Using Diatom-based Analysis of Sediment Records from Central Minnesota Lakes for TMDL and Nutrient Criteria Development

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PROJECT SUMMARY

Surface sediment samples from 29 shallow (46-664 ppb total phosphorus) central and westcentral Minnesota lakes and 37 lakes from Itasca County, MN, were appended onto an existing 79 Minnesota lakes diatom calibration set. The new 145 lake diatom training set has improved performance over earlier Minnesota diatom training sets. A transfer function for inferring total phosphorus was generated from the 145 lake calibration set using a two component weighted averaging partial least squares model. Six lakes identified as outliers were removed from the 145 lake data set to create a total phosphorus transfer function covering a gradient spanning lakes from 5.7 to over 500 ppb TP. The transfer function was applied to estimate historical water column total phosphorus from subfossil diatom assemblages in eight sediment cores recovered from lakes in westcentral Minnesota; the transfer function was also applied to subfossil diatom assemblages in 55 MN cores used by Ramstack *et al*. (2003) and six cores from SW Minnesota. In each core, diatom-inferred TP from a contemporary sediment sample was compared to two samples deposited before regional European settlement to identify baseline or reference nutrient conditions in each lake. Many of the shallow west central Minnesota lakes are currently meso- to hypertrophic. Pre-settlement conditions in the eight lakes were generally meso- to eutrophic and often showed within-lake variability. An ecoregional comparison of pre-European and modern diatom inferred conditions in shallow and deep lakes showed that in all ecoregions shallow lakes tended toward higher pre-settlement nutrient conditions compared to deep lakes. Each ecoregion had different background conditions in their shallow lakes with NLF shallow lake with the lowest background TP concentrations and the NGP/WCBP with the highest. NLF shallow lakes showed little change between pre-settlement and modern, in contrast to CHF and NGP/WCBP lakes which showed singnificant increases in TP concentrations.

INTRODUCTION

Nutrient loading to surface waters continues to drive water quality management and policy efforts in the United States. In a continuing effort to better understand natural variability and background nutrient conditions in Minnesota lakes, the Minnesota Pollution Control Agency has developed their efforts around a multiple line of evidence approach to setting nutrient criteria (Heiskary et al. 2004b, 2005). One of the lines of evidence applies an inference model based on a calibration set of modern diatom-environmental relationships to diatom communities preserved in sediment cores recovered from depositional basins of lakes to reconstruct historical nutrient (total phosphorus, TP) concentrations (Edlund and Kingston 2004, Heiskary et al. 2004b, 2005).

Diatom calibration and training sets have become powerful tools for paleoecological reconstruction and monitoring of surface water quality. Over the past 15 years, statistical methods have been developed to reconstruct specific environmental parameters from diatom assemblages. Whereas earlier diatom-based methods provide qualitative measures of historical water chemistry or productivity using categorical indicator values (ter Braak and van Dam 1989, Agbeti 1992), the development of weighted averaging regression and calibration introduced a method of quantitative reconstruction of historical environmental variables (Birks *et al*. 1990a,b). The method develops a transfer function based on a training set of diatom assemblages from modern lakes and their relationship to select environmental gradients that independently explain the variation in species distribution. The transfer function is next applied to historical diatom assemblages in sediment cores to mathematically reconstruct specific environmental variables. The weighted averaging method is statistically robust and based on ecologically sound organismal responses (ter Braak and Prentice 1988, Birks *et al*. 1990b). This approach has been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), DOC, and salinity (e.g. Anderson 1989, Fritz *et al*., 1991, 1999, Dixit *et al*. 1992; Hall and Smol 1992).

For inferring historical total phosphorus (TP), diatom-based reconstructions have become standard tools for determining historical loading patterns (Fritz *et al*. 1993, Anderson and Rippey 1994, Reavie *et al*. 1995, Rippey and Anderson 1996). In the Minnesota region, the most readily applied training set was initially developed by Ramstack (1999) from surface-sediment diatom assemblages from 55 Minnesota lakes of varying trophic status that were earlier cored for a regional mercury study (Engstrom *et al*. 1999). Ramstack's training set targeted "top-bottom" or modern vs pre-European reconstructions of environmental parameters in Minnesota lakes (Ramstack 1999, Heiskary and Swain 2002, Ramstack *et al*. 2003, 2004). The 55 Minnesota Lakes training set has been further applied to other Minnesota lake sediment records (Edlund and Engstrom 2001, Kingston *et al*. 2004); results have been further used for the development of nutrient criteria in Minnesota lakes (Heiskary and Swain 2002). Although a primary use of this model is regional TP reconstructions, the model was limited in its applicability because of weaknesses with reconstructing phosphorus levels above 60-80 ppb. This was due to the lack of higher TP lakes in the training set, truncation of species distributions along the TP gradient (Anderson 1997), and lack of lakes from major Minnesota ecoregions. For these reasons the original training set was amended to include 24 eutrophic to hypereutrophic lakes from the Western Corn Belt Plains (WCBP) and Northern Glaciated Plains (NGP) with elevated modern TP values (45-660 ppb TP). The resulting 79 lake model was applied to top-bottom reconstructions on six newly cored lakes and on five previously cored southern Minnesota lakes (Ramstack *et al*. 2003, Edlund and Kingston 2004, Heiskary et al. 2004b, 2005).

Shallow and polymictic lakes confound the general limnological models that characterize dimictic lakes. Shallow lakes often have nutrient dynamics strongly driven by internal loading (Søndergaard et al. 1999), may be ephemeral, and shift among alternative stable states due to perturbations from nutrients, alien fishes, and extent and loss of macrophyte cover (Moss 2003, González et al. 2005) In many regions of Minnesota shallow lakes dominate the landscape; however, they are also some of the most impaired lakes in the state and the target of TMDL and nutrient criteria development (Heiskary et al. 2004a, 2005).

The initial survey of 55 Minnesota lakes (Heiskary and Swain 2002, Ramstack et al. 2003, 2004) did not specifically target shallow lakes. Thus, two efforts have been completed to develop diatom inference models to treat shallow Minnesota lakes. As noted above, surface sediments in 24 shallow lakes in southwest Minnesota (WCBP and NGP ecoregions) were collected in 2002-2004 to amend the 55 lake set and applied to six shallow lake sediment cores. The second effort, the current subproject, sampled surface sediments from 29 shallow lakes in westcentral Minnesota. Additionally, surface diatom assemblages and environmental data from 37 lakes in Itasca County were made available to bring the Minnesota lakes diatom calibration set to a total of 145 lakes. This training set was applied to eight sediment cores from shallow lakes in westcentral Minnesota to determine pre-European nutrient conditions and also applied to all lakes for which sediment cores have been collected to date in Minnesota (69 lakes). A subset of lakes was also selected from the 145 lake training set to explore the possibility of developing a calibration set targeting only shallow lakes (57 lakes, Zmax < 6m).

METHODS-CORING, DATING, AND SUBSAMPLING

Surface sediment samples (0-2 cm) and contemporary water chemistry were collected in 2003 from 29 lakes in central Minnesota (Heiskary et al. 2004). Sediment samples were digested in 30% H_2O_2 for 2 hours at 85˚C, cooled, and oxidation byproducts removed with six rinses with distilled water. Subsamples of rinsed material were dried onto coverslips, which were attached to microslides with Naphrax mountant.

Piston cores were collected from nine lakes in west central Minnesota in May 2004. Cores were taken using a drive-rod piston corer equipped with a 2.4 m long, 7 cm diameter polycarbonate barrel (Wright 1991). Target lakes and core recovery are provided in Table 2. Cores were vertically transported to shore, and the top 15-30 cm of unconsolidated sediment removed with extrusion in 2-cm increments. The remaining core material was capped, sealed, and transported to 4°C storage.

Magnetic susceptibility provides a non-destructive measure of relative quantity and size of ferro-magnetic minerals. Increases in magnetic susceptibility signatures may be correlated with land use changes including land clearance, increased terrestrial-derived sediments, and paleosols. Cores were subdivided into 1.4-m long sections for magnetic susceptibility logging on a Bartington MS2 core logging sensor with an automated trackfeed. Susceptibility measures were taken at 1-cm intervals, which integrated a signal over a 5-10-cm length of core. Data were spliced at core breaks for plotting. Following susceptibility logging, cores were split lengthwise, physically described, and digital images taken of each core section using a Geoscan digital core scanner. Following scanning, cores were returned to storage at 4°C.

Magnetic susceptibility was plotted against downcore depth for each sediment core. Features in the magnetics profile were correlated with core descriptions. From the magnetics and physical features, samples were selected for diatom analysis and unsupported ^{210}Pb gamma analysis.

Two to three downcore samples from each core were selected for measurement of unsupported ^{210}Pb using a high-resolution germanium well gamma detector and multichannel analyzer (Table 2). The presence of any unsupported ^{210}Pb in a core subsample would be an indication that the sample is dated at less than seven half-lives of ^{210}Pb, or approximately 150 years, or from a time period of very high sedimentation that would mask an unsupported ^{210}Pb signal. This analysis provides another line of evidence (in addition to magnetics and physical changes in the core) that downcore sediment levels were deposited before European settlement.

The uppermost core sample found with no unsupported ^{210}Pb and a second sample taken from sediments deposited ca 50 years earlier were processed for diatom analysis. Mean linear and bulk sedimentation rates calculated from the NGP and WCBP lakes in the Ramstack (1999) lake set were used to calculate a pre-1850 SW Minnesota linear sedimentation rate (2.17 +/- 0.32 mm/yr), which guided our downcore sampling. The time interval represented by two presettlement samples were selected to correlate with the 1750 A.D. and 1800 A.D. sampling levels used in the Ramstack (1999) 55 MN lakes analysis (see also Heiskary and Swain 2002, Ramstack *et al*. 2003, 2004). Without more detailed dating analysis on each core, we can only be certain that the two presettlement samples are dated from greater than 150 years before present; we cannot assign a specific calendar date to those samples based on gamma analysis and magnetic susceptibility logging.

METHODS-ENVIRONMENTAL DATA

Contemporary water chemistry and physical measures were collected on three to five sampling dates between May and October 2003 from 31 lakes in central and westcentral Minnesota and reported as mean epilimnetic (integrated 0-2 m sample) values (Table 3; see also Heiskary *et al*. 2003). Samples were collected and analyzed using standard techniques (Heiskary *et al*. 2003). Physical measures of lake and watershed morphometry were taken directly or from the Minnesota Department of Natural Resources (1968). During the last seasonal sampling a short sediment core was recovered and the 0-2 cm section removed to represent a record of the diatom assemblage accumulated in conjunction with sampling. Two lakes did not have sediment samples recovered (Clark, Shaokaton) and were removed from the data set leaving 29 central and westcentral Minnesota lakes (WCMN).

The raw environmental data taken from the 29 central and westcentral Minnesota lakes (WCMN) were combined with the 24 southwest Minnesota lakes data set (Edlund and Kingston 2004), the original 55 Minnesota lake diatom training set (Ramstack et al. 2003), and with a 37 lake data set from Itasca County, MN, assembled by Drs John Kingston and Euan Reavie (NRRI, Ely Field Station). Environmental data soures are provided in Table 4. Differences in analytical methods and data reporting between all of the data sets were reconciled to create the full 145 MN lake data set. The final 145 Minnesota lake data set includes the following environmental and physical variables: chl a, pH, total phosphorus, total nitrogen, alkalinity/ANC, chloride, conductivity, color, Secchi depth, ecoregion, maximum lake depth, mean lake depth, lake area, and watershed area (Table 5).

METHODS-DIATOM ANALYSIS

Diatom remains were counted in surface sediment samples from all 29 westcentral Minnesota lakes. A total of 400 diatom valves were counted along up to six random transects on Naphrax-mounted microslides using either an Olympus BX5O or Leitz Ortholux light microscope fitted with full immersion optics capable of 875-1250X magnification and N.A.>1.30. Our analysis used the same enumeration criteria as Ramstack (2003), i.e. diatoms were counted when over 50% of the valve was present or when a distinct valve fragment was present (e.g., central area of *Amphora libyca* or valve end in *Asterionella formosa*).

Diatom remains were also counted from three samples from each of six sediment cores. The uppermost sample from 0-2 cm represents contemporary lake conditions. Two downcore samples from each core represent "pre-European" settlement conditions in the lakes. The two downcore samples taken from Diamond Lake (27-0125, Hennepin Co.) did not contain diatom microfossils suitable for counting. Diatoms were severely corroded, typically a response to saline or alkaline conditions, intense benthic grazing, or frequent mixing events.

Diatoms were identified using floras and monographs by Hustedt 1927-1966, 1930, Patrick and Reimer 1966, 1975, Collins and Kalinsky 1977, Camburn *et al*. 1978, 1984-1986, Krammer and Lange-Bertalot 1986, 1988, 1991a, b, Cumming *et al*. 1995, Reavie and Smol 1998, Camburn and Charles 2000, and Fallu et. al. 2000. A workshop was held in February 2005 between the labs at SCWRS and NRRI to coordinate, harmonize, and document the taxonomy used in developing the 55 MN lakes, 24 SW MN lakes, Itasca Co., and the WC MN lakes diatom training sets.

METHODS-NUMERICAL ANALYSIS

Relationships among environmental variables and species distributions for all 145 lakes in the training set were explored using canonical correspondence analysis (CCA), a multivariate ordination technique for direct gradient analysis (ter Braak & Prentice, 1988) available in the CANOCO 4 software package (ter Braak and Smilauer 1998). Species present at greater than 1% relative abundance in two or more samples or at greater than 5% relative abundance in one sample were included in ordination analyses; the same selection criteria were used by Ramstack *et al*. (2003). A total of 13 environmental variables (ecoregion omitted) and 170 species was included in the ordination analyses. Environmental data that were not normally distributed were square-root or log(x+1) transformed. The distribution of environmental variables and species among samples was initially explored with principal components analysis (PCA) and detrended correspondence analysis (DCA), respectively, to screen for outliers and determine gradient length. A CCA with forward selection was used to identify a subset of environmental variables that independently explained a significant portion of variance in the species data ($p<0.05$). For each environmental variable identified in forward selection a constrained CCA was run to test significance and percent variance explained. For all CCA ordinations, rare taxa were downweighted and Monte Carlo permutation run to test for significance. Environmental variables that independently explained significant variation in the species distributions can then be used as predictor variables to develop transfer functions using weighted averaging regression and calibration (Birks *et al*., 1990).

A transfer function for reconstructing log(x+1)TP was developed by exploring both weighted averaging (WA) regression and weighted averaging partial least square (WAPLS) with inverse deshrinking and bootstrap error estimation using C2 software (Juggins 2003). The strength of the transfer functions were evaluated by calculating the squared correlation coefficient (r^2) and the root mean square error (RMSE) between the observed log(x+1)TP with the model estimates of log(x+1)TP for all samples. Bootstrapping is used in model validation to provide a more realistic error estimate (RMSEP, the root mean square error of prediction) because the same data are used to both generate and test the WA or WAPLS model (Fritz *et al*. 1999). Outliers were identified from plots of model and bootstrap residuals; samples with residuals greater than the standard deviation of logTP ($SD_{log(x+1)TP}$=0.461) in the training set were considered for removal for development of the final transfer function.

The final model chosen was a two component WAPLS model based on 139 lakes following removal of six outlier lakes (Diamond_H, George_B, Loon_J, McKinney, Tanners, TurtleIT). Model performance results included: r^2=0.854, RMSE=0.171, $RMSEP_{boot}$=0.241). These represented performance improvements over both the 55 MN lakes and 79 MN lakes model. The 145 lake model represented a training set with TP values from 5-370 ppb, and with deshrinking could perform reconstructions from 5.7-571 ppb.

Downcore reconstructions of environmental variables are strongest if the fossil assemblage is analogous to a modern sample in the training set. The software ANALOG 1.6 (Birks, unpublished) was used to calculate a minimum dissimilarity coefficient (DC) between each fossil sample and its nearest modern analogue using the squared chi-squared distance metric. A minimum DC of less than 0.7920 (the fifth percentile of distance distributions among the modern samples) identified a fossil sample with a good modern analogue.

RESULTS & DISCUSSION

The 29 lakes (Table 1) added to the existing 79 Minnesota lakes focused on shallow lakes and their diatom flora and were located if the CHF, NLF, NGP, and WCBP ecoregions of Minnesota. These lakes typify the shallow (Zmean = 1.8m), eutrophic to hypereutrophic condition common in these two ecoregions. Modern conditions in each lake, an environmental synthesis, and a regional context have been presented in Heiskary *et al*. (2005). In general, the lakes are characterized by elevated nutrient concentrations. Some of the lakes have also experienced historical loss of macrophytes (Heiskary *et al*. 2005) with primary production now dominated by water column productivity.

Piston cores were recovered from nine central Minnesota lakes (Table 2). All lakes contained modern and pre-European sedimentation (Table 3) and were prepared for diatom analyis. Diamond Lake (Hennepin Co.) did not have adequate preservation of diatoms to permit analysis of the pre-European samples and was removed from futher analyses.

Total phosphorus was identified as an environmental variable explaining significant independent variation in the modern diatom distributions in Minnesota. Thus a robust diatom-TP inference model was constructed based on a WAPLS two component model of diatom-TP relationships among 139 of the 145 lakes data set. Performance diagnostics for the model are given in the Methods.

The logTP transfer function was applied to downcore diatom assemblages in eight sediment cores recovered in 2004 and further applied to 55 sediment cores analyzed earlier by Ramstack *et al*. (2003) and six cores analyzed by Edlund and Kingston (2004) to calculate diatom-inferred total phosphorus (DI-TP). From each core, two samples representing sediments deposited before regional European settlement provide a measure of baseline or natural nutrient conditions in these lakes. Presettlement conditions can be compared to a DI-TP estimated from a third core sample (0-2 cm) representing modern conditions and to monitoring records collected by MPCA (Table 5).

Many of the shallow west central Minnesota lakes are currently meso- to hypertrophic (Table 5, Fig. 1). Pre-settlement conditions in the eight lakes were generally meso- to eutrophic and often showed within-lake variability (Fig. 1, Table 6). The two NLF lakes (Platte and Red Sand) tended toward lower pre-E DI-TP although Red Sand deserves some discussion. From the two regions of the core that were analyzed, it is evident that this lake has undergone remarkable change. The modern Red Sand diatom community is dominated by small benthic fragilarioid taxa with generally mesotrophic TP optima and reconstructs near its monitored TP average of 30 ppb. In contrast, the presettlement community is dominated by a planktonic flora that is poorly represented in our modern training set (see analogue in Table 6). Using the 145 lake model, Lakes Monson and McCormic show decreases in modern DI-TP. The modern TP levels in Monson are 90 ppb, but the modern DI-TP is near 30 ppb. The modern diatom community in Monson is dominated by Fragilaria crotonensis, which is driving this uncharacteristically low reconstructed TP value.

The 145 lake model was also applied to all 69 cores taken to date in Minnesota (Ramstack et al. 2003, Kingston and Edlund 2004, this study) to explore differences among ecoregions between shallow and deep lakes (Fig. 2, Table 7, 8). This ecoregional comparison of pre-European and modern diatom inferred conditions in shallow and deep lakes showed that in all ecoregions shallow lakes tended toward higher pre-settlement nutrient conditions compared to deep lakes. Each ecoregion had different background conditions in their shallow lakes with NLF shallow lakes showing the lowest background TP concentrations and the NGP/WCBP with the highest. NLF shallow lakes showed little change between pre-settlement and modern in both shallow and deep lakes, in contrast to CHF and NGP/WCBP lakes which showed significant increases in TP concentrations between pre-European and modern DI-TP.

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TABLES

Table 1. Names, Minnesota DNR designator, locations, and ecoregions of 29 west-central Minnesota lakes.

Lake	Lake ID	County	Ecoregion
Tiger	10-0108	Carver	CHF
Jennie	21-0323	Douglas	NGP
Diamond	27-0125	Hennepin	CHF
French	27-0127	Hennepin	CHF
Praire	27-0177	Hennepin	CHF
Quamba	33-0015	Kanabec	CHF
Ringo	34-0172	Kandiyohi	CHF
Florida Slough	34-0204	Kandiyohi	CHF
East Solomon	34-0246	Kandiyohi	WCP
West twin	41-0102	Lincoln	NGP
East Twin	41-0108	Lincoln	NGP
Johanna	61-0006	Pope	CHF
Nelson	61-0101	Pope	CHF
Fremont	71-0016	Sherburne	CHF
Silver	72-0013	Sibley	CHF
Titlow	72-0042	Sibley	WCP
Cedar	73-0226	Stearns	CHF
Cedar	73-0255	Stearns	CHF
McCormic	73-0273	Stearns	CHF
Hattie	75-0200	Stevens	NGP
Monson	76-0033	Swift	CHF
Hollerberg	76-0057	Swift	NGP
Hassel	76-0086	Swift	NGP
Trace	77-0009	Todd	CHF
Pelican	86-0031	Wright	CHF
Cedar	86-0073	Wright	CHF
Smith	86-0250	Wright	CHF
Platte	18-0088	Crow Wing	NLF
Red Sand	18-0386	Crow Wing	NLF

Table 2. Lakes cored in May 2004 and length of core recovered.

Lake Name	Lake ID	County	Core length (cm)	Field sectioned (cm)
Platte	18-0088	Crow Wing	190	0-40
Red Sand	18-0386	Crow Wing	206	0-70
Diamond	27-0125	Hennepin	157	0-36
Quamba	33-0015	Kanabec	196	0-24
Johanna	61-0006	Pope	123	0-26
Fremont	71-0016	Sherburne	151	0-74
Silver	72-0013	Sibley	111	0-20
McCormic	73-0273	Stearns	158	0-30
Monson	76-0033	Swift	178	0-28

Table 3. Unsupported 210-Pb quantified from select core depths from central MN lakes. ND= no detection. *Red Sand 99.5 cm shows some unsupported levels of 210-Pb; however, this value also had an uncertainty of >1.75 pCi/g and thus this depth is considered to be from at or near background unsupported 210-Pb values.

Lake Name	Lake ID	County	Sample depths (cm)	Unsupported 210-Pb (pCi/g)
Platte	18-0088	Crow Wing	154.5	ND
Red Sand	18-0386	Crow Wing	49.5	6.4
Red Sand	18-0386	Crow Wing	99.5	1.9*
Diamond	27-0125	Hennepin	66.5	ND
Quamba	33-0015	Kanabec	141.5	ND
Johanna	61-0006	Pope	64.5	ND
Fremont	71-0016	Sherburne	128.5	ND
Silver	72-0013	Sibley	65.5	ND
McCormic	73-0273	Stearns	89.5	ND
Monson	76-0033	Swift	66.5	0.802
Monson	76-0033	Swift	110.5	ND

Table 4. Units and sources of environmental and physical data used in developing the 145 Minnesota lakes diatom training set.

Variable	units	55 MN lakes	24 SWMN lakes	Itasca Co	Cent MN lakes
chl a	μg/L	Ramstack *et al.* 2003*	2002 MPCA data from SAH**	E. Reavie, NRRI	Heiskary & Lindon 2005
pH	—	Ramstack *et al.* 2003	2002 MPCA data from SAH	E. Reavie, NRRI	Heiskary & Lindon 2005
total phosphorus	μg/L	Ramstack *et al.* 2003	2002 MPCA data from SAH	E. Reavie, NRRI	Heiskary & Lindon 2005
total nitrogen	μg/L	Ramstack *et al.* 2003	2002 MPCA data from SAH	E. Reavie, NRRI	Heiskary & Lindon 2005
alkalinity/ANC	meq/L	Ramstack *et al.* 2003	2002 MPCA data from SAH	E. Reavie, NRRI	Heiskary & Lindon 2005
chloride	mg/L	Ramstack *et al.* 2003	2002 MPCA data from SAH	E. Reavie, NRRI	Heiskary & Lindon 2005
conductivity	μS/cm	Ramstack *et al.* 2003	2002 MPCA data from SAH	E. Reavie, NRRI	Heiskary & Lindon 2005
color	Pt-Co	Ramstack *et al.* 2003	2002 MPCA data from SAH	E. Reavie, NRRI	Heiskary & Lindon 2005
secchi depth	m	Ramstack *et al.* 2003	MPCA data from SAH	E. Reavie, NRRI	Heiskary & Lindon 2005
ecoregion	***	Heiskary *et al.* 2002	Heiskary *et al.* 2003	E. Reavie, NRRI	Heiskary & Lindon 2005
Zmax	m	Heiskary *et al.* 2002	Heiskary *et al.* 2003	E. Reavie, NRRI	Heiskary & Lindon 2005
Zmean	m	unpub LCMR data	Heiskary *et al.* 2003	E. Reavie, NRRI	Heiskary & Lindon 2005
lake area	ha	Heiskary *et al.* 2002	Heiskary *et al.* 2003	E. Reavie, NRRI	Heiskary & Lindon 2005
watershed area	ha	Heiskary *et al.* 2002	Heiskary *et al.* 2003	E. Reavie, NRRI	Heiskary & Lindon 2005

*Ramstack *et al.* (2003) data were taken directly from the publication; however, Dan Engstrom (SCWRS) provided the original spread sheets used in calculating these values.
**SAH=Steve A. Heiskary, Minnesota Pollution Control Agency
***Omerick 1987

Table 5. The final 145 Minnesota lakes data set includes the following environmental and physical variables: pH, ANC, conductivity, color, chloride, total phosphorus, total nitrogen, chlorophyll-a, ecoregion, Secchi depth, lake area, maximum lake depth, watershed area, mean lake depth.

Project	Code	MN DNR ID	pH	ANC	Cond	Color	Cl	TP	TN	Chla	Eco-region	SD	lake area	Z max	Wshed area	Z mean
			SU	μeq/L	μS/cm	Pt-Co	mg/L	ug/l	ug/L	ug/L	USEPA	m	ha	m	ha	m
55Lakes	August	38-0691	7.25	290.0	40	96.7	0.9	15	440	2.42	NLF	1.6	76.5	5.8	937	2.5
55Lakes	Bass	22-0074	8.96	3338.0	343	20.2	15.0	81	1354	24.96	WCP	1.1	75.7	6.1	136	3.1
55Lakes	Bean	38-0409	7.64	526.0	53	8.5	0.3	17	283	6.59	NLF	1.9	12.5	7.9	64	4.6
55Lakes	Bear	38-0405	7.45	342.0	45	9.1	0.4	11	161	1.36	NLF	4.8	18.3	8.8	60	4.5
55Lakes	Beaver	74-0023	8.86	2501.0	268	9.4	15.0	30	1123	12.23	WCP	1.4	37.8	8.2	71	4.4
55Lakes	Calhoun	27-0031	8.70	2150.0	547	9.0	117.0	28	791	5.78	Metro	3.9	168.5	27.4	2515	10.7
55Lakes	Carver	82-0166	8.70	2190.0	574	23.5	123.0	36	883	8.27	Metro	1.6	19.6	11.0	864	4.6
55Lakes	Christmas	27-0137	8.90	2620.0	304	6.5	23.0	15	660	3.10	Metro	5.6	105.7	26.5	189	11.0
55Lakes	Diamond	34-0044	8.55	3365.0	332	15.6	16.1	80	1400	33.82	NCHF	2.1	644.8	8.2	3590	4.8
55Lakes	Dickman	19-0046	7.89	1480.0	310	13.3	58.0	105	1533	63.97	Metro	0.6	9.1	2.4	57	2.4
55Lakes	Duck	07-0053	8.91	2892.0	298	11.7	16.2	65	1190	44.52	WCP	0.9	116.6	7.6	385	3.0
55Lakes	Dunns	47-0082	8.64	2232.0	291	15.3	17.5	139	1775	52.54	NCHF	0.8	63.0	6.1	1381	3.6
55Lakes	Dyers	16-0634	7.57	690.0	72	68.6	0.8	27	406	3.25	NLF	1.8	27.8	6.1	854	2.8
55Lakes	Elmo	82-0106	8.50	2870.0	303	8.0	17.0	10	485	2.82	Metro	2.7	114.6	42.7	2076	13.4
55Lakes	Fish_D	19-0057	7.59	1613.0	415	19.0	101.0	7 9	797	37.60	Metro	0.9	12.5	10.1	1506	1.8
55Lakes	Fish_J	32-0018	8.82	3245.0	370	9.3	20.2	38	996	15.32	WCP	1.2	120.7	8.2	649	4.5
55Lakes	Forsythe	31-0560	6.89	233.0	32	84.6	0.7	21	702	5.41	NLF	2.0	27.1	3.1	191	1.8
55Lakes	George_B	07-0047	9.18	1982.0	220	25.1	11.2	130	2067	80.79	WCP	0.5	36.2	8.5	54	2.9
55Lakes	George_K	34-0142	8.82	4548.0	450	4.8	28.4	15	627	3.16	NCHF	3.4	91.6	9.1	102	4.9
55Lakes	Gervais	62-0007	8.32	2320.0	529	17.5	102.0	3 3	1100	16.30	Metro	2.0	94.4	12.5	4028	5.8
55Lakes	Harriet	27-0016	8.90	2090.0	494	8.5	96.0	27	736	7.26	Metro	3.5	138.6	25.0	387	8.8
55Lakes	Hendersn	34-0116	8.61	4176.0	410	7.1	17.6	22	896	4.58	NCHF	3.6	29.1	12.2	59	6.6
55Lakes	Hook	43-0073	8.44	2952.0	359	15.0	25.3	68	1788	23.26	NCHF	1.8	133.1	5.5	620	2.1
55Lakes	Johanna	62-0078	8.25	1620.0	511	16.5	119.0	3 6	1000	13.89	Metro	2.5	86.4	12.5	1026	5.2
55Lakes	Kreighle	73-0097	8.50	2008.0	178	3.3	1.2	11	600	2.00	NCHF	4.2	41.0	17.1	88	5.2
55Lakes	L_Bass	31-0575	8.16	2421.0	209	16.6	1.8	13	406	2.93	NLF	4.4	64.5	18.9	540	7.6
55Lakes	L_Carnel	82-0014	8.80	2120.0	224	7.0	8.3	9	460	2.31	Metro	4.8	46.7	19.2	1854	3.9
55Lakes	L_Long	27-0179-02	8.80	1680.0	184	9.0	3.7	9	440	2.18	Metro	5.1	21.8	23.2	32	18.7
55Lakes	L_Trout	69-0682	7.37	306.0	3 7	2.9	0.3	7	265	0.73	NLF	6.4	107.6	29.0	140	13.1
55Lakes	Locator	69-0936	6.99	123.0	2 5	58.0	0.4	9	382	1.81	NLF	2.8	54.1	15.9	1489	8.2
55Lakes	Loiten	69-0872	7.05	150.0	2 5	28.9	0.3	8	353	1.45	NLF	4.3	39.0	14.9	242	9.1
55Lakes	Long_I	31-0570	8.08	2294.0	202	10.1	2.1	13	539	2.16	NLF	5.0	54.5	22.9	165	5.4
55Lakes	Long_K	34-0066	8.46	3407.0	348	8.8	9.2	19	563	5.33	NCHF	3.7	129.8	13.4	363	5.4
55Lakes	Loon_I	31-0571	8.55	2468.0	219	9.3	2.8	11	563	3.79	NLF	3.7	92.9	21.0	364	6.3

55Lakes	Marcott	19-0042	7.76	2393.0	345	10.3	36.0	19	610	4.53	Metro	4.0	7.5	10.1	251	2.0
55Lakes	McCarrns	62-0054	8.60	1591.0	395	19.0	74.7	48	1117	13.05	Metro	2.1	30.1	17.4	412	7.6
55Lakes	Ninemile	38-0033	7.39	356.0	44	16.9	0.8	17	518	2.09	NLF	2.8	120.3	9.1	209	2.4
55Lakes	Nipisiqt	38-0232	7.40	486.0	52	23.2	0.3	16	495	3.45	NLF	2.9	23.7	5.5	298	4.3
55Lakes	Owasso	62-0056	8.15	2030.0	314	15.0	81.0	40	1108	12.24	Metro	2.7	150.9	12.2	423	3.4
55Lakes	Richrdsn	47-0088	8.29	2715.0	349	17.9	17.4	98	1500	26.80	NCHF	1.9	48.3	14.3	1168	5.9
55Lakes	Sagatgn	73-0092	8.45	1741.0	157	6.9	3.7	27	1048	3.28	NCHF	4.0	88.7	14.3	252	3.0
55Lakes	Schultz	19-0075	7.80	1690.0	249	17.5	32.0	26	655	2.74	Metro	3.4	5.3	4.9	69	2.4
55Lakes	Shoepack	69-0870	6.59	100.0	21	116.8	0.2	19	593	6.14	NLF	1.5	155.4	7.3	1768	4.3
55Lakes	Snells	31-0569	8.18	2507.0	230	17.9	6.3	24	765	4.49	NLF	3.0	35.8	15.2	288	6.0
55Lakes	Square	82-0046	8.70	2430.0	228	4.0	5.6	12	351	1.49	Metro	6.8	81.9	20.7	226	9.1
55Lakes	Stahl	43-0104	8.39	3107.0	309	19.9	11.6	46	1332	18.65	NCHF	1.0	54.6	10.7	630	4.8
55Lakes	Sweeney	27-0035-01	8.38	4200.0	883	18.0	183.0	4 6	647	20.61	Metro	1.7	28.3	7.6	1011	3.7
55Lakes	Tanners	82-0115	8.90	2370.0	505	26.0	99.0	56	1131	10.80	Metro	2.9	30.2	13.7	669	7.0
55Lakes	Tettgche	38-0231	7.32	303.0	38	32.9	0.4	17	435	2.96	NLF	2.5	26.7	4.6	103	1.3
55Lakes	Tooth	69-0756	6.84	189.0	30	38.5	0.4	12	445	2.87	NLF	3.9	23.6	13.1	151	6.0
55Lakes	Turtle	62-0061	8.26	2320.0	279	7.5	22.0	27	876	6.54	Metro	2.3	133.3	8.8	180	3.7
55Lakes	Twin	27-0035-02	8.55	2927.0	604	13.7	100.0	22	613	2.13	Metro	3.8	8.7	17.1	33	9.4
55Lakes	Wilson	38-0047	7.45	342.0	43	13.7	0.3	13	249	3.05	NLF	4.0	257.1	14.9	719	5.9
55Lakes	Windy	38-0068	6.94	148.0	27	98.2	0.3	12	461	1.85	NLF	2.0	184.6	11.9	1705	7.0
55Lakes	Wolf	38-0242	7.76	610.0	70	17.7	1.9	14	385	2.14	NLF	4.1	13.1	7.3	68	3.7
SWMN	Bingham	17-0007	8.46	3600.0	457	14.0	23.0	217	2144	11.07	WCP	2.0	106.0	3.0	440	2.1
SWMN	Ctnd_CT	17-0022	8.44	3000.0	466	14.0	20.6	84	1434	33.52	WCP	0.5	61.5	2.7	1140	1.5
SWMN	Talcott	17-0060	8.78	3320.0	751	24.0	25.4	364	2856	163.5	WCP	0.3	375.6	1.8	134198	1.2
SWMN	Loon_J	32-0020	8.42	4400.0	518	18.0	25.0	664	2080	19.93	WCP	0.5	293.4	2.1	7772	1.2
SWMN	Clear	32-0022	8.40	4200.0	536	16.0	36.8	110	2220	28.38	WCP	0.7	182.5	3.0	466	1.8
SWMN	DeadCoon	41-0021	8.75	3480.0	717	22.0	13.8	176	2394	52.00	NGP	0.9	233.1	2.1	4922	1.5
SWMN	Benton	41-0043	8.61	3333.0	525	21.1	13.1	137	1804	33.06	NGP	0.6	1046.9	2.7	10026	2.1
SWMN	Shaoktn	41-0089	8.66	3225.0	613	20.0	8.0	124	2378	55.10	NGP	1.1	402.7	3.7	3601	2.4
SWMN	ETwin	42-0070	8.88	5933.0	722	16.7	16.0	104	2283	37.57	NGP	1.0	113.3	6.7	466	3.0
SWMN	WTwin	42-0074	9.08	2900.0	615	13.8	23.3	46	1330	9.35	NGP	2.1	95.9	3.0	466	1.8
SWMN	SchlGrv	42-0002	8.70	5240.0	1099	20.0	21.4	127	2352	62.42	NGP	0.5	140.8	3.4	803	2.4
SWMN	Ctnd_LY	42-0014	8.78	3280.0	1481	22.0	23.6	141	2732	96.18	NGP	0.7	130.7	2.4	5570	1.8
SWMN	Yankton	42-0047	8.46	3240.0	785	18.0	24.6	137	2080	50.66	NGP	0.5	154.6	2.1	389	1.8
SWMN	Rock	42-0052	8.43	3480.0	740	14.0	16.0	140	1878	27.97	NGP	0.6	170.8	2.1	1114	1.5
SWMN	Goose	42-0093	8.44	3760.0	805	18.0	12.0	150	2298	23.27	NGP	0.6	56.3	2.4	389	2.1
SWMN	BTwin	46-0133	8.59	4267.0	514	20.0	32.0	141	2907	52.63	WCP	0.4	180.1	3.0	466	2.4
SWMN	Lime	51-0024	8.82	2580.0	653	23.3	24.7	227	3707	223.4	WCP	0.3	136.8	2.1	15933	1.5
SWMN	Bloody	51-0040	8.53	3160.0	652	13.0	14.8	89	1678	42.32	WCP	0.5	108.1	3.4	259	1.5
SWMN	Sarah	51-0063	8.42	2840.0	638	9.0	14.4	102	1640	36.03	NGP	0.5	482.8	1.5	4378	1.2

SWMN	Currant	51-0082	8.72	3840.0	711	20.0	19.8	133	2486	74.74	NGP	0.4	215.7	2.4	648	1.5
SWMN	EGraham	53-0020	8.44	3080.0	668	22.0	23.8	214	2328	73.42	WCP	0.3	211.7	2.4	9171	1.8
SWMN	WGraham	53-0021	8.75	2840.0	664	16.0	21.4	110	1720	55.66	WCP	0.4	212.9	2.4	8083	1.8
SWMN	Curtis_H	87-0016	8.75	4080.0	890	20.0	24.4	191	3162	143.8	WCP	0.2	145.7	1.8	1995	1.5
SWMN	Wood	87-0030	8.64	3400.0	893	18.0	21.8	138	1914	39.58	WCP	0.4	185.8	3.0	2332	1.5
CentMN	Tiger	10-0108	8.90	3466.6	370	50.0	48.3	120	2470	45.00	CHF	0.6	232.7	2.4	1798	0.9
CentMN	Platte	18-0088	8.10	1385.0	106	35.0	2.7	33	890	11.76	NLF	1.5	706.6	7.0	7911	3.0
CentMN	RedSand	18-0386	8.80	1310.0	132	20.0	11.8	33	930	4.58	NLF	3.3	203.2	7.0	1842	2.1
CentMN	Jennie	21-0323	9.60	3200.0	498	20.0	19.5	210	5450	113.7	NGP	0.3	127.9	1.5	855	0.9
CentMN	Diamond	27-0125	9.20	2600.0	240	22.5	40.8	180	2280	73.05	CHF	0.8	164.3	2.4	328	1.8
CentMN	French	27-0127	9.00	2006.6	224	50.0	33.0	370	5250	180.2	CHF	0.4	142.5	0.9	1502	0.6
CentMN	Prairie	27-0177	8.50	2100.0	145	20.0	1.4	30	890	7.64	CHF	1.0	13.8	1.8	37	0.9
CentMN	Quamba	33-0015	8.00	1556.6	95	103.3	3.2	90	1530	34.47	CHF	0.9	86.6	3.4	9406	1.8
CentMN	Ringo	34-0172	8.80	3742.8	276	20.0	14.0	90	2360	44.50	CHF	0.5	289.8	3.0	595	1.5
CentMN	FLSlough	34-0204	8.80	3866.6	344	33.3	12.0	140	2130	49.33	CHF	0.8	312.4	1.2	17015	0.8
CentMN	ESolomo	34-0246	8.80	5500.0	454	22.5	20.3	90	2240	17.34	WCP	1.8	285.7	4.0	5223	2.9
CentMN	WTwin_LI	41-0102	9.30	4600.0	476	46.7	24.0	320	5050	138.3	NGP	0.2	87.4	1.3	820	0.7
CentMN	ETwin_LI	41-0108	10.20	4266.6	466	36.7	20.7	210	5720	132.7	NGP	0.2	87.0	1.4	820	0.7
CentMN	Johan_PO	61-0006	9.10	2750.0	272	20.0	10.5	80	1860	34.75	CHF	1.3	641.0	3.7	2828	2.1
CentMN	Nelson	61-0101	8.90	4666.6	376	10.0	11.0	50	1600	17.53	CHF	0.8	163.1	2.7	332	1.8
CentMN	Fremont	71-0016	9.50	1466.6	112	28.3	11.7	110	1870	49.07	CHF	1.1	195.9	3.0	995	2.1
CentMN	Silver	72-0013	8.50	3233.4	277	25.0	20.8	160	3310	63.47	CHF	0.3	251.3	2.7	1516	1.4
CentMN	Titlow	72-0042	8.40	4466.6	452	23.3	35.7	230	2140	42.47	WCP	0.2	373.9	1.2	14324	0.6
CentMN	Ceda_ST1	73-0226	8.40	3600.0	219	20.0	4.6	10	870	5.69	CHF	3.0	36.4	11.0	578	6.1
CentMN	Ceda_ST2	73-0255	9.30	2373.4	203	20.0	13.0	40	1060	4.09	CHF	1.4	85.0	2.4	496	1.5
CentMN	McCormic	73-0273	9.50	2295.0	226	17.5	18.3	60	1490	12.51	CHF	1.8	85.4	3.7	398	2.1
CentMN	Hattie	75-0200	8.70	5000.0	502	20.0	19.3	320	2270	40.24	NGP	0.5	193.0	2.7	4720	1.8
CentMN	Monson	76-0033	9.00	3050.0	528	17.5	11.5	90	1840	45.77	CHF	1.5	61.9	6.4	471	3.7
CentMN	Hollerbe	76-0057	9.70	3933.4	335	36.7	12.7	90	2320	25.83	NGP	0.6	105.2	1.5	1308	1.1
CentMN	Hassel	76-0086	8.80	4150.0	376	35.0	12.5	270	4150	91.85	NGP	0.2	285.7	1.5	9444	1.2
CentMN	Trace	77-0009	9.00	3050.0	423	27.5	63.5	120	2070	26.22	CHF	1.1	112.1	2.7	272	1.8
CentMN	Pelican	86-0031	9.20	1640.0	142	30.0	11.5	170	2780	94.64	CHF	0.4	1130.3	2.7	3118	1.5
CentMN	Cedar_WR	86-0073	8.50	2025.0	146	22.5	10.1	20	800	4.42	CHF	3.6	59.5	14.3	216	4.6
CentMN	Smith	86-0250	9.00	2600.0	241	27.5	29.3	150	3140	62.88	CHF	0.4	91.5	1.5	307	0.9
ItascaCo	Adele	31-0642	6.30	65	21.26	25.0	0.3	17	430	3.77	NLF	3.6	7.3	7.9	212	1.9
ItascaCo	Balsam	31-0259	7.47	1550	160.7	29.0	0.5	20	495	3.35	NLF	3.0	291.4	11.3	4132	4.9
ItascaCo	Beatrice	31-0058	6.31	140	24.37	18.0	0.9	15	433	4.30	NLF	3.7	46.2	8.8	280	3.7
ItascaCo	Beav_IT	31-0638	5.95	172	21.97	27.5	0.8	25	425	4.85	NLF	3.5	6.9	11.9	131	3.1
ItascaCo	Bluewatr	31-0395	7.96	2660	262.8	2.0	0.8	9	205	2.55	NLF	5.8	146.5	36.6	197	16.5
ItascaCo	Caribou	31-0620	6.97	380	51.11	2.5	0.8	5	211	1.40	NLF	8.8	96.1	46.3	184	14.3

ItascaCo	Cedar_IT	31-0829	8.03	3327	287.9	13.3	1.1	13	465	6.60	NLF	3.0	68.6	15.0	659	5.2
ItascaCo	Coon	31-0524	7.32	850	91.43	18.0	2.2	14	500	4.67	NLF	3.9	240.8	11.0	474	3.9
ItascaCo	Crooked	31-0193	7.45	1340	149.2	76.0	1.3	19	554	5.66	NLF	2.3	171.2	18.3	9317	4.1
ItascaCo	Decker	31-0934	7.73	1770	167.2	53.0	0.3	60	1171	28.02	NLF	1.0	130.7	3.7	4363	1.6
ItascaCo	Deer_IT1	31-0334	7.84	1990	189.2	17.0	1.1	23	525	7.00	NLF	2.7	742.0	15.2	5582	3.4
ItascaCo	Deer_IT2	31-0719	8.10	2360	232.1	2.0	5.2	12	366	3.75	NLF	4.2	1649.1	36.9	1097	14.5
ItascaCo	Dixon	31-0921	7.96	2570	228.5	55.0	0.9	35	788	14.04	NLF	2.2	255.2	8.8	20012	3.7
ItascaCo	Dora	31-0882	7.69	2020	196.7	39.0	1.3	34	729	8.77	NLF	2.1	248.1	5.5	113582	2.0
ItascaCo	Grave	31-0624	7.72	2430	251.1	11.5	1.5	7	377	4.35	NLF	4.3	203.3	11.9	1400	4.9
ItascaCo	Horsesho	31-0696	7.06	710	77.23	10.0	0.8	19	795	4.51	NLF	3.3	108.9	7.6	35	2.2
ItascaCo	Ice	31-0372	7.05	720	108.9	32.0	6.5	20	496	4.89	NLF	3.8	15.7	16.1	99	4.8
ItascaCo	Island	31-0913	7.64	1840	186.3	11.0	1.9	30	711	10.68	NLF	3.3	1236.9	10.7	3828	5.2
ItascaCo	LtBowstr	31-0758	8.14	2540	263.7	16.0	1.4	19	437	4.20	NLF	2.0	127.0	9.0	2511	5.5
ItascaCo	LtCutFot	31-0852	7.56	1407	138.9	93.3	1.1	44	833	21.93	NLF	1.4	264.3	6.1	9096	2.7
ItascaCo	McKinney	31-0370	7.15	590	84.24	61.5	4.1	79	781	9.95	NLF	2.4	43.3	10.4	673	2.7
ItascaCo	Owen	31-0292	6.70	240	33.99	31.5	0.5	20	556	4.60	NLF	3.8	100.4	10.4	395	3.3
ItascaCo	Pokegama	31-0532	7.84	2420	254.7	15.0	3.6	15	395	4.85	NLF	4.6	2709.8	34.1	17140	10.8
ItascaCo	RoundIT1	31-0209	7.08	460	25.70	59.0	1.3	35	938	13.98	NLF	2.8	39.4	5.2	61	2.7
ItascaCo	RoundIT2	31-0268	7.15	450	57.53	10.0	0.8	18	511	2.94	NLF	4.9	183.3	12.2	193	4.7
ItascaCo	RoundIT3	31-0896	7.77	1890	190.2	40.5	1.1	61	763	23.36	NLF	1.4	1165.5	7.3	26300	3.7
ItascaCo	Sand	31-0826	8.20	1940	189.7	31.0	3.8	24	610	9.81	NLF	2.4	1837.1	21.7	62371	5.2
ItascaCo	Shallow	31-0084	7.67	1450	161.0	7.0	2.8	11	384	3.20	NLF	4.3	217.1	24.4	306	9.1
ItascaCo	Splthand	31-0353	7.57	1320	141.9	43.0	1.1	29	568	10.35	NLF	1.9	558.8	10.4	7483	4.6
ItascaCo	Stingy	31-0051	7.11	520	65.47	56.0	0.7	27	675	12.20	NLF	2.0	144.5	7.6	1024	4.9
ItascaCo	Sugar	31-0554	7.85	2600	267.9	5.0	1.8	11	295	3.47	NLF	3.5	487.8	32.0	1903	13.3
ItascaCo	Thstldew	31-0158	7.71	1500	160.1	33.5	0.6	20	420	8.40	NLF	3.2	128.3	13.7	1020	7.1
ItascaCo	TroutIT1	31-0216	7.90	2680	347.2	9.5	5.4	20	418	3.22	NLF	4.3	748.2	41.2	2822	15.2
ItascaCo	TroutIT2	31-0410	7.96	2400	238.8	3.0	0.5	7	225	1.30	NLF	4.8	703.5	41.2	970	14.6
ItascaCo	TurtleIT	31-0725	7.63	2510	235.9	8.0	1.7	10	357	1.30	NLF	4.7	830.3	39.6	6085	10.4
ItascaCo	Wabana	31-0392	7.86	2260	213.8	4.0	1.0	8	265	1.60	NLF	5.8	882.5	35.1	3813	8.4
ItascaCo	Winnigsh	11-0147	7.94	2720	265.2	12.5	2.6	19	463	6.47	NLF	3.2	28256	21.3	345739	4.6

Table 6. Diatom-inferred total phosphorus (DI-TP) reconstructions from 145 MN lakes training set. Surface sediment samples (surf) and sediment core samples (number following lake name is core depth in cm). The uppermost core samples represent modern lake conditions (ca. 2000-2004 AD); the two deepest samples from each core represent sediments deposited before regional European settlement. The 2002-2003 mean epilimnetic TP and range of observed TP values are listed for some lakes. The dissimilariy coefficient (DC) is calculated as the squared chi-squared distance between a fossil sample and its nearest modern analog among the modern 145 lakes. A good analogue is defined with a DC<0.7920, the fifth percentile of distance distributions among the modern samples. Several spurious reconstructions are highlighted in gray.

Name	Name	DI-TP (ppb)	2002-2003 obs mean TP (ppb)	2002-2003 TP range (ppb)	analog?	DC
Fremont	Frem (surf)	50	110	N/A	—	—
	Frem2	71	—	—	good	0.4316
	Frem129	66	—	—	no	0.9919
	Frem134	57	—	—	poor	0.927
Johanna	Joha_P (surf)	87	80	N/A	—	—
	Joha_P2	64	—	—	good	0.2791
	Joha_P65	54	—	—	good	0.6544
	Joha_P70	93	—	—	poor	0.9198
McCormic	McCorm (surf)	70	60	N/A	—	—
	McCorm2	99	—	—	good	0.5231
	McCorm85	62	—	—	good	0.7015
	McCorm90	164	—	—	good	0.5117
Monson	Monson (surf)	37	90	N/A	—	—
	Monson2	26	—	—	good	0.4661
	Monso106	67	—	—	good	0.5756
	Monso111	65	—	—	no	1.1135
	Monson67*	54	—	—	poor	0.8761
	Monson72*	66	—	—	poor	0.9227
Platte	Platte (surf)	46	33	N/A	—	—
	Platt2	48	—	—	good	0.2413
	Platt155	45	—	—	good	0.7133
	Platt160	23	—	—	no	1.0538
Quamba	Quamba (surf)	59	90	N/A	—	—
	Quamb2	57			good	0.1184
	Quamb120	47			good	0.318
	Quamb125	51			good	0.2798
Red Sand	RedSand (surf)	35	33	25-42	—	—
	RedSa2	38			good	0.2132
	RedSa100	307			no	1.2169
	RedSa105	64			no	1.0953
Silver	Silver (surf)	208	160	N/A	—	—
	Silver2	245			good	0.3985

	Silver66	52			good	0.5961
	Silver71	56			good	0.6376
Big Twin	BTwin (surf)	124	141	126-154	—	—
	BTwin2	125	—	—	good	0.3812
	BTwin80	84	—	—	good	0.669
	BTwin90	103	—	—	good	0.4051
Bloody	Bloody (surf)	147	89	67-121		
	Bloody2	135	—	—	good	0.396
	*Bloody52	157	—	—	good	0.445
	Bloody62	95	—	—	good	0.6938
	Bloody72	117	—	—		
Clear	Clear (surf)	90	110	69-137		—
	Clear2	120	—	—	good	0.7409
	Clear58	67	—	—	good	0.5664
	Clear68	55	—	—	good	0.5846
Cottonwood	Ctnd_CT (surf)	116	83	63-133		—
	Ctnd_CT2	114	—	—	good	0.2097
	Ctnd_CT72	426	—	—	good	0.6139
	Ctnd_CT82	161	—	—	good	0.7338
East Twin	ETwin (surf)	143	104	84-121		—
	ETwin2	157	—	—	good	0.5737
	ETwin68	169	—	—	poor	0.8279
	ETwin78	212	—	—	poor	0.8824
Shaokaton	Shaoktn (surf)	116	124	75-159		—
	Shaoktn2	121	—	—	good	0.6883
	Shaoktn56	59	—	—	good	0.5212
	Shaoktn66	94	—	—	good	0.4058

*Monson67, Monson72, and Bloody52 was determined to represent sediments deposited after European settlement.

Table 7. Regional patterns among shallow and deep lakes for pre-European and modern diatom-inferred total phosphorus (DI-TP), and MPCA monitoring data.

Ecoregion	n	preE DI-TP	modern DI-TP	modern TP
Metro	20	32	31	34
NLF (shallow)	6	30	27	22
NLF (deep)	16	17	15	14
CHF (shallow)	8	63	82	100
CHF (deep)	8	37	34	40
WCP (deep)	5	68	44	69
WCP/NGP (shal)	6	93	126	109

Table 8. Diatom-inferred TP for 69 Minnesota lake cores. Two samples (1800s, 1750s) represent sediments deposited before European settlement, and two samples (surf, 0-2 cm) represent modern lake conditions. These data were used to estimate regional trends among shalllow and deep lakes. Cells shaded in gray were without modern analogues or poor reconstructions and not included in regional estimates presented in Table 7.

Project	Lake	MN DNR ID	Eco-region	Z max	TP	DI-TP	DI-TP	DI-TP	DI-TP
			USEPA	m	µg/l	surf	0-2 cm	1800s	1750s
55Lakes	Dickman	19-0046	Metro	2.4	105	120	120	45	40
55Lakes	Schultz	19-0075	Metro	4.9	26	29	29	37	36
55Lakes	Sweeney	27-0035-01	Metro	7.6	46	26	26	30	20
55Lakes	Turtle	62-0061	Metro	8.8	27	23	23	34	29
55Lakes	Fish_D	19-0057	Metro	10.1	79	35	35	51	37
55Lakes	Marcott	19-0042	Metro	10.1	19	19	19	17	39
55Lakes	Carver	82-0166	Metro	11.0	36	38	38	44	28
55Lakes	Owasso	62-0056	Metro	12.2	40	26	26	40	41
55Lakes	Gervais	62-0007	Metro	12.5	33	34	34	56	58
55Lakes	Johanna	62-0078	Metro	12.5	36	40	40	38	35
55Lakes	Tanners	82-0115	Metro	13.7	56	16	16	30	27
55Lakes	Twin	27-0035-02	Metro	17.1	22	13	13	17	23
55Lakes	McCarrns	62-0054	Metro	17.4	48	50	50	21	34
55Lakes	L_Carnel	82-0014	Metro	19.2	9	11	11	28	27
55Lakes	Square	82-0046	Metro	20.7	12	10	10	21	11
55Lakes	L_Long	27-0179-02	Metro	23.2	9	9	9	45	51
55Lakes	Harriet	27-0016	Metro	25.0	27	35	35	14	16
55Lakes	Christmas	27-0137	Metro	26.5	15	35	35	30	36
55Lakes	Calhoun	27-0031	Metro	27.4	28	40	40	18	22
55Lakes	Elmo	82-0106	Metro	42.7	10	9	9	21	20
CentMN	Silver	72-0013	NCHF	2.7	160	208	245	52	56
CentMN	Fremont	71-0016	NCHF	3.0	110	50	71	66	57
CentMN	Quamba	33-0015	NCHF	3.4	90	59	57	47	51
CentMN	Johan_PO	61-0006	NCHF	3.7	80	87	64	54	93
CentMN	McCormic	73-0273	NCHF	3.7	60	70	99	62	164
55Lakes	Hook	43-0073	NCHF	5.5	68	61	61	60	52
55Lakes	Dunns	47-0082	NCHF	6.1	139	58	58	34	32
CentMN	Monson	76-0033	NCHF	6.4	90	37	26	67	65
55Lakes	Diamond	34-0044	NCHF	8.2	80	83	83	36	30
55Lakes	George_K	34-0142	NCHF	9.1	15	16	16	60	62
55Lakes	Stahl	43-0104	NCHF	10.7	46	41	41	39	42

55Lakes	Hendersn	34-0116	NCHF	12.2	22	30	30	47	32
55Lakes	Long_K	34-0066	NCHF	13.4	19	22	22	18	21
55Lakes	Richrdsn	47-0088	NCHF	14.3	98	55	55	33	30
55Lakes	Sagatgn	73-0092	NCHF	14.3	27	13	13	34	43
55Lakes	Kreighle	73-0097	NCHF	17.1	11	15	15	34	31
SWMN	Shaoktn	41-0089	NGP	3.7	124	116	121	59	94
SWMN	ETwin	42-0070	NGP	6.7	104	143	157	169	212
CentMN	Platte	18-0088	NLF	7.0	33	46	48	45	23
CentMN	RedSand	18-0386	NLF	7.0	33	35	38	307	64
55Lakes	Forsythe	31-0560	NLF	3.1	21	23	23	22	22
55Lakes	Tettgche	38-0231	NLF	4.6	17	20	20	22	26
55Lakes	Nipisiqt	38-0232	NLF	5.5	16	21	21	33	33
55Lakes	August	38-0691	NLF	5.8	15	13	13	20	16
55Lakes	Dyers	16-0634	NLF	6.1	27	23	23	32	30
55Lakes	Shoepack	69-0870	NLF	7.3	19	18	18	19	12
55Lakes	Wolf	38-0242	NLF	7.3	14	26	26	9	14
55Lakes	Bean	38-0409	NLF	7.9	17	27	27	31	26
55Lakes	Bear	38-0405	NLF	8.8	11	19	19	14	10
55Lakes	Ninemile	38-0033	NLF	9.1	17	19	19	15	11
55Lakes	Windy	38-0068	NLF	11.9	12	8	8	9	9
55Lakes	Tooth	69-0756	NLF	13.1	12	10	10	9	9
55Lakes	Loiten	69-0872	NLF	14.9	8	7	7	8	8
55Lakes	Wilson	38-0047	NLF	14.9	13	23	23	46	41
55Lakes	Snells	31-0569	NLF	15.2	24	12	12	14	9
55Lakes	Locator	69-0936	NLF	15.9	9	6	6	9	8
55Lakes	L_Bass	31-0575	NLF	18.9	13	13	13	25	26
55Lakes	Loon_I	31-0571	NLF	21.0	11	10	10	20	11
55Lakes	Long_I	31-0570	NLF	22.9	13	16	16	19	10
55Lakes	L_Trout	69-0682	NLF	29.0	7	8	8	11	10
SWMN	Ctnd_CT	17-0022	WCP	2.7	84	116	114	426	161
SWMN	Clear	32-0022	WCP	3.0	110	90	120	67	55
SWMN	BTwin	46-0133	WCP	3.0	141	124	125	84	103
SWMN	Bloody	51-0040	WCP	3.4	89	147	135	95	117
55Lakes	Bass	22-0074	WCP	6.1	81	72	72	74	84
55Lakes	Duck	07-0053	WCP	7.6	65	38	38	45	60
55Lakes	Beaver	74-0023	WCP	8.2	30	36	36	53	60
55Lakes	Fish_J	32-0018	WCP	8.2	38	43	43	88	88
55Lakes	George_B	07-0047	WCP	8.5	130	30	30	79	53

FIGURES

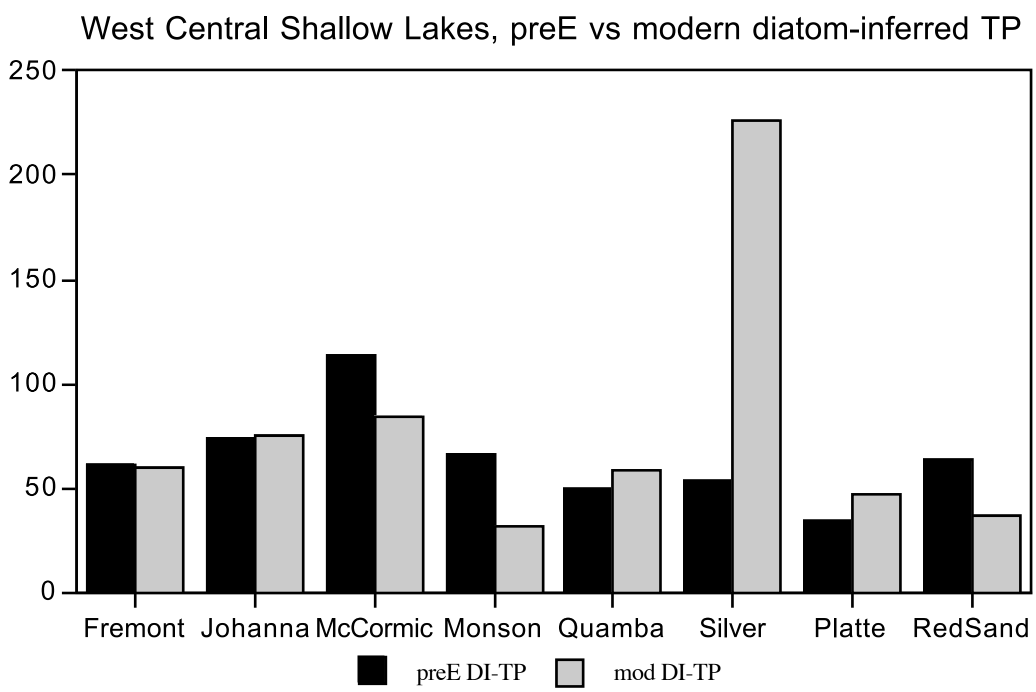

Figure. 1. Comparison of pre-European and modern diatom-inferred total phosphorus in eight westcentral Minnesota lakes

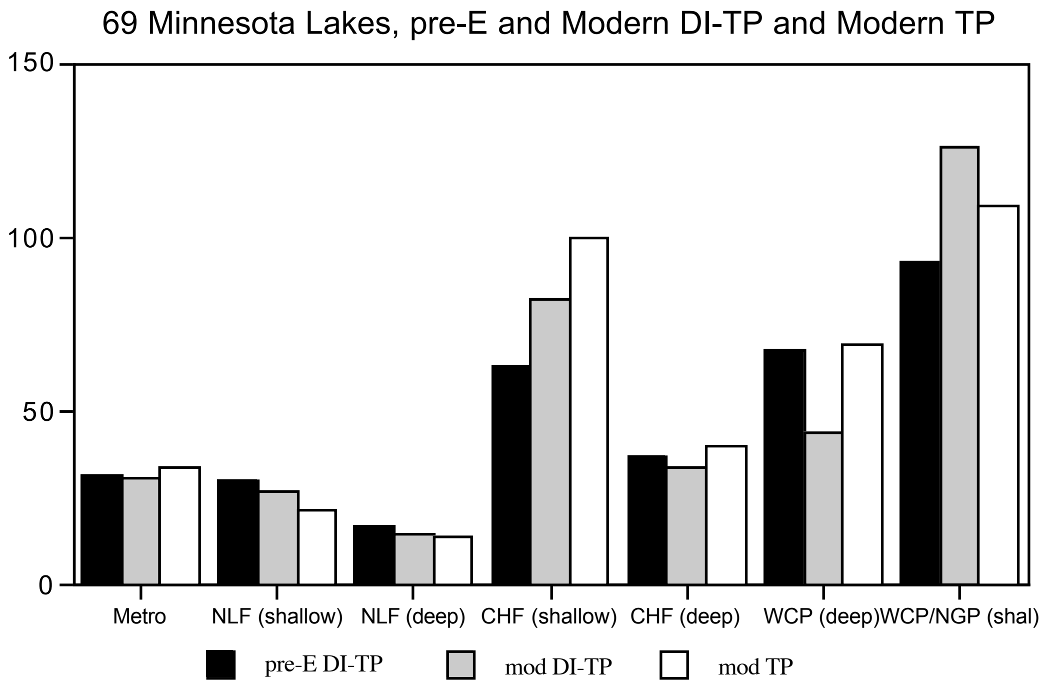

Figure 2. Ecoregional comparison of shallow and deep lakes from analysis of 69 Minnesota lake sediment cores. Shallow lakes were defined as <6m deep or with high littoral extent.