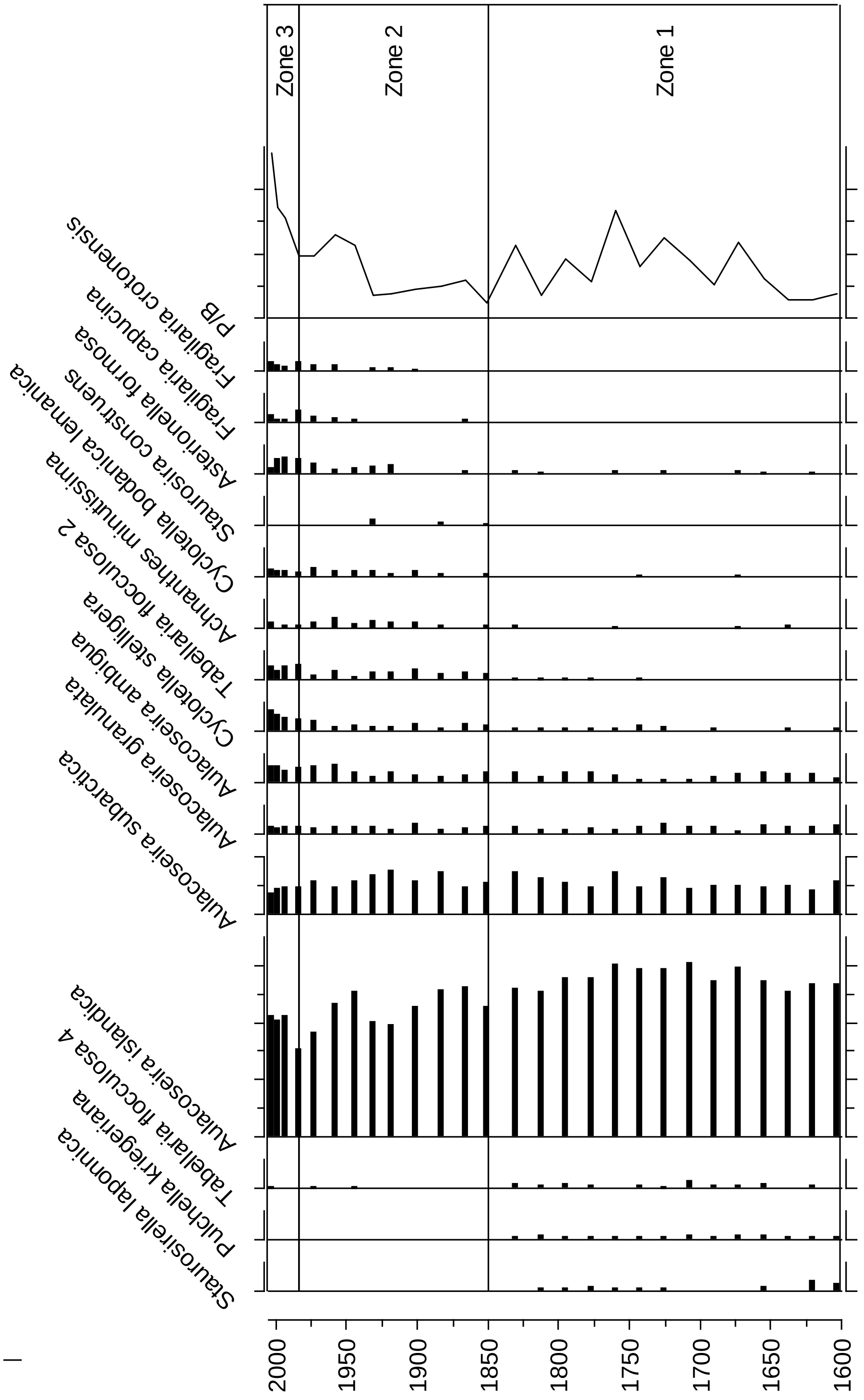


Figure 10. Relative abundance of diatom taxa and P/B ratio from Rainy Lake core, 1600-2005 A.D. See Fig. 8 for details.

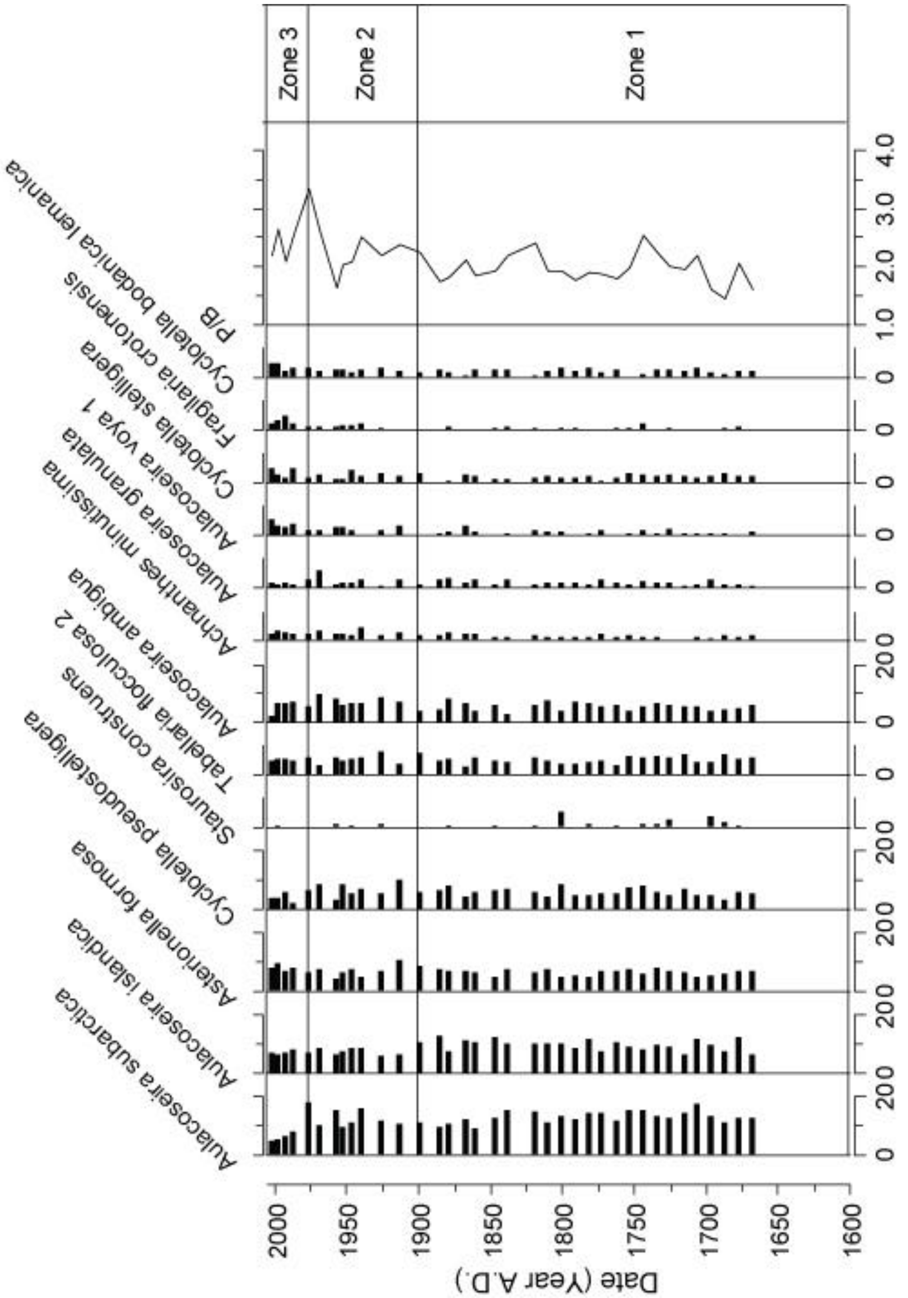


Figure 11. Relative abundance of diatom taxa and P/B ratio from Lac La Croix, 1668-2005 A.D. See Fig. 8 for details.

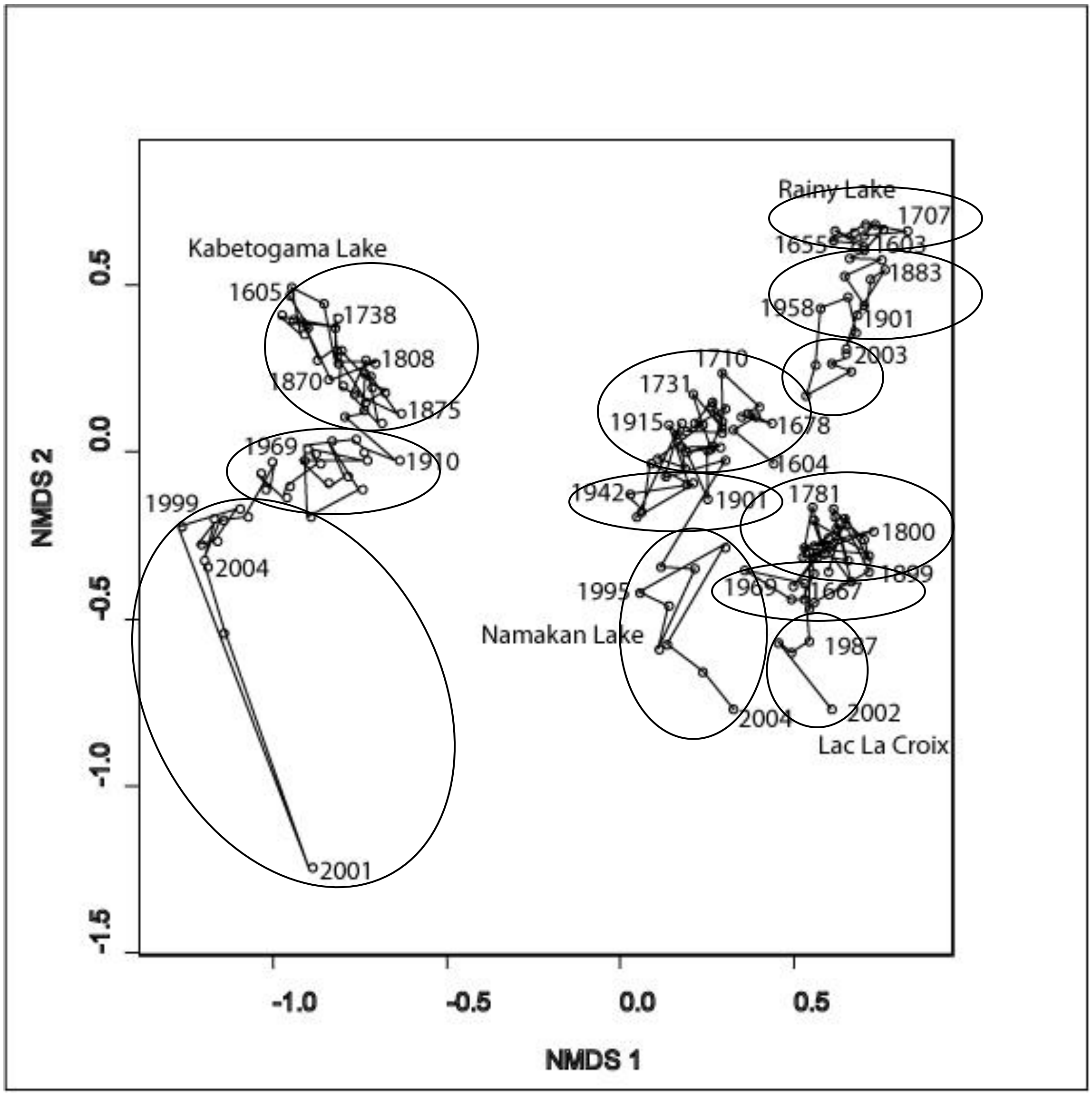


Figure 12. Non-metric Multidimensional Scaling (NMS) analysis displaying dated samples from Kabetogama Lake, Namakan Lake, Rainy Lake and Lac La Croix. Line segments connect samples in each core in chronological order. Circled clusters of samples represent diatom biostratigraphic zones in each core identified using CONISS as first order and second order zones. Shifts between clusters represent periods of significant change in diatom communities.

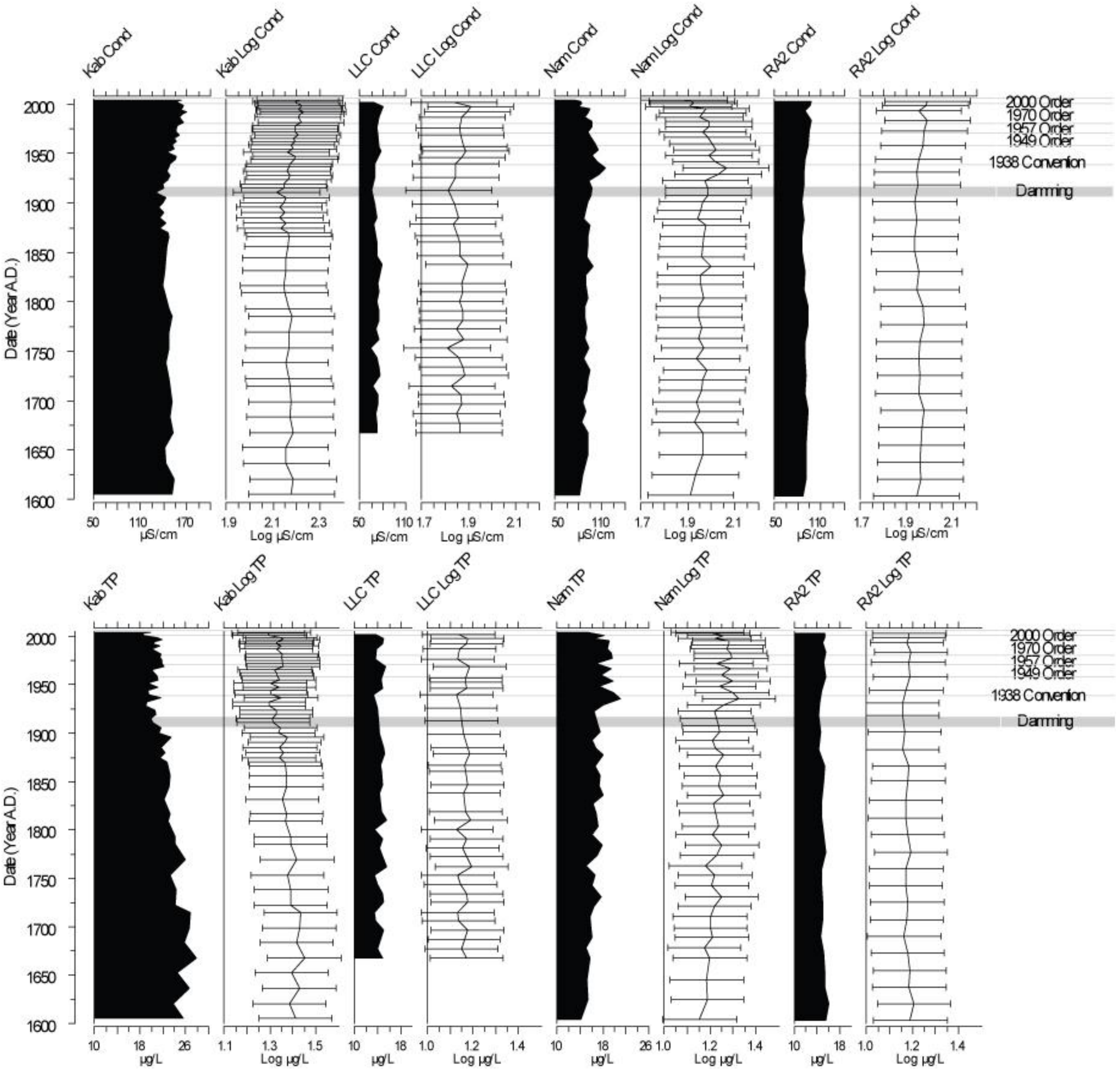


Figure 13. Diatom-inferred conductivity (Cond) and total phosphorus (TP) reconstructions for Kabetogama Lake (KAB), Namakan Lake (NAM), Rainy Lake (RA2) and Lac La Croix (LLC) along with their reconstruction error. Damming and hydromanagement periods impacting Kabetogama Lake, Namakan Lake and Rainy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

Chapter 4: Climate Change and Water Governance: a Case Study of the International Joint Commission

Governance has been identified by many scholars as a challenge to managing natural resources in a sustainable way. In addition, climate change is impacting natural resources, and complicating management. In light of these concerns, it is important that key characteristics of sustainable management not be ignored. Scientific legitimacy, integrative ecosystem approach, long-term monitoring and pro-active governance are all important characteristics of successful sustainable management plans. However, these characteristics have not all been included in the day-to-day functioning of the International Joint Commission. This paper looks specifically at the key characteristics required for sustainable management of transboundary water resources and determines if the International Joint Commission, and particularly the International Rainy Lake Board of Control, are applying them to policies for regulation and management of border waters shared by Ontario (Canada) and Minnesota (USA).

Introduction

Water resources, specifically freshwater resources, are essential to humans and ecosystems but these resources are also vulnerable to climate change, which affects both the chemical and physical attributes of water resources (Bates *et al.*, 2008), through changes in temperature norms, precipitation patterns, snowmelt, runoff, evaporation and soil moisture as well as the frequency of disturbances, such as drought, and severe storms, among other factors (Schimel *et al.*, 2008). All of these changes have direct and indirect effects on water resources, humans (Falkenmark *et al.*, 2004), and the ecosystems that are dependent on the resource (Lettenmaier *et al.*, 2008). This vulnerability to climate change can be a barrier to effective long-range planning and management of water resources (Draper and Kundell, 2007).

In developed countries, most water management systems run under the assumption of "stationarity", the idea that natural systems fluctuate within a certain range of variability (Milly *et al.*, 2008). This assumption results in a "wait and see" approach to water governance and management of water resources. A "wait and see" approach will not be an effective strategy to deal with the uncertainty of climate change (Milly *et al.,* 2008).

Furthermore, several studies have identified current governance institutions as one of the primary reasons why natural resources are managed in unsustainable ways (Dietz et al., 2003; Ostrom et al., 2003; Veeman and Politylo, 2003; Fischer, 2007 *et al.*). Water resource governance, as the Global Water Partnership (2002) defines it, is "the range of political, social, economic and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society." Scholars and practitioners alike call for water resource governance, especially under climate change conditions, to be both pro-active and sustainable.

In the past, various arguments have existed about how water-sharing states should govern their resources. The Harmon Doctrine (1896) claimed that water resources within sovereign territories should be used without any restrictions; this is also known as the "territorial sovereignty theory" (Shiva, 2002). In contrast, "the doctrine of absolute territorial integrity" gave rights to downstream riparian states and therefore restricted the use of water “to not cause harm to other countries sharing the water” (Kliot, 2000). This concept of “no harm” also emerged in the International Law Association’s Helsinki Rules in 1966 (International Law Association, 1966) and the International Law Commission’s “Law of Non-Navigational Uses of International Watercourse” in 1997 (International Law Commission, 1997). Both of these agreements targeted international audiences, and primarily focused on measures to avoid international conflicts over water. Even though sustainability was introduced in both documents, it was a minor component compared to the focus on human needs. For example, Article 7 of “Law of Non-Navigational Uses of International Watercourse” focuses on the obligation not to cause harm. Article 7.1 states that “Watercourse States shall, in utilizing an international watercourse in their territories, take all appropriate measures to prevent the causing of significant harm to other watercourse States” (International Law Commission, 1997). There is no mention of harm to the water resources. Both doctrines represent anthropocentric views.

In recent years, new rules and statements emerged beginning with the Dublin Statement on Water and the Environment of 1992. Significant goals were established in regards to water governance (Rogers and Hall, 2003). For example, principle 2 of the Dublin Statement states that “Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels.” This was also reflected when the International Law Association revised the Helsinki Rules and established the Berlin Rules in 2004 (International Law Association, 2004). The Berlin Rules specifically looked at all water resources and developed principles that provided: (1) the right of public participation, (2) the obligation to use best efforts to achieve both conjunctive and integrated management of waters, and (3) duties to achieve sustainability and the minimization of environmental harm.

Scholars have also developed guidelines promoting sustainable governance for common pool resources (Dietz *et al.*, 2003), earth systems (Biermann, 2007) and water resources (Falkenmark *et al.*, 2004; Hall, 2005; Mandarano *et al.*, 2008; GWP, 2009; Zawahri, 2009). These guidelines focus on attributes of authority and administration that will strengthen water resource governance. The "Authority" is the designation of the person(s)/institution that is legally responsible for the resource and is capable of making binding decisions. The "Administration" is delegated responsibilities for implementing the policies and decisions, coordinating activities, and mediating conflicts over the resource, specifying what is done to achieve the policy goals. The Administration administers the regulatory systems, programs, infrastructure, and conflict management processes. Both authority and administration are necessary in order to achieve sustainable governance of resources.

In addition, sustainable water management requires pro-active governance with inclusive, transparent and flexible characteristics. Early inclusion of all stakeholders allows concerns to be raised early and therefore actively develop decisions that will not create undesired tensions (Rogers and Hall, 2003). Transparency allows the public to hold an organization accountable and for downfalls to be quickly identified (GWP, 2009). These problems can be quickly acted upon and therefore prevent conflicts. With local and national authorities changing continually, governance also needs to be flexible towards the changes in society and therefore, needs to be flexible in its decisions (Mandarano *et al*., 2008). When new scientific findings come to light, decisions may need to be modified to increase the effectiveness of the programs and ultimately the end goals.

While governance needs to be proactive, it also needs to incorporate sustainable practices. Sustainable management needs to be supported by scientific legitimacy and long-term planning within an integrated ecosystem approach. Scientific legitimacy is important when making decisions as it will allow decision makers to have better knowledge of the system and therefore develop policies or decisions that will minimize impacts (Falkenmark *et al.*, 2004). These decisions also have to consider generations to come. Reactionary decisions that are made on the basis of short-term solutions could result in long-term damages. For example, in Arizona, where water resources are scarce, more and more communities are drilling wells to access water stored underground. Even though they can access the water now and use it, well drillers have not considered the long-term effects of their unregulated pumping such as aquifer collapse (McKinnon, 2009). Therefore, it is important to incorporate long-term thinking when making sustainable decisions (Dietz, 2003).

Finally, sustainable decisions need to consider the problem via an ecosystem approach. Changes made on land can have wide-ranging effects on lake ecosystems (Ramstack *et al.*, 2004). Many studies have documented anthropogenic impacts on water quality in lakes and streams (e.g., Hall and Smol, 1996; Hall *et al.*, 1999; Quinlan *et al.*, 2002; Ramstack *et al.*, 2004; Pienitz *et al.*, 2006; Smol, 2008). Changes in the water quality vary from chemical changes to biological community shifts. Thus, it is important to have a full understanding of how decisions can impact the whole ecosystem. These characteristics along with pro-active governance are necessities for sustainable water resource management.

In this paper, I develop the key concepts required for sustainable management of water resources in light of climate change. First, I present a framework for discussing international water governance (Figure 2). Then, I evaluate the governance of the International Joint Commission (IJC; the regulatory authority for Canada:USA transboundary resources) with regard to (1) how they have managed water resources and (2) how responsive the IJC was to the effects of climate change, while at the same time promoting sustainable water use. I use the case of the Rainy Lake - Namakan Reservoir region (Ontario, Canada and Minnesota, USA) to explore these ideas. This paper fills a gap in the literature by identifying the main sustainable management criteria and evaluating whether the IJC followed these criteria. This is an important contribution because researchers have discovered that climate change is impacting our resources and because poor governance has been identified as the primary reason why water resources are not managed in a sustainable manner.

International Water Governance through Authority and Administration

As diagramed in the Transboundary Water Resources Framework, there are several critical characteristics of sustainable water governance and management based on a clear articulation of authority and adminstration (Figure 1). Authority includes the legal right to govern as expressed in a law, treaty, and/or joint agreement as well as designation of the party with decision making power based on the legal document. This authority is often delegated to an administrative body for water resource programs to implement governance, conflict management procedures, and sustainable resource management.

A strong foundation of authority and administration are keys to a successful water management program (Figure 1). The authority is recognized as the political body having the right to govern over a water resource (Roseneau, 2003) and issue directives regarding that resource. Governance is especially problematic in the U.S. as documented by Mandarano *et al.* (2008) given the lack of clear authority in managing interstate water resources. Watershed basins are usually not self-contained within a political boundary; instead, watersheds may flow through several political boundaries.

An authority can be formalized via the establishment of an institution such as a commission or board through a constitution and bylaws, which is then legitimized through the signing of treaties and agreements by the relevant parties (Conca, 2006; Conca *et al.*, 2006; Zawahri, 2009). For example, Rhine River riparian governments established the International Commission for the Protection of the Rhine by signing the Bern Convention in 1963. In developing an authority, governments allow the authority to “monitor member’s activities, make commitments more credible, sanction defectors, lower transaction costs and gather information” (Zawahri, 2009) as well as meet changing conditions (Mandarano *et al*, 2008). The Permanent Indus Commission (PIC) was able to monitor both India’s and Pakistan’s activities throughout several wars and was able to overcome individual state’s fears of cheating by communicating directly with the states for over 40 years (Zawahri, 2009). During war years, the Commission’s programs were reduced but officials were still able to meet and schedule inspections, rising above the deterioration of bilateral relations between India and Pakistan.

Another requirement for the authority is to manage multiple water purposes, as this type of authority has proven to be more successful (Sherk, 2005; Mandarano *et al.*, 2008). For example, the Agences de l’Eau in France (Water Agencies) manage water resources to preserve and improve water quality, fight against pollution, improve knowledge of the resource, monitor the resource, and educate the public. They also are responsible for fiscal “water” works within their hydrological basins. They have been managing the water resources in their respective regions for over 20 years.

Once the authority has been identified, its administrative function needs to be outlined and should aim to manage multiple water purposes. The administration part of governance helps the authority achieve its goals. It includes a regulation system and programs, an infrastructure (physical and technological), and often a conflict management process for addressing disputes among parties. The regulatory system gives the authority tools prescribing how decisions can be and should be reached and implemented. It should also include a rule compliance mechanism (Dietz *et al.*, 2003) that acts as deterrence to “breaking the law.” The administration also hosts the different programs for water resource management from biological monitoring of the systo public education. For example, the Convention for the Protection of the Rhine River

(ICPR, 1963) outlines in Article 10 the decision-making process of the International Commission for the Protection of the Rhine (ICPR), and Article 11 outlines implementation procedures. The ICPR's administration also coordinates six different working groups which could be seen as programs, ranging from a group that focuses on micropollutants all the way to one that focuses on the economy.

Physical and technological infrastructure can assist governance by developing a governing institution with basin-wide presence (Dietz, 2003). Infrastructure can also facilitate effective communication among all governance levels (local to transnational), provide tools for decision-analysis, and a place of work that is dedicated to their mission. An infrastructure solidifies the working of the authority but requires a dedicated budget. Without a permanent budget, the working of the administration can be dampened and priorities challenged. In creating a permanent budget, the administration can work efficiently and stay focused on the issues that come to hand. The administration does not have to spend human resources applying for or finding money that would be used to fund research, staff, and facilities or even prescribing which programs should be funded or not. Instead, having a permanent budget would allow for more effective water management.

Characteristics of Sustainable Water Resource Management

Pro-active governance (inclusive, transparent, and flexible)

Inclusive water governance needs to include all stakeholders within the basin. For example, interstate water resources require a form of governance that can achieve collaboration among different agencies at both the state and national level (Mandarano *et al.*, 2008). Inclusive water governance also requires the local “civil society” to be involved (Biermann, 2007). These beliefs were further reinforced in the 2000 Hague Ministerial Declaration, which stated public involvement and stakeholder interest have to be part of water resource management in order for governance to be effective (Rogers and Hall, 2003). Ostrum *et al.* (1999) also pointed out that management of freshwater resources depends on the cooperation of appropriate international institutions (when the resource is international) and national, regional, and local institutions. Thus, involving the civil society can create “local watchdogs” that can monitor and support government actions and policies, help regulate public-private arrangements to overcome some of the institutional weakness at higher tiers of authority, and ease the resolution of water conflicts (Hall, 2005) along with bridging the gap between science, policy and the public sphere. For example, in Minnesota (US), watershed districts are required to have a Citizen Advisory Committee (CAC). According to the Watershed District Act, Minnesota Statute 103D. 331, the CAC is made up of district residents and their role is to consider issues that are pertinent to the district, and review and comment on the working of the managers in charge of managing the watershed. The CAC is in this sense the “local watch-dog.” By having stakeholders involved in water resource management, the credibility of the authority can be strengthened.

To further reinforce credibility, the institution should be open and transparent (GWP, 2009). Because water resources tend to be transboundary at local and national levels, vulnerable relationships can be created between authorities (Priscoli, 1998;

Priscoli & Llama, 2001; Zawahri, 2009). These vulnerabilities emerge when negative impacts occur and the cause(s) are not revealed to or accepted by the injured party. For example, the dumping of toxic materials upstream affects the riparian system downstream and creates tensions between the up and downstream governing authorities. In order to minimize these tensions, states must communicate (Priscoli, 1996, 1998; Zawahri, 2009) and resolve differing perspectives.

Stakeholders have a clearer image of what the governing system is doing when a transparent communication system is in place. It lessens the notion of mistrust and encourages interactions among parties. Furthermore, it is important for the institution to bridge the gap between the scientific, political and public spheres (Rofougaran and Karl, 2005). One way to bridge the gap is to ensure that the institutions clearly communicate with and educate the public on the reasons for their rulings. The bottled water debate is a clear example of how institutions responsible for distributing tap water have failed to communicate to their users on their effective water processing capabilities. Many citizens do not realize that bottled water is poorly regulated (Parag and Roberts, 2009), and is sometimes only tap water placed in a bottle (Splash report, 2003). Parag and Roberts (2009) explain that increasing bottled water consumption is not only linked to better advertisement by bottling companies but also “the growing distrust of tap-water quality and the state’s ability to protect the health of its citizens.” The authors suggest that public involvement, transparency and better science communication are some institutional and procedural changes required to restore trust. Clearly, if the institution responsible for distributing tap water had a more transparent communication system that was bridging the gap between the science and the public, this mistrust and misuse of water resources could have possibly been avoided.

The administrative function of governance must be designed to permit flexibility. Participants, programs and rules/policies have to be flexible in order to meet the needs and changes in political ideologies at the state and federal levels (Mandarano *et al*., 2008), and also respond quickly to new scientific findings (Dietz, 2003; Bookman and Turner 2006; Biermann, 2007). Drieschova *et al.* (2008) argue that the tensions over the 1944 treaty between the U.S. and Mexico are due to the lack of flexibility. The tensions grew because Mexico fell behind on its required water deliveries to the United States (Phillips, 2002). As per the treaty, Mexico had to make up the water deficit within the next five year ‘billing’ cycle. However, during that time Mexico was still in a drought. Disputes rose between the nations in regards to the timing of repayment. Thus, it is important for institutional regimes to be flexible in order to meet changing and unpredictable conditions and therefore promote sustainable water management.

Finally, water administrations must have rules that clearly outline how the parties will address disputes (Hall, 2005; GWP, 2009). Conflict management processes facilitate cooperation/collaboration and promote peaceful resource management (Priscoli, 1996; Giordano *et al.*, 2005; Zawahri, 2009). Zawahri (2009) discussed how the Permanent Indus Commission has, for over 40 years, peacefully managed the Indus River System and used several conflict management processes to resolve conflicts once they arose. The Permanent Indus Commission has scheduled a series of meetings in order for negotiations to be successful. In situations when they are unable to manage the conflict, they call upon a foreign secretary board to intervene. If this fails, a neutral expert will attempt to negotiate. The next level of management is a court of arbitration of seven judges. In addition, conflict management processes need to be fair and effective as they are important components of robust institutions (Ostrum, 1990; Johnson and Nelson, 2004).

Sustainable Management: Monitoring to Support an Integrated Approach

To increase sustainability over time, resource monitoring (both environmental and biological) has always been an important activity that can be used to support decision making and design of effective programs. However, today it is even more important as climate patterns are changing and the impacts are less predictable. Monitoring of the resource can provide the managers and stakeholders early indications of resource health. Without environmental monitoring data, trends would not be identified and forecasting models could not be developed and used for prediction. In 1999, the World Bank funded the Water and Environmental Management of the Aral Sea Basin Project. One of the key components for the project was transboundary monitoring. Data from the monitoring stations were useful for more effective management of the irrigated systems. The monitoring component for the project was so successful that more funds were allocated to it and 12 additional international monitoring sites were constructed. Data from these stations are actively used to improve the timing and scheduling of irrigation releases (The World Bank, 2004).

Water related problems are becoming increasingly complex which demands an integrated ecosystem approach to management. A recent study by Hall *et al.* (1999)

discovered that changes in biological communities were not only linked to climate but also urbanization and agriculture. Thus, it is important to have an integrated understanding of the ecosystem. As Falkenmark *et al.* (2004) explain, water scientists need to interact with a large number of other scientists, (*e.g.* agricultural, medical, social, economic, ecological and environmental) along with water law makers and geophysical scientists. However, the dominant approach to water management is a single-discipline approach (Falkenmark *et al.*, 2004). For example, public works would be more concerned with water allocation, whereas parks and recreation might visualize the resource more in terms of recreation. This approach does not allow a complete understanding of all aspects affecting the water resource; reducing the capacity for prediction and ultimate prevention of adverse effects. Thus, in order for water resources to be managed in a sustainable way, all aspects of the water resource system must be considered and an integrated ecosystem approach must be used.

Case Study: The International Joint Commission and the International Rainy Lake Board of Control

History and Establishment of the Authority

The Boundary Waters Treaty between the United States and Canada established in 1909 the International Joint Commission (IJC), the authority over shared water resources. The charge for the authority was to prevent and resolve conflicts over the use and quality of the freshwater (inland waters) shared by Canada and the USA. Since its inception, the IJC created several boards to carry out its responsibilities (IJC, 2009). One of these boards is the International Rainy Lake Board of Control (IRLBC). The

IRLBC acts as the administration for the Rainy Lake Basin region (Figure 1, 2); it was designed to help manage the border waters of Rainy Lake and Namakan Reservoir both of which were impounded at the start of the 20th century to insure minimal flow for power generation all year round. At first, the dams were operated in a “manage as we go” fashion by the American and Canadian lumber companies who owned the dams. However, in 1925 after several damaging flood events, the IJC was asked to become involved.

Since 1925, the IJC has implemented a number of regulations (Table 1). The first new regulations were spelled out in the 1940 Convention, which assigned the IJC as the legal authority for controlling the Rainy Lake Basin under emergency conditions. Next, the 1949 Order, which was based on findings of the International Rainy Lake Board of Control, established in 1941, proposed regulations in regards to extreme water-level events in Rainy Lake. The 1949 Order required dam owners to manage the water-levels to closely mimic the single rule curve. The single rule curve provided a reference for minimum water-levels behind the dams throughout the year.

However, in 1957, a supplementary order was implemented in response to excessive spring runoff in 1950 and 1954. No change was made to the Rainy Lake single rule curve but a maximum rule curve was added for the Namakan Reservoir creating a rule curve band (a minimum and maximum water level). Finally, due to high and low water events between 1957 and 1968, the 1970 Order implemented a rule curve band for Rainy Lake and amended the rule curves for Namakan Reservoir.

The 1970 order was sustained until 2000 when a new supplemental order was implemented. The modification to the order was initiated when an *ad hoc* group made up of United States and Canadian citizens, known as the Rainy-Namakan Water Level International Steering Committee, determined that the current (1970) order negatively impacted biological communities. In response, the 2000 Order was adopted by the IJC stating that the Commission:

> "continue to carry out its responsibilities under the 1938 Convention for avoiding emergency conditions by instituting rule curves and other requirements which provide a careful balance between upstream and downstream concerns, and among the various interests, including environmental concerns, hydropower, flood risk, and boating. The draft Supplementary Order also takes into account improvements to water quality in the Rainy River allowing lower discharges under low-flow conditions than were previously desirable." (IJC 2000)

Furthermore, the 2000 Order stipulated that the biological communities and their habitats be monitored by resource management agencies to determine biological response to the new water-level manipulations. Since 2000, no modifications have been prescribed to the supplemental order. Instead, a Rule Curve Assessment Work Group was formed and over the course of several workshops developed monitoring programs, protocols, and identified funding sources. Since 2000 a number of studies were implemented (IJC, 2008), most of which focused on the effects of water-level fluctuation on biological communities and specific organisms such as loons, muskrats, wetland vegetation, etc. (IRRWPB/IRLBC, 2006, 2007, 2008); other studies in the basin focused on mercury uptake in prey fish and trophic state indicators (IRLBC, 2003)

In 2008, at a gap analysis workshop, managers, scientists, and local residents developed a plan of study for the coming years and raised concerns about the potential termination of monitoring stations and long-term studies. The importance of monitoring stations and long term studies was reiterated during the International Lake of the Woods Water Quality Forum in 2008 and 2009, in part because there was increasing evidence of climate change effects within the region (ILWWQF, 2009).

Climate Change in Rainy Lake-Namakan Reservoir Region

As previously mentioned, the Rainy Lake – Namakan Reservoir Region, located at US-Canadian border of Minnesota and Ontario and in and near Voyageurs National Park, has not been immune to climate change. Moin (2008) and the IJC (2009b) indicated that the US-Canada border area may experience climate change. Serieyssol *et al.* (2009) showed that mean winter air temperature records from Kenora, Ontario, located less than 100 km north-west of International Falls, Minnesota, showed an increase in seasonal winter temperatures post-1970 and were correlated with biological changes in the border lakes. This change in winter temperature is reflected in earlier ice-out dates and later ice-in dates (Kallemeyn *et al.*, 2003). Jensen *et al.* (2007) identified a similar trend in the Laurentian Great Lakes, as did Johnson and Stefan (2006) in Minnesota, and Kallemeyn *et al.* (2003) in Voyageurs National Park, where Rainy Lake and Namakan Reservoir are located.

Forecasting models predict Minnesota temperature increases of up to four degrees Fahrenheit by 2100 (EPA, 1997). Clearly, climate change is occurring in Minnesota (Johnson and Stefan, 2006) and will continue (EPA, 1997). In addition, the EPA anticipates Minnesota precipitation will increase by 15% in winter, summer, and fall (EPA, 1997). Recently, Serieyssol *et al.* (in prep.) identified an increase in precipitation during the fall season at International Falls, Minnesota. These changes in temperature and precipitation may increase runoff and drought events in Minnesota (EPA, 1997). Furthermore, ecosystem boundaries could shift north and biological communities may change. Serieyssol *et al.* (2009 and in prep.) identified diatom community changes related to climate change. Clearly, climate change is occurring in the region and affecting the resources, but is the IJC prepared for it?

Recommendations for Sustainable Management in the Rainy Lake-Namakan Reservoir Region

In 2009, the Boundary Waters Treaty (BWT) of 1909 celebrated a "century of cooperation protecting our shared waters" (IJC, 2009). The BWT established the IJC to investigate, resolve and prevent boundary water disputes between the United States and Canada and subsequently established the IRLBC in 1941 to help it carry out its responsibilities. In addition, the board actively participates in the International Watershed Initiative (IWI) which "promotes an integrated, ecosystem approach to issues arising in transboundary waters through enhanced local participation and strengthened local capacity." Conflict management and an integrated ecosystem approach are important when dealing with climate change. However, long-term monitoring cannot be ignored when managing for sustainability. As a result, I focused this investigation on (1) conflict management, (2) IWI approach and (3) long-term monitoring. All three elements are important for the sustainable, conflict-free management of water resources, particularly in the Rainy Lake- Namakan Reservoir Region of the IJC.

Conflict Management

Overall, only minor conflicts have occurred regarding the Rainy Lake-Namakan Reservoir. Most disputes have happened in regard to water-level changes and water quality. Disputes brought to the IJC have focused on adverse effects researchers have discovered, specifically that the regulated waters have negatively affected the aquatic biota since the dams were built (i.e. Sharp, 1941; Johnson *et al.*, 1966; Chevalier, 1977; Kraft, 1988; Kallemeyn *et al.*, 2003). These concerns have been raised by the National Park Service, since the creation of Voyageurs National Park in 1975 (Kallemeyn *et al.*, 2003).

However, in 1991, water-level concerns were raised again and could not be ignored, when the Rainy Lake and Namakan Reservoir International Steering Committee (RLNRISC) was formed. This committee was not affiliated with the IJC and included diverse stakeholders, including the United States and Canadian representatives from private industry, the public, and government agencies (including the scientific community). The task of the committee was to reach a consensus about how the lakes in the Rainy Lake-Namakan reservoir should be managed.

The committee undertook extensive analysis of scientific data, discussions, and public consultation (Kallemeyn *et al.*, 2003). Two years later, the RLNRISC submitted their report to the IJC suggesting that the 1970 Order should be modified. Specifically, the committee wanted to see earlier and greater low and high water-levels during the spring refill period, a reduction of the overall annual fluctuation (less extreme low and high water levels), and recommended the drawdown in the fall be more modest (IRLBC, 1999). A few months later, Boise Cascade Corporation, then owner of the dams and also a member of the RLNRISC, submitted a statement to the IJC against the modification of the 1970 Order. In 1995, the IJC requested that the IRLBC, the regional board supervising the management of the waters in that region, review the 1970 Order, because they are the final decision-making body. Four years later, the IRLBC recommended that the 1970 Order be modified. In 2000, the IJC issued a new supplementary order. It is important to note that throughout this time period, the IJC's governance remained re-active to disputes. The IJC was not promoting exchange between the public, industry and government; it was the stakeholders that initiated the interactions by developing on their own committee, the RLNRISC.

However, in 2003, in response to the dispute over water levels and consultation with stakeholders, the IJC finally recognized the importance of local stakeholders by expanding the IRLBC board to include two local residents; one from Canada and the other from the United States. Thus, the board went from two to four members with half of the membership representing local residents. To date, the board still includes two local residents along with two members from government agencies.

Furthermore, the board expanded their communication and outreach with the broader community. They initiated a quarterly website newsletter to inform the public of the board’s activities in 2003 (IRLBC/IRRWPB, 2003). They also published semi-annual reports, redesigned their website, developed workshops, attended local water related conferences and continued to hold annual public meetings. Since 2006, the board has worked to meet regularly with resource agencies. In addition, board members have had greater interaction amongst themselves, increasing their meetings from four in 2003 to seven in 2008. These pro-active gestures by the IJC promoted cooperation and collaboration between all involved parties. These processes were not only inclusive but also improved transparent communication, both key factors in managing conflicts. All these traits lead to collaborative decision making process. In addition, these characteristics have been further reinforced in the working of the IRLBC, as they are now part of the International Watersheds Initiative (IJC, 2009a), which requires the board to hold regular public hearings.

Integrated Ecosystem Approach

While conflict management is critical for water management, an integrated ecosystem approach is essential for sustainable management. The IJC developed the Integrated Watersheds Initiative (IWI) “to facilitate the development of watershed-specific responses to emerging challenges such as intensified population growth and urbanization, global climate change, changing uses of water, pollution from air and land, and introductions of exotic species” (IJC, 2009). The idea of this approach was first introduced in 1997. It was further developed in consultation with different governmental levels: states and provinces, First Nations, and local authorities. In 2005, the Rainy River was chosen as one of the pilot projects. Because the International Rainy River Water Pollution Board (IRRWPB) and the IRLBC work together closely, the IRLBC also became part of the IWI with the International Rainy River Water Pollution Board.

Since 2005, IJC commissioners have been working to strengthen this integrated watershed initiative. They meet yearly to develop and reinforce this initiative. The IJC also has supported this integrated ecosystem approach by providing funding for a better understanding of how the reservoir and Rainy River function together. In 2006, the IRRWPB and IRLBC established an informal working group made up of relevant stakeholders. The working group was tasked with developing cooperative mechanisms to balance hydropower and ecosystem needs, particularly during the fish spawning period. The working group agreed to establish an annual 2½ month period when no hydropower peakings would take place during the spawning season. Dam owners, natural resource specialist and other stakeholders were able to approach issues from all different angles.

Another example using an integrative approach took place at a recent "Rule Curve" workshop, sponsored by the IJC in March 2008. Representative from all fields (natural and social sciences) were asked to develop a gap analysis of what studies needed to be done for the evaluation of the 2000 Order in 2015. The workshop included culture specialists, dam engineers, provincial and state natural resources representatives, and aquatic ecologists. This inclusiveness allowed for a better understanding of the watershed’s ecosystem. Furthermore, in April 2008, both the International Rainy River Pollution Board and the IRLBC indicated to the IJC that they supported the merger of both boards. This merger would bring the two boards in the same watershed into one decision making unit which would allow a more comprehensive approach to water resources in the region.

It must also be noted that the IJC is still working on enhancing and strengthening the Integrative Watershed Initiative (IWI) boards. The IWI boards were developed to anticipate, prevent and resolve watershed disputes at a local level. This watershed approach recognizes the interconnections between land and water on a whole basin scale. In 2009, the IJC determined that the IWI was effective and is necessary especially in light of emerging issues such as climate change. The IWI functionings need to be flexible; each IWI board needs to be individualized to each local region so as to maximize local involvement (IJC, 2009a). IWI boards are also more cost-effective but will require further funding from the U.S. and Canada in order to develop this initiative. The IWI boards are cost-effective in that they link the boards with local groups on both side of the border. This allows communication to occur and ensures that duplicate projects are not implemented, and priority projects are initiated in an efficient matter.

Long-term Monitoring

Integrated ecosystem approach is not the only element required for sustainable management; long-term monitoring is equally important. When the IJC stipulated in its 2000 Order that resources should be monitored, a committee was formed to oversee development and implementation of a long-term monitoring program (15 years). The committee soon realized that "such a long-term monitoring program would require long-term commitments not only from the natural resource agencies, but also from industry, other agencies, and the public concerned with these significant water resources, and that obtaining the financial resources needed to support the program would be a significant and ongoing challenge (Kallemeyn *et al.*, 2003)". These concerns are consistently reflected in the joint semi-annual reports from the International Rainy River Water Pollution Board and the International Rainy Lake Board of Control (Annual Report 2000, 2002; Spring 2004; Fall 2005, 2006, 2007, 2008,). Lack of financial support for monitoring stations was again reiterated as a concern during an IJC rule curve workshop (IJC, 2008). Furthermore, even though focus has been on physico-biological-chemical monitoring, socio-economic monitoring is still lacking (IRRWPB/IRLBC, 2009).

Although the IJC encourages long-term monitoring, it has not provided long-term financial support. It has instead reiterated that environmental and natural resource agencies must "step up their support for IWI … by carrying out monitoring and analytical studies to provide essential baseline data and to discern and improve understanding of significant trends in transboundary basins" (IJC 2009a). With the 2009 down turn in the economy, monitoring resources are threatened. It is important for the IJC to not only support monitoring efforts verbally but also financially. Both biological, chemical, and socio-economic monitoring are extremely important in decision-making. The IJC needs to start thinking of how to allocate some of their budget to support these efforts. Gaps in monitoring data could lead to inefficient and reactive decisions rather than pro-active and sustainable policies.

Conclusions

Conflict management, integrative ecosystem approach and long-term monitoring are essential characteristics for sustainable water management. These elements are especially important due to the potential impacts of climate change. The International Joint Commission in the Rainy Lake-Namakan Reservoir Region has been quite successful for incorporating these characteristics in its working environment. However, it does not fully support the implementation of long-term monitoring efforts. The IJC has relied for several decades on the federal and state agencies on both sides of the border to fund monitoring stations. In order to promote sustainable management, the IJC needs to consider long-term funding for monitoring of the resource.

The management of transboundary freshwater resources under potential climate change is a global challenge. Transboundary water-managing organizations like the IJC will need to implement pro-active governance practices and ensure that they obtain or support long-term monitoring data collection. The data are important to making sustainable decisions and are integral to making integrated ecosystem decisions. Without these elements, tensions could arise, unsustainable decisions made, and valuable data lost or not collected. All these scenarios could lead to the breakdown of an organization that celebrated a century of cooperation protecting shared waters.

Table 1. Rainy Lake Basin administrative origin and history 1909 to 2009; water flow and regulation.

Year	**Decision**
1909	**Boundary Waters Treaty** *United States and Canada establish the International Joint Commission and define its role via the signing of the Boundary Waters Treaty*.
1909	**International Dam** *Dam completed at International Falls/Fort Frances.*
1914	**Canadian Dam and International Dam** *Dams completed at Kettle Falls.*
1925	**Rainy Lake Reference** *United States 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	**Final report for the Rainy Lake Reference** *IJC submits the final report for the Rainy Lake Reference to the United States and Canada.*
1940	**1940 Convention** *Governments ratified the report with the 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	**Rainy Lake Board of Control**

The IJC establishes the International Rainy Lake Board of Control and directed it to examine and report on emergency issues.

1949 **The 1949 Order**

The 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 **The 1957 Order**

The 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 **The 1970 Order**

The 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**

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.

1987-1995 **U.S Congress**

U. S. Congress passes and President signs an act requiring the dam operators to 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. 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, sponsored by Senator Wellstone, had a sunset provision that said it would remain in effect until the IJC reviewed and made a decision on the Steering Committee's recommendations.

2000 **2000 Order**

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 **Consolidated Order**

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.

2005 **Integrated Watershed Initiative**

The International Rainy Lake Board of Control and the International Rainy River Water Pollution Board take part in the IJC's Integrated Watershed Initiative

Modified from Larry Kallemeyn (personal communication 2007)

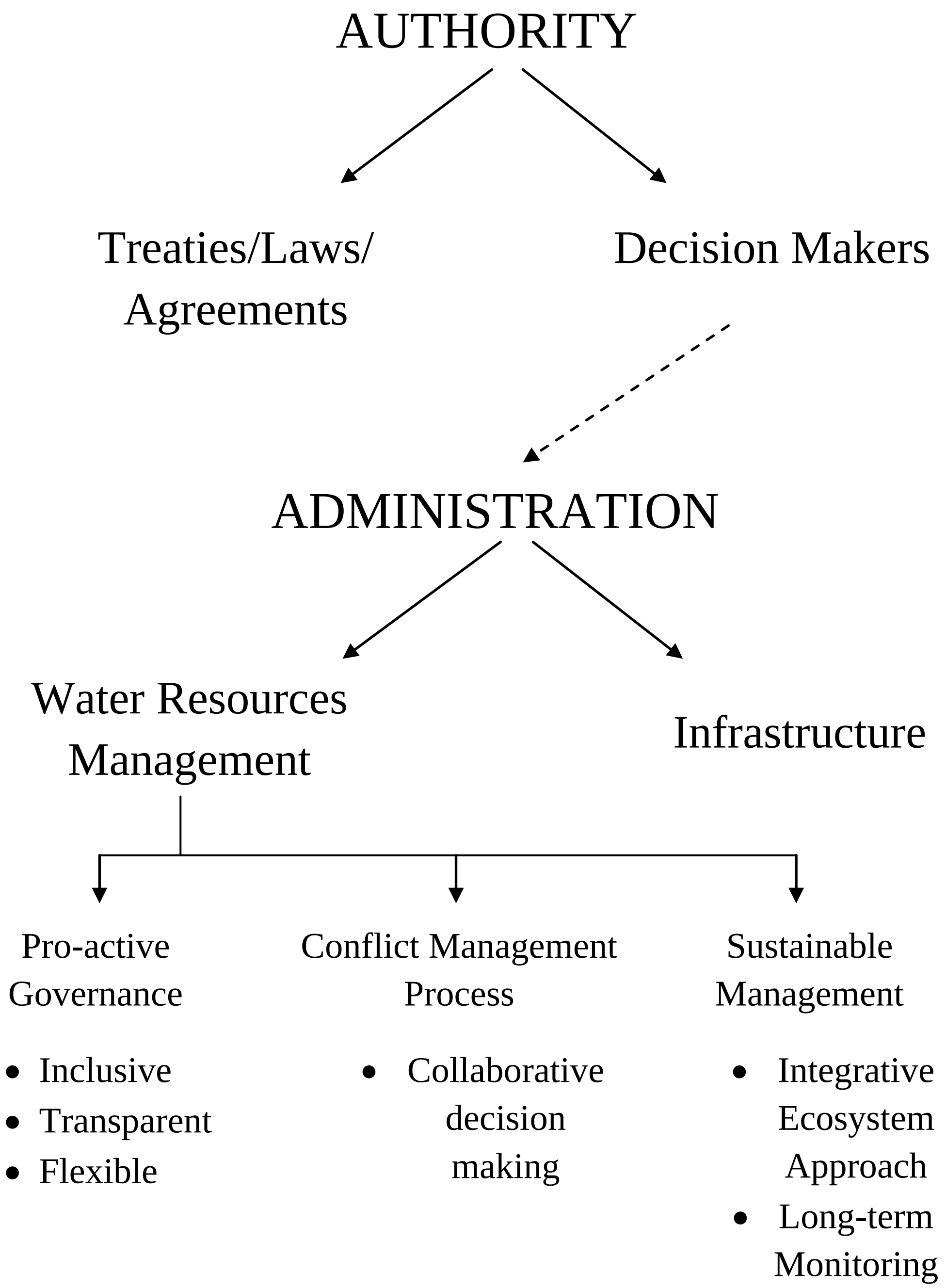
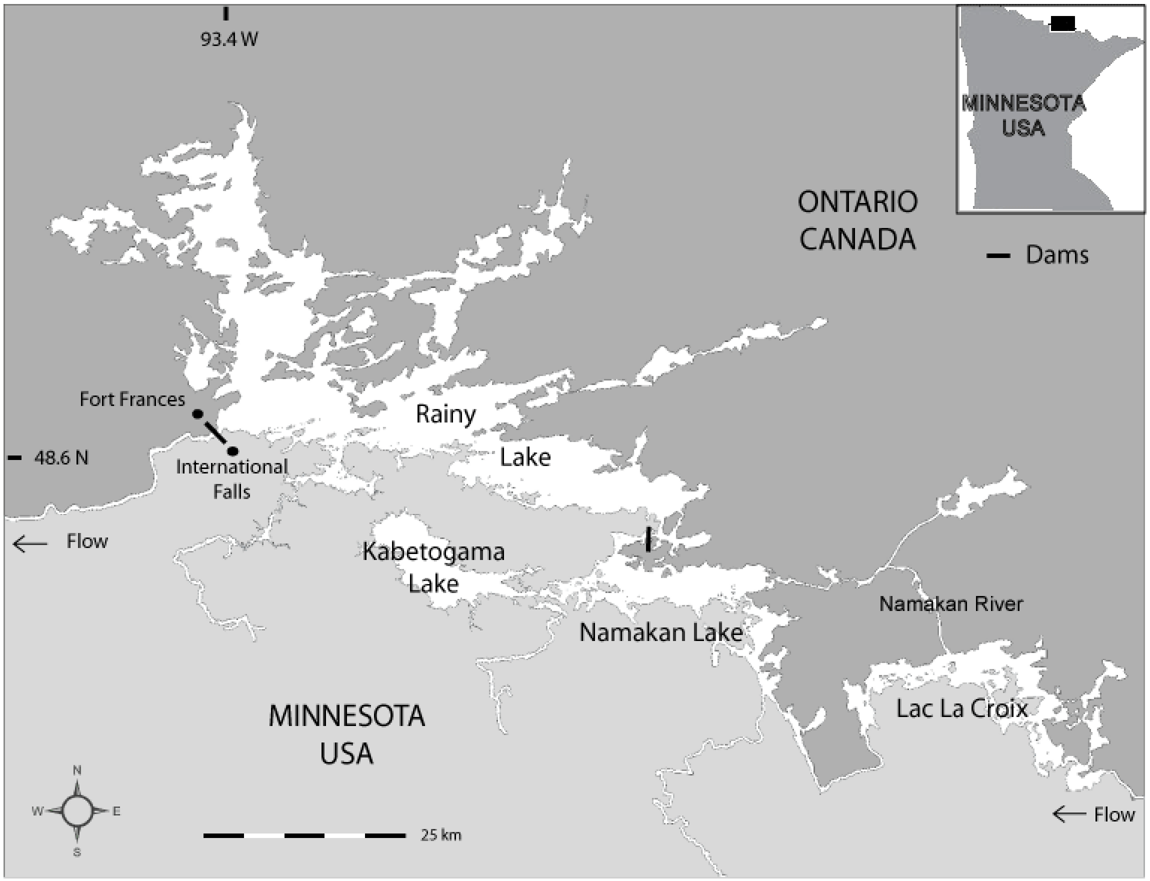


Figure 1. Transboundary Water Resources Framework: Critical Characteristics for Sustainable Management.



Source: National Park Service

Figure 2. Map of the Rainy Lake Basin located in the border region of Ontario, Canada and Minnesota, United States. Dams are denoted as black bars.

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Appendix 1: Calibration Set and Transfer Function

Contemporary water chemistry for Kabetogama, Namakan and Rainy Lakes were extrapolated from a United States Geological Survey data set (Payne 1991, Christensen et al. 2004) Water chemistry parameters included: conductivity, pH, total nitrogen, and total phosphorus. Environmental data were associated with diatom remains identified and counted in surface sediment samples (0-1 cm) from cores collected during the 2005 field season in Voyageurs National Park.

Water quality data from Kabetogama Lake, Namakan Lake and Rainy Lake sites were then appended to a 71 Northern Lakes and Forests ecoregion in Minnesota and Lake Of the Woods in Ontario (NLFLOW) lake data set (Paterson et al. 2007). The NLFLOW calibration set included 16 surface sediment samples from Lake of the Woods and 55 surface samples from the Northern Lakes and Forests ecoregion of Minnesota (Table 1). It is important to note that even though 16 samples came from the same lake (Lake of the Woods), they come from a lake that is morphometrically complex and large with varied water chemistry. Image files and consultation with authors involved in the NLFLOW data set insured the harmonization of the taxonomy among all datasets.

We used constrained canonical correspondence analysis (CCA) to test the significance of each environmental variable using Monte Carlo tests with 200 permutations. Backward elimination was used to determine if each environmental variable was significantly explaining the variance in the species data ($p<0.05$). For all CCAs, rare taxa were downweighted. Only species present at greater 1 % relative abundance in two or more samples or at greater than 5 % relative abundance in one sample were included in the ordination analyses; the same selection criteria were used by Ramstack *et al.* (2003).

All environmental variables were log transformed to approximate normal distributions except pH which did not require any transformation. A total of 112 diatom species was included in the analyses (Table 2). A transfer function was developed using weighted averaging (WA) regression with inverse deshrinking and bootstrapping (100 permutations) cross-validation for TP and Cond. Outliers were identified from plots of models and bootstrap residuals in the training set were removed for the final transfer function. The WA reconstructions were performed using the program C2 (Juggins 2003). The strength of the transfer functions (Table 3) was evaluated by calculating squared correlation coefficient (r^2) of observed versus diatom-inferred environmental variables, the root mean square error (RMSE), and the RMSE of prediction (RMSEP) as described by Ramstack et al.(2003) and Reavie et al. (2006). The performance result indicates that Cond and TP show high correlation between the observed and the estimated values.

Canonical Correspondence Analysis indicates that the four environmental variables account for 19**%** of the variance in the diatom data. Using constrained CCAs, all four variables had a statistically significant ($p<0.05$) influence on the diatom distribution. Conductivity was the strongest explanatory variable (7.7%**)** followed by pH (6.4%**),** TP (4.6%) and then TN (2.3%). Axis 1 accounts for 8.3% of the explained variation in the diatom data and is most closely related to Cond and pH. Axis 2 explains 5.3% of the variance and is closely related to TP and TN. In the CCA biplot (Fig. 1), LOW and Voyageurs samples except for Kab are well distributed in the CCA plot.

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Table 1. The final 73 Minnesota lakes data set includes the following environmental variables: conductivity, pH, total nitrogen and total phosphorus. * Island Lake was removed from the training set while reconstructing TP (Payne 1991, Ramstack 2003, Christensen et al. 2004, Paterson et al. 2007)

Lake	**Cond** uS/cm	**logCond**	**pH** SU	**TN** ug/l	**logTN**	**TP** ug/l	**logTP**
August	40	1.6	7.25	437	2.64	16	1.2
Balsam	162	2.21	7.47	501	2.7	20	1.31
Bean	52	1.72	7.64	282	2.45	18	1.26
Bear	45	1.65	7.45	162	2.21	12	1.08
Beatrice	25	1.39	6.31	437	2.64	15	1.19
Beaver IT	22	1.34	5.95	427	2.63	26	1.41
Bluewater	263	2.42	7.96	204	2.31	10	0.98
Caribou	51	1.71	6.97	214	2.33	6	0.78
Cedar IT	288	2.46	8.03	468	2.67	14	1.14
Coon	91	1.96	7.32	501	2.7	15	1.18
Crooked	148	2.17	7.45	550	2.74	20	1.3
Decker	166	2.22	7.73	1175	3.07	60	1.78
Deer IT1	191	2.28	7.84	525	2.72	23	1.37
Deer IT2	234	2.37	8.1	363	2.56	13	1.11
Dixon	229	2.36	7.96	794	2.9	36	1.56
Dora	195	2.29	7.69	724	2.86	35	1.54
Dyers	72	1.86	7.57	407	2.61	28	1.45
Forsythe	32	1.51	6.89	708	2.85	22	1.34
Grave	251	2.4	7.72	380	2.58	8	0.9

Lake	Cond	logCond	pH	TN	logTN	TP	logTP
Horseshoe	78	1.89	7.06	794	2.9	19	1.29
Ice	110	2.04	7.05	501	2.7	20	1.31
Island *	186	2.27	7.64	708	2.85	30	1.48
Little Bass	209	2.32	8.16	407	2.61	14	1.15
Little Trout	37	1.57	7.37	263	2.42	8	0.9
Locator	25	1.4	6.99	380	2.58	10	1
Loiten	25	1.4	7.05	355	2.55	9	0.95
Long	204	2.31	8.08	537	2.73	14	1.15
Loon	219	2.34	8.55	562	2.75	12	1.08
Little Bowstring	263	2.42	8.14	437	2.64	19	1.29
Little Cut Foot	138	2.14	7.56	832	2.92	45	1.65
Nine Mile	44	1.64	7.39	525	2.72	18	1.26
Nipisiquit	52	1.72	7.4	501	2.7	17	1.23
Owen	34	1.53	6.7	562	2.75	20	1.31
Platte	107	2.03	8.1	891	2.95	34	1.53
Pokegama	257	2.41	7.84	398	2.6	16	1.2
Red Sand	132	2.12	8.8	933	2.97	34	1.53
Round IT2	58	1.76	7.15	513	2.71	19	1.28
Round IT3	191	2.28	7.77	759	2.88	62	1.79
Sand	191	2.28	8.2	617	2.79	25	1.39
Shallow	162	2.21	7.67	389	2.59	12	1.08
Shoepack	21	1.32	6.59	589	2.77	20	1.3
Snells	229	2.36	8.18	759	2.88	25	1.4
Splithand	141	2.15	7.57	575	2.76	30	1.47
Stingy	66	1.82	7.11	676	2.83	28	1.44

Lake	Cond	logCond	pH	TN	logTN	TP	logTP
Sugar	269	2.43	7.85	295	2.47	11	1.06
Tettegouche	38	1.58	7.32	437	2.64	18	1.26
Thistledew	158	2.2	7.71	417	2.62	21	1.32
Tooth	30	1.48	6.84	447	2.65	13	1.11
Trout IT1	347	2.54	7.9	417	2.62	21	1.32
TroutI T2	240	2.38	7.96	224	2.35	8	0.9
Wabana	214	2.33	7.86	263	2.42	9	0.95
Windy	27	1.43	6.94	457	2.66	13	1.11
Winnibagash	263	2.42	7.94	468	2.67	19	1.29
Wolf	71	1.85	7.76	389	2.59	15	1.18
PP-1	110	2.04	7.88	562	2.75	17	1.22
PP-2	107	2.03	7.69	537	2.73	16	1.21
PP-3	117	2.07	7.84	501	2.7	11	1.06
PP-4	115	2.06	7.89	447	2.65	11	1.04
PP-5	120	2.08	7.86	407	2.61	9	0.95
PP-6	115	2.06	7.81	447	2.65	9	0.93
PP-7	120	2.08	7.92	479	2.68	11	1.04
PP-9	115	2.06	7.68	603	2.78	19	1.27
PP-10	115	2.06	7.75	603	2.78	21	1.33
PP-11	117	2.07	7.76	562	2.75	20	1.3
PP-12	63	1.8	7.53	355	2.55	7	0.83
PP-13	78	1.89	7.57	324	2.51	8	0.89
PP-15	83	1.92	7.6	437	2.64	9	0.93
PP-17	100	2	7.71	550	2.74	22	1.35
PP-18	115	2.06	7.62	589	2.77	20	1.31

Lake	Cond	logCond	pH	TN	logTN	TP	logTP
PP-19	112	2.05	7.79	501	2.7	25	1.39
Namakan	45	1.65	7.02	40	1.6	9	0.94
Kabetogama	93	1.97	7.36	72	1.86	19	1.27
Rainy	98	1.99	7.53	37	1.57	10	1.01

Table 2. Diatom taxa used in development of WAinv log TP and log Cond transfer function, number of occurences and maximum relative abundance in 73 NLFLOW lake training set, total phosphorus optima (ug/L) and conductivity optima (uS/cm) (Payne 1991, Ramstack 2003, Christensen et al. 2004, Paterson et al. 2007).

DIATCODE	no. lakes	Maximum percent abundance	TP Optimum (ug/L)	log TP Optimum	Cond Optimum (uS/cm)	log Cond Optimum
ACECONSP	20	2.4	21.6	1.3	122.8	2.1
ACEGRANA	17	1.2	16.0	1.2	73.4	1.9
ACHMINUT	58	25.5	16.8	1.2	59.8	1.8
AMPINARI	9	1.7	19.8	1.3	215.3	2.3
AMPLIBYC	13	0.7	21.7	1.3	158.6	2.2
AMPPEDIC	26	2.7	17.4	1.2	166.8	2.2
AMPVENET	1	0.7	33.9	1.5	107.2	2.0
ASTFORMO	66	61.6	15.1	1.2	88.6	1.9
AULALPIG	13	3.6	16.7	1.2	99.2	2.0
AULAMBIG	68	67.2	21.7	1.3	114.4	2.1
AULDISTA	10	14.8	14.4	1.2	32.1	1.5
AULGRANU	45	62.4	22.2	1.3	127.9	2.1
AULISLAN	18	43.0	15.6	1.2	106.2	2.0
AULITALI	1	1.2	15.1	1.2	70.8	1.9
AULLIRBI	4	5.5	17.3	1.2	25.6	1.4
AULPFAFF	7	4.6	17.2	1.2	74.4	1.9
AULSUBAR	30	18.1	12.3	1.1	89.2	2.0
BELBEROL	6	1.2	33.1	1.5	143.9	2.2
BRABREBI	12	5.2	17.5	1.2	55.0	1.7

DIATCODE	no. lakes	Maximum percent abundance	TP Optimum (ug/L)	log TP Optimum	Cond Optimum (uS/cm)	log Cond Optimum
BRAVITRE	9	3.9	11.6	1.1	29.8	1.5
COCNEODI	23	1.8	20.9	1.3	156.0	2.2
COCPLACE	11	0.8	14.6	1.2	111.5	2.0
COCPLAEU	8	1.5	19.3	1.3	214.9	2.3
COCPLALI	16	1.2	25.0	1.4	147.1	2.2
CRACUSPI	2	2.8	19.1	1.3	41.9	1.6
CRAHALOP	11	2.0	12.3	1.1	39.8	1.6
CSPDUBIU	14	12.5	20.0	1.3	110.2	2.0
CSPINVIS	13	6.9	24.4	1.4	172.5	2.2
CSPSPP	8	3.8	9.6	1.0	107.6	2.0
CSPTHOLI	6	3.7	40.8	1.6	182.5	2.3
CYCBODLE	59	11.9	12.5	1.1	92.9	2.0
CYCCO/GO	23	67.6	12.6	1.1	201.2	2.3
CYCCOMRA	5	2.4	10.4	1.0	210.6	2.3
CYCKRAMM	7	2.0	13.3	1.1	185.1	2.3
CYCMENEG	5	3.1	14.0	1.1	50.6	1.7
CYCMICHI	40	15.4	14.4	1.2	110.7	2.0
CYCOCELL	15	6.8	9.8	1.0	64.5	1.8
CYCROSSI	7	0.3	15.1	1.2	118.0	2.1
CYCSTECX	56	56.8	12.9	1.1	55.8	1.7
CYMAFFIN	3	1.2	13.4	1.1	157.1	2.2
ENCSILES	12	2.6	18.1	1.3	50.7	1.7
ENPMICRO	15	6.2	17.5	1.2	76.0	1.9
EPIADNAT	1	0.3	15.1	1.2	70.8	1.9

DIATCODE	no. lakes	Maximum percent abundance	TP Optimum (ug/L)	log TP Optimum	Cond Optimum (uS/cm)	log Cond Optimum
EUNZASUM	3	26.8	19.2	1.3	21.2	1.3
FRACAPGR	31	6.3	21.4	1.3	133.7	2.1
FRACAPME	26	14.1	12.2	1.1	106.2	2.0
FRACAPUC	22	18.3	22.0	1.3	167.6	2.2
FRACAPVR	19	3.7	22.6	1.4	87.3	1.9
FRACONV2	2	18.9	33.9	1.5	131.2	2.1
FRACROTO	58	37.5	15.6	1.2	171.5	2.2
FRANANAN	1	3.6	33.9	1.5	107.2	2.0
FRATENER	20	5.1	10.9	1.0	102.2	2.0
FRAVAUCH	24	4.1	22.5	1.4	137.8	2.1
GOMANGUS	3	0.5	16.9	1.2	97.5	2.0
GOMDICHO	10	4.2	13.9	1.1	212.3	2.3
GOMPAVUL	16	1.2	25.7	1.4	91.8	2.0
GOMPUMIL	4	2.9	31.0	1.5	111.0	2.0
GOMTRUNC	2	1.4	31.4	1.5	112.2	2.1
MARMARTY	11	1.8	23.9	1.4	169.9	2.2
NAVCINCT	1	0.3	7.9	0.9	37.2	1.6
NAVCRYCP	17	3.2	20.5	1.3	43.4	1.6
NAVCRYP0	32	3.0	17.2	1.2	119.6	2.1
NAVLEPTO	6	1.0	15.4	1.2	36.1	1.6
NAVLIBON	1	0.2	34.7	1.5	195.0	2.3
NAVLUNDI	5	0.5	17.1	1.2	81.6	1.9
NAVMINIM	18	4.9	18.4	1.3	52.8	1.7
NAVPHYLL	3	0.7	17.5	1.2	109.7	2.0

DIATCODE	no. lakes	Maximum percent abundance	TP Optimum (ug/L)	log TP Optimum	Cond Optimum (uS/cm)	log Cond Optimum
NAVPSEUV	10	2.7	18.6	1.3	48.1	1.7
NAVRADIO	20	1.7	16.5	1.2	79.9	1.9
NAVSEMIN	31	4.6	20.6	1.3	76.7	1.9
NAVVITIO	4	6.5	21.7	1.3	26.1	1.4
NITACIDO	9	1.2	31.5	1.5	185.5	2.3
NITAMPHI	18	2.5	17.5	1.2	160.4	2.2
NITFONTI	14	2.7	16.0	1.2	55.5	1.7
NITGRACI	24	1.7	17.8	1.2	78.9	1.9
NITINCOG	11	0.5	22.6	1.4	75.0	1.9
NITLINVS	1	0.2	33.9	1.5	131.8	2.1
NITPALEA	6	0.8	26.2	1.4	50.8	1.7
NITPALEC	5	0.5	17.7	1.2	259.7	2.4
NITPERMI	5	1.0	15.7	1.2	46.7	1.7
NITRADICU	3	0.7	24.1	1.4	144.5	2.2
PINBICPU	5	2.2	21.5	1.3	32.7	1.5
PLALANCE	5	1.6	23.4	1.4	53.9	1.7
PRABREBC	9	5.1	17.5	1.2	47.3	1.7
PRABREIN	19	14.1	20.0	1.3	73.4	1.9
PRABREVI	45	11.6	19.8	1.3	95.1	2.0
RHOCURVA	3	0.3	22.6	1.4	190.5	2.3
RHPGIBBA	3	0.5	12.6	1.1	133.4	2.1
ROSLINEA	16	3.7	19.0	1.3	65.7	1.8
SELLAEVI	9	1.0	22.7	1.4	66.7	1.8
SELPUPUL	32	7.5	16.2	1.2	54.2	1.7

DIATCODE	no. lakes	Maximum percent abundance	TP Optimum (ug/L)	log TP Optimum	Cond Optimum (uS/cm)	log Cond Optimum
SLLANSAT	2	3.1	33.9	1.5	125.5	2.1
SLLPINNA	56	18.3	19.7	1.3	83.9	1.9
SRACONBI	5	2.7	22.7	1.4	144.6	2.2
SRACONPU	10	5.8	30.4	1.5	169.6	2.2
SRACONST	39	21.5	20.5	1.3	101.8	2.0
SRACONVE	40	29.9	20.3	1.3	66.4	1.8
SRAELLEP	14	23.6	20.5	1.3	47.1	1.7
SUSALPIN	6	3.8	10.8	1.0	229.8	2.4
SUSHANTZ	20	21.4	16.4	1.2	257.8	2.4
SUSMEDIU	26	4.9	13.4	1.1	107.1	2.0
SUSMI/PA	34	46.0	16.1	1.2	125.5	2.1
SUSNIAGA	43	7.0	17.3	1.2	132.9	2.1
SYLPARAS	10	0.5	15.9	1.2	79.7	1.9
SYNACUAN	12	3.0	20.8	1.3	147.3	2.2
SYNACUS	2	1.2	28.2	1.5	109.9	2.0
SYNDELIC	2	2.6	8.9	1.0	34.4	1.5
SYNRADIA	14	1.7	13.5	1.1	133.2	2.1
SYNRUMFA	2	2.4	32.4	1.5	107.4	2.0
SYNULNA	27	5.2	12.7	1.1	200.0	2.3
TABFLOC2	58	41.8	13.3	1.1	70.8	1.9
TABQUADR	5	1.0	15.6	1.2	96.4	2.0

Table 3. 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 RMSEP $_{\text{bootstrapped}}$

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

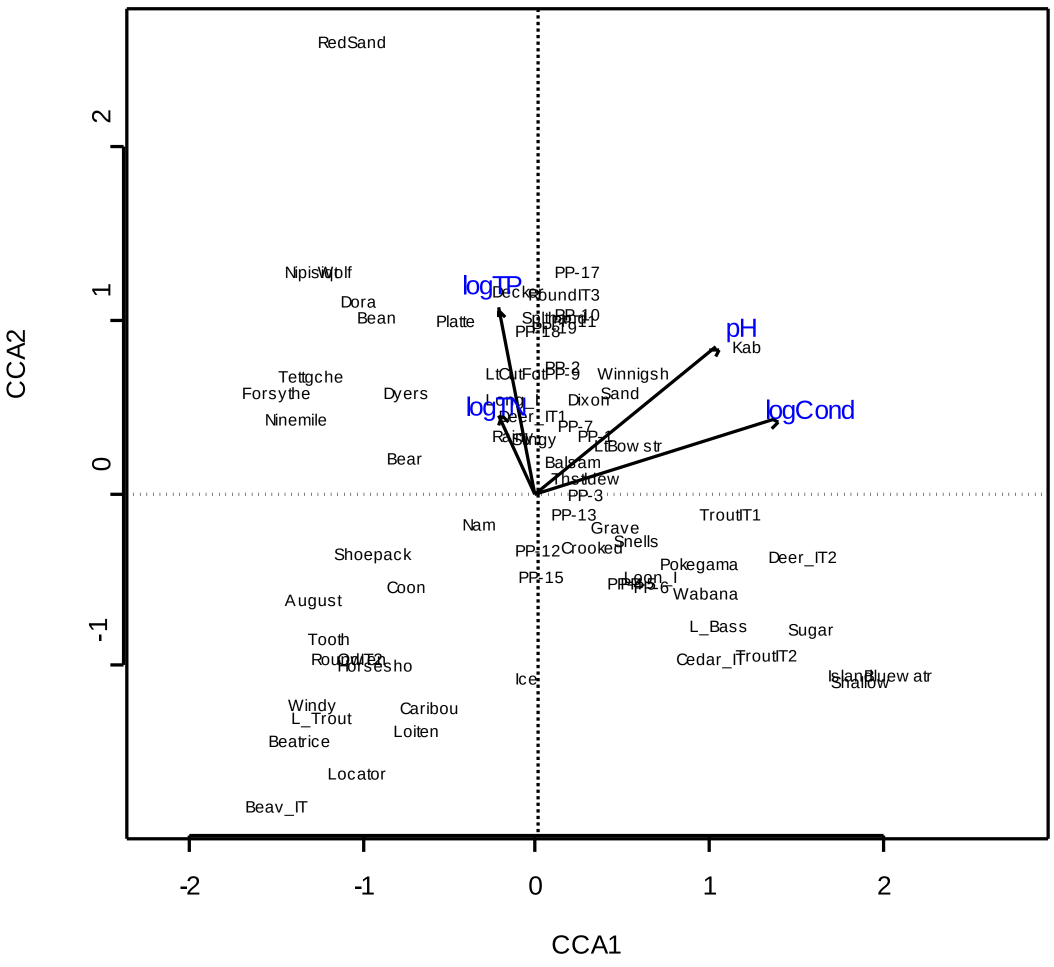

Figure 1. CCA biplot of 73 NLFLOW lakes in species- environment multivariate space.

Appendix 2: Environmental and Anthropogenic Data used for Variance Partitioning

Both environmental and anthropogenic data were gathered from the literature and agency records from both the United States and Canada (Demmon1946; Horn 1960; NCFES 1960-2005; Broschart et al. 1989; Environment Canada, precipitation and temperature data for Fort Frances; Water Survey Canada, hydrology data; NOAA, precipitation data for International Falls; University of Virginal Library, historical census data; and, Steve Windels personal communications). Three data categories were identified for the research: climate, water-level, and landscape. Climate record included both precipitation (mm) and temperature (ºC). Two weather stations, one in Fort Frances, ON, and the other in International Falls, MN, were merged to create a full continuous climate record. Fort Frances and International Falls are adjacent cities only separated physically by the Rainy River and politically by the international border. Seasonal and annual precipitation (mm; 1912-1959) and temperature (ºC; 1912-2005) from the weather station in Fort Frances were obtained from Environment Canada. Precipitation data from 1951 till 2005 were obtained from the National Oceanic and Atmospheric Administration weather station. Data in bold within the table were extrapolated by using data trends from the Kenora, ON weather station.

Monthly water-level data were accessed and uploaded though Water Survey Canada (http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm) 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 minima and maxima were recorded for each lake.

The landscape category includes both anthropogenic and wildlife changes in the region. It consists of human population size, logging, and beaver population size. The Historical Census Browser website (http://mapserver.lib.virginia.edu/) of the University of Virginia, Geospatial and Statistical Center provided human census data for both Koochiching and Itasca Counties (Minnesota). Logging data were very important to gather for the region as it is the dominant industry and played an important role in modifying the landscape in the Lower Rainy River Drainage Basin. 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; the numbers extrapolated are in bold within the table. Logging after the initial cut in the region was for pulpwood production. Because pulpwood trends were lacking prior to 1959 for the region, we used pulpwood production data of 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 and are denoted in bold within the table. Post 1959 data for annual total pulpwood production data from Koochiching, Lake and St. Louis Counties were used (NCFES 1960-2005).

Beaver population can alter the hydrologic regimes while cutting wood and building dams (Naiman et al. 1994) and are therefore relevant while considering landscape changes. Beaver were extirpated in the 1800s during the fur trade (Naiman et al. 1986) in Voyageurs National Park, but have recolonized the region since the 1940s (Broschart et al. 1989). 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).

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Date (A.D.)	**Climate**							
	Precipitation (mm)							
	Fort Frances, ONT *					International Falls, MN		
	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring
1900								
1901								
1902								
1903								
1904								
1905								
1906								
1907								
1908								
1909								
1910								
1911								
1912	577.7	**56.1**	114.3	238.8	189.9			
1913	736.1	39.4	205.3	340.9	163.7			
1914	660.5	38.6	158.3	288.5	169.9			
1915	**660.5**	60.8	**211.05**	**288.5**	**169.9**			
1916	**745.4**	**109.4**	**201.35**	**364.4**	**170.55**			
1917	503.5	135.9	41.6	216.8	147.9			
1918	558.8	88.7	122.5	185.4	148			

1919	817.1	97.3	117.4	439.2	188.1			
1920	600.1	60	145.2	242.3	113.6			
1921	661	133.1	134.7	257	170.8			
1922	733.8	77	229.6	237	142.8			
1923	585.9	128.3	114.2	288.8	106.8			
1924	579.6	64.1	128.3	252.6	130.8			
1925	772.3	81.5	225.5	289.8	179			
1926	768.2	108	87.8	268.7	285.5			
1927	624.3	75.4	176	243.4	127			
1928	692	54.5	110.3	373.4	173.5			
1929	526.2	41.4	121.8	191.4	149.8			
1930	692.8	106.9	174.1	215.6	210.5			
1931	618.2	47.1	156.8	214.6	209.2			
1932	745.2	78.1	133.9	327.5	194.5			
1933	900.6	83.3	170.1	356.4	255.8			
1934	867.3	113.8	146	325.3	298.6			
1935	1018.8	131.2	152.1	594.1	160.8			
1936	750.9	91.1	153.7	302.2	171			
1937	968.9	165.4	305.5	379.8	137.7			
1938	674.4	95.7	270	185.8	123.4			
1939	**731.8**	142.2	**189.1**	276.6	187.6			
1940	606.8	77.3	142.2	162.3	241.4			
1941	1034.6	76.8	269.1	400.4	279.3			
1942	913.5	34.6	175.3	478	183.9			
1943	733.7	149.2	173.9	307	138.8			
1944	816.8	38.1	227.8	368.8	185.6			

1945	749.9	82.5	156.7	283.7	218.8			
1946	744	90.9	127.6	284.7	234.6			
1947	1273.1	349.6	260.9	338.9	226.4			
1948	707.6	184	145.8	315.1	150.3			
1949	737.7	114.1	165.4	371.7	207.6			
1950	755.5	85.6	235.5	354.2	195.4			
1951	749.2	78.3	152.7	310.9	185.4	712	73	138
1952	501.9	71.6	50	357.8	53.2	437	51	47
1953	741	90.1	173.4	297.9	149.5	647	70	147
1954	635.5	132.7	182.7	211	146.9	509	95	147
1955	865.3	78.9	145	338.6	278.7	818	74	133
1956	632.5	87.1	195.2	205.3	133.8	466	68	138
1957	761.8	86.5	147.8	364.5	195.1	680	62	144
1958	583.5	61.9	59.3	253.6	191.1	486	40	54
1959	753.2	68.6	159.1	335.6	188.1	598	47	134
1960	661.9	60.5	139.9	293.3	142.7	512	46	108
1961	696.3	105.5	133.5	226.6	247.9	626	76	123
1962	882.4	127.8	282.3	331	143.7	727	80	215
1963	716.7	83.3	233.1	283.5	117.4	631	58	209
1964	848.1	82.8	174.4	424.6	161.4	676	65	145
1965	963.5	76	201.7	285.3	389.9	751	38	156
1966	806.6	112.3	170.2	413.4	115.8	649	78	141
1967	778.5	113.2	195.4	333.1	133.6	554	66	133
1968	935.5	94.8	178.4	416.9	246.4	737	59	144
1969	806.4	180.6	124.9	294.2	199.4	595	118	88
1970	756.8	126.8	244.6	150	239	575	62	157

1971	773.3	117.8	139.6	202.8	335.5	631	71	99
1972	721.8	124.2	150.1	275	164.1	493	50	102
1973	810.8	67.9	113.3	402.3	233.9	717	34	100
1974	810.5	102.2	229.7	334.3	136.1	616	54	159
1975	789.4	152.5	176.7	287.5	168.8	653	110	120
1976	720.3	140.3	126.1	415.2	49	555	59	76
1977	952	94.1	258.8	277.4	319	808	58	222
1978	818.1	86.9	180.1	377.5	172.6	638	51	137
1979	734.9	109.6	208.3	252.5	178.8	557	64	155
1980	630.7	81.3	76	244.3	217	499	48	55
1981	658.6	57.3	151.1	237.9	210.8	561	26	131
1982	822	108.1	180.9	251	303.3	690	125	151
1983	848.9	75.3	99.1	360.3	291.3	634	41	65
1984	715.8	83.7	91.3	305.4	220.1	541	44	73
1985	1045.9	111.1	352	361.3	238.9	770	60	268
1986	677.8	116.8	163.2	250.2	159.2	460	53	104
1987	726.6	112.4	137.8	361.4	119.6	496	30	108
1988	865	64.4	108.9	449.6	201	634	20	81
1989	718.6	155	112.5	353.6	128	571	62	83
1990	675.2	95.9	118	290.9	133.7	516	40	97
1991	817.8	151.5	216.6	248.1	230.3	707	74	196
1992	911.1	154.9	131.8	347.5	109.3	595	84	103
1993	773.5	41.3	57.5	369.6	107.4	546	63	122
1994	680.4	60.1	97.3	274.4	242.1	624	31	94
1995	723.2	97.1	115.1	270.9	176.5	617	60	108
1996						726	115	103

1997						482	61	100
1998						572	49	148
1999						738	25	243
2000						579	26	126
2001						698	16	208
2002						588	10	98
2003						428	9	66
2004						685	30	166
2005						711	81	185

Date (A.D.)	**Climate cont.**						
	Precipitation (mm)		Temperature (Degrees C)				
	International Falls, MN		Fort Frances, ONT				
	Summer	Fall	Annual	Winter	Spring	Summer	Fall
1900							
1901							
1902							
1903							
1904							
1905							
1906							
1907							
1908							
1909							

1910							
1911							
1912			1.8	-17.05	1.6	16.5	4.3
1913			2.6	-16.5	1.4	17.5	6.8
1914			2.1	-15.8	2.9	17.8	6.3
1915			2.6	-13.6	2.5	14.7	3.4
1916			0.2	-14.4	-0.7	16.3	3.1
1917			0.1	-19.5	0.3	16.4	3.7
1918			3.1	-17.4	3.8	17.1	5.4
1919			3	-9.9	3.7	18.8	2.5
1920			2.6	-16.3	1.3	16.6	6.5
1921			3.4	-10.5	3	18.6	3.2
1922			2.9	-14.6	4.1	16.9	6.1
1923			2.4	-16.6	-0.1	17.4	6.2
1924			0.9	-13.4	0.8	15.2	5.2
1925			2.1	-16.7	3	16.9	3.4
1926			1.9	-12.5	2.1	16.4	2.2
1927			2.3	-13.9	3.2	16.2	4.9
1928			3.9	-14.5	3	17.4	6
1929			2	-15.2	3.1	18	4.1
1930			4	-14.1	3.7	19.2	5.6
1931			6	-8.4	4.1	19	8.5
1932			2.4	-10.8	0.7	18.8	3.7
1933			1.5	-15.9	1.9	18.9	2.5
1934			1.9	-16.4	1	16.2	5.2
1935			1.9	-14.5	1.2	17.3	2.9

1936			1.9	-18.2	2.3	19.8	3.6
1937			2.9	-15.3	2.6	20.1	5.1
1938			3.6	-13.7	4.2	17.6	5.6
1939			3.1	-15.4	1.3	17.7	6.2
1940			3.6	-9.8	2.3	17.5	6
1941			4.3	-11.3	5.3	17.6	5
1942			3.3	-10	5	15.9	4.2
1943			2.3	-15.7	1	17.4	5.3
1944			3.6	-10.8	2.7	16.3	6.2
1945			2.2	-13.2	2.6	16.6	3.8
1946			2.7	-15.4	4.9	16.9	4
1947			2	-14.1	0.3	17.6	4.7
1948			2.3	-17.1	1.8	17.4	6.4
1949			2.2	-15.4	2.2	18	4.2
1950			0.7	-16.7	-1	16.2	5.1
1951	317	173	1.9	-14.7	2.4	16.6	3.2
1952	312	45	4	-13.2	4.2	17.8	5.3
1953	265	143	3.8	-11.6	2.6	18.2	7.5
1954	165	131	2.6	-12.9	0	16.8	5.1
1955	341	250	2.3	-13.6	2.9	19.1	3.5
1956	150	103	2.3	-14.7	-0.1	17.2	5.5
1957	311	186	2.4	-15.6	2.5	17	5
1958	235	142	2.7	-12.1	4.3	15.5	5.6
1959	264	152	2.3	-18.1	2.9	18.6	2.2
1960	206	133	2.7	-11.3	1.5	17.3	5.7
1961	212	234	3.5	-13.6	3.1	18.2	5.3

1962	322	109	2.5	-16.1	2.9	17	6.1
1963	259	101	3.4	-16.2	3.5	18.4	9
1964	362	114	2.7	-13.2	2.2	16.9	4.9
1965	230	307	1.7	-17	1.1	16.3	3.7
1966	356	91	1.8	-14.9	2	18.2	3.6
1967	239	104	1.7	-16	1	16.7	4.8
1968	324	204	2.6	-14.8	3.4	16.3	5.9
1969	259	144	2.6	-14.6	2.7	16.5	4.4
1970	150	206	2.1	-14.4	0.4	18.9	5.3
1971	189	286	2.6	-16.3	2.2	17.5	6
1972	221	107	1.5	-16.7	3	17.3	3.6
1973	342	250	4	-13.5	4.8	18	5.7
1974	307	91	2.7	-14.8	1.2	17.7	4.7
1975	294	127	3.1	-11.6	1.6	18.4	5.7
1976	371	56	2.4	-12.7	3.2	18.7	2.5
1977	238	282	3.6	-16.8	7.4	17.2	5.1
1978	308	142	2.2	-16.4	3.2	17.3	5.3
1979	216	135	1.6	-19	1.1	16.9	4.3
1980	202	191	2.6	-12.7	3.6	17.7	4.1
1981	205	194	4.1	-12.8	4.7	17.8	5.7
1982	201	224	1.7	-16.7	2.3	15.9	4.4
1983	296	223	3.7	-9.5	3.1	18.9	5.9
1984	252	156	3.4	-13.7	2.4	17.9	5.3
1985	296	165	1.8	-14.8	5.2	15.6	2.3
1986	198	110	3.6	-14.5	5.6	17.3	3.4
1987	291	70	5.4	-8.9	6.5	18	5.4

1988	358	161	2.9	-14.1	4.1	19.2	4.2
1989	328	105	1.9	-15	1.8	18.3	4.3
1990	274	86	3.7	-13.7	3.4	18.2	5.6
1991	235	209	3.7	-14.1	5.6	19.1	2.9
1992	296	93	3.1	-10.2	3.5	15.1	4.5
1993	302	91	2.5	-13.5	3.3	16.9	2.3
1994	287	206	3.4	-15.8	4.4	17.2	7
1995	231	203	2.3	-11.8	2.4	18.9	2.1
1996	279	224	1	-16.9	-0.7	17.6	3.3
1997	168	184	2.9	-14	0.9	17.7	4.9
1998	215	157	5.3	-6.9	5.4	17.9	6.2
1999	310	166	4.6	-11.3	5.2	17.9	5.8
2000	276	151	3.5	-10.4	5.4	17.2	5.5
2001	330	142	4.3	-14.9	4	18.4	6.3
2002	417	63	3.3	-9	0.1	18.7	3.5
2003	245	105	3.3	-13.3	3.1	18.5	4.8
2004	187	261	3	-12.4	3	15.6	7.5
2005	282	199	4.1	-13.1	3.7	18.5	6.2

Date (A.D.)	**Water-level**					
	Minimum (m)			Maximum (m)		
	Namakan	Rainy	Lac La Croix	Namakan	Rainy	Lac La Croix
1900						
1901						
1902						
1903						
1904						
1905						
1906						
1907						
1908						
1909						
1910						
1911						
1912		335.695			337.724	
1913	338.066	336.271		340.206	338.048	
1914	338.325	336.514		341.538	338.057	
1915	338.285	335.816		340.849	337.92	
1916	338.087	337.249		342.248	339.093	
1917	337.895	335.966		340.513	337.941	
1918	337.438	335.801		339.459	337.371	

1919	337.347	336.35		340.489	338.011	
1920	337.569	336.786		341.486	338.026	
1921	337.462	336.868		341.029	337.913	
1922	337.584	336.716		341.364	337.694	
1923	337.164	335.664		339.224	337.02	
1924	337.237	335.71		339.245	336.822	
1925	337.859	336.828		341.245	337.795	
1926	337.703	336.819		341.41	338.081	
1927	338.977	337.386	360.371	341.97	338.438	362.642
1928	337.597	336.228	360.325	341.437	338.017	361.59
1929	337.554	336.06	360.264	341.072	337.895	361.179
1930	337.201	335.67	360.295	340.751	336.761	361.407
1931	337.737	336.502	360.402	340.782	336.807	361.331
1932	337.92	336.472	360.432	341.029	337.828	361.667
1933	338.377	336.734	360.341	340.846	337.691	361.17
1934	337.883	336.935	360.411	341.342	337.874	362.508
1935	337.657	336.716	360.487	341.41	337.965	361.889
1936	337.551	336.6	360.197	341.059	337.493	362.118
1937	337.24	336.438	360.243	341.394	337.859	362.148
1938	337.807	337.127	360.335	341.836	338.255	362.819
1939	337.532	336.624	360.335	341.029	337.731	361.721
1940	337.35	336.517	360.268	340.885	337.279	361.606
1941	337.398	336.53	360.31	341.44	338.602	362.093
1942	338.264	337.34	360.447	341.032	337.862	361.895
1943	337.853	337.066	360.447	341.44	338.051	362.377
1944	339.053	337.234	360.554	341.486	338.118	362.368

1945	338.569	337.478	360.53	340.989	337.868	362.215
1946	338.221	337.298	360.499	341.288	337.923	361.889
1947	339.038	336.984	360.67	341.077	337.938	362.133
1948	338.285	337.017	360.243	341.019	337.862	362.438
1949	337.804	337.133	360.182	341.181	337.877	361.615
1950	338.264	336.731	360.7	342.196	339.233	363.718
1951	338.331	336.685	360.609	341.138	337.859	362.422
1952	338.422	336.646	360.517	341.166	337.953	361.615
1953	337.974	336.838	360.487	341.059	337.871	362.133
1954	338.051	336.63	360.396	341.394	338.185	362.925
1955	338.261	336.831	360.374	340.949	337.868	361.298
1956	338.154	336.786	360.42	341.007	337.846	362.215
1957	338.09	336.646	360.432	341.172	337.917	361.999
1958	338.279	336.563	360.396	340.971	337.374	360.685
1959	338.471	336.831	360.377	340.968	337.789	361.279
1960	338.227	336.761	360.417	340.952	337.834	361.764
1961	338.794	336.902	360.307	341.001	337.837	361.932
1962	338.752	336.844	360.408	341.096	337.886	361.996
1963	338.221	336.862	360.319	341.056	337.825	361.438
1964	338.218	336.508	360.307	341.214	338.115	362.127
1965	338.627	336.786	360.56	341.05	337.825	362.432
1966	339.029	336.978	360.377	341.321	338.182	362.593
1967	339.05	336.679	360.368	341.105	337.843	362.124
1968	338.947	336.834	360.277	341.708	338.386	362.956
1969	338.2	336.56	360.639	341.004	337.907	362.459
1970	338.261	336.447	360.511	341.181	338.032	362.59

1971	338.182	336.795	360.481	340.913	337.926	362.197
1972	338.081	336.499	360.551	341.029	337.837	362.209
1973	338.785	336.902	360.396	340.943	337.752	361.673
1974	338.09	336.682	360.603	341.035	338.209	362.279
1975	338.24	336.661	360.481	340.974	337.764	361.999
1976	338.56	336.777	360.005	340.919	337.785	362.203
1977	338.401	336.74	359.978	341.303	338.008	362.547
1978	338.09	336.67	360.514	340.919	337.843	362.179
1979	338.435	336.691	360.426	340.92	337.719	362.476
1980	338.461	336.703	360.327	340.741	337.624	361.276
1981	338.56	336.814	360.416	340.861	337.726	362.23
1982	338.273	336.671	360.463	340.897	337.812	362.158
1983	338.711	336.862	360.744	340.902	337.836	361.496
1984	338.452	336.742	360.356	340.898	337.835	361.933
1985	338.603	336.751	360.443	341.021	338.035	361.956
1986	338.295	336.759	360.621	340.922	337.805	362.207
1987	338.543	336.654	360.474	340.962	337.737	361.885
1988	338.749	336.88	360.471	341.062	337.853	362.507
1989	338.435	336.816	360.413	340.895	337.851	361.963
1990	338.959	336.989	360.358	340.897	337.771	362.195
1991	338.809	336.965	360.337	340.932	337.736	361.52
1992	338.735	336.902	360.559	340.964	337.852	362.079
1993	338.835	336.763	360.512	340.925	337.776	361.722
1994	338.839	336.71	360.505	340.938	337.769	362.198
1995	338.785	336.821	360.377	340.92	337.754	361.346
1996	338.939	336.868	360.69	341.014	338.094	362.626

1997	338.929	336.812	360.235	340.834	337.656	361.826
1998	338.837	336.478	360.113	340.498	337.22	360.958
1999	338.89	336.951	360.551	340.899	337.75	361.743
2000	339.532	336.995	360.586	340.775	337.725	361.541
2001	339.514	336.867	360.49	341.445	338.243	362.619
2002	339.376	336.842	360.376	341.191	338.568	361.38
2003	339.38	336.577	360.258	340.621	337.394	360.988
2004	339.342	336.857	360.503	340.85	337.662	361.709
2005	339.33	336.856	360.401	340.948	337.962	362.068

Date (A.D.)	Water-level cont.			
	Differences between minimum and maximum (m)			
	Namakan	Kabetogama	Rainy	Lac La Croix
1900				
1901				
1902				
1903				
1904				
1905				
1906				
1907				
1908				
1909				
1910				
1911				
1912			2.029	
1913	2.019	2.019	1.777	
1914	3.118	3.118	1.543	
1915	2.364	2.364	2.104	
1916	3.732	3.732	1.844	
1917	1.999	1.999	1.975	
1918	1.94	1.94	1.57	
1919	2.963	2.963	1.661	
1920	3.801	3.801	1.24	

1921	3.447	3.447	1.045	
1922	3.655	3.655	0.978	
1923	1.958	1.958	1.356	
1924	1.656	1.656	1.112	
1925	3.334	3.334	0.967	
1926	3.633	3.633	1.262	
1927	2.332	2.332	1.052	
1928	3.661	3.661	1.789	
1929	3.269	3.269	1.835	
1930	3.385	3.385	1.091	
1931	2.9	2.9	0.305	0.72
1932	2.983	2.983	1.356	1.011
1933	2.173	2.173	0.957	0.74
1934	3.318	3.318	0.939	1.689
1935	3.655	3.655	1.249	1.275
1936	3.172	3.172	0.893	1.532
1937	3.946	3.946	1.421	1.731
1938	3.686	3.686	1.128	2.311
1939	3.264	3.264	1.107	1.25
1940	3.348	3.348	0.762	1.29
1941	3.92	3.92	2.072	1.675
1942	2.487	2.487	0.522	1.146
1943	3.5	3.5	0.985	1.68
1944	2.164	2.164	0.884	1.568
1945	2.216	2.216	0.39	1.316
1946	2.868	2.868	0.625	1.186

1947	1.941	1.941	0.954	1.368
1948	2.524	2.524	0.845	1.911
1949	3.227	3.227	0.744	1.378
1950	3.58	3.58	2.502	2.452
1951	2.536	2.536	1.174	1.523
1952	2.441	2.441	1.307	0.965
1953	2.922	2.922	1.033	1.511
1954	2.939	2.939	1.555	2.005
1955	2.487	2.487	1.037	0.853
1956	2.52	2.52	1.06	1.478
1957	2.693	2.693	1.271	1.362
1958	2.548	2.548	0.811	0.207
1959	2.382	2.382	0.958	0.829
1960	2.533	2.533	1.073	1.185
1961	2.101	2.101	0.935	1.363
1962	2.039	2.039	1.042	1.373
1963	2.63	2.63	0.951	0.98
1964	2.537	2.537	1.579	1.614
1965	2.169	2.169	1.039	1.555
1966	2.061	2.061	1.179	1.89
1967	1.83	1.83	1.122	1.625
1968	2.552	2.552	1.528	2.239
1969	2.495	2.495	1.28	1.636
1970	2.556	2.556	1.555	1.943
1971	2.559	2.559	1.131	1.391
1972	2.625	2.625	1.329	1.272

1973	2.03	2.03	0.822	1.051
1974	2.579	2.579	1.515	1.625
1975	2.375	2.375	1.045	1.266
1976	2.066	2.066	0.96	1.955
1977	2.662	2.662	1.237	2.375
1978	2.56	2.56	1.128	1.438
1979	2.021	2.021	1.009	1.798
1980	2.021	2.021	0.903	0.786
1981	2.15	2.15	0.909	1.601
1982	2.34	2.34	1.096	1.277
1983	2.025	2.025	0.932	0.64
1984	2.199	2.199	1.072	1.382
1985	2.215	2.215	1.273	1.32
1986	2.427	2.427	1.02	1.373
1987	2.275	2.275	1.072	1.067
1988	2.01	2.01	0.963	1.748
1989	2.193	2.193	0.981	1.35
1990	1.78	1.78	0.757	1.57
1991	1.806	1.806	0.712	1.06
1992	1.977	1.977	0.917	1.182
1993	1.903	1.903	1.017	1.083
1994	1.866	1.866	1.058	1.449
1995	2	2	0.938	0.855
1996	1.879	1.879	1.222	1.38
1997	1.691	1.691	0.835	1.49
1998	1.584	1.584	0.742	0.746

1999	1.901	1.901	0.795	1.103
2000	1.188	1.188	0.724	0.767
2001	1.529	1.529	1.376	1.968
2002	1.924	1.924	1.739	0.8
2003	1.098	1.098	0.816	0.649
2004	1.38	1.38	0.791	1.204
2005	1.404	1.404	1.107	1.414

Date (A.D.)	**Landscape**				
	Human Population	Logging			Beaver Population* Index
		Pulpwood (1000 std. cords)*	Boardfeet*	Aspen (1000 std. cords)*	
1900	4573				
1901	4575.9				
1902	4578.8				
1903	4581.7				
1904	4584.6				
1905	4587.5				
1906	4590.4				
1907	4593.3				
1908	4596.2				
1909	4599.1				

1910	23639		114,720,770		
1911	23639.9		113,631,730		
1912	23640.8		128,775,580		
1913	23641.7		134,207,180		
1914	23642.6		136,161,740		
1915	23643.5		132,162,130	**1100**	0
1916	23644.4		128,684,040	**1180**	0
1917	23645.3		145,975,420	**1260**	0
1918	23646.2		109,273,820	**1340**	0
1919	23647.1		88,047,170	**1420**	0
1920	37396		75,820,670	1500	0
1921	37399		62,694,170	**1580**	0
1922	37402		46,580,980	**1660**	0
1923	37405		86,550,820	**1740**	0
1924	37408		93,318,230	**1820**	0
1925	37411		96,417,545	1900	0
1926	37414		67,375,620	**1855**	0
1927	37417		95,695,495	**1810**	0
1928	37420		84,546,260	**1765**	0
1929	37423		50,926,660	**1720**	0
1930	41302		**56,848,977**	1675	0
1931	41307.1		**49,467,864**	**1655**	0
1932	41312.2		**42,086,751**	**1635**	0
1933	41317.3		**34,705,638**	**1615**	0
1934	41322.4		**27,324,525**	**1595**	0
1935	41327.5		**19,943,412**	1575	0

1936	41332.6		**12,562,299**	**1646.667**	0
1937	41337.7			**1718.333**	0.036
1938	41342.8			**1790**	0.072
1939	41347.9			**1861.667**	0.108
1940	49926			1933	0.144
1941	49929.5			2162	0.18
1942	49933			2359	**0.22**
1943	49936.5			2317	**0.26**
1944	49940			2386	**0.30**
1945	49943.5			**2222**	**0.35**
1946	49947			**2059**	**0.39**
1947	49950.5			**1895**	**0.43**
1948	49954			**1731**	0.47
1949	49957.5			**1568**	**0.48**
1950	50231			**1685**	**0.49**
1951	50232			**1801**	**0.49**
1952	50233			**1918**	**0.50**
1953	50234			**2035**	**0.51**
1954	50235			**2152**	**0.52**
1955	50236			**2268**	**0.53**
1956	50237			**2385**	**0.54**
1957	50238			**2502**	**0.54**
1958	50239			2619	0.55
1959	50240	464		3034	0.81
1960	56196	547			1.06
1961	56199.4	516			1.32

1962	56202.8	512			1.09
1963	56206.2	588			0.86
1964	56209.6	569			0.63
1965	56213	542			0.80
1966	56216.4	582			0.97
1967	56219.8	574			1.14
1968	56223.2	547			1.31
1969	56226.6	574			0.64
1970	52661	592			1.16
1971	52663.2	581			1.57
1972	52665.4	671			0.84
1973	52667.6	714			0.95
1974	52669.8	809			1.38
1975	52672	706			1.40
1976	52674.2	632			1.51
1977	52676.4	625			1.35
1978	52678.6	622			1.84
1979	52680.8	625			1.93
1980	60640	565			1.59
1981	60644.2	558			2.25
1982	60648.4	559			1.68
1983	60652.6	738			1.83
1984	60656.8	847			2.09
1985	60661	698			1.85
1986	60665.2	750			1.83
1987	60669.4	883			1.87

1988	60673.6	815			1.85
1989	60677.8	866			1.83
1990	57162	910			1.90
1991	57165.4	892			1.63
1992	57168.8	1014			1.78
1993	57172.2	1210			1.94
1994	57175.6	1205			2.05
1995	57179	1176			1.49
1996	57182.4	1188			1.46
1997	57185.8	950			1.23
1998	57189.2	1006			1.00
1999	57192.6	1061			1.05
2000	58347	1081			1.69
2001	58343.7	1047			1.55
2002	58347	1143			1.63
2003	58350.3	1089			1.41
2004	58353.6	1215			1.19
2005	58356.9	1222			0.97

Appendix 3: Diatom Species Plates

Plate 1: (X1500)

Fig. 1-2 *Aulacoseira islandica* (O. Müller) Simonsen

Fig. 3-4 *Aulacoseira ambigua* (Grunow) Krammer

Fig. 5 *Aulacoseira lirata* (Ehrenberg) Ross

Fig. 6 *Aulacoseira alpigena* (Grunow) Krammer

Fig. 7-8 *Aulacoseira granulata* (Ehrenberg) Simonsen

Fig. 9-11 *Aulacoseira subarctica* (O. Müller) Haworth

Fig. 12-13 *Aulacoseira tenella* (Nygaard) Simonsen

Fig. 14-18 *Aulacoseira distans* (Ehrenberg) Simonsen

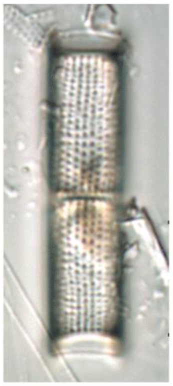
Fig. 19-20 *Cyclotella michiganiana* Skvortzov

Fig. 21-24 *Cyclostephanos invisitatus* (Hohn & Hellerman) Theriot, Stoermer & Håkansson

Fig. 25-26 *Cyclotella ocellata* Pantocsek

Fig. 27 *Cyclotella meneghiniana* Kutzing

Fig. 28-29 *Cyclostephanos dubius* (Fricke) Round in Theriot, Håkansson, Kociolek, Round & Stoermer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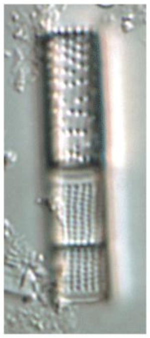
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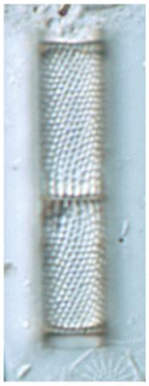
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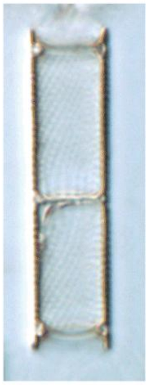
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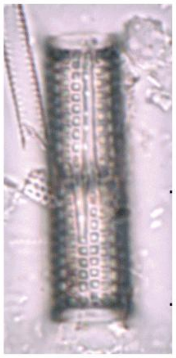
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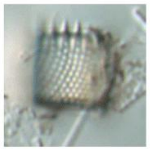
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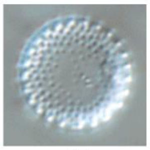
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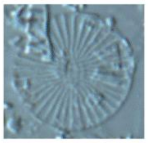
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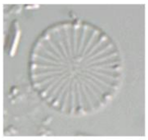
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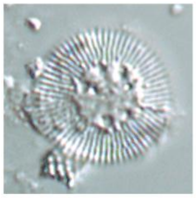
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Plate 2: (X1500)

Fig. 1-4 *Cyclostephanos* sp. 1 as in Reavie and Smol 1998

Fig. 5-6 *Cyclostephanos tholiformis* Stoermer, Håkansson and Theriot

Fig. 7-12 *Cyclotella stelligera* (Cleve & Grunow) Van Heurck

Fig. 13-14 *Cyclotella stelligeroides* Hustedt

Fig. 15-18 *Stephanodiscus parvus* Stoermer & Håkansson

Fig. 19-22 *Stephanodiscus minutulus* (Kützing) Cleve & Möller

Fig. 23-24 *Stephanodiscus* kab

Fig. 25 *Stephanodiscus tenuis* Hustedt

Fig. 26-31 *Stephanodiscus medius* Håkansson

Fig. 32-35 *Stephanodiscus medius* var. voya 1

Fig. 36-37 *Stephanodiscus alpinus* Hustedt in Huber-Pestalozzi

Fig. 38 *Stephanodiscus hantzschii* Grunow in Cleve & Grunow


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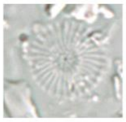
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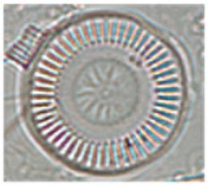
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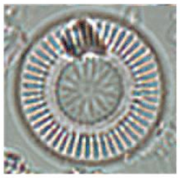
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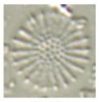
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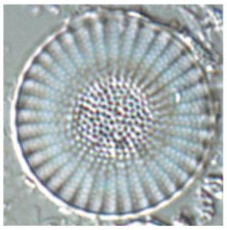
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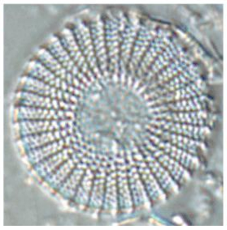
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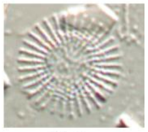
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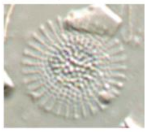
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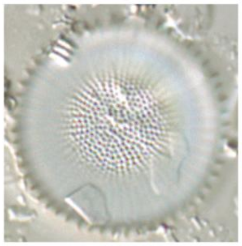
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Plate 3: (X1500)

Fig. 1 *Stephanodiscus niagarae* Ehrenberg

Fig. 2-6 *Puncticulata radiosa* (Grunow) Håkansson

Fig. 7-12, 14 *Urosolenia eriensis* (H.L. Smith) Round & R.M. Crawford in Round, Crawford & Mann

Fig. 13-14 *Urosolenia longiseta* (Zacharias) M.B. Edlund & Stoermer

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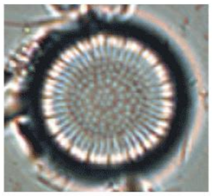

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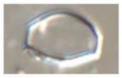

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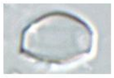

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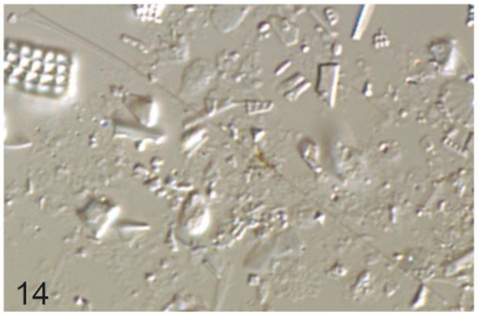

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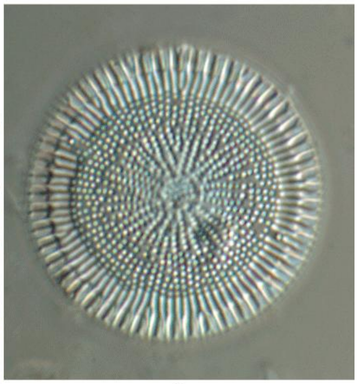

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Plate 4: (X1500)

Fig. 1-5 *Fragilaria capucina* Desmazières

Fig. 6-8 *Fragilaria capucina* var. *mesolepta* (Rabenhorst) Rabenhorst

Fig. 9-12 *Fragilaria capucina* var. *perminuta* (Grunow) Lange-Bertalot

Fig. 13-15 *Fragilaria vaucheriae* (Kützing) Petersen

Fig. 16 *Fragilaria vaucheriae kab*

Fig. 17-18 *Fragilaria voya 4*

Fig. 19 *Fragilaria voya 6*

Note: This could be *F. rumpens var. fragilaroides* (See Patrick and Reimer)


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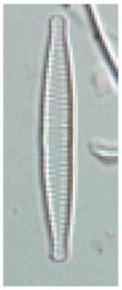
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Plate 5: (X1500)

Fig. 1 *Fragilaria tenera* (W. Smith) Lange-Bertalot

Fig. 2 *Fragilaria nanana* Lange-Bertalot

Fig. 3 *Fragilaria voya 1*

Note: This looks like a cross between *F. nanana* and *F. crotonensis*

Fig. 4 *Synedra acus voya*

Note: This specimen has a little bit denser striae

Fig. 5 *Fragilaria fasciculata* (Agardh) Lange-Bertalot

Fig. 6-7, 10-13 *Fragilaria capucina* var. *gracilis* (Østrup) Hustedt

Fig. 8 *Fragilaria voya 7*

Fig. 9 *Synedra rumpens* var. *familaris* (Kützing) Hustedt

Note: This is the equivalent of *Fragilaria sp6* in Joy Ramstack's collection

Fig. 14-16 *Fragilaria rumpens* var. *voya 1*

Noter: This taxon is smaller then the nominate and has greater striae density

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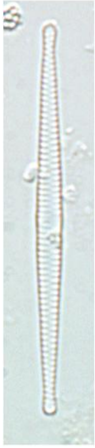

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Plate 6: (X1500 except *Hanaea* X1000)

Fig. 1-2 *Fragilaria crotonensis* Kitton

Fig. 3 *Fragilaria crotonensis* var. *oregona* Sovereign

Fig. 4 *Synedra acus* Kützing

Fig. 5 *Hannaea voya 1*

Fig. 6 *Hannaea voya 2*

Fig. 7-8 *Staurosirella pinnata* var. *lancettula* (Schumann) Poulin in Poulin, Hamilton & Proulx

Fig. 9-10 *Staurosirella lapponica* (Grunow in Van Heurck) Williams & Round

Fig. 11-12 *Staurosirella pinnata* var. *intercedens* (Grunow in Van Heurck) P. B. Ham. in Hamilton, Poulin, Prévost, Angell & Edlund

Fig. 13 *Staurosirella dubia* (Grunow) Morales & Manoylov

Fig. 14 *Fragilaria oldenburgiana* Hustedt

Fig. 15-17 *Staurosirella pinnata* (Ehrenberg) Williams & Round

Fig. 18-20 *Fragilaria pinnata* var. *acuminata* A. Mayer


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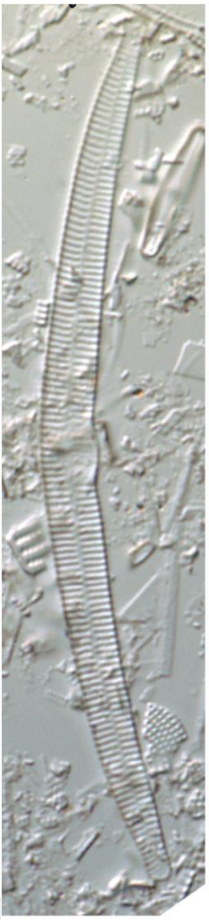
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Plate 7: (X1500)

Fig. 1-3 *Pseudostaurosira brevistriata* (Grunow) D.M. Williams & Round

Fig. 4 *Staurosirella leptostauron* (Ehrenberg) D.M. Williams & Round

Fig. 5-6 *Staurosira construens* Ehrenberg

Fig. 7 *Staurosira construens* var. *pumila* (Grunow) J.C. Kingston

Fig. 8-11 *Pseudostaurosira parasitica* (W. Smith) Grunow

Fig. 12-14 *Fragilaria microstriata* Marciniak

Fig. 15 *Fragilaria pinnata* var. *lancettula* f. *subcapitata* Fusey

Fig. 16 *Fragilaria sp. 4 PIRLA*

Fig. 17-18 *Staurosira construens kab*

Fig. 19-20 *Martyana martyi* (Héribaud) Round in Round, Crawford & Mann

Fig. 21 *Pseudostaurosira robusta* (Fusey) D.M. Williams & Round

Fig. 22-23 *Staurosira construens* var. *binodis* (Ehrenberg) P. B. Ham. in Hamilton, Poulin, Prévost, Angell & Edlund

Fig. 24-25 *Pseudostaurosira parasitica voya 1*

Fig. 26, 31 *Fragilaria exigua RS*

> Note: this specimen is similar to the one identified as *F. exigua* in Reavie and Smol

Fig. 27 *Fragilaria nitzschiodes* (Grunow)

Fig. 28 *Stauroforma exiguiformis* (Lange-Bertalot) Flowers, Jones & Round

Fig. 29-30 *Fragilaria virescens capitata* Østrup


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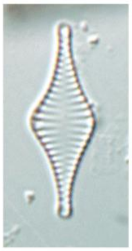
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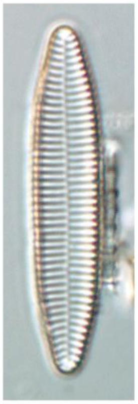
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Plate 8: (X1500)

Fig. 1 *Eunotia pectinalis* (O.F. Müller) Rabenhorst

Fig. 2 *Eunotia voya 1*

Fig. 3 *Eunotia paludosa* Grunow

Fig. 4 *Eunotia implicata* Nörpel, Lange-Bertalot & Alles

Fig.5 *Eunotia incisa* W. Smith

Fig. 6 *Eunotia praerupta* var. *mesodon* f. *polaris* (Ǻ. Berg) Symoens

Fig. 7-8 *Planothidium peragalii* (Brun & Héribaud) Round & Bukhtiyarova

Fig. 9 *Diatoma tenue*

Fig. 10 *Diatoma tenue* var. *elongatum* Lyngbye

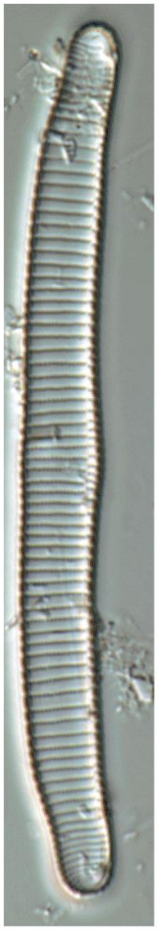
Fig. 10-11 *Achnanthes joursacense* Héribaud

Fig. 12-15 *Achanthes lanceolata* spp. *frequentissima* Lange-Bertalot

Fig. 17-20 *Achnanthes lanceolata* spp. *rostrata* Hustedt

Fig. 21 *Eunotia zasuminensis* (Cajeb.) Koerner

Fig. 22 *Asterionella formosa* Hass.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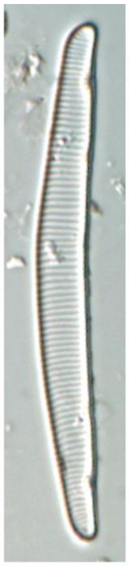
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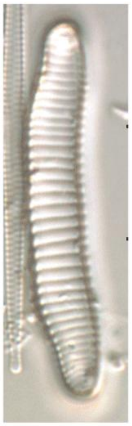
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Plate 9: (X1500)

Fig. 1-3 *Planothidium oestrupii* (H. Bachm & A. Cleve) Round & Bukhtiyarova

Fig. 4, 9 *Eucocconeis lapponica* var. *ninckei* (Guermeur & Mang.) Stoermer & Yang

Fig. 5, 8 *Achnanthes delicatula* ssp. *hauckiana* (Grunow) Lange-Bertalot

Fig. 6 *Achnanthes grischuna* Wührich

Fig. 7 *Achnanthes* cf. *grana*

Fig. 10 *Achnanthes helvetica* (Hustedt) Lange-Bertalot

Fig. 11-12 *Achnanthes bioretti* Germain

Fig. 13 *Achnanthes ricula* Hohn and Hellerman

Fig. 14 *Eucocconeis flexella* var. *alpestris* (Brun) Hustedt

Fig. 15 *Eucocconeis* cf. *flexella var. alpestris* (Brun) Hustedt

Fig. 16 *Achnanthes curtissima* Carter

Fig. 17 *Achnanthes* cf *microscopica*

Fig. 18-20 *Achnanthes lewisiana* Patrick

Fig. 21 *Achnanthes chlidanos voya 1*

Fig. 22-23 *Achnanthes* cf. *levanderi*

Fig. 24, 31 *Achnanthidium minutissimum* (Kützing) Czarnecki

Fig. 25 *Achnanthes subatomoides* (Hustedt) Lange-Bertalot & Archibald in Krammer & Lange-Bertalot

Fig. 26-30 *Achnanthes levanderi* Hustedt

Fig. 32-34 *Achnanthes didyma* Hustedt

Fig. 35-37 *Achnanthes conspicua* Mayer

Fig. 38-39 *Rossithidium petersenii* (Hustedt) Round & L. Bukhtiyarova ex Aboal


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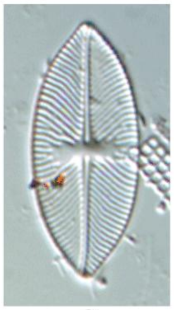
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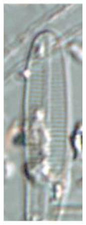
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Plate 10: (X1500)

Fig. 1-2 *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova

Fig. 3-4 *Achnanthes ventralis* (Krasske) Lange-Bertalot in Lange-Bertalot & Krammer

Fig. 5 *Achnanthes voya 1*

Fig. 6 *Achnanthes minutissima var. macrocephala* Grunow

Fig. 7-8 *Achnanthes bicapitata* Hustedt

Fig. 9-10 *Achnanthes nitidiformis* Lange-Bertalot

Fig. 11 *Cocconeis voya 1*

Fig. 12 *Cocconeis placentula var. euglypta* (Ehrenberg) Grunow

Fig. 13-15 *Cocconeis neothumensis* Krammer

Fig. 16 *Amphora dusenii* Brun

Fig. 17-18 *Karayevia clevei* (Grunow in Cleve & Grunow) Round & Bukhtiyarova

Fig. 19-20 *Karayevia laterostrata* (Hustedt) Round & Bukhtiyarova

Fig. 21-22 *Amphora ovalis* var. *affinis* (Kützing) Van Heurck ex DeToni Ehrenberg

Fig. 23 *Amphipleura pellucida* (Kützing) Kützing

Fig. 24-25 *Amphora fogediana* Krammer

Fig. 26-27 *Amphora inariensis* Krammer

Fig. 28-30 *Amphora pediculus* (Kützing) Grunow ex A. Smith


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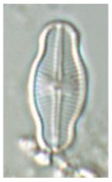
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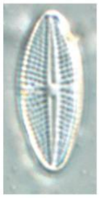
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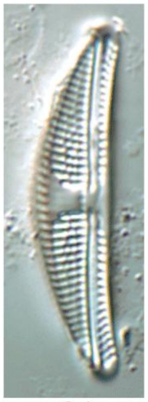
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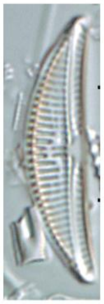
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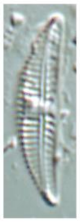
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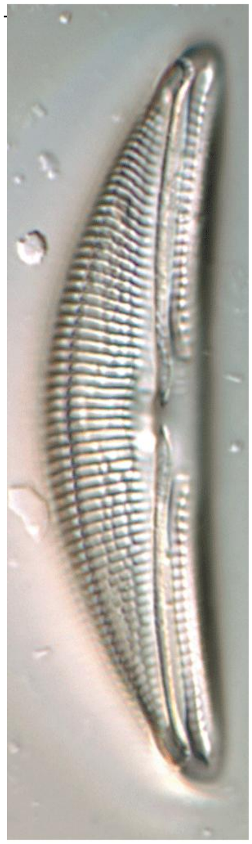
Plate 11: (X1500)

Fig. 1-2 *Amphora ovalis* (Kützing) Kützing

Fig. 3 *Cymbella amphicephala* Naegeli

Fig. 4 *Cymbella descripta* (Hustedt) Krammer & Lange-Bertalot
Fig. 5 *Cymbella cesatii* (Rabenhorst) Grunow
    Note: this specimen is a little bit small
Fig. 6 *Cymbella aspera* (Ehrenberg) Peragalli



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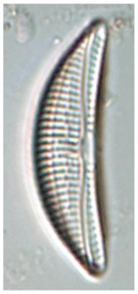

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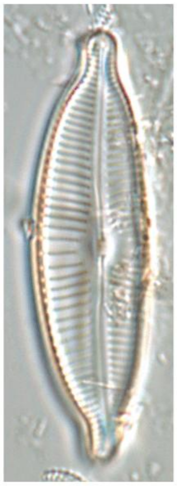

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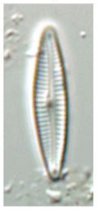

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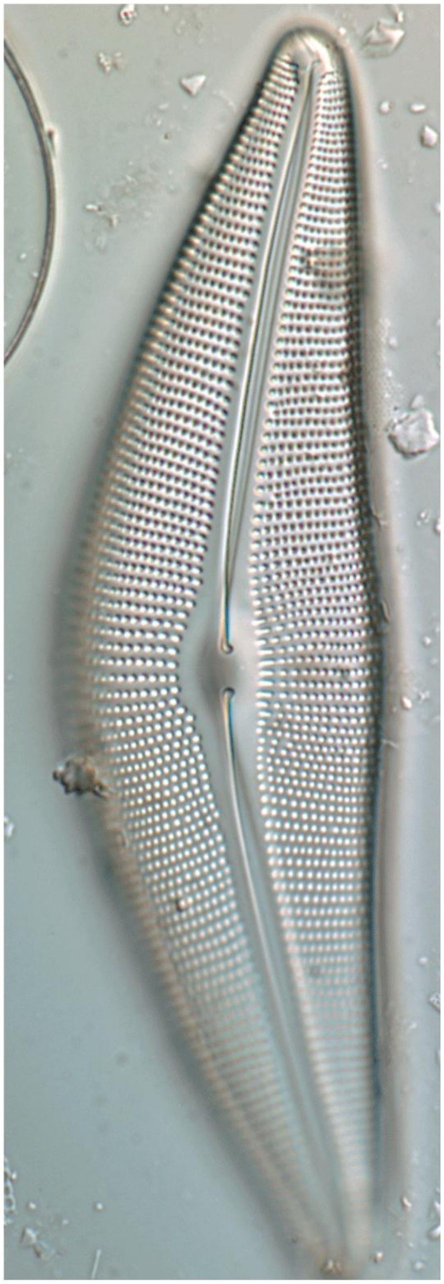

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Plate 12: (X1500)

Fig. 1 *Cymbella mexicana* (Ehrenberg) Cleve

Fig. 2 *Cymbella proxima* Reimer

Fig. 3 *Cymbella cistula* (Ehrenberg in Hemprich & Ehrenberg) Kirchner in Cohn

Fig. 4-5 *Cymbella microcephala* var. *crassa* Reimer

Note: This specimen does not quite fit the specimen found in Patrick and Reimer as it has parallel striae

Fig. 6-7 *Encyonema gracile* Rabenhorst


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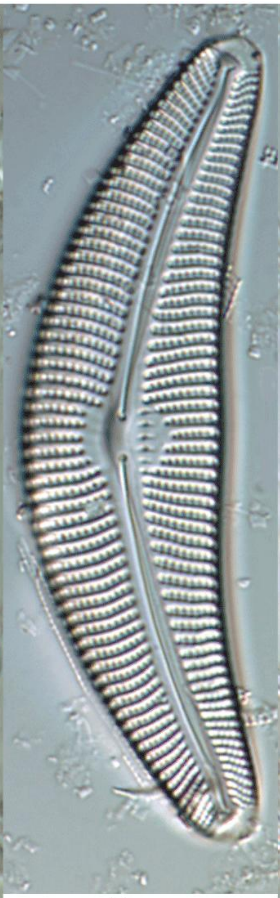
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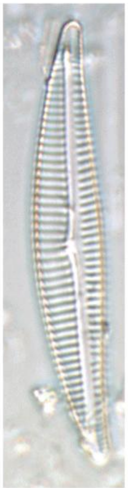
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Plate 13: (X1500)

Fig. 1 *Cymbopleura inaequalis* (Ehrenberg) Krammer

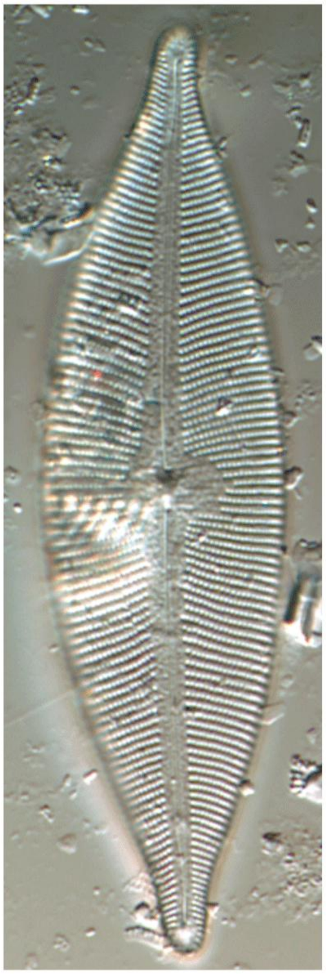
Fig. 2 *Encyonema voya 1*

Note: *Encyonema sp.4 Quebec* in Fallu

Fig. 3 *Encyonema silesiacum* (Bleisch ex Rabenhorst) D. G. Mann in Round, Crawford & Mann

Fig. 4 *Encyonema minutum* (Hilse ex Rabenhorst) D. G. Mann in Round, Crawford & Mann

Fig. 5-6 *Encyonema triangulum* (Ehrenberg) Kützing



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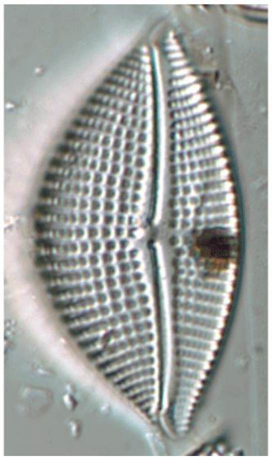

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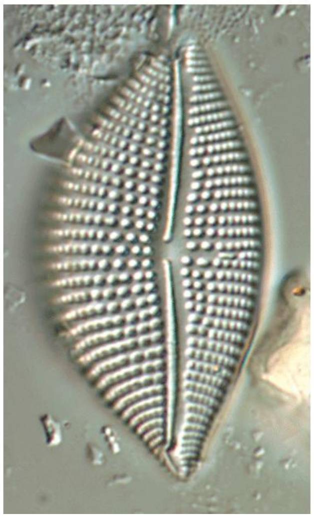

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Plate 14: (X1500)

Fig. 1 *Diploneis modica* Hustedt

Fig. 2 *Diploneis elliptica* (Kützing) Cleve

Fig. 3 *Diploneis parma* Cleve

Fig. 4 *Brachysira neoexilis* Lange-Bertalot

Fig. 5,7 *Caloneis bacillum* (Grunow) Cleve

Fig. 6 *Caloneis silicula* (Ehrenberg) Cleve

Fig. 8 *Caloneis undulata* (Gregory) Krammer in Krammer & Lange-Bertalot

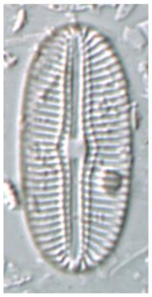
Fig. 9 *Caloneis lauta* Carter & Bailey-Watts

Fig. 10 *Caloneis cf ventricosa* var. *minuta* (Gunow) Mills

Fig. 11-12 *Hippodonta costulata* (Grunow) Lange-Bertalot, Metzeltin & Witkowski

Fig. 13 *Hippodonta capitata* (Ehrenberg) Lange-Bertalot

Fig. 14-16 *Reimeria sinuata* (Gregory) Kociolek & Stoermer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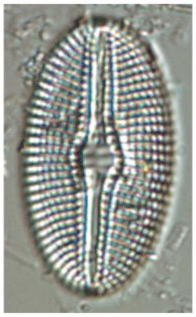
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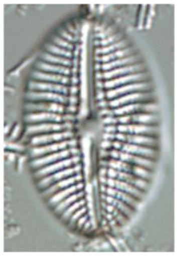
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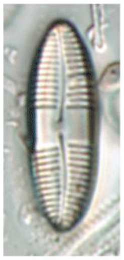
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Plate 15: (X1500)

Fig. 1-2 *Gomphonema affine* Kützing

Fig. 3-4 *Gomphonema olivaceum* (Lyngbye) Desmazieres

Fig. 5 *Gomphonema angustatum* (Kützing) Rabenhorst

Fig. 6 *Gomphonema grovei* M. Schmidt

Fig. 7-8 *Gomphonema* sp.

Fig. 9 *Gomphonema minutum* (Agardh) Agardh

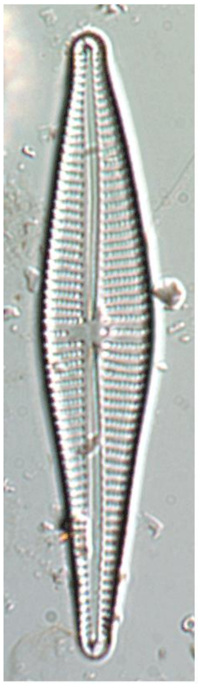
Fig. 10 *Gomphonema dichotomum* Kützing

Fig. 11-12 *Gomphonema gracile* Ehrenberg

Fig. 13-15 *Gomphonema pumilum* (Grunow) Reichardt & Lange-Bertalot

Fig. 16 *Gomphonema clevei* Fricke

Fig. 17-18 *Pulchella kriegeriana* (Krasske) Krammer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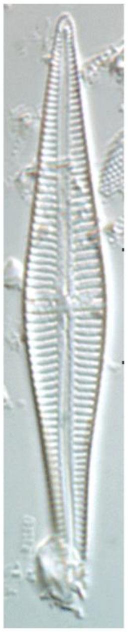
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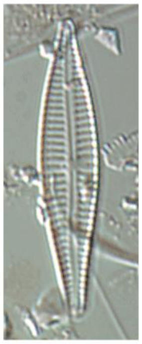
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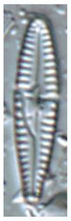
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Plate 16: (X1500)

Fig. 1 *Neidium bisulcatum* (Lagerstedt) Cleve

Fig. 2,5 *Gomphonema truncatum* Ehrenberg

Fig. 3-4 *Neidium cf densiestriatum* (Østrup) Krammer

Fig. 6-9 *Gomphonema acuminatum* Ehrenberg

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Plate 17: (X1500)

Fig. 1 *Pinnularia abaujensis* var. *rostrata* Patrick

Fig. 2 *Pinnularia microstauron var. voya*

Fig. 3 *Pinnularia hilseana* Janisch

Fig. 4 *Pinnularia pulchra* Østrup

Fig. 5 *Pinnularia microstauron* var. *adirondackensis* Camburn & Charles

Fig. 6-7 *Pinnularia kwacksii* Camburn & Charles

Fig. 8 *Pinnularia kab 1*

Fig. 9 *Pinnularia microstauron* var. *brebissonii* (Kützing) Mayer

Note: This specimen differs from nominate form by its elliptical pattern

Fig. 10 *Pinnularia voya 1*

Fig. 11 *Chamaepinnularia soehrensis* var. *hassica* (Krasske) Lange-Bertalot

Note: This specimen looks like the one found in Camburn and Charles. Other publications do not have such a wide central area.


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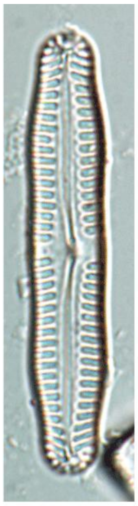
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Plate 18: (X1500)

Fig. 1 *Stauroneis anceps* f. *gracilis* Rabenhorst

Fig. 2 *Stauroneis anceps* Ehrenberg

Fig. 3 *Stauroneis prominula* (Grunow) Hustedt

Fig. 4 *Stauroneis kriegerii* Patrick

Fig. 5-6 *Stauroneis smithii* var. *incisa* Pantocsek

Fig. 7-8 *Stauroneis smithii* Grunow

Fig. 9 *Gyrosigma attenuatum* (Kützing) Rabenhorst

Fig. 10-11 *Geissleria voya 3*


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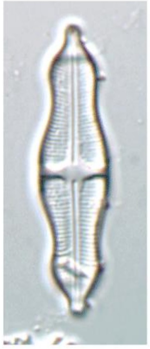
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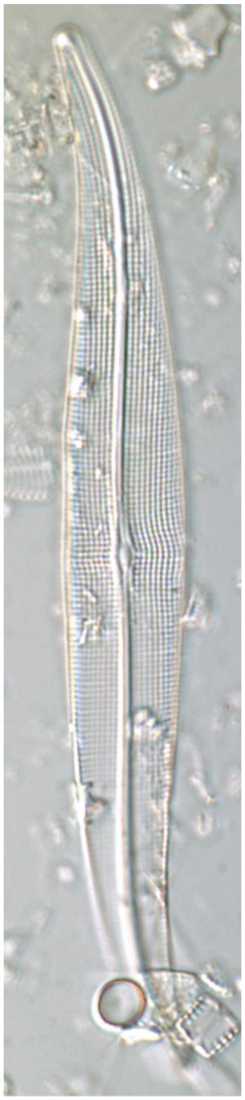
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Plate 19: (X1500)

Fig. 1-2 *Navicula voya 1*

Fig. 3-5 *Navicula* cf. *plicata*

Note: similar but on the small size

Fig. 6 *Navicula vulpina* Kützing

Fig. 7 *Navicula voya 28*

Note: too wide to be *N. rhyncocephala*

Fig. 8 *Navicula voya 3*

Fig. 9 *Navicula voya 26*

Fig. 10-11 *Navicula lenzii* Hustedt

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Plate 20: (X1500)

Fig. 1-3 *Navicula arvensis* Hustedt

Fig. 4-5 *Navicula minusculoides* Hustedt

Fig. 6-8 *Navicula minuscule* var. *muralis* (Grunow) Lange-Bertalot

Fig. 8-9 *Navicula voya 7*

Fig. 10 *Navicula subtilissima voya 1*

Fig. 11 *Navicula submolesta* Hustedt

Fig. 12-13 *Navicula madumensis* Jørgensen

Fig. 14-15 *Navicula farta* Hustedt

Fig. 16 *Navicula submuralis* Husted

Fig. 17-18 *Navicula subminuscula* Manguin

Fig. 19-20 *Navicula lapidosa* Krasske

Fig. 21-22 *Navicula voya 27* (possibly *N. arvensis*)

Fig. 23 *Navicula voya 8*

Note: This is similar to *N. sp39 Quebec* in Fallu

Fig. 24 *Navicula voya 17*


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Plate 21: (X1500)

Fig. 1-3 *Navicula radiosa* Kützing

Fig. 4 *Navicula pseudotuscula* Hustedt

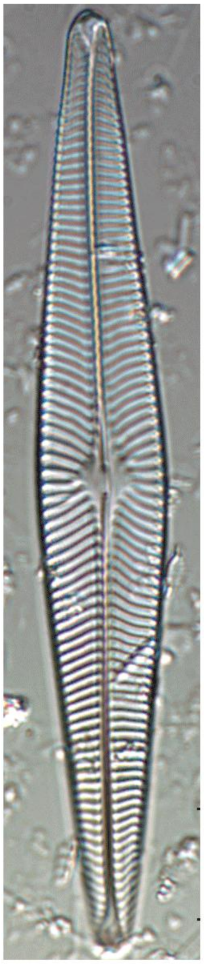
Fig. 5 *Navicula fracta voya 1*

Fig. 6-7 *Navicula pusio* Cleve

Fig. 8 *Navicula scutelloides* W. Smith

Fig. 9 *Navicula pseudoscutiformis* Hustedt

Fig. 10 *Navicula reinhardtii* Grunow



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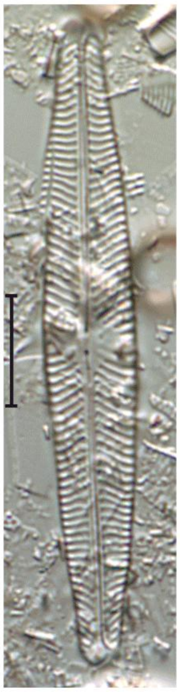

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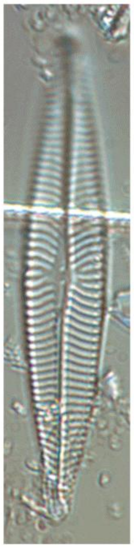

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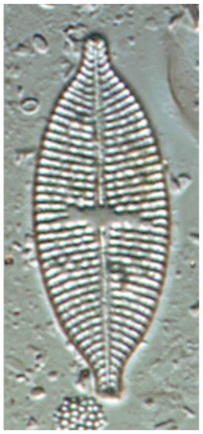

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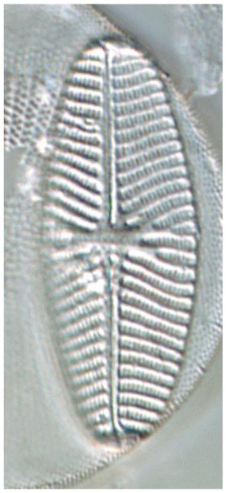

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Plate 22: (X1500)

Fig. 1 *Navicula levanderii* Huestedt

Fig. 2 *Navicula tridentula* Krasske

Fig. 3 *Navicula gerlofii* Schimanski

Fig. 4-5 *Navicula digitulus* Hustedt

Fig. 6 *Navicula difficilima* Hustedt

Fig. 7 *Navicula pseudoventralis* Hustedt

Fig. 8 *Navicula clementis voya 1*

Fig. 9 *Navicula circumborealis* Lange-Bertalot in Lange-Bertalot & Moser

Fig. 10 *Navicula impexa* Hustedt

Fig. 11 *Navicula bryophila* Petersen

Fig. 12 *Navicula detenta* Hustedt

Fig. 13 *Navicula laterostrata* Hustedt

Fig. 14 *Navicula lateropunctata* Wallace

Fig. 15 *Navicula decussis* Østrup

Fig. 16 *Navicula declivis* Hustedt

Fig. 17 *Navicula occulata* Krasske

Fig. 18 *Navicula voya 29*

Fig. 19-20 *Navicula seminulum* (Grunow)

Fig. 21-22 *Navicula seminulum type 1*

Fig. 23 *Navicula voya 9*

Fig. 24-25 *Navicula explanata* Hustedt

Fig. 26 *Navicula porifera* Hustedt


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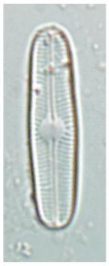
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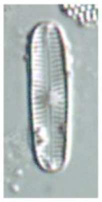
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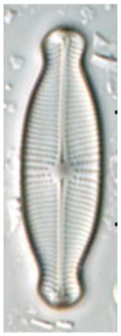
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Plate 23: (X1500)

Fig. 1-2 *Navicula cocconeiformis* Grégory ex Greville

Fig. 3 *Navicula kuelbsii* Lange-Bertalot

Fig. 4 *Navicula voya 18*

Fig. 5-8 *Navicula jaernefeltii* Hustedt

Fig. 9-12 *Navicula aboensis* (Cleve) Hustedt

Fig. 13 *Geissleria voya 4*

Fig. 14-16 *Navicula cf modica*

Note: Striae at the terminal ends are parallel instead of converging

Fig. 17-18 *Navicula secure* Patrick

Fig. 19-21 *Navicula minima* Grunow in Van Heurck

Fig. 22-24 *Navicula utermohleii* Hustedt


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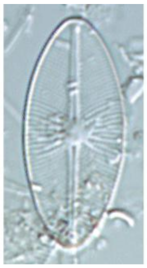
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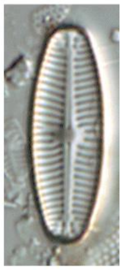
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Plate 24: (X1500)

Fig. 1 *Navicula cryptotenella* Lange-Bertalot

Note: as in Fallu

Fig. 2 *Navicula lanceolata* (Agardh) Ehrenberg

Fig. 3 *Navicula cryptotenella* Lange-Bertalot

Fig. 4-5 *Navicula meniscus* Schumann

Fig. 6 *Navicula kab 1*

Fig. 7 *Navicula aurora* Sovereign

Fig. 8-9 *Navicula recens* (Lange-Bertalot) Lange-Bertalot

Fig. 10 *Navicula cf gregaria voya 4*

Fig. 11-12 *Navicula leptostriata* Jørgensen


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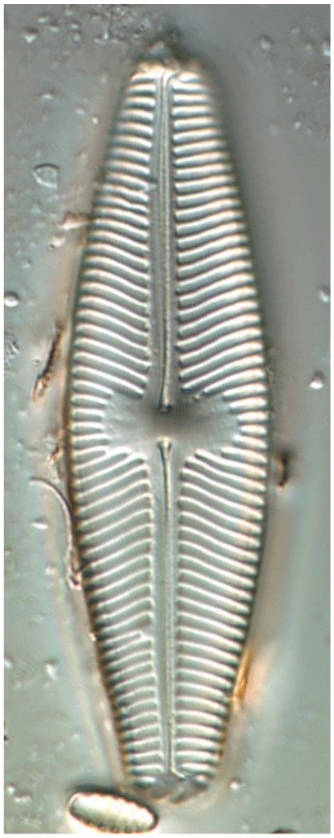
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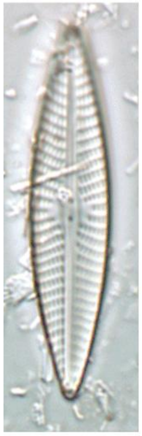
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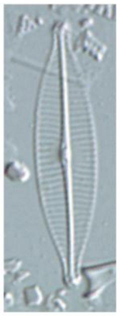
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Plate 25: (X1500)

Fig. 1-3 *Nitzschia liebetruthii* Rabenhorst

Fig. 4 *Nitzschia angustata voya 1*

Fig. 5-6 *Nitzschia inconspicua* Grunow

Fig. 7 *Nitzschia angustata* (W. Smith) Grunow

Fig. 8 *Nitzschia amphibia* Grunow

Fig. 9 *Nitzschia heufleriana* Grunow

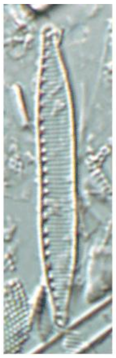
Fig. 10-11 *Nitzschia solita* Hustedt

Fig. 12 *Nitzschia voya 2*

Note: similar to *Nit. perminuta*

Fig. 13 *Nitzschia frustulum* (Kützing) Grunow

Fig. 14-16 *Nitzschia perminuta* (Grunow) Peragallo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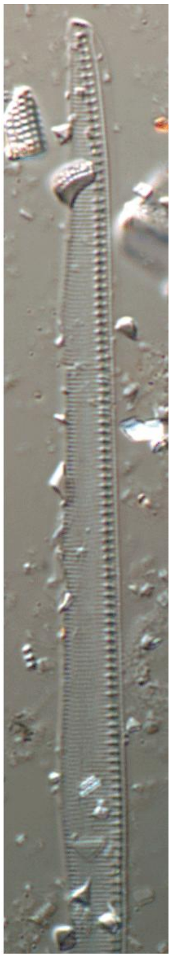
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Plate 27: (X1500)

Fig. 1-2 *Nitzschia palea* (Kützing) W. Smith

Fig. 3 *Nitzschia pumilla* Hustedt

Fig. 4-5 *Nitzschia dissipata var. media* (Hantzsch) Grunow

Fig. 6 *Nitzschia radicula* Hustedt

Fig. 7-8 *Nitzschia gracilis* Hantzsch

Fig. 9-10 *Nitzschia paleacea* (Grunow) Grunow in Van Heurck

Fig. 12 *Nitzschia incognita* Legler & Krasske

Fig. 13 *Nitzschia capitellata* Hustedt in A. Schmidt et al.

Fig. 14 *Nitzschia rectiformis* Hustedt

Fig. 15 *Nitzschia tubicola* sensu lato Grunow in Cleve & Grunow

Fig. 16 *Nitzschia pura* Hustedt

Fig. 17 *Nitzschia fonticola* Grunow

Fig. 18 *Nitzschia lacuum* Lange-Bertalot

Fig. 19 *Nitzschia voya 1*

Note: similar to *Nitz. fonticola* in Cumming, Wilson, Hall & Smol

Fig. 20 *Nitzschia recta* Hantzsh

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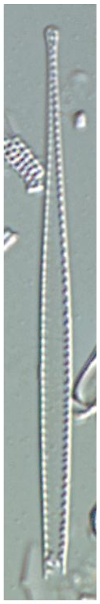

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Plate 28: (X1500)

Fig. 1 *Entomoneis ornata* (J.W. Bailey) Reimer

Fig. 2 *Rhopalodia gibba* (Ehrenberg) Müller

Fig. 3 *Epithemia adnata* (Kützing) Brébisson

Fig. 4 *Hantzschia amphioxys* (Ehrenberg) Grunow

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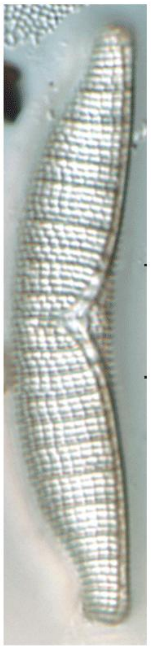

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Plate 29: (X1500)

Fig. 1 *Stenopterobia densestriata* (Hustedt) Krammer

Fig. 2-3 *Surirella splendida* (Ehrenberg) Kützing

Fig. 4 *Stenopterobia delicatissima* (Lewis) Brébisson

Fig. 5 *Surirella angusta* Kützing

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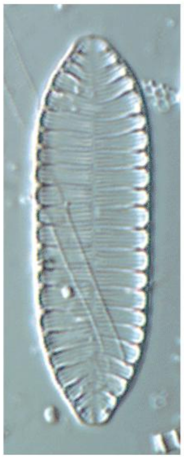

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