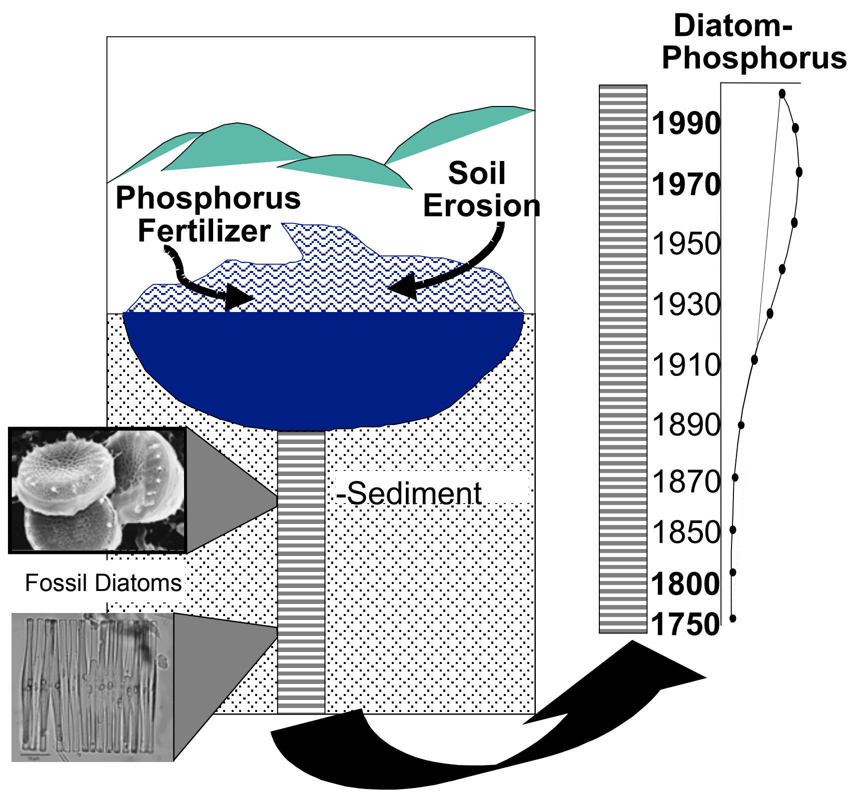
Water Quality Reconstruction from Fossil Diatoms: Applications for Trend Assessment, Model Verification, and Development of Nutrient Criteria for Lakes in Minnesota, USA

Part of a series on Minnesota Lake Water Quality Assessment



Minnesota Pollution Control Agency

September 2002

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Environmental Outcomes Division

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Diatom reconstruction
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Water Quality Reconstruction from Fossil Diatoms: Applications for Trend Assessment, Model Verification, and Development of Nutrient Criteria for Lakes in Minnesota, USA

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Abstract

Diatom reconstructions of historical phosphorus and chloride concentrations and sediment accumulation rate, based on sediment cores from 55 lakes in Minnesota, provide a unique opportunity for examining temporal and spatial trends in eutrophication, validating eutrophication models, and providing historical perspective for developing nutrient criteria. Sediment cores, obtained by a piston corer between 1995 and 1998, were sectioned and dated. Sections corresponding to 1750, 1800, 1970, and 1993 time-periods were used in this analysis. Distinct regional patterns in historic (mean of 1750 and 1800) phosphorus concentrations were evident: Northern Lakes and Forests lakes averaged 15 µg/L (± 1), North Central Hardwoods Forests lakes averaged 24 µg/L (± 2), and Western Corn Belt Plains lakes averaged 47 µg/L (± 6). Comparing these values to the recent 1990s values suggests no change in the NLF lakes (15 µg/L ± 1), but significant increases in the CHF (38 µg/L ± 5) and WCP lakes (67µg/L ±16). Comparisons were made between the historic values and two empirical models routinely used to help set in-lake phosphorus goals in Minnesota. The first model (Vighi and Chiaudani 1985), based on the morphoedaphic index, is used to predict the background phosphorus concentration of a lake. The second (MINLEAP) is an ecoregion-based model that predicts in-lake phosphorus based on morphometry, watershed area, and ecoregion characteristics (Wilson and Walker 1989). Comparisons between historic phosphorus concentrations and model predictions indicate good correspondence at model-predicted values less than about 30 µg/L. Lastly, the use of diatom-inferred values is explored as a part of Minnesota's efforts to develop water quality standards for nutrients.

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List of Acronyms and Abbreviations

AGNPS	Agricultural Nonpoint Source Model
BWCAW	Boundary Waters Canoe Area Wilderness
CHF	North Central Hardwood Forests ecoregion
Cl	Chloride
CLP	Clean Lakes Program
CRP	Conservation Reserve Program
CSAR	County state-aid road
CWP	Clean Water Partnership Program
DI	diatom-inferred
LAP	Lake Assessment Program
LCMR	Legislature Commission on Minnesota Resources
MDNR	Minnesota Department of Natural Resources
MINLEAP	Minnesota Lake Eutrophication Evaluation and Assessment Procedure (model)
MPCA	Minnesota Pollution Control Agency
NLF	Northern Lakes and Forests ecoregion
OHW	ordinary high water level
P	phosphorus
ppb	parts per billion = micrograms per liter (µg/L)
ppm	parts per million = milligrams per liter (mg/L)
PVC	polyvinyl chloride
SNF	Superior National Forest
SWCD	Soil and Water Conservation District
TP	total phosphorus
WCP	Western Corn Belt Plain ecoregion

Introduction

Diatom reconstructions of historical phosphorus concentration, based on sediment cores from 55 lakes in Minnesota, provide a unique opportunity for examining temporal and spatial trends in eutrophication, validating eutrophication models, and providing historical perspective for developing nutrient criteria. There have been numerous diatom-based water quality reconstruction studies in Minnesota, which have focused on: individual lakes, e.g., Lake Harriet (Brugam and Speziale, 1983) and Shagawa Lake (Bradbury and Megard, 1972); paired comparisons: Meander and Dogfish Lakes (Bradbury, 1986); or a few lakes representing different regions or degrees of anthropogenic influence: Shagawa, Minnetonka, Sallie and St. Clair Lakes (Bradbury, 1975). However no previous Minnesota study has used sediment diatoms to assess spatial and temporal changes in trophic status across a wide geographic range of Minnesota lakes.

Quantitative diatom reconstruction of water quality can define the timing and extent of cultural disturbances and identify pre-disturbance conditions (Reavie et al. 1995a). Reconstruction can also reveal geographic areas where lakes tend to be naturally eutrophic and hence whose remediation is not as likely to improve water quality. Numerous diatom-reconstruction studies have been conducted across North America (Dixit et al. 1992) and Europe for these and related purposes. Some example applications of diatom reconstruction include:

- Hall and Smol (1995) used diatom-reconstruction to assess impact of shoreland development on a range of Ontario lakes.
- Garrison and Wakeman (2001) used diatom reconstruction to evaluate the affect of logging and shoreland development on softwater and hardwater lakes in Wisconsin.
- Laird and Cumming (2001) and Laird et al. (2001) used diatom reconstruction to evaluate the impact of logging on British Columbia lakes.
- Siver et al. (1999) used diatom reconstruction of 23 Connecticut lakes to evaluate changes in lake pH, conductivity, and trophic status relative to changes in land use over the past 100 years.
- Anderson and Rippey (1994) monitored lake recovery from point source eutrophication.

In our study sediment cores obtained by a piston corer between 1995 and 1998 were sectioned and dated. Sections corresponding to c. 1750, 1800, 1970, and 1993 time-periods were used in this analysis. These cores were originally collected as a part of a larger Legislative Commission on Minnesota Resources (LCMR) project entitled "Atmospheric and Nonpoint Pollution Trends in Minnesota Lakes". This was a multi-faceted project that was originally designed to examine temporal and spatial patterns in Hg accumulation in Minnesota lakes (Engstrom et al. 1999). In the current project diatom reconstructions of pH, chloride (Cl), color, acid neutralizing capacity (ANC), and total phosphorus (TP) were conducted for the 55 lakes for the noted time periods. In a separate aspect of this project the core slices were analyzed for several trace metals and organic contaminants.

This paper focuses on the diatom-reconstructions of historical TP and Cl concentrations and sediment accumulation rates for the 55 study lakes. TP has long been viewed as the primary nutrient contributing to the lake eutrophication and is a one of three routinely used indicators of trophic status (Carlson, 1977). Reconstruction of historic phosphorus (P) concentrations, via fossil diatoms, is a good means for assessing trends in trophic status over time. When these results are combined with ancillary information on lake and watershed characteristics we can better understand man's role in these trends (note P and TP will be used interchangeably in this report to refer to total phosphorus). Cl is often used as a tracer in water quality studies because its concentration in water is not significantly affected by biological or chemical processes in a lake. It is typically found at low concentrations in freshwater lakes in Minnesota, absent man-induced inputs from road salting or wastewater discharges. As such it can provide another indicator of man (or in some instances) climate-induced changes in lake-water chemistry.

Hall and Smol (1992) pose some standard questions that diatom reconstructions often are used to answer and are summarized as follows:
1. Was the lake originally eutrophic?
2. Did nutrient levels increase over time?
3. What type of land use practice is associated with nutrient increases?
4. Are lakes presently recovering in response to abatement efforts?

These questions capture several of the issues we would like to address in this paper. As such, we will focus on the following in this paper:

1. How do modern-day diatom-inferred TP concentrations compare to observed TP from the training and independent data sets?
2. How have TP and Cl concentrations and sediment accumulation rates changed from pre-European to modern-day for the individual lakes, groups of lakes, and ecoregions? And, how do the study lakes compare to the larger population of lakes for a given ecoregion (i.e., how representative are they)?
3. How do these changes relate to modern-day land use composition and changes in land use over time?
4. Can we explain observed changes in these variables based on data and historical information on the lakes and their watersheds (e.g., land use)?
5. How do pre-European TP values compare with models used to estimate "background" or "ecoregion-based" estimates of TP?
6. How can diatom-inferred (DI) TP be used in goal setting and development of nutrient criteria for lakes?

Methods

Water Quality Data

Water quality samples were collected using standard techniques as routinely employed in MPCA's lake assessments. Surface samples were collected with an integrated sampler, constructed from a PVC tube 6.6 feet (2 meters) in length with an inside diameter of 1.24 inches (3.2 centimeters). Sampling procedures were employed as described in the MPCA

Quality Control Manual. Samples were analyzed for nutrients, color, solids, pH, alkalinity, turbidity, conductivity, chloride and chlorophyll (Appendix I). Temperature and dissolved oxygen profiles and Secchi disk transparency measurements were also taken on each sample date. Characteristic water chemistry values for each of the lakes were calculated as the average from a minimum of two samples obtained between 1993 and 1998. Water analyses were performed by both the Minnesota Department of Health and the Natural Resources Research Institute using U.S. Environmental Protection Agency (EPA)-approved methods. A comparison of results between the two laboratories, based on sample splits, shows good concordance for most parameters. Results of this comparison are available. All water quality data were stored in STORET. In addition, historical (1970 to 1999) water quality data was obtained from the STORET database and used in case studies for individual lakes and to further assess the performance of diatom reconstructions.

Sediment Cores

A single sediment core spanning the last 200-300 years of lake history was collected from the deeper region of each of the 55 lakes. The cores were collected during the open-water season by means of a piston corer fitted with a 7.5 cm clear plastic core barrel and operated from the lake surface by rigid drive-rods. The sediments were extruded vertically from the top of the tube at 1 to 4 cm intervals and stored under refrigeration until subsampled for various analyses. Sediments were dated by ^{210}Pb methods to determine age and sediment accumulation rates for the past 150-200 years. Lead-210 was measured by ^{210}Po distillation and alpha spectroscopy (Eakins & Morrison, 1978), and dates were calculated by the constant rate of supply (c.r.s.) model (Appleby & Oldfield, 1983).

Diatom Species Assemblages

Diatom assemblages were analyzed from four levels in each lake's core, corresponding to c. 1750, 1800, 1970, and 1993 (modern, or top 2 core of the core). This sampling strategy was intended to assess: 1) the trajectory of change from 1970 to the mid-1990s, 2) the magnitude of trophic change from pre-industrial to modern times, and 3) variation possible in diatom assemblages due to natural variation in the environment alone, by comparing the two pre-industrial samples.

A 10% hydrochloric acid solution was used to dissolve carbonates in the samples and hydrogen peroxide was used to oxidize organic matter. After the chemical treatments, samples were rinsed and stored in distilled water. The diatom suspensions were settled on to coverslips and affixed to slides with Naphrax, a high refractive index mountant. At least 400 diatom valves were identified along transects in the modern samples. In the earlier (1750, 1800, and 1970) core sections, 300 valves were counted, except where the concentration of diatoms was extremely low. In these cases, 10 transects were counted. Due to poor diatom preservation, the reconstructions for 1970 for Marcott Lake and Sagatagan Lake were based on 145 and 80 diatom valves, respectively. In seven of the 1750 and 1800 samples, reconstructions were not performed because of poor preservation. Diatoms were identified to species following Krammer and Lange-Bertalot

(1991) and Patrick and Reimer (1966, 1975). Further details on methods may be found in Ramstack (1999) and Ramstack et al. (2002, in press).

Calculation of Inferred Historical Chemical Conditions

Relationships between water-chemistry variables and modern diatom assemblages were evaluated by using canonical correspondence analysis (CCA) in the program CANOCO (ter Braak, 1988). A total of 108 diatom taxa were used in these ordinations. Weighted averaging (WA) calibration with inverse deshrinking was used to develop transfer functions for reconstructing water-chemistry variables from fossil diatom assemblages in deeper core sections. Water chemistry variables included: pH, acid neutralizing capacity (ANC), conductivity, potassium, magnesium, calcium, sodium, chloride, sulfate, silica, Secchi depth, water color, dissolved organic carbon, total phosphorus, total nitrogen, and chlorophyll a.

Root mean square error (RMSE, square root of sum of squares of two components) was used to provide an overall estimation of the integrity of prediction of the diatom-inferred TP and Cl from the modern diatom assemblages. In addition to the apparent RMSE, a bootstrapping technique was employed to calculate a prediction RMSE (RMSEP), which yields a more realistic estimate of error.

Geographic Information Collection

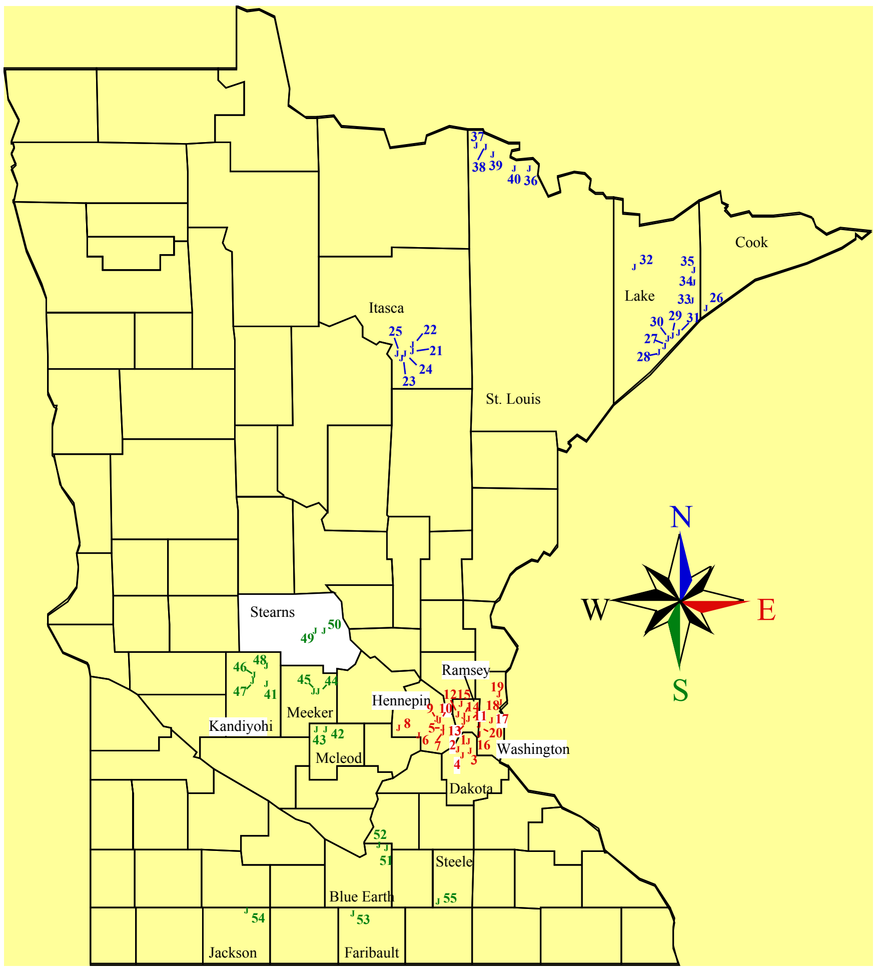
Watershed characteristics were mapped by GIS technology as part of this study. An ARC/INFO database was created with four thematic layers (base map, land cover, roads, and slope) for each of the 55 watersheds. Source data include 1991 NAPP color infrared stereo aerial photos, USGS 7.5' digital elevation maps, USGS Hydrological Investigation Atlas and Minnesota DOT roads data. Land use in each watershed was classified in the following categories: built-up, road surface, agricultural, deciduous forest, mixed forest, conifer forest, and wetland.

Background

Lake and watershed characteristics

As noted previously, the lakes were not selected randomly and hence we must be careful in any extrapolation from this population to an entire ecoregion (Figure 1). It is instructive, however, to make some comparisons between the study lakes and the overall assessed lakes from each ecoregion to provide perspective on how representative they may be for the ecoregion as a whole. Morphometric and watershed land use data are summarized in Table 1 based on data in Appendix I and II. The "interquartile (IQ) range" is a non-parametric statistic and is used (here and elsewhere in the report) as a basis for describing the central tendency of the population. The IQ range represents those observations between the 25^{th} and 75^{th} percentiles when all observations are ranked.

Figure 1. (a) Study-lake locations.



#	DNR ID #	Name
1	19-0046	Dickman
2	19-0057	Fish
3	19-0042	Marcott
4	19-0075	Schultz
5	27-0031	Calhoun
6	27-0137	Christmas
7	27-0016	Harriet
8	27-0179-02	Little Long
9	27-0035-01	Sweeney
10	27-0035-02	Twin
11	62-0007	Gervais
12	62-0078	Johanna
13	62-0054	McCarrons
14	62-0056	Owasso
15	62-0061	Turtle
16	82-0166	Carver
17	82-0106	Elmo
18	82-0014	L. Carnelian
19	82-0046	Square
20	82-0115	Tanners
21	31-0560	Forsythe
22	31-0575	Little Bass
23	31-0570	Long
24	31-0571	Loon
25	31-0569	Snells
26	16-0634	Dyers
27	38-0409	Bean
28	38-0405	Bear
29	38-0232	Nipisiquit
30	38-0231	Tettegouche
31	38-0242	Wolf
32	38-0691	August
33	38-0033	Ninemile
34	38-0047	Wilson
35	38-0068	Windy
36	69-0682	Little Trout
37	69-0936	Locator
38	69-0872	Loiten
39	69-0870	Shoepack
40	69-0756	Tooth
41	34-0044	Diamond
42	43-0073	Hook
43	43-0104	Stahl
44	47-0082	Dunns
45	47-0088	Richardson
46	34-0142	George
47	34-0116	Henderson
48	34-0066	Long
49	73-0097	Kreighle
50	73-0092	Sagatagan
51	07-0047	George
52	07-0053	Duck
53	22-0074	Bass
54	32-0018	Fish
55	74-0023	Beaver

Figure 1. (b) Ecoregion Map

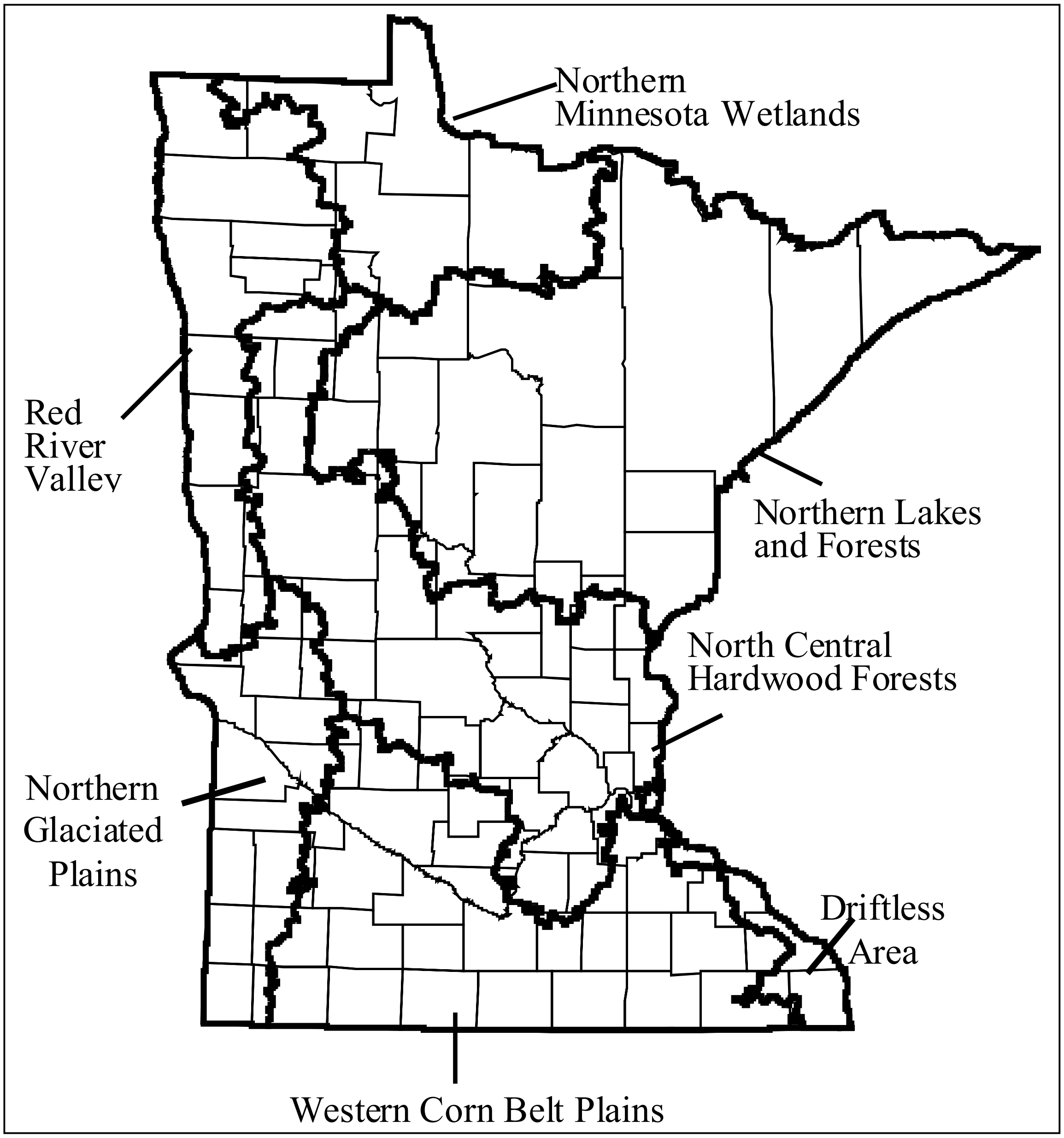


Table 1. Lake morphometry and watershed land use. Interquartile range for "assessed" lakes (morphometry) and reference lakes (land use) compared to diatom study lakes.

	NLF-Assess (~1,200 lakes)	*Diatom (20 lakes)*	*CHF-Assess (~800 lakes)*	*Diatom (30 lakes)*	*WCP-Assess (~95 lakes)*	*Diatom (5 lakes)*
Area (ha)	29 - 181	29-112	30 - 180	26-96	72 - 288	38-116
Max. depth (m)	6.6 - 17.2	9.4 - 17.3	5.8 - 14.5	7.0 - 15.4	2.1 - 4.2	7.6 - 8.2

Land use %	*NLF-Ref*	*Diatom*	*CHF-Ref*	*Diatom*	*WCP-Ref*	*Diatom*
Forest	54 – 81	60 - 91	6 - 25	4 - 26	0 – 15	4 - 18
Water/Marsh	14 - 31	1 - 7	14 – 30	2 - 9	3 – 26	0 - 4
Cultivated/Past	0 - 1	0 - 1	36 – 68	0 - 33	48 - 76	70 - 86
Urban	0 - 7	0 - 1	2 – 9	5 - 86	0 - 16	4 - 17

The NLF and CHF study lakes were quite representative of the assessed population in terms of morphometry. In contrast, the WCP lakes tended to be deeper and smaller than the norm for the region. In terms of land use composition, the study lakes were fairly comparable to the reference lakes for the NLF and WCP ecoregions. The CHF study lakes, however, had a stronger urban influence than the reference lakes but in both instances this was by design (i.e., 20 urban lakes were included to assess impacts of urbanization). In the case of reference lake selection we avoided heavily urbanized watersheds and in the diatom-reconstructions specific comparisons between the agricultural and urban portion of the ecoregion were a focus of the study.

Selection of time periods

The 1750 and 1800 time periods were intended to represent a period in Minnesota's history prior to major European settlement of the State. This assumes there were no major water quality related impacts on lakes as a result of native cultures on or near the lakes. Various accounts from Schoolcraft (1872) and others help place this time period in perspective. Mitchell (1915) notes that "during the century and a half from 1655 to 1805 Minnesota was explored by a number of white travelers – often fur traders." Prominent exploration for this period included Father Hennepin coming to Minnesota in the late 1670's and Zebulon Pike's exploration of the Mississippi River, which brought him as far north as Leech Lake in 1805 (Schoolcraft, 1872). He was later followed by Schoolcraft in 1832, who is credited with the discovery of Lake Itasca as the headwaters of the Mississippi River. Mitchell (1915), in an account of the history of Stearns County and central Minnesota, noted the westward movement of the Ojibway toward the "great Dakota city at Mille Lacs" in about 1750. The Dakota moved south and westward and Mitchell notes that Stearns County served as a "frontier" between the Ojibway and Dakota for about 100 years. Minnesota was organized as a "territory" in 1849 and a census at that time indicated a population of "4,940 souls" (Lawson and Nelson, 1905).

Harrison (1985) described the European influence in northeastern Minnesota from 1750 to 1800 as largely limited to fur traders. Fur trading posts during this period, likely mark some of the first European influence near watercourses, as they were typically located on major waterways near Indian campsites on elevated land. Logging was and is a significant use of land in northern Minnesota. Logging in eastern Minnesota (Pine, Aitkin, and Carlton) began in about 1830 and was pursued intensively until about 1890 when the white pine were essentially gone (Harrison, 1985). Loggers moved northward into the Superior National Forest area, where logging prospered from c. 1880 to c.1940. Settlement followed logging in many areas by the 1850s. So, based on these and other accounts, the European influence in the 1750 to 1800 time frame was likely limited to fur trading outposts and some early forts constructed near rivers or lakes.

Marschner (1930) mapped the “pre-settlement” vegetation for Minnesota based on survey notes, descriptions, and maps made by the US General Land Office between about 1850 to 1905. Marschner’s maps, along with Heinselman’s (1974) description of this work, provide a basis to compare vegetation in pre-European era to modern-day vegetation. These comparisons, in some instances, provide potential explanations for observed water quality changes derived from the diatom reconstructions. One theme that emerges from this and related works (e.g., Heinselman, 1973; Waddington, 1969) was the significance of fire in modifying the pre-European vegetation both in the prairie and forested areas of Minnesota. Fires, while having a dramatic impact on the vegetation, may also influence runoff quantity and quality (e.g., sediment transport; Garrison and Wakeman, 2001) and may serve to explain some of the observed (lake-specific) differences between pre-European and modern-day TP and Cl concentrations. Suppression of fire over the past century has minimized the impact of this factor in modern times.

Results and Discussion

I. Temporal and Spatial Trends in Phosphorus and Chloride Concentrations and Sediment accumulation rates

Comparisons of pre-European and modern-day sediment core data, combined with modern-day water chemistry measurements, were used to assess temporal and spatial trends on a region-wide and lake-specific basis. More specifically, comparisons of historic phosphorus (P) and chloride (Cl) concentrations (based on diatom reconstructions) from pre-European time period (1750 and 1800), modern-day (1970 and 1990s) and observed 1990s water chemistry are made in this report. In addition information on sediment accumulation rates and changes in sediment accumulation rates (addressed in more detail in Engstrom et al. 1999) were used to help describe temporal and spatial changes in lake condition. Our primary framework for stratifying data is based on ecoregion, however we will also make within-region comparisons where appropriate, capitalizing on the original study design that selected lakes in six distinct groups (Figure 1).

a. Comparison of modern-day observed and diatom-inferred TP

Prior to describing historic condition and trends it is instructive to examine how modern-day observed data compare with the diatom reconstructions. The root mean square error (RMSE) is a common statistic used to describe the "error" (strength of the transfer function) associated with the diatom reconstruction model that is used to estimate or infer TP or other measurements from the diatom assemblages in the core (Ramstack, 1999). The correlation coefficient (R^2) and RMSE (apparent) and RMSEP (bootstrapped prediction error) for TP and Cl are as follows:

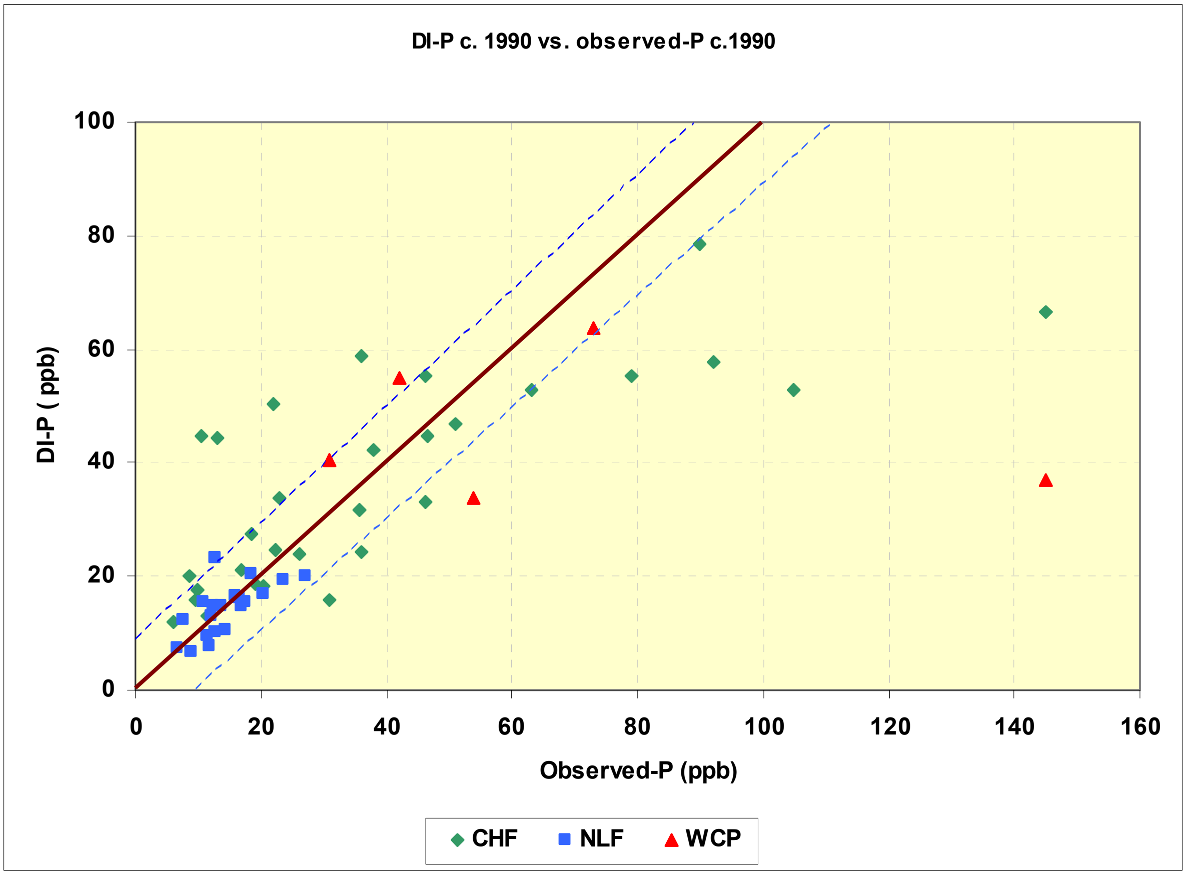
	R^2	RMSE	RMSEP
log Cl	0.77	0.43	0.54
log TP	0.68	0.19	0.25

Based on the above it is evident that the correlation of inferred Cl to observed is greater than that for TP, however the error associated with the estimate is greater for Cl as compared to TP. These correlation coefficients, RMSE and RMSEP values are similar with those found elsewhere in the literature. For example Bennion (1994) reported a R^2 = 0.79, RMSE=0.16 and RMSEP=0.28 for TP from a set of 30 shallow lakes in England and Fritz et al. (1993) report a R^2 = 0.73 and RMSE = 0.41 for TP for a set of 41 Michigan lakes. In our study differences that are greater than the RMSEP (log TP = 0.25) are considered significant (Ramstack, 1999).

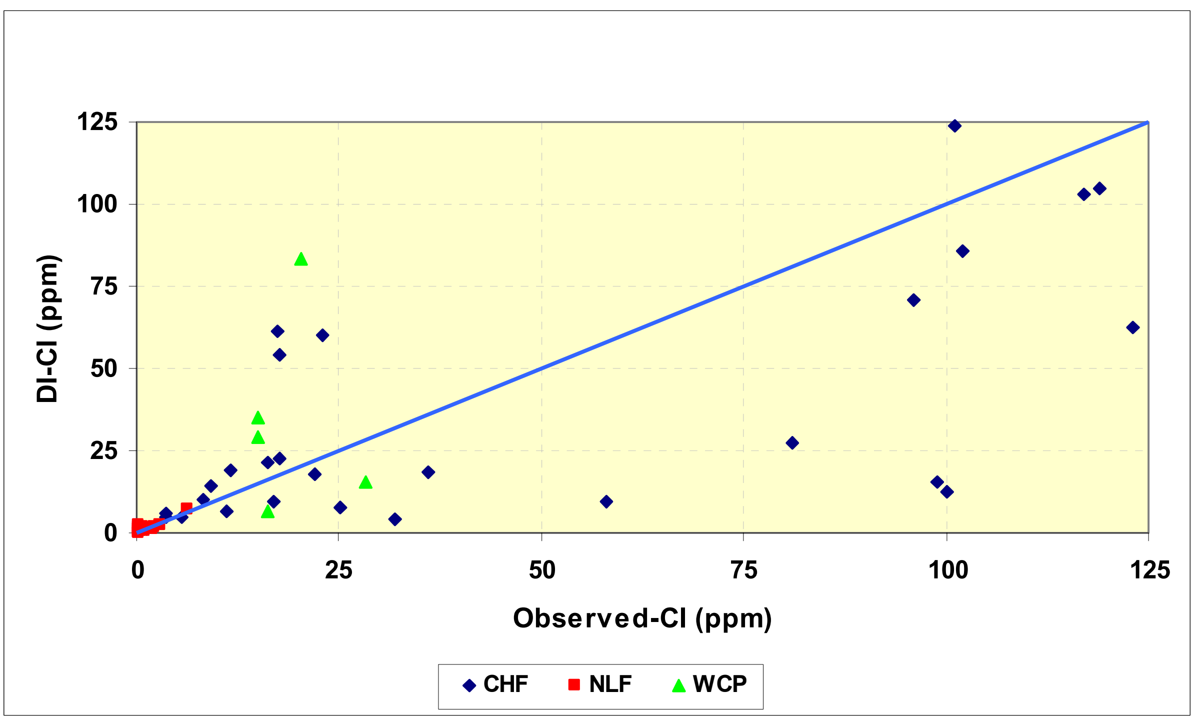
Scatterplots (Figures 2a and b) provide a visual comparison of observed TP and Cl vs. diatom-inferred TP and Cl. As with other diatom reconstruction studies (e.g. Reavie et al. 1995b) the agreement between the reconstructed and observed values is best at the lower end of the trophic (TP) and Cl scales. For example the mean difference between modern-day observed and diatom-inferred P for all NLF lakes averaged 3 µg/L (Figure 2a) (Note: µg/L and ppb, parts per billion, are equivalent and used interchangeably in this report). Observed TP for these lakes was 30 µg/L or less – corresponding to oligotrophic to mesotrophic condition. The CHF lakes observed data ranged from less than 10 µg/L up to 140 µg/L. Here the difference between observed and diatom-inferred averaged 15 µg/L, however 22 of 30 lakes were 10 µg/L or less. The WCP lakes observed TP ranged from about 30 µg/L to 145 µg/L. The difference between diatom-inferred and observed averaged 34 µg/L but this was driven largely by George Lake (Figure 2a). The median difference for the five WCP lakes was 13 µg/L. Cl prediction, likewise, is best at the lower end of the scale (e.g., about 20 mg/L or less; Figure 2b). Most of the lakes where observed Cl was much higher than modern-day diatom-inferred are located in the Metro area and are subject to high Cl loading from road salt (e.g., Fish, Twin, Sweeney, and Carver Lakes).

Figure 2 (a,b,c). Comparison of c. 1990 diatom-inferred (DI) P (a) and Cl (b), and c. 1990 observed P and Cl (training set). 1:1 line and ± 10 ug/L confidence interval (CI) included.

(a)

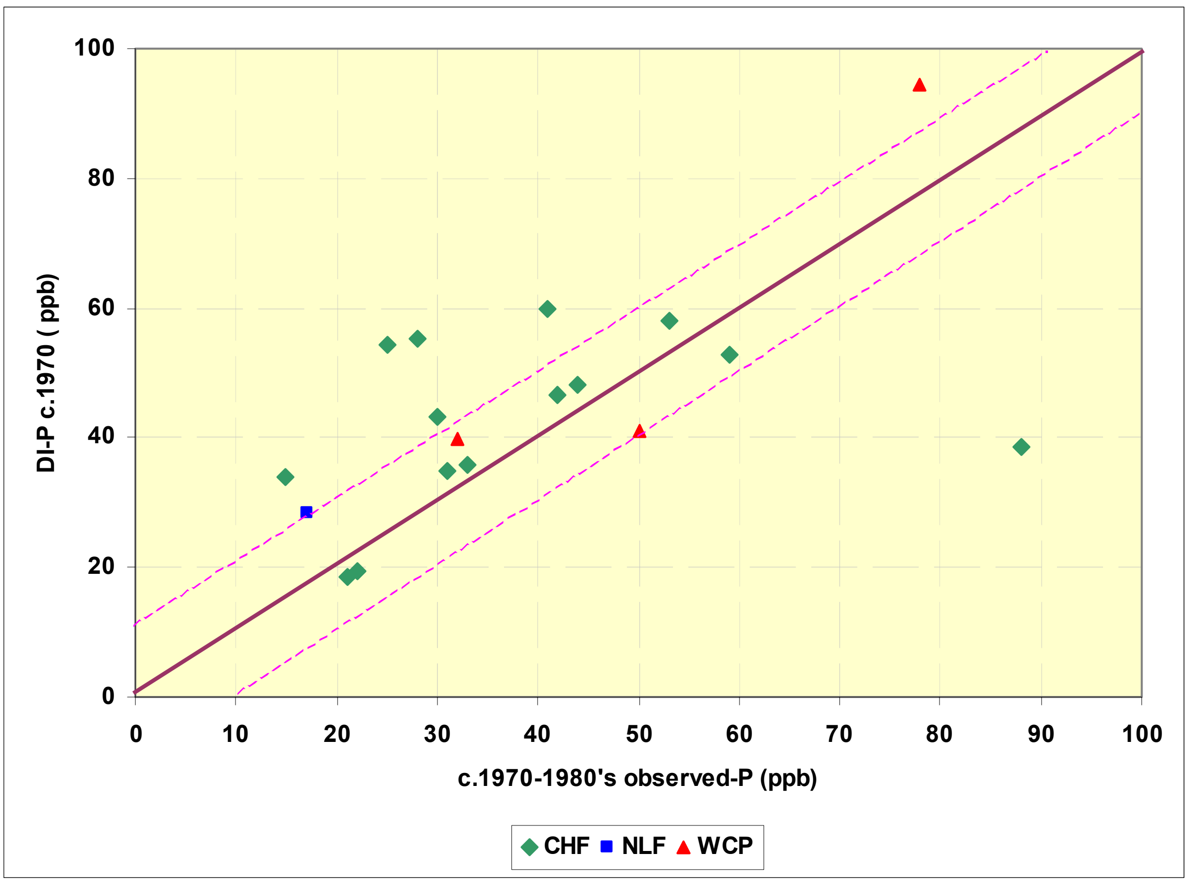


(b)



Since the observed data went into model development they do not provide independent verification of the models. With this in mind, comparisons were made between the c.1970 diatom reconstructions and available observed data for that period. In this case we averaged available water quality data for the period from c.1970 to c.1980 and compared the averages to the diatom-inferred P (Figure 2c). Based on comparisons for 18 lakes we found the mean difference to be 13 µg/L with 12 of 18 lakes exhibiting a difference of 10 µg/L or less. Regressing observed P vs. diatom-inferred P yielded an R^2 of 0.34, which was lower than the R^2 for the entire training set. However, if we removed one outlier (Lake Owasso where observed P = 88 µg/L) from this dataset the R^2 improved to 0.63. Five lakes: Christmas, Elmo, McCarrons, Harriet and George (34-0142) exhibited slightly higher DI-P as compared to the observed data. Each of these lakes exhibited either highly variable TP or trends in the 1970s based on observed data.

Figure 2c. Comparison of DI-P c. 1970 to mean observed-P for c. 1970-1980.



b. Defining historic or "background" phosphorus

Pre-European P is calculated here as the mean of 1750 and 1800 reconstructed values (Table 2).

Table 2. Diatom-inferred P for 1750 and 1800 time periods. Includes standard error and coefficient of variation of the mean.

Ecoregion	N	Mean	(SE)	CV	1750	(SE)	1800	(SE)
NLF	20	14.7	(1.0)	7%	14.2	(1.1)	15.2	(1.1)
CHF	30	24.2	(1.7)	7%	23.3	(1.8)	25.0	(1.8)
Metro	20	22.6	(1.8)	8%	22.3	(2.0)	22.9	(1.8)
Non-Metro	10	27.4	(3.5)	13%	25.3	(3.5)	29.4	(3.9)
WCP	5	46.9	(5.9)	13%	54.6	(10.2)	45.3	(6.9)
Overall	55	22.8	(1.6)	7%	22.3	(1.7)	23.3	(1.7)

Very good correlation between the 1750 and 1800 DI-P values is evident for the Northern Lakes and Forests (NLF) lakes (Figure 3a). Individual mean difference (1800-1750) was 2.1 ± 0.4 µg/L with a CV (difference/1800) of 16 percent. This suggests there was no major region-wide change in land use or other impact that may have influenced the trophic status of this set of lakes over that time period. It also suggests that "natural variability" was minimal in these lakes over this time period. Individual lakes that exhibited differences greater than the average (±SE) and CV's include: Snells (31-0659) and Loon (31-0571) in Itasca County.

The North Central Hardwoods Forests (CHF) ecoregion lakes exhibited a mean pre-European reconstructed P of 24.2 (± 1.7) ug/L. No significant difference was noted overall between the two time periods for the CHF lakes. Individual mean difference was 4.4 ± 0.8 µg/L with a CV of 16 percent. Further sub-setting of these lakes into "Metro" vs. "West-central (non-Metro)" did not reveal any significant differences between the two time periods. A cross comparison between the Metro vs. non-metro lakes revealed slightly, but not significantly, higher P concentrations for the 1750 to 1800 time periods. Seven lakes exhibited differences greater than the mean difference (±SE) and mean CV:

Lake	Reconstructed TP ug/L 1750	Reconstructed TP ug/L 1800	Difference TP µg/L 1800-1750	Diff./1800 Percent
Sweeny (27-0035-01)	24	29	+5	18%
Fish (19-0057)	25	37	+12	33%
Henderson (34-0116)	23	40	+17	42%
George (34-0142)	37	27	-10	35%
Richardson (47-0088)	27	33	+6	18%
Sagatagan (73-0092)	15	31	+16	52%
Square (82-0046)	11	18	+7	40%

The Western Corn Belt Plains (WCP) ecoregion is represented by only five lakes. The overall mean reconstructed P is 46.9 (± 5.9) ug/L and no significant difference is noted between the 1750 (49 ± 7 ug/L) as compared to the 1800 value (45 ± 7 µg/L). Individual differences averaged 13.8 ± 4.3 µg/L (CV of 33 percent). A high degree of variability (expressed as standard error) is evident in the 1750 and 1800 reconstructed values, but this is consistent with modern-day observed data as well. While, on average, there was no significant difference between the 1750 and 1800 values two of five lakes did exhibit a fairly large difference between years as follows, with George being statistically significant based on RMSE (Ramstack, 1999):

Lake	1750	1800	1800-1750	CV %
George (07-0047)	32 ug/L	58 ug/L	+26	46
Bass (22-0074)	65 ug/L	46 ug/L	-19	41

b. Comparison of pre-European and modern-day P

Northern Lakes and Forests Ecoregion

Observed 1990s P concentrations range from 7-28 µg/L and averaged 14.7 (±1.3) µg/L overall for the 20 lakes. This concentration range is typical of minimally impacted lakes in the NLF (Appendix II). Variability, expressed as standard error of the mean (SE), was typically 2-3 µg/L or less and averaged 2.6 µg/L overall. Dyers Lake (16-0634) exhibited the highest P (28 µg/L) and standard error (13 µg/L). This may have been a function of limited sampling visits (N = 3). Its large watershed: surface area ratio (30:1) may result in short water residence time and higher and temporal variability in in-lake P concentration.

Pre-European inferred P values range from 9 to 27 µg/L and averaged 14.7 (±1.0) µg/L overall. Based on a comparison of mean reconstructed P and modern-day (1990s) DI-P and observed P (± SE) there is no significant difference between the populations, i.e., P concentration in the 1990s is essentially unchanged (on average), for this group of lakes, from the 1750-1800 base (pre-settlement) concentrations. A plot of modern-day (1990s) vs. diatom-inferred allows for a comparison of individual lakes (Figure 3). A 1:1 line and a "confidence interval (CI)" of ± 10 µg/L are included as a basis for visually comparing the values. This CI is a conservative estimate of the variability associated with measurement of the observed mean (2.6 µg/L on average) plus the "error" associated with the diatom model used to infer TP (RMSEP = 0.25 log TP). For the NLF, 13 lakes are within ± 5 µg/L and all but three are within the ± 10 µg/L (CI). Three lakes: Dyers, Forsythe, Snells (Itasca County) exhibited 1990s observed-P concentrations slightly in excess (6 to10 µg/L) of the pre-European P concentration – however these values are well within the error associated with the reconstructions. Little Bass Lake (Itasca County) exhibits c.1990 DI-P and observed-P concentrations that are significantly (> 10 µg/L) lower than the pre-European P.

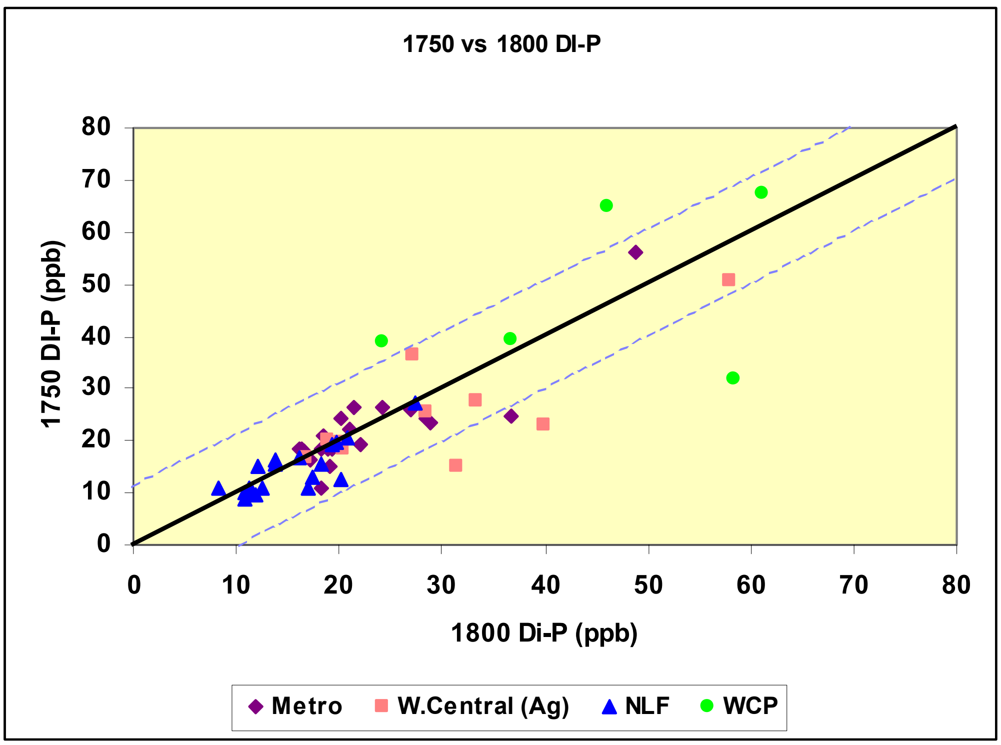
A comparison of reconstructed P data for the 1970s and the 1990, reveals little or no change for 14 of 20 lakes (Figure 4). Three lakes: Windy, Forsythe, and Dyers exhibit slightly, but not significantly, higher 1990s P as compared to 1970s reconstructed. Forsythe had a major oil pipeline put through its watershed which may have increased P loading between c. 1970 and c. 1990. Sediment accumulation rates for Forsythe, Windy and Dyers all indicate increases between c. 1970 to c. 1990 (Appendix III). Three lakes: Long, Little Bass, and Wilson exhibited 1990s DI-P concentrations less than 1970s reconstructed, of these only Little Bass was significantly different.

Table 3. Comparison of diatom-inferred P and observed P by ecoregion.

	Historic (diatom-inferred)				Observed
	Year (N)	**1750-1800 Mean (SE)**	**1970**	**1990s**	**1990**
NLF	20	14.7 (1.0)	15.3 (1.2)	14.3 (1.0)	14.7 (1.3)
CHF	30	24.2 (1.7)	38.9 (3.5)	36.8 (3.3)	39.0 (6.0)
Metro	20	22.6 (1.8)	36.7 (3.8)	34.6 (3.5)	33.1 (5.5)
Non-Metro	10	27.4 (3.5)	43.5 (7.5)	41.2 (7.1)	49.3 (12.3)
WCP	5	46.9 (5.9)	54.6 (10.2)	46.0 (5.7)	67.0 (16.0)

Figure 3(a, b). Comparison of (a) 1750 and 1800 DI-P and (b) pre-European (mean of 1750 and 1800) DI-P and c.1990 DI-P.

(a)



(b)

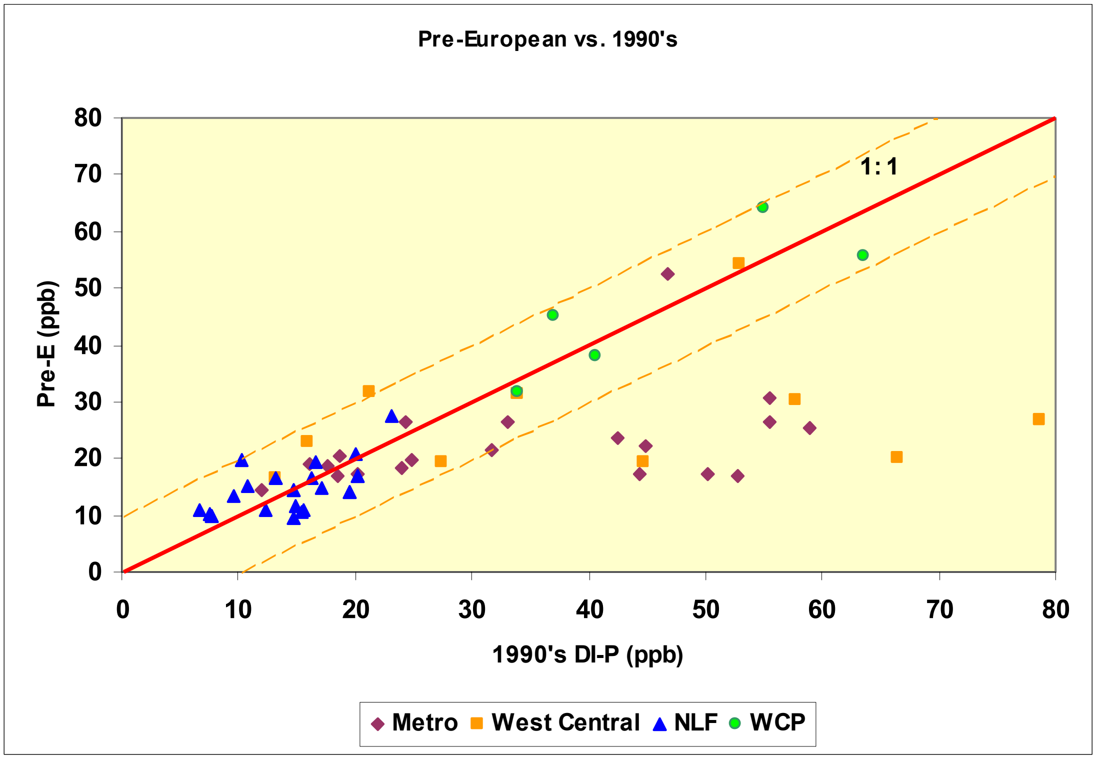
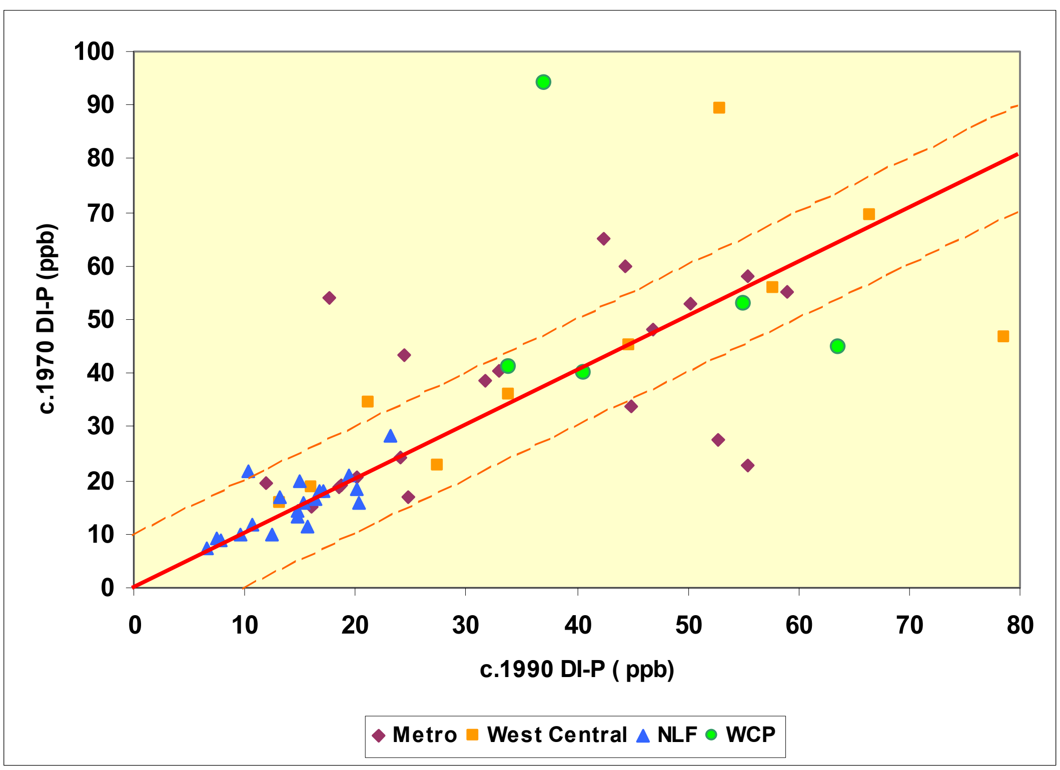


Figure 4. Comparison of 1970 DI-P and 1990 DI-P.



North Central Hardwood Forests Ecoregion

Within the CHF ecoregion we have subdivided the lakes into two groups for analysis purposes. The first group is composed of 20 lakes in the seven county metropolitan area that surround Minneapolis and St. Paul and are referred to as "metro" lakes. This provides an opportunity to take a closer look at the impact of watershed urbanization on lake trophic status. The second group, comprised of 10 lakes in west central Minnesota, is referred to as "non-metro." Based on Table 3, the non-metro lakes exhibited slightly, but not significantly, higher (27.4 ± 3.5 ug/L) background P as compared to the metro lakes (22.6 ± 1.8 ug/L).

Overall, the 1990s DI-P and observed-P for the CHF lakes are significantly higher than the pre-European values (Table 3). This is not surprising given the change in land use from pre-European, typically Big Woods to prairie transition landscapes (Marschner, 1930), to modern-day land use (row crop agricultural and urban) across this ecoregion. No difference was noted overall, however, between the 1970s and 1990s reconstructed P. In each of the time periods the "non-Metro," lakes tended to have slightly higher P concentrations as compared to the "Metro" lakes – about 4 to 6 µg/L on average.

Figures 3 and 4 provide a further opportunity to make comparisons between the two subsets (metro and non-metro) and identify lakes that may be exhibiting significant change between time periods. For example, George Lake's (34-0142) modern-day P is over 10 µg/L lower than its pre-European and 1970s reconstructed P. Several lakes in the metro (Dickman, Fish, Sweeny, McCarron, and Tanners) and non-metro (Dunns, Richardson, Diamond and Stahl) exhibited significantly higher 1990s P as compared to pre-European (Figure 3). Clean Lakes Program (CLP) or Clean Water Partnership (CWP) projects have been conducted (or are underway) on Fish, McCarron, Tanners, Dunns, Richardson, and Diamond lakes -- projects that produced data useful to this study, and whose intent is to reduce nutrient loading to the lakes.

Comparison of 1990s to 1970s diatom-inferred P provides an indication of lakes that may have undergone more recent changes in trophic status (Figure 4). Five metro lakes (Harriet, Calhoun, Christmas, Little Carnelian, Elmo, and Carver) and two non-metro lakes (George and Hook), exhibit 1990s observed-P and DI-P that were 10 µg/L or more lower than 1970s reconstructed P, however, only Elmo would be considered statistically significant. In addition, two metro lakes: Fish and Dickman exhibit significantly higher observed-P and DI-P as compared to 1970s reconstructed.

Overall, there was no significant difference between pre-European P, 1970s diatom and 1990s diatom and observed values for four of five WCP lakes. The lack of difference is in part a function of the high variability (expressed as standard error) associated with the means. George Lake's 1990s DI-P is comparable to historic and significantly lower than the 1970s DI-P. However its observed P was among the highest in this study (145 µg/L). The difference between c. 1990s observed and reconstructed was larger than most of the lakes in the data set (Figure 2) but this type of error is not uncommon for highly eutrophic lakes – as reconstructions on highly eutrophic lakes are often difficult (Reavie et. al. 1995b). Bass Lake's 1990s observed-P is higher than 1970s DI-P and concentrations, however, the 1990s DI-P is not significantly different than presettlement-P. Fish and Beaver Lakes' 1990s observed-P and DI-P are actually lower than or similar to the 1970s DI-P and pre-European P. Closer inspection of observed data for all five lakes will be addressed in individual case studies.

c. Sediment accumulation rates

Sediment accumulation rates are proportional to the net delivery of sediment (organic and inorganic) from the watershed and in-lake production (algae and plants) to a lake. The actual rate of sediment accumulation at the core site is a product of the size of the watershed area, landuse and soil characteristics, combined with the area and depth of the lake. Modern-day and pre-European sediment accumulation rates were calculated for most of the lakes in the study. Rates were calculated in terms of kg $m^{-2}yr^{-1}$ (areal rates) for the 1750-1800 time period (pre-European) and for c.1990s (modern-day). Linear rates were then estimated for the periods: 1750-1800 and 1900-modern-day and expressed as mm/yr. However, dry-mass rates, which correct for variable water content in the sediments (Engstrom, personal communication), were the primary focus of this analysis.

NLF lakes modern-day and pre-European sediment accumulation rates were relatively low (Table 4). Pre-European values averaged 0.13 kg $m^{-2}yr^{-1}$ and with a maximum value of 0.21 (Figure 5). The average increase, based on ratios of modern-day/pre-European, was about 70 percent (Table 4) with most ratios between 1.0 to 3.0 (Figure 5) and an overall range of 0.7 (Little Bass) up to 4.7 (Wolf). Modern rates of sediment accumulated are sometimes much higher than before settlement, resulting in much more variability in modern rates, as compared to pre-settlement (Figure 5).

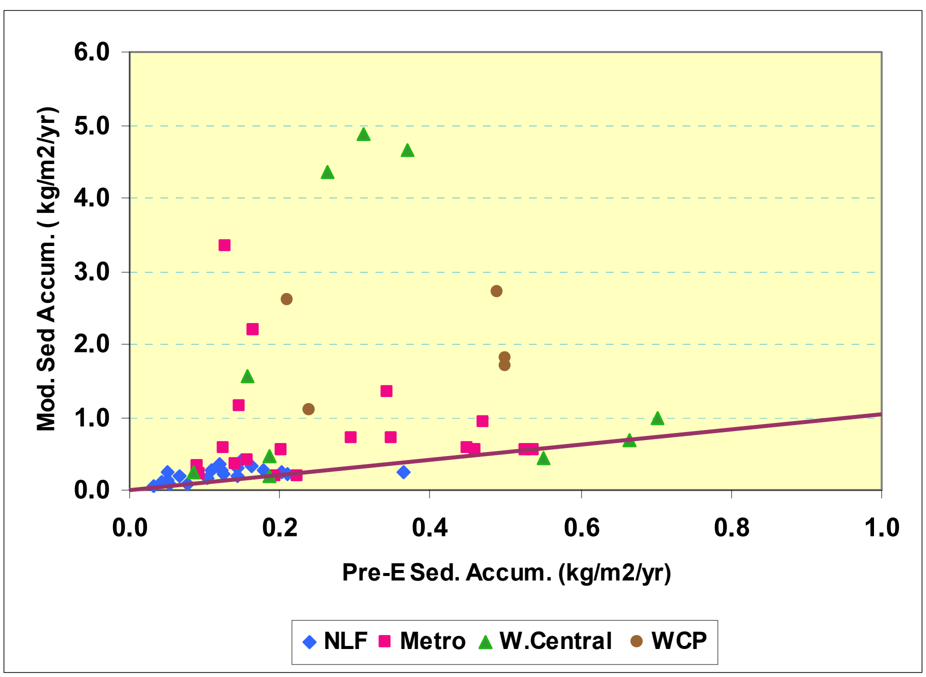
CHF exhibit modern-day and pre-European sediment accumulation rates that are higher and more variable than the NLF lakes (Table 4). Pre-European areal rates were about two to three-fold higher than the NLF lakes. Based on this dataset there was no significant difference in pre-European sediment accumulation rates between the Metro and non-Metro lakes. However, the Metro lakes exhibited a much larger range in values (Table 4). Pre-European rates in CHF lakes ranged from a low of 0.12 (Turtle) up to 0.7 kg $m^{-2}yr^{-1}$ (Diamond), with most values between about 0.15 to 0.55 kg $m^{-2}yr^{-1}$. Modern-day values were much higher, averaging 0.82 and 1.85 kg $m^{-2}yr^{-1}$ for the Metro and non-Metro lakes respectively. Modern-day values range from a minimum of 0.19 (Sagatagan) up to 4.89 kg $m^{-2}yr^{-1}$ (Richardson). The relative change (modern/pre-European) in sediment accumulation rate was much higher in the CHF lakes as compared to the NLF lakes (Table 4). Among the highest were Carver (27:1), Dunns and Richardson (16:1), Elmo (13.5:1) and Hook (12.6:1). Several lakes exhibited either no change (Sagatagan, George, and Marcott) or even reductions in sedimentation rate (Little Carnelian). As a group, there was no correlation between pre-European and modern-day sediment accumulation rates for the CHF lakes (Figure 5).

Modern-day and pre-European sediment accumulation rates and change in rate in WCP lakes were quite similar to the West-Central (CHF) lakes (Table 4). Modern-day rates range from a low of 1.1 kg/km^2/yr (Duck) up to 2.7 (Fish). Pre-European rates ranged from 0.21 (Beaver) to about 0.50 kg/km^2/yr (George, Fish and Bass). Beaver Lake exhibited the largest change (~11-fold) of the WCP lakes.

Table 4. Comparison of modern-day (1990s) and pre-European (1750-1800) sediment accumulation rates (mass per unit area and linear accumulation) for study lakes. Mean (±SE).

Eco	N	Mod-day mass kg $m^{-2}yr^{-1}$	Pre-Euro mass kg $m^{-2}yr^{-1}$	Mod/ Pre ratio
NLF	20	0.22 (±0.02)	0.13 (±0.02)	1.7 (±0.2)
CHF	29			
Metro	19	0.82 (±0.18)	0.27 (±0.04)	3.0 (±1.4)
West-C	10	1.85 (±0.62)	0.35 (±0.07)	5.3 (±2.1)
WCP	5	1.98 (±0.30)	0.39 (±0.07)	5.1 (±1.7)

Figure 5. Modern-day and pre-European sediment accumulation rates by ecoregion. The line represents no change; points significantly above the line indicate lakes where modern sediment accumulation is much higher than before settlement.



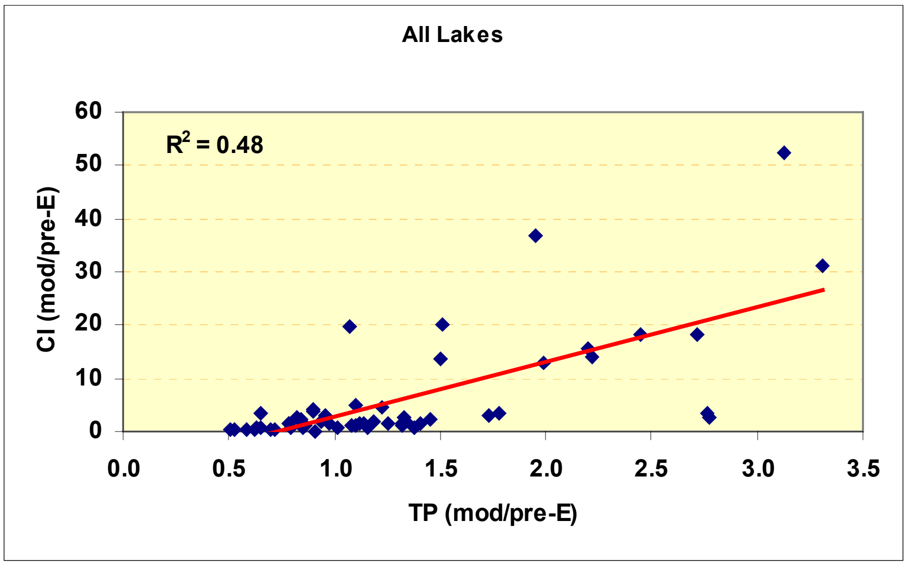
d. Change in TP and Cl as a function of landuse and sediment accumulation rates

GIS landuse data provides a basis for assessing the influence of different landuse types or changes in landuse on water quality characteristics of the study lakes. In the urbanized

Metro lakes, for example, we see a significant correlation ($R^2 = 0.42$) between the change in TP and Cl concentrations from pre-European to modern-day (Figure 6). This correlation is even stronger in the agricultural west-central lakes (R^2= 0.60) and the NLF lakes (R^2=0.83).

Figure 6. Relationship between pre-European / modern-day (ratios) for chloride and total phosphorus. Entire data set (a) and Metro lakes (b)

(a)



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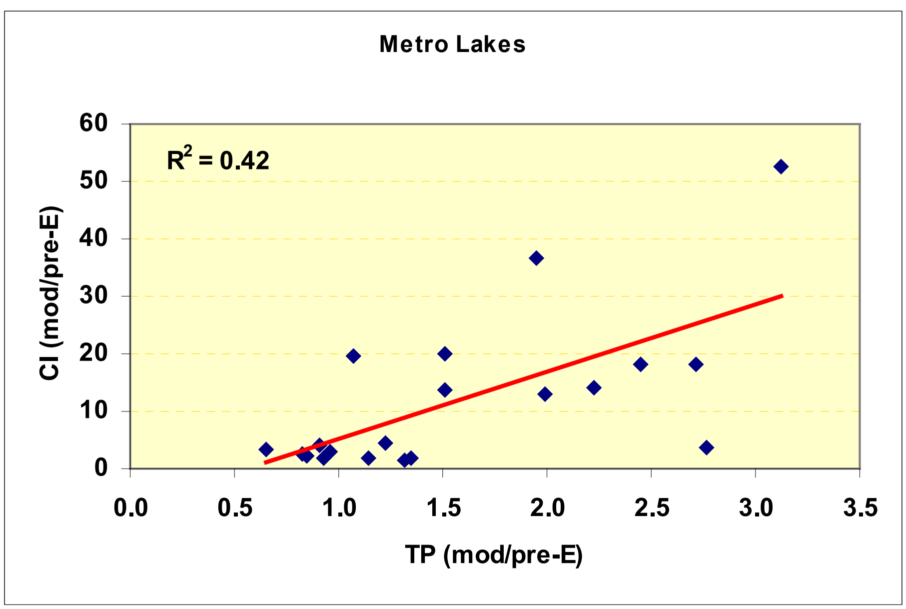
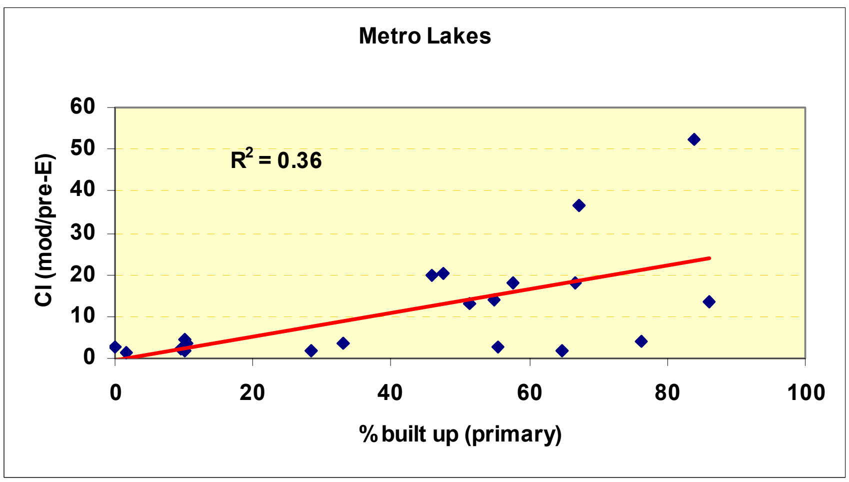
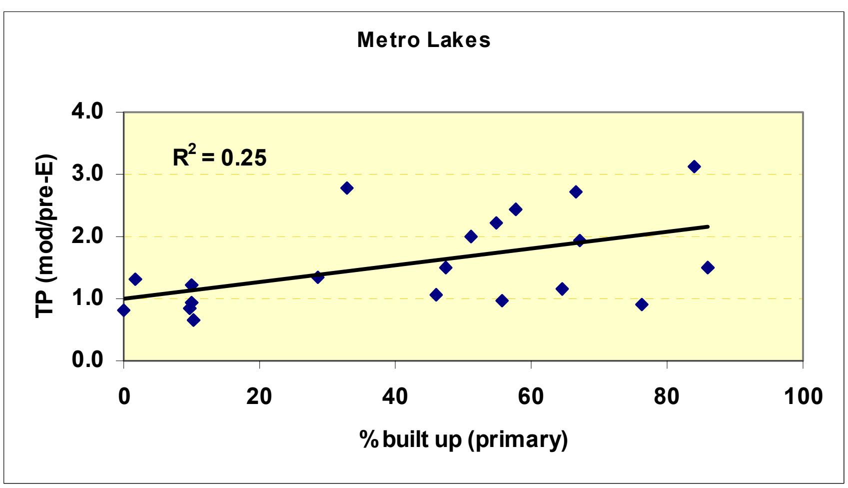
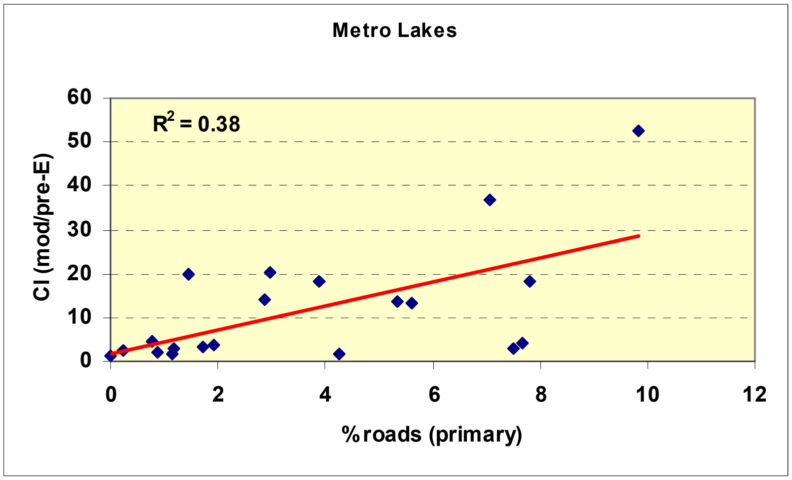


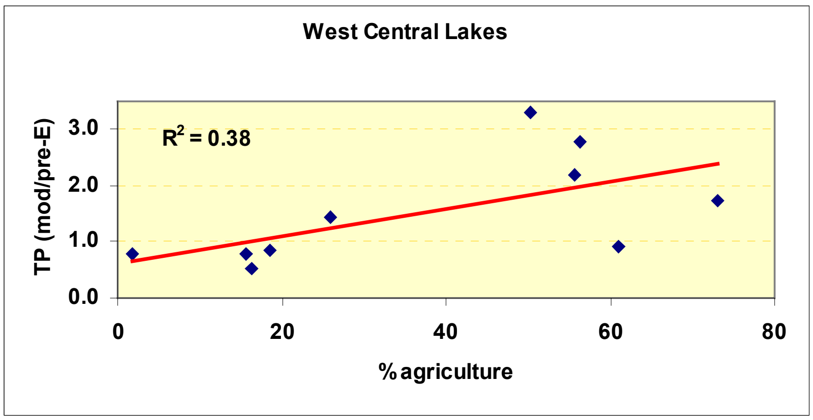
Using the GIS landuse data, with a focus on the primary (direct) watershed, we can explore the relationships between landuse characteristics and historical changes in TP and Cl. For the Metro lakes we are able to explain 36 percent of the variation in Cl and 25 percent of the variation in TP as a function of the percent of land that is "built-up" in the primary watershed (Figure 7). The percent "roads" explains a slightly higher percentage of the variation in Cl (38 percent) and TP (26 percent). Lake Calhoun, for instance, with a very large (2,515 ha total, 1,236 ha primary) and urbanized watershed (88 percent built-up and 9 percent roads) exhibited the highest change in TP and Cl of any Metro lake. Turtle Lake, in contrast, which has a small watershed (180 ha) and suburban-type development (80 percent built-up, 2.4 percent roads) exhibited essentially no change in TP but had a 19-fold increase in Cl concentration. In this case, road-salt usage on a road network that rings the lake would account for the increase in Cl. Dickman Lake, in contrast with a moderate percentage of built-up landuse but small road network in its watershed, had the highest TP concentration (and second highest change in TP) of any lake in the Metro, however it exhibited minimal change in Cl concentration (Figure 7).

Figure 7. Change in Cl and TP as a function of landuse composition.





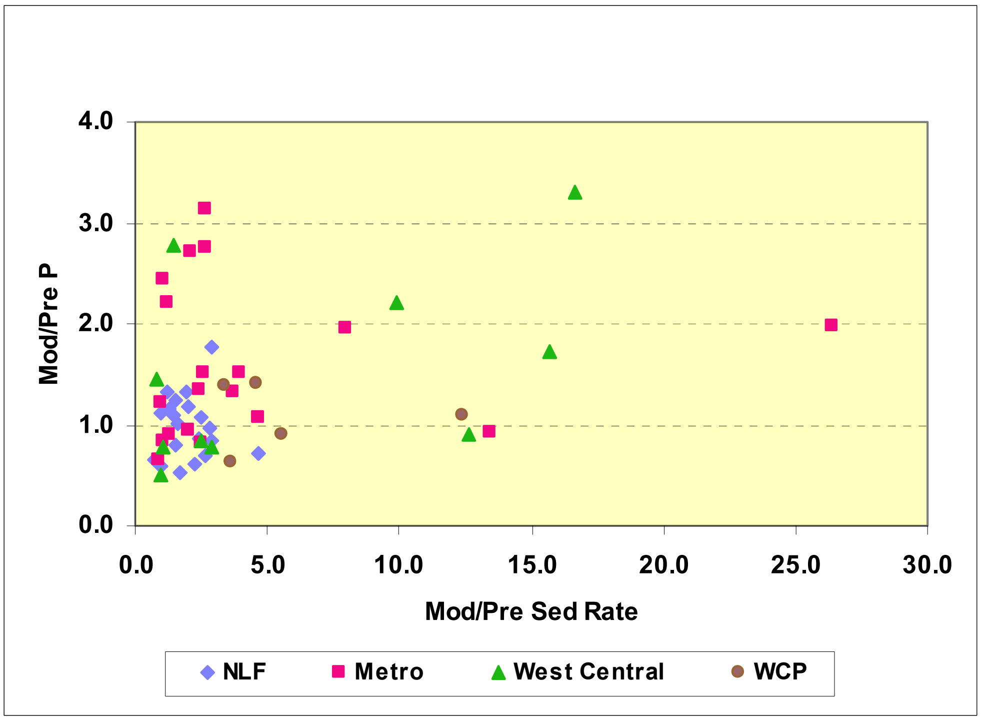




In the west-central CHF lakes, changes in TP or Cl were not correlated to percent built-up or percent roads, however the percent in agricultural land use exhibited a high correlation with TP (R^2= 0.38) and a weak correlation with Cl (R^2= 0.14). There was essentially no correlation between these landuse characteristics and the change in TP or Cl for the NLF lakes (primarily because few lakes had built-up or agricultural uses in their watersheds).

There is no correlation between pre-European to modern-day change in phosphorus and change in sediment accumulation rates among the lakes (Figure 8). In general, NLF lakes clustered near a line of no change (mod/pre-E ~ 1.0), with P change from about 0.5 to 1.5 and sedimentation change from about 1.0 to 2.5. The Metro-CHF lakes exhibited a wide range of P change from about 0.6 to 2.5. Carver Lake exhibited the largest change in sedimentation accumulation rate (27:1) while Calhoun exhibited the largest change in TP (3.1:1) of the Metro lakes. The West Central-CHF lakes ranged from ratios of 1:1 or less in George, Sagatagan, and Long to ratios of 15:1 or greater in Dunns and Richardson (Figure 8). Hook Lake, McLeod County, exhibited a change in sediment accumulation rate of about 13:1, however modern-day TP was essentially unchanged from pre-European (Figure 8). All five WCP lakes exhibited increases in sediment accumulation rate ranging from about 4-fold to 13-fold, however modern-day: pre-European TP ranged from 0.6 (decrease) up to 1.4. Thus, across the 55 study lakes, and within the individual ecoregions, we saw little or no relationship between the change in sediment accumulation rates and the change in TP between modern-day and pre-European time periods. There was, however, evidence of a substantial increase in soil erosion to the lake for lakes with highly agricultural watersheds in the CHF and WCP ecoregions. This is in contrast to lakes with more urbanized watersheds where increase in sediment accumulation was generally not as great. However, increases in P were of a similar order of magnitude for both groups (Figures 6 and 8).

Figure 8. Pre-European to modern-day change in phosphorus concentration compared to change in sediment accumulation rates.



II. Lake-group and Lake-specific Trend Analysis

Individual lakes and groups of lakes were analyzed in greater detail in an attempt to develop more individualized case studies and where possible to aid in interpretation of the trends (or lack thereof) revealed by the diatom reconstructions of water quality. In this vein long-term CLMP and other data sources were reviewed, along with available reports and historical information which might help explain current and historic water quality of these lakes. These results will be presented by the various lake groups (Figure 1) within each ecoregion.

a. Northern Lakes and Forests ecoregion

Voyageurs National Park

This subset includes five lakes located within Voyageurs National Park. These lakes are remote and none are accessible by road. Pre-settlement vegetation was characterized by "jack-pine barrens and opening" interspersed with "aspen-birch" and "white and Norway pine" (Marschner, 1930). Historically, fire (combined with shifts in climate) was perhaps the most significant factor influencing vegetation growth and potentially influencing runoff to the lakes. Heinselman (1973) documented the fire history for the BWCA, immediately southeast of these lakes, and noted several significant fires in the period from 1610 to 1692 and 1755 to 1759.

Beaver, through their hydrologic modifications in watersheds, were another significant "natural" factor that affected lakes throughout northeastern Minnesota (Engstrom, personal communication). Beaver were historically abundant but were almost extirpated by trapping for the fur trade. Over the past few decades they have made a dramatic comeback and again are a significant factor in many northern Minnesota watersheds.

Modern-day landuse is predominately forest with wetlands dotted through the watersheds of most. Shoepack Lake, with about 20 percent of its watershed in wetlands, has the darkest coloration of the five lakes (117 Pt-Co units). All five lakes would be considered oligotrophic based on pre-European and modern-day diatom reconstructions (Table 5). Shoepack, with its high coloration and slightly elevated P might be an exception and could be considered "dystrophic." Wetzel (1975) discusses this concept at length and its "appropriateness" as a trophic state category. Dystrophic lakes may often have elevated P arising from decomposition of plant matter in wetlands but because of the dark coloration of the water algae concentrations are often quite low because of light assimilation.

No significant increases in P or Cl were noted in any of the lakes and, if anything, slight declines may be indicated in the case of Tooth and Locator Lakes (Table 5). Sediment accumulation rates were fairly uniform for Locator, Loiten, and Tooth Lakes from c. 1800 to modern-day (Appendix III). Little Trout exhibited an increase from a background of ~0.05 kg $m^{-2}yr^{-1}$ up to 0.25 kg $m^{-2}yr^{-1}$ in the 1940-1960 time period but declined to about 0.1 kg $m^{-2}yr^{-1}$ by the 1990s. A major fire occurred in Voyageurs in 1936 and may have encompassed all or a portion of Little Trout's watershed. Shoepack, while somewhat more variable over the entire core-profile (Engstrom et al. 1999), was relatively unchanged from 1800 to modern-day. Though we do not have the specific fire history for these watersheds, Heinselman's (1973) records for the BWCA indicate extensive burns in 1755 - 1759 immediately to the southeast of these lakes. Should this, or other burns, have extended into the watersheds of these lakes it may account for the slight elevation in P and Cl in the pre-European reconstructions for Tooth and Locator Lakes. Significant changes in beaver populations and the resulting hydrologic changes might also be important in some of these watersheds.

Table 5. Voyageur's Park-area lakes diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
Little Trout	TP µg/L	10	11	9	8
	Cl mg/L	1.0	1.4	1.0	0.3
Locator	TP µg/L	10	11	8	7
	Cl mg/L	0.5	0.6	0.2	0.2
Loiten	TP µg/L	11	11	10	12
	Cl mg/L	0.6	0.9	0.6	1.2
Shoepack	TP µg/L	15	18	16	20
	Cl mg/L	1.0	1.0	0.8	1.6
Tooth	TP µg/L	15	12	10	10
	Cl mg/L	1.6	0.6	0.4	0.4

North Shore

This subset includes ten lakes located near the north shore of Lake Superior, most of which are in or near the Superior National Forest (SNF). Pre-settlement vegetation was characterized primarily by "white and Norway pine," most of which was cut in the early lumbering period (Heinselman, 1973). There is minimal development around these lakes but most are accessible by a road. Modern-day landuse is dominated by forest as is common in this ecoregion. Wetlands are a common feature of the landscape as well. Runoff from the wetlands and coniferous forests contribute the humic coloration that is common in many lakes in this area such as August, Dyer and Windy. There is essentially no development in the watersheds of these lakes with the exception of a few cabins. Wolf Lake has the highest percentage of "built up" use at six percent of the watershed because of the presence of Wolf Ridge Environmental Learning Center, which was built in stages after 1989. However this built-up area is not adjacent to the lake. While most are accessible by roads, road surfaces comprise less than one percent of the watersheds by area. Logging was a prominent activity throughout this region with much of the activity during the early to mid 1900s.

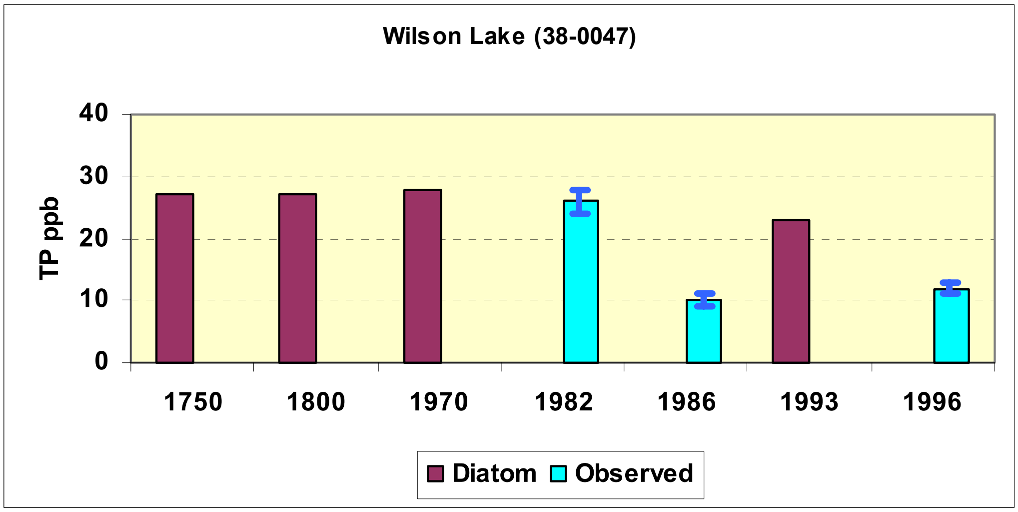
Pre-European sediment accumulation rates were relatively low (0.2 kg $m^{-2}yr^{-1}$ or less typically), however modern-day rates are about two-fold higher than pre-European for most of these lakes. Wolf Lake, with a 4.7 fold increase, had the greatest change in sediment accumulation rate. Ninemile, Windy, and Wolf Lakes exhibited distinct (sustained) increases in sediment accumulation rate from about 1960 through 1990s that could be related to forestry or road-building activities in the watershed. Any increase in sediment accumulation in these lakes is largely attributable to the inorganic fraction as the carbonate fraction (% of total) is relatively constant through the cores (Appendix III). None of the North Shore or SNF lakes show a return to pre-logging sediment accumulation rates, despite the fact that these watersheds reforested quickly and have not been appreciably disturbed since the early 1900s (Engstrom et al. 1999). One hypothesis for this lack of recovery is the colonization of many of these watersheds by earthworms, which had been absent in the glaciated region (Frelich, personal communication).

Pre-European P concentrations for most of the lakes suggest oligotrophic conditions with the possible exceptions of Wilson and Nipisiquit, which were more mesotrophic (Table 6). Cl concentrations were historically very low in these lakes, typically 1 mg/L or less, and have remained so. Wilson Lake was the highest at about 2 mg/L. As a group, no significant modern-day increases in P or Cl are evident. Minor increases in P (above pre-European) may have occurred in Ninemile, Bear and Wolf. Bear is the only lake in this group that exhibited an increase in P and Cl over the 1970 to c.1990 time frame (Table 6). Sediment accumulation rate did not change appreciably in the lake over this period or from pre-European time (Appendix). Wilson Lake, which had the highest P of the group, shows little change from pre-European times through 1970 and possibly has had a decline in P by the 1990s based on the DI-P and observed data (Figure 9). Sediment accumulation rate exhibited a minor decline over this period (1970-1990s). August Lake exhibited peak P and Cl in the 1800 core sample. This increase appears to coincide with significant fires that swept through much of this area (and possibly including August Lake's watershed) in 1796 (Heinselman, 1973). Modern-day P and Cl are quite similar to the 1750 values (Table 6). However modern-day sediment accumulation rates are about two-fold higher than pre-European (Appendix).

Table 6. North Shore-area lakes diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
August	TP µg/L	13	17	12	11
	Cl mg/L	0.5	0.8	0.3	0.3
Bean	TP µg/L	17	16	17	16
	Cl mg/L	0.8	0.9	1.0	0.9
Bear	TP µg/L	10	12	11	16
	Cl mg/L	0.3	0.4	0.5	1.1
Ninemile	TP µg/L	10	12	16	15
	Cl mg/L	0.3	0.7	1.4	1.1
Nipisiquit	TP µg/L	19	19	18	17
	Cl mg/L	1.4	1.3	1.5	1.4
Tettegouche	TP µg/L	16	14	14	15
	Cl mg/L	0.8	0.7	0.8	0.9
Wilson	TP µg/L	27	27	28	23
	Cl mg/L	2.2	1.8	3.3	2.2
Windy	TP µg/L	9	11	9	8
	Cl mg/L	0.3	0.6	0.3	0.2
Wolf	TP µg/L	11	8	13	15
	Cl mg/L	0.6	0.3	1.1	1.2
Dyers	TP µg/L	21	21	18	20
	Cl mg/L	1.3	1.2	1.0	1.7

Figure 9. Wilson Lake DI-P and observed-P. Observed P represented as summer-mean and standard error.



North Central – Grand Rapids Area

This subset includes five lakes near the city of Grand Rapids. Pre-settlement vegetation was characterized primarily by "aspen-birch" (typically post-fire succession; Heinselman, 1973) and "white pine" or "conifer bog" (e.g. near Forsythe Lake, which has much lower alkalinity then the other four lakes). While their modern-day watersheds are characterized primarily by forest and wetland, there is more agricultural landuse evident and more development in the lakeshore area as compared to the other two subsets in the NLF ecoregion. Norton (personal communication, 2001), assembled some history for these lakes that is summarized in the following paragraph.

The development of the Bass Brook Railroad in 1890 allowed for logging and some development in this area. White pine logging was initiated in the late 1880's and continued until about 1910. Coniferous forests are now a minor portion of the landscape in this area. Based on a review of USGS quadrangles, lakeshore development was initiated in the early 1950s (Table 7). Currently, Loon Lake has the highest number of homes on the shoreline – with a majority of the development likely occurring over the past couple decades. Agriculture, in the form of crops and pasture, was historically more significant in the watersheds of these lakes as compared to the other two NLF lake groups (Table 7). Based on reviews of aerial photographs from 1966, agriculture occupied a fair amount of shoreline on Little Bass, Loon and Snells. GIS data from the 1990s indicates that agriculture is a significant landuse component in the Snells Lake watershed (43 %), but is relatively minor in the other lakes. In some cases, such as Loon, agricultural landuse likely gave way to shoreland development (Table 7).

Table 7. Grand Rapids-area lakes shoreland development and landuse (Norton, personal communication)

Lake	Homes on shoreline	Homes on shoreline	% crop & pasture in shoreland	% agricultural landuse in watershed
Year	**1951**	**1990s**	**1966**	**1990s**
Forsythe	0	5	5	5
Little Bass	11	21	20	11
Loon	4	37	30	12
Long	4	10	10	9
Snells	2	5	40	43

Pre-European sediment accumulation rates ranged from 0.10 to 0.15 $kg/km^2/yr$ in four of the lakes with Little Bass Lake being almost three-fold higher (0.36 $kg/km^2/yr$). The change in sediment accumulation rate (mod/Pre-E) ranged from 1.3 (Long) to 2.8 (Forsythe). Sediment accumulation in Little Bass actually decreased when comparing modern-day to pre-European (0.7). Temporal changes in accumulation rate varied among the lakes, however some patterns were evident. Most lakes exhibited increases in sediment accumulation beginning c. 1900 with peak sediment accumulation occurring c. 1920 (Snells, Long and Loon), c. 1940 (Little Bass) and c. 1980 (Forsythe). With the exception of Little Bass, the bulk of the accumulation was inorganic sediment (i.e., soil erosion). In Little Bass, the increase was associated with the carbonate fraction (Engstrom et al. 1999), which is often associated with changing primary productivity. The increase in inorganic sediments likely resulted from extensive logging early in the 1900s followed by the establishment of agriculture (typically pasture and hay) in the watersheds following clearing of the land. Agriculture was a significant land use in the shoreland of Little Bass, Loon and Snells into the 1960s (Table 7) and remains a significant land use component (43%) for Snells. With the exception of Forsythe, all lakes show an increase in the organic fraction and decrease in inorganic fraction near the top of the cores, which may be indicative of decreased soil erosion.

There was no consistent change from pre-European P to modern-day P for this set of lakes (Table 8). Peak P concentrations were found in four of five lakes in the 1970 level of the cores. And in all five lakes, c. 1993 core samples exhibited lower P than the 1970 core sample. Of these five lakes, only Snells maintained any appreciable amount of agriculture near the shoreland area (Table 7) and it also exhibited the highest P concentration. Loon and Little Bass, which exhibited the largest increase in development along the shoreline and largest relative decrease in agricultural use in the shoreland area (Table 7), both exhibited declines in P from 1970 to 1990 (Table 8).

Table 8. Grand Rapids-area lakes diatom-inferred phosphorus and chloride.

		1750	1800	1970	1990
Forsythe	TP µg/L	16	14	18	17
	Cl mg/L	1	1	2	1
Little Bass	TP µg/L	20	20	22	10
	Cl mg/L	2	3	2	1
Loon	TP µg/L	13	20	17	13
	Cl mg/L	2	4	2	3
Long	TP µg/L	11	13	20	15
	Cl mg/L	1	1	5	2
Snells	TP µg/L	11	17	21	19
	Cl mg/L	1	9	7	7

b. North Central Hardwood Forests ecoregion: West Central Lakes

Kandiyohi County: George, Long, Henderson and Diamond

George, Long, Henderson and Diamond Lakes are located in northern Kandiyohi County. Pre-settlement vegetation in this portion of the county was characterized by "aspen-oak" and "oak openings" near Green Lake, transitioning to "prairie" near George and Henderson Lakes, with Diamond Lake's watershed characterized by prairie (Marschner, 1930). These lakes, and Kandiyohi County in general, were "discovered" by European settlers in the early 1850s (Lawson and Nelson, 1905). A series of photographs show the prominence of pasturing on the shores of lakes and streams in the area as well (Plates 1 and 2). Prairie, pasture and hayfields were evident across much of the area as well and forests tended to be located near the lakeshores (Plates 3 and 4). Development often focused near the lakes and early settlements, such as "Diamond Lake Settlement" were established in the 1860's. These settlements expanded to include features such as mills or the creamery on Lake George (Plate 5, 1898).The four lakes represent a range in size and depth. George is the smallest at 29 ha and Diamond is the largest at 645 ha. Maximum depths range from 8.2 m (Diamond) up to 13.4 m (Long). Watershed areas range from 3,590 ha (Diamond) to 59 ha (Henderson) and watershed : lake surface ratios range from 1:1 (George) to 6:1 (Diamond).

Plate 1. Shakopee Creek (Lawson and Nelson, 1905)

Plate 2. Lake Mary late 1800's (Lawson and Nelson, 1905)

Pre-European sediment accumulation rates ranged from 0.19 (Henderson) to 0.67 kg/km^2/yr (George). Mod/Pre-E sediment accumulation varied from 0.8 (Long) to 2.5 (Henderson). Steady increases in sediment accumulation changes from c.1850 and peaking c. 1950 were evident for Diamond, Henderson and Long. Rates declined following that period, however recent increases in the organic fraction were evident near the top of the cores in all four lakes. Sediment accumulation in George Lake was relatively unchanged over the length of the core and no significant peaks were evident.

Plate 3. Norway Lake late 1800's (Lawson and Nelson, 1905)

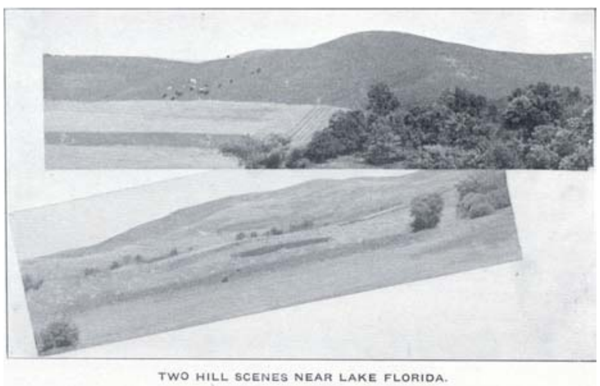


Plate 4. Lake Florida late 1890's (Lawson and Nelson, 1905)

George Lake has a very small watershed (102 ha ~ 1:1 ratio) with a high percentage (41%) of built-up landuse, however this built-up landuse is comprised largely of cabins and homes that ring the lake. The Kandiyohi County Lake Parcel Listing dated December 3, 2001 shows a total of 109 riparian property owners on George Lake. Decision Hills Bible Camp, owned by the United Methodist Church, owns six of these parcels and is the largest single property owner on the lake with about 3,200 feet or 22 percent of the lakeshore frontage.

The accompanying road network comprises only 1% of the watershed. Agricultural landuse accounts for only seven percent of the watershed, which is much less than typical for this ecoregion (Appendix II) and none of it is directly adjacent to the lake.

Tom Bonde (personal communication, 2002) assembled some history on the lake that is summarized as follows:

The lake was first surveyed in 1857 by Hardin Nowlin, Deputy Surveyor, U. S. Surveyor Generals Office. The Gazetteer of Meandered Lakes of Minnesota published in July 1928 gives the meandered area as 273.30 acres or some 40 acres larger than its present size. Although Nest Lake lies only about 400 feet to the north of George Lake, it appears that George Lake originally drained south into Henderson Lake which would have made George Lake part of the Hawk Creek/Minnesota River drainage.

In about 1878 John Adams, son of the owner of the Green Lake Mill, found that the water level of Nest Lake had reached the point where it was insufficient to power the mill. Noting that the water level of George was higher than Nest, he dug a ditch across the 400 -foot divide connecting the two lakes. It was said that he used up much of George's water-supply but it is likely that that he didn't lower George by more than 3 or 4 feet --- the bottom elevation of the power intake at the dam. This diversion brought George into the Middle Fork Crow River Watershed, increasing the drainage area of the Middle Fork Crow Watershed by 490 acres. At the same time the diversion tied George into a complex and somewhat questionable relationship with Nest, which at the time was a fluctuating reservoir. During this same era George was the location for a hub creamery that suggests additional commercial activity near the lake (Plate 5).


TWO VIEWS OF HUB CREAMERY ON LAKE GEORGE

Plate 5. Lake George c. 1900 (Lawson and Nelson, 1905)

Prior to 1992 the connection between George and Nest lakes consisted of a 48-inch culvert passing under CSAR No. 32, which separates the two lakes. The Kandiyohi County Highway Department replaced the 48-inch culvert with a 36-inch x 110-foot CMP culvert with 10-foot aprons when CSAR No. 32 was rebuilt and resurfaced. Due to the fact that the old culvert had been filling with sand, the DNR requested that the elevation of the new culvert be raised. The highway department complied and the project was completed on October 19, 1992. The changes in elevation of the culvert are as follows:

	George Lake (S. end)	Nest Lake (N. end)
Old culvert invert	1161.5	1161.9 *
New culvert invert	1164.13 *	1163.13

* Controlling elevation

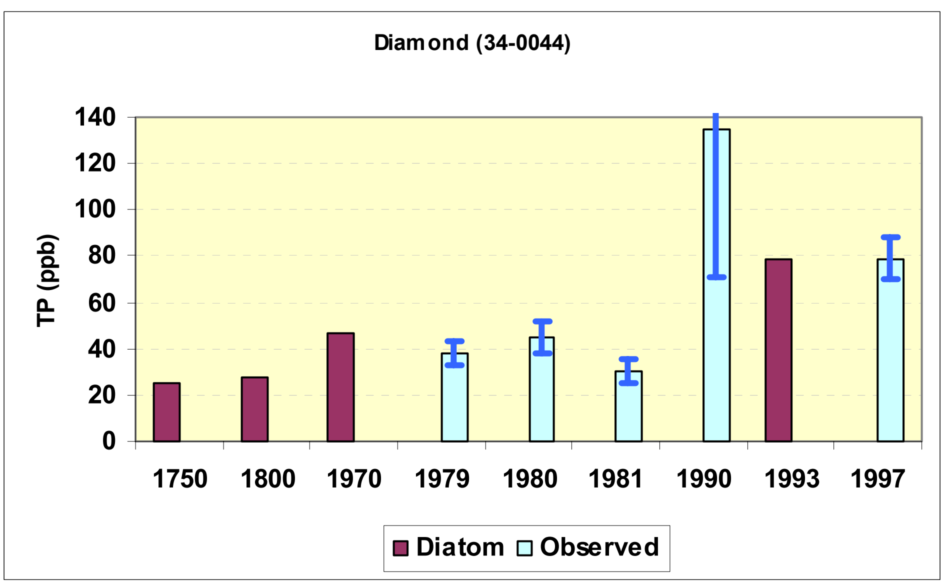
Exchange of water between George and Nest would have occurred at elevation 1161.9 prior to 1992. At the present time, exchange will not occur until the elevation of either lake reaches 1164.13.This in effect raised the controlling elevation by 2.23 feet. A complicating factor in the free exchange of water between George and Nest lakes is the small wetland that lies between CSAR No. 32 and Nest Lake. A sand ridge, probably caused by Nest ice push, has been formed, impounding the wetland. The low point in the sand ridge, as surveyed on January 31,1991, was at elevation 1168.2 or about 4 feet above the invert of the new culvert. Fluctuations in water level are common on George Lake with elevations ranging from a maximum of 1166.8 ft. (1969) to a low of 1162.9 ft. (1989) based on MDNR records dating to 1948. Lake level was below the OHW when the sediment core was collected in 1993.

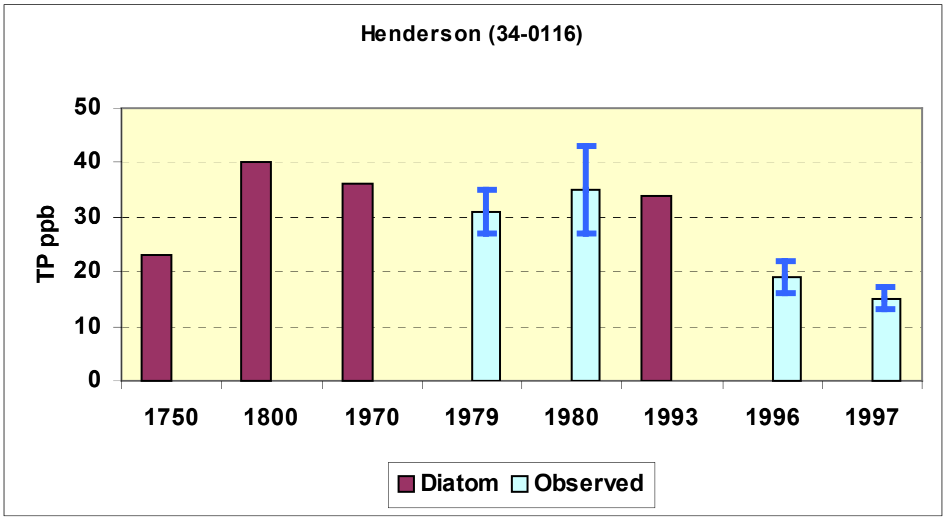
MDNR Fishery survey records provide the following insights on shoreland and watershed characteristics (Gilbertson, personal communication, 2002):

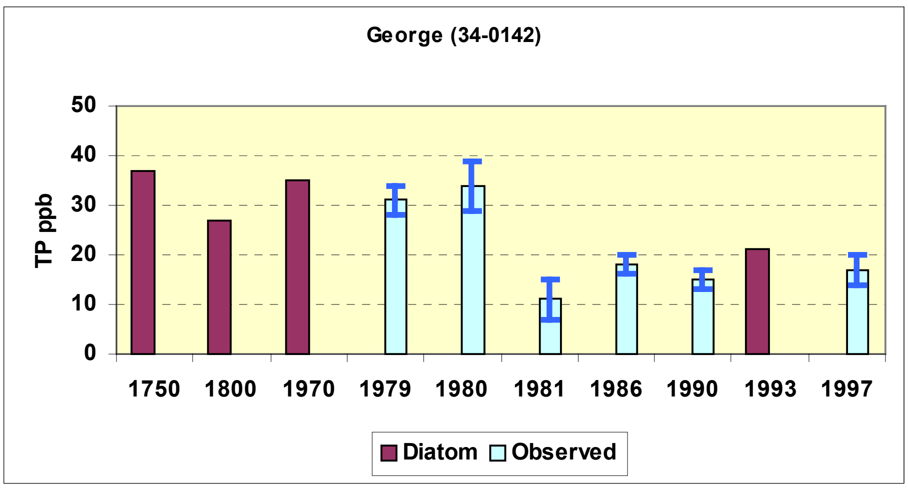
- 1955: 1 resort, 12 cottages, immediate watershed about 75% pastured;
- 1975: 87 cottages, 1 resort and a church camp; immediate watershed about 25% cultivated and 45% developed;
- 1990: 95 homes, no resort, church camp; immediate watershed 75% residential development, essentially no pasture and cultivated land converted to CRP.

The 1970 DI-P value is quite consistent with pre-European TP values (Table 9) and corresponds quite well with monitoring data from 1979 and 1980 (Figure 10). DI-P from c. 1993 reveals a decline, which is further supported by monitoring data from 1981, 1986, 1990 and 1997 (Figure 10). A strong and significant improving trend in Secchi depth is evident for the lake based on CLMP data from 1974 – 2000 (http://www.pca.state.mn.us/water/lakequality.html). In contrast to many lakes in this study, modern-day Cl levels have stayed relatively close to pre-European values (Table 9). The reduction of agricultural use in the shoreland area, combined with changes in outlet elevation (water level) and climatic fluctuations may have contributed to declines in TP between 1970 to c.1990.

Figure 10. Kandiyohi County: Comparison of DI-P and observed-P for Diamond, Henderson, and George Lakes.







Henderson Lake has a very small watershed (59 ha; 2:1 ratio) with a mix of modern-day landuses, which include: built-up (36 %), agricultural (28 %), wetland (13 %) and forests (11 %). The entire shoreland area though is characterized by built-up (cabins) or wetland landuse. Roads comprise five percent of the watershed. None of the agricultural land is presently directly adjacent to the lake. A photograph from the 1860's reveals a shoreline comprised of short grass and brush that was apparently subject to erosion (Plate 6). It was acknowledged that Henderson Lake was a favorite Indian camping place (Lawson and Nelson, 1905).

Plate 6. Henderson Lake late 1800's (Lawson and Nelson, 1905)

Bonde (2002, personal communication) assembled some history on the lake from a lakeshore property owner (Dennis Peterson, Kandiyohi County Commissioner). In this account they document the presence of much agriculture (animal pasturing and feedlots in particular) in the watershed from the early 1900s up until about mid 1960s. They also document frequent problems with high water in the early to mid 1900's and attributed this to periods of high precipitation and alterations in the outlet(s) of the lake (man and animal-induced). Following a ditch clean out in 1957, lake levels fell two to three feet and the lake was reportedly clearer. Problems with high water levels returned in the 1960's with the construction of Highway 71 and an outlet structure that was placed 1.5 to 2 feet above the high water mark at that time. Shoreline erosion during periods of high water continues into the 1990s. During the period from 1962 (construction of Highway 71) to about 1992 the amount of livestock in the watershed was reduced dramatically. This also marks the period when many of the cabins and homes around the lake were built.

MDNR fishery survey records (Gilbertson, personal communication, 2002) provide the following perspectives on shoreland and watershed landuse:

- 1956: no outlet; 10 cottages and 1 resort; immediate watershed agricultural;
- 1975: no outlet; 26 cottages; small pasture area near lake, row crop agriculture and tiling are common;
- 1990: 38 cottages; residential development around majority of lake – in general there has been a conversion from pasture to homes around the lake.

Henderson's pre-European P and Cl values were quite variable as compared to the other Kandiyohi lakes (Table 9). Whether this is an artifact of the diatom reconstruction or is evidence of some significant disturbance, such as fire, or more likely, climate-driven changes that influenced lake level and hydrology (Engstrom, personal communication) is unclear at this point. It is possible there may have been some intensive use of shoreland areas of Henderson Lake prior to European settlement (Plate 6). Also, historical drainage patterns and linkages between the lakes (that may have allowed runoff from Henderson Lake to enter George Lake) may have been different than those of modern-day. Modern-day lake level records (1949-2002) indicate wide fluctuations (5.24 ft.) ranging from 1167.49 ft. (1984) to 1162.25 ft. (1949). Lake level was above the OHW in 1993.

Modern-day DI-P values are near the 1800 values but are high relative to 1750. Likewise, modern-day DI-Cl concentrations are near the 1800 value but high relative to 1750. Sediment accumulation rates show significant increases between c. 1860 and c. 1950 and then declining between c. 1960 and c. 1980. Comparison of 1970s to 1990s diatom-TP and Cl suggest fairly stable conditions for the lake. Monitoring data from 1979 and 1980 are very consistent with DI-P from 1970 and c. 1993, however more recent measurements in 1996 and 1997 show further declines in TP that are below the 1750 DI-P concentration (Figure 10). Slight improvements in Secchi are evident for the lake as well for the period from 1992 to 1999 (http://data.pca.state.mn.us). Overall, these data suggest that modern-day TP and Cl levels are consistent with, or lower than, those of the 1800 time-period, however all three time periods are elevated in comparison to the 1750.

Long Lake has a larger watershed (363 ha) than George or Henderson, however it is small relative to the size of the lake (2.5:1 ratio). The watershed is characterized primarily by agricultural (35%), forest (33%) and built-up (16%) landuse, while roads occupy only one percent of the watershed. Much of the shoreland area is forest, wetland or built-up, with minimal direct contact with agricultural land.

Based on photos from the late 1800s the lake had a heavily–forested shoreline (Plate 7) and much of the watershed was "aspen-oak land" with a mix of prairie based on Marschner (1930). Some history for the lake was assembled by Tom Bonde (personal communication, 2002) and is summarized as follows:

"The following notes were taken by Howard Buffington in an interview with 86 year-old Foster Hudson, who has lived on the lake all his life. Howard's parents purchased the resort on the east end of the lake in 1959 and he now lives near the public access at the outlet near the west end of the lake. He owns sizable pieces of land on both sides of Hwy. 23, some of which he is actively developing as home sites. In the 1880's the land surrounding Long was pastured. Horses and cattle grazed right up to the shoreline (which is consistent with photographs from this period, e.g., Plate 2). This continued up through the 1950's and 60's in gradually decreasing numbers with only a few remaining in the 1970s. Turkey raising became popular in the late 50's extending through 1975 or so. The turkeys were raised right on the shore in large numbers and this appeared to be the worst time for weeds in the lake. There were fewer weeds in 1920 and 1921. Other pertinent notes are summarized as follows:

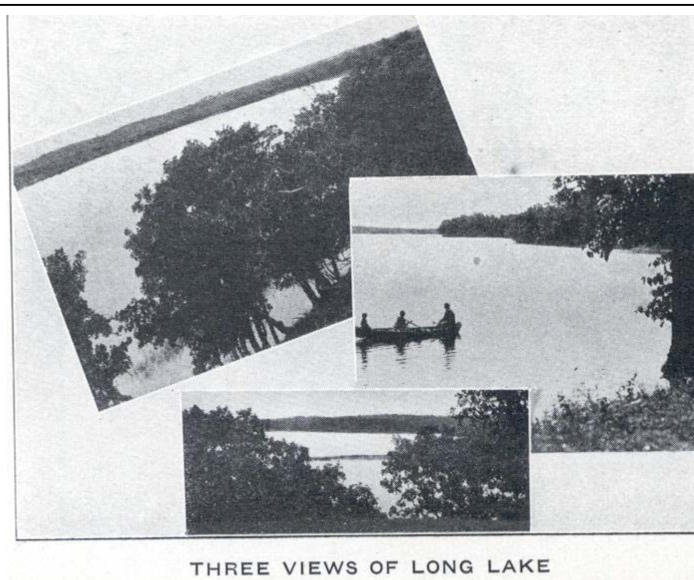


Plate 7. Long Lake, late 1800's (Lawson and Nelson, 1905)

- A tanker of crude or diesel oil spilled over and into the lake in the 1920's, maybe 1924-25, and "killed" the entire lake.
- A dam was built across the outlet in 1928-32. Prior to this, cattle walked across the lake at the point where the power line crosses. The dam increased the water level of the lake 18 to 24 inches.
- A gravel pit has existed across the highway and east of the outlet for many years. The gravel company dredged the outlet in the 1930's to provide water for their operation. Gravel operations have continued, and in recent years expanded to cover a large area north of the lake.
- The highway came through in 1931 or 1932 accompanied with the construction of another bridge next to the railroad bridge that had been built in 1886."

MDNR fishery survey records provide the following perspectives on watershed and shoreland land use:

- 1955: 34 cottages and 3 resorts; immediate watershed 20% developed, turkey barn and pasturing along north shore;
- 1975: 42 cottages and 3 resorts; immediate watershed 60% developed, 10% pasture, and little tiling;
- 1994: 185 homes and 4 resorts; shoreland 35% residential and 54% forested.

Modern-day TP and Cl are slightly elevated above pre-European values and there appears to be a slight increase in both parameters from the 1970s to the 1990s (Table 9). Sediment accumulation rates, while declining substantially from c.1960 to c.1980, remained constant or increased slightly between c. 1980 and c. 1990. Most of the increase was in the form of organic and carbonate fractions (reflecting increased productivity in the lake). Modern-day TP concentrations are relatively low as compared to other CHF lakes (in this study and compared to reference lakes, Appendix II). Cl concentrations, however, which were within the typical range for CHF lakes in the 1970 core sample, appear to be increasing based on the c. 1993 sample and are now above the typical range (Appendix II). Whether this is a function of an increased road network in the watershed, increased road-salt usage and/or related to onsite septic systems or runoff from impervious surfaces in the shoreland area is unclear based on available information. Minimal water quality data were available for the lake, with the exception of CLMP Secchi data that reveal a significant increase in transparency from the 2.9 to 3.6 m range for the period from 1990 to 2000 (http://www.pca.state.mn.us/water/lakequality.html).

Diamond Lake has the largest watershed (3,590 ha) and watershed: lake ratio (6:1) of the four Kandiyohi County lakes. The watershed is characterized primarily (74%) by agricultural uses including row crop, pasture, and feedlots. Wetlands comprise about nine percent of the watershed, however many basins have been drained or ditched. Pre-settlement vegetation tended toward prairie to the south and oak-aspen to the north of the lake (Marschner, 1930) and this land now is largely in cultivated or other agricultural uses. Photographs from the late1800's show a tree-lined shore and prairie/pasture-like upland (Plate 8).

There is extensive evidence of concern regarding the water quality of Diamond Lake based on various reports and memoranda.

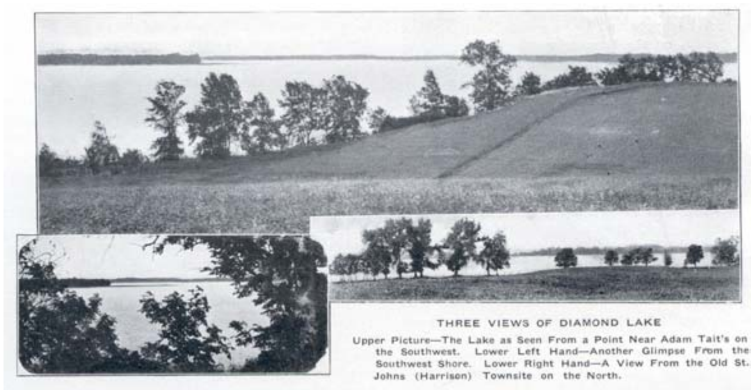


Plate 8. Diamond Lake, late 1800's (Lawson and Nelson, 1905)

- In 1972, for example, the MPCA, in a report to Kandiyohi County, noted in-lake TP concentrations of 40-50 µg/L (essentially equivalent to the 1970 DI-P value, Table 9) and very high TP concentrations in tributaries to the lake.
- In 1986 a private consultant documented high nutrient concentrations.
- In 1988 AGNPS modeling, conducted by the SWCD and MPCA, attempted to estimate relative contributions of TP to the lake from different land uses. Row crop cultivation was thought to be an important source. Documentation for the modeling effort identified 23 feedlots in the watershed.
- In 1990 a public meeting was held to address water quality concerns. Shortly thereafter, Diamond Lake entered the CWP in response to declining water quality.

MDNR fishery survey records provide the following perspectives on shoreland and watershed landuse (Gilbertson, personal communication, 2002):

- 1954: 56 cottages and 5 resorts; immediate watershed 80% hardwood and 15% agricultural;
- 1971: 206 cottages, 65 homes, and 2 resorts; immediate watershed 45% cottages and resorts and 50% farms and fields;
- 1991: 355 cottages (many converted to year round residences) and county park; immediate watershed 70% row crop and livestock (increased tiling) and 15% cottages.

TP concentrations were already above resettlement by the 1970s, however these levels increased further by the 1990s (Table 9). These trends are evident in both the diatom reconstructions as well as monitored data (Figure 10). The 1970 DI-P corresponds quite well with monitoring data from 1979-1981 (Figure 10). TP has increased further by c. 1993 based on DI-P and monitored data. Cl concentrations rose as well over between the pre-European and modern-day period – with the largest increase between 1800 and 1970. The diatom-reconstructions and observed data point toward the increased eutrophication of Diamond Lake since European settlement. While a large increase in TP was noted between 1800 and 1970 an almost equal increase was noted over the 1970 to 1993 timeframe. Sediment accumulation rates, which peaked c. 1950 and declined until c.1970, increased again between c.1970 and c.1990. The organic and carbonate fractions tended to drive this increase. The modern-day increases in P and overall eutrophication of the lake can be attributed to the extensive agricultural activities in the watershed, combined with runoff from its urbanized shoreline.

Table 9. Kandiyohi County lakes diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
George	TP µg/L	37	27	35	21
	Cl mg/L	6	5	8	7
Henderson	TP µg/L	23	40	36	34
	Cl mg/L	4	28	29	22
Long	TP µg/L	20	19	23	27
	Cl mg/L	7	6	10	15
Diamond	TP µg/L	25	28	47	79
	Cl mg/L	4	8	18	22

Meeker County: Dunns and Richardson

Dunns and Richardson are two adjacent lakes in the same watershed. Richardson is the smaller but deeper of the two and receives the majority of the runoff from its 1,168 ha watershed. It, in turn, drains to Dunns Lake, which is somewhat larger (63 ha) but is much shallower with a maximum depth of 6.1 m. It has a small direct watershed of 165 ha in addition to Richardson's watershed. Dunns was most likely named after one of the earliest settlers of Meeker County, Timothy Dunn, who settled near Darwin in 1856 (Alden, 1888). Richardson likely was named after a surveyor who settled near Kingston (Smith, 1877). As with the other nearby counties the pre-settlement vegetation of Meeker County was characterized by a transition from "oak openings' to the north and "wet prairie" to the south (Marschner, 1930) – which likely includes much of Richardson Lake's watershed. Alden (1888) notes "In no portion of the great State of Minnesota is Meeker County surpassed for its beautiful scenery; its rolling prairies interspersed and diversified with natural and domestic groves; it famous lakes, meandering streams and carpet of flowers….As an agricultural and stock-raising region Meeker County cannot be excelled." The latter observation suggests the importance of agriculture in the county, in these early years, as well as today.

The modern-day watershed is characterized by extensive agricultural landuse and is dotted by numerous wetlands. A 1996 LAP study (Heiskary et al. 1997) noted numerous animal feeding operations in the watershed with the following estimated numbers of animals: 220 dairy, 80 beef, 1.6 million chickens, 80,000 turkeys, 850 hogs, and 6,000 mink, as estimated by the Meeker SWCD. Since that time there has been a reduction in hog and mink farming, however there has been an increase in poultry farming in the watershed (Chimelewski, 2002 personal communication). The high number of animals in the watershed suggests that large amounts of manure are present in the watershed, and unless properly land-applied or otherwise processed, it could represent a significant source of pollution to the lakes. There were about 69 homes around the two lakes with the majority on Dunns. Following the LAP study a CWP project was undertaken on these lakes.

Pre-European TP and Cl levels for the lakes suggest fairly stable conditions between 1750 and 1800 (Table 10). TP and Cl tended to be higher in Richardson as compared to Dunns. This makes sense for TP as Richardson would act essentially as a sedimentation basin for the upper watershed of the two lakes, hence reducing the load to Dunns.

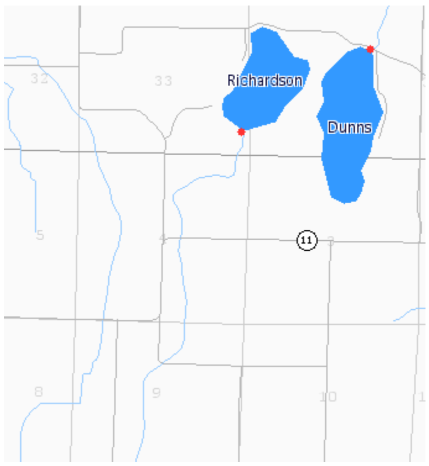


Plate 9. Dunns and Richardson Lakes (MDNR Web site)

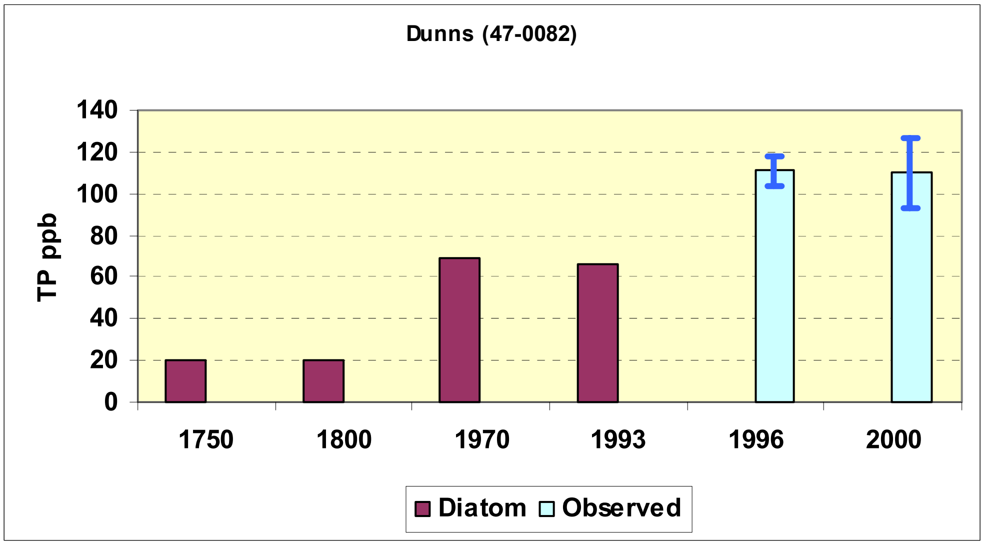
Modern-day TP and Cl show a dramatic increase in both lakes, with TP increasing three-fold in Dunns and two-fold in Richardson. Cl increased almost thirty-fold in Dunns and about three-fold in Richardson over these time frames. Sediment accumulation rates increased steadily in both lakes from c.1880 to c.1930, declined between c.1930 to c.1940, and increased steadily thereafter into the 1990s (Appendix III). The various fractions (inorganic, carbonate and inorganic) were relatively constant in Dunns Lake from c.1880 to modern-day and likely reflects the upstream sedimentation in Richardson Lake. In Richardson Lake the carbonate fraction accounts for about 40-60 percent of the sediment in modern times, suggesting increased productivity in the lake (a response to nutrient enrichment).

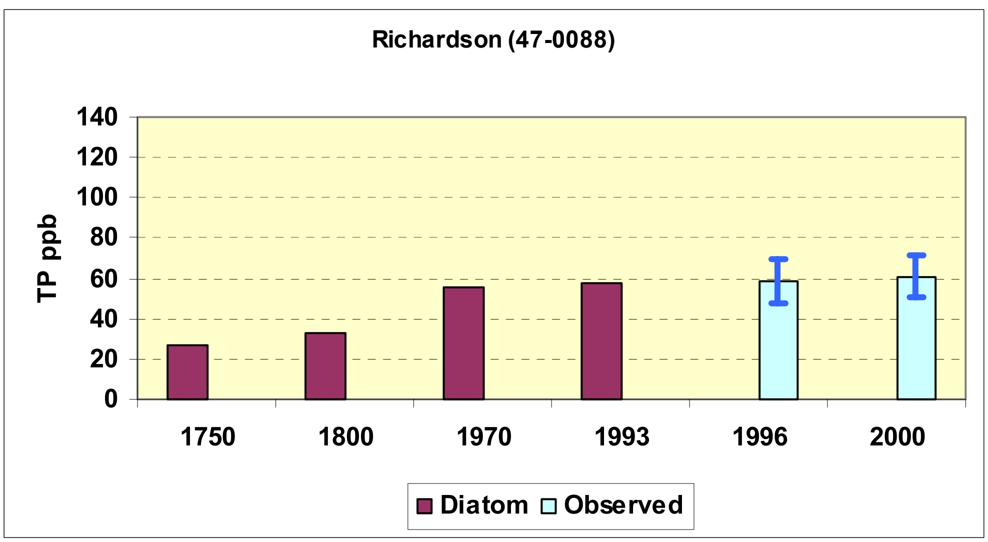
What is very interesting in the modern-day comparisons is that TP concentrations in Dunns Lake are now greater than those in Richardson Lake. This was observed in the LAP study and was attributed in part to internal recycling of TP within the lake as a result of periodic wind-mixing of the lake during the summer. For Richardson the 1970 and c. 1993 diatom values compare quite well with observed values from 1996 and 2000 (Figure 11) and no significant trend is noted. The 1996 observed TP for Richardson was consistent with the TP predicted by the MINLEAP model, which implies that Richardson exhibits in-lake TP values consistent with that expected for a lake of its volume and watershed area in the CHF ecoregion. The modern-day diatom TP values for Dunns Lake tend to underestimate observed TP values for 1996 and 2000, which is not uncommon for highly eutrophic lakes (Reavie et al. 1995b). Based on these data it appears that major increases in TP and Cl loading to these lakes occurred prior to 1970 and have likely been sustained since that time.

Table 10. Meeker County lakes diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
Dunns	TP µg/L	20	20	69	66
	Cl mg/L	2	2	60	54
Richardson	TP µg/L	27	33	56	58
	Cl mg/L	16	21	67	61

Figure 11. Meeker County: Comparison of DI-P and observed summer-mean P for Dunns and Richardson Lakes.





McLeod County: Hook and Stahls

Hook and Stahl Lakes are located near Hutchinson in McLeod County. This county, as do Kandiyohi and Meeker Counties, lies on the transition from the North Central Hardwoods Forests and Western Corn Belt Plains. Both lakes would be just within the CHF ecoregion. Pre-settlement vegetation would have been characterized as "oak openings and barrens" (Marschner, 1930), which represented a transition from the Big Woods to the north and east and prairies to the south and west. The history of McLeod County (Curtis-Wedge, 1917) provides some perspective on this area in the mid 1800's to early 1900's. The account begins with "This county has long been noted for the number and attractiveness of its lakes and lakelets;" however, the following chronology emphasizes the importance of agriculture in this county following European settlement.

- 1770's to 1790's – Indians participated in active fur trading in the area though they did not tend to make permanent villages or habitation in the "Big Woods."
- 1855 – Marked the first subsistence agriculture in the county in the Glencoe and Hutchinson area. Much tree clearing during this time period.
- 1860 – 137 farms in county;
- 1870 – 943 farms in county;
- 1880 – 1,743 farms in county;
- 1890 – 2,070 farms in county;
- 1900 – 2,335 farms in county;
- 1910 – 2,268 farms in county (county ~ 317,440 acres of which 94% was in farms).

<u>Hook Lake</u> has a small watershed relative to its size (4.7:1) and of this, 220 ha (28% of total watershed) drains through Echo Lake. About 76 percent of the watershed is in agricultural land use and the shoreline is a mix of wetland, built up and agricultural use. Land use in the watershed was estimated as a part of MDNR fishery surveys. A 1947 survey identified five homes on the lake (Hutchinson MDNR area fishery office files). A 1974 survey identified the watershed as 70% agriculture (dairy, farms, fields, and pasture), 20% mixed hardwood forest, and 10% grass and marsh. Shoreline cover was 80% mixed hardwood forest and 20% agriculture. A total of eight dwellings were counted. A 1987 survey identified the immediate watershed as 80% agriculture and 20% wooded or lowland. Shoreline was 58% wooded, 40% marsh, and 2% pasture. A total of 19 dwellings were counted on the lake. A 1995 fisheries management re-survey found the watershed to be 85% agriculture row crops, 10% marsh, and 5% small-scattered plots of undeveloped forest. A total of 19 homes were counted around the lake, of which most were occupied year round. Shoreline was 65% undeveloped forest, 20% marshland, and 15% residential. More development occurred along the shoreline since 1995. Though agriculture has remained a significant portion of the overall landuse in the watershed it appears there may have been a reduction in the amount of agriculture in the shoreland area based on the MDNR information.

Pre-European TP and Cl values were relatively high as compared to other lakes in the study and suggest eutrophic conditions for the lake (Table 11). A distinct increase in TP was evident in 1970, followed by a decline c. 1993. Based on observations on land use included in the MDNR fishery records there appeared to be a shift from agricultural land use in the shoreland area in the 1970s to more residential and forested uses. Very little data are available for this lake with the exception of CLMP Secchi data. A single measure of TP and chlorophyll-a in 1981 suggests very eutrophic conditions for the lake (268 and 114 µg/L, respectively) while four measures collected as a part of this study in 1996 and 1997 averaged 63 and 25 µg/L respectively. Secchi data for 1990 to 2000 show widely fluctuating Secchi reading ranging from 0.3 m in 1992 to a peak of 3 m in 1997, with no obvious trend (http://www.pca.state.mn.us/water/lakequality.html). The peak Secchi in summer of 1997 followed a partial winterkill in winter 1996 (www.dnr.state.mn.us). This likely allowed for a pulse in the zooplankton population that in turn reduced the amount of algae. DNR notes suggest that late summer algal blooms are common on the lake.

Stahls Lake has a moderate sized watershed relative to its surface area (11:1) and much of the watershed drains through shallow lakes such as French, Popp, and Mud. These lake/wetland complexes account for about 22 percent of the watershed, while agriculture accounts for about 58 percent. There is little built-up land use in the watershed and wetland and forested uses and some agriculture would characterize most of the shoreline. MDNR fishery records (Hutchinson area office) provide some perspective on modern-day landuse composition and changes. A 1973 survey identified shore cover as 70% cultivated farmland, 20% mixed hardwoods, and 10% private homes; with a total of 10 homes and one farm were counted on the lake. Cultivated farm-land with mixed hardwoods comprised the shoreline, along with large cattail marshes on north and west shores. A 1990 survey identified the immediate watershed as 40% forest or woodland and 60% agricultural pasture and row crops. Shoreline was primarily hardwoods with a small portion of pasture. Approximately 10 acres of marsh exist on north and west side of lake. A total of nine homes were counted. A 1998 fisheries management re-survey found the surrounding watershed to be 20% undeveloped forest or woodland, 50% agriculture row crops, 20% livestock /pasture, and 10% marshland. A total of 17 cabins were counted on the lake, of which most were year round. Shoreline was 53% undeveloped forest or woodland, 10% agriculture row crops, 25% marshland, and 12% residential. Much of the lakeshore is unaltered due to it being a county park and not much room is left for development.

Pre-European TP and Cl were relatively low suggesting mesotrophic conditions for the lake (Table 11). Distinct increases in both parameters were evident in the modern-day reconstructed values with about two-fold increases for TP and ten to twenty-fold increases for Cl. TP values have been relatively stable from 1970 to c. 1993 based on the reconstructions. There is very little water quality data for this lake. The increased modern-day TP is likely a function of the extensive agricultural land use in the watershed (based on modern-day landuse and the history of the county). The increased Cl is likely a function of the agricultural land use, however if road salt is used on the road network adjacent to the lake or in its watershed this could also lead to elevated concentrations in the lake.

Table 11. McLeod County lakes diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
Hook	TP µg/L	51	58	89	53
	Cl mg/L	40	59	26	7
Stahls	TP µg/L	18	20	45	45
	Cl mg/L	1	1	10	19

Stearns County: Krieghle and Sagatagan

Krieghle and Sagatagan are moderate sized and relatively deep (17.1 and 14.3 m maximum depth respectively) lakes in Stearns County. Watershed to lake ratios are about 2:1 and 3:1 respectively. Both are characterized by a high percentage of forested landuse throughout the watershed. There is minimal agricultural or built-up land use in either watershed and shoreland areas tend to be forested. Pre-settlement vegetation in this area was characteristic of the "Big Woods" (Marschner, 1930). The first European settlers in Stearns began to arrive around 1849 and agriculture began to emerge as well (Mitchell, 1915).

The only built-up landuse on Sagatagan corresponds to St. Johns University and Abbey, which has been located there since the late 1800's. Mitchell (1915), in a history for Stearns County, provided details on the Abbey and related development: "The site had been selected several years before; it was on the shores of a primeval forest…the material used for the building was granite boulders found on the spot and along the shores of the lake." The original building (~1867) was about 46 x 50 feet. A sawmill was constructed on the north fork of the Watab River, about ¼ of a mile north of the building to help facilitate building efforts (1868). The mill was destroyed by fire in 1873, was rebuilt but burned again ten years later. Much work was done on the site between 1895 – 1910. In 1910 the science hall was constructed and a new laundry was built (no mention however regarding wastewater disposal).

Sagatagan's pre-European TP and Cl were much more variable than were Krieghle's values (Table 12). The elevated TP and Cl in Sagatagan in 1800 may point to some disturbance in the watershed at that time. Both lakes exhibit modern-day TP and Cl levels consistent with pre-European values (1750 in particular). Cl levels are slightly higher in Sagatagan, presumably because of the road network and parking lots in the vicinity of the lake. There are minimal data available for these lakes in STORET with the exception of CLMP Secchi for Krieghle. In 1999 and 2000 Secchi averaged 4.8 and 5.9 m, respectively, which further indicates the low trophic status of the lake.

Table 12. Stearns County Lakes' diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
Krieghle	TP µg/L	17	17	16	13
	Cl mg/L	1	1	1	1
Sagatagan	TP µg/L	15	31	19	16
	Cl mg/L	1	10	1	5

Central Hardwoods Forests ecoregion: Metro-area lakes

Dakota County: Fish, Dickman, Marcott, and Schultz

Pre-settlement vegetation throughout much of Dakota County was characterized as either "big woods" or "oak openings" (Marschner, 1930). All four of the Dakota County lakes are quite small ranging in size from 5.3 ha (Schultz) to 12.5 ha (Fish). Maximum depths range from 2.4 m (Dickman) up to 10.1 m (Fish). Total watershed areas are quite variable among the lakes ranging from 57 ha (Dickman) up to 1,506 ha (Fish). Watershed characteristics and land use changes can help explain the observed changes for most of these lakes.

<u>Fish Lake</u>, for example, had minimal development in its watershed up until the late 1960's. From 1971 to 1975 the residential area around the lake was developed (Storland, 2002, personal communication) resulting in increased runoff entering the lake. In 1980 an outlet structure was constructed to aid in managing water levels and allowing for the movement of water downstream. Expansion of the watershed began in 1983 with the installation of a lift station from Hurley Lake to Fish Lake and the subsequent installation of stormwater pipes from McCarthy Lake to Hurley Lake. In 1987 three more lift stations were constructed: Mooney lake to McCarthy Lake, Bald Lake to Hurley Lake, and Country Hollow to McCarthy Lake. These efforts increased the watershed of Fish Lake from about <u>106 ha to about 1,506 ha</u>. The significant increase in TP and extraordinary increase in Cl in Fish Lake from the 1970s to the 1990s could be attributed to the expansion of its watershed and highly urbanized nature (76% of watershed by area built up or roads) of its watershed.

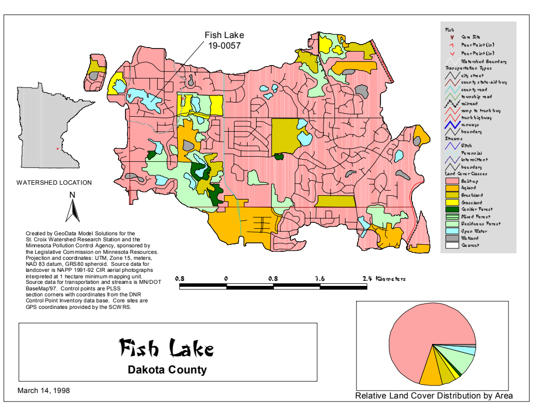


Plate 10. Fish Lake watershed and landuse.

Minimal water quality data are available in STORET for Fish Lake, however that which is available supports the trend revealed by the diatom reconstructions. A 1989 survey of the lake revealed a summer-mean TP of 53 (±9) µg/L that corresponds quite well to c. 1993 DI-P value (Table 13). Historic CLMP Secchi data reveal a summer-mean Secchi of 5.4 m in 1978, which would be consistent with the mesotrophic conditions revealed by the 1970 DI-P value. In contrast, summer-mean Secchi for the ten-year period from 1989 to 1999 averaged about 1.5 m, which would be consistent with the more eutrophic conditions revealed by the c. 1993 DI-P value and the monitoring conducted in support of this study.

Dickman Lake (south St. Paul), in contrast, has a very small watershed of about 57 ha and is quite small (9.1 ha) and shallow (2.4 m maximum depth). Modern-day landuse in the watershed is a combination of built-up (38%), forest (31%), grassland, and some agricultural land on the fringe of the watershed. Most of the "built-up" portion of the watershed is along the north side of the lake. Engstrom (personal communication) notes that most, if not all of the built-up area (that is comprised of several homes) was developed sometime between mid 1970s and 1990s.

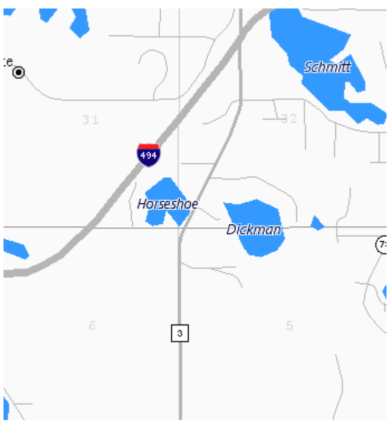


Plate 11. Dickman Lake (MDNR Web site).

Significant increases in TP, above pre-European levels, were evident by the 1970s. However concentrations increased further, doubling between 1970 to c. 1993, based on the diatom-inferred data (Table 13). This was among the largest increase in TP noted in this study over the 1970 – 1990 time frame. Cl, however, remained near pre-European levels in the 1970s but increased three-fold by the 1990s. The increase in TP from pre-European times to 1970 was likely due to agricultural land use in the watershed. However, change in TP between the 1970 and 1990s time period was likely a result of development and increased impervious area in the watershed. Though there are no direct storm sewers into the lake (Thureen, 2002, personal communication) salt usage on adjacent Highway 3 (Plate 11) and local roads likely contribute to the large increase in Cl. The small area, shallowness, and limited flushing of Dickman Lake make it particularly susceptible to eutrophication and buildup of Cl with even small increases in nutrient and Cl loading.

Marcott Lake (also referred to as Ohman's Lake) as included in this study refers to the last lake in a chain of four lakes referred to as Marcott Lake (Plate 12). It has a fairly small (56 ha.) primary watershed and its shoreland area is characterized by forested landuse. The upper watershed includes a mix of built-up, forest and some agriculture, however several upstream lakes/wetlands serve to filter runoff prior to the lake. It appears that the combination of relatively undisturbed shoreland and the upstream network of lakes/wetlands have served to minimize downstream transport of TP to Marcott Lake. While TP has stayed near pre-European levels in the lake Cl concentrations have increased markedly since the 1970s, presumably due to high percentage of watershed area in roads (6%), road construction/reconstruction (Highways 3 and 55), increased salt usage on roads and/or increased impervious areas in the upper watershed. While activities in the total watershed during the 1970-1990s timeframe allowed for increased

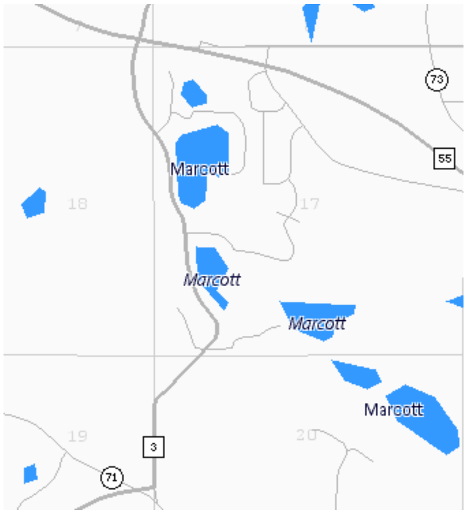


Plate 12. Marcott Lakes watershed

Cl loading to the lake, other activities intended to minimize TP loading to the lake appear to have been successful as TP levels have remained fairly constant over that period. Threen (personal communication, 2002) notes that measures have been taken to minimize the direct impact of stormwater to this chain of lakes and current city policy states that no further stormwater will be directed to the lakes. There is minimal water quality data available in STORET for the lake, however CLMP data from 1989 and 1990 revealed an average Secchi of 4.5 m. Secchi data suggest mesotrophic conditions, which would be consistent with the DI-P values for 1970 and c. 1993 (Table 13).

Schultz Lake has a very small primary watershed (18 ha.) characterized primarily by forested landuse and some built-up area along its north shore. The lake itself is located in the confines of Lebanon Hills County Park. The remainder of the watershed has a similar landuse composition and drains through an upstream lake/wetland. The small percentage of roads and built-up area would help account for the minimal change in Cl over pre-European levels. TP has exhibited a small increase over pre-European but has remained stable over the period from 1970s to 1990s. CLMP Secchi data in STORET for the period from 1992 to 2000 reveal an average transparency of about 3.0 m which would be consistent with the mesotrophic status indicated by the c. 1993 DI-P value (Table 13).

Table 13. Dakota County lakes diatom-inferred phosphorus and chloride concentrations.

		1750	*1800*	*1970*	*1993*
Dickman	TP µg/L	15	19	27	53
	Cl mg/L	3	3	3	10
Fish	TP µg/L	25	37	23	55
	Cl mg/L	9	9	7	124
Marcott	TP µg/L	19	22	19	`19
	Cl mg/L	3	8	8	18
Schultz	TP µg/L	18	18	24	24
	Cl mg/L	2	3	5	4

Hennepin County: Calhoun and Harriet, Christmas, Little Long, Sweeny and Twin

Calhoun and Harriet are among the largest lakes in the Metro area at 169 and 139 ha and are the centerpiece for the Minneapolis park system. Calhoun has a very large drainage area (primary = 1,236 ha and total = 2,515 ha), while Harriet, which is immediately adjacent to Calhoun has a rather small watershed (387 ha). In 1857, one year after Minneapolis was incorporated as a town, land was first donated for park development (Derby et al. 1997). Lake Harriet was brought into the park system in 1885 by donation and Calhoun followed in 1909. Throughout this time period and the decades to follow the watershed of these lakes became increasingly urbanized, however adjacent parkland served to protect the riparian areas of these lakes. Reports by the Minneapolis Park Board (Pulscher, 1997) and Brugam and Speziale (1983) provide extensive information on the history of the lakes and their watershed. A few pertinent excerpts will be included here.

Examination of events in the Chain of Lakes since European settlement provides some information about possible historical factors influencing water quality in the lakes (Table 14). It is reasonable to assume that watershed development during the early 1900s and construction of a storm sewer system during 1910-1940 caused some degree of water quality degradation in the lakes (Pulscher 1997). Brugam and Speziale (1983) noted increased rates of sediment accumulation (based on sediment core analysis) in the mid 1920's as the watershed area of the lakes increased with the installation of storm sewers. It is also evident that the majority of the development in the watershed and creation of stormwater networks occurred over the first half of the 1900's and was substantially completed prior to the 1970s. According to Brugam and Speziale (1983) this storm sewer and pumping network resulted in the sudden eutrophication of Lake Harriet in 1975 and it seems likely that the pumping station and pipeline from Calhoun in 1967 probably had the biggest single influence on Lake Harriet.

Table 14. Historical Events in Chain of Lakes Watershed. Drawn in part from Jensen and Brezonik (in Derby et al. 1996).

Date	Activity
1805	Establishment of Fort Snelling at confluence of Mississippi and Minnesota Rivers, approximately 6 miles from Chain of Lakes
1828	Indian village *Teakapeotonwe* located on east shore of Lake Calhoun
1853	Military reserve land, including Chain of Lakes, opened for settlement by non-natives
1857	Shift from prairie to subsistence farming (based on an increase in ragweed pollen; Brugam and Speziale, 1983)
1870	Downtown Minneapolis developed
1870-1880s	"Resort era" of Chain of Lakes
1890s	Installation of streetcar line to Chain of Lakes from Minneapolis
1883-1908	Shoreland of Chain of Lakes purchased by Minneapolis Park Board
1889-1925	Lake Calhoun, Cedar Lake, Lake Harriet and Lake of the Isles dredged

1911-1917	Inter-lake canals constructed, causing a 6-foot drop in water level of Cedar Lake and a 9-foot drop in the water level of Brownie Lake
1910-1920	First storm sewers routed to the Chain of Lakes
1920-1940	Construction of most storm sewers within the Minneapolis portion of the watershed
1933	Well water pumped to Brownie Lake to augment water levels in Chain of Lakes
1957-1965	Water from nearby Bassett's Creek pumped into Brownie Lake to augment water levels in Chain of Lakes
1967	Pumping station and pipeline installed between Lake Calhoun and Lake Harriet

Table 15. Calhoun and Harriet history of storm sewer additions [1]

Lake	Area	Cumulative	Decade	Total Area
	Acres	Acres	Built	Acres
Lake Calhoun	368	368	1920s	
	408	776	1930s	
	134	910	1940s	
	154	1064	1960s	
	77	1141	1970s	
	105	1246	1980s	
	2	1248	1990s	1248
Lake Harriet	100	100	Teens	
	159	259	1920s	
	402	661	1930s	
	4	665	1940s	
	3	668	1950s	
	160	828	1960s	
	38	866	1980s	866

1. This does not include 35 acres in Brownie Lake watershed (~1930's – 1960), 224 acres in Cedar Lake watershed (~1920's – 1970s), and 751 acres in Lake of the Isle's watershed (~1920 – 1980s).

The diatom reconstructions for Calhoun and Harriet suggest similar pre-European P concentrations that were on the order of 16 – 19 µg/L (Table 16). However, by the 1970s, TP concentrations were on the order of 50 - 60 µg/L based on the diatom reconstructions. This peak in TP followed the extensive storm sewering that had occurred during the 1920s-1960s (Table 15). And for Harriet, this followed the connection with Calhoun in 1967. Water quality monitoring data from the early to mid-1970s would appear to corroborate the diatom reconstruction (Figure 12). The reconstruction for the early 1990s indicated a small non-significant decrease in TP in Calhoun, but a significant decline in Harriet. (Observed data from the mid to late 1990s also suggests some significant declines in TP as compared to the 1970s.) Observed data for Harriet in 1971 and 1972 average 41 (±2) µg/L. Concentrations were variable in the 1980s and a concentration of 50 (±7) µg/L was measured in 1992. However by the mid to late 1990s concentrations had stabilized at about 24 (±2) µg/L, which was a substantial improvement from the elevated concentrations of c. 1970 and relatively close to pre-European concentrations.

These recent declines in TP could be attributed to aggressive implementation of best management practices including street sweeping, improvements in stormwater treatment, and related activities. Recent activities, conducted as a part of the Clean Water Partnership Project on the Chain of Lakes contribute to the recent improvements and should ensure protection of water quality into the future. Examples of more recent projects are summarized in Table 17.

The c. 1970 increases (over pre-European values) in Cl for Calhoun and Harriet Lakes were among the largest in this study with 30 to 40-fold increases in Lake Harriet and 40 to 50-fold increases in Lake Calhoun. This is not too surprising given that over 95% of both watersheds are characterized as “built up” or roads. The extensive storm sewer networks serve to bring Cl-laden runoff into the lakes and much of this network was completed by the 1970s (Table 15). The decline in Cl in Harriet between 1970 and c. 1993 may be attributable to increased flushing of Harriet as a result of pumping water from Calhoun to Harriet. Lennander (in Derby et al. 1997) estimated that pumping from Calhoun contributed about 60 percent of the surface inflow to Harriet (on average) for the period 1983 to 1993 and led to decreased residence time (increased flushing) in Harriet.

Table 16. Hennepin County lakes diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
Calhoun	TP µg/L	18	16	53	50
	Cl mg/L	2	2	91	103
Harriet	TP µg/L	19	16	60	44
	Cl mg/L	5	4	144	71
Sweeny	TP µg/L	24	29	40	33
	Cl mg/L	11	10	13	17
Twin	TP µg/L	21	18	17	25
	Cl mg/L	9	7	8	12
Christmas	TP µg/L	24	20	34	45
	Cl mg/L	10	4	28	60
Little Long	TP µg/L	18	19	15	16
	Cl mg/L	4	2	6	6

Table 17. Actions taken in the Chain of Lakes Clean Water Partnership (Minneapolis Park & Recreation Board, 1993.)

Lake	Grit Chambers	Alum Treatment	Wetland/Ponds
Cedar		1996	1996
Brownie			
Isles	1994, 1997, 1999	1997	
Calhoun	1995, 1998, 1999	2001	1998-99
Harriet	1994, 1995, 1996	2001	1998

Sweeny (27-0035-01) and Twin (27-0035-02)

Sweeny and Twin represent two distinct bays of a lake near Golden Valley and St. Louis Park. Sweeny, the larger of the two at 28 ha, receives the majority of the drainage from its 1,011 ha watershed. Twin Lake, at 9 ha, has a very small (33 ha) and relatively undeveloped watershed. A very comprehensive history was developed for the Sweeny Lake watershed by Barr (1994) in a "Watershed and Lake Management Plan" developed for the Bassett Creek Water Management Commission. Some important features relative to our study are as follows:

- 1950's - Sweeny Lake and direct watershed about 30 percent developed.
- 1960's - Direct watershed near 100 percent developed, total watershed 80 percent developed. Significant commercial and industrial development underway.
- 1970s - Some detention ponds built in St. Louis Park and Golden Valley. In the early 1970s a storm sewer system from an adjacent 126 ha drainage area was routed directly to the lake but by mid 1970s it was rerouted through a DNR-protected wetland on the south end of the lake. An aeration system was placed in the lake and was used for summer aeration from 1973 to 1988.
- 1980s – Several flood control projects carried out. In 1988 aeration system was converted to year-round use.
- 1990s – Major widening and reconstruction of Highway 394 carried out. Several ponds dredged or created for flood control.

Based on this history it is apparent that extensive development activities have taken place in this watershed from the 1950's through the 1990s. Extensive storm sewer networks were a part of this development and numerous treatment basins were created in latter years to try to minimize flooding and water quality impacts of development and stormwater. Barr (1994) indicated that stormwater from the total watershed, with the exception of direct watershed, is treated to some degree via treatment basins or wetlands. Twin Lake, in contrast, has a very small watershed that is largely characterized as parkland and has minimal road networks that drain to it.

A review of diatom-inferred values for the two lakes (Table 16) shows some similarities and differences between the two lakes. Pre-European TP and Cl values were slightly higher in Sweeny as compared to Twin Lake – likely a function of relative watershed size. By the 1970s increased TP and Cl were evident in Sweeny Lake, which was likely a function of the urbanization of the watershed and increased stormwater delivered to the lake. The 1970 DI-P (40 µg/L) is lower than some monitoring data (60 – 100 µg/L) provided in Barr (1994). A reduction in DI-P (33 µg/L) in the 1990s was found, which is consistent with some 1992 monitoring data (summer-mean TP = 33 µg/L) provided by Barr (1994). Diatom-inferred Cl concentrations increased in the lake, however, from 13 to 17 mg/L.

Twin Lake, in contrast, exhibited very stable TP and Cl values through the 1970s. However, the 1990s data indicate an increase in both parameters. Sediment accumulation rates exhibited peaks c.1950 and c.1985 followed by a significant decline c.1995 (Appendix III). The organic and carbonate fractions comprise about 65 percent of the modern-day sediment. Increases in these two fractions often are associated with increased biologic productivity in lakes. Though its watershed is small (4:1 ratio), built-up (36 %) and road areas (15%) comprise about 50 percent of the watershed area. This may suggest some increased development (e.g., increase in impervious surfaces) and/or stormwater entered the lake in the 1990s as compared to the 1970s.

Christmas (27-0137) and Little Long (27-0179-02) Lakes

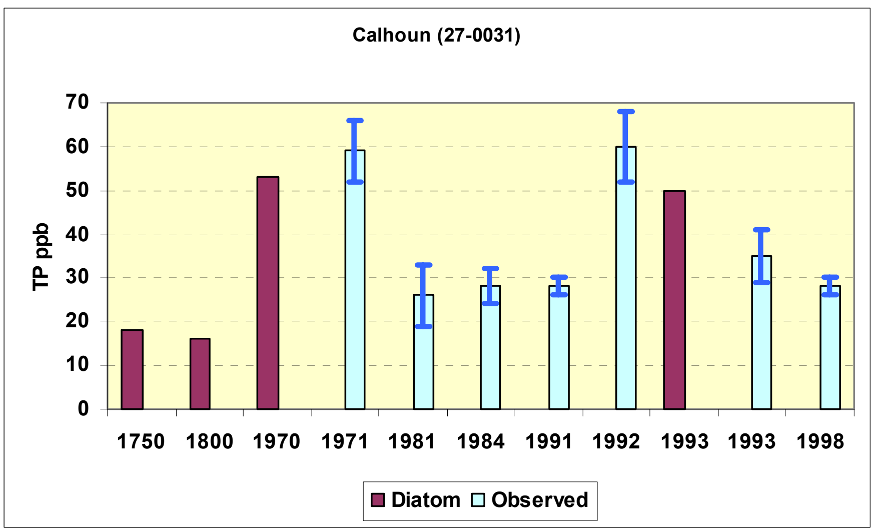
Christmas Lake is located in the west Metro area just south of Lake Minnetonka. Christmas Lake is managed as a two-story lake, which means that warm-water species, such as bluegills, and coldwater species, such as rainbow trout, can survive in the same lake. Christmas Lake is one of the few lakes in the metro area with habitat to support trout all year long (http://www.dnr.state.mn.us). Christmas Lake's shoreline was originally developed in 1920's or 1930's and much of the shoreline and adjacent neighborhood development was complete by the 1970s to 1980s (Osgood, personal communication). A small storm sewer system exists on the southwest corner of the lake (in Shorewood). In addition, substantial inflow from Curry Creek, which is fed upstream by storm-sewers in Chanhassen, enters the lake. Much of the City of Chanhassen's development occurred in the late-1970s through 1980s, which led to increased stormwater collection that was routed through Curry Creek. County Road 17 is located in the watershed. All homes around the lake are served by sanitary sewers.

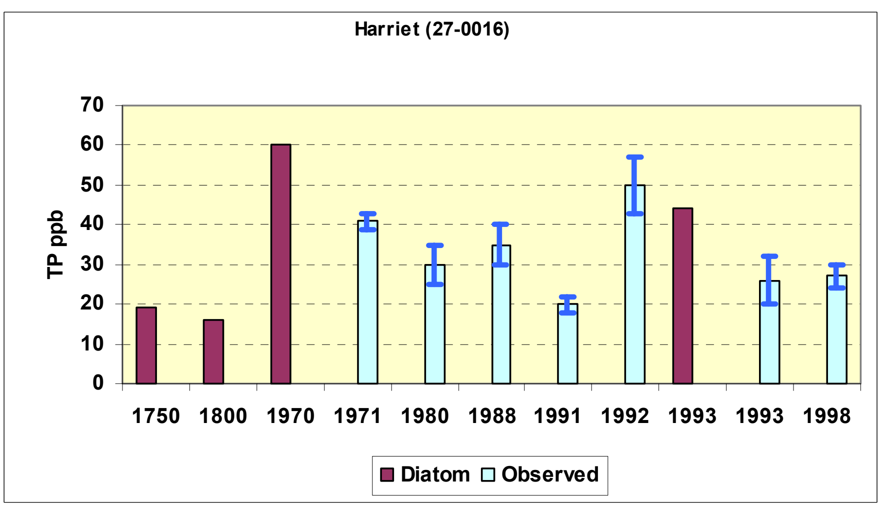
Pre-European P and Cl values averaged 22 µg/L and 7 mg/L, respectively, as compared to modern-day values of 40 µg/L and 44 mg/L respectively (Figure 12). Sediment accumulation rates peaked c.1910, declined from c.1920 to c.1970 and peaked again c.1990 (Appendix III). The inorganic fraction was dominant throughout this period of record. Increased P and Cl between the 1970 and 1990s time periods was quite marked with increases of 30 percent (11 µg/L) and 100 percent (33 mg/L), respectively. The increased Cl and sediment accumulation could easily be attributed to the increased development in the watershed, development of storm sewer networks, and salt usage (County Road 17 for example). The 1970 DI-P value is in the range of monitored data from the 1970s to mid 1980s (Figure 12), however the DI-P value from c.1993(45 µg/L) is much higher than observed data from 1997 and 1998 (mean of 13 µg/L). Osgood (personal communication) contends that Christmas Lake may be exhibiting early signs of

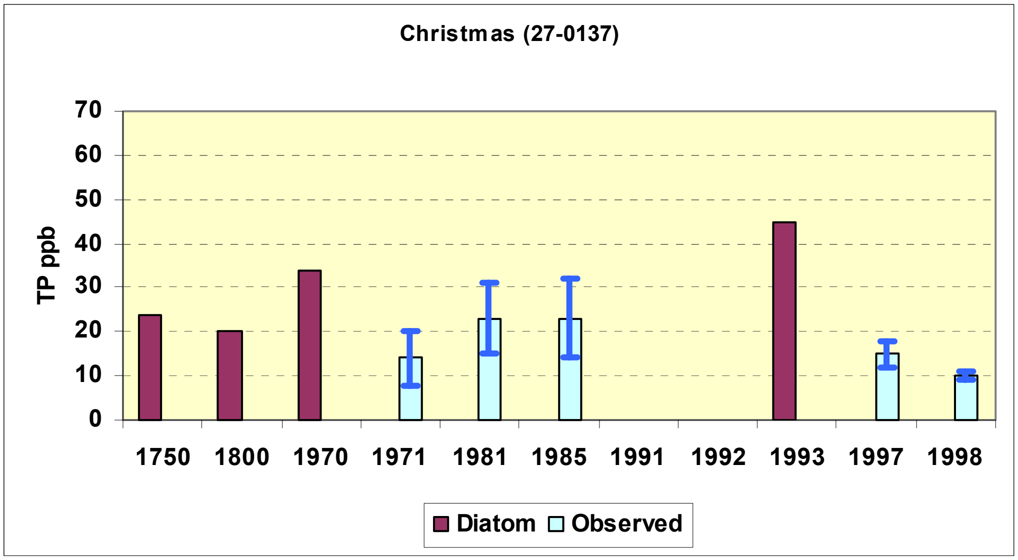
eutrophication and that *Daphnia* (which feed on algae) may be keeping algal and TP levels somewhat suppressed.
STORET data (http://www.pca.state.mn.us/water/lakequality.html) indicate that chlorophyll-a values are lower than anticipated and Secchi higher than anticipated based on TP, as is often the case in lakes with high populations of large *Daphnia*.

<u>Little Long Lake</u> (22 ha) has a relatively small (32 ha) watershed that is substantially undeveloped. No large stormwater networks drain to the lake and no dramatic changes in land use or development are evident in the watershed of this lake from the 1970s to the 1990s (Osgood, personal communication). One major road, County Road 15, is located in its watershed. Sediment accumulation rates increased between c.1880 and c.1940 and declined thereafter (Appendix I). No significant change in P or Cl are noted in comparisons of pre-European and modern diatom reconstructed values and modern-day P and Cl levels (Table 16) are much lower than nearby Christmas Lake, which receives more extensive stormwater inputs. Modern-day sediment accumulation rates are only slightly higher than pre-European and are about two-fold less than that measured in Christmas Lake. The inorganic fraction is relatively constant through the core at about 65 percent.

Figure 12. Hennepin County: Comparison of DI-P and observed summer-mean P for Calhoun, Harriet, and Christmas Lakes.







Ramsey County: Gervais, Johanna, McCarrons, Owasso, and Turtle

Ramsey County has numerous lakes and the five included here represent a range in size, watershed area and water quality. The pre-settlement vegetation for much of Ramsey County consisted of "oak openings' and "Big Woods" (Marschner, 1930).

Lake Gervais is a moderate-sized (94 ha) lake with a large watershed relative to its size (43:1). Its primary watershed is rather small (243 ha) however. Though 88 percent of its watershed is built up (Appendix 1) or in roads (including major county, state and interstate roads) much of the runoff entering the lake filters through upstream lakes, such as Kohlman, and wetlands. Information compiled by Noonan (2002, personal communication) from the Cities of Little Canada (Schroeder, 2002), Maplewood (Priefer, 2002) North St. Paul and Ramsey-Washington Metro Watershed District (Aichinger, 2002) provide some insights into development around the lake. The area surrounding the lake received heavy development pressure in the 1960's and again in the late 1980s. The majority of the area was sewered as a part of initial development and most was complete by the 1970s. Although the immediate lakeshore is not served by storm sewers, the watershed is defined by a network of storm sewers and small creeks and ditches (Aichinger, 2002, personal communication). The single most significant landuse change in the watershed was the development of the Maplewood Mall area in 1975. A variety of ponding projects were undertaken as a part of development, redevelopment, or road construction in the 1970s and 1980s. The first projects, with water quality as a primary interest, were initiated in the early to mid 1990s and include such projects as the Gervais Mill Pond, Kohlman Basin Project, Sod Farm ponding, and County Ditch 7a improvements for example. No major in-lake projects have been undertaken, however there has been periodic macrophyte harvesting and herbicide treatments.

Gervais exhibited among the highest pre-European P and Cl values of any CHF lake in this study. These values suggest eutrophic conditions for the lake. (There is the possibility that there may be dating problem with this core and hence these core slices may not be “pre-European but much more recent (Engstrom personal communication, 2002).) Sediment accumulation rates increased steadily from c.1900 to c.1940 and decreased since that time. Modern-day rates are similar to pre-European (Appendix III). Modern-day TP values are essentially unchanged from pre-European values – similar to sediment accumulation rates. Cl, however, increased with the largest increase occurring between 1970 and c.1993 (Table 18). The extensive development over the period from 1970 to mid 1990s (increase in impervious area) combined with salt usage on the extensive road network tributary to the lake would explain the large increase in Cl. Monitoring data from the 1970s to 1990s correspond quite well with the DI-P values for that period (Figure 12). Data from 1996 suggest some further declines in TP (Figure 13) that could be attributed to the various ponding and water quality projects conducted during the 1990s combined with slowed development in the watershed (as compared to the prior two decades). This is further supported by data from the RWMW District that shows summer-mean TP concentrations ranging from 31 to 38 μg/L for the period from 1997 to 2001 (Aichinger, personal communication, 2002).

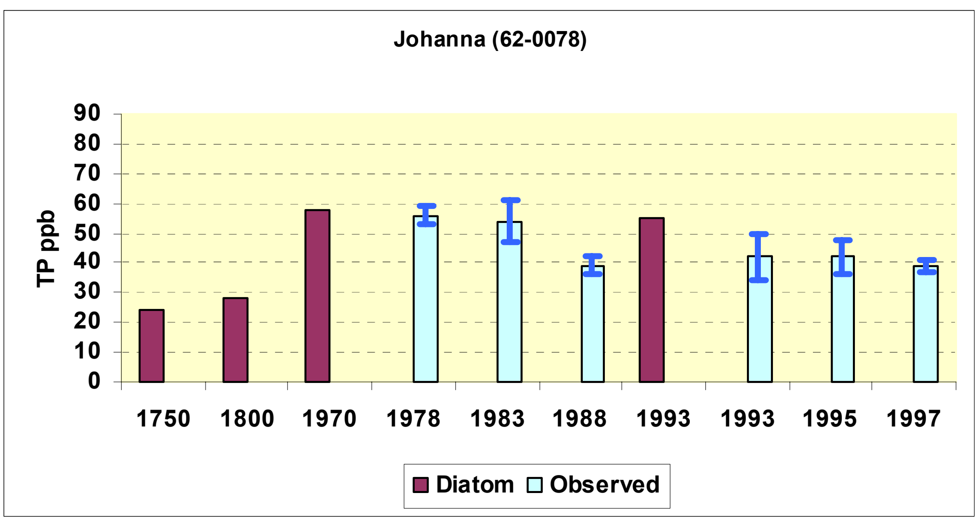
Lake Johanna is roughly the same size as Gervais but has a much smaller watershed (12:1 ratio). Its primary watershed is rather small (228 ha) and about one-half of its indirect watershed drains through Lake Josephine. Most of the residential development in the primary watershed occurred between 1951-1954 (Schartz, City of Roseville, and Moore, City of Arden Hills, personal communication to Noonan, 2002). Most homes were originally served by on-site sewage systems with sewer being installed in 1961. Other major development in the watershed included the development of the Northwestern College site on the eastern side of the lake in 1985. Storm sewer construction was initiated on the southern side of the lake in 1989 and the western side in 1998. Ditch and ponding improvements were made in 1987 and 1995, likely in response to the increased stormwater from the developed portions of the watershed.

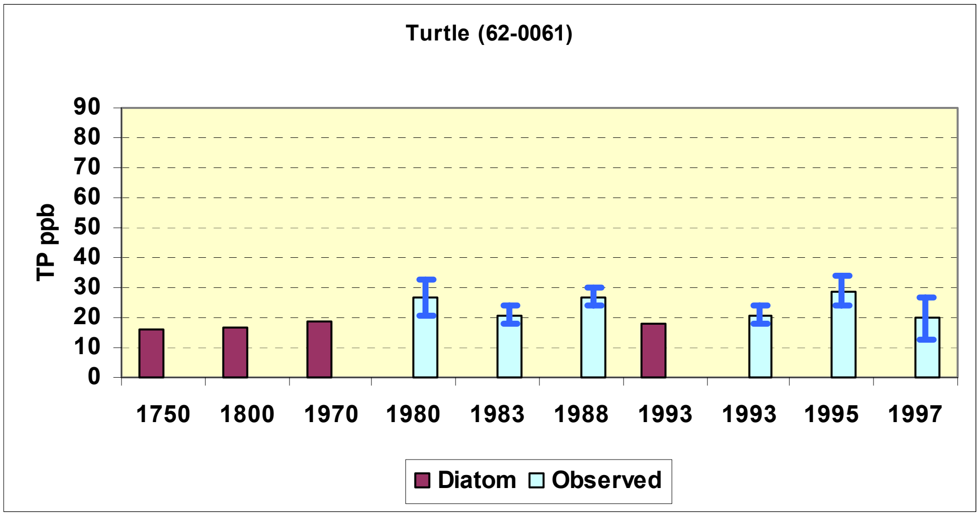
Pre-European TP and Cl were relatively low and suggest mesotrophic conditions for the lake. Sediment accumulation rate increased between c.1880 to c.1950 and has been relatively stable since (but about three-fold higher than pre-European levels). Modern-day TP concentrations are almost two-fold higher and Cl are about 30-fold higher than pre-European values. Urbanization of the watershed from the 1950s through the 1960s could account for much of the increase in TP and Cl, as compared to pre-European values (Figure 13) (however the agricultural uses of the land prior to the urbanization likely made their contribution as well). The extensive road network in the watershed, combined with salt-usage, would readily explain the elevated modern-day Cl levels. TP has been relatively stable to declining for the period from 1970 to c. 1993 based on DI-P values and monitored data (Figure 13). Recent water quality data indicate further declines in TP in the lake, which suggests that a combination of projects to minimize the impact of urban runoff and a cessation of major development (disturbance) in the watershed have contributed to reductions in TP loading to the lake. These efforts, however, did not affect Cl loading.

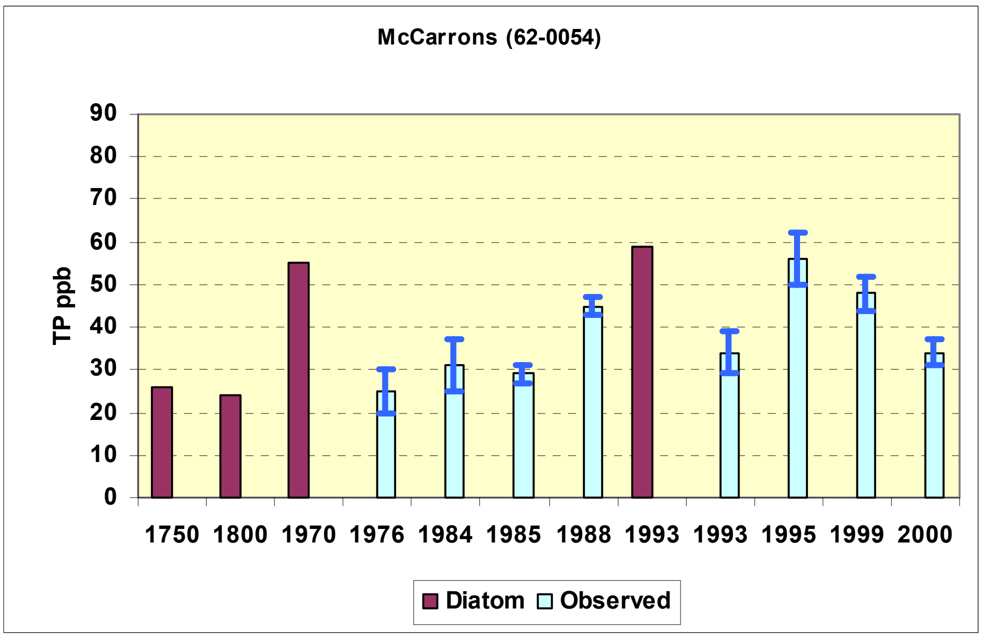
Lake McCarrons is a small (30 ha) but deep (17.4 m) lake with a moderate sized watershed (13.7:1 ratio). It has a highly urbanized watershed, much of which drains through a wetland complex on the northwest side of the lake. Pre-European TP and Cl were relatively low and suggest mesotrophic conditions for the lake. Sediment accumulation rates have been quite variable since pre-European times and peaked c.1940. Modern-day rates are surprisingly similar to pre-European, however the inorganic fraction has become increasingly important in the modern-day sediments (Appendix III). Modern-day TP by comparison is over two-fold higher and Cl eight to seventeen-fold higher (Table 17). Monitoring data from the 1970s and 1980s reveal slightly lower TP concentrations as compared to the 1970 DI-P, however data from the 1990s corresponds quite well with DI-P for c. 1993. Cl concentrations while high in 1970 were even higher in c. 1993, suggesting an increase in the usage of road salt and/or an increase in the storm sewer network draining to the lake.

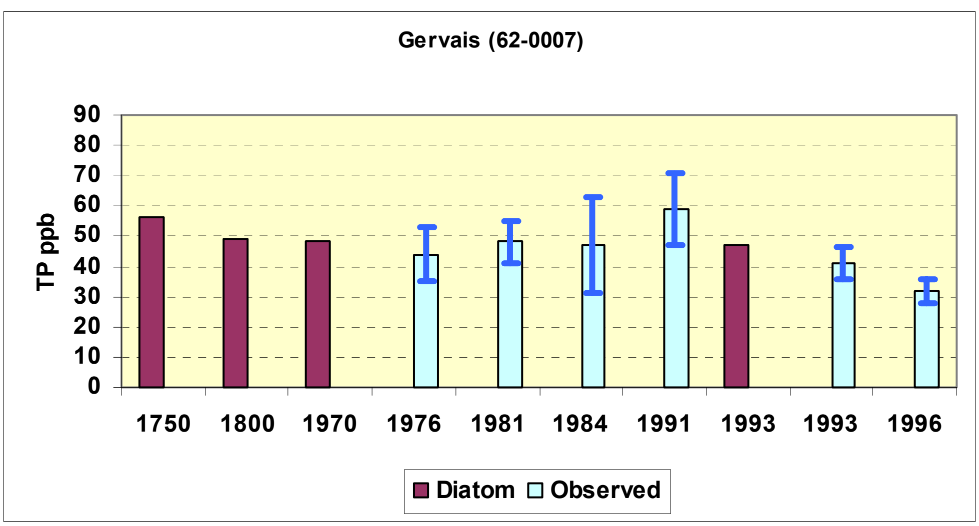
The lake has been the subject of extensive study and BMP implementation through the Clean Lakes Program in the 1980s and 1990s. Much of the effort has focused on improving nutrient retention in the wetland on the northwest corner of the lake that was put in place in the 1980s. This work has met with varying degrees of success and detailed reports are available from Metropolitan Council Environmental Services. Sedimentation in this wetland complex may have contributed to a reduction in the inorganic fraction of the lakes' modern-day sediment.

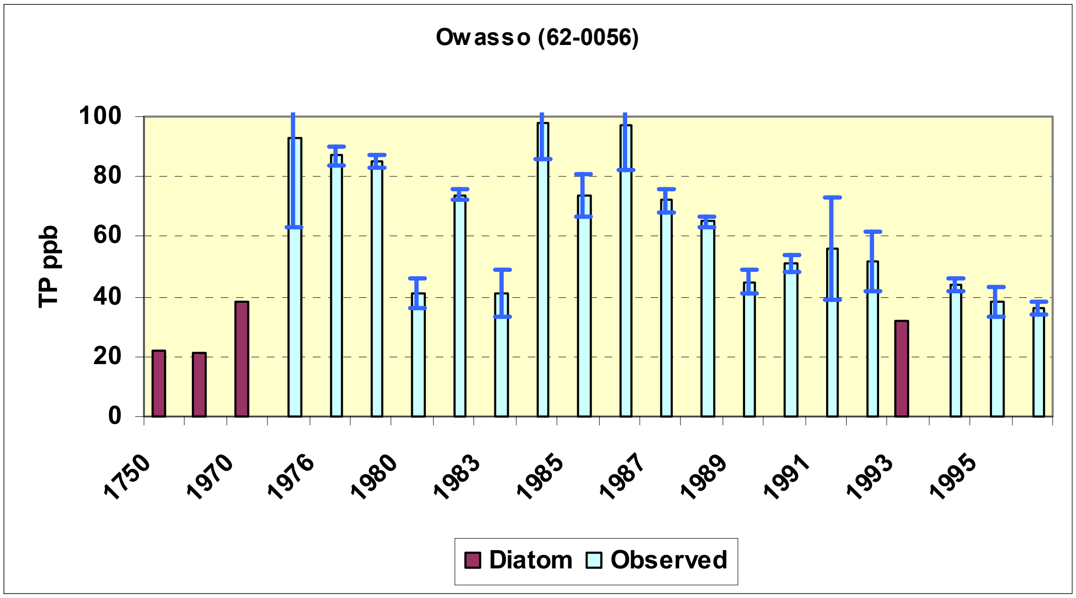
Figure 13. Ramsey County: Comparison of DI-P and observed summer-mean P for Johanna, Turtle, McCarrons, Gervais, and Owasso Lakes.




Turtle (62-0061)
TP ppb
90
80
70
60
50
40
30
20
10
0
1750
1800
1970
1980
1983
1988
1993
1993
1995
1997
Diatom
Observed


McCarrons (62-0054)
TP ppb
90
80
70
60
50
40
30
20
10
0
1750
1800
1970
1976
1984
1985
1988
1993
1993
1995
1999
2000
Diatom
Observed


Gervais (62-0007)
TP ppb
90
80
70
60
50
40
30
20
10
0
1750
1800
1970
1976
1981
1984
1991
1993
1993
1996
Diatom
Observed



Lake Owasso is a fairly large lake (151 ha) for the area and has a relatively small watershed (2.8:1 ratio). As with other lakes in the area over 90 percent of the watershed is built up or in roads. Much of the shoreland development around the lake occurred between about 1920-1950 based on records from the cities of Shoreview and Roseville (personal communication to Noonan, 2002). Since that time there have been many rebuilds or reconstructions with much larger homes. The City of Roseville noted a later surge in construction between 1970- 1980s with 33 additional homes being built. Most homes were served by on-site systems prior to 1961 when sanitary sewer was installed throughout the area. Storm sewer construction was initiated in 1978 in Roseville with subsequent projects in 1986 and 1990. Most projects aimed at improving ponding in the watershed were initiated in the late 1980s with projects continuing into the 1990s. An outlet control structure (to Wabasso) was put in place around 1990.

Concern over the water quality of the lake was evident in the 1970s and 1980s based on proposals for Clean Lake Program studies. A 1985 CLP concept plan (Owasso Lake file, MPCA) acknowledged that much of the inflow to the lake arises from three stormwater culverts, along with several minor inlets. It also acknowledged large historic fluctuations in lake level ranging from lows of 883.0 feet in 1926 to highs of 888.79 feet in 1978. It also noted that over 400 residences were on the lake or had easements to the lake. A later report to the Grass Lake Watershed Management Organization (Barr, 1991) describes water quality management alternatives with a focus on improving stormwater detention in the watershed.

Pre-European TP and Cl levels suggested mesotrophic conditions for the lake (Table 18). Sediment accumulation rates increased steadily from c.1900 and exhibited peaks in c.1960 and c.1980. Some reduction in rate is evident since that time (Appendix I). As with the other Ramsey County lakes significant increases in TP and Cl were noted in the 1970s and 1990s, as compared to pre-European DI-P and DI-Cl. These increases could be directly attributed to development in the watershed and the surrounding road network. The magnitude of the increase was not as great as in some of the lakes and there was no marked increase in TP or Cl between 1970 and c.1993. Monitoring data from the 1970s and 1980s suggest elevated TP concentrations over this period (perhaps reflective of the extensive development and re-development occurring during this period of time). In contrast, data from the mid to late 1990s (Figure 13) indicate declining TP (consistent with the DI-P for c. 1993) and declines in sediment accumulation rate are a reflection of a period of less development and increased efforts to improve stormwater retention in upstream ponds and wetlands. CLMP Secchi data indicate improving transparency over this period as well with summer averages ranging from 1.4 – 1.6 m in the 1980s to 1.9 – 3.0 m during the 1990s (http://www.pca.state.mn.us/water/lakequality.html).

Turtle Lake in Shoreview is moderate sized (134 ha) and has a very small watershed (1.3:1 ratio). Because of its small watershed, and high dependence on groundwater to maintain lake level, there have been periodic fluctuations in lake level, especially during periods of drought. Groundwater augmentation was used periodically in response to this problem but was eliminated in the late 1980s (Maloney, City of Shoreview, personal communication to Noonan, 2002).

Development in the watershed is primarily single-family residential that was constructed from about 1920-1970 (City of Shoreview, 2002). In recent years there have been many rebuilds and reconstructions, which typically translate to increased impervious area on lakeshore lots. Sanitary sewer was installed around the lake in about 1968 to 1972, with on-site septic systems being used prior to that time. With the exception of the County Road I storm sewer (1993), along the west shore, there are no significant storm sewers draining to the lake. Turtle Lake has a smaller percentage of land in roads (3%) than the other Ramsey County lakes and has a relatively high percentage of its watershed in wetlands (14 %). However salt usage is common on the three major roads that surround the lake.

Turtle Lake's small watershed has undoubtedly contributed to the low modern-day TP for the lake. Pre-European TP and Cl were the lowest of the five Ramsey County lakes. Modern-day TP values are only slightly higher. Cl values, initially low in 1970, had increased 17-fold by c. 1993 (Table 18). Sediment accumulation rates increased at a steady pace from c.1880 to modern-day, with modern-day rates about four-fold higher than pre-European (Appendix III). Inorganic and organic fractions were relatively similar from c.1860 to modern-day.

The increase in Cl can be attributed to increased salt usage on the local, county and state roads that border the lake on all four sides. Changes in the storm sewer network from the 1970s to 1990s may also have directed more runoff to the lake (and more Cl) and may have contributed to the continued increase in sediment accumulation rate as well.

Monitoring data correspond fairly well to DI-P values and based on data from 1980 to 1997 a minor decline in TP may have occurred. Given the variability in the data this cannot be considered a significant change though (Figure 13). CLMP Secchi data from

1980 to 2000 suggest a slight, but not significant improving trend in transparency from 1.7 – 2.8 m range to 2.0 – 2.9 m range (http://www.pca.state.mn.us/water/lakequality.html). One interesting note for Turtle Lake is that the City of Shoreview was among the first in the Metropolitan area to institute an ordinance that "banned" the use of P-bearing fertilizers in the 1980s. While there are many sources of P to urban lakes this measure may have helped minimize P loading to lakes, such as Turtle, and hence minimized further increases in P.

Table 18. Ramsey County lakes diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
Gervais	TP µg/L	56	49	48	47
	Cl mg/L	29	30	43	86
Johanna	TP µg/L	24	28	58	55
	Cl mg/L	3	3	88	105
McCarrons	TP µg/L	26	24	55	59
	Cl mg/L	7	10	74	175
Owasso	TP µg/L	22	21	38	32
	Cl mg/L	2	1	27	27
Turtle	TP µg/L	16	17	19	18
	Cl mg/L	1	1	4	17

Washington County: Carver, Elmo, Little Carnelian, Square and Tanners Lakes

Washington County has numerous lakes also and the five lakes in this study represent a range of size, depth and quality. Pre-settlement vegetation for much of the county is characterized as "oak openings" (Marschner, 1930).

Carver Lake, in Woodbury, is a small lake (20 ha) with a large watershed (43:1 ratio). Modern-day landuse is characterized by a mix of built up (52%) agricultural (18%) and forested (11%) uses. Roads comprise about six percent of the watershed. Some history on the lake and watershed was compiled by Aichinger (2002, personal communication).

Development in the watershed began in the late 1960's and early 1970s and consisted of residential subdivisions. I-494 freeway was also built during this period of time. In the mid 1980s there was a steady increase in new residential development in the eastern and northeastern sub-watersheds. Most of the stormwater is routed through treatment ponds prior to discharge to the lake. Significant commercial development in the northern sub-watershed followed and in the late 1990s a new freeway interchange was completed and resulted in the development of almost all remaining open land into commercial and town home projects. However during this entire period there was essentially no development on the lake shore and, with the exception of four homes on the west side of the lake, the shoreline is in public ownership and part of Woodbury's park system. RWMW District initiated a major stormwater treatment project and stormwater channel restoration in 1992 to treat stormwater from the eastern portion of the watershed. The City completed a multi-pond treatment system in about 1990.

Pre-European TP and Cl were fairly low and suggest mesotrophic conditions for the lake. Modern-day increases in TP (as of 1970) were on the order of three-fold and Cl was about 18-fold. Sediment accumulation rates increased significantly due to agricultural activity on steep watershed slopes between c.1880 and 1950 (ten-fold change, Appendix III). Another increase in sediment accumulation rate was noted between c.1970 and c.1980, followed by a decline in recent times. (The relative change from pre-European to 1990s (27:1 ratio) was among the highest in this study.) The development and road building that occurred just prior to 1970 and previous agricultural uses in the watershed would readily account for the increased P and Cl concentrations and changes in sediment accumulation rate. DI-P and Cl both declined significantly in the 1990s, as compared to the 1970 diatom values (Table 19). Observed TP data from 1988 and 1993 bracket the c. 1993 DI-P (Figure 14). This reduction may reflect the work that was being done to address stormwater impacts in the early 1990s. Monitoring by RWMW District indicates further reductions in in-lake P as of 1996 (Figure 14) that represents a significant improvement over concentrations of the early 1970s -- approaching pre-European concentrations. TP data collected since that time, by RWMW District (Aichinger, 2002, personal communication), suggest highly variable TP measures and the possibility of increasing TP in Carver Lake. Continued monitoring and evaluation of the data will be needed to determine if this represents a short-term response or a significant change the water quality of the lake.

<u>Lake Elmo</u>, with a maximum depth of 43 m, is among the deepest lakes in the state. Its primary watershed is relatively small (5:1 ratio) but its total watershed is rather large (18:1 ratio) when upstream Eagle Point Lake is included.

A review of MPCA files (Hall, 2002, personal communication) found that the Twin Cites Associated Milk Producers put a creamery into operation in the village of Lake Elmo in May 1924 with a discharge to Lake Elmo. The discharge was quite controversial even at that time. The Minnesota Department of Health (MDH) investigated complaints in 1926 and 1931, but did not find "any appreciable pollution resulting from the discharge of milk plant waste." They did note receding lake levels due to low water conditions, with increased exposure of the lake bottom (this combined with wastes would contribute to elevated Cl). The MDH did another investigation in July 1951. Twin Cites Associated Milk Producers was still was making butter and discharging to the lake at that time. The MDH measured surface total phosphorus levels of .095 to .130 mg/l. It was estimated that the plant discharged 2.2 pounds of phosphorus per day. Algal analysis indicated that the phytoplankton was dominated by blue-green algae (*Aphanizomenon sp*. in particular) and pollution tolerant diatoms (*Melosira)*. The 1951 report refers to a 15-foot variation in lake level.

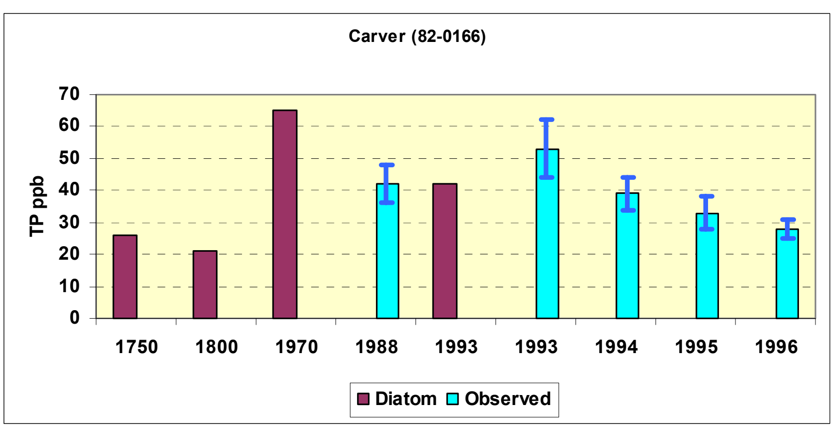
Development, in the form of cabins, along the lakeshore dates to the early 1900's (Hanson, personal communication, 2002). The shoreland is fully developed, according to Lake Elmo's comprehensive plan and all homes use on-site septic systems. The watershed is relatively rural as reflected by the high percentage of agricultural land (43%)

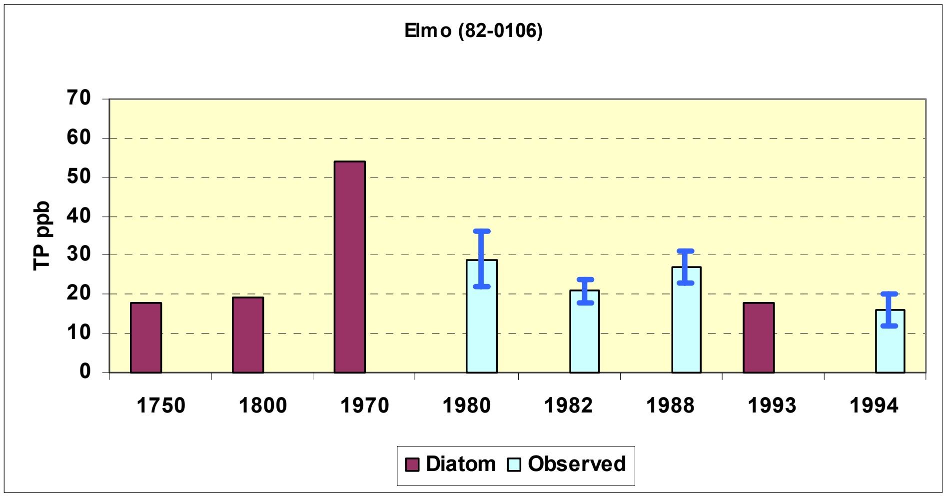
in its watershed. The Valley Branch Watershed District completed a major flood-relief project in 1987 (Hanson, personal communication, 2002). The project involved lowering the outlet elevation of the lake by 1.8 feet and diverting nutrient-rich upstream water from the Eagle Point watershed through a pipe laid across the bottom of Lake Elmo. This pipe handles most runoff events and effectively reduces the total watershed of the lake. This minimizes urban runoff to the lake, however runoff from County Road 17 on the east side of the lake continues to run directly into the lake.

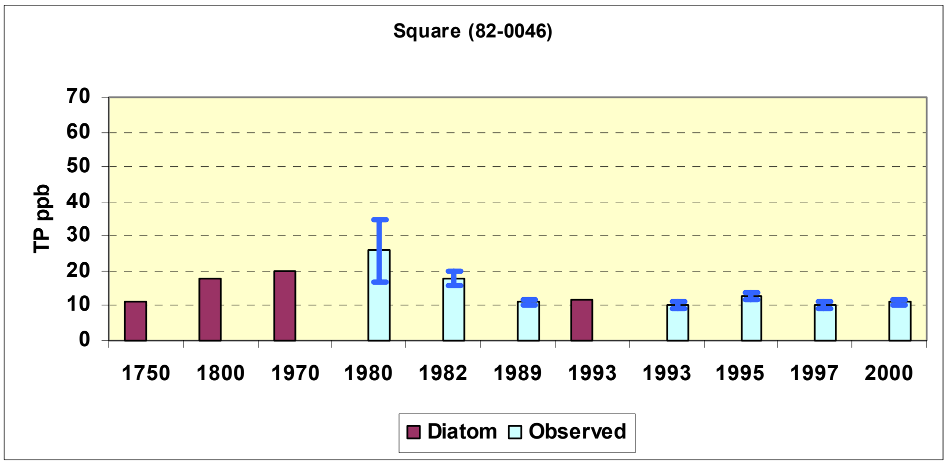
Pre-European TP and Cl values were quite low and suggest mesotrophic conditions for the lake (Figure 14). Sediment accumulation rates increased between c.1930 and c.1960 but exhibited a decline between 1960 and c.1990 (Appendix III). By 1970 TP had increased almost three-fold and Cl 29-fold over pre-European values (Table 19). The elevated TP was likely a function of runoff from highly urbanized and agricultural watershed to the west of the lake (includes the City of Oakdale) as well as a "residual" affect from the previous creamery discharge to the lake. This decline in water quality, along with water level concerns, prompted the project that diverted water from this portion of the watershed. A significant decline in diatom-inferred P and Cl was noted in the c. 1993 as compared to c. 1970 (Ramstack, 1999). Modern-day TP (diatom and observed) are in the range of pre-European values, however Cl remains elevated.

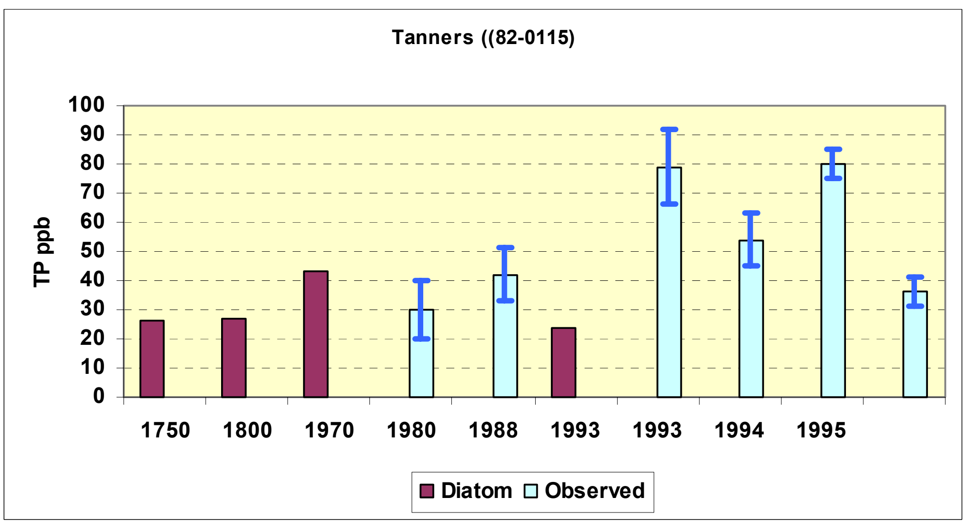
CLMP Secchi data from 1985 to 1993 track this trend as well. Prior to completion of the project (1985-1988) Secchi depth averaged 2.1 m (corresponds to TP of 45-50 µg/L based on Carlson's TSI). Following the project a steady increase in Secchi was noted and the average for the period 1989-1993 was about 4.2 m (http://www.pca.state.mn.us/water/lakequality.html).

Figure 14. Washington County: Comparison of DI-P and observed summer-mean P for Carver, Elmo, Little Carnelian, Square, and Tanners Lakes.









<u>Little Carnelian</u> is a small (47 ha) but relatively deep (19 m) lake. It has a large total watershed (39:1 ratio) that is characterized largely by agricultural (41%) and forested (20%) land use. Less than 10 percent is built up or in roads. The vast majority of its watershed drains through Big Carnelian, which retains much of the upstream nutrient and sediment load from the watershed.

Little Carnelian is located at the end of the Carnelian Marine Watershed District gravity outlet system. This interconnected system was completed in 1985 after flooding occurred upstream on Big Marine and Big Carnelian Lakes (Doneux, personal communication, 2002). Little Carnelian Lake, which had a water surface elevation of 821 feet in 1977, reached a high of 856 feet in 1997. Both increased runoff and the introduction of drainage from upstream (Big Marine/Big Carnelian Lakes) caused this increase. Much of the residential development in the shoreland area is in the form of large (5-10 acre) lots that were developed after the outlet was established in 1985.

Pre-European TP and Cl were low and fairly stable and suggest mesotrophic conditions for the lake. Modern-day TP values were slightly, but not significantly, higher than pre-European. Cl was about three-fold higher than pre-European and a further increase was noted between 1970 and c. 1993 (Table 18). Sediment accumulation rate increased dramatically from c.1930 to c.1950 and declined rapidly thereafter (Appendix III). Monitored TP from 1991 and 1992 averaged 20-23 µg/L, which is very consistent with the c.1993 DI-P. Summer-mean TP from surveys in 1997 and 2000 averaged 9-14 µg/L, which suggests a decline in TP to below pre-European levels. CLMP Secchi transparency data from 1991 to 1998 reveal a significant increase in transparency from about 3.9 m to 4.8 m over this period (http://www.pca.state.mn.us/water/lakequality.html). Secchi measurements were consistent with the TP measured over this period (in terms of TSI) and further provide evidence of an improvement in trophic status. The linking of Little Carnelian with the upper watershed between c. 1970 and c. 1993 could account for the increased Cl concentration in the lake. This additional water loading though has apparently not adversely affected in-lake P or sediment accumulation rate and, based on more recent observed data, there may be a further reduction in P (Figure 14).

<u>Square Lake</u> is among the clearest lakes in the Metro area with long-term mean transparency on the order of 6.7 m. It is moderate sized (82 ha) and quite deep (21 m) and has a fairly small watershed (2.8:1 ratio). Its watershed has a low percentage of built up land use (14%) and a small road area (2%). About 45 percent of the watershed is in forested use. All these factors (morphometry, watershed size, and land use) contribute to its low nutrient concentration. The lake is managed as a two-story fishery and is stocked annually with rainbow trout, as noted on the MDNR website. The lake has historically been popular with scuba divers and fisherman: and with the stocking of trout, has become even more heavily used. Square Lake is also home to Square Lake Regional Park, which has a swimming beach and a boat ramp.

A number of small-scale studies have been completed to characterize the existing water quality of Square Lake and include the following:

- Diagnostic-Feasibility (CLP) Study of Seven Metropolitan Area Lakes, Part Two: Square Lake, Met Council (Osgood, 1983);
- Marine on St. Croix Watershed Management Plan, 1989;
- Study of the Water Quality in Metropolitan Lakes - 1980-1998, Met Council (e.g., Anhorn 1994-2000);
- Square Lake Sediment Analysis, St. Croix Science Museum, 1997;

- Report of the Square Lake Adhoc Issues Committee, May Township Comprehensive Plan; and Washington County Comprehensive Plan.

It is also the subject of a Clean Water Partnership study has been underway since the mid 1990s. That project focused on stormwater inputs to the lake and recommends numerous measures to educate lake users and property owners in the watershed, with a focus on protecting the high water quality of the lake. It also acknowledges that groundwater represents the predominate source of water to the lake (~70%) as compared to surface runoff that contributes about five percent by volume.

Pre-European TP and Cl were quite low and suggest oligotrophic conditions for the lake. By 1970 a small increase in TP and about a five-fold increase in Cl was evident (Table 19). Modern-day sediment accumulation rates were largely unchanged from pre-European (Appendix III). The combination of the diatom reconstructions and sedimentation record suggests that land use changes (e.g., increased impervious area) in the watershed have contributed to subtle increases in P loading but more significant increases in Cl loading to the lake. Diatom data from c. 1993 suggest a decline in TP and stable Cl concentrations from c. 1970. Extensive monitoring data are available for the lake through the combined efforts of Met Council and the Washington SWCD. Data from the 1980s through 2000 suggest a decline in TP consistent with the diatom-inferred values (Figure 14). CLMP Secchi data, over the same period, suggest fairly stable (absent year-to-year variability) transparency up to 1993 (typically 7.0 – 8.0 m range), with a slight decline to 6.2 – 6.9 m from that point forward (http://www.pca.state.mn.us/water/lakequality.html). The CLP and CWP studies on Square Lake acknowledge the importance of *Daphnia* in controlling algal (chlorophyll-a) levels in the lake and it is more likely that any declines in transparency are more related to reductions in the *Daphnia* population rather than increased nutrient concentrations. These findings, combined with the results from this study, suggest that modern-day changes in land use contributed significantly to Cl loading and to a lesser degree P loading to the lake. The more recent decline in in-lake P (between c. 1970 and mid 1990s) suggest that current land use practices (e.g. stormwater management) may be successful in minimizing additional P loading to the lake. This, combined with extensive education and related efforts, suggest that Square Lake's good water quality should continue into the future, though some questions remain on the importance of biological interactions in the lake and their role in controlling chlorophyll-a and transparency levels.

<u>Tanners Lake</u> is a small (30 ha) lake with a moderate sized watershed (22:1 ratio). Its modern-day watershed is characterized by built up (80%) land use and has a significant portion of the watershed in roads (8%). Pertinent history of the lake and its watershed were summarized by Aichinger (2002, personal communication). Tanners Lake was a resort lake for St. Paul residents until about 1950. The first development dates to the 1930's and 40's with several cabins and homes built on the lake. Additional homes, businesses and condominium projects were built around the lake in the late 1950's and 1960's. A major freeway, I-94, was completed just south of the lake in the early 1960's. Storm sewers and sanitary sewers were constructed concurrent with development. Most storm sewers drained directly to the lake. Much of the remaining watershed was

developed in commercial and high density residential in the 1960's and stormwater from this area was directed to the lake as well.

Watershed projects aimed at improving the quality of stormwater that entered the lake date to the late 1980s when the Ramsey-Washington-Metro Watershed (RWMW) District completed a project to modify a wetland on the north end of the lake. In 1996 the Tanners Lake Water Quality Improvement project included the construction of a multi-cell stormwater treatment pond, extended detention pond and alum treatment of stormwater from the northern sub watershed.

Pre-European TP and Cl levels were somewhat higher than the other Ramsey County lakes and suggest meso-to mildly eutrophic conditions for the lake. TP increased two-fold and Cl ten-fold by 1970. Sediment accumulation rates increased steadily from c. 1900 to c. 1970 (Appendix III). The development that occurred in the two to three decades prior to that time, combined with I-94 to the south of the lake would readily explain the increase in TP, Cl and sediment accumulation. TP data from 1980 and 1988 agree fairly well with the 1970 DI-P data (Figure 14). This trend was reversed by c. 1993 with significant declines in both TP and Cl based on the diatom reconstructions. Likewise sediment accumulation rates declined to near pre-European levels over this time. Observed TP data from 1993-1996 are quite variable and suggest the possibility of unstable or increasing P during this period. This period coincided with the water quality improvement project. TP had declined to near the 1993 DI-P value by 1996 – which could be reflecting improvements from the water quality project. More recent TP data (1997-2001), collected by RWMW District (Aichinger, 2002, personal communication), are fairly consistent with that from mid 1990s, with summer-mean concentrations varying from about 40-83 µg/L, and no overall trend in evidence.

Table 19. Washington County lakes diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
Carver	TP µg/L	26	21	65	42
	Cl mg/L	11	5	170	62
Elmo	TP µg/L	18	19	54	18
	Cl mg/L	4	5	147	10
Little Carnelian	TP µg/L	18	16	21	20
	Cl mg/L	3	2	6	10
Square	TP µg/L	11	18	20	12
	Cl mg/L	1	1	6	5
Tanners	TP µg/L	26	27	43	24
	Cl mg/L	5	4	53	15

c. Western Corn Belt Plains ecoregion: Duck, George, Bass, Beaver and Fish Lakes

These five lakes were added to the original "50 lakes" to allow for some perspective on temporal changes in Western Corn Belt Plains lakes. Of the five, Duck, Bass, Beaver and Fish have been the subject of LAP studies and Duck has been involved in the CWP. Bass, Beaver, Fish, and George were also used as ecoregion "reference " lakes in the mid 1980s. These studies will provide some additional monitoring data and other information for these lakes.

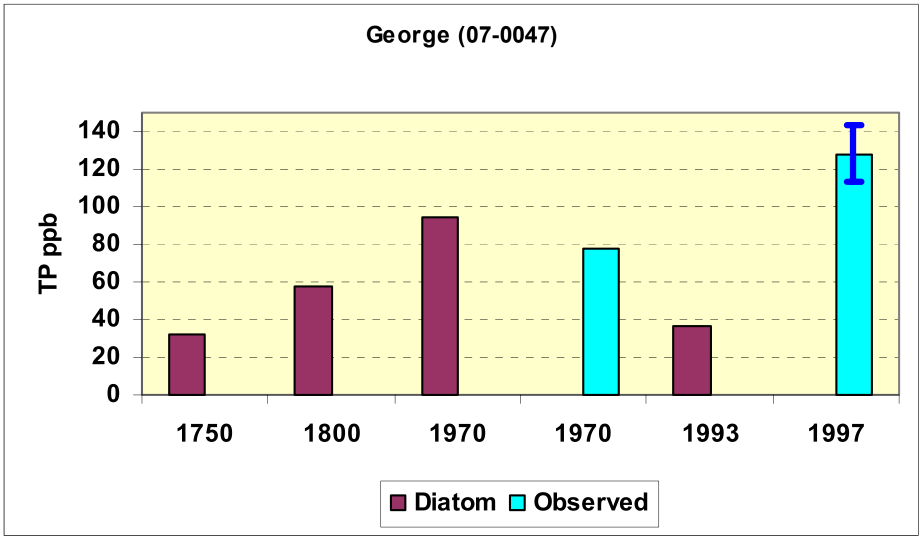
Three of the five lakes (Bass, Fish and Beaver) are located in an area that in pre-European times would be considered part of the "Prairie Lake Region" (Afinson, 1997), with Duck and George near the transition to the "Big Woods" (Harrison, 1985). The Prairie Lakes Region was dominated by dominated by tall grass vegetation. Woody vegetation tended to grow only near water margins or on topographic breaks (Afinson, 1997). Prairie fires, mostly started by lightning, were a common event (Heinselman, 1974) as was drought (Afinson, 1997) – both of which could influence the water quality of lakes.

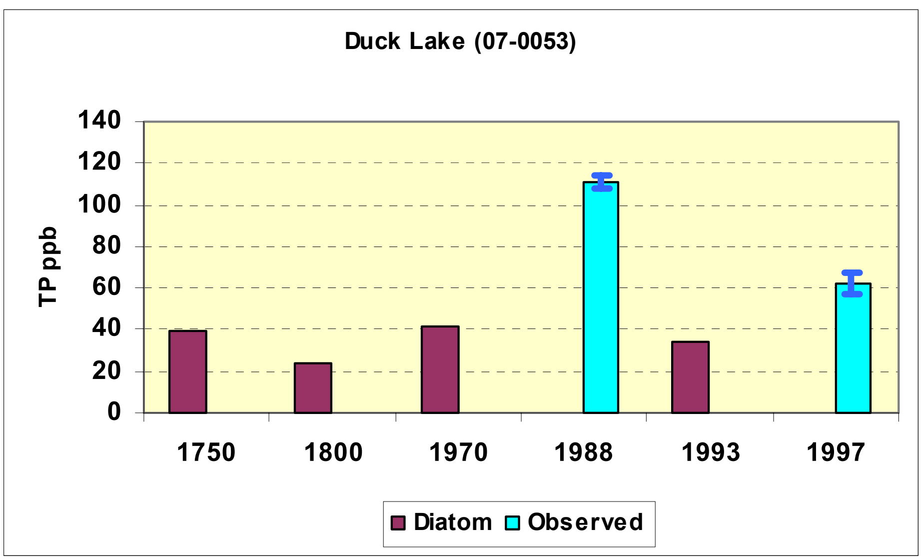
"The French were probably the first white men to set foot in Blue Earth County" (Hughes, 1909), in the form of fur traders and isolated trading posts in the late 1600s LeSueur arrived at the mouth of the Blue Earth River in 1700. Significant European influence on the landscape dates to mid 1800s, as the Dakota were driven from the area in the 1860's. The founding of Mankato, for instance, dates to 1852 (Harrison, 1985). Hughes (1909) notes that "during the spring of 1852 most of the land in the valley of the Minnesota, between Mankato and Kasota, was staked out in 160 acre claims and occupied by settlers." By the late 1800's agriculture was quite prominent in Blue Earth County with about 2,000 farms noted by 1873. Harrison (1985) further notes that originally over 50 percent of the county was quite wet but much was drained by the latter part of the 19th century.

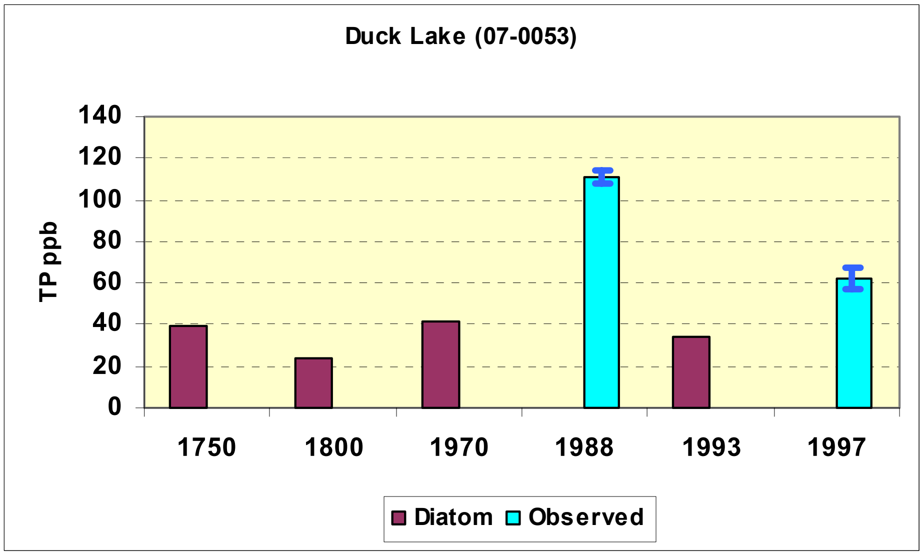
<u>Duck Lake</u> is a moderate-sized lake north of Madison Lake in Blue Earth County. It has a small watershed relative to its size (3.3:1) that is dominated by agricultural land use, which is typical for the region. This lake was the focus of a LAP study and a CWP project. MDNR fishery files indicate lakeshore homes numbered 52 in 1950, 76 in 1956 and 121 by 1974. A 1988 LAP study indicated high development with about 100 permanent homes (Dindorf, 1989). Although there are no major tributaries to the lake, about 15 culverts and tiles drain the surrounding watershed. The lake draws to Ballantyne Lake. Historical information assembled as a part of the descriptive history of the lake (Dindorf, 1989) reveals a healthy northern pike fishery and abundant lily pads in the shallow bays in the 1940's to 1960's. One observer noted that commercial fisherman fished carp in the lake in the 1950's. A file review by Hugh Valiant (MDNR area fishery manager, personal communication) revealed fish surveys were conducted in 1939 (no data found), 1950, 1956, 1970, 1974, 1985, 1990, 1995 and 2000. Winterkill of fish was documented once, in 1955-56. Curly-leaf pondweed was first documented in 1970. Submerged macrophytes seemed to be more diverse in 1950 and grew to 9 or 10 feet (consistent with anecdotes provided by citizens as a part of the LAP study). Surveys also noted that livestock watered along 8% of the shoreline during the 50 and 56 surveys.

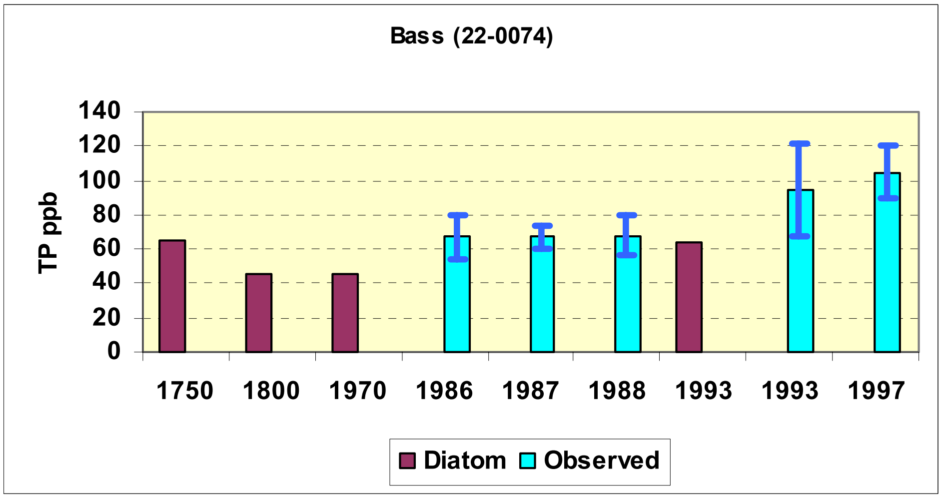
The pre-European DI-P values suggest the lake was mildly eutrophic. Pre-European DI-P and DI-Cl values suggest a high degree of variability in lake chemistry. No distinct trend is evidenced in the comparison of these values with the modern values. The modern-day TP values also show a high degree of variability (Figure 14). Monitoring data from the 1988 LAP study suggest hypereutrophic conditions for the lake during the drought that was characteristic of the late 1980s. While monitoring data suggest the lake is more eutrophic in modern times, the diatom-inferred values suggest minimal change between the two time periods.

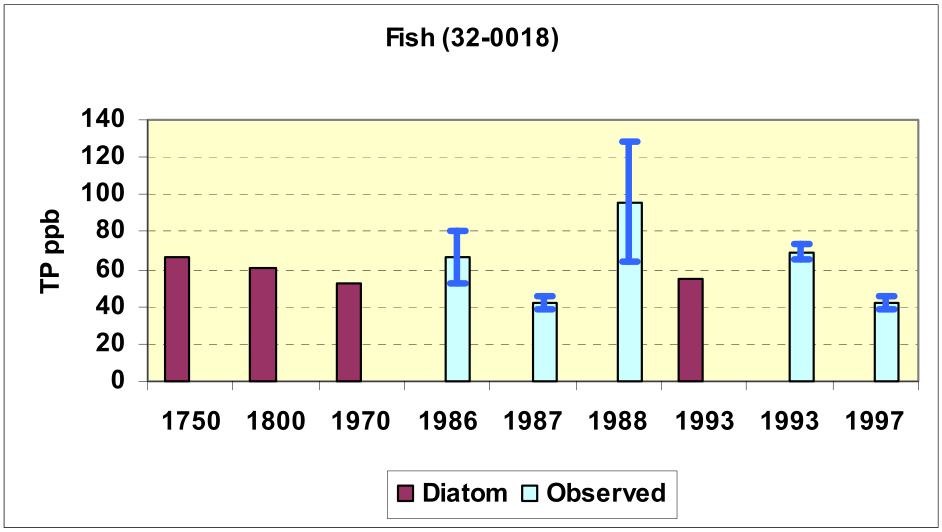
Figure 15. Western Corn Belt Plains Lakes: Comparison of DI-P and observed summer-mean P for George, Duck, Bass, Fish and Beaver.

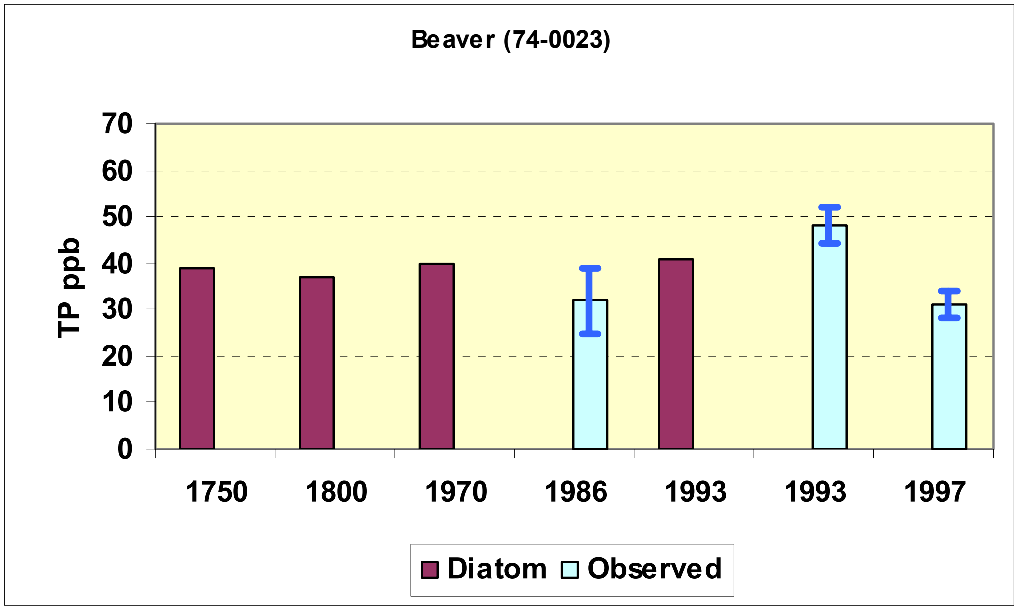





Duck Lake (07-0053)
TP ppb
140
120
100
80
60
40
20
0
1750
1800
1970
1988
1993
1997
Diatom
Observed


Bass (22-0074)
TP ppb
140
120
100
80
60
40
20
0
1750
1800
1970
1986
1987
1988
1993
1993
1997
Diatom
Observed


Fish (32-0018)
TP ppb
140
120
100
80
60
40
20
0
1750
1800
1970
1986
1987
1988
1993
1993
1997
Diatom
Observed



George Lake, also near Madison Lake, is a shallow lake with a very small watershed relative to its surface area (1.5:1). Its watershed is highly agricultural but its shoreline is heavily wooded and relatively undeveloped. Little is known about the lake based on MPCA files and MDNR fishery reports. Only one year of CLMP data was available for the lake. Hugh Valiant (2002), in a review of the MDNR area George Lake fishery file, noted it has a history of occasional winterkill of fish, with significant mortality documented in the severe winters of 1955-56, 1978-79 and 2000-01. It was opened for liberalized fishing in 1950-51 but no information in the file regarding severity of winterkill. The first fisheries lake survey was done relatively recently, in 1970, followed by surveys in 1985, 1990, 1995 and 2000. Lakeshore homes increased from three to eight, from 1970 – 2000. Curled pondweed was first documented in 1985 and Secchi readings have been in the 0.3 to 1.0 m range in all surveys.

A high degree of variability in pre-European TP and Cl is evidenced (Figure 15 and Table 20). The dramatic increase in TP and Cl between 1750 and 1800 suggest a major disturbance or perhaps climatic change between these two time periods. Drought, which would concentrate salts, could contribute to increased Cl concentrations. Since P increased as well there was likely some disturbance in the watershed that would promote increased erosion or transport of P to the lake. Fire is one possible explanation. The core section from 1970 suggests highly eutrophic conditions that appear to be supported by a water sample from the same period (Figure 14). Reconstructed TP for c. 1993 suggest a significant decline in TP from the 1970s time period, however water samples from 1997 suggest continued, if not increasing TP concentration in the lake.

Bass Lake is a small lake near Winnebago in Faribault County. This lake was used as an "ecoregion reference" lake in the 1980s. It has a small watershed relative to its surface area (1.8:1) that is characterized by a mix of agricultural and forested land. Its shoreline is fairly well developed with about 50 homes based on a 1993 LAP study (Weir, 1993).

This represented an increase over the eight homes noted in a 1947 MDNR fishery survey. In a review of these surveys Valiant (personal communication) notes that near-shore land use has changed from 45% deciduous, 30% cultivated, 10% pasture and 15% pastured savannah in 1947 to a much higher percentage of cultivated land in recent surveys. There are no major tributaries in the watershed, however the lake receives tile drainage from about 5-10 field tiles (Weir, 1993). Water level has been a long-term concern and a tile was constructed in 1932 to allow flow from Rice Lake to augment Bass Lake. This tile was blocked in 1988 as a part of a fish reclamation project.

Fish surveys from 1947 – 1954 suggest abundant bluegill and crappie populations, however winterkills in 1977, 1978 and 1979 allowed for dominance by black bullhead. In the early fish surveys the lake appeared to be considerably influenced from time to time by the riverine fish community (Valiant, personal communication). Clarity was relatively low at times, there was evidence of significant carp and bigmouth buffalo populations and even a 1956 letter on file complaining about loss of submergent macrophyte. Fish surveys also revealed that curly-leaf pondweed was the dominant macrophyte by 1986 and it was likely present in the lake since 1978. The senescence of curly-leaf was implicated in the mid-summer pulse in TP in the lake (Weir, 1993).

Pre-European TP and Cl data again suggest a high degree of variability between the 1750 to 1800 timeframe (Table 19). Modern-day TP and Cl values suggest a marked increase in both parameters from 1970 to mid 1990s. TP measurements suggest extremely stable concentrations from 1986 to 1988. These values correspond quite well with the c. 1993 sediment core TP (Figure 15). Data from the 1993 LAP study and data collected in 1997 suggested an increase in TP concentration in recent years (Figure 14). CLMP data from mid 1990s to 2000 suggest a decline in Secchi transparency from the 1.3 m range to 0.8 m as well (http://www.pca.state.mn.us/water/lakequality.html). The increase in Cl from 1970 to the 1990s, while well within the pre-European variability, may be a combined function of tile runoff, road salting, and seepage from septic tanks.

Beaver Lake is one of the few lakes in Steele County. It has a small watershed relative to its surface area (1.9:1) that is characterized by a mix of agricultural and forested land use. It has a highly developed shoreline. Beaver Lake was used as an ecoregion reference lake and was the subject of a 1992 LAP study (Ganske, 1993). Water level fluctuations were common here as well as in other lakes with small watersheds and a system was developed to allow diversion of water from an adjacent watershed, though it was seldom used. There are no significant tributaries to the lake but there is a ditched inlet on the north side and about 11 drain tiles inlets enter the lake.

Pre-European TP and Cl values were quite stable and suggest mildly eutrophic conditions for the lake. Modern TP values did not exhibit any significant change from the pre-European values (Figure 15), however Cl increased dramatically between the two time periods and increased further between 1970 and c. 1993 (Table 20). There is good correspondence between observed TP values from 1986, 1993, 1997 and the diatom-inferred value for c. 1993. Curly-leaf pondweed is present in Beaver Lake and may contribute to variability in TP concentrations. The increased Cl in the lake is likely a combination of drain tile runoff, road salt and seepage from surrounding septic systems.

Fish Lake is located 2.5 miles southeast of Windom. Fish Lake is the deepest lake in the MDNR Windom management area with a maximum depth of 26 feet. The lake is managed for walleye as the primary species with black crappie, bluegill, channel catfish, smallmouth bass and yellow perch as secondary species (http://www.dnr.state.mn.us). It has a moderate sized watershed relative to its size (5.4:1) that is dominated by agricultural uses. Its shoreline is fairly well developed, with about 88 homes based on a 1993 LAP study (Runholt, 1994). The remainder of the shoreline is forested. Fish Lake was used as an ecoregion reference lake.

Pre-European TP values were quite stable, as were Cl, and suggest eutrophic conditions for the lake. Modern day TP values suggest a decline in TP as compared to pre-European values. Modern day diatom reconstructions correspond quite well to monitored data from the 1980s to the 1990s and suggest no recent trends in trophic status, though year-to-year variability is evidenced (Figure 15). In contrast to TP, modern-day Cl values were two to three-fold higher than pre-European and a further increase was evidenced from 1970 to c. 1993 (Table 20). Again field tile drainage, road salt and septic tank seepage are likely causes of the increased Cl.

Table 20. Western Corn Belt Plains lakes diatom-inferred phosphorus and chloride.

		1750	*1800*	*1970*	*1990*
Duck	TP µg/L	39	24	41	34
	Cl mg/L	10	5	7	7
George	TP µg/L	32	58	94	37
	Cl mg/L	7	23	23	16
Bass	TP µg/L	65	46	45	64
	Cl mg/L	22	41	10	29
Beaver	TP µg/L	39	37	40	41
	Cl mg/L	5	7	13	35
Fish	TP µg/L	67	61	53	55
	Cl mg/L	20	20	61	83

III. Comparison of diatom-inferred P with empirical model estimates of background P

MPCA staff use two empirical "models" to help predict present-day "minimally-impacted" lake condition and "background" P concentration. The first model, MINLEAP (Wilson and Walker, 1989), is intended to provide an estimate of the anticipated P concentration based on a lake's size, depth, size of its watershed, and ecoregion it is located in. Ecoregion reference lake data, representative stream water quality, and ecoregion-based estimates of precipitation, evaporation, and runoff provide the empirical basis for the model. While the model is intended to provide a prediction of the present-day P concentration anticipated for a minimally-impacted lake of a given depth, area and watershed area in a given ecoregion, the prediction is sometimes viewed as "background" for the lake. While this was not the original intent, the MINLEAP values are routinely used in the eutrophication goal-setting process for Minnesota lakes. As such we felt comparisons of MINLEAP-predicted values to diatom-inferred P concentrations would help place the MINLEAP results in perspective.

The second model is based on the morphoedaphic index (MEI), routinely used as a measure of productivity in fishery science (Vighi and Chiaudani, 1985 and Chow-Fraser, 1991). The MEI relies on lake mean depth and alkalinity or conductivity as a basis for predicting fishery productivity. Vighi and Chiaudani (1985) used the MEI in conjunction with P concentration data from lakes thought to be near background P as a basis for developing their empirical model. They felt "…that in lakes subject to cultural eutrophication, anthropogenic discharges increase the nutrient loads, and consequently, their productivity without substantial modifications of the parameters usually utilized for calculation of the MEI." They acknowledge further the importance of reconstructing background conditions " . . . therefore the reconstruction of the trophic condition of a lake before cultural influence is an important factor in lake management." They felt that "Finding a relationship between the MEI and the P concentration in unpolluted lakes would thus be very useful in lake management because such a relationship would allow this evaluation, in culturally eutrophied lakes, of the fraction of P concentrations due to natural P sources." An underlying assumption of this equation is that P loading from the watershed is somewhat proportional to the delivery (dissolution and erosion) of soil minerals from the watershed via overland runoff and groundwater.

Their dataset consisted of 53 (primarily North American and European) lakes with: surface areas > 0.2 km^2 (20 ha), mean depth 1.7 – 313 m, [P] = 2.5 – 20 µg/L (range from "ultra-oligotrophic" to mesotrophic"). Some pertinent equations are as follows:

eq. (1) MEI_{alk} = alkalinity (mequiv $^{-1}$/mean depth
(2) $MEI_{cond.}$ = conductivity (uS)/mean depth
(3) $\text{Log}\,[P] = 1.48 + 0.33\ (\pm\ 0.09)\ \text{Log}\ MEI_{alk\ (all\ lakes)}$
(4) $\text{Log}\,[P] = 0.75 + 0.27\ (\pm\ 0.11)\ \text{Log}\ MEI_{cond\ (all\ lakes)}$
(5) $\text{Log}\,[P] = 1.44 + 0.33\ (\pm\ 0.10)\ \text{Log}\ MEI_{alk\ (North\ American\ lakes)}$

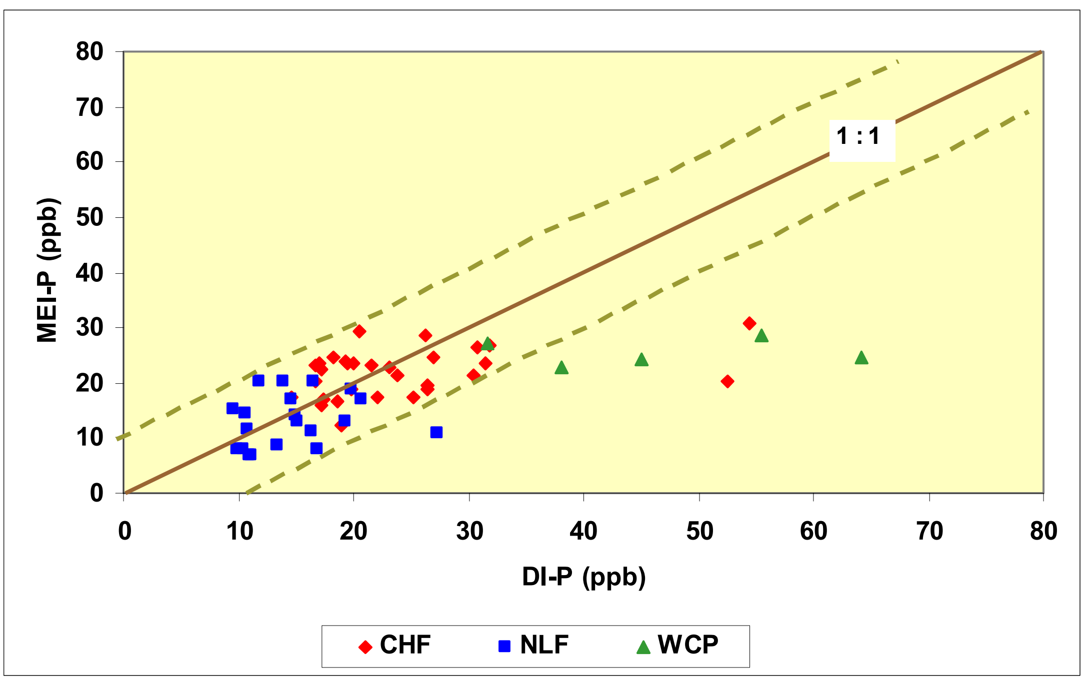
We tend to use alkalinity (Eq. 5) in our predictions as it is less likely to be influenced by factors associated with cultural eutrophication. Based on monitoring data from this study (Appendix 1) Cl exhibited a very significant correlation with conductivity (R^2= 0.73) but a much weaker correlation (R^2= 0.32) with alkalinity. Hence, modern-day increases in Cl (which are common to many of the lakes) could yield an increase in conductivity, as a function of increased impervious area and salt usage, which may not result in a corresponding increase in nutrient loading.

Figure 16 provides a comparison of pre-European DI- P (mean of 1750 and 1800) versus MEI-P for all lakes. A 1:1 line of "perfect agreement" and an "envelope" of ± 10 µg/L were used to provide a visual basis for the comparison. This "envelope" or confidence interval was intended to account for error in the MEI-based estimates and error associated with the DI-P values. This CI is quite conservative given the RMSEP associated with the reconstructions and the CI suggested in the MEI-based P values (e.g., Eq. 5 above).

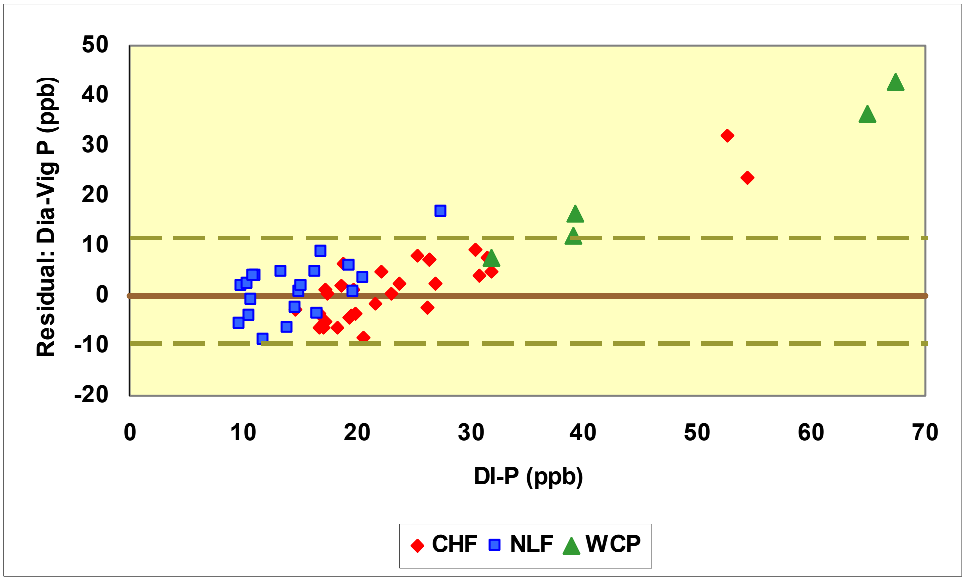
Based on this comparison 48 of 55 lakes fell within the "envelope," including 19 of 20 NLF, 28 of 30 CHF and 1 of 5 WCP lakes. Lakes outside the envelope had <u>higher</u> DI-P values (as compared to MEI-P): Wilson (NLF), Hook and Gervais (CHF), and Beaver, George, Bass, and Fish (WCP). Interestingly, Wilson and Gervais modern-day P values are lower than the pre-European DI-P values.

An analysis of residuals, expressed as pre-European DI-P minus MEI-P and plotted against the DI-P does not show any distinct high or low bias in predictions for concentrations below about 30 µg/L (Figure 16b). Above 30 µg/L, however, the DI-P values were consistently higher than the MEI- P values. This may be a reflection of the dataset used for the MEI-based regression, which was limited to lakes with "background" P concentrations less than about 25 µg/L. Hence there may be some limitations in applying the equation to lakes that may have had background P much in excess of this value. Alternately it could mean that for those lakes, which deviate from the relationship (Figure 16), that P loading is somehow disproportionate to the delivery of minerals to the lake.

Figure 16 (a, b). MEI-P compared to pre-European DI-P and residuals. Residuals calculated as DI-P minus MEI-P.



(b)



The next comparison involved the MINLEAP prediction as compared to the diatom prediction (Figure 17a). Again we have used a ±10 µg/L confidence interval (CI) for the comparisons but given the typical standard error associated with the MINLEAP predictions, which averaged ± 11.5 µg/L for this dataset, this is a very conservative CI and a larger than with the MEI may be appropriate. Overall, we see poorer agreement between the two predictions, with 29 of 55 lakes within the ± 10 µg/L CI. However, no distinct P threshold is evident when we review the residuals (Figure 17b), as was the case in the comparison of the MEI-P to the DI-P (Figure 16).

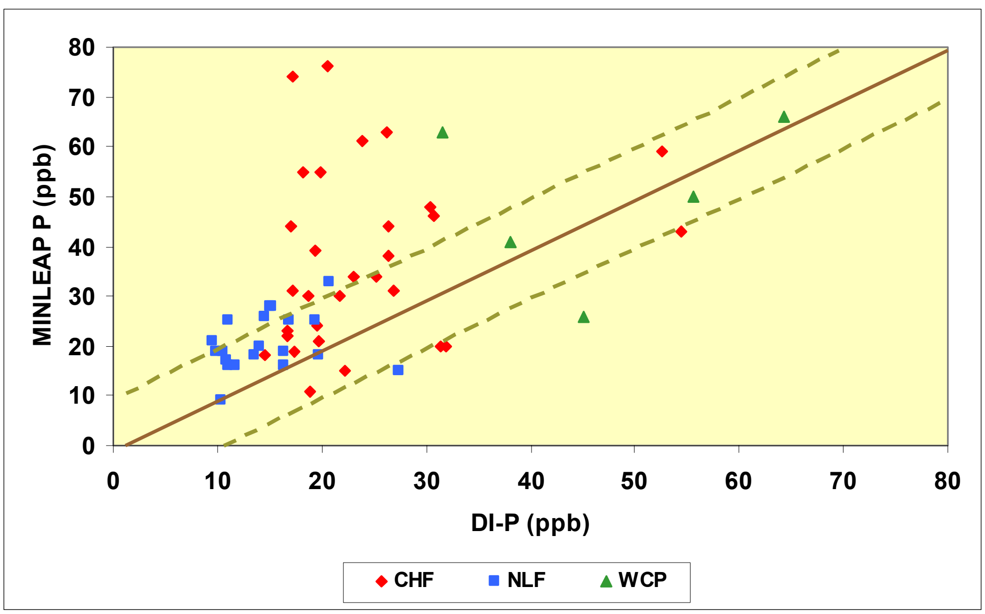
For the NLF lakes, the two predictions were reasonably close and 14 of 20 lakes were within the ± 10 µg/L CI. The remaining six lakes were within ± 15 µg/L and five of six had MINLEAP-P values that were greater than the DI-P values. Only Wilson Lake exhibited a MINLEAP-P that might be considered significantly lower than the DI-P for the NLF lakes. Given the lack of change between pre-European and modern-day DI-P values for lakes in this region (Figure 3) the relatively good agreement (between MINLEAP-P and diatom reconstructed) for the NLF lakes is not too surprising. Modern-day observed-P corresponds closely with MINLEAP-P for most of the NLF lakes, with many of the lakes exhibiting observed values that are slightly lower than the MINLEAP prediction (Figure 17c). This is most likely a function of the stream inflow-P used in the model (~50 µg/L), which is likely higher than the actual inflow-P for many of these remote lakes (e.g. in Voyageurs National Park).

The CHF has several lakes with significantly higher MINLEAP-P values as compared to the DI-P values. Of the nine lakes with MINLEAP-P values more than 20 µg/L higher than the DI-P values, eight were in the CHF and of these, six were in the Metro area. In general, these nine lakes tended to have very large watershed: lake ratios (34:1) as compared to the overall dataset (13:1) and tended to have upstream lakes in their watershed that serve to reduce P loading to the lake. Since P loading in MINLEAP is primarily a function of watershed size the model often overestimates P loading and modern-day in-lake P for lakes with very large watersheds (especially those with significant upstream lakes). This was particularly evident for several of the Metro lakes including: Marcott, Dickman, Schultz, Calhoun, Sweeney, Little Carnelian, and Carver, which exhibited MINLEAP-P values which were much higher than the DI-P values. Dickman, Fish, Dunns, Richardson, and Diamond Lakes'modern-day observed P concentrations were significantly greater than MINLEAP (Figure 17c). In contrast, Marcott and Little Carnelian exhibit significantly lower observed-P as compared to MINLEAP. In the case of these two lakes the total watershed of the lake is large but there tends to be several intervening wetlands (Marcott) or lakes (Big Carnelian is directly upstream of Little Carnelian) that would reduce upstream P loading.

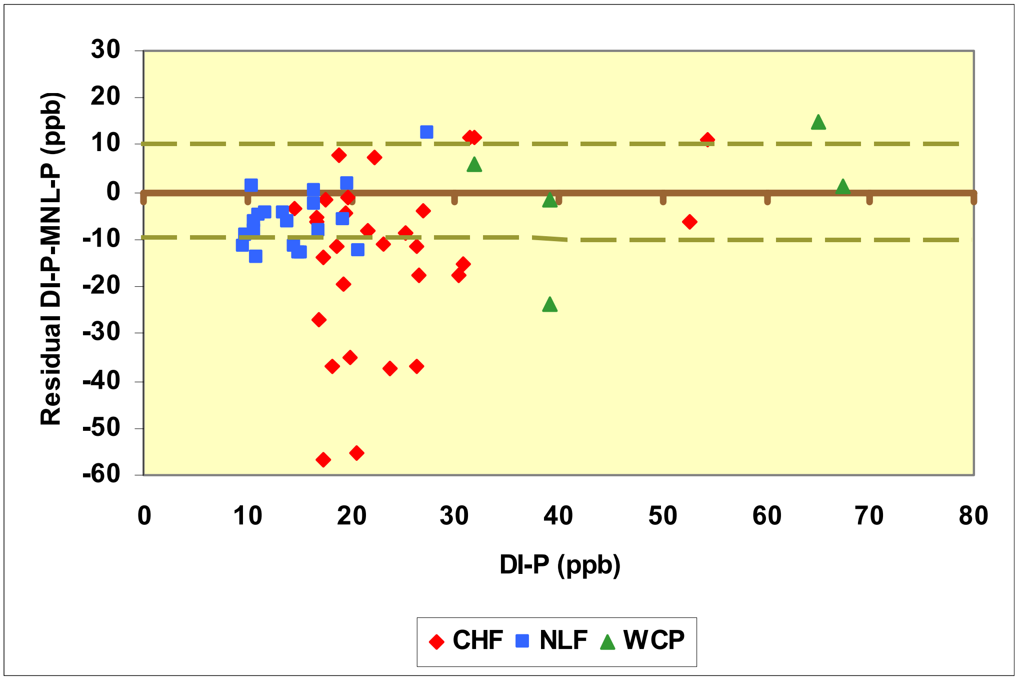
Surprisingly, three of five WCP lakes: George, Fish, and Beaver exhibited very close agreement between the MINLEAP-P and DI-P, which suggests these lakes may be very near their "background" condition. Duck Lake, which has a large watershed and upstream lakes, exhibited a higher MINLEAP-P value as compared to the DI-P. However for Bass and George Lakes observed-P is much higher than MINLEAP-P which suggests there may be some room for improvement (Figure 17c). Fish Lake, in contrast, exhibited a lower observed-P as compared to the MINLEAP-P and, when combined with the diatom results, suggest the lake may be very near background.

Figure 17(a,b,c). MINLEAP-P compared to a) pre-European DI-P, b) residuals (DI-P – MINLEAP-P), and c) modern-day observed-P.

(a)

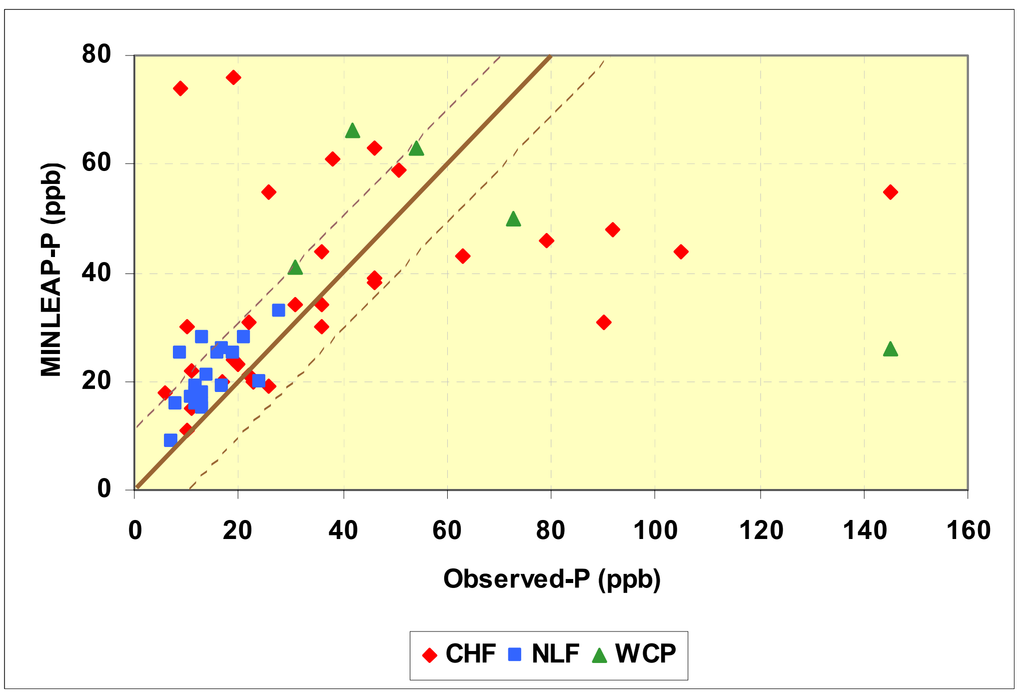


(b)



30
20
10
0
-10
-20
-30
-40
-50
-60
Residual DI-P-MNL-P (ppb)
0
10
20
30
40
50
60
70
80
DI-P (ppb)
CHF NLF WCP

(c)



80
60
40
20
0
MINLEAP-P (ppb)
0
20
40
60
80
100
120
140
160
Observed-P (ppb)
CHF NLF WCP

IV. Using DI-P concentrations as a part of nutrient criteria development

Pre-European DI-P (background P) concentrations should not be used as the sole basis for setting modern-day nutrient criteria, however they can be used to place modern-day data sets and proposed criteria in perspective. In this vein we have made a comparison (Table 21) of: MPCA reference lake data, MPCA "assessed" data (as expressed in the 305(b) report to Congress), EPA's assessed data from the recent EPA ecoregion criteria documents (USEPA, 2000), mean DI-P based on the 1750 and 1800 core samples, and the P criteria values which were originally developed in 1988 (Heiskary and Wilson, 1989).

Ecoregion-based patterns are evident in all datasets. We have previously recognized this in the present-day datasets and the diatom reconstructions serve to reinforce the concept that there are and were (pre-European influence) regional patterns in lake trophic status across Minnesota. The NLF is relatively nutrient poor and is characterized by a relatively small range in P concentration in all datasets. The CHF exhibits somewhat higher P concentrations and a fairly large range. This is particularly evident among the MPCA and EPA "assessed" datasets. The reference lake and DI-P data sets have somewhat smaller ranges (27 and 8 µg/L respectively). The WCP datasets are typically small in number of observations and are characterized by very high P concentrations and ranges in excess of 200 µg/L. All lakes can be considered eutrophic to hypereutrophic based on the WCP datasets. Overlap among the ranges is evident for the NLF and CHF datasets, however there is no overlap between the NLF and WCP and only minimal overlap between the CHF and the WCP ecoregions.

Pre-European DI-P can provide perspective for modern-day data sets that are used for criteria setting. While it may not be reasonable to expect all lakes in a given ecoregion to attain or be restored to "pre-European" condition (though some lakes may be near those concentrations) it is reasonable to set achievable expectations (criteria) for modern conditions within an ecoregion framework. Further, if we compare the pre-European values, for each ecoregion, to the previously developed criteria and associated datasets (Table 21) it is apparent that the previously proposed criteria levels are not "overly" protective or stringent for the ecoregion. The IQ range of the NLF pre-European DI-P values rank near the 25th percentile for the modern-day reference and assessed lakes, while the criteria value is near the 75th percentile for the MPCA and EPA assessed lakes (Table 21). CHF pre-European DI-P values rank near the 10th to 25th percentiles for the reference and assessed lakes, while the criteria value ranks between the 25th to 50th percentile for reference and assessed lakes (Table 21). WCP lakes, used in this study, were among the deepest and had the lowest TP concentrations in the ecoregion. Pre-European DI-P concentrations for these lakes rank near the 10th percentile for both the reference and assessed lakes, while the criteria value ranks near the 25th percentile (Table 21). This suggests that protection of currently low modern-day P (as compared to other lakes in the ecoregion) in these deeper lakes is important. However, the pre-European DI-P concentrations from these five lakes may not be the most appropriate yardstick for evaluating other, shallower lakes in these two regions. Augmenting this database with lakes more typical of the WCP and NGP would be desirable. In general, pre-European

DI-P data provide further insights into regional patterns in trophic status and change over time and will be a valuable addition to the previously noted data sets: modern-day reference and assessed lake data, user perception, and related information used in the development of ecoregion-based P criteria (Heiskary and Wilson, 1989).

Table 21. Comparison of IQ range of phosphorus (µg/L) based on MPCA reference, 305(b) assessed, EPA assessment and DI-P for 1750-1800

Ecoregion (number)	MPCA Reference 25-75 %tile	MPCA Assessed 25-75 %tile	EPA Assessed 25-75 %tile	DI-P (1750-1800) 25-75 %tile	1988 P criteria swim. use
NLF (50)	14 - 27	13 - 30	10 - 30	11 - 16	30
CHF (51)	23 - 50	28 - 120	20 - 100	18 - 26	40
WCP (46)	65 - 150	130 - 325	60 - 155	38 - 56	90

Conclusions and Recommendations

Diatom reconstruction of water chemistry is an increasingly common tool for assessing environmental changes over time and space. There are numerous applications of this technique in Minnesota (e.g., Bradbury, 1975; Brugam and Speziale, 1983) and elsewhere throughout the world (e.g. Bennion et al. 1996; Hall and Smoll, 1996, and Dixit et al. 1992). Siver et al. (1999), for example, used diatom reconstruction and GIS data to assess the degree to which lakes in Connecticut have changed during the last century and compared changes to alterations in the watershed. Garrison and Wakeman (2000) used sediment diatoms to document the affect of shoreland development on four lakes in Wisconsin. All of these studies reinforce the value of diatoms for assessing environmental impact on lakes.

Diatom reconstructions in this study compare favorably (in terms of R^2 and RMSEP) to other similar studies (e.g., Bennion, 1994 and Fritz et al. 1993). As with other diatom reconstruction studies the agreement between the DI-P values and observed-P are best at the lower end of the trophic scale (e.g. Reavie et al. 1995). For example, the NLF ecoregion lakes' observed-P ranged from 7 – 27 µg/L and exhibited a mean difference between observed and diatom-inferred of 3 µg/L. The difference for all NLF lakes was less than 10 µg/L (Figure 2a). CHF ecoregion lakes' observed TP, in contrast, ranged from 6 -145 µg/L. Here mean difference (between observed and DI-P) was 15 µg/L and in 22 of 30 lakes the difference was 10 µg/L or less. WCP ecoregion lakes' observed-P ranged from about 31 – 145 µg/L and difference between DI-P and observed averaged 34 µg/L but this was driven largely by George Lake (Figure 2a).

Independent validation has become an important part of these type of studies (Anderson, 1997). With this in mind, comparisons were made between the c.1970 diatom reconstructions and observed data for that period. In this case we averaged available data for the period from c.1970 to c.1980 and compared this to the diatom data (Figure 2c). Based on comparisons for 18 lakes we found the mean difference to be 13 µg/L with 12 of 18 lakes exhibiting a difference of 10 µg/L or less. Regressing observed vs. diatom-inferred revealed an R^2 of 0.34, which was lower than the R^2 for the entire training set. However if one outlier (Lake Owasso, observed P = 88 µg/L) is removed the R^2 improved to 0.63. Five lakes: Christmas, Elmo, McCarrons, Harriet and George (34-0142) exhibited slightly higher DI-P as compared to the observed data. Each of these lakes exhibited either highly variable TP or trends in the 1970s based on observed data. Lake Owasso was the sole lake where the diatom-inferred P significantly underestimated the observed data (Figure 13). However, the data from mid 1970s is somewhat sketchy (based on two observations per year) so it is unclear if the diatom-reconstruction is in error or the "observed" data may not be accurately characterized. The 1980 summer-mean TP (Figure 13), for example, was based on 10 observations and corresponds quite well with c. 1970 DI-P.

The difference between reconstructed and observed values is a function of errors in reconstruction and errors (variability) associated with observed (monitored) data. Anderson and Rippey (1994) note that given all possible sources of error, an average difference of about 20-25 µg/L between diatom-inferred and observed P can be considered satisfactory. Based on Figures 2a and 2c we see that a majority of lakes in our study fell within ± 10 µg/L and most were within ± 25 µg/L. As previously noted, the model tended to underestimate observed P at higher P concentrations, which is common to many studies. Reavie et al. (1995b) note that diatoms found at high P concentrations are likely most tolerant and further increases in P will not yield dramatic changes in diatom composition. In their study they removed lakes with TP values above 85 µg/L since they provided poor TP reconstruction. This may be the case for some of the outliers in our study as well where Dickman, George (07-0047), Dunns and Richardson Lakes are greater than 85 µg/L P (Figure 2a) and exhibit rather poor agreement with observed data. Another alternative is to add additional P-rich lakes to the data set and limit the training set and diatom inference model development to these lakes. This should allow for improved prediction at this end of the trophic spectrum (Anderson, 2002; personal communication).

In the case of Dickman, George, Dunns and Richardson and several other lakes in the study, observed data are often based on only two or three sample visits. This often results in large standard error associated with the means (15 µg/L or more for these four lakes) for these highly eutrophic lakes. Future studies could minimize this type of "error" by increasing the number of samples used to characterize "observed" modern-day chemistry. Bennion (1994), for example, recognized high variability in the shallow eutrophic ponds she was studying and employed monthly sampling over one year as a basis for characterizing mean condition.

At the lower end of the trophic scale there were a few lakes where DI-P "overestimated" observed-P (Figure 2a). In four of five lakes, Calhoun, Harriet, Christmas, and Fish (32-0007), declining trends in P were evident based on observed data (Figures 12 and 15). In these instances the difference between the time interval represented by the core slice and the corresponding water quality collection could be rather critical – in contrast to lakes that are not undergoing any change. Thus, it is possible that the water quality data used in the reconstruction did not perfectly "correspond" to the same interval as represented by the c. 1993 core. In these instances expanding collection of observed data over one or more summers (increase number of observations for the training set) would be desirable to ensure that the observed data adequately characterize the time interval in question. Should this not be possible, other data sets (e.g., CLMP Secchi measures) may provide insights into trophic status trends and variability.

Distinct regional patterns in TP were evident based on pre-European DI-P. Lakes in the three ecoregions: NLF, CHF, and WCP averaged 14.7 ± 1.0, 24.2 ± 1.7, and 46.9 ± 5.9 µg/L respectively. No distinct difference was evident between the "Metro" CHF lakes (22.6 ±1.8 µg/L) and the "non-Metro" CHF lakes (27.4 ± 3.5 µg/L). Region-wide comparisons of pre-European DI-P to modern-day (1990s) DI-P revealed no significant change for either the NLF or the WCP lakes (Table 3). However the CHF lakes, as a group, exhibited significantly higher modern-day DI-P as compared to pre-European (Table 3).

Pre-European condition in our study lakes was not necessarily "pristine," in the sense of low TP, in all instances. While the majority of the lakes exhibited minimal change in TP between the 1750 and 1800 time periods several lakes, including: Snells and Loon (NLF ecoregion); Fish, Henderson, George, Richardson and Sagatagan (CHF ecoregion); and George and Bass (WCP ecoregion) exhibited substantial differences (Figures 9-14). Pre-European impacts on trophic status were most likely driven by climate change (e.g., development of the Big Woods 300-350 years ago (Engstrom, 2002, personal communication). On a more localized basis fire, drought, and/or significant fluctuations in lake level may have been important. In a few instances Indian settlements in the shoreland area may have been a factor, e.g., the Henderson Lake shoreland area was noted as a favorite Indian camping place in the 1800's (Plate 6). Reavie et al. (1995a) note that pre-European increases in P loading in Dutch Lake (British Columbia) may have been caused by Indian settlements in the shoreland area.

Fire was a common feature in both the forested and prairie regions (Heinselman, 1973 and Waddington, 1969). Schindler et al. (1980) noted increased runoff and TP concentration in streams following both fires and windstorms, however, these affects were relatively short-lived in areas that re-vegetated quickly (about two to three years in the ELA in Ontario). Laird and Cumming (2001) noted increased erosion and input of mineral sediment in some lakes (watersheds) that have experienced fires, however fires of limited extent and intensity may not be detected in lake-sediment records (MacDonald et al., 1981 in Laird and Cumming, 2001). The fire "signature" would result in a decline in the organic matter in the sediment (because of an increase in inorganic matter). Garrison and Wakeman (2001), in a detailed study of four Wisconsin lakes, noted that the period following wild fires in mid 1890's had a greater impact on sediment accumulation rates than did logging activity in the 1870's. The destruction of the vegetation during the fires resulted in increased Al and sediment accumulation, however there was minimal P in these low mineral soils so large changes in P were not noted. The CHF and WCP lakes (noted above) are located in areas transitional between the "Big Woods," "oak openings," and "prairie" as described by Marschner (1930). These areas were frequented by fire in pre-European times (Waddington, 1969) but with European settlement fire suppression was common. Fire suppression allowed for increased forest growth in the riparian areas of lakes and streams, which would minimize runoff and P loading.

There was minimal change in landuse from pre-European to modern-day in the NLF lakes with 15 of 20 having 80 percent or more of their modern-day watersheds in forested use. Though there may have been some significant shifts in the type of forests in the watersheds, as a result of logging and fire suppression, the dominant landuse remains forest, with a fair percentage of wetland as well (Appendix I). As a group, there was no significant change in TP from pre-European to modern-day (Figure 3, Table 3). This is consistent with Siver et al. (1999) who noted that lakes with watersheds that maintained greater than approximately 80 percent forests since c.1890 did not generally undergo significant chemical changes. Hall and Smol (1996) found that modern-day TP in Ontario lakes, with forested watersheds and developed shorelines, was similar to pre-European TP despite the cottages on the shoreline.

Lakes in regions, such as the CHF, that have experienced substantial change in landuse from pre-European (forest and prairie) to modern-day (urban and agriculture) exhibit significant changes in TP (Figure 3 and Table 3) and Cl (Figure 7). This applies to lakes in both the urban and rural portion of the region. Siver et al. (1999) note that lakes with watersheds that experienced an increase of greater than 25 percent residential land use have significantly increased in specific conductivity and pH and become more eutrophic in nature. This degree of change would apply to most of the Metro lakes in our data set where modern-day percent "built-up" accounts for from one percent to over 80 percent of watershed land use (Appendix I). The percent of built-up land use has been shown to explain 36% and 25%, respectively, of the change in DI-Cl and DI-P from modern-day: pre-European in our study. Recent and significant land use changes (urbanization) contributed to increased TP in Fish and Dickman Lakes for example. Both lakes are rather small and shallow and were unable to assimilate increased loads associated with expansion of its watershed (Fish) or residential and road runoff (Dickman).

A shift from agricultural uses (row crop or pasture) in the shoreland, or immediate watershed, to residential or built-up landuse appeared to result in declines in TP for several lakes (groups) in the study. The Grand Rapids area lakes: Forsythe, Little Bass, Loon, Long and Snells exhibited stable or declining TP between c.1970 and c.1990. Of these, Little Bass and Loon experienced the biggest decline in percent of agriculture in the shoreland, largest increase in number of homes (Table 7) and largest decline in TP (Table 8). Snells and Forsythe experienced minimal changes in shoreland land use and essentially no change in TP from c.1970 to c.1990. Snells, which has the highest modern-day percentage (43%) of agriculture of these five lakes, also exhibited the highest modern-day TP (Table 8). George and Henderson Lakes (Kandiyohi County) both experienced a decline in agricultural use and increase in shoreland development between c.1970 and c.1990. George exhibited a significant decline in TP and Henderson was relatively stable over this period (Table 9). Hook Lake (McLeod County) also seemed to benefit from a reduction in agricultural landuse in the shoreland area. Long (Kandiyohi), which originally had minimal agriculture in its watershed, experienced intensive residential development along its shoreland over this period and experienced and an increase in DI-P and DI-Cl. Diamond Lake, in contrast to George and Henderson Lakes, experienced both increased shoreland development and row crop agriculture (facilitated by wetland drainage and tiling) and as a result exhibited a significant increase in TP from c. 1970 to c. 1990.

Of the 20 Metro lakes more lakes exhibited declines in DI-P between c.1970 and c.1990 than exhibited increases. In general, lakes with watersheds that were "developed" in the mid 1900's often exhibited declines in P by c. 1990 based on the diatom reconstructions and /or more recent observed data. Calhoun, Harriet, Sweeny, Johanna, Owasso, Turtle, Elmo, Square and Tanners are among the lakes exhibiting lower TP concentrations in c.1990 as compared to c.1970. These apparent declines may be attributed to a variety of individual circumstances, however in most cases the development in the watersheds had "matured" and there was less new construction or disturbances (in contrast to when development was first initiated). And, in several cases there have been concerted efforts to improve stormwater handling and implement best management practices to reduce transport of P to the lakes. This is in direct contrast to cultivated lands that undergo disturbance each year allowing for erosion and transport of sediment and nutrients to receiving waters.

Empirical models, such as the Vighi and Chiaudani (MEI) model, can provide reasonably accurate estimates of pre-European TP concentrations for lakes with a minimum of data. Our DI-P data set provides a unique opportunity to attempt to validate this equation by means of diatom-inferred sediment cores – which in our case represent (1750 – 1800) a time period for Minnesota, that precedes much of the development and land use changes associated with European settlement of the state. Comparisons of MEI-based P to pre-European DI-P demonstrated good agreement where for lakes with "background" P of about 30 µg/L or less. An analysis of residuals (pre-European DI-P minus MEI-P) showed a distinct bias at concentrations above 30 µg/L, whereby MEI-P underestimated DI-P (Figure 16). This was presumed to be a reflection of the data base used to develop the MEI-P equation, which was limited to lakes with "background" P of about 25 µg/L or less. As such, we would recommend use of the MEI-based model only where background P was likely 30 µg/L or less.

A comparison of MINLEAP-P vs. pre-European DI-P, for the NLF lakes, revealed relatively similar results. In 16 of 20 NLF lakes the MINLEAP prediction was higher than the pre-European DI-P but agreed quite well with modern-day observed data (Figure 17c). All NLF study lakes were at or below the P concentration range used in MINLEAP development (i.e., all 20 lakes could be considered minimally impacted and representative of the region). In 26 of 30 CHF lakes MINLEAP predicted a higher P as compared to the pre-European DI-P (Figure 17c). This was not surprising given the changes that have occurred in many of these lakes since pre-European times. For three of five WCP lakes the MINLEAP prediction was very close to the pre-European DI-P. And, as noted previously, these five lakes exhibited highly variable P concentrations but did not exhibit very distinct trends based on comparisons of pre-European to modern-day P concentrations. In general we recommend that MINLEAP should continue to be used as originally intended – as a basis for evaluating lake condition in an ecoregion- based context and as one element in a goal-setting process. However, it generally will not provide a reliable estimate of background condition.

Distinct regional patterns in trophic status (based on TP) are evident for Minnesota based on modern-day assessments (e.g., Heiskary et al. 1987 and Appendix II) and in the pre-European DI-P in this study. Recognition of regional differences in modern-day trophic status led to development of ecoregion-based TP goals for Minnesota lakes (Heiskary and Wilson, 1989). USEPA (2000), as a part of the Clean Water Action Plan, recognized the importance of these regional patterns on a national scale and has requested that states develop ecoregion-based nutrient standards for lakes. As a part of nutrient criteria development USEPA recommend the use of "reference" sites as one basis for criteria development and state further, that in the absence of true reference sites, the 25th percentile (lower quartile) of assessed lakes might serve as reference condition (USEPA, 2000). Alternately, diatom-reconstruction of P, across a representative range of lakes (within a given ecoregion), might serve the same purpose.

Diatom reconstructions can be used to place modern-day data in perspective with historic condition. For example, in this study the NLF ecoregion, DI-P values are near the 25th percentile of the reference and assessed populations (Table 20). While the study lakes were not randomly selected they are representative of lakes in this region in terms of area, depth, and land use characteristics. In the CHF ecoregion the DI-P values are near the 25th percentile of the reference lakes but are below the 25th percentile of the assessed lakes, which suggests that the majority of lakes in the CHF ecoregion are well above background P. Again the study lakes were quite representative in terms of area and depth, but because of the emphasis on Metro lakes the study lakes had a higher percentage of land in urban uses as compared to the CHF reference lakes.

Pre-European DI-P values for the five WCP lakes rank well below the 25th percentile for both the reference and assessed data (Table 20). This suggests that these five lakes may not be representative of the larger population or that modern-day condition is substantially changed from pre-European. Modern-day land use in the watersheds of these lakes is typical of lakes in the WCP, however these five lakes tend to be much deeper and surface areas slightly smaller than the norm for this region. The combination of greater depth and small surface area allow all five of the lakes to thermally stratify through much of the summer, which may minimize internal recycling of P and results in lower TP in the upper mixed layer of the lakes. Very few lakes (ten percent or less) in the WCP or NGP are deep enough to stratify based on previous region-wide assessments (Heiskary et al. 1987), hence from this standpoint these lakes cannot be deemed "typical" of the larger population. Based on these observations it is likely that these five lakes may be among the least eutrophic both in modern-day and in pre-European times and hence the diatom-inferred values might be viewed as a "best case" for lakes in the WCP ecoregion.

In summary:

- Distinct regional patterns in TP were evident in both modern-day observed and pre-European diatom-inferred data sets.
- Performance of the diatom inference model (in terms of RMSEP and R^2) developed for this study was comparable to, or better than, that of similar studies conducted elsewhere in the world.
- Independent validation of model predictions for 1970 with observed TP data for 1970-1980 exhibited very good correspondence between observed and diatom-inferred values.
- As a group there was no significant difference between pre-European and modern-day DI-P for the NLF lakes. These lakes, with the possible exception of the five lakes near Grand Rapids, have experienced minimal change in landuse as compared to lakes in the other ecoregions.
- Significant increases in DI-P from pre-European to modern-day were evident for several of the CHF lakes. For lakes in the rural portion of the ecoregion increased P is likely a reflection of intensive agricultural uses in the watershed. For lakes in the metro portion of the region increased P could be associated with the urbanization of the watershed.
- There were several lakes in the Metro portion of the CHF ecoregion that exhibited a decline in DI-P between c. 1970 and c. 1993. Observed water quality data showed similar trends in many of these lakes. It was presumed that the slowing of development ("maturing") of these watersheds over this period and active efforts to reduce P loading via BMP implementation combined to reduce in-lake P in several lakes.
- There was evidence in several NLF and CHF lakes that a reduction of agricultural use in the shoreland area and immediate watersheds may have contributed to observed declines in DI-P from c. 1970 to c. 1993. Though this change was often followed by varying degrees of residential or urban development it was felt that as the initial impacts associated with development (e.g., increased runoff, sediment and TP loading) subsided that a more "stable" situation resulted as compared to cultivated lands that are annually disturbed or pastured shorelands that may be prone to erosion excessive runoff.

The following recommendations arise from our analysis of the 55 lakes data set to date:

- More P-rich (eutrophic) lakes should be added to the 55 lakes training set. In particular a cross-section of lakes representative of the WCP and NGP ecoregions should be added. This would allow for a refinement of the diatom-transfer model for more P-rich lakes and allow for an improved characterization of pre-European lake trophic status in this nutrient-rich prairie region of Minnesota. This in turn would ensure the development of realistic water quality goals and aid in the development of nutrient criteria.
- The MPCA should collaborate with any similar studies or efforts that would increase the number and range of lakes in the training set. Again this will improve the predictive power of the diatom-transfer model and improve our ability to assess trends over time.

- Any future studies should ensure accurate characterization of modern-day water quality. At a minimum four sample dates from June through September should be employed and ideally eight to twelve observations over two summers might be desirable to accurately describe modern-day condition and provide some indication of variability.
- This study allowed for the comparison of two very distinct time periods: pre-European and modern-day. However, without analysis of additional core slices, representing intervening time periods, we cannot accurately describe changes in lake condition that may have occurred between these two time periods and understand the role of man's activity in the watersheds and the specific impact it had on lake water quality. As time and funds permit consideration should be given to analysis of additional core slices for at least a subset of lakes in this study.
- A significant effort was made to compile modern-day water quality data to help validate the DI-P concentrations and trends. There may be additional relevant data for these lakes that could be added to this data set to enhance this analysis. As time and funds permit additional data should be sought and added to the data set.
- There have been a number of other core-based diatom reconstruction studies done on specific lakes in Minnesota. It may be of value to compile data from these studies and where possible the actual training sets to allow for an improved understanding of temporal trends in the water quality of Minnesota lakes and possible improvements in the 55 lakes training set.

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Appendix I.

1. Morphometry and watershed characteristics for study lakes.
2. Watershed land use for the study lakes.
3. Observed water quality data for the study lakes.

Appendix II.

1. Morphometry and watershed characteristics for reference lakes.
2. Watershed land use for reference lakes
3. Typical water quality for reference lakes

Appendix III

1. Study Lakes Sediment Loss on Ignition and Accumulation Rates

Appendix I
Table 1. Study Lake Location, Morphometry and Watershed Area

LakeID	County	Group	Lake	Eco	Latitude N	Longitude W	Lake Area (ha)	Max. Depth (m)	Total Wshed (ha)	Primary Wshed (ha)
19-0042	Dakota	Metro	**Marcott**	CHF	44° 48.95'	93° 04.02'	7.5	10.1	251	56
19-0046	Dakota	Metro	**Dickman**	CHF	44° 51.69'	93° 04.74'	9.1	2.4	57	57
19-0057	Dakota	Metro	**Fish**	CHF	44° 49.35'	93° 10.03'	12.5	10.1	1506	106
19-0075	Dakota	Metro	**Schultz**	CHF	44° 47.07'	93° 07.74'	5.3	4.9	69	18
27-0016	Hennepin	Metro	**Harriet**	CHF	44° 55.15'	93° 18.58'	138.6	25.0	387	387
27-0031	Hennepin	Metro	**Calhoun**	CHF	44° 56.63'	93° 18.79'	168.5	27.4	2515	1236
27-0035-01	Hennepin	Metro	**Sweeney**	CHF	44° 59.44'	93° 20.48'	28.3	7.6	1011	78
27-0035-02	Hennepin	Metro	**Twin**	CHF	44° 59.52'	93° 20.17'	8.7	17.1	33	33
27-0137	Hennepin	Metro	**Christmas**	CHF	44° 53.85'	93° 32.47'	105.7	26.5	189	189
27-0179-02	Hennepin	Metro	**Little Long**	CHF	44° 56.88'	93° 42.47'	21.8	23.2	32	32
34-0044	Kandyohi	WC	**Diamond**	CHF	45° 11.16'	94° 51.23'	644.8	8.2	3590	1850
34-0066	Kandyohi	WC	**Long**	CHF	45° 19.87'	94° 51.13'	129.8	13.4	363	363
34-0116	Kandyohi	WC	**Henderson**	CHF	45° 13.82'	94° 59.56'	29.1	12.2	59	59
34-0142	Kandyohi	WC	**George**	CHF	45° 14.55'	94° 59.06'	91.6	9.1	102	87
43-0073	Mcleod	WC	**Hook**	CHF	44° 57.21'	94° 20.47'	133.1	5.5	620	399
43-0104	Mcleod	WC	**Stahl**	CHF	44° 57.18'	94° 25.24'	54.6	10.7	630	186
47-0082	Meeker	WC	**Dunns**	CHF	45° 09.50'	94° 25.74'	63.0	6.1	1381	165
47-0088	Meeker	WC	**Richardson**	CHF	45° 09.57'	94° 26.40'	48.3	14.3	1168	1168
62-0007	Ramsey	Metro	**Gervais**	CHF	45° 01.05'	93° 04.30'	94.4	12.5	4028	243
62-0054	Ramsey	Metro	**McCarrons**	CHF	44° 59.85'	93° 06.67'	30.1	17.4	412	43
62-0056	Ramsey	Metro	**Owasso**	CHF	45° 02.28'	93° 07.45'	150.9	12.2	423	224
62-0061	Ramsey	Metro	**Turtle**	CHF	45° 06.22'	93° 08.18'	133.3	8.8	180	180
62-0078	Ramsey	Metro	**Johanna**	CHF	45° 02.43'	93° 09.93'	86.4	12.5	1026	228
73-0092	Stearns	WC	**Sagatagan**	CHF	45° 34.47'	94° 23.45'	88.7	14.3	252	252
73-0097	Stearns	WC	**Kreighle**	CHF	45° 34.72'	94° 28.69'	41.0	17.1	88	88
82-0014	Washington	Metro	**Little Carnelian**	CHF	45° 07.07'	92° 47.79'	46.7	19.2	1854	162
82-0046	Washington	Metro	**Square**	CHF	45° 09.40'	92° 48.26'	81.9	20.7	226	226
82-0106	Washington	Metro	**Elmo**	CHF	44° 59.37'	92° 52.96'	114.6	42.7	2076	569
82-0115	Washington	Metro	**Tanners**	CHF	44° 57.00'	92° 58.88'	30.2	13.7	669	669
82-0166	Washington	Metro	**Carver**	CHF	44° 54.36'	92° 58.83'	19.6	11.0	864	864
16-0634	Cook	NE	**Dyers**	NLF	47° 31.62'	90° 58.79'	27.8	6.1	854	854
31-0560	Itasca	NE	**Forsythe**	NLF	47° 15.97'	93° 36.06'	27.1	3.1	191	191
31-0569	Itasca	NE	**Snells**	NLF	47° 14.46'	93° 40.61'	35.8	15.2	288	288
31-0570	Itasca	NE	**Long**	NLF	47° 13.63'	93° 39.39'	54.5	22.9	165	165
31-0571	Itasca	NE	**Loon**	NLF	47° 13.95'	93° 38.42'	92.9	21.0	364	144
31-0575	Itasca	NE	**Little Bass**	NLF	47° 17.05'	93° 36.09'	64.5	18.9	540	540
38-0033	Lake	NE	**Ninemile**	NLF	47° 34.55'	91° 04.88'	120.3	9.1	209	209
38-0047	Lake	NE	**Wilson**	NLF	47° 40.45'	91° 04.53'	257.1	14.9	719	719
38-0068	Lake	NE	**Windy**	NLF	47° 44.13'	91° 04.31'	184.6	11.9	1705	1464
38-0231	Lake	NE	**Tettegouche**	NLF	47° 20.66'	91° 16.18'	26.7	4.6	103	103
38-0232	Lake	NE	**Nipisiquit**	NLF	47° 21.31'	91° 14.94'	23.7	5.5	298	60
38-0242	Lake	NE	**Wolf**	NLF	47° 22.61'	91° 11.58'	13.1	7.3	68	68
38-0405	Lake	NE	**Bear**	NLF	47° 17.05'	91° 20.62'	18.3	8.8	60	60

38-0409	Lake	NE	**Bean**	NLF	47° 18.51'	91° 18.02'	12.5	7.9	64	34
38-0691	Lake	NE	**August**	NLF	47° 45.79'	91° 36.37'	76.5	5.8	937	372
69-0682	St. Louis	NE	**Little Trout**	NLF	48° 23.72'	92° 31.63'	107.6	29.0	140	140
69-0756	St. Louis	NE	**Tooth**	NLF	48° 23.88'	92° 38.59'	23.6	13.1	151	151
69-0870	St. Louis	NE	**Shoepack**	NLF	48° 29.82'	92° 53.27'	155.4	7.3	1768	1635
69-0872	St. Louis	NE	**Loiten**	NLF	48° 31.60'	92° 55.61'	39.0	14.9	242	242
69-0936	St. Louis	NE	**Locator**	NLF	48° 32.47'	93° 00.34'	54.1	15.9	1489	444
07-0047	Blue Earth	South	**George**	WCP	44° 14.02'	93° 52.29'	36.2	8.5	54	54
07-0053	Blue Earth	South	**Duck**	WCP	44° 13.07'	93° 48.89'	116.6	7.6	385	385
22-0074	Faribault	South	**Bass**	WCP	43° 49.22'	94° 04.67'	75.7	6.1	136	136
32-0018	Jackson	South	**Fish**	WCP	43° 50.82'	95° 02.67'	120.7	8.2	649	649
74-0023	Steele	South	**Beaver**	WCP	43° 53.52'	93° 20.90'	37.8	8.2	71	71

Table 2. Study Lake Landuse Composition for Total Watershed

Lake ID	Lake	Slope	% built	% road [1]	% agric.	% grass	% brush	% conifer	% mixed	% decid	% wet	% water	Eco
19-0042	Marcott	3.3	20	6	12	14	3	0	0	33	2	10	CHF
19-0046	Dickman	2.9	38	2	10	18	0	7	0	24	0	0	CHF
19-0057	Fish	2.3	71	5	9	2	0	1	0	9	1	2	CHF
19-0075	Schultz	2.5	1	0	1	15	12	0	0	57	7	6	CHF
27-0016	Harriet	1.9	91	11	0	0	0	0	0	8	1	0	CHF
27-0031	Calhoun	1.8	88	10	0	2	0	0	0	3	2	5	CHF
27-0035-01	Sweeney	2.0	93	1	0	0	0	0	0	4	1	2	CHF
27-0035-02	Twin	3.0	36	15	0	4	0	0	0	54	2	0	CHF
27-0137	Christmas	2.7	83	4	2	5	0	0	0	5	2	0	CHF
27-0179-02	Little Long	4.1	0	2	18	0	0	0	0	58	24	0	CHF
34-0044	Diamond	1.8	4	1	74	1	0	0	0	6	9	5	CHF
34-0066	Long	2.3	16	1	35	2	3	2	4	27	9	1	CHF
34-0116	Henderson	1.9	36	5	28	8	0	0	11	0	13	0	CHF
34-0142	George	2.1	41	1	7	12	1	6	3	21	9	0	CHF
43-0073	Hook	1.7	3	1	76	2	0	0	0	6	8	5	CHF
43-0104	Stahl	1.8	0	1	58	0	0	0	0	14	22	5	CHF
47-0082	Dunns	1.4	3	1	73	2	0	0	0	5	12	3	CHF
47-0088	Richardson	1.3	3	1	76	2	0	0	0	4	14	0	CHF
62-0007	Gervais	1.7	77	4	0	8	0	0	0	3	5	3	CHF
62-0054	McCarrons	2.0	79	4	0	8	0	0	0	6	3	0	CHF
62-0056	Owasso	1.9	84	6	0	0	0	0	0	2	7	3	CHF
62-0061	Turtle	1.4	80	3	0	0	0	0	0	0	14	6	CHF
62-0078	Johanna	1.6	82	5	0	1	0	0	0	3	2	6	CHF
73-0092	Sagatagan	2.4	2	1	22	1	0	2	0	57	10	5	CHF
73-0097	Kreighle	2.6	0	2	23	0	0	0	0	71	5	0	CHF
82-0014	L. Carnelian	2.0	8	1	41	5	0	1	2	20	6	15	CHF
82-0046	Square	4.3	14	2	20	3	11	2	0	43	3	0	CHF
82-0106	Elmo	1.9	31	3	43	7	0	0	0	9	4	3	CHF
82-0115	Tanners	1.8	75	5	0	7	0	0	0	2	9	2	CHF
82-0166	Carver	2.1	52	6	18	8	0	0	0	11	5	0	CHF
16-0634	Dyers	2.4	0	1	0	1	0	38	23	31	6	0	NLF

Lake ID	Lake	Slope	% built	% road [1]	% agric.	% grass	% brush	% conifer	% mixed	% decid	% wet	% water	Eco
31-0560	Forsythe	1.4	0	1	5	22	11	0	5	45	11	0	NLF
31-0569	Snells	1.3	0	1	43	0	1	14	17	19	4	0	NLF
31-0570	Long	2.1	0	1	8	0	6	0	7	66	12	0	NLF
31-0571	Loon	1.8	3	1	12	1	4	1	14	43	5	15	NLF
31-0575	Little Bass	1.9	5	1	11	5	7	1	4	56	8	3	NLF
38-0033	Ninemile	2.9	0	1	0	0	0	48	42	10	0	0	NLF
38-0047	Wilson	2.9	0	0	0	0	13	0	83	0	4	1	NLF
38-0068	Windy	2.2	0	0	0	0	14	2	76	0	7	1	NLF
38-0231	Tettegouche	3.7	0	0	0	0	0	0	76	21	3	0	NLF
38-0232	Nipisiquit	3.6	0	0	0	0	0	3	52	25	2	19	NLF
38-0242	Wolf	3.7	6	0	0	2	0	0	87	5	0	0	NLF
38-0405	Bear	4.9	0	0	0	0	0	25	68	6	0	0	NLF
38-0409	Bean	5.3	0	0	0	0	0	0	67	23	0	11	NLF
38-0691	August	2.7	0	0	0	0	3	91	0	0	4	2	NLF
69-0682	Little Trout	3.4	0	0	0	0	0	100	0	0	0	0	NLF
69-0756	Tooth	3.6	0	0	0	0	1	90	0	0	9	0	NLF
69-0870	Shoepack	2.2	0	0	0	0	3	15	60	0	20	2	NLF
69-0872	Loiten	3.1	0	0	0	0	0	6	88	0	6	0	NLF
69-0936	Locator	2.7	0	0	0	0	3	23	61	0	5	8	NLF
07-0047	George	2.5	0	2	81	0	0	0	0	18	0	0	WCP
07-0053	Duck	1.6	4	2	86	0	0	1	0	1	7	1	WCP
22-0074	Bass	2.1	15	2	70	1	0	0	0	11	4	0	WCP
32-0018	Fish	1.4	2	1	90	0	0	0	0	4	0	4	WCP
74-0023	Beaver	2.1	15	2	61	0	0	0	0	24	1	0	WCP

[1]. Roads are included in % built up, percentage indicates percent of watershed in roads.

3. Study Lake Observed Water Quality Data (used for reconstructions). Mean based on collections from 1996-1998.

LakeID	Lake	Region	pH	Cond.	Alk	Cl	Sulfate	DOC	Color	TP	TN	Chl-a	Secchi
			SU	umhos	mg/L	mg/L	mg/L	mg/L	Pt-Co	ug/L	mg/L	ug/L	M
19-0042	Marcott	CHF	7.8	345	120	36.0	0.9	6.9	10	19	0.6	4.5	4.0
19-0046	Dickman	CHF	7.9	310	74	58.0	2.4	7.9	13	105	1.5	64.0	0.6
19-0057	Fish	CHF	7.6	415	81	101.0	5.6	7.7	19	79	0.8	37.6	0.9
19-0075	Schultz	CHF	7.8	249	85	32.0	1.5	7.6	18	26	0.7	2.7	3.7
27-0016	Harriet	CHF	8.9	494	105	96.0	8.8	5.7	9	13	0.5	2.9	3.6
27-0031	Calhoun	CHF	8.7	547	108	117.0	10.9	6.1	9	22	0.5	4.8	3.3
27-0035-01	Sweeney	CHF	8.4	883	210	183.0	56.4	5.5	18	46	0.6	20.6	1.7
27-0035-02	Twin	CHF	8.5	604	146	100.0	49.1	7.5	14	22	0.6	2.1	3.8
27-0137	Christmas	CHF	8.9	304	131	23.0	4.2	6.2	7	11	1.0	3.1	6.5
27-0179-02	Little Long	CHF	8.8	184	84	3.7	0.3	6.2	9	10	0.4	2.2	5.1
34-0044	Diamond	CHF	8.7	335	170	16.1		8.8	20	90	1.6	46.1	1.6
34-0066	Long	CHF	8.4	357	170	9.2		5.2	10	19	0.6	6.5	2.7
34-0116	Henderson	CHF	8.5	414	208	17.6		8.1	8	23	0.9	5.2	3.2
34-0142	George	CHF	8.8	460	230	11.2		6.8	5	17	0.7	4.6	2.7

43-0073	Hook	CHF	8.4	379	152	25.3	4.6	12.7	15	63	1.8	24.9	2.4
43-0104	Stahl	CHF	8.4	312	153	11.6	4.5	12.2	19	46	1.4	22.4	1.0
47-0082	Dunns	CHF	8.5	297	112	17.5		12.0	15	145	1.8	59.2	0.7
47-0088	Richardson	CHF	8.2	354	135	17.4		9.0	17	92	1.5	29.2	1.8
62-0007	Gervais	CHF	8.3	529	116	102.0	14.6	7.2	18	51	0.9	27.8	1.2
62-0054	McCarrons	CHF	8.5	420	82	74.7		7.3	10	36	1.0	23.2	1.8
62-0056	Owasso	CHF	8.1	314	102	81.0	4.7	8.1	15	36	1.0	33.2	2.1
62-0061	Turtle	CHF	8.3	279	116	22.0	8.3	7.7	8	20	0.7	6.3	2.1
62-0078	Johanna	CHF	8.2	511	81	119.0	6.0	7.1	17	46	0.9	33.8	2.3
73-0092	Sagatagan	CHF	8.4	162	90	3.7		7.9	10	31	1.2	4.1	4.0
73-0097	Kreighle	CHF	8.5	183	105	1.2		7.2	5	11	0.6	2.4	4.3
82-0014	Little Carnelian	CHF	8.8	224	106	8.3	3.3	5.7	7	9	0.5	2.3	5.1
82-0046	Square	CHF	8.7	228	122	5.6	3.0	3.8	4	6	0.3	1.5	6.9
82-0106	Elmo	CHF	8.5	303	144	17.0	8.4	6.4	8	10	0.5	2.8	2.7
82-0115	Tanners	CHF	8.9	505	119	99.0	5.2	8.6	26	36	0.9	27.7	1.5
82-0166	Carver	CHF	8.7	574	110	123.0	15.0	7.1	24	38	0.6	8.3	2.0
16-0634	Dyers	NLF	7.6	72	35	0.8	3.7	9.7	69	27	0.4	3.2	1.8
31-0560	Forsythe	NLF	6.9	32	12	0.7	0.6	13.7	90	21	0.7	6.1	2.0
31-0569	Snells	NLF	8.1	230	129	6.3	1.2	10.8	18	24	0.8	4.9	3.0
31-0570	Long	NLF	8.0	206	119	2.1	0.5	7.9	9	13	0.5	2.2	5.0
31-0571	Loon	NLF	8.5	225	130	2.8	0.5	8.0	9	12	0.6	4.3	3.7
31-0575	Little Bass	NLF	8.1	209	124	1.8	1.5	7.9	17	13	0.4	3.2	4.4
38-0033	Ninemile	NLF	7.4	44	18	0.8	3.4	6.7	17	17	0.5	2.1	2.8
38-0047	Wilson	NLF	7.5	43	17	0.3	3.1	4.8	14	13	0.2	3.0	4.0
38-0068	Windy	NLF	6.9	27	7	0.3	2.6	12.6	98	12	0.5	1.9	2.0
38-0231	Tettegouche	NLF	7.3	38	15	0.4	2.4	7.3	33	17	0.4	3.0	2.8
38-0232	Nipisiquit	NLF	7.4	52	24	0.3	2.7	5.9	23	16	0.5	3.5	2.9
38-0242	Wolf	NLF	7.8	70	30	1.9	3.5	5.0	18	14	0.4	2.1	3.7
38-0405	Bear	NLF	7.5	45	17	0.4	4.1	3.8	9	11	0.2	1.4	4.8
38-0409	Bean	NLF	7.6	53	26	0.3	2.7	4.5	8	17	0.3	6.6	1.9
38-0691	August	NLF	7.2	40	14	0.9	2.4	12.6	97	15	0.4	2.4	1.6
69-0682	Little Trout	NLF	7.4	37	15	0.3	3.1	4.4	3	7	0.3	0.7	6.4
69-0756	Tooth	NLF	6.8	30	9	0.4	3.3	10.0	39	12	0.4	2.9	3.9
69-0870	Shoepack	NLF	6.6	21	5	0.2	1.1	14.3	117	19	0.6	6.1	1.6
69-0872	Loiten	NLF	7.1	25	7	0.3	3.1	8.7	29	8	0.4	1.5	4.5
69-0936	Locator	NLF	7.0	25	6	0.4	2.7	10.8	58	9	0.4	1.8	2.8
07-0047	George	WCP	9.2	225	98	28.4		11.0	30	145	2.1	92.6	0.5
07-0053	Duck	WCP	9.0	298	140	16.2		8.3	10	54	1.1	29.9	0.9
22-0074	Bass	WCP	9.0	360	180	15.0		8.5	20	73	1.1	29.8	1.2
32-0018	Fish	WCP	8.9	368	160	20.2		6.4	10	42	1.0	20.5	1.1
74-0023	Beaver	WCP	8.9	270	120	15.0		8.7	10	31	1.0	15.9	1.4
LakeID	**Lake**	**Region**	**pH**	**Cond.**	**Alk**	**Cl**	**Sulfate**	**DOC**	**Color**	**TP**	**TN**	**Chl-a**	**Secchi**
			SU	umhos	mg/L	mg/L	mg/L	mg/L	Pt-Co	ug/L	mg/L	ug/L	M

Appendix II. Modern-day morphometric, watershed land use, and chemistry characteristics for ecoregion reference lakes.

Table 1. Minnesota Lake Water Quality Data Base Summary (2000). Distribution of Carlson TSI values and lake basin morphometry measurements by ecoregion (N = number of lakes).

Percentiles

Northern Lakes and Forests

Parameter / Percentile	N	95	90	75	50	25	10	5
Area (acres)	1,213	18	29	71	192	448	1,188	2,173
Depth, max. (feet)	1,041	10	14	22	36	57	87	112
Depth, mean (feet)	33	4	8	14	18	24	43	49
TSI-P	804	32	36	41	47	53	58	61
TSI-Chla	441	32	35	39	45	50	57	61
TSI-Secchi	971	34	36	39	44	49	55	59
TSI-Mean	1,223	34	36	40	45	51	55	59

North Central Hardwood Forests

Parameter	N	95	90	75	50	25	10	5
Area (acres)	839	18	34	73	184	444	1,013	1,924
Depth, max. (feet)	688	8	10	19	31	48	70	83
Depth, mean (feet)	197	5	6	10	15	21	28	31
TSI-P	604	42	45	52	61	73	82	86
TSI-Chla	559	42	45	50	60	69	74	77
TSI-Secchi	853	39	42	46	53	60	70	73
TSI-Mean	877	41	44	48	56	65	73	77

Western Corn Belt Plains

Parameter	N	95	90	75	50	25	10	5
Area (acres)	96	42	83	178	393	711	1,844	2,900
Depth, max. (feet)	69	3	5	7	9	14	30	48
Depth, mean (feet)	25	4	4	5	7	10	14	15
TSI-P	80	63	63	71	78	82	88	92
TSI-Chla	73	55	60	64	69	74	80	81
TSI-Secchi	99	51	54	59	70	73	77	83
TSI-Mean	101	55	60	66	71	77	81	83

Northern Glaciated Plains

Parameter	N	95	90	75	50	25	10	5
Area (acres)	34	77	128	164	410	995	3,800	11,528
Depth, max. (feet)	23	5	5	7	9	14	18	25
Depth, mean (feet)	16	4	4	5	7	8	11	11
TSI-P	24	58	64	74	79	87	91	92
TSI-Chla	19	44	58	62	66	69	70	72
TSI-Secchi	33	48	52	53	65	67	73	77
TSI-Mean	34	56	60	65	69	72	74	81

TABLE 2. Typical Land Use Composition for Ecoregion Reference Lakes (~ 90 lakes total). Interquartile range (25-75th percentile) of land use composition by ecoregion.

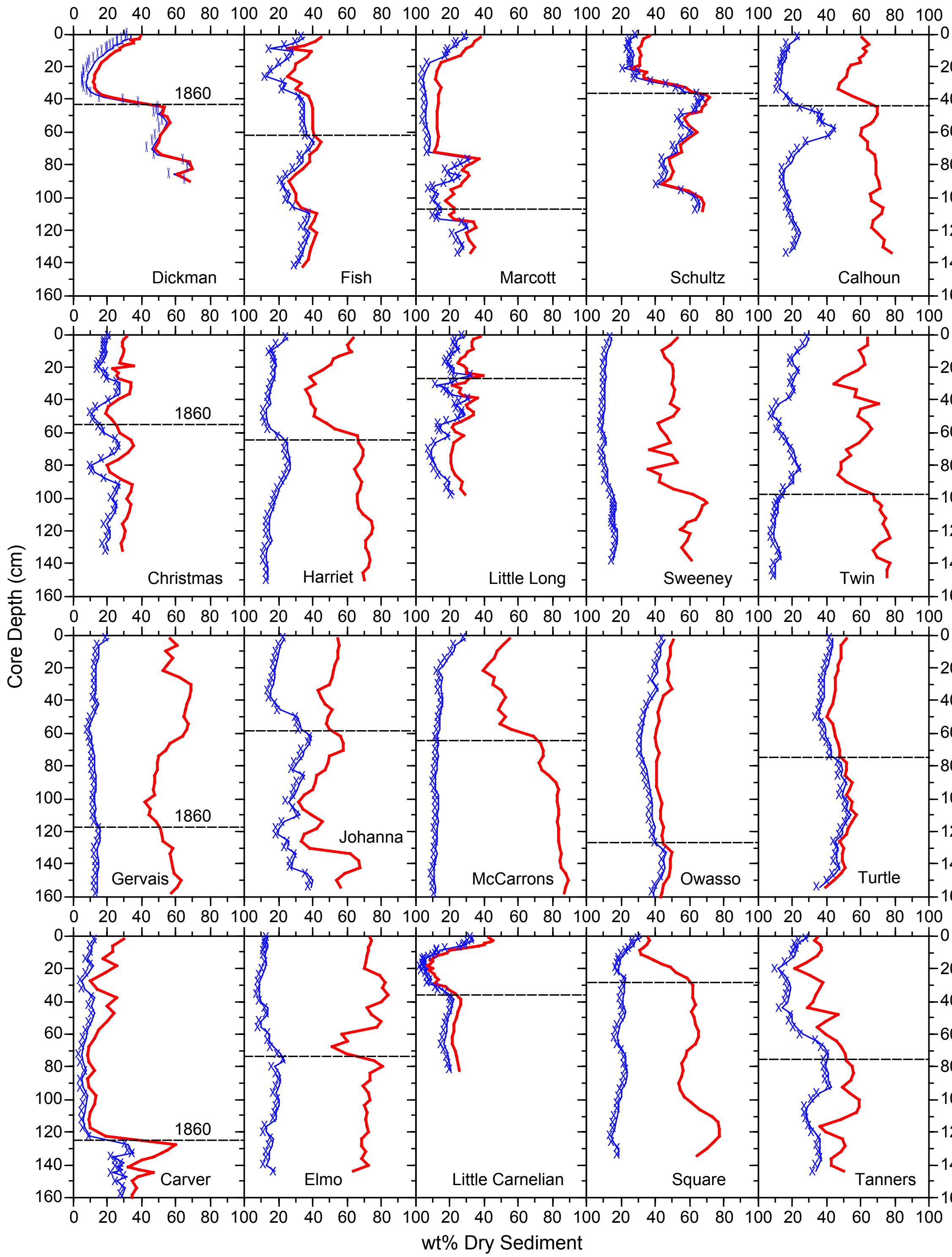
LAND USE (%)	Northern Lakes Forests	North Central Hardwood Forests	Western Corn Belt Plains	Northern Glaciated Plains
Forest	54-81%	6-25%	0-15%	0-1%
Water & Marsh	14-31%	14-30%	3-26%	8-26%
Cultivated	< 1%	22-50%	42-75%	60-82%
Pastured	0-6%	11-25%	0-7%	5-15%
Cultivated & Pastured	0-7%	36-68%	48-76%	68-90%
Developed	0-7%	2-9%	0-16%	0-2%

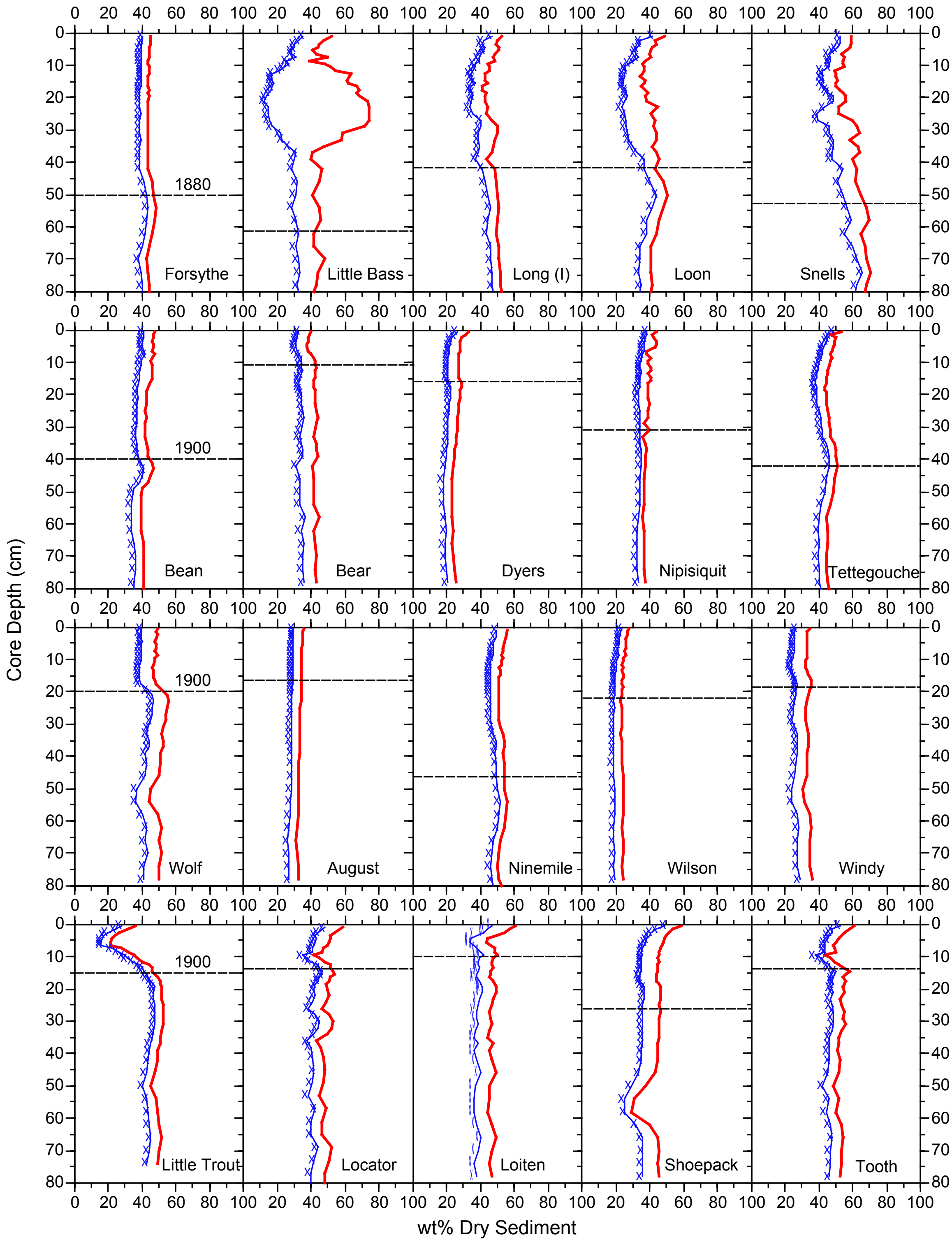
Table 3. Ecoregion Reference Lake Data Base Water Quality Summary
(Summer Average Water Quality Characteristics for Lakes by Ecoregion)*

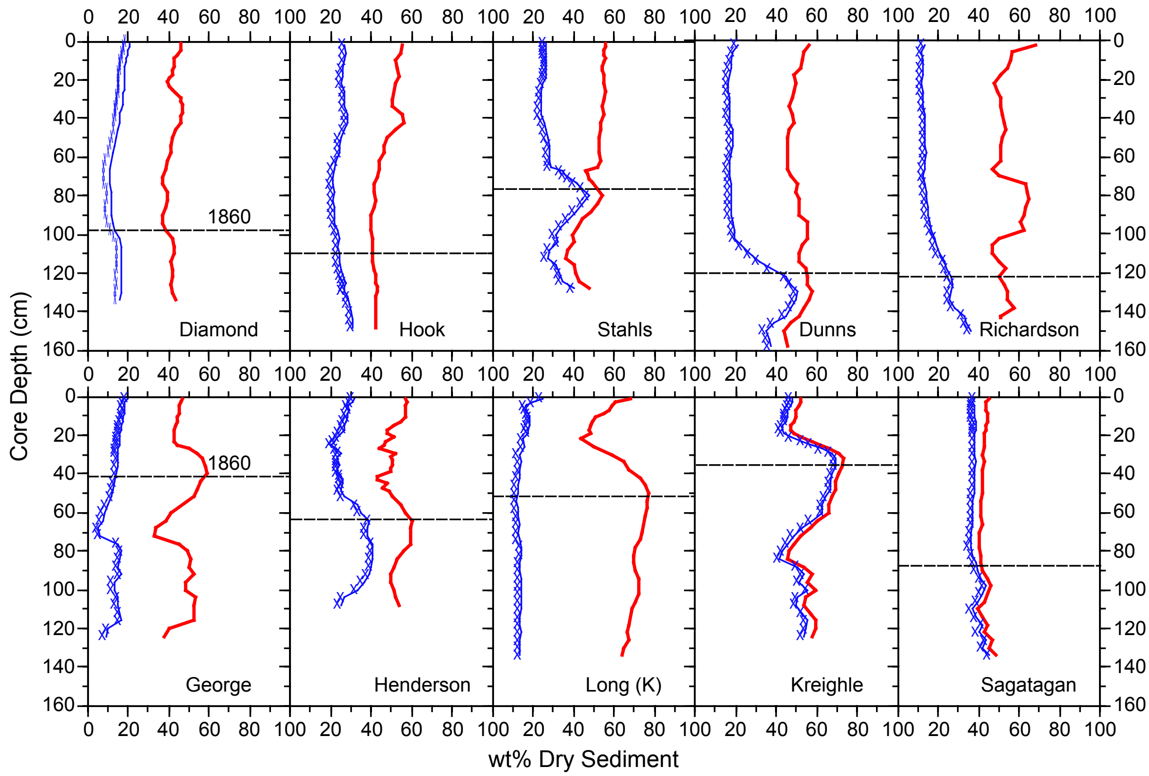
Parameter	Northern Lakes and Forests	North Central Hardwood Forests	Western Corn Belt Plains	Northern Glaciated Plains
Total Phosphorus (ug/l)	**14 - 27**	**23 - 50**	**65 - 150**	**130 - 250**
Chlorophyll mean (ug/l)	**4 - 10**	**5 - 22**	**30 - 80**	**30 - 55**
Chlorophyll maximum (ug/l)	**< 15**	**7 - 37**	**60 - 140**	**40 - 90**
Secchi Disk (feet) (meters)	**8 - 15 (2.4 - 4.6)**	**4.9 - 10.5 (1.5 - 3.2)**	**1.6 - 3.3 (0.5 - 1.0)**	**1.0 - 3.3 (0.3 - 1.0)**
Total Kjeldahl Nitrogen (mg/l)	**0.4 – 0.75**	**< 0.60 - 1.2**	**1.3 - 2.7**	**1.8 - 2.3**
Nitrite + Nitrate-N (mg/l)	**<0.01**	**<0.01**	**0.01 - 0.02**	**0.01 - 0.1**
Alkalinity (mg/l)	**40 – 140**	**75 - 150**	**125 - 165**	**160 - 260**
Color (Pt-Co Units)	**10 – 35**	**10 - 20**	**15 - 25**	**20 - 30**
pH (SU)	**7.2 - 8.3**	**8.6 - 8.8**	**8.2 - 9.0**	**8.3 - 8.6**
Chloride (mg/l)	**0.6 – 1.2**	**4 - 10**	**13 - 22**	**11 - 18**
Total Suspended Solids (mg/l)	**< 1 – 2**	**2 - 6**	**7 - 18**	**10 - 30**
Total Suspended Inorganic Solids (mg/l)	**< 1 – 2**	**1 - 2**	**3 - 9**	**5 - 15**
Turbidity (NTU)	**< 2**	**1 - 2**	**3 - 8**	**6 - 17**
Conductivity (umhos/cm)	**50 – 250**	**300 - 400**	**300 - 650**	**640 - 900**
TN:TP ratio	**25:1 - 35:1**	**25:1 - 35:1**	**17:1 - 27:1**	**7:1 - 18:1**

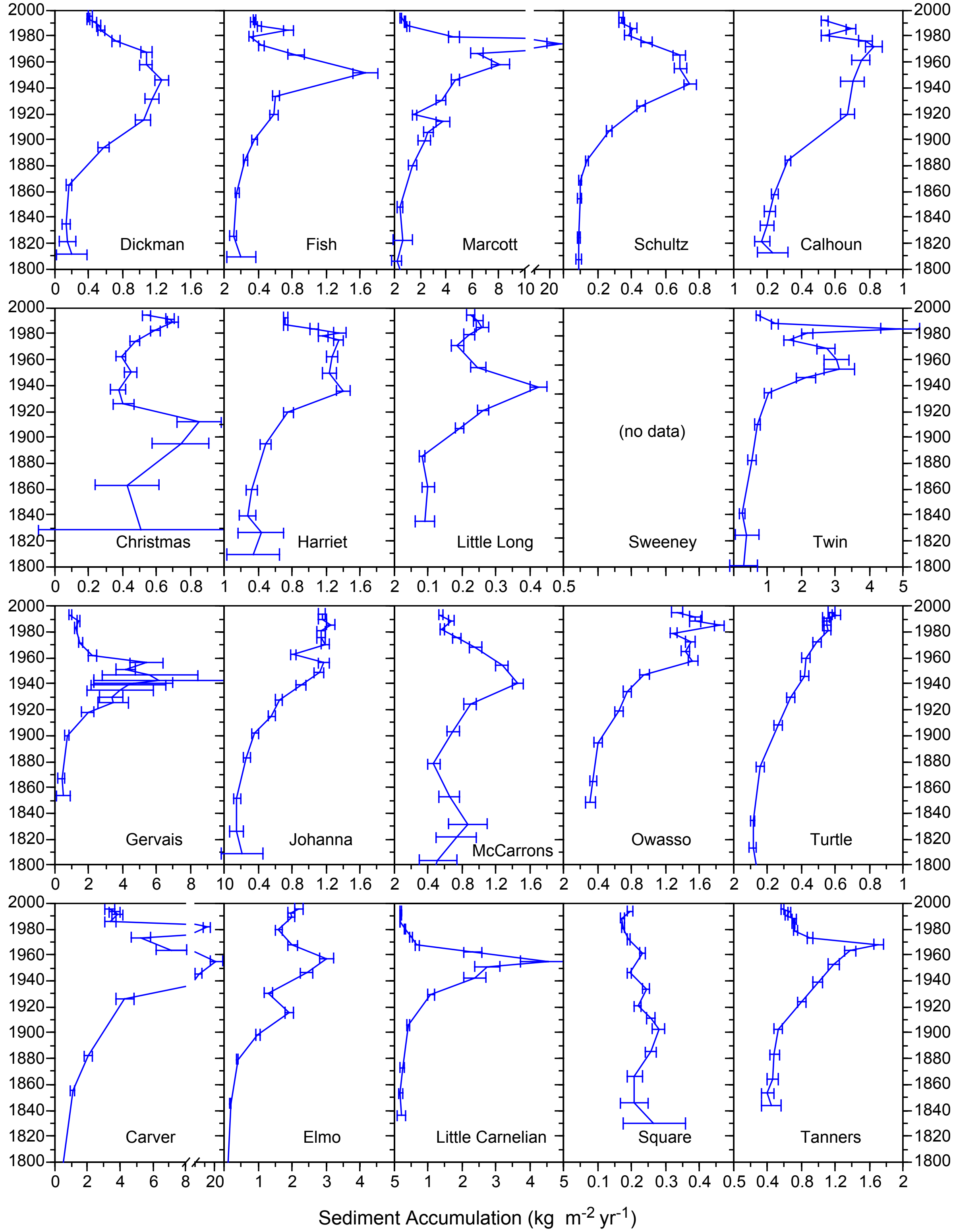
*Based on Interquartile range (25th - 75th percentile) for ecoregion reference lakes.
Derived in part from Heiskary, S. A. and C. B. Wilson (1990).

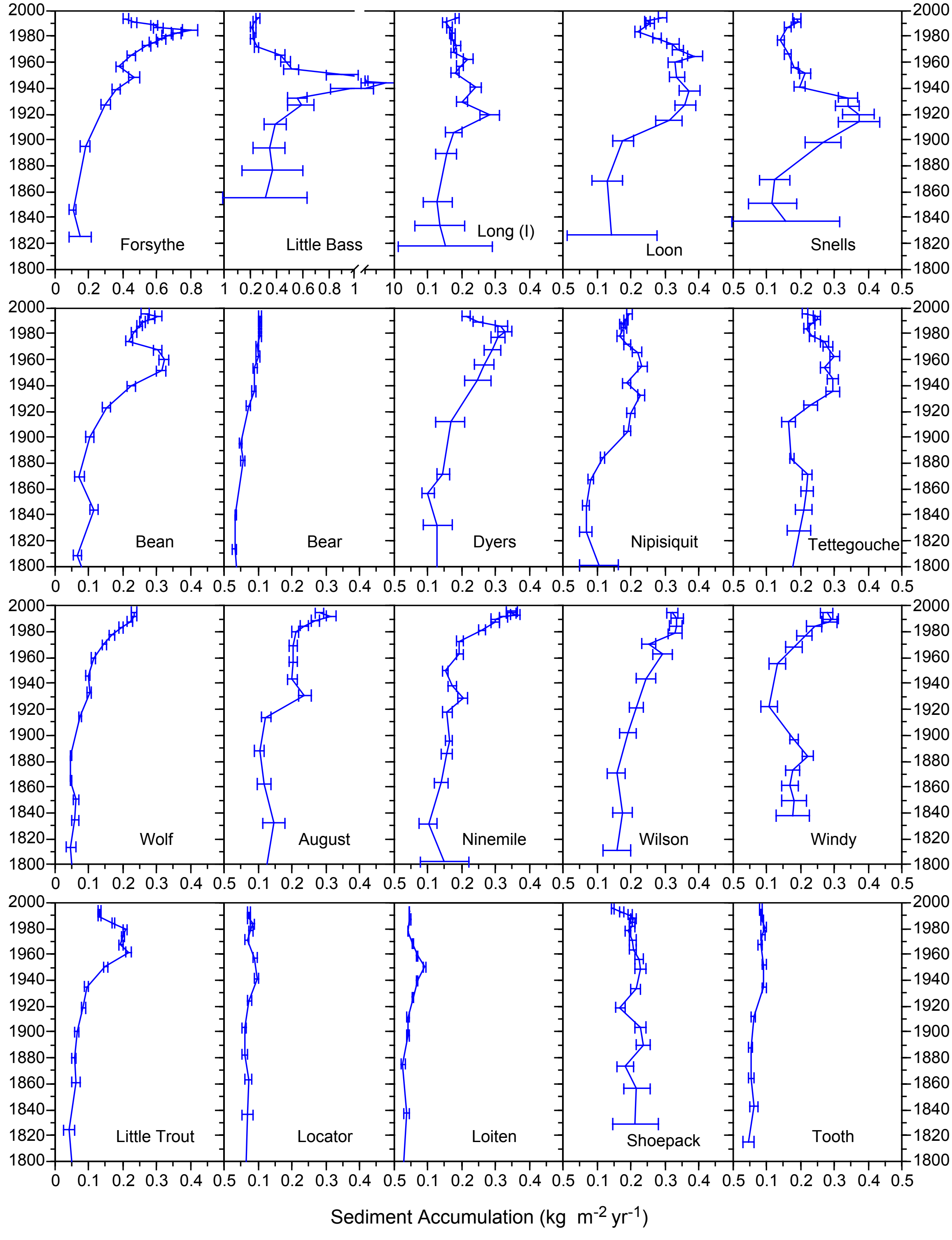
Appendix III. Sediment Loss on Ignition and Accumulation Rate. Fractions expressed as: 1) % organic ("x"), 2) % carbonate (solid line), and 3) % inorganic.

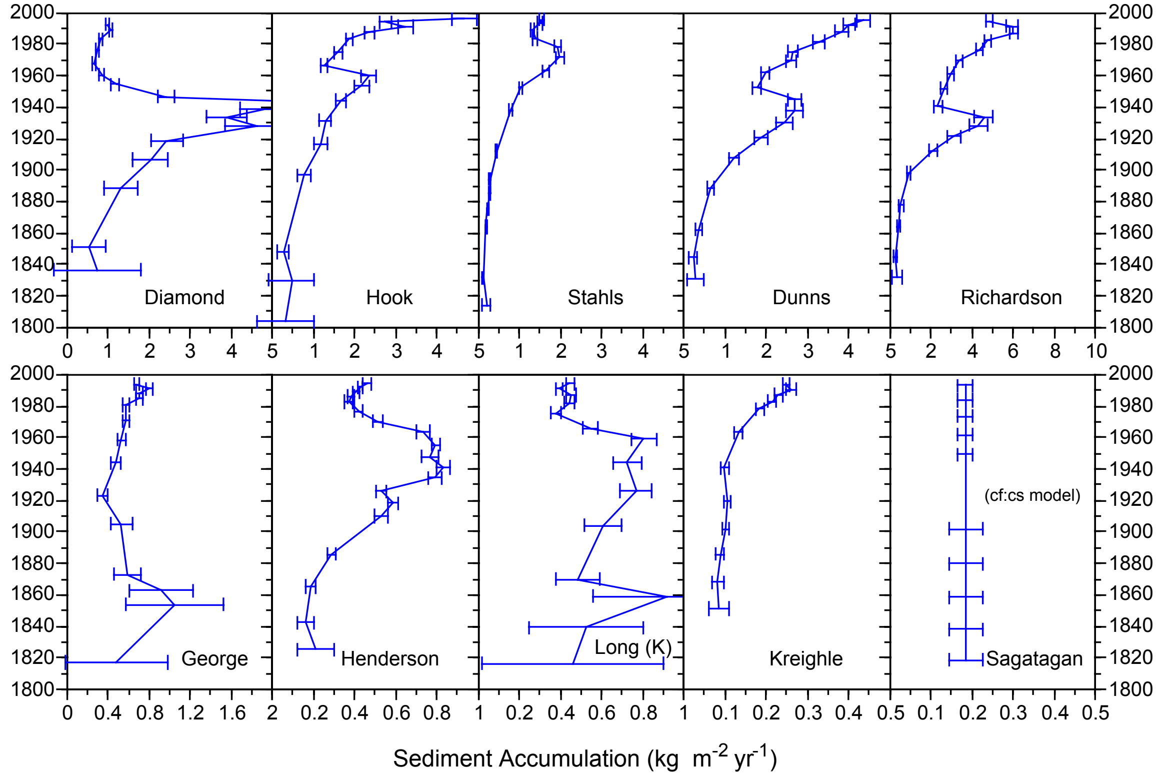



Forsythe
1880
Little Bass
Long (I)
Loon
Snells
Bean
1900
Bear
Dyers
Nipisiquit
Tettegouche
Wolf
1900
August
Ninemile
Wilson
Windy
Little Trout
1900
Locator
Loiten
Shoepack
Tooth
Core Depth (cm)
wt% Dry Sediment


Diamond
Hook
Stahls
Dunns
Richardson
George
Henderson
Long (K)
Kreighle
Sagatagan
1860
1860
Core Depth (cm)
wt% Dry Sediment


Dickman
Fish
Marcott
Schultz
Calhoun
Christmas
Harriet
Little Long
(no data)
Sweeney
Twin
Gervais
Johanna
McCarrons
Owasso
Turtle
Carver
Elmo
Little Carnelian
Square
Tanners
Sediment Accumulation (kg m-2 yr-1)


Forsythe
Little Bass
Long (I)
Loon
Snells
Bean
Bear
Dyers
Nipisiquit
Tettegouche
Wolf
August
Ninemile
Wilson
Windy
Little Trout
Locator
Loiten
Shoepack
Tooth
Sediment Accumulation (kg m-2 yr-1)


Diamond
Hook
Stahls
Dunns
Richardson
George
Henderson
Long (K)
Kreighle
Sagatagan
(cf:cs model)
Sediment Accumulation (kg m-2 yr-1)