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Natural Resource Stewardship and Science

Monitoring Water Quality of Inland Lakes, Great Lakes Network, 2011

Data Summary Report

Natural Resource Data Series NPS/GLKN/NRDS—2012/363

ON THE COVER
Jessica Ruuti, biological technician at Isle Royale National Park, overlooking Epidote Lake. Photo by Richard Damstra.

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Data Summary Report

Natural Resource Data Series NPS/GLKN/NRDS—2012/363

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols. Additionally, this report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Abstract

The Great Lakes Inventory and Monitoring Network monitored water quality of inland lakes at six national park units in 2011: Voyageurs National Park (VOYA), Apostle Islands National Lakeshore (APIS), Isle Royale National Park (ISRO), Pictured Rocks National Lakeshore (PIRO), Indiana Dunes National Lakeshore (INDU), and Sleeping Bear Dunes National Lakeshore (SLBE). The primary objective of this monitoring program is to monitor water quality in order to describe the current status and to detect trends of common limnological parameters within sampled lakes. We hope to be able to provide early warnings of change, work with researchers to understand the causes of change, and provide interpretation of our results to park staff.

Thirty-three index lakes were sampled during the open water season in 2011. Field measurements included depth profiles of temperature, pH, specific conductance, and dissolved oxygen; water clarity; and water level relative to a benchmark. Water samples were collected for laboratory analyses of total phosphorus, total nitrogen, nitrate+nitrite-nitrogen, ammonium-nitrogen, dissolved silica, calcium, sodium, magnesium, potassium, sulfate, chloride, dissolved organic carbon, alkalinity, and chlorophyll *a*. Total and methyl-mercury were measured at five lakes at VOYA. Total suspended solids were measured at four lakes each at ISRO and VOYA. Sediment samples were collected at APIS and INDU for analysis of diatom communities.

Additional lakes were sampled at ISRO, PIRO, INDU, and SLBE one to three times each during the season. Field measurements were conducted at all of the lakes and laboratory analyses of water samples were conducted on some of the lakes.

Results show that many lakes exceed the U.S. Environmental Protection Agency (USEPA) reference criteria for Secchi depth, pH, chlorophyll *a*, total phosphorus, total nitrogen, and nitrate+nitrite-nitrogen for their respective ecoregion. Calculations of trophic state indices show most index lakes to be mesotrophic.

Graphs of several parameters over time show hints of trends occurring for some parameters at some parks. We expect monitoring to continue in 2012 at the same index lakes, with additional sites, visits, and parameters included as funding permits.

Acknowledgments

We depend on park staff and park support for the successful implementation of the water quality monitoring program each year. The assistance we receive varies by park, but examples include boat maintenance, lab space, use of sampling equipment, boat transportation, vehicles, gasoline, housing, and more. Personnel from several divisions, including maintenance, interpretation, law enforcement, and especially natural resources have lent a hand. Special thanks to the primary field staff: Lora Loope, Leah Kainulainen, Chris Otto, Jaime LeDuc, Ted Gostomski, Jessica Ruuti, and Joshua Dickey. Thanks also to the many other people who assisted with field sampling in 2011 (if we try to name them all we are sure to accidentally omit someone). Lora Loope, Leah Kainulainen, Ryan Maki, Ted Gostomski, and David VanderMeulen reviewed an earlier version of this report and provided helpful suggestions. We are especially grateful to Brenda Moraska Lafrancois, Lora Loope, Ryan Maki, Chris Otto, and David VanderMeulen for discussions surrounding the interpretation of our results.

Introduction

The Great Lakes Inventory and Monitoring Network (hereafter the Network or GLKN) conducted water quality monitoring at six parks with inland lakes resources in 2011: Voyageurs National Park (VOYA), Apostle Island National Lakeshore (APIS), Isle Royale National Park (ISRO), Pictured Rocks National Lakeshore (PIRO), Indiana Dunes National Lakeshore (INDU), and Sleeping Bear Dunes National Lakeshore (SLBE). Water quality as a vital sign ranked highly across Network parks (Route 2004). Because monitoring water quality is mandated by the National Park Service - Water Resources Division (WRD), the Network receives some funding from WRD annually to cover part of the costs. The protocol for monitoring water quality of inland lakes (Elias et al. 2008) encompasses the following vital signs:

- core suite (temperature, dissolved oxygen, conductivity, pH, water clarity)
- water level
- advanced suite (alkalinity, dissolved organic carbon, silica, chloride, sulfate, calcium, sodium, potassium, magnesium, chlorophyll-*a*, total phosphorus, total nitrogen, ammonium-nitrogen, nitrate+nitrite-nitrogen)
- primary productivity (as estimated by chlorophyll-*a* measurements)
- nutrient dynamics (as measured by the phosphorus and nitrogen species)

The Network also monitors diatoms (an additional vital sign) in lake bottom sediments approximately every five years on a rotating schedule (Ramstack et al. 2008) under a cooperative agreement with the St. Croix Watershed Research Station (SCWRS). Diatom monitoring is closely tied to water quality monitoring and aids in the interpretation of water quality results. Monitoring a lake's diatom community can be used as biological proxy for several water quality parameters, including hindcasting lake conditions before monitoring began.

In collaboration with the U.S. Geological Survey (USGS), we collected water samples from five lakes at VOYA for total and methyl-mercury (bioaccumulative contaminants vital sign).

The Network's intent in monitoring water quality of inland lakes is to contribute to an understanding of the health of ecosystems and provide insights on water quality issues in the parks. Our primary objective is to describe the current status of lake water quality and to detect trends in common limnological parameters within sampled lakes. Many years of data collection will be needed before trends can be determined for most parameters; however, we hope to be able to provide early detection of change that may then lead to increased monitoring, research, or management action. Now that five years of data have been analyzed (six years at INDU and VOYA), we are beginning to better understand the natural variability that occurs in a given lake intra- and interannually. This understanding is crucial to distinguish true change from the 'noise' inherent in the system, as well as that which occurs due to sampling equipment, laboratory analyses, and individual bias.

This report provides brief updates on the water quality monitoring program for inland lakes, including results from the 2011 field season and graphs of select parameters over time since monitoring began. Results from previous years (Elias 2007, 2009; Elias and VanderMeulen 2008; and Elias and Damstra 2011) can be found on the GLKN website (http://science.nature.nps.gov/im/units/glkn/index.cfm).

Methods

Study Sites

In developing the protocol for monitoring inland lakes water quality, the Network and the parks selected index lakes for annual monitoring. These lakes span gradients of chemical and physical parameters, visitor use, watershed size, and spatial distribution within each park (Elias et al. 2008). We sampled all 33 index lakes (Table 1) in 2011. Additional lakes were sampled at least once in ISRO (N=8), PIRO (N=1), SLBE (N=4), and INDU (N=1).

Table 1. Lakes/lagoons sampled for water quality in 2011 and types of data collected. The parks are listed in order from west to east. Index lakes are shown in **bold font**.

Lake or Lagoon	Core Suite	Advanced Suite	Diatoms	Mercury
Voyageurs National Park				
Locator	x	x		
Shoepack	x	x		x
Ek	x	x		x
Brown	x	x		x
Peary	x	x		x
Cruiser	x	x		
Ryan	x	x		x
Little Trout	x	x		
Apostle Islands National Lakeshore				
Michigan Island	x	x	x	
Outer Island	x	x	x	
Stockton Island	x	x	x	
Little Sand Bay	x	x	x	
Isle Royale National Park				
Ahmik	x	x		
Sargent	x	x		
Richie	x	x		
Beaver	x	x		
Harvey	x	x		
George	x	x		
Siskiwit	x	x		
Desor	x	x		
Feldtmann	x	x		
Epidote	x			
Whittlesey	x			
Wood	x			
Intermediate	x			
LeSage	x			
Chickenbone	x			
Amygdaloid	x			
Hidden	x			
Pictured Rocks National Lakeshore				
Grand Sable	x	x		
Legion	x	x		
Beaver	x	x		
Little Beaver	x			
Chapel	x	x		
Miners	x	x		

Table 1. Lakes/lagoons sampled for water quality in 2011 and types of data collected. The parks are listed in order from west to east. Index lakes are shown in **bold font** (continued).

Lake or Lagoon	Core Suite	Advanced Suite	Diatoms	Mercury
Indiana Dunes National Lakeshore				
Long	x	x	x	
Middle Lagoon	x	x	x	
Sleeping Bear Dunes National Lakeshore				
Manitou	x	x		
Florence	x	x		
Narada	x	x		
Shell	x	x		
Bass (North)	x	x		
Otter	x	x		
Tucker	x	x		
North Bar	x	x		
Round	x	x		
Loon	x	x		

Water Quality Sampling

Field Methods

In accordance with the protocol (Elias et al. 2008), we conducted field sampling at the deepest part of each index lake three times during the open water season (Table 2). Each lake is sampled at approximately the same location on each site visit; GPS, bathymetric map, depth sounder, and detailed directions aid field personnel in returning to the same location.

Table 2. Dates of water quality sampling at index lakes, 2011.

	Round 1	Round 2	Round 3
VOYA	6/9 - 6/17	7/13 - 7/21	8/15 - 8/25, 9/22
APIS	6/15 - 6/16	7/25 - 7/26	8/29 - 8/31
ISRO	6/15 - 6/30	7/14 - 7/28	8/20 - 9/02
PIRO	6/13 - 6/23	7/25 - 8/01	8/29 - 9/02
INDU	5/2 - 5/4	8/25 - 8/26	9/14 - 9/15
SLBE	6/29 - 7/05	7/21 - 8/01	9/08 - 10/11

*additional sampling occurred at INDU on 7/20.

We used multi-probe sondes to collect profile data on temperature, dissolved oxygen, specific conductance, and pH. Different manufacturers' sondes were used at different parks: YSI (Model 6820) at PIRO, Eureka Manta (unit 318) at APIS, Eureka Manta Sub 2 (unit 178) at ISRO, Eureka Manta (unit 132) at VOYA, Hydrolab (Model DSX5) at SLBE, and Hydrolab (Model MS5.0) at INDU. At each site, we also measured water clarity with a Secchi disk or transparency tube, took a GPS reading, recorded environmental conditions (e.g., wind speed and direction, wave height, sky cover, air temperature), measured water level relative to a benchmark using a hand-held eye level and a light-weight stadia rod, and noted field personnel and instruments.

We collected 0-2 m integrated water samples for laboratory analyses using an integrated tube sampler (MPCA 2004a, 2004b; WDNR 2004). On lakes that were less than 2 m deep, we used the tube sampler on an angle to collect a sample from the full water column or collected a grab sample at approximately elbow depth. Sample water was composited in a high density polyethylene container. See Elias et al. (2008) and Elias and VanderMeulen (2008) for details on collection and handling of water samples.

At index lakes, we collected water samples for nutrients and chlorophyll *a* (chl-*a*) during each visit; samples for the remaining parameters (Table 3) were collected only during the second round of sampling (during August at Narada Lake, SLBE). During sampling round 2, we also collected a near-bottom water sample with a Van Dorn sampler for analysis of total phosphorus and total nitrogen. This near-bottom sampling was conducted only in lakes that were thermally stratified. At some non-index lakes we took field measurements (core suite) and collected water for laboratory analysis (advanced suite), while at others we only measured field variables (see Table 1).

Table 3. Parameters measured and abbreviations used in text. Bold font indicates parameters measured three times per season at index lakes (one to three times at non-index lakes); remaining parameters were measured once during mid-season.

Parameter	Abbreviation	Parameter	Abbreviation
Alkalinity	Alk	**Total Nitrogen**	**TN**
Calcium	Ca^{+2}	**Ammonium-Nitrogen**	**NH_4-N**
Chloride	Cl^-	**Nitrate+Nitrite-Nitrogen**	**NO_3+NO_2-N** or **NO_x**
Chlorophyll-*a*	**chl-*a***	Total Mercury (VOYA only)	THg
Dissolved Organic Carbon	DOC	Methyl-mercury (VOYA only)	MHg
Magnesium	Mg^{+2}	**Specific Conductance**	**SC25**
Potassium	K^+	**Dissolved Oxygen**	**DO**
Silica	SiO_2	**pH**	**pH**
Sodium	Na^+	**Temperature**	**Temp**
Sulfate	SO_4^{-2}	**Secchi Disk Depth**	**Secchi**
Total Phosphorus	**TP**	**Transparency Tube**	**T-tube**

At VOYA, we collected samples for total and methyl-mercury at five lakes (Brown, Ek, Peary, Ryan, and Shoepack) following U.S. Geological Survey (USGS) procedures (M. Brigham, USGS, personal communication). As in previous years, this was a collaborative effort with USGS – we collected the samples and sent them to the USGS laboratory in Middleton, Wisconsin; the lab analyzed the samples; M. Brigham managed the data for USGS; we managed the data for GLKN.

Analytical Laboratories

We contracted with White Water Associates (WWA) for analysis of major ions (Ca^{+2}, Cl^-, Mg^{+2}, K^+, Na^+, SO_4^{-2}), alkalinity, dissolved organic carbon (DOC), and dissolved silica (SiO_2). WWA has conducted these analyses since the beginning of our water quality monitoring program in

2006. The St. Croix Watershed Research Station (SCWRS) analyzed samples for nutrients (TP, TN, NO_3+NO_2-N, and NH_4-N) and chlorophyll *a* (chl-*a*). They have done these same analyses for us since 2009. As in prior years, mercury samples from VOYA were analyzed by the USGS lab in Middleton, Wisconsin.

All samples were processed and handled according to standard operating procedures (Axler et al. 2008) and as required by the respective laboratories.

Sediment Sampling

We collected lake bottom sediment samples in late summer/fall from four lagoons at APIS and two lakes/lagoons at INDU (see Table 1). Samples were collected with a drop corer and were handled and processed according to standard operating procedures (Ramstack et al. 2008). The bottom sediment samples will be analyzed for diatom community assemblages by researchers at SCWRS. When living, the diatoms were in the water column or attached to submerged plants or rocks but settled onto the lake bottom after dying. Results from this project will facilitate our understanding of changes in water quality, as diatom communities reflect the water quality conditions that exist over a few weeks or months rather than at a single moment in time (as with water samples). Diatom community assemblages serve as indicators of water quality because the species composition changes as environmental conditions change. Analysis of diatom communities complements our discreet water quality sampling, and provides a way to compare current conditions with those of the past, even before Europeans settled the region, by examining deeper sections of a sediment core.

Bathymetric Mapping

Hard-copy bathymetric maps exist for many of the index lakes, though electronic maps for these lakes are often not available. We began constructing bathymetry maps at ISRO in 2007 using a GPS mapping unit mated with a depth finder, and continued the process in subsequent years. Depth and location data were collected along transects, crisscrossing each lake. Data were then downloaded into GIS and processed. Draft maps are completed and final maps are in progress. We plan to construct bathymetric maps for all index lakes in the six parks over the next few years.

Data Handling

Methods for using laboratory data below detection limit and reporting limit (method detection limit [MDL] and method quantitation limit [MQL], respectively; i.e., censored data) in statistical analyses are numerous and diverse (e.g., Helsel 1990, Helsel and Cohn 1988). Because data were summarized but not analyzed statistically for this report, values below MQL, including '0' were used. 'ND' (non-detect) is indicated when the laboratory reported it as such. Results of 'ND' were reported 6 times, all of which were for single measurements that did not require calculation of a mean.

Quality Assurance and Quality Control

Steps to ensure quality assurance and quality control (QA/QC) were undertaken routinely, according to standard operating procedures (Ledder and Elias 2008), as part of monitoring water quality. The following steps were taken in 2011:

- the measurement sensitivity of each sonde was calculated under laboratory conditions prior to the field season and under field conditions during the season
- sondes were calibrated daily, adhering to acceptance criteria
- calibration logs were maintained with each instrument
- measurements taken in the field with the sondes were saved electronically and backed-up on paper data sheets
- duplicate field measurements were taken at the rate of approximately 10%
- duplicate water samples were collected at the rate of approximately 10%
- equipment blanks were conducted prior to and during the field season to ensure we were not introducing any contamination to the samples.

In addition, contract laboratories conducted their own QA/QC that included blanks, duplicates, and spikes, and generated QA/QC reports that accompanied water sample results.
Network quality assurance criteria stipulate that results for water sample duplicates should be within 10% of each other for all parameters except nutrients and chl-*a*, which should be within 30% of each other (Ledder and Elias 2008). Most of our duplicates fell within the acceptable criteria. Those that did not meet quality assurance criteria were usually very close to laboratory detection or reporting limits. In such cases, actual small differences can result in large relative percent differences (e.g., the actual difference between 1 and 2 µg/L is small, but the relative difference is 67%). We have included all values in this report unless specifically noted otherwise; however, duplicates were not used when calculating means. Values that do not meet our quality assurance criteria are flagged as such in the National Park Service database, NPSTORET, and the EPA database, STORET.

Results and Discussion

Data relative to USEPA reference criteria and trophic status are presented below for all parks so that comparisons across parks can be easily observed. Water level data and explorations of change over time for select parameters are presented for individual parks in the "Park-Specific Comments and Additional Results" section below. Appendices A-F contain all 2011 data for the six parks with the exception of profile data measured with multiprobe sondes; only data from 1.0 m (0.5 m in shallow lakes) are included. All data, including all profile data, are posted in EPA's STORET database and can be accessed at http://www.epa.gov/storet/dw_home.html. Graphs of temperature and oxygen profiles are not included in this report, but are available upon request.

EPA Reference Criteria

National park units are often considered to be relatively pristine and are commonly referred to as representative of reference conditions. However, our data show that many of GLKN's index lakes do not meet the EPA reference criteria for Secchi depth, pH, chlorophyll *a* (chl-*a*), total phosphorus (TP), total nitrogen (TN), and nitrate+nitrite-nitrogen (NO_3+NO_2-N) for their ecoregions (USEPA 2000a, 2000b, 2000c).

Secchi Depth

Many lakes at VOYA, ISRO, PIRO, and SLBE do not meet the EPA reference criteria for Secchi depth (Figure 1; USEPA 2000a, 2000b). Reasons for shallow Secchi measurements (i.e., lower than expected water clarity) vary by lake, but are primarily due to algae and naturally-occurring tannin-stained water. Changes in Secchi depth over time may indicate a change in trophic status, but confounding factors such as changes in personnel, field conditions (e.g., rough water), and timing of sampling must be taken into consideration.

Water transparency at APIS and INDU was sometimes measured with a transparency tube because the shallow depths of the lakes/lagoons allowed the Secchi disk to be seen on the bottom. Lakes are included in Figure 1 only when at least two Secchi measurements were available. Data in Figure 1 for APIS are from Stockton and Outer islands and Little Sand Bay (LSB) lagoons, none of which meet EPA reference criteria. Outer and Stockton Island lagoons are heavily stained with tannic acid, and LSB lagoon is often turbid from suspended sediment. Long Lake (INDU) had shallow Secchi measurements due to suspended sediments.

pH

Most lakes had pH values within the USEPA limits, though exceptions occurred at VOYA (Shoepack Lake) and PIRO (Legion Lake) (Figure 2; USEPA 2000a, 2000b, 2000c). Lakes on the low end of the pH scale are likely naturally acidic; aquatic communities of acidic lakes can be distinctly different from others with more neutral water. For example, acidic lakes may have few or no fish species and the top predators may be invertebrates, amphibians, or reptiles.

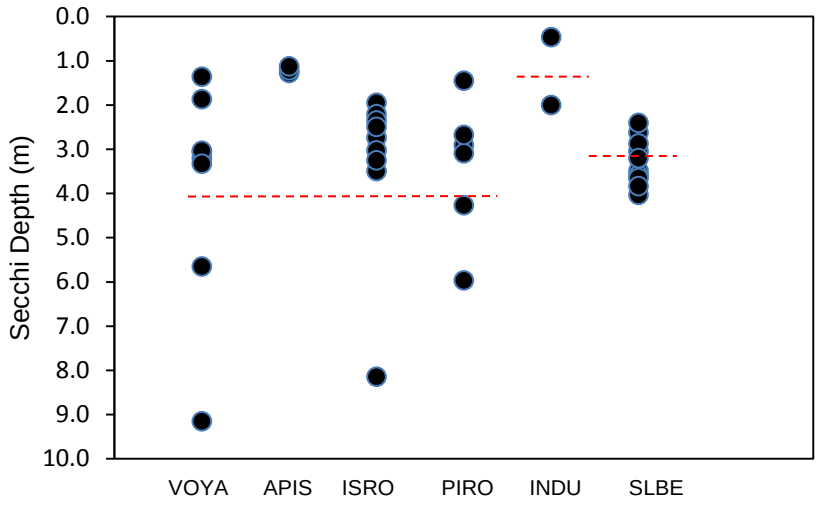

Figure 1. Mean Secchi disk depth measurements in lakes across five park units in the Great Lakes Network, 2011. The dotted lines indicatethe EPA reference criteria for the approporiate ecoregions (4.2 m for VOYA, APIS, ISRO, PIRO - USEPA 2000a; 1.44 m for INDU - USEPA 2000c; and 3.2 m for SLBE - USEPA 2000b). Measurements above the dotted lines do not meet the reference criteria. Park codes as in text.

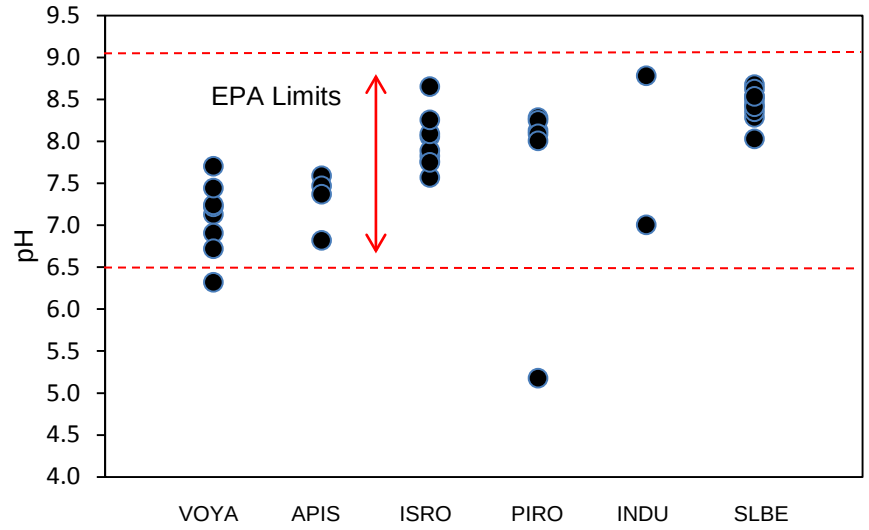

Figure 2. Mean near-surface pH values (1.0 m at VOYA, ISRO, PIRO, and SLBE; 0.5 m at APIS and INDU) of lakes across six park units in the Great Lakes Network, 2011. The dotted lines indicate the lower (6.5) and upper (9.0) USEPA reference criteria (USEPA 2000a, 2000b, 2000c). Park codes as in text.

***Chlorophyll* a**

Both waterbodies at INDU met the EPA reference criterion for chl-*a* of 3.66 µg/L, and approximately half of the lakes at SLBE fell below the EPA criterion of 2.02 µg/L (Figure 3). All of the lagoons at APIS and most of the lakes at VOYA, ISRO, and PIRO had mean chl-*a* concentrations above the criterion of 1.38 µg/L. The criteria are stringent and for some ecoregions the number of lakes sampled to develop the criteria was inadequate, which could bias

the criteria. Specifically, the chl-*a* criterion using the fluorometric method of analysis for Ecoregion VIII, level III ecoregion 50 (that of VOYA, APIS, ISRO, and PIRO) was derived from only two samples (USEPA 2000a). At this time, it is more important to heed the status and trends in the trophic state of the lakes (see below) than to be concerned about exceeding EPA reference criteria for chl-*a*.

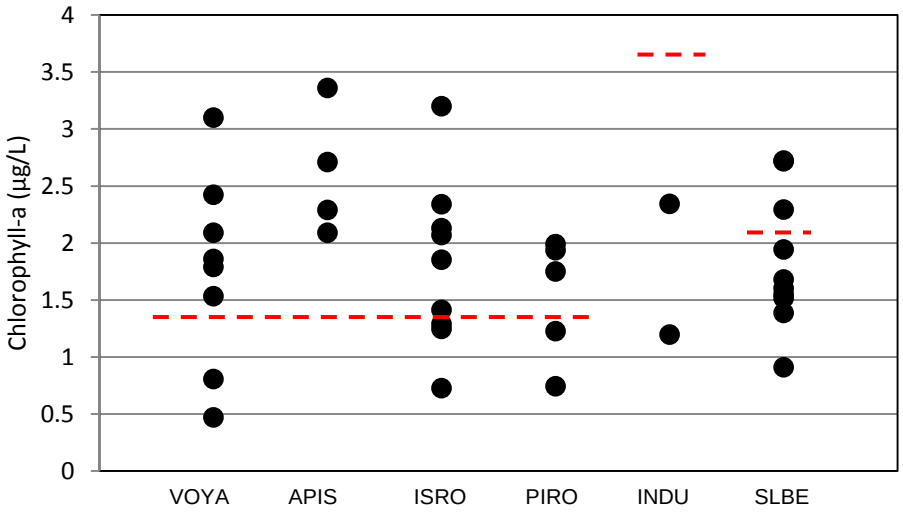

Figure 3. Mean chlorophyll *a* values of lakes across six park units in the Great Lakes Network, 2011. The dotted lines indicate the EPA reference criteria for the approporiate ecoregions (1.38 µg/L for VOYA, APIS, ISRO, PIRO - USEPA 2000a; 3.66 µg/L for INDU - USEPA 2000c; and 2.02 µg/L for SLBE - USEPA 2000b). Measurements above the dotted lines do not meet the reference criteria.The reference criterion for INDU was calculated via regression so the laboratory method of analysis was consistent across parks (i.e., fluorometric rather than spectrophotometric). Park codes as in text.

Nutrients

Nutrient concentrations are very low in many lakes – near method detection limits for TP and NO_3+NO_2-N and often below method quantitation limits. However, because the reference criteria are also very low, many lakes at VOYA, APIS, ISRO, and PIRO exceeded the reference criteria for TP, TN, and NO_3+NO_2-N (Figures 4, 5, and 6). The majority of lakes in these parks do not receive direct anthropogenic inputs (e.g., fertilizer runoff, failing septic systems, sewage treatment plant effluent), so sources of phosphorus and nitrogen are likely from within the lakes (re-suspension from lake sediment during mixing) or from atmospheric deposition. Little Sand Bay Lagoon at APIS is an exception, as it receives runoff from a watershed that lies mostly outside of park borders. Mean TP concentration for the lagoon in 2011 was 22 ug/L, which was higher than any of the other lakes sampled at any park (though considerably lower than the 52 ug/L measured in 2010). The lagoons at APIS are not really lakes, however, and probably should not be held to the same standards. The lagoons are better classified as wetlands with open water areas. Nutrient criteria have not been developed for wetlands in Wisconsin.

With the greater amount of surrounding agricultural and developed land at INDU and SLBE, some lakes in these parks are subject to direct anthropogenic inputs. Yet the majority of lakes in

these two parks have mean TP and TN concentrations below the reference criteria (Figures 4 and 5). As in the other four parks, mean concentrations of NO_3+NO_2-N in many INDU and SLBE lakes exceed the reference criteria.

Miners Lake (PIRO) and North Bar and Otter lakes (SLBE) have particularly high mean concentrations of NO_3+NO_2-N (191, 315, and 225 ug/L, respectively). While not reaching levels that threaten human health (the drinking water standard for nitrate is 10,000 ug/L), the consistently high levels in these lakes are of interest and warrant further study. Our attempts to get funding for groundwater studies have been unsuccessful to date; additional sources of funding should be sought. If the sources of NO_3+NO_2-N are anthropogenic, appropriate management actions can be initiated.

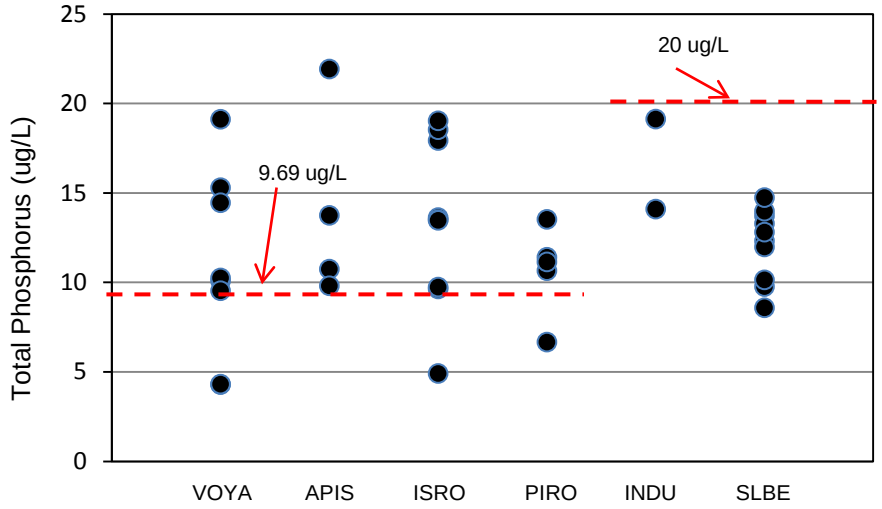

Figure 4. Mean total phosphorus (TP) levels for lakes across six parks in the Great Lakes Network, 2011. The dotted lines indicate the USEPA reference criteria for the approporiate ecoregions (9.69 µg/L for VOYA, APIS, ISRO, PIRO - USEPA 2000a; 20 µg/L for INDU and SLBE - USEPA 2000c, USEPA 2000b.) Park codes as in text.

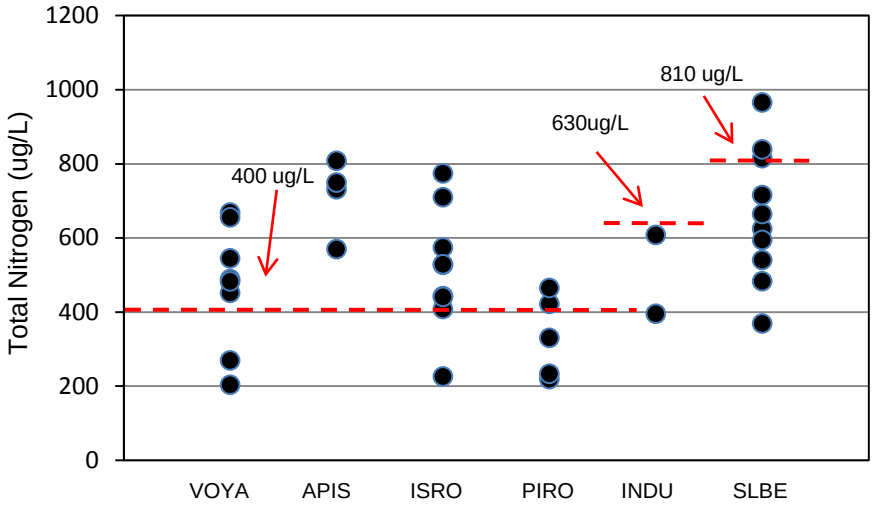

Figure 5. Mean total nitrogen (TN) levels for lakes across six parks in the Great Lakes Network, 2011. The dotted lines indicate the USEPA reference criteria for the approporiate ecoregions (400 µg/L for VOYA, APIS, ISRO, PIRO - USEPA 2000a; 630 µg/L for INDU - USEPA 2000c, and 810 µg/L for SLBE - USEPA 2000b.) Park codes as in text.

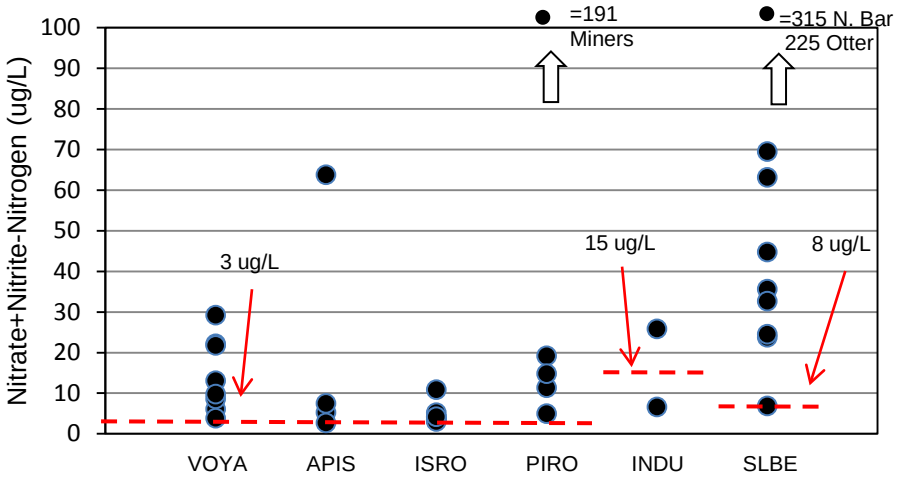

Figure 6. Mean nitrate+nitrite-nitrogen (NO_3+NO_2-N) levels for lakes across six parks in the Great Lakes Network, 2011. The dotted lines indicate the USEPA reference criteria for the approporiate ecoregions (3 µg/L for VOYA, APIS, ISRO, PIRO - USEPA 2000a; 15 µg/L for INDU - USEPA 2000c, and 8 µg/L for SLBE - USEPA 2000b.) Note the break in the scale for lakes at PIRO and SLBE. Park codes as in text.

Trophic State

Carlson and Simpson (1996) define trophic state as the total algal biomass in a waterbody at a given time and location. The Carlson trophic state index (TSI; Carlson 1977) of a lake can be calculated using values of Secchi depth, chl-*a* concentration, or TP concentration. We used chl-*a* concentration, which is the preferred method, to calculate TSI for lakes in 2011. Most GLKN index lakes are mesotrophic (Figure 7), with TSI values between 30 and 50. Generally, lakes

with a TSI <30 are considered oligotrophic and usually have clear water and low phosphorus levels, while lakes with TSI values >50 are considered eutrophic and usually have limited transparency and high phosphorus concentrations (Wetzel 2001).

See Appendices A-F for calculations of TSI in 2011 based on Secchi, TP, and chl-*a*.

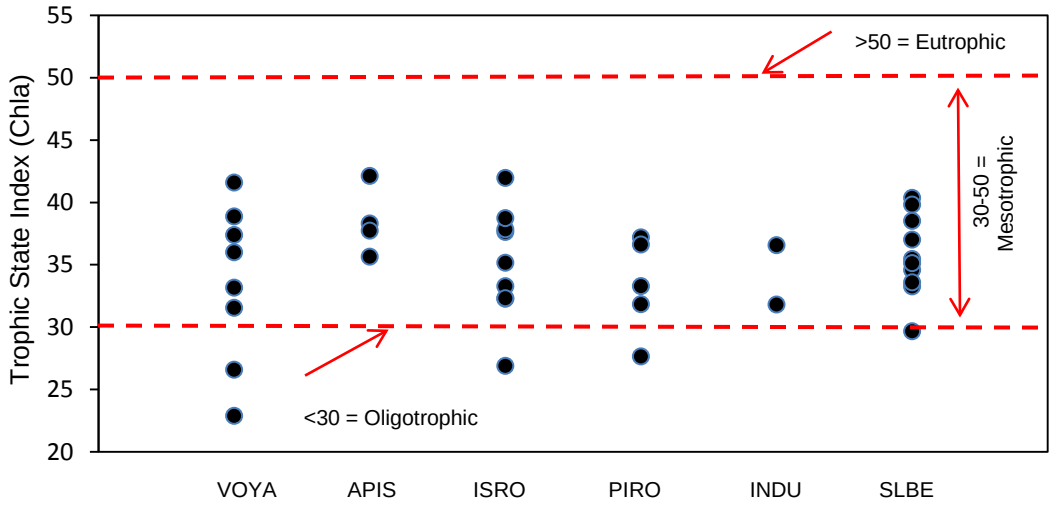

Figure 7. Trophic state indices calculated from mean chlorophyll-*a* measurements of lakes across Great Lakes Network parks, 2011. Park codes as in text.

Summary

The EPA's criteria for defining what constitutes a reference condition are stringent, based on the 25th percentile of all sampled lakes in each EPA-defined ecoregion. Because most of the inland lakes monitored through this protocol have been protected since the parks were created, it is surprising that many of them do not meet these criteria. The ecoregions defined by the EPA are large, often including major portions of several states. It may be that the park lakes we monitor differ from the other lakes in their respective ecoregions, as was found by Lafrancois et al. (2009) in a study of lakes on the Grand Portage Indian Reservation (Minnesota). The higher nutrient and chl-*a* concentrations and shallower Secchi measurements of many of our sampled lakes may be due to naturally occurring conditions (e.g., tannic acid, soil type, geology, landscape position) rather than degradation. An analysis similar to that of Lafrancois et al. (2009) is warranted for the lakes in the six parks included in this report to determine whether the EPA reference criteria are appropriate for the park lakes.

Challenges and Opportunities

The water quality monitoring program faces a number of challenges every year. Consistency across parks and years and conducting monitoring at all six parks every year are probably the two biggest challenges. Consistency issues include changes in personnel from year to year, subtle differences in data and sample collection techniques among personnel, differences in the timing of data and sample collection among years and across parks, differences among multiprobes, and differences among contract laboratories.

In the first years of implementing the monitoring program, some inconsistencies were unavoidable. However, we have made improvements every year. With multi-year agreements in place for laboratory analyses, we expect to avoid many of the contracting hassles we experienced in prior years and to receive more reliable results. We have had less turn-over of personnel in recent years, further increasing our consistency.

We continue to add elements to our routine monitoring through partnerships with researchers and/or assisting with other park projects. Our data have become increasingly useful, as demonstrated by the 11 requests for data we received in fiscal year 2011. We now have a vertical array of continuously logging thermistors in three lakes, one each at ISRO (Lake Richie), VOYA (Little Trout Lake), and PIRO (Grand Sable), increasing the number of data points we need to manage by a couple of orders of magnitude.

Park-Specific Comments and Additional Results

In the following sections, we show preliminary explorations of select parameters at individual parks using the entire period of record for our vital sign monitoring effort. While statistical analyses of trends are possible with the amount of data we have, we have not conducted such analyses because we feel the early monitoring inconsistencies may confound any trends. However, we are beginning to see some hints of trends, and the collection of more data will make future analyses more robust.

In the next sections we also discuss any additional sampling conducted in each park, and conclude with comments on logistics and plans for future monitoring.

Voyageurs National Park

Additional Data Collected and Exploration of Trends

In June 2011, with the help of park staff, we deployed an array of continuously logging temperature probes in Little Trout Lake. The probes record temperature hourly from the surface of the water to the lake bottom, at approximately 1-m intervals from 0 to 16 m depth, at 20 m, 25 m, and bottom (approximately 28 m). Coupled with our synoptic profile data, we expect to learn much about the timing and depth of mixing, as well as the suitability of conditions for coldwater fish species. We downloaded the summer data in September 2011 and re-set the array for winter conditions under the ice.

Several mixing events are visible in the summer 2011 data (Figure 8). Cooler temperatures rose to the surface for several days in mid-to-late June, and again in mid-September, prior to the fall turnover; during the mid-summer months, temperatures >20 °C extended to 5 m or more on multiple occasions. Damstra and Elias (2012) showed adequate habitat existed throughout the summer for both lake trout (*Salvelinus namaycush*) and cisco (*Coregonus artedii*).

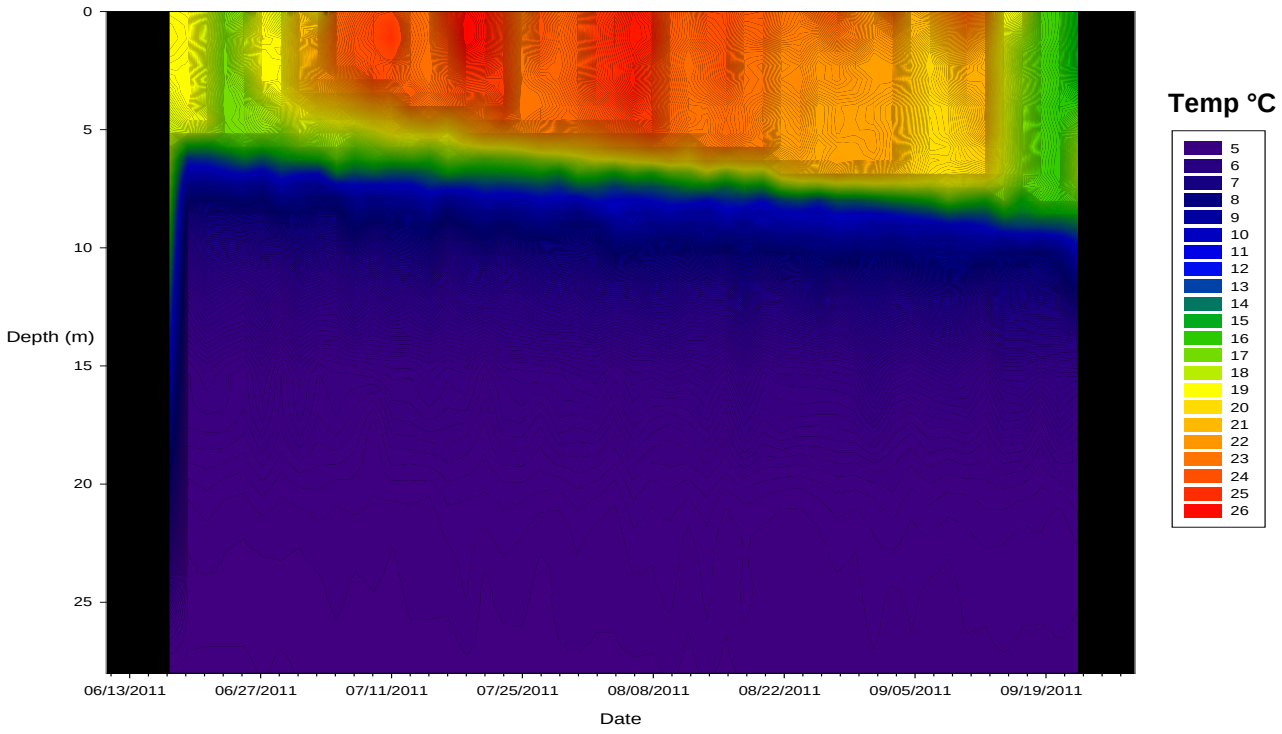

Figure 8. Hourly temperature data collected throughout the water column in Little Trout Lake, Voyageurs National Park, 17 June – 22 September 2011.

When our monitoring program began in 2006, conditions were droughty—especially as the summer progressed—and lake levels were low. In subsequent years the amount of precipitation increased, and lake levels generally responded accordingly. All of the index lakes except Locator have seen increases in water levels since 2006 (Figure 9). The failure of a beaver dam downstream of Locator Lake in late 2008 likely caused the lowering of lake levels. Acquiring more information on beaver activity upstream and downstream of each lake will greatly increase our understanding of water level changes in the index lakes.

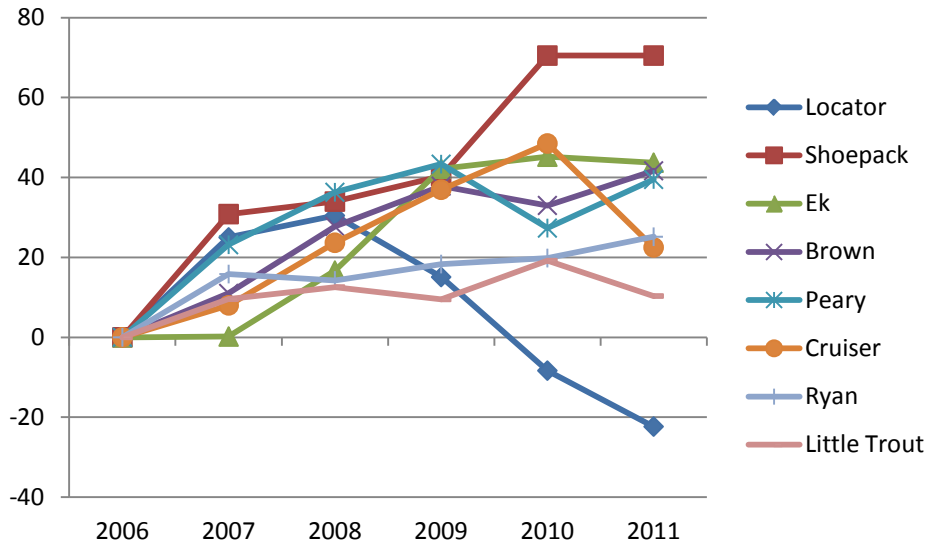

Figure 9. Mean summer lake levels, Voyageurs National Park, 2006-2011. Water level is measured relative to a permanent benchmark at each lake. All lake water levels are relative to the 2006 mean, which is set to zero.

Sediment samples collected from 16 lakes in 2010 were analyzed for diatom community composition. This marked the second sampling of these lakes (the first sampling occurred in 2006) and allowed for analysis of change in diatom communities over the last five years. Preliminary results of this analysis show relatively large changes in diatom community composition in several lakes since 2006 (Edlund et al., in prep.). Shallow lakes, such as Ek, Jorgens, and Ryan may be experiencing mixing less frequently or to shallower depths. Changes in diatom species at Ek, Jorgens, Cruiser, and Little Trout lakes suggest slight increases in pH, conductivity, and nutrients. That these potential changes may not be evident from our synoptic data (below) substantiates the value of continued diatom monitoring, as diatoms serve as continuous integrators of water quality. Changes in diatom community composition may indicate changes in water chemistry that we are unable to capture in only three visits per summer.

If changes are occurring in the field parameters we measure (specific conductance, pH, and water clarity as measured by Secchi disk depth), they are not obvious (Figures 10a, b, and c). Some lakes may be experiencing a slight decrease in specific conductance (e.g., Peary, Ryan); Cruiser and Ek lakes may be exhibiting a slight increase in pH, but in general, pH measurements are surprisingly variable from year to year. The mean TSI at all index lakes at VOYA seems to be trending downward (Figure 10d), and may reflect differences in weather (e.g., hot, dry years may lead to greater algal production). Shoepack, Ek, and Peary lakes, which are relatively shallow, were eutrophic (TSI >50) in 2006 and 2008 (2007 chl-*a* data are not available), but dropped into the mesotrophic range thereafter (TSI between 30 and 50). Cruiser Lake began as mesotrophic, but since has dropped into the oligotrophic category (TSI <30). Little Trout Lake was also in the oligotrophic range in 2011.

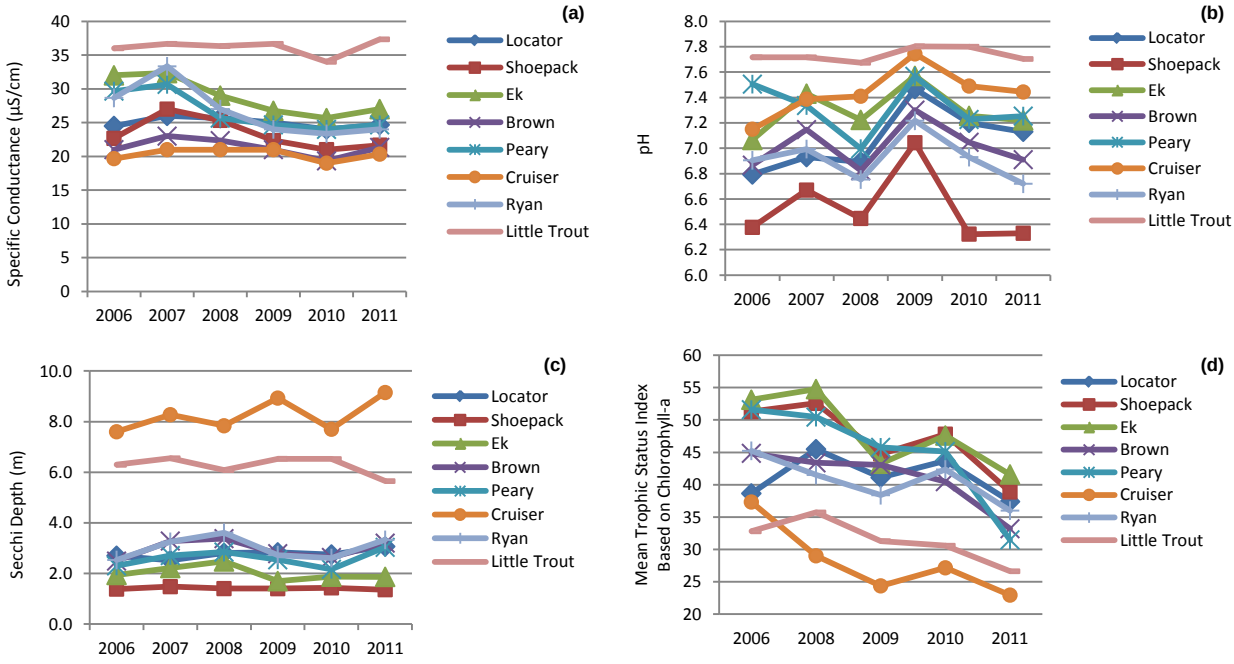

Figure 10. Mean measurements of specific conductance and pH at 1 m depth (**a** and **b**, respectively), water clarity as measured by Secchi disk depth (**c**), and Trophic State Index as calculated from chlorophyll *a* measurements (**d**) for index lakes at Voyageurs National Park, 2006 - 2011. Chlorophyll *a* data are not available for 2007. Park codes as in text.

With the exceptions of TP in Shoepack and Ek Lakes (decreasing, and perhaps increasing slightly, respectively), mean concentrations of TP and TN have not changed appreciably since 2006 (Figures 11a, 11b). Cruiser and Little Trout lakes have consistently been below EPA reference criteria; Shoepack, Ek, and Peary lakes have been above EPA reference criteria. Locator, Brown, and Ryan lakes, have shown minor variations above and below the EPA reference criterion for TP, but have been slightly greater than the TN criterion.

Even though several of the index lakes exceed the EPA reference criterion for TP, none of the lakes exceed Minnesota's eutrophication criterion (30 ug/L) for lakes designated as Aquatic Recreation Use (Class 2B) for the Northern Lakes and Forest Ecoregion (Heiskary and Wilson 2008). Minnesota has also established eutrophication criteria for the response variables chl-*a* (9 ug/L) and Secchi depth (2.0 m). Several lakes have occasionally exceeded the chl-*a* criterion and/or had Secchi depth measurements that were shallower than the criterion. Cruiser and Little Trout lakes are subject to stricter state criteria (TP = 12 ug/L, chl-*a* = 3 ug/L, and Secchi depth = 4.80 m) because they are designated as lake trout lakes. They have met these criteria.

Variations in the concentrations of NO_3+NO_2-N and NH_4-N are generally consistent across lakes (Figures 11c, 11d; that is, lakes experienced increases and decreases in the same years. Exceptions are Ryan Lake for NO_3+NO_2-N and Shoepack Lake for NH_4-N. Causes for these exceptions are unknown at this time. The unusually high NO_3+NO_2-N value for Locator Lake in 2006 was due to a single sample in July (102 ug/L) that may have been contaminated, as levels have been consistently low since then.

Silica is also a nutrient required by plants (e.g., diatoms) and animals (e.g., freshwater sponges). Concentrations of silica have varied little since 2006, with the exception of Brown Lake in 2008 (Figure 11e). Silica is incorporated into the cell walls of diatoms and the skeletal structure of freshwater sponges, and a portion of it is released when the diatoms and sponges die. The relatively high concentration of silica in Brown Lake in 2008 may have been due to the timing of a diatom die-off and subsequent bloom.

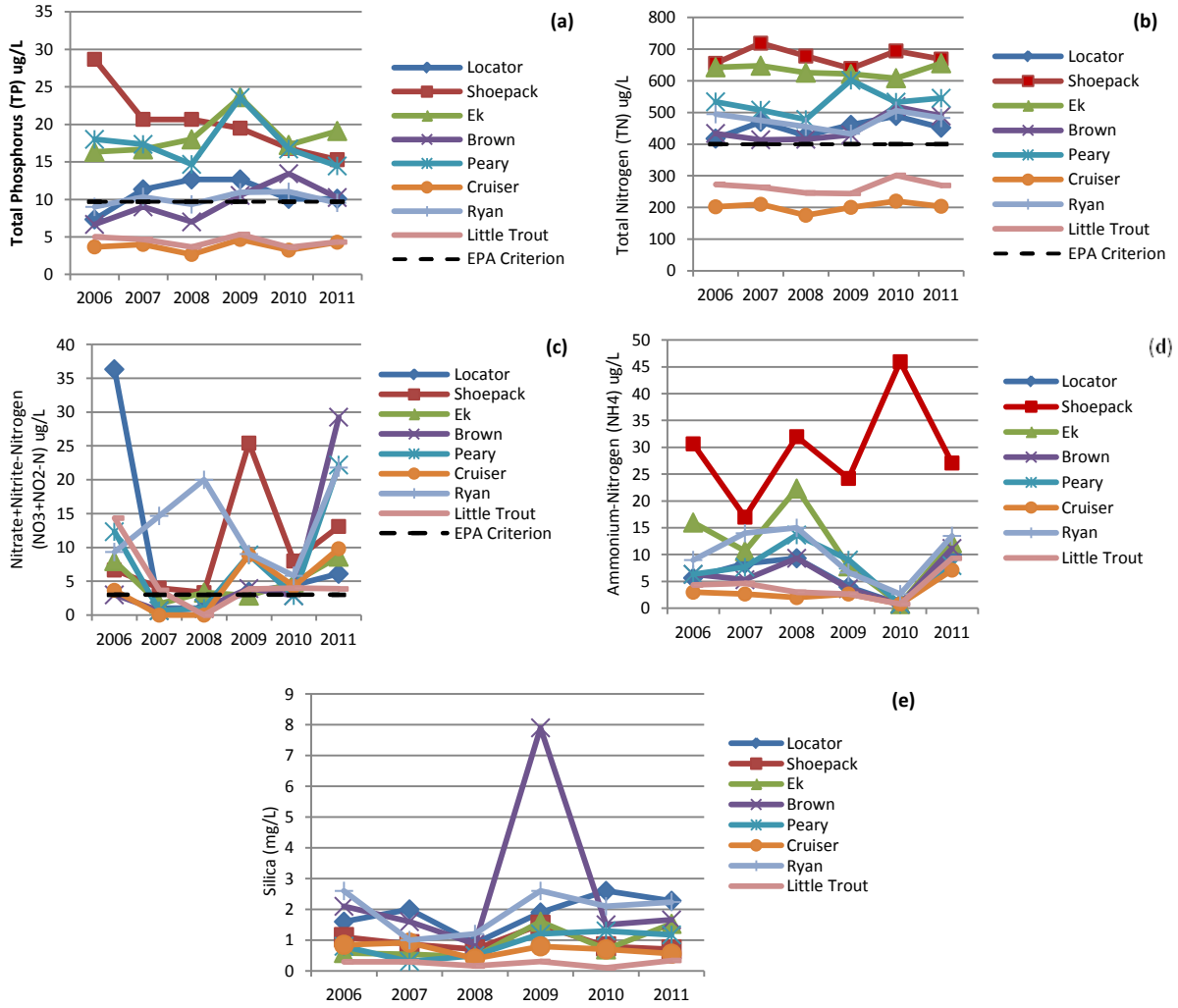

Figure 11. Mean concentration of nutrients in lakes at Voyageurs National Park 2006 – 2011: total phosphorus (**a**), total nitrogen (**b**), nitrate+nitrite-nitrogen (**c**), ammonium-nitrogen (**d**), and silica (**e**).

Once again we collaborated with USGS on mercury sampling in five lakes (Ek, Shoepack, Brown, Ryan, and Peary) in 2011. Such collaboration is beneficial to both agencies, as it reduces costs yet continues the flow of data for lakes susceptible to high levels of mercury methylation. Total mercury concentrations (THg) generally increased slightly between 2006 and 2009, then decreased slightly after 2009 (Figure 12a). Methylmercury concentrations did not follow a

similar pattern (Figure 12b). It is likely that characteristics of individual watersheds play an important role in the methylation process (e.g., size of watershed, amount of wetland area, vegetation cover type) and, therefore, in determining the concentrations of methylmercury observed in the water and biota of these lakes.

A proposal to the NPS/USGS Water Quality Partnership Program was funded in 2012 (Brigham et al. 2012.). The purpose of the project will be to analyze recent (2000 – 2012) trends in total mercury and methylmercury concentrations in select lakes at VOYA, and to examine trends in atmospheric deposition of key contaminants. Data analysis will begin after final sample collection and lab analyses in 2012, and we expect it will provide examples of how concentrations of a key contaminant in lakes may be changing in response to changes in pollutant loads.

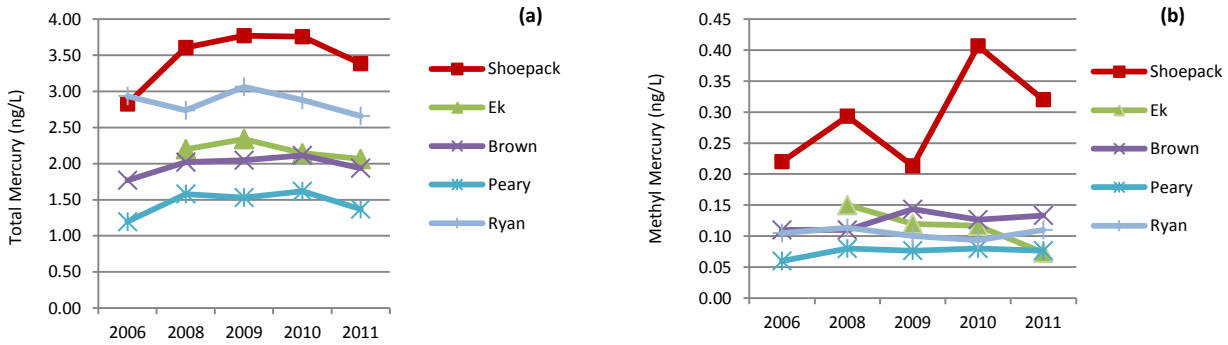

Figure 12. Mean total mercury (**a**) and methyl-mercury (**b**) concentrations in five inland lakes at Voyageurs National Park, 2006-2011 (samples were not collected in 2007).

Of the other parameters we measure annually, alkalinity, DOC, and Cl^- showed no clear trends (Figures 13a, b, and c). Chloride levels showed the same general rise-and-fall pattern across lakes, with minor exceptions. Sulfate concentrations seem to be declining in all lakes (Figure 13d), though Ryan and Ek lakes showed a sharp increase in 2011. Cations are not included here, as they are strongly correlated with specific conductance, which is discussed above. See Appendix A for all of the data.

We also collected water samples for analysis of total suspended solids at four lakes (Ek, Peary, Cruiser, and Little Trout). Results (reported in Appendix A) will be used by our collaborators at the St. Croix Watershed Research Station in a climate change modeling project.

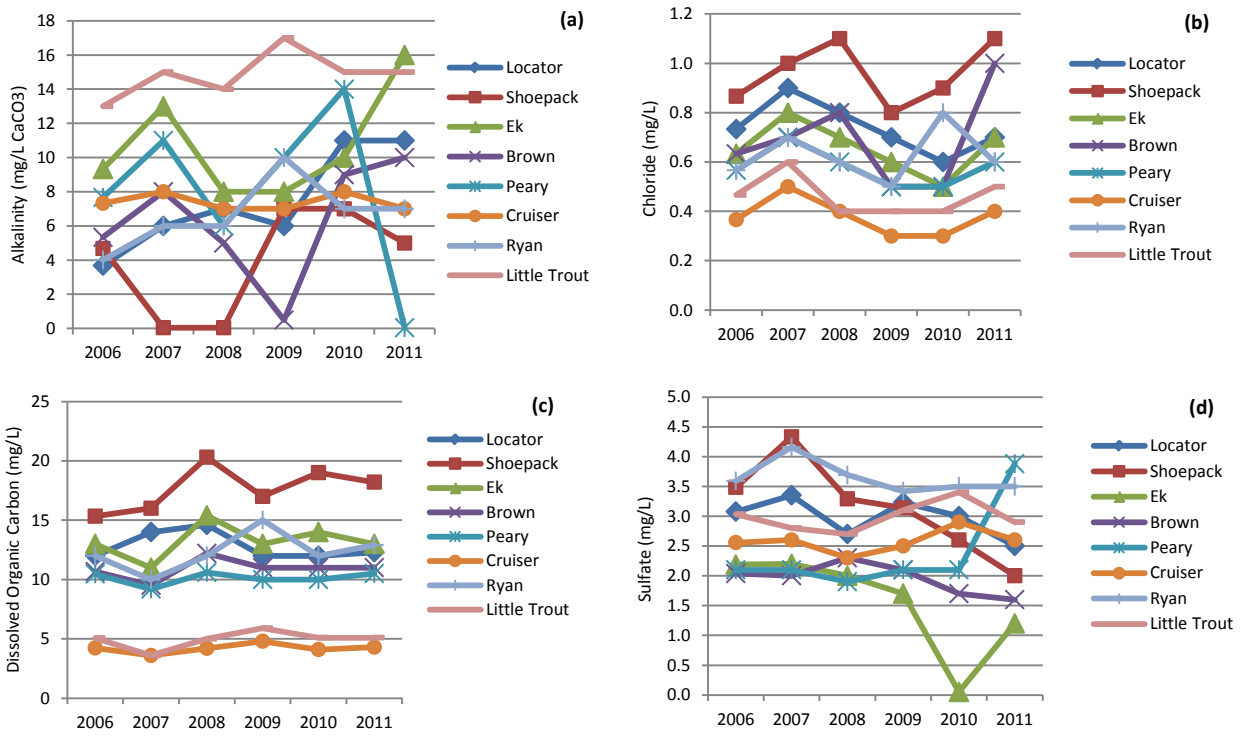

Figure 13. Concentrations of alkalinity **(a)**, chloride **(b)**, dissolved organic carbon **(c)**, and sulfate **(d)** in index lakes at Voyageurs National Park, 2006-2011.

Logistics

Jaime LeDuc, who is in a position shared by the park and the Network through the Student Career Experience Program (SCEP) returned as crew leader in 2011. Additional field assistance was acquired by GLKN paying for park staff time. All index lakes were sampled on schedule except for Little Trout Lake in the final round of sampling. This lake was sampled by the Network aquatic ecologist and a park biotech in September, at which time the temperature array was set for under-ice condition.

We expect to continue monitoring the eight index lakes in 2012, with J. LeDuc again as crew leader. The temperature array in Little Trout Lake continues to log data hourly, year-round.

Apostle Islands National Lakeshore

Additional Data Collected and Exploration of Trends

In the late summer of 2008, we installed permanent benchmarks at Stockton Island and Little Sand Bay (LSB) lagoons and temporary benchmarks at Michigan and Outer Island lagoons (these two lagoons are in designated wilderness areas where permanent benchmarks are not allowed). At the time, it was thought that if all the lagoons behaved similarly, then perhaps the two with permanent benchmarks could serve as proxies for the other two. Our data show that water levels do not behave similarly in the four lagoons (Figure 14a). Water level in the Michigan Island Lagoon has generally mirrored that of Lake Superior – rising and falling in

sync. In July 2011, we were able to measure the water level in the lagoon relative to Lake Superior (it required extremely calm water conditions), and found the two waterbodies to be within 2 cm of one another (basically, the same level, accounting for the possible margin of error). Stockton Island and LSB lagoons may or may not track Lake Superior levels, depending on whether each lagoon is connected to Lake Superior at the time of sampling. When the outlets to the lake are open, the lagoons are at the same level as the lake, though seiches may affect the lagoon water levels. When the outlets are closed, water in the lagoons may back up to levels higher than Lake Superior. The water levels in Outer Island Lagoon fluctuate independently of Lake Superior levels, and generally behave more like an inland lake than a coastal wetland lagoon. In July 2011, we measured the lagoon water level at approximately 22 cm higher than Lake Superior.

More information on the water levels of the lagoons and their connection to the groundwater table would be of interest. The die-back of juniper (*Juniperus communis*) on the dunes is currently under investigation by the park, and may be related to water levels. Mean 2011 water levels in all four lagoons were lower than mean 2009 levels (Figure 14b; 2008 is not included because only one or two measurements were taken, later in the summer). As our climate changes, understanding the connection of the lagoons to the groundwater will help predict how changing Lake Superior water levels may affect the lagoons.

In 2011, sediment samples were collected from Michigan, Outer, and Stockton Islands lagoons for analysis of diatom communities. A sample was not collected from LSB lagoon because the flow of water there prevents sediments from accumulating, except in the backwaters. This marked the second sampling of these lagoons (the first sampling occurred in 2007) and will allow analysis of change in diatom communities over the last five years.

Mean specific conductance may be declining slightly in Michigan, Outer, and LSB lagoons (Figure 15a). Mean pH shows a large amount of interannual variation at Stockton and LSB lagoons, which is likely explained by the influence of Lake Superior water. When the outlet to the lake is open, the lagoon water closely matches lake water; when the outlet is closed, lagoon water is influenced by watershed characteristics. The trophic state of all four lagoons, calculated using chl-*a* concentration, has declined since 2008, though all lagoons remain in the mesotrophic category (TSI between 30 and 50; Figure 15c). TSI calculated using TP concentrations shows a very different pattern over the same time period (Figure 15d). Higher TP concentrations either have not led to increased algae production, perhaps due to the dark tannin-staining of the water, or zooplankton may have reduced the algae biomass through grazing.

How to read the graphs in Figure 14a using the solid line (Lake Superior) as an example.

- The water level of the June 2009 sampling date is set to zero, and all subsequent measurements are relative to that time.
- The water levels on the July and August 2009 sampling dates were approximately 5 cm and 12 cm higher, respectively, than the June level.
- In June 2010, the water level was approximately 14 cm lower than in June 2009.
- In July and August 2010, the level rose slightly but remained approximately 11 cm lower than the June 2009 level.
- In June 2011, Lake Superior was 15 cm lower than June 2009.
- July and August 2011 water levels rose 10-12 cm since June, but remained slightly lower than the June 2009 level.

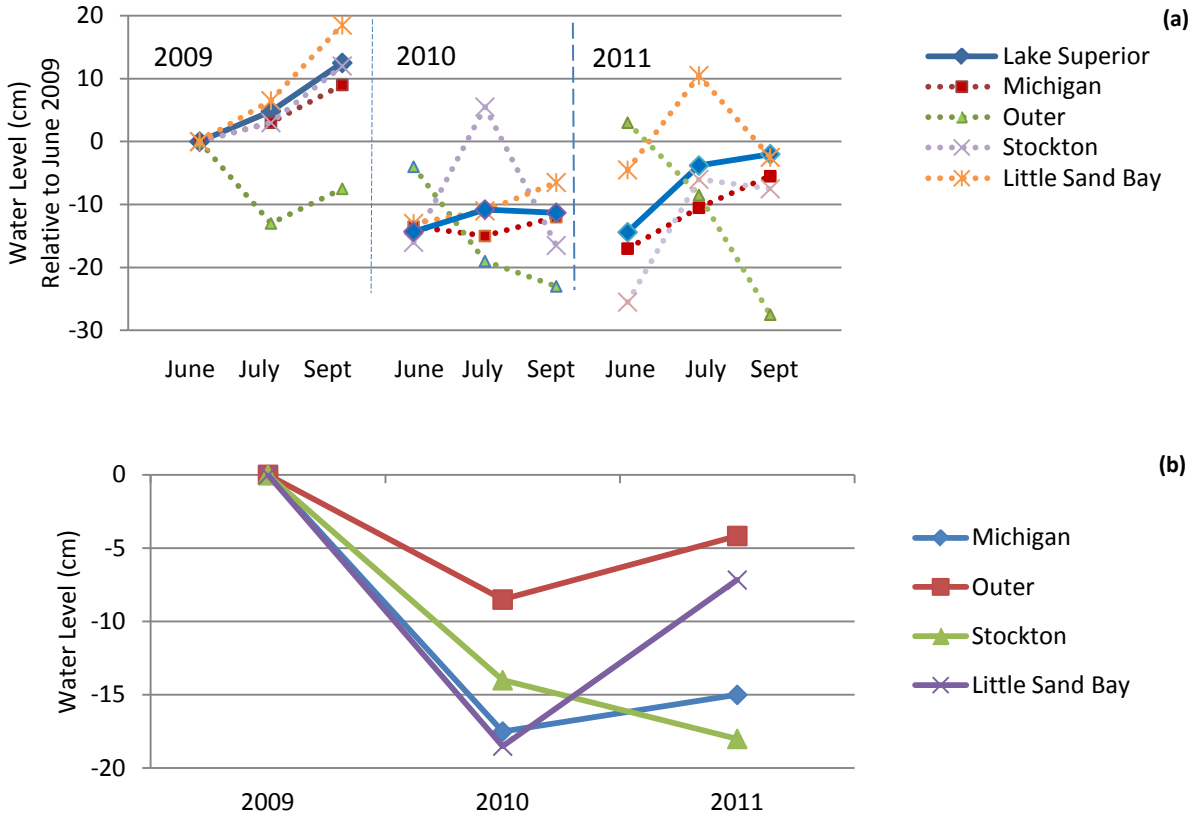

Figure 14. (a) Water levels of Apostle Island lagoons and Lake Superior. All levels are relative to June 2009, which is set to zero. Water levels are measured relative to a benchmark at each lagoon. Lake Superior data are acquired from the Army Corps of Engineers. **(b)** Mean summer water levels of Apostle Island lagoons relative to 2009, which is set to zero.

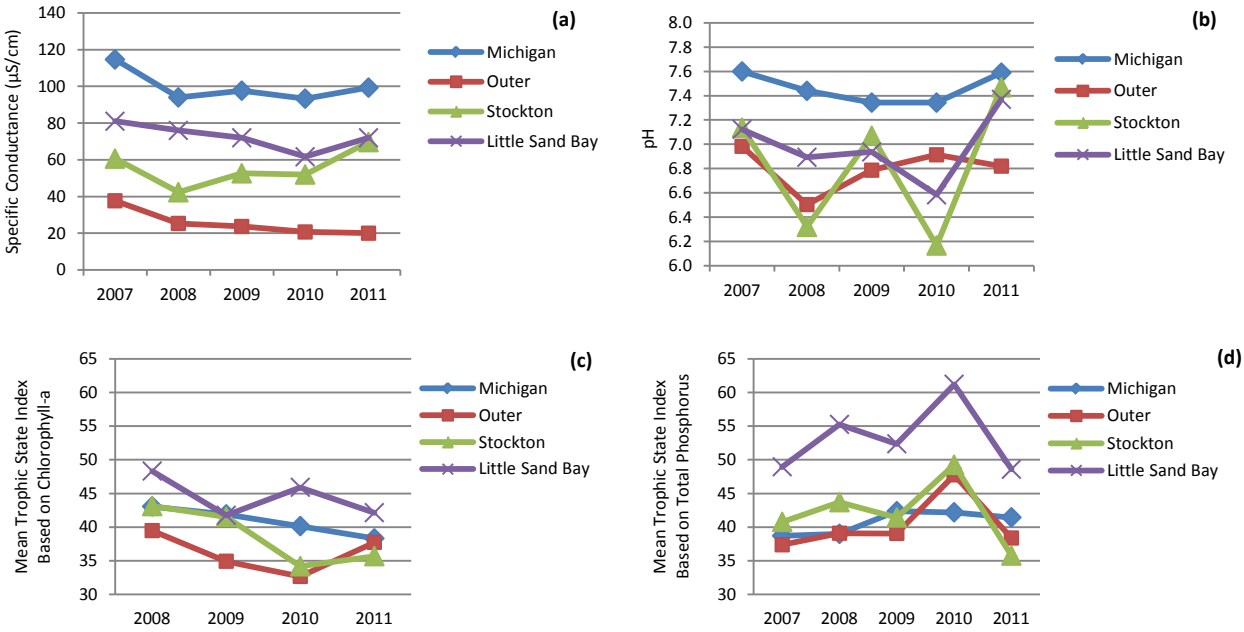

Figure 15. Mean measurements of specific conductance and pH at 0.5 m depth (**a** and **b**, respectively), and trophic state index values calculated using chlorophyll *a* concentration (**c**) and total phosphorus concentration (**d**) for lagoons at Apostle Islands National Lakeshore, 2007-2011. Chlorophyll *a* data are not available for 2007.

Any potential trends in nutrient concentrations between 2007 and2011 are masked by high variability (Figures 16a-e). This is likely due in part to the relatively rapid rates of nitrification that occur in these lagoons, which function more like wetlands than like lakes. TP and TN concentrations at LSB and Stockton Island lagoons are affected by the exchange of water with Lake Superior, and in the case of LSB, runoff from the entire watershed is received via the Little Sand River. This watershed differs from those of the other lagoons in land use and ownership, as agriculture occurs on privately held parcels upstream of the park. Fluctuating silica levels (Figure 16e) are similarly influenced by Lake Superior water and the timing of the growth and demise of diatoms and freshwater sponges (uptake of silica during periods of growth and release of silica upon death).

Of the other parameters we measure annually (alkalinity, DOC, and anions; cations are not included here as they are strongly correlated with specific conductance, which is discussed above; see Appendix B for all of the data), Outer Island lagoon may be experiencing a decline in sulfate concentration, or the level in 2007 may have been abnormally high. No other potential trends are evident (Figure 17a-d). Interpretation of the chemistry of Stockton Island and LSB lagoons is confounded by their intermittent connection to Lake Superior.

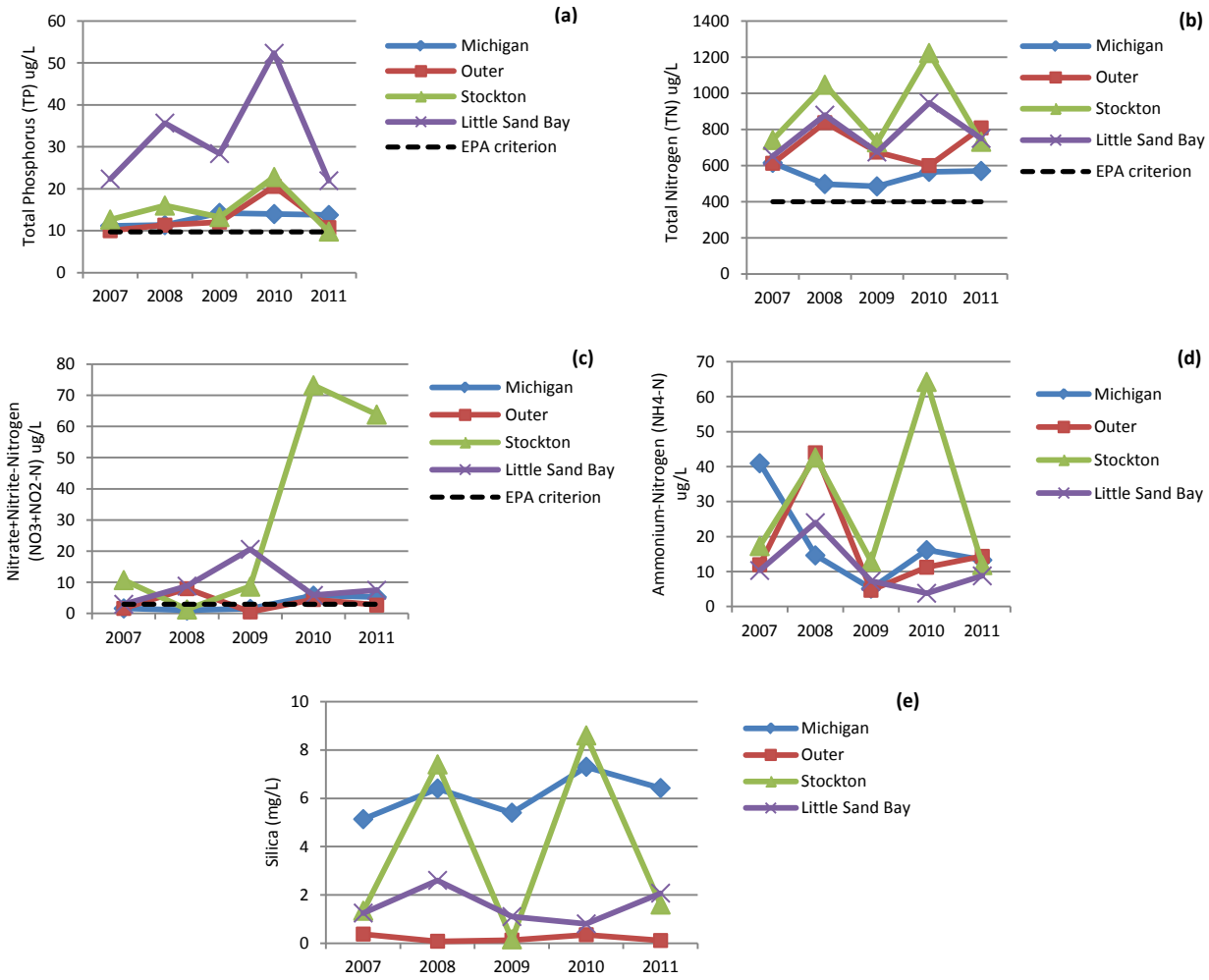

Figure 16. Mean concentration of nutrients in lagoons at Apostle Islands National Lakeshore 2007-2011: total phosphorus (**a**), total nitrogen (**b**), nitrate+nitrite-nitrogen (**c**), ammonium-nitrogen (**d**), and silica (e).

Logistics and Recommendations

All sampling was completed in 2011 by GLKN staff as planned. We expect to continue monitoring the four lagoons in 2012.

Recommendations for future monitoring are to:

1. Discontinue monitoring the lab parameters (advanced suite) at Stockton Island and LSB lagoons. The intermittent mixing of lagoon water with that of Lake Superior introduces high variability, overriding any potential evidence of trends. Discuss with park staff whether or not to continue monitoring field parameters at these lagoons.
2. Continue monitoring all parameters at Outer Island lagoon, as there is no connection with Lake Superior and this lagoon is the most lake-like of the four lagoons currently monitored at APIS.
3. Consider dropping Michigan Island Lagoon from the inland lakes protocol. The dense aquatic vegetation and accretion of peat make this system a wetland with a small amount

of open water habitat rather than a lake. Including it in a wetland monitoring protocol would be appropriate.

4. Monitor water levels in the lagoons (only if other parameters are measured) via continuous logging devices.

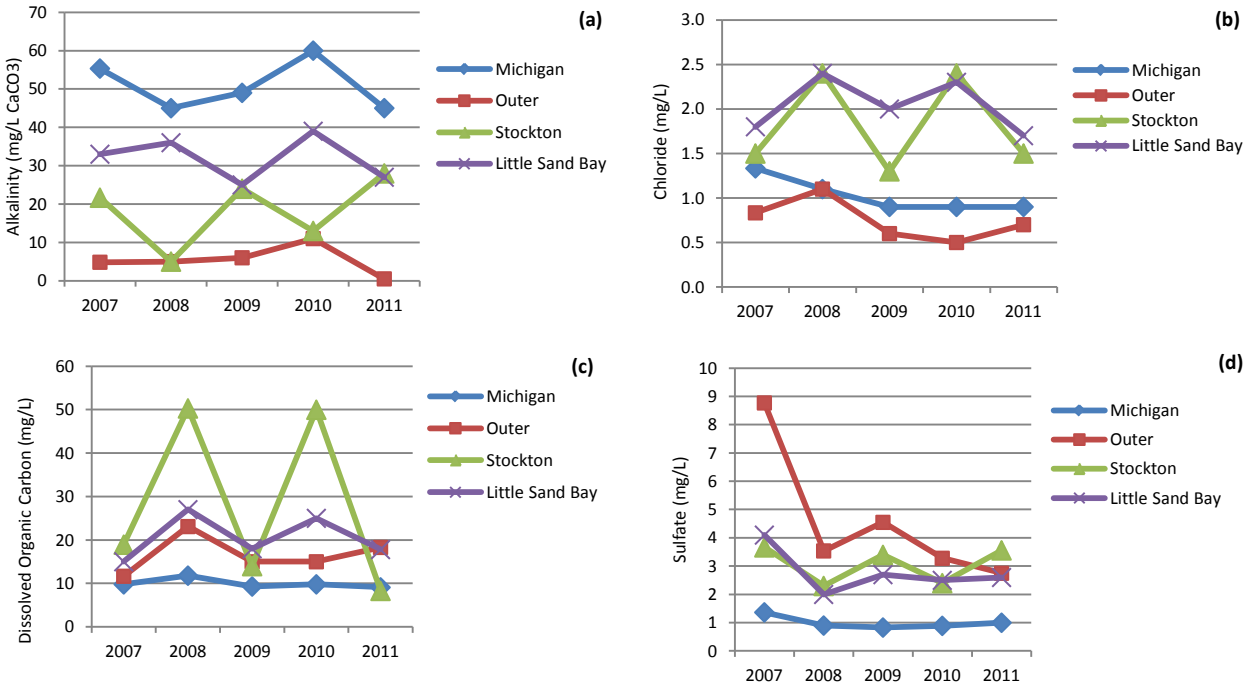

Figure 17. Concentrations of alkalinity (**a**), chloride (**b**), dissolved organic carbon (**c**), and sulfate (**d**) in lagoons of Apostle Islands National Lakeshore, 2007-2011.

Our understanding of lagoon water level fluctuations would benefit greatly from a study of groundwater connection to the lagoons. Our data suggest the lagoons do not respond uniformly to precipitation or changes in the water level of Lake Superior. Identifying the groundwater influences and the differences among the lagoons will better enable park managers to prepare for climate change.

Isle Royale National Park

Additional Data Collected and Exploration of Trends

Cyanobacterial blooms were not evident in 2011, unlike some recent years. When they have occurred in the past, we suspect that warmer temperatures, longer growing seasons, and increased frequency of mixing in the water column (which re-suspends nutrients) may have contributed to the blooms. To better understand these processes, GLKN deployed an array of temperature probes near the deepest part of Lake Richie – a lake that has experienced algal blooms in recent years – in the spring of 2010. Except for cleaning the probes and downloading

data, the array has been collecting hourly temperature data since then, year-round, throughout the water column.

Data from June through September 2011 show surface temperatures approached 28 °C in mid-July, which is quite warm for a lake of this depth (11 m) and latitude (Figure 18). Temperatures ≥20 °C extended to depths greater than 6 m, which is more than half of the water column. Complete mixing of the water column occurred in early-to-mid-June during a storm event. Partial mixing occurred twice in June and in late July due to separate rain and sustained wind events.

Koelz (1929) and Hubbs and Lagler (1949) found cisco (*Coregonus artedii*) inhabiting Lake Richie in 1929 and 1945, respectively. This species was not observed in sampling by Kallemeyn et al. (1998) in the mid-1990s, nor by assessments performed by park staff in 2011 (unpublished data), causing park resource managers to be concerned about possible extirpation of cisco from the lake. Through analysis of the data collected via the temperature array and our synoptic profile data, we have been able to determine that suitable summer habitat, with the temperature and oxygen levels required by cisco, no longer exists in Lake Richie on a consistent basis (Damstra and Elias 2012). Because cisco populations are declining and there is limited summer habitat in Lake Richie and other lakes in the park, there is now a policy of catch-and-release only for cisco in all inland lakes of the park.

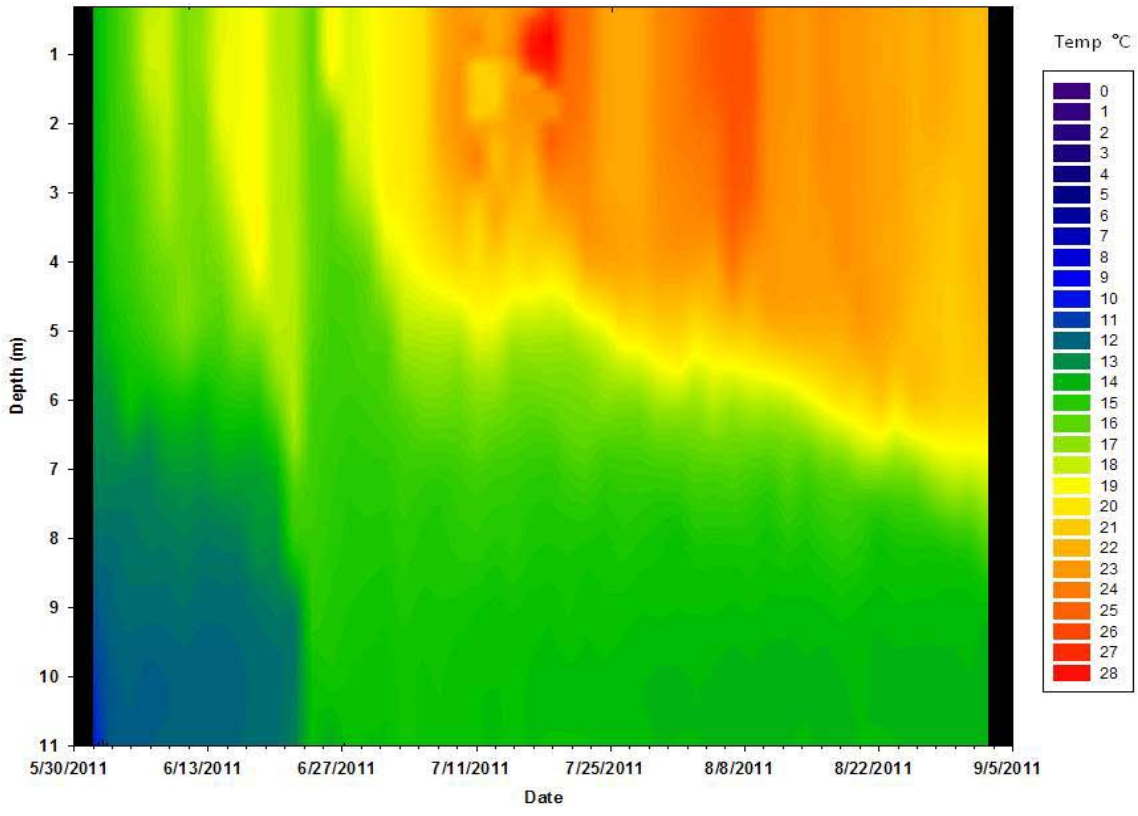

Figure 18. Hourly temperature data collected throughout the water column in Lake Richie, Isle Royale National Park, 30 May – 5 September 2011.

Water levels of index lakes generally have been highest during the first sampling round and gradually declined throughout the season. Since monitoring began in 2007, several lakes experienced their highest mean summer level in 2011 (Figure 19). Beaver Lake is the exception, with water levels on a downward trend. Large changes have occurred in several lakes, sometimes from one year to the next (e.g., 38 cm at Feldtmann between 2009 and 2010, >25 cm at Richie and Sargent between 2010 and 2011). Watershed size, basin morphometry, and beaver activity upstream or downstream of the lake are important influences on each lake's water level. More information is needed on beaver activity in the watersheds of all index lakes to determine the effects on water levels due to weather or climate from those due to beaver activity.

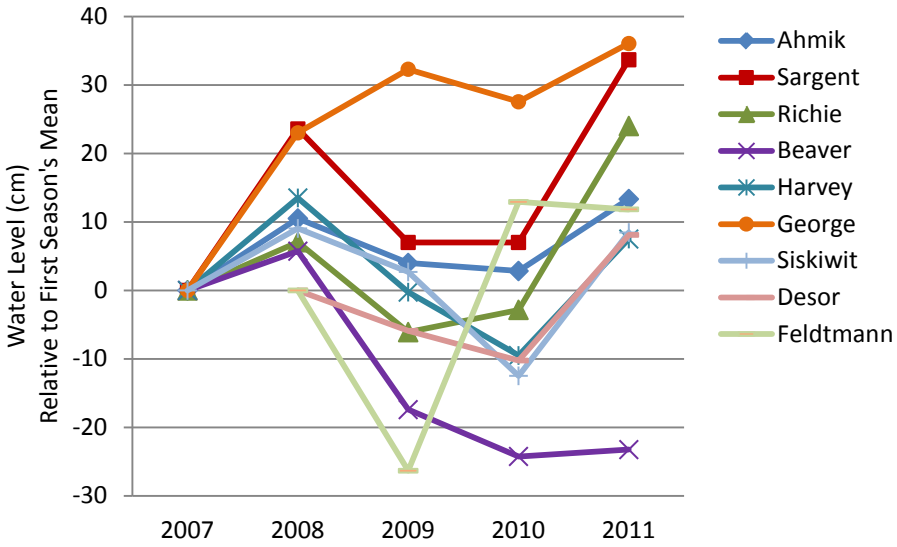

Figure 19. Mean summer water levels of index lakes at Isle Royale National Park, 2007-2011. Water level is measured relative to a permanent benchmark at each lake. All lake water levels are relative to the mean of the first season (i.e., 2007 or 2008 set to zero).

Trends in specific conductance and Secchi depth are not evident for any of the index lakes (Figures 20a and c). Mean pH values are surprisingly variable from year to year (Figure 20b), with Lake Harvey showing a slight increase, and Lake George showing a surprising decrease since monitoring began in 2007.

The mean trophic state indices as calculated by chl-*a* concentration indicate most lakes have been in the mesotrophic range (TSI values between 30 and 50) since monitoring began (Figure 20d). Siskiwit Lake tends to be oligotrophic (TSI <30), while Lake Richie has been eutrophic some years (TSI >50). Some lakes (e.g., Sargent, Desor, Harvey, George) seem to be showing a slight decrease in trophic state.

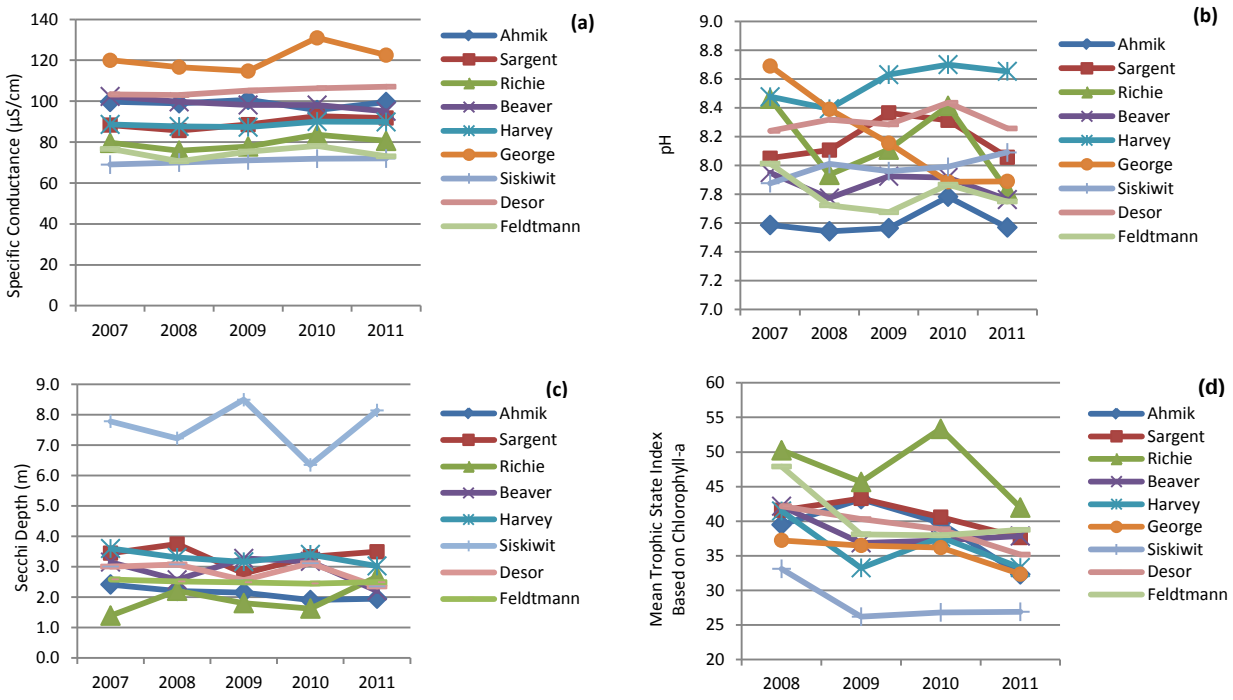

Figure 20. Mean measurements of specific conductance and pH at 1 m depth (**a** and **b**, respectively), water clarity as measured by Secchi disk depth (**c**), and Trophic State Index as calculated from chlorophyll *a* measurements (**d**) for index lakes of Isle Royale National Park, 2007-2011. Chlorophyll *a* data are not available for 2007.

Siskiwit Lake is the only lake with mean TP and TN concentrations consistently below EPA reference criteria (Figures 21a, 21b). Interannual variations in TP and TN have been relatively large in some lakes (notably, Ahmik and Richie), but no trends are evident. With the exception of Siskiwit Lake, all lakes showed a remarkably consistent pattern in mean NO_3+NO_2-N concentrations, increasing and decreasing together (Figure 21c). Relatively consistent patterns in NH_4-N concentrations also occurred, with Lake Ahmik exhibiting an exaggerated version of the variations (Figure 21d). Mean silica concentrations have seen little variation over the monitoring period, and no trends are evident (Figure 21e).

Of the other parameters we measure annually (alkalinity, DOC, and anions; cations are not included here as they are strongly correlated with specific conductance, which is discussed above; see Appendix C for all of the data), the lakes generally show patterns similar to one another, rising and falling in unison, for alk, Cl^-, DOC, and SO_4^{-2} (Figure 22a-d). Any hints of trends in these parameters are weak at best, with interannual variations overriding potential trends.

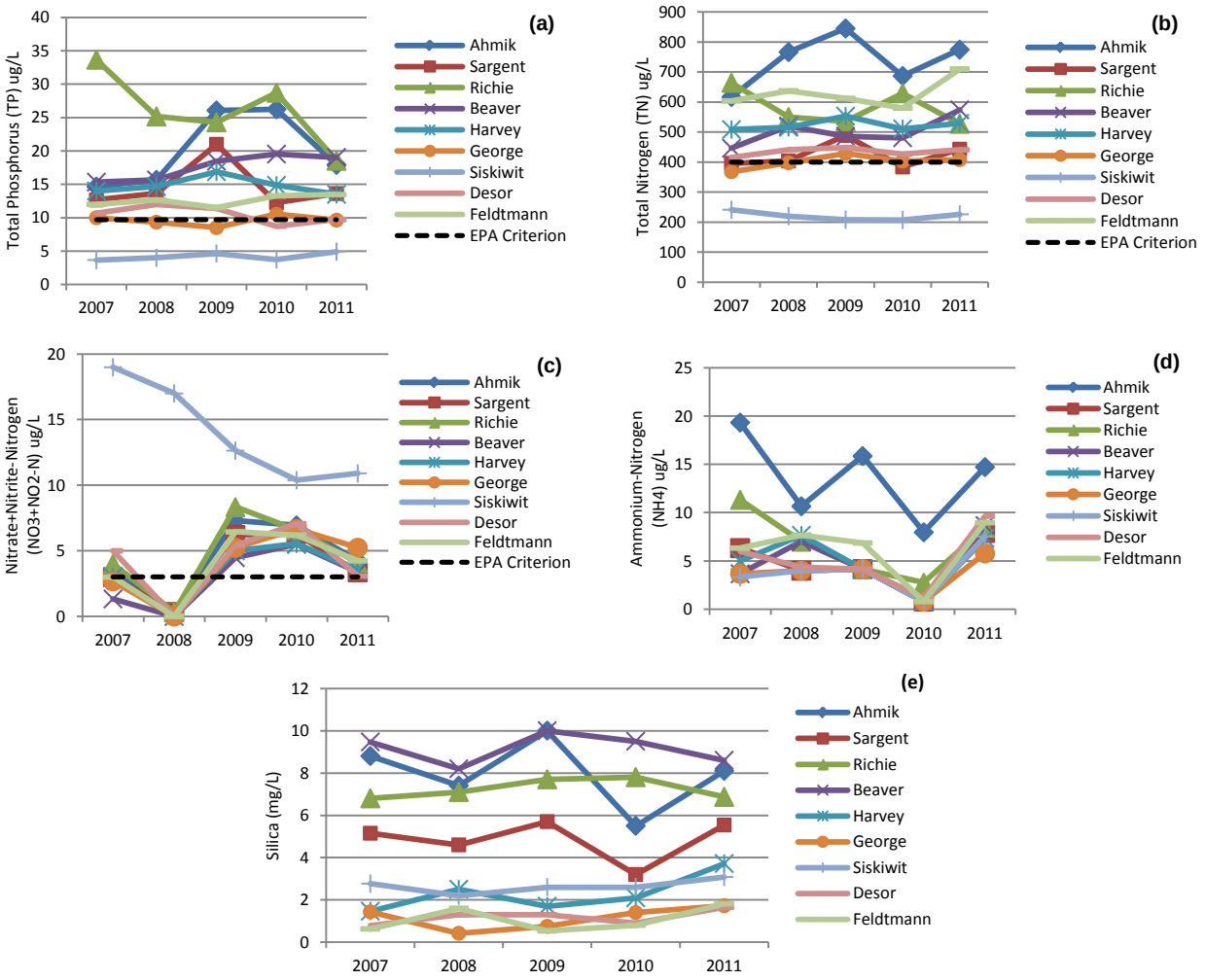

Figure 21. Mean concentration of nutrients in index lakes at Isle Royale National Park, 2007-2011: total phosphorus (**a**), total nitrogen (**b**), nitrate+nitrite-nitrogen (**c**), ammonium-nitrogen (**d**), and silica (**e**).

We also collected water samples for analysis of total suspended solids at four lakes (Richie, Siskiwit, Harvey, and Ahmik). Results (reported in Appendix C) will be used by our collaborators at the St. Croix Watershed Research Station in a climate change modeling project.

Other work completed at ISRO in 2011 included sampling at eight non-index lakes (Epidote, Whittlesey, Wood, Intermediate, LeSage, Chickenbone, Amygdaloid, and Hidden; see Appendix C for the data); bathymetric mapping of these non-index lakes, as well as increased coverage of some index lakes; stream temperature monitoring at two sites each on Benson and Washington creeks; depth monitoring in Washington Creek; deploying and retrieving a temperature array in Siskiwit Lake for University of Maine researchers, and assisting them in other aspects of their project; investigating reports of cyanobacteria blooms at Feldtmann Lake and Lake Desor; providing logistical and field support for park, USGS, U.S. Fish and Wildlife Service, and outside research projects.

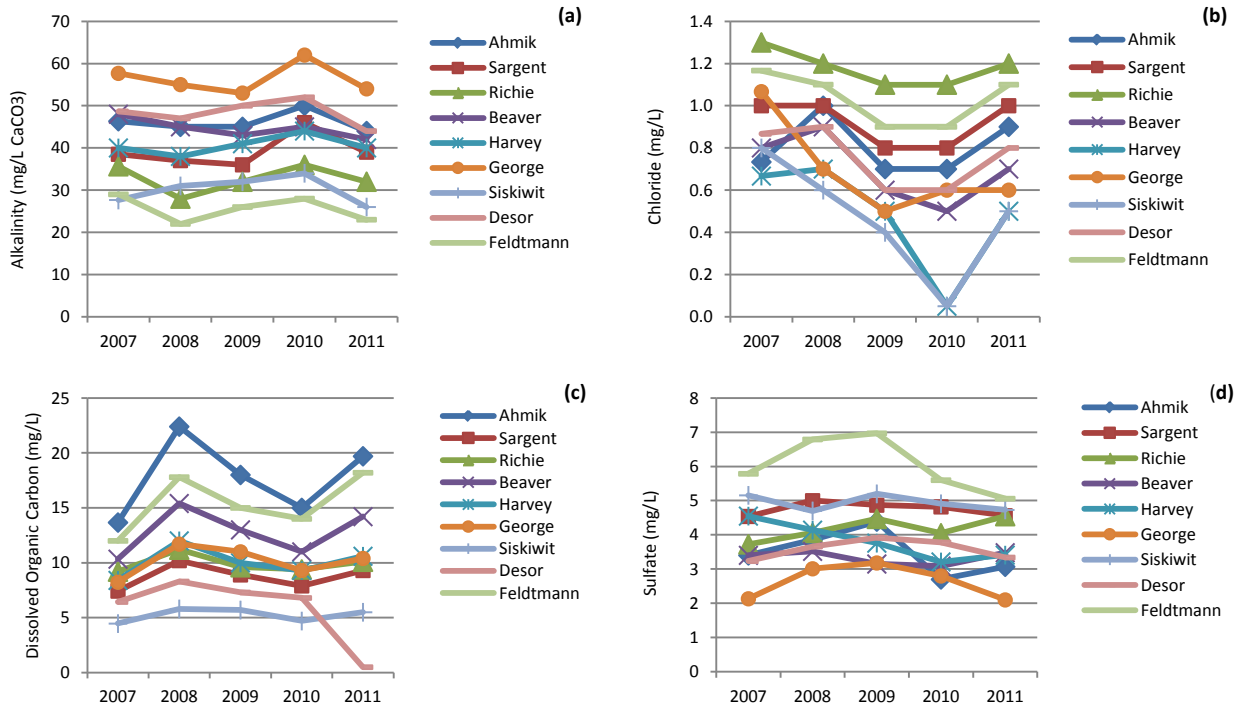

Figure 22. Concentrations of alkalinity (**a**), chloride (**b**), dissolved organic carbon (**c**), and sulfate (**d**) in index lakes at Isle Royale National Park, 2007-2011.

Logistics

All three sampling rounds occurred on schedule in 2011. Sampling was conducted by GLKN and through an exchange of assistance with ISRO staff and University of Maine researchers. Whenever possible, GLKN staff shared boat operations with park staff to save fuel and boating hours.

We expect monitoring to continue at the nine index lakes in 2012. We will also collaborate with USGS to collect samples for analysis of algal toxins at Sargent, Richie, Harvey, Desor, LeSage, and Chickenbone lakes. (PMIS #169376: Determination of Algal Toxin Concentrations in Surface Waters at Isle Royale National Park, Sleeping Bear Dunes National Lakeshore, and Pictured Rocks National Lakeshore,). Though LeSage and Chickenbone are not index lakes, field measurements will be conducted and water samples will be collected for analyses of nutrients and chl-*a* during all three sampling rounds.

The temperature array in Lake Richie will continue collecting hourly data throughout 2012, and will again be re-set for under-ice conditions during the winter of 2012-2013. We expect to limit data collection on Benson and Washington creeks to one site each, continuing with the downstream sites established in 2011.

Pictured Rocks National Lakeshore

Additional Data Collected and Exploration of Trends

Mean summer water levels have dropped substantially at Chapel Lake since 2008 (Figure 23). Beaver activity at the outlet of Chapel Lake likely impacts water levels. Legion Lake has experienced the most variable water levels since monitoring began. It is a seepage lake that is largely influenced by precipitation and evaporation.

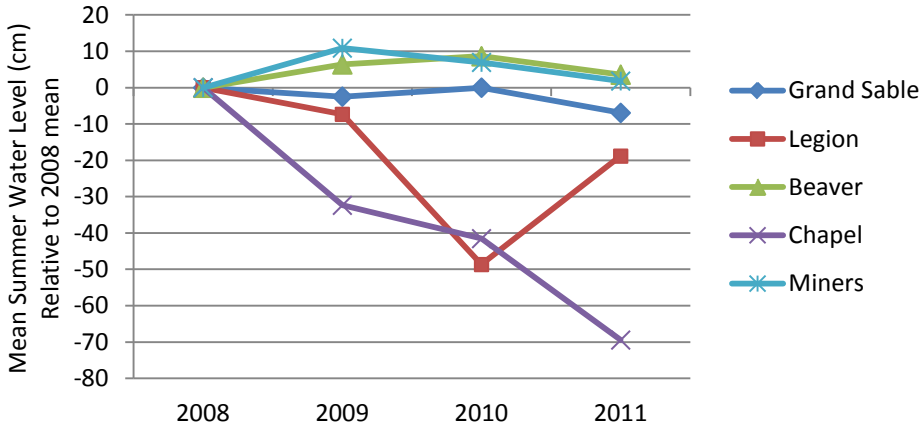

Figure 23. Mean summer lake levels, Pictured Rocks National Lakeshore, 2008-2011. Water level is measured relative to a permanent benchmark at each lake. All lake water levels are relative to the 2008 mean, which is set to zero.

No clear trends are evident in the field-measured parameters (Figures 24a-c), with the possible exception of specific conductance at Miners Lake. If wind speed or the frequency of high wind events has increased over time, the specific conductance in a shallow lake like Miners could increase due to increased mixing. Index lakes at PIRO have generally been mesotrophic throughout our monitoring tenure, with TSI values between 30 and 50 (Figure 24d), though mean TSI seems to be trending downward at several lakes. The pattern of decreasing TSI values may reflect differences in weather (e.g., hot, dry years may lead to greater algal production). See Appendix D for TSI calculations based on Secchi disk data for Little Beaver Lake.

While some variation in mean nutrient levels occurred in all lakes since monitoring began in 2007, no clear trends are evident (Figures 25a - e). Miners Lake, which showed the greatest amount of interannual variation, is a shallow flow-through lake that is frequently mixed during the growing season. Such mixing brings nutrients that have settled into bottom sediments back into suspension. Miners Lake also receives substantial groundwater inputs along the east side of the lake (L. Loope, PIRO aquatic ecologist, personal communication). The source of the relatively high NO_x levels in Miners Lake is of interest to park and GLKN staff. Our collaborative efforts to procure funding to study this have not been successful to date; we will pursue additional funding opportunities as they arise.

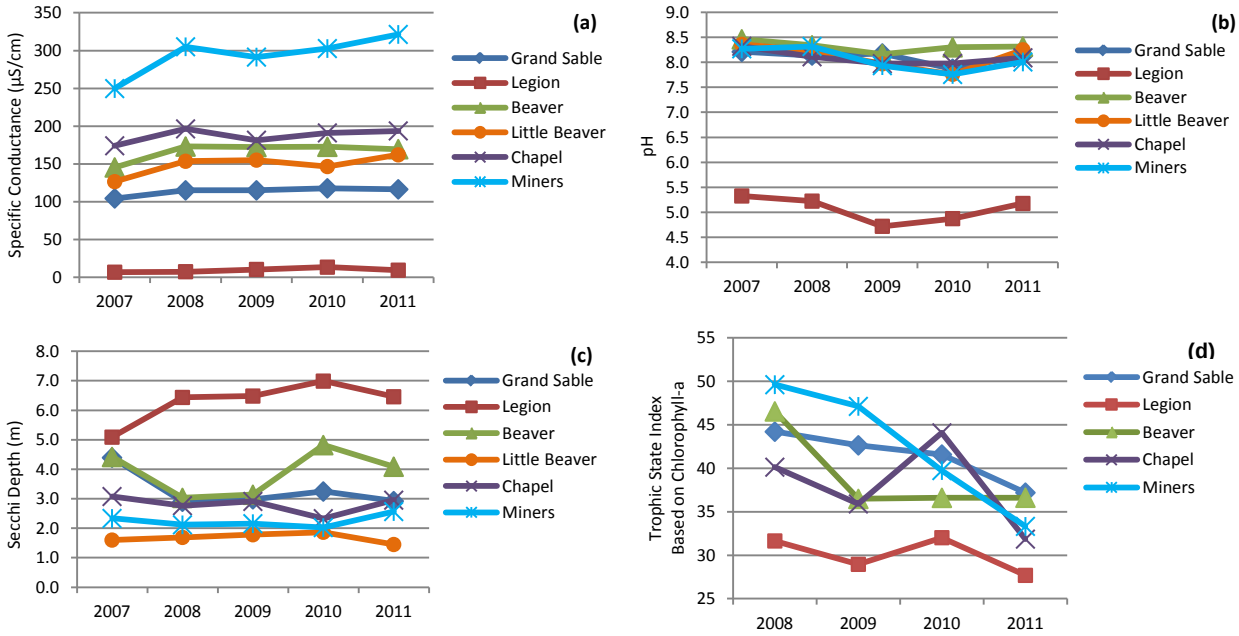

Figure 24. Mean measurements of specific conductance and pH at 1 m depth (**a** and **b**, respectively), water clarity as measured by Secchi disk depth (**c**), and Trophic State Index as calculated from chlorophyll *a* measurements (**d**) for index lakes of Pictured Rocks National Lakeshore, 2007-2011. Chlorophyll *a* data are not available for 2007.

Silica levels were extremely low in Legion Lake, indicating a lack of connection to the groundwater (Kenoyer and Anderson 1989). In Chapel and Beaver lakes, silica appears to be increasing slightly, but the concentration measured at any given time is influenced by the timing of growth and die-back of diatoms and freshwater sponges; dissolved silica is removed from the water during periods of growth and released when the organisms die.

No trends are obvious among the other parameters we measure annually (alkalinity, DOC, and anions (Figure 26a-d; cations are not included here as they are strongly correlated with specific conductance, which is discussed above; see Appendix D for all of the data). The deepest and shallowest lakes (Chapel and Miners, respectively) showed patterns similar to one another for Cl^- and DOC; likewise, Grand Sable, Legion, and Beaver lakes showed similar patterns to one another. All five index lakes showed little variation in alkalinity since monitoring began in 2007.

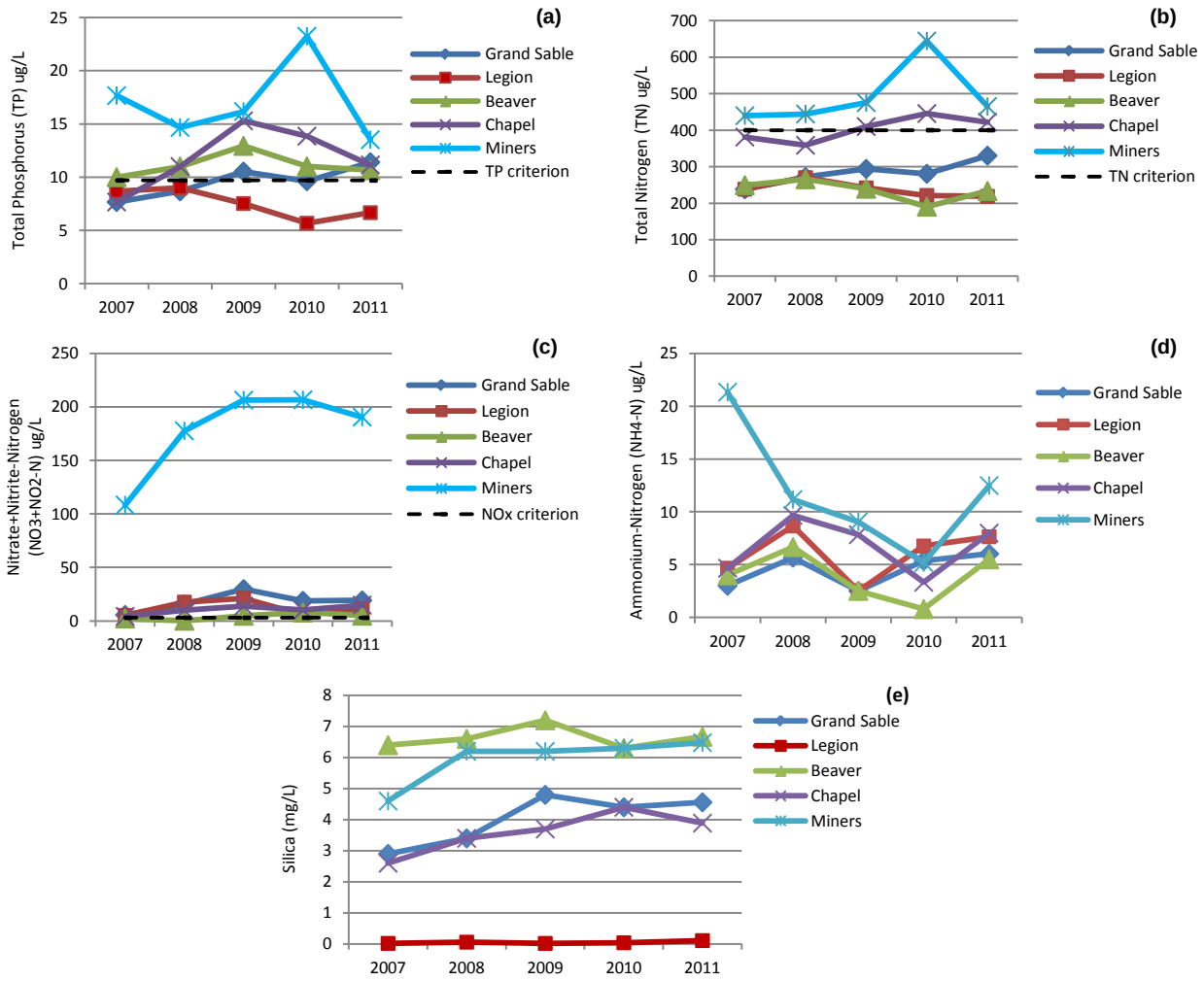

Figure 25. Mean concentration of nutrients in index lakes at Pictured Rocks National Lakeshore, 2007-2011; total phosphorus (**a**), total nitrogen (**b**), nitrate+nitrite-nitrogen (**c**), ammonium-nitrogen (**d**), and silica (**e**).

Logistics

All sampling was completed by park staff as planned in 2011. In addition to the index lakes, field measurements were collected at Little Beaver Lake.

In early October 2011, GLKN and park staff deployed an array of temperature probes in Grand Sable Lake. The array was set for under-ice conditions, with a sub-surface float at approximately 2 m depth and probes extending from 2 m to the bottom. The array collected hourly data throughout the winter, then was re-set in April 2012 to collect data during summer/ice-off conditions. Hourly data collection will continue throughout 2012.

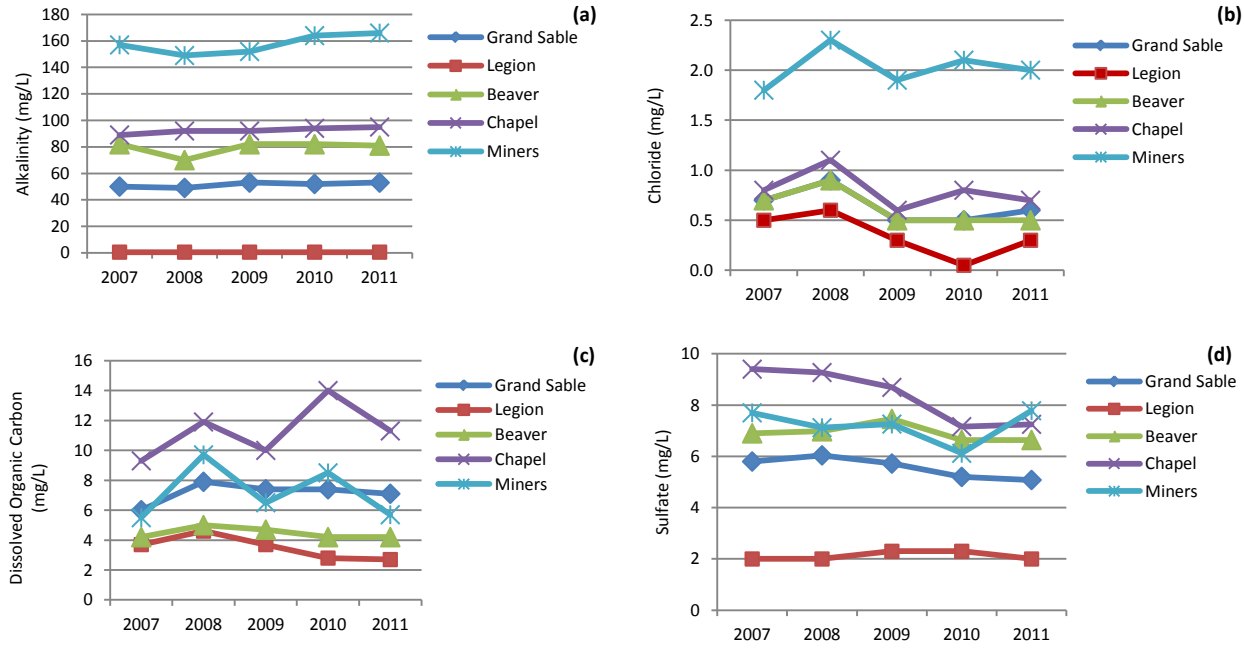

Figure 26. Concentrations of alkalinity (**a**), chloride (**b**), dissolved organic carbon (**c**), and sulfate (**d**) in index lakes at Pictured Rocks National Lakeshore, 2007-2011.

Personnel have been consistent over the last four years; their expertise has been beneficial to the program and has resulted in reliable data. With the assistance of park staff again in 2012, we expect to continue monitoring the five index lakes. We will also work with USGS to collect samples for analysis of algal toxins at Beaver, Miners, Trappers, and Grand Sable lakes (PMIS # 169376: Determination of Algal Toxin Concentrations in Surface Waters at Isle Royale National Park, Sleeping Bear Dunes National Lakeshore, and Pictured Rocks National Lakeshore). Although Trappers is not an index lake, field measurements will be taken and water will be collected for analyses of nutrients and chl-*a* during all three regularly scheduled rounds of sampling.

Indiana Dunes National Lakeshore

Additional Data Collected and Exploration of Trends

We have been measuring water levels at Long Lake relative to a USGS groundwater well cap since 2006. In 2010, the USGS replaced the well, and we were able to convert our measurements to values that corresponded to the height of the new well. As a back-up, water level has also been measured from a fixed point on the boardwalk since 2010. Unfortunately, in 2011 USGS personnel discovered that the old well had heaved 1.82 ft sometime between when it was installed (2002) and when it was replaced (2010). Because we don't know when this change in elevation occurred, we cannot use any of our data collected between 2006 and 2010.

At Middle Lagoon, we have been measuring water level from the bridge. Since 2008, the water level in the lagoon has risen approximately 20 cm (Figure 27a). Typically, the lowest water levels have occurred early in the season (Figure 27b).

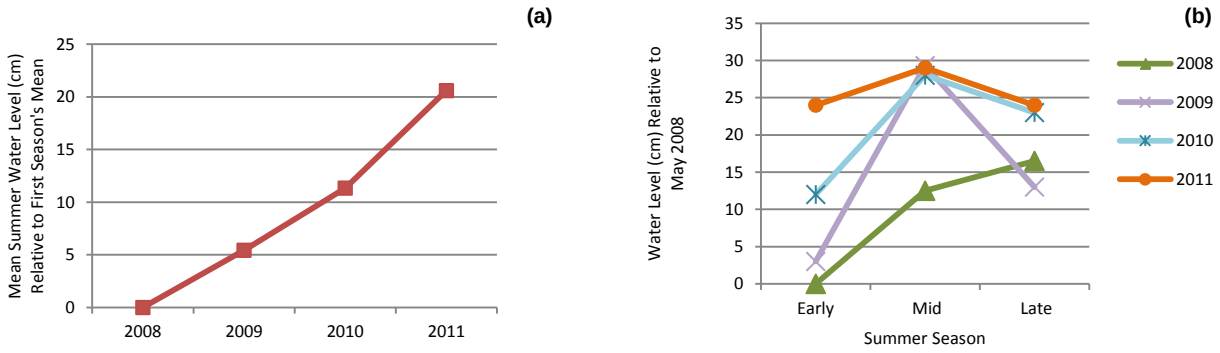

Figure 27. Mean summer water levels at Middle Lagoon, Indiana Dunes National Lakeshore, relative to the 2008 mean, which is set to zero (**a**). Water levels throughout the summer in Middle Lagoon, 2008-2011 (**b**).

In 2011, sediment samples were collected from both Long Lake and Middle Lagoon for analysis of diatom communities. This marked the second sampling of Long Lake (the first sampling occurred in 2007) and will allow analysis of change in diatom communities over the last five years. Middle Lagoon was sampled for the first time and will serve as a benchmark for analysis of change in the future.

Due to the amount of interannual variability and short-term record, it is difficult to determine whether any trends in the field-measured parameters are occurring in Middle Lagoon (Figure 28a and b). Mean specific conductance decreased in Middle Lagoon since the high levels in 2008, and are again nearly the same as they were in 2007. Mean pH levels decreased in Middle Lagoon since 2007, but because of our short record, we do not know what the pH was prior to 2007. If it was similar to that of 2007, what we see now may be indicative of a trend, but if pH prior to 2007 was lower, then 2007 may have been an anomaly. Specific conductance may be trending upwards in Long Lake, but no change in pH is evident.

Trophic state indices (TSIs) as calculated by chlorophyll-*a* concentration of both Long Lake and Middle Lagoon have remained within the mesotrophic category (TSI between 30 and 50) since monitoring began and have declined dramatically since 2009 (Figure 28c). However, when TSI is calculated using TP concentration, both waterbodies have been in the eutrophic range (TSI >50) some years, and a similar decline has not occurred in Long Lake (Figure 28d). The likely explanation for the difference in the two calculations of TSI is that both lakes are dominated by macrophytes, and the available phosphorus is used by the macrophytes rather than resulting in algal blooms. The apparent decrease in TSI since 2009 could be the result of increased macrophyte growth, though this is not something we measure.

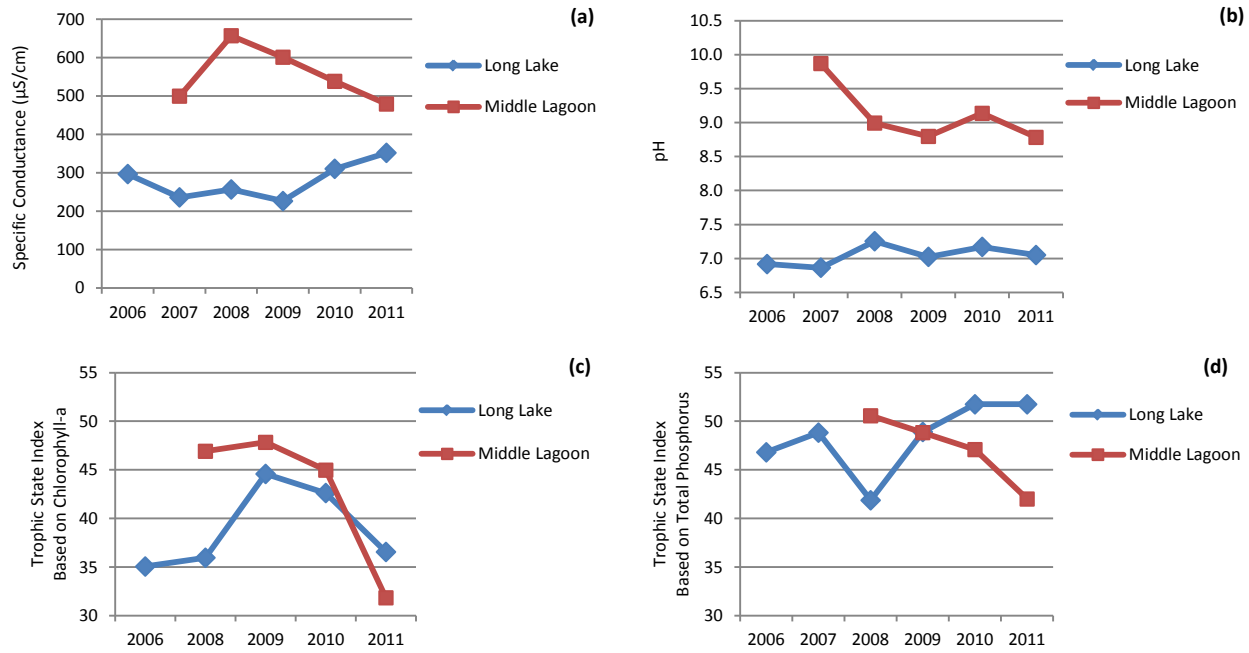

Figure 28. Mean measurements of specific conductance and pH at 0.5 m depth (**a** and **b**, respectively), and trophic state index values calculated using chlorophyll *a* concentration (**c**) and total phosphorus concentration (**d**) for lakes at Indiana Dunes National Lakeshore, 2006-2011. Chlorophyll *a* data are not available for 2007.

Mean TP and TN concentrations have fluctuated around the levels of the EPA reference criteria (Figures 29a and b). Both TP and TN seem to have decreased in Middle Lagoon since 2008. Concentrations of NO_3+NO_2-N and NH_4-N appear to have changed dramatically since monitoring began (Figured 29c and d), but the values are actually quite low and the changes do not represent large ecological shifts. Silica concentrations have also been variable (Figure 29e), and are influenced by the uptake and release by diatoms and freshwater sponges. Dissolved silica is removed from the water during periods of growth and released when the organisms die.

Of the other parameters we measure annually (alkalinity, DOC, and anions; cations are not included here as they are strongly correlated with specific conductance, which is discussed above; see Appendix E for all of the data), alkalinity shows little interannual fluctuation and no clear trend (Figure 30a). Chloride levels are high in both waterbodies, especially Middle Lagoon (Figure 30b), and likely indicate contamination. Dissolved organic carbon concentration may be increasing in Long Lake and declining slightly in Middle Lagoon (Figure 30c); additional years of monitoring will help determine whether this is occurring. Sulfate concentration seems to have declined in both Long Lake and Middle Lagoon (Figure 30d).

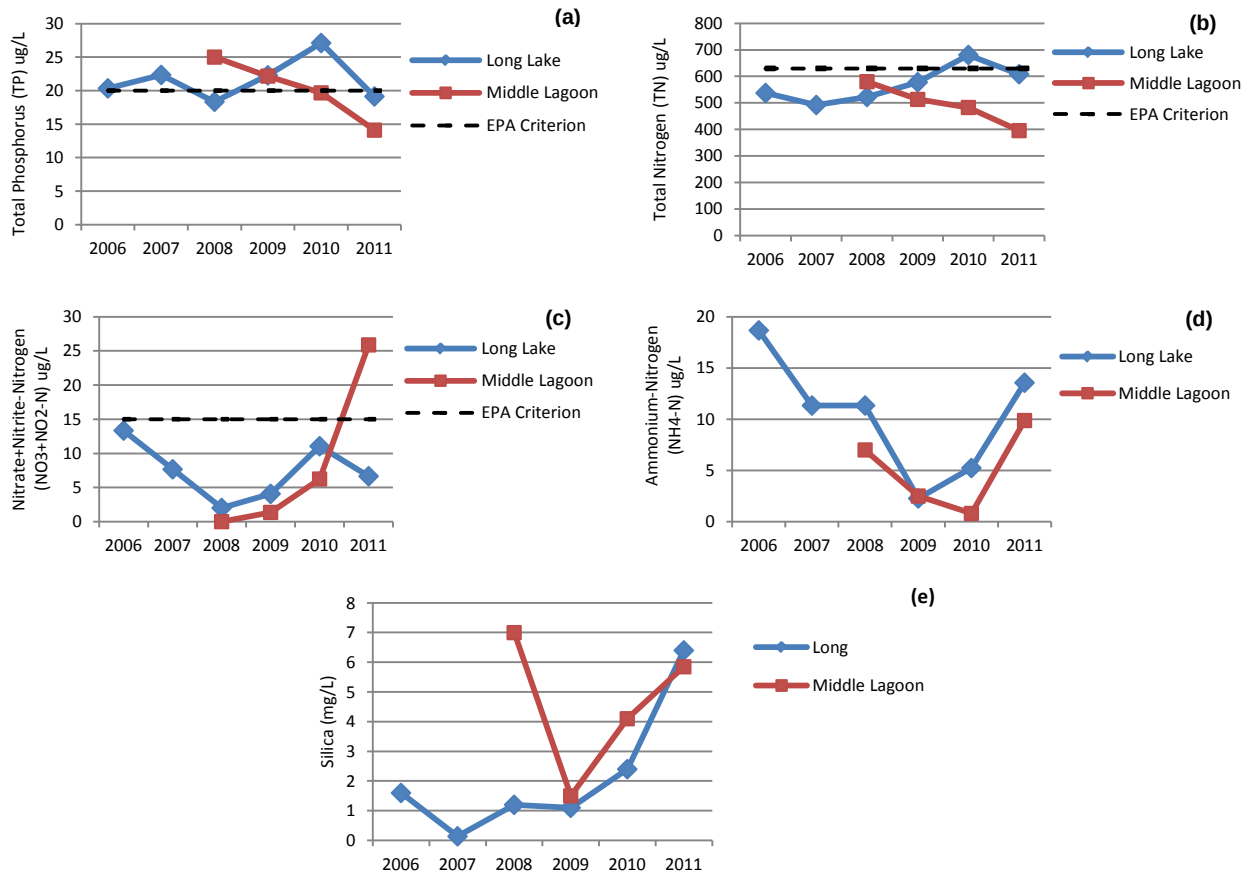

Figure29. Mean concentration of nutrients in lakes at Indiana Dunes National Lakeshore, 2007-2011: total phosphorus (**a**), total nitrogen (**b**), nitrate+nitrite-nitrogen (**c**), ammonium-nitrogen (**d**), and silica (**e**).

Logistics

All sampling was completed by INDU staff as planned in 2011. Although Middle Lagoon is not one of the index lakes in the GLKN monitoring program, all parameters were measured.

We expect to continue monitoring field parameters at Long Lake and Middle Lagoon in 2012. Laboratory parameters will continue to be measured at Long Lake, and as funds permit, at Middle Lagoon. We will begin to discuss with park staff the idea of dropping Long Lake from the program. Long Lake does not function as an inland lake, but rather is a wetland that is increasingly becoming filled-in with aquatic vegetation. Sampling will again be conducted by park staff in 2012. As we finalize a protocol for wadeable streams, we expect the Little Calumet River to be included in that project.

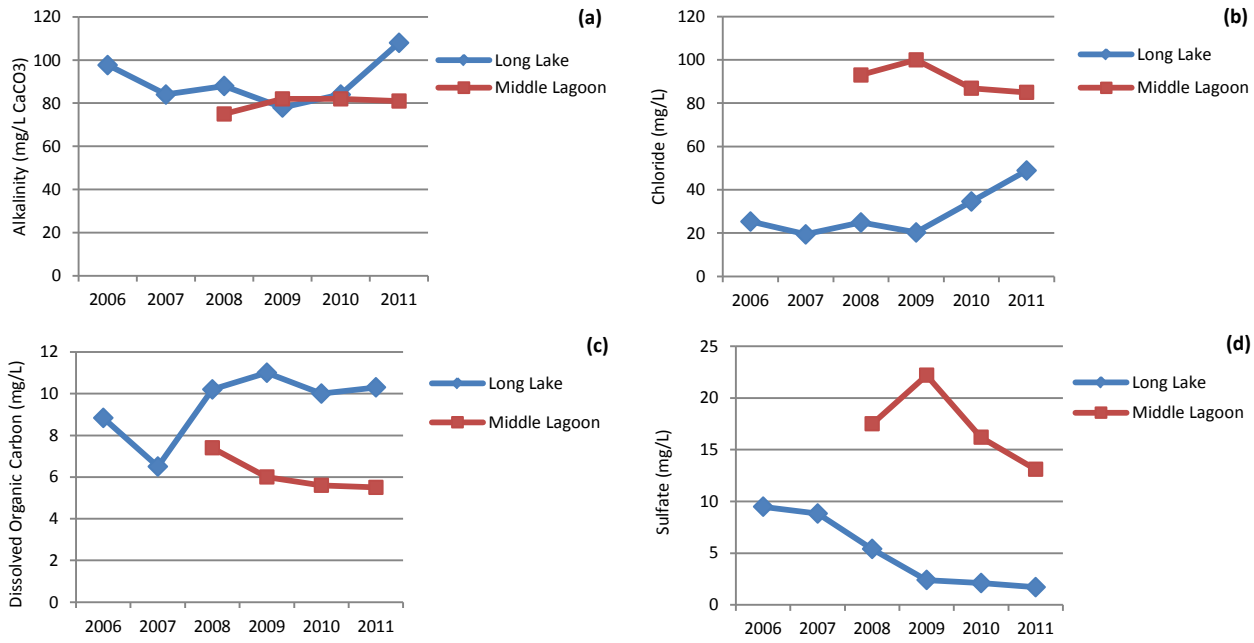

Figure 30. Concentrations of alkalinity (**a**), chloride (**b**), dissolved organic carbon (**c**), and sulfate (**d**) in lakes at Indiana Dunes National Lakeshore, 2006-2011.

Sleeping Bear Dunes National Lakeshore

Additional Data Collected and Exploration of Trends

Water levels of Shell, Otter, Tucker, Loon, and Round lakes have changed little since monitoring began (Figure 31). Bass Lake has experienced large fluctuations, dropping approximately 35 cm between 2008 and 2009, and rising nearly the same amount in 2011. Bass Lake may be influenced by beaver activity at its connection to School Lake, which might explain the large fluctuations. Water levels in Manitou, Florence, and North Bar lakes have declined since monitoring began. North Bar has an intermittent connection to Lake Michigan and its water level can change dramatically depending on whether the connection is open or closed.

The water chemistry of Florence Lake suggests isolation from the groundwater (low alkalinity and specific conductance compared to the other lakes in the park), and the lake is more strongly influenced by precipitation and evaporation than the other lakes. Investigations of the inlets to Lake Manitou may reveal whether the lake is being influenced by beaver activity or is responding to changes in weather and climate.

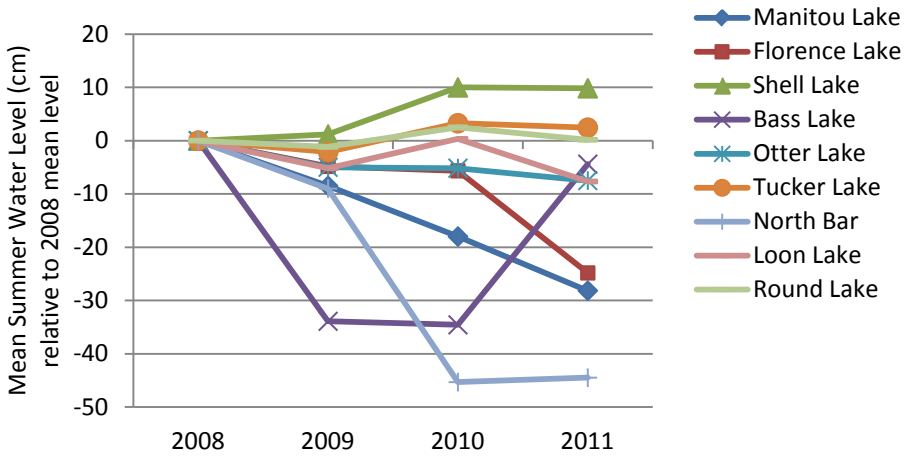

Figure 31. Mean summer water levels of lakes at Sleeping Bear Dunes National Lakeshore, 2008-2011. Water level is measured relative to a permanent benchmark at each lake. All lake water levels are relative to the 2008 mean, which is set to zero.

No clear trends in specific conductance, pH, or Secchi depth are apparent (Figures 32a-c). While the pH data look 'noisy,' the variations are only approximately 0.2 standard units, in most cases. Secchi depth measurements have varied considerably at Narada Lake, but as only a single measurement is taken each summer, the variation may in part reflect the Secchi reading conditions (e.g., clear vs. cloudy sky, calm vs. windy). The mean trophic state index as calculated from chlorophyll *a* concentration resulted in almost all of the lakes being categorized as mesotrophic (TSI between 30 and 50; Figure 32d). Narada Lake had a TSI >50 in 2010, indicating a eutrophic state. All of Narada Lake's scores are based on a single late season measurement per year, and do not represent seasonal means. The TSI of several lakes seems to have declined between 2008 and 2011 (e.g., Florence and Manitou). Additional years of data will help determine whether this is part of a long-term trend or shorter-term variations.

With the exception of TN in Shell Lake, mean TP and TN concentrations generally remained below EPA reference criteria since monitoring began (Figures 33a and b). Mean concentrations of NO_3+NO_2-N, however, have often been above the EPA criterion (Figure 33c). Especially noteworthy are the high levels of NO_x at Otter and North Bar lakes (Figure 33c). Park and GLKN staff collaborated on a proposal in 2010 to determine the source of the high NO_x concentrations, but we did not receive funding. We will pursue additional funding opportunities as they arise. Mean NH_4-N concentrations showed much variability among lakes and within some lakes across years (Figure 33d), obscuring any potential trends. Silica concentrations seem to be increasing in Round and Shell lakes; however the timing of the growth and demise of diatoms and freshwater sponges influences silica levels at any given time. Silica is incorporated into the cell walls of diatoms and the skeletal structure of freshwater sponges, and a portion of it is released when the organisms die. The very low silica levels of Florence Lake are further evidence of its isolation from groundwater (Kenoyer and Anderson 1989).

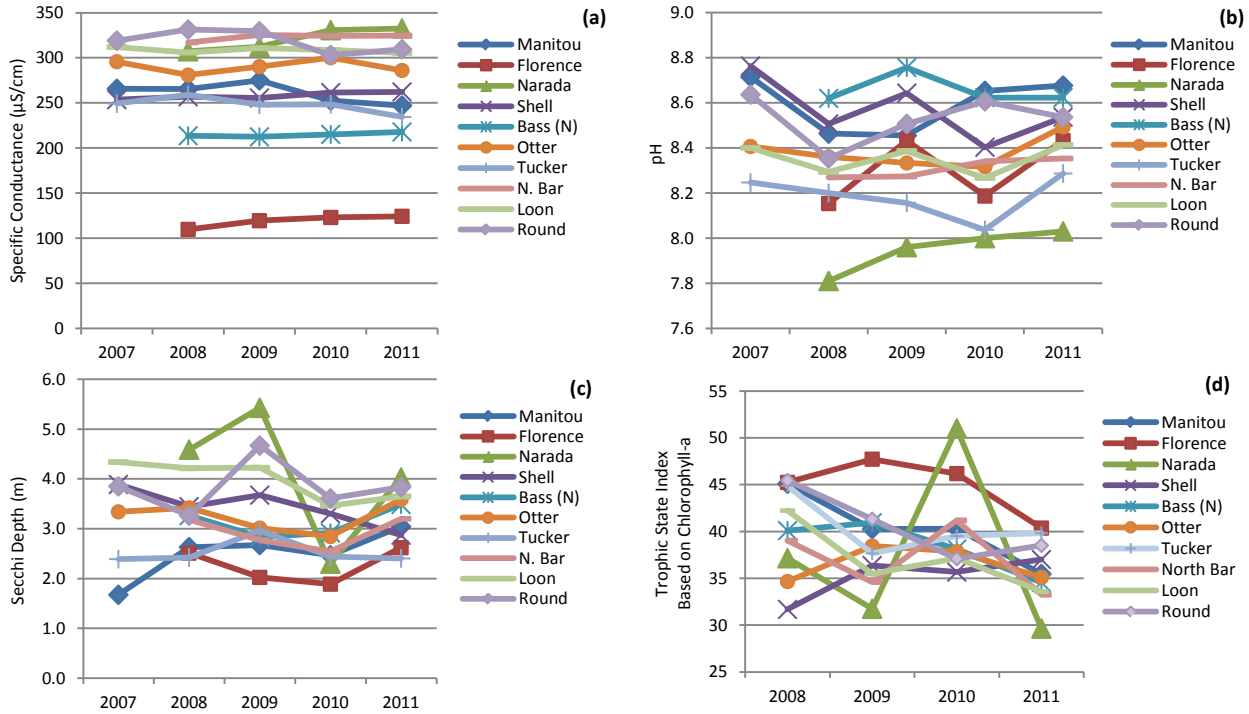

Figure 32. Mean measurements of specific conductance and pH at 1 m depth (**a** and **b**, respectively), water clarity as measured by Secchi disk depth (**c**), and Trophic State Index as calculated from chlorophyll *a* measurements (**d**) for lakes of Sleeping Bear Dunes National Lakeshore, 2007-2011. Chlorophyll *a* data are not available for 2007.

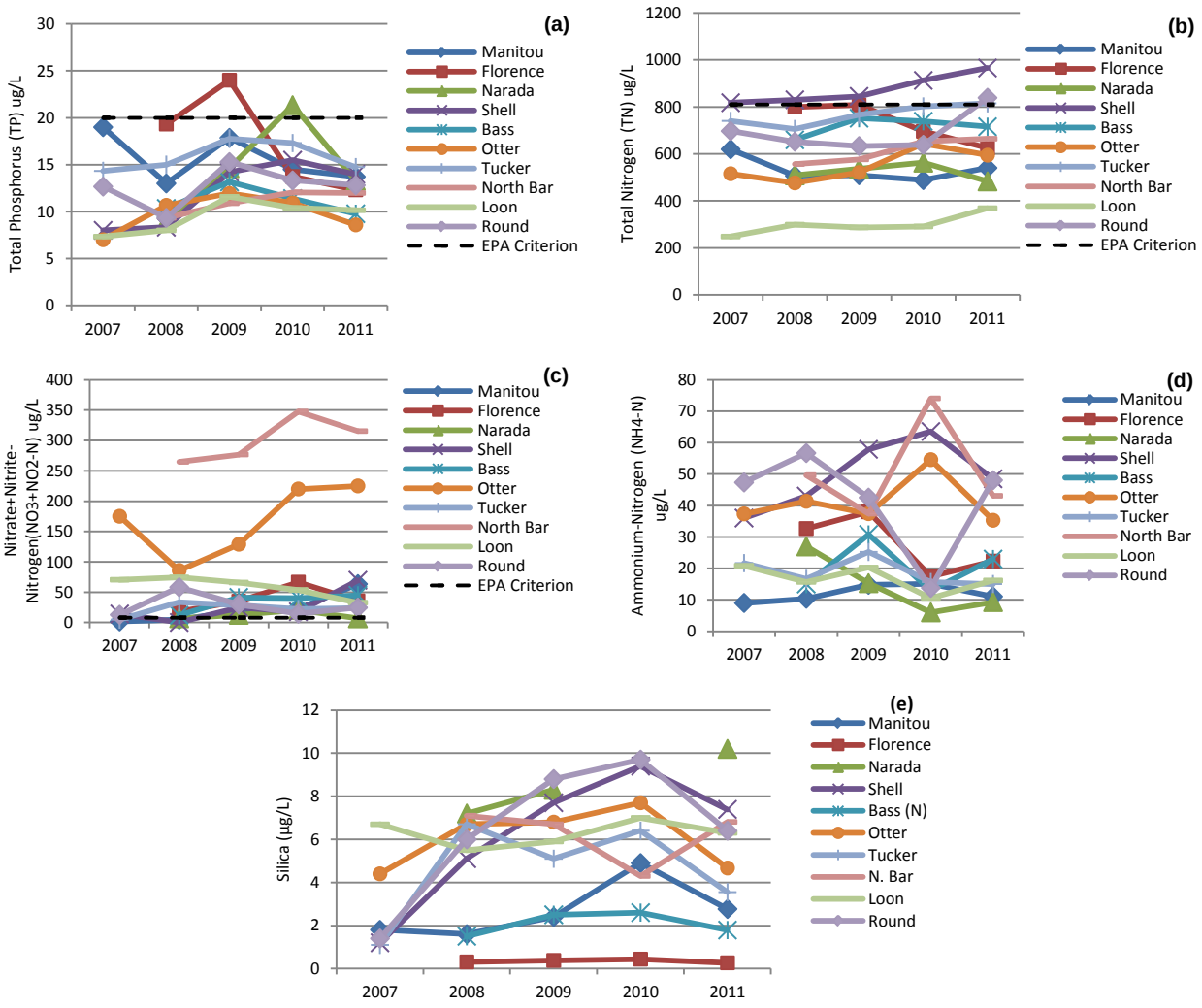

Figure 33. Mean concentration of nutrients in lakes at Sleeping Bear Dunes National Lakeshore, 2007-2011: total phosphorus (**a**), total nitrogen (**b**), nitrate+nitrite-nitrogen (**c**), ammonium-nitrogen (**d**), and silica (**e**).

No obvious trends are evident among the other parameters we measure annually (alkalinity, DOC, and anions), (Figures 34a-d; cations are not included here as they are strongly correlated with specific conductance, which is discussed above; see Appendix F for all of the data). The high Cl^- levels at Round Lake may be due to the run-off of road de-icing chemicals into the lake. The relatively high SO_4^{-2} levels of Shell Lake are probably naturally occurring.

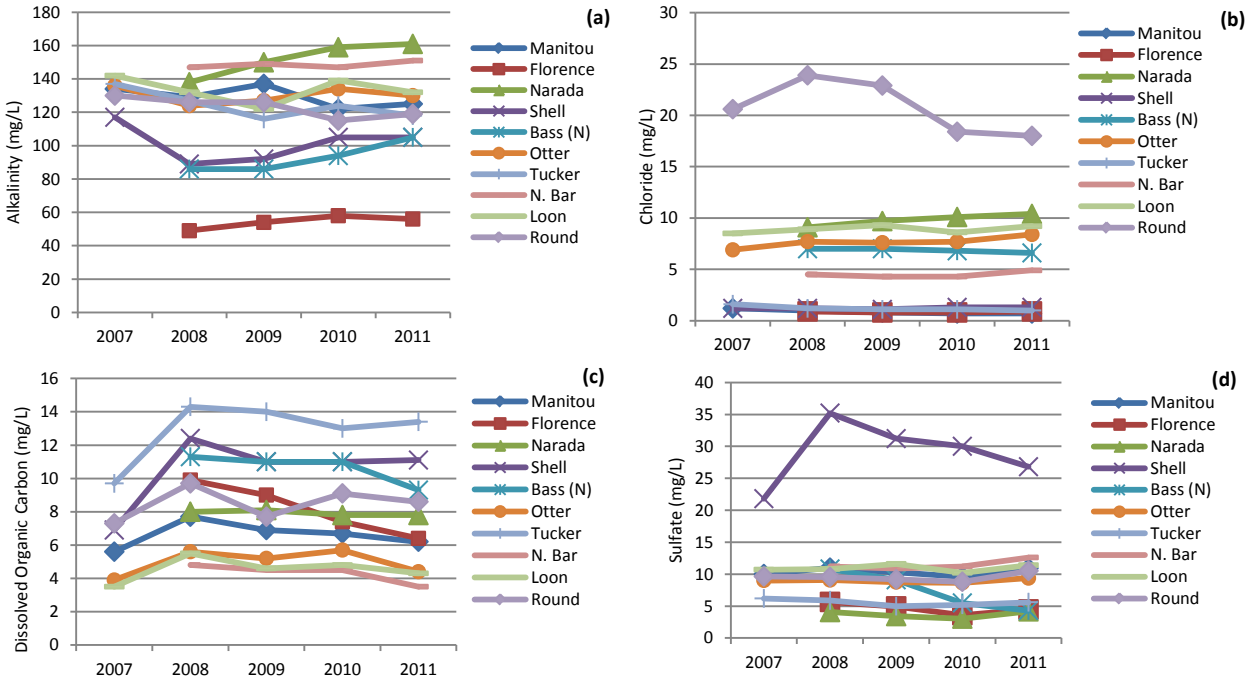

Figure 34. Concentrations of alkalinity (**a**), chloride (**b**), dissolved organic carbon (**c**), and sulfate (**d**) in lakes at Sleeping Bear Dunes National Lakeshore, 2007-2011.

Logistics

All sampling was completed by SLBE staff as planned in 2011. Four lakes (North Bar, Otter, Narada, and Tucker) were sampled in addition to the index lakes. Narada was sampled in September only so as not to disturb nesting loons. All lakes with the exception of Narada now have permanent benchmarks installed.

We expect to continue monitoring Manitou, Florence, Shell, Bass [North], North Bar, and Loon lakes in 2012 . We will also work with USGS to collect samples for analysis of algal toxins in these lakes (PMIS # 169376: Determination of Algal Toxin Concentrations in Surface Waters at Isle Royale National Park, Sleeping Bear Dunes National Lakeshore, and Pictured Rocks National Lakeshore).

We will work with park staff to determine when it is appropriate to deploy an array of continuous logging temperature probes in one index lake. Because we need to rely on park personnel to maintain the array (download data, re-set for summer and winter conditions, clean the probes, etc.), we must be sure these additional duties can be accomplished.

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Appendix A. Field and laboratory results for Voyageurs National Park, 2011.

Multiprobe measurements for pH, specific conductance, dissolved oxygen, and temperature are reported from 1.0 m depth. Results in **bold font** indicate values less than the laboratory reporting limit (also known as the method quantitation limit, or MQL). Blank cells indicate that no results are available. Abbreviations used are as follows (units of measurement are in parentheses):

Alk	Alkalinity (mg/L $CaCO_3$)
Ca^{+2}	Calcium (mg/L)
Cl^{-}	Chloride (mg/L)
DOC	Dissolved Organic Carbon (mg/L)
Mg^{+2}	Magnesium (mg/L)
K^{+}	Potassium (mg/L)
SiO_2	Silicate (mg/L)
Na^{+}	Sodium (mg/L)
SO_4^{-2}	Sulfate (mg/L)
NH_4-N	Ammonium-Nitrogen (µg/L)
NO_3+NO_2-N	Nitrate+Nitrite (µg/L)
TN	Total Nitrogen (µg/L)
TP	Total Phosphorus (µg/L)
TN-Hypolimnion	Bottom TN (µg/L)
TP - Hypolimnion	Bottom TP (µg/L)
chl-*a*	Chlorophyll-*a* (µg/L)
TSS	Total Suspended Solids (mg/L)
DO	Dissolved Oxygen (mg/L)
SC25	Specific Conductance (µS/cm)
pH	pH (standard units)
Temp	Temperature (°C)
Secchi	Secchi Depth (m)
Water Level	Water Level (m)
M Hg	Methyl-mercury (ng/L)
T Hg	Total Mercury (ng/L)
TSI(chl-*a*)	Trophic State Index calculated from chlorophyll-*a* concentration
TSI(TP)	Trophic State Index calculated from TP concentration
TSI(Secchi)	Trophic State Index calculated from Secchi depth

Appendix A. Voyageurs National Park, 2011.

Parameter	Month/Yr	Locator	Shoepack	Ek	Brown	Peary	Cruiser	Ryan	Little Trout*	Duplicate	Duplicate Location
Alk	7/11	**7**	**5**	16	10	**ND**	**7**	**7**	15	11	Locator
Ca^{+2}	7/11	2.3	2.1	2.6	2.0	2.2	1.9	2.2	3.6	2.3	Locator
Cl^{-}	7/11	0.7	1.1	0.7	1.0	0.6	0.4	0.6	0.5	0.7	Locator
DOC	7/11	12.3	18.2	13.0	11.0	10.5	4.3	12.9	5.1		
Mg^{+2}	7/11	1.0	0.9	1.2	0.9	1.1	0.8	0.9	1.6	1.0	Locator
K^{+}	7/11	0.6	0.5	0.6	0.6	0.5	0.5	**0.4**	0.4	0.6	Locator
SiO_2	7/11	2.3	0.7	1.5	1.7	1.2	0.6	2.2	0.3	2.3	Locator
Na^{+}	7/11	0.9	0.9	1.0	1.0	1.0	0.7	0.9	0.9	1.0	Locator
SO_4^{-2}	7/11	2.5	2.0	1.2	1.6	3.9	2.6	3.5	2.9	2.5	Locator
NH_4-N	6/11	**8.0**	31.6	11.3	13.8	**7.7**	**6.1**	21.5	12.5	8.6	Ek
NH_4-N	7/11	10.1	13.7	12.1	11.4	8.9	8.9	10.1	10.5	10.1	Locator
NH_4-N	8/11	12.0	36.0	13.2	8.3	**7.3**	**6.4**	8.9	**5.0**	11.5	Locator
NH_4-N	average	10.0	27.1	12.2	11.2	8.0	7.1	13.5	9.3		
NO_3+NO_2-N	6/11	**6.6**	23.6	**8.0**	13.5	**3.1**	**5.5**	52.1	**7.6**	**5.6**	Ek
NO_3+NO_2-N	7/11	**7.7**	10.1	9.9	70.3	59.1	17.9	10.1	**4.1**	10.3	Locator
NO_3+NO_2-N	8/11	**4.1**	**5.6**	8.1	**3.9**	**4.4**	**6.0**	**3.2**	**0.0**	**4.0**	Locator
NO_3+NO_2-N	average	6.1	13.1	8.6	29.3	22.2	9.8	21.8	3.9		
TN	6/11	450	675	655	464	439	186	488	260	646	Ek
TN	7/11	457	669	647	521	692	231	483	278	468	Locator
TN	8/11	449	662	665	481	503	194	477	270	423	Locator
TN	average	451.8	669	655	489	545	204	483	269		
TP	6/11	12.1	15.2	19.4	8.8	12.0	3.8	8.9	5.2	16.1	Ek
TP	7/11	10.0	14.6	21.8	12.7	14.7	5.8	10.4	5.6	9.9	Locator
TP	8/11	8.2	16.0	16.1	9.3	16.7	3.3	9.3	**2.1**	8.4	Locator
TP	average	10.1	15.3	19.1	10.3	14.5	4.3	9.5	4.3		
TN - Hypolimnion	7/11	525	656	822	621	505	230		634	545	Locator
TP - Hypolimnion	7/11	9.7	11.4	29.5	14.2	19.8	6.9		44.4	12.1	Locator

Appendix A. Voyageurs National Park, 2011 (continued).

Parameter	Month/Yr	Locator	Shoepack	Ek	Brown	Peary	Cruiser	Ryan	Little Trout*	Duplicate	Duplicate Location
chl-a	6/11	3.0	1.6	3.7	1.7	2.1	0.6	2.1	0.6	4.6	Shoepack
chl-a	7/11	1.6	3.2	2.6	0.6	**0.2**	**0.4**	1.0	**0.3**	1.4	Locator
chl-a	8/11	1.7	2.5	3.0	2.4	3.1	**0.4**	2.5	1.5	1.8	Locator
chl-a	average	2.1	2.4	3.1	1.5	1.8	0.5	1.9	0.8		
TSS	6/11										
TSS	7/11			1.40		1.25	-0.55		-0.13		
TSS	8/11			1.08		1.00	0.70		0.80		
TSS	average			1.24		1.12	0.08		0.33		
DO	6/11	9.4	8.2	9.6	8.6	8.6	9.5	8.7	9.3		
DO	7/11	7.8	6.9	8.2	6.6	6.9	9.7	7.3	8.5		
DO	8/11	10.2		7.5	8.3	8.2	8.5	7.3	9.8		
DO	average	9.1	7.6	8.4	7.8	7.9	9.2	7.8	9.2		
SC	6/11	24	21	26	20	23	20	23	37		
SC	7/11	24	21	27	21	24	20	23	37		
SC	8/11	26	26	28	23	28	21	26	38		
SC	average	25	23	27	21	25	20	24	37		
pH	6/11	7.2	6.2	7.4	7.0	7.4	7.5	6.9	7.5		
pH	7/11	7.1	6.4	7.2	6.9	7.3	7.4	6.8	7.8		
pH	8/11	7.1	6.3	7.1	6.9	7.0	7.4	6.5	7.8		
pH	average	7.1	6.3	7.2	6.9	7.2	7.4	6.7	7.7		
Temp	6/11	16.6	17.1	20.2	19.8	20.0	17.9	19.0	18.7		
Temp	7/11	23.3	24.5	22.8	26.9	26.9	23.9	25.6	23.2		
Temp	8/11	24.9		22.8	21.8	21.9	23.6	20.9	14.9		
Temp	average	21.6	20.8	21.9	22.8	22.9	21.8	21.8	18.9		
Secchi	6/11	3.00	1.40	1.70	2.80	3.10	9.45	3.20	5.50		
Secchi	7/11	2.10	1.50	1.70	3.50	3.60	8.50	3.30	6.05		
Secchi	8/11	4.10	1.18	2.20	3.30	2.40	9.50	3.48	5.40		
Secchi	average	3.1	1.4	1.9	3.2	3.0	9.2	3.3	5.7		

Appendix A. Voyageurs National Park, 2011 (continued).

Parameter	Month/Yr	Locator	Shoepack	Ek	Brown	Peary	Cruiser	Ryan	Little Trout*	Duplicate	Duplicate Location
Water Level	6/11	-1.575	-1.625	-0.869	-0.505	-1.25	-0.73	-0.97	-1.10		
Water Level	7/11	-1.55	-1.47	-1.12	-0.565	-1.245	-0.77	-0.97	-1.07		
Water Level	8/11	-1.625	-1.55	-0.87	-0.665	-1.27	-1.285	-0.965	-1.305		
Water Level	average	-1.58	-1.55	-0.95	-0.58	-1.26	-0.93	-0.97	-1.16		
M Hg	6/11		0.34	0.06	0.16	0.06		0.12		0.06	Shoepack
M Hg	7/11		0.25	0.1	0.16	0.12		0.1			
M Hg	8/11		0.37	0.06	0.08	0.05		0.11			
M Hg	average		0.3	0.1	0.1	0.1		0.1			
T Hg	6/11		3.54	2.22	1.91	1.53		3.34		2.16	Shoepack
T Hg	7/11		3.47	2.23	2.06	1.39		2.77			
T Hg	8/11		3.14	1.74	1.84	1.19		1.87			
T Hg	average		3.4	2.1	1.9	1.4		2.7			
TSI (chl-a)	6/11	41	35	44	36	38	26	38	26		
TSI (chl-a)	7/11	35	42	40	25	15	21	31	19		
TSI (chl-a)	8/11	36	40	41	39	42	21	39	34		
TSI (chl-a)	average	37	39	42	33	32	23	36	27		
TSI (TP)	6/11	40	43	47	35	40	23	36	28		
TSI (TP)	7/11	37	43	49	41	43	30	38	29		
TSI (TP)	8/11	35	44	44	36	45	21	36	15		
TSI (TP)	average	37	43	47	38	43	25	37	24		
TSI (Secchi)	6/11	44	55	52	45	44	28	43	35		
TSI (Secchi)	7/11	49	54	52	42	42	29	43	34		
TSI (Secchi)	8/11	40	58	49	43	47	28	42	36		
TSI (Secchi)	average	44	56	51	43	44	28	43	35		

* final round of sampled at Little Trout Lake occurred on 9/22/11, rather than 8/11.

Appendix B. Field and laboratory results for Apostle Islands National Lakeshore, 2011.

Multiprobe measurements for pH, specific conductance, dissolved oxygen, and temperature are reported from 0.5 m depth. Results in **bold font** indicate values less than the laboratory reporting limit (also known as the method quantitation limit, or MQL). Blank cells indicate that no results are available. Abbreviations used are as follows (units of measurement are in parentheses):

Alk	Alkalinity (mg/L $CaCO_3$)
Ca^{+2}	Calcium (mg/L)
Cl^{-}	Chloride (mg/L)
DOC	Dissolved Organic Carbon (mg/L)
Mg^{+2}	Magnesium (mg/L)
K^{+}	Potassium (mg/L)
SiO_2	Silicate (mg/L)
Na^{+}	Sodium (mg/L)
SO_4^{-2}	Sulfate (mg/L)
NH_4-N	Ammonium-Nitrogen (µg/L)
NO_3+NO_2-N	Nitrate+Nitrite (µg/L)
TN	Total Nitrogen (µg/L)
TP	Total Phosphorus (µg/L)
chl-*a*	Chlorophyll-*a* (µg/L)
DO	Dissolved Oxygen (mg/L)
SC25	Specific Conductance (µS/cm)
pH	pH (standard units)
Temp	Temperature (°C)
Secchi	Secchi Depth (m)
T-tube	Transparency Tube (cm)
Water Level	Water Level (m)
TSI(chl-*a*)	Trophic State Index calculated from chlorophyll-*a* concentration
TSI(TP)	Trophic State Index calculated from TP concentration
TSI(Secchi)	Trophic State Index calculated from Secchi depth

Appendix B. Apostle Island National Lakeshore, 2011.

Parameter	Month/Yr	Michigan Island	Outer Island	Stockton Island	Little Sand Bay	Duplicate	Duplicate Location
Alk	7/11	45	**ND**	28	27	27	Little Sand Bay
Ca^{+2}	7/11	13.0	2.0	10.7	8.9	9.3	Little Sand Bay
Cl^{-}	7/11	0.9	0.7	1.5	1.7	1.7	Little Sand Bay
DOC	7/11	9.1	18.3	8.3	17.8	17.7	Little Sand Bay
Mg^{+2}	7/11	3.6	0.8	2.5	2.9	2.9	Little Sand Bay
K^{+}	7/11	**0.3**	0.5	0.5	0.5	0.4	Little Sand Bay
SiO_2	7/11	6.4	**ND**	1.6	2.1	2.1	Little Sand Bay
Na^{+}	7/11	0.7	0.7	1.3	1.8	1.8	Little Sand Bay
SO_4^{-2}	7/11	1.0	2.8	3.6	2.6	2.4	Little Sand Bay
NH_4-N	6/11	16.4	15.7	14.5	9.7	9.4	Little Sand Bay
NH_4-N	7/11	**5.5**	**4.9**	**6.7**	**6.0**	14.9	Little Sand Bay
NH_4-N	8/11	18.1	22.6	14.4	10.7	15.2	Stockton
NH_4-N	average	13.3	14.4	11.9	8.8		
NO_3+NO_2-N	6/11	**5.8**	**4.1**	**6.8**	**2.5**	**2.5**	Little Sand Bay
NO_3+NO_2-N	7/11	**4.5**	**0.0**	181	14.6	16.5	Little Sand Bay
NO_3+NO_2-N	8/11	**5.6**	**4.1**	**3.6**	**5.5**	**3.7**	Stockton
NO_3+NO_2-N	average	5.3	2.7	63.8	7.5		
TN	6/11	498	756	969	745	746	Little Sand Bay
TN	7/11	635	845	556	690	666	Little Sand Bay
TN	8/11	577	823	669	813	669	Stockton
TN	average	570	808	731	749		
TP	6/11	9.0	11.0	13.1	25.1	25.1	Little Sand Bay
TP	7/11	16.8	9.8	4.7	18.7	19.5	Little Sand Bay
TP	8/11	15.5	11.4	11.6	22.0	12.3	Stockton
TP	average	13.7	10.7	9.8	21.9		

Appendix B. Apostle Island National Lakeshore, 2011 (continued).

Parameter	Month/Yr	Michigan Island	Outer Island	Stockton Island	Little Sand Bay	Duplicate	Duplicate Location
chl-a	6/11	1.6	2.4	2.1	4.7	4.2	Little Sand Bay
chl-a	7/11	2.1	1.7	**0.4**	2.9	3.5	Little Sand Bay
chl-a	8/11	3.2	2.2	5.7	2.5	5.9	Stockton
chl-a	average	2.3	2.1	2.7	3.4		
DO	6/11	8.8	8.8	8.7	7.2		
DO	7/11	7.5	8.2	10.3	8.2		
DO	8/11	7.0	8.0	8.0	7.2		
DO	average	7.8	8.3	9.0	7.6		
SC	6/11	80	19	28	64		
SC	7/11	102	20	96	77		
SC	8/11	116	21	85	75		
SC	average	99	20	70	72		
pH	6/11	7.6	6.7	6.7	7.1		
pH	7/11	7.4	6.7	7.8	7.5		
pH	8/11	7.8	7.1	7.9	7.6		
pH	average	7.6	6.8	7.5	7.4		
Temp	6/11	16.4	17.9	16.3	19.6		
Temp	7/11	22.5	23.2	17.0	22.4		
Temp	8/11	21.2	22.3	21.5	21.8		
Temp	average	20.0	21.1	18.3	21.3		
Secchi	6/11	bottom	1.25	0.85	0.875		
Secchi	7/11	1.25	bottom	bottom	1.225		
Secchi	8/11	bottom	1.3	1.575	1.275		
Secchi	average	1.25	1.28	1.21	1.13		

Appendix B. Apostle Island National Lakeshore, 2011 (continued).

Parameter	Month/Yr	Michigan Island	Outer Island	Stockton Island	Little Sand Bay	Duplicate	Duplicate Location
T-tube	6/11	>120					
T-tube	7/11		110.1	>120			
T-tube	8/11	>120					
T-tube	average						
Water Level	6/11	-1.77	-1.57	-1.275	-1.025		
Water Level	7/11	-1.71	-1.69	-1.08	-0.875		
Water Level	8/11	-1.66	-1.88	-1.095	-1.005		
Water level	average	-1.71	-1.71	-1.15	-0.97		
TSI (chl-a)	6/11	35	39	38	46		
TSI (chl-a)	7/11	38	36	22	41		
TSI (chl-a)	8/11	42	38	48	39		
TSI (chl-a)	average	38	38	36	42		
TSI (TP)	6/11	36	39	41	51		
TSI (TP)	7/11	45	37	27	46		
TSI (TP)	8/11	44	39	39	49		
TSI (TP)	average	41	38	36	49		
TSI (Secchi)	6/11		57	62	62		
TSI (Secchi)	7/11	57			57		
TSI (Secchi)	8/11		56	53	56		
TSI (Secchi)	average	57	57	58	58		

Appendix C. Field and laboratory results for Isle Royale National Park, 2011.

Multiprobe measurements for pH, specific conductance, dissolved oxygen, and temperature are reported from 1.0 m depth. Results in **bold font** indicate values less than the laboratory reporting limit (also known as the method quantitation limit or MQL). Blank cells indicate that no results are available. Abbreviations used are as follows (units of measurement are in parentheses):

Alk	Alkalinity (mg/L $CaCO_3$)
Ca^{+2}	Calcium (mg/L)
Cl^{-}	Chloride (mg/L)
DOC	Dissolved Organic Carbon (mg/L)
Mg^{+2}	Magnesium (mg/L)
K^{+}	Potassium (mg/L)
SiO_2	Silicate (mg/L)
Na^{+}	Sodium (mg/L)
SO_4^{-2}	Sulfate (mg/L)
NH_4-N	Ammonium-Nitrogen (µg/L)
NO_3+NO_2-N	Nitrate+Nitrite (µg/L)
TN	Total Nitrogen (µg/L)
TP	Total Phosphorus (µg/L)
TN - Hypolimnion	Bottom TN (µg/L)
TP - Hypolimnion	Bottom TP (µg/L)
chl-*a*	Chlorophyll-*a* (µg/L)
TSS	Total Suspended Solids (mg/L)
DO	Dissolved Oxygen (mg/L)
SC25	Specific Conductance (µS/cm)
pH	pH (standard units)
Temp	Temperature (°C)
Secchi	Secchi Depth (m)
Water Level	Water Level (m)
TSI(chl-*a*)	Trophic State Index calculated from chlorophyll-*a* concentration
TSI(TP)	Trophic State Index calculated from TP concentration
TSI(Secchi)	Trophic State Index calculated from Secchi depth

Appendix C1. Isle Royale National Park, Index Lakes, 2011.

Parameter	Month/Yr	Ahmik	Sargent	Richie	Beaver	Harvey	George	Siskiwit	Desor	Feldt-mann	Duplicate	Duplicate Location
Alk	7/11	44	39	32	42	40	54	26	44	23	34	Sargent
Ca^{+2}	7/11	11.6	9.7	9.7	9.8	9.8	20.6	8.6	13.3	9.9	10.4	Sargent
Cl^{-}	7/11	0.9	1.0	1.2	0.7	0.5	0.6	0.5	0.8	1.1	0.9	Sargent
DOC	7/11	19.7	9.3	10.1	14.2	10.6	10.4	5.5	7.6	18.2	9.5	Sargent
Mg^{+2}	7/11	5.1	3.8	3.1	5.0	4.2	1.9	2.5	4.4	2.2	4.0	Sargent
K^{+}	7/11	**0.1**	**0.2**	**0.2**	**0.1**	**ND**	**0.1**	**0.3**	0.5	**0.3**	**0.2**	Sargent
SiO_2	7/11	8.1	5.5	6.9	8.6	3.7	1.7	3.1	1.7	1.8	5.4	Sargent
Na^{+}	7/11	1.7	2.0	1.6	2.6	1.9	1.0	1.3	1.8	1.3	2.3	Sargent
SO_4^{-2}	7/11	3.1	4.6	4.6	3.5	3.4	2.1	4.7	3.3	5.1	6.2	Sargent
NH_4-N	6/11	9.2	8.5	9.8	**7.2**	**5.9**	**0.8**	**6.6**	**6.0**	**6.6**	**6.5**	Siskiwit
NH_4-N	7/11	10.8	**6.7**	**7.5**	**7.6**	**7.1**	**4.3**	8.3	15.0	**6.4**	**6.7**	Sargent
NH_4-N	8-9/11	24.1	8.6	8.1	11.2	9.1	12.2	**7.7**	**8.0**	13.9	**5.9**	Richie
NH_4-N	average	14.7	7.9	8.5	8.7	7.4	5.8	7.5	9.6	9.0		
NO_3+NO_2-N	6/11	**4.5**	**4.6**	**3.5**	**3.4**	**3.0**	**0.0**	23.4	**2.6**	**3.1**	24.0	Siskiwit
NO_3+NO_2-N	7/11	**4.4**	**3.5**	**5.0**	**3.6**	**4.6**	12.8	**6.6**	**2.5**	**6.0**	**3.8**	Sargent
NO_3+NO_2-N	8-9/11	**3.9**	**2.0**	**3.8**	**3.1**	**3.1**	**2.9**	**2.8**	**4.1**	**3.6**	**3.4**	Richie
NO_3+NO_2-N	average	4.2	3.4	4.1	3.4	3.5	5.2	10.9	3.1	4.2		
TN	6/11	729	417	520	552	497	405	217	455	697	243	Siskiwit
TN	7/11	756	444	546	598	532	398	220	406	715	434	Sargent
TN	8-9/11	838	468	516	572	558	421	241	462	718	529	Richie
TN	average	774	443	527	574	529	408	226	441	710		
TP	6/11	14.6	12.5	16.8	20.0	14.4	10.2	4.9	11.0	13.1	5.8	Siskiwit
TP	7/11	16.0	13.0	18.4	19.0	13.2	8.0	5.2	8.4	15.0	12.2	Sargent
TP	8-9/11	23.3	15.4	20.4	18.1	13.0	10.8	4.7	9.8	12.3	20.2	Richie
TP	average	17.9	13.6	18.5	19.0	13.5	9.6	4.9	9.7	13.5		

Appendix C1. Isle Royale National Park, Index Lakes, 2011 (continued).

Parameter	Month/Yr	Ahmik	Sargent	Richie	Beaver	Harvey	George	Siskiwit	Desor	Feldt-mann	Duplicate	Duplicate Location
TN-Hypolimnion	7/11		490	609	499	500		239	841		484	Sargent
TP-Hypolimnion	7/11		16.8	21.9	27.5	16.4		6.1	19.2		19.1	Sargent
chl-a	6/11	1.6	1.7	3.5	1.7	1.6	1.5	0.5	2.7	3.0	0.7	Siskiwit
chl-a	7/11	0.8	2.0	2.8	2.6	0.8	0.7	0.6	0.7	2.1	1.4	Sargent
chl-a	8-9/11	1.4	2.5	3.3	2.1	1.9	1.7	1.1	2.2	1.9	2.1	Richie
chl-a	average	1.2	2.1	3.2	2.1	1.4	1.3	0.7	1.9	2.3		
TSS	6/11											
TSS	7/11	0.27		1.70		0.50		0.45				
TSS	8-9/11	-0.80		2.00		1.60		0.51			1.80	Richie
TSS	average	-0.3		1.9		1.1		0.5				
DO	6/11	8.0	9.2	8.8	8.9	9.3	9.1	9.8	9.5	9.0		
DO	7/11	7.0	8.2	8.0	8.1	8.3	8.1	8.8	8.5	8.3		
DO	8-9/11	7.7	8.4	7.7	8.0	8.1	7.9	8.7	8.5	8.1		
DO	average	7.6	8.6	8.2	8.3	8.6	8.4	9.1	8.8	8.5		
SC	6/11	89	90	79	90	88	122	71	106	71		
SC	7/11	99	92	81	96	90	124	72	107	72		
SC	8-9/11	110	94	83	99	92	121	73	108	76		
SC	average	100	92	81	95	90	123	72	107	73		
pH	6/11	7.5	7.8	7.8	7.7	8.4	7.9	8.0	8.1	7.8		
pH	7/11	7.4	8.2	7.9	7.8	8.6	7.9	8.2	8.4	7.8		
pH	8-9/11	7.8	8.2	7.8	7.9	8.9	7.9	8.1	8.3	7.7		
pH	average	7.6	8.1	7.8	7.8	8.7	7.9	8.1	8.3	7.8		
Temp	6/11	18.3	16.9	17.5	18.8	19.5	14.6	16.6	16.1	18.7		
Temp	7/11	23.8	24.0	22.7	22.5	25.0	23.0	21.0	24.9	21.1		
Temp	8-9/11	20.6	22.2	23.0	21.0	23.1	21.1	20.6	21.3	21.0		
Temp	average	20.9	21.0	21.0	20.7	22.5	19.6	19.4	20.8	20.3		

Appendix C1. Isle Royale National Park, Index Lakes, 2011 (continued).

Parameter	Month/Yr	Ahmik	Sargent	Richie	Beaver	Harvey	George	Siskiwit	Desor	Feldt-mann	Duplicate	Duplicate Location
Secchi	5/11			2.5								
Secchi	6/11	1.60	2.90	2.70	2.10	3.05	3.25	9.65	2.05	3.13		
Secchi	7/11	1.75	3.75	2.88	1.50	3.65	bottom	6.63	2.90	1.50		
Secchi	8-9/11	2.50	3.83	2.63	3.02	2.38	bottom	8.15	2.10	2.85		
Secchi	average	1.95	3.49	2.74	2.21	3.03	3.25	8.14	2.35	2.49		
Water Level	5/11			-0.89								
Water Level	6/11	-0.405	-1.2	-0.84	-1.39	-0.995	-0.395	-0.57	-0.73	-0.515		
Water Level	7/11			-0.63								
Water Level	7/11	-0.33	-1.09	-0.665	-1.38	-1.01	-0.435		-0.71	-0.64		
Water Level	8-9/11	-0.5	-1.32	-0.765	-1.575	-1.205	-0.505	-0.795	-0.915	-0.825		
Water Level	9/11			-0.82								
Water Level	average	-0.41	-1.20	-0.77	-1.45	-1.07	-0.45	-0.68	-0.79	-0.66		
TSI (chl-a)	6/11	35	36	43	36	35	35	24	40	41		
TSI (chl-a)	7/11	28	38	41	40	28	27	26	27	38		
TSI (chl-a)	8-9/11	34	39	42	38	37	36	31	38	37		
TSI (chl-a)	average	32	38	42	38	33	32	27	35	39		
TSI (TP)	6/11	43	41	45	47	43	38	27	39	41		
TSI (TP)	7/11	44	41	46	47	41	34	28	35	43		
TSI (TP)	8-9/11	50	44	48	46	41	38	27	37	40		
TSI (TP)	average	45	42	46	47	42	37	27	37	42		
TSI (Secchi)	6/11	53	45	46	49	44	43	27	50	44		
TSI (Secchi)	7/11	52	41	45	54	41		33	45	54		
TSI (Secchi)	8-9/11	47	41	46	44	48		30	49	45		
TSI (Secchi)	average	51	42	46	49	44	43	30	48	48		

Appendix C2. Isle Royale National Park, Non-index Lakes, 2011.

Parameter	Epidote 7/12/2011	Whittlesey 6/13/2011	Wood 6/13/2011	Intermediate 7/14/2011	LeSage 9/2/2011	Chickenbone 7/13/2011	Amygdaloid 8/1/2011	Hidden 5/27/2011
DO	7.7	9.3	10.0	8.8	7.8	8.2	8.2	9.5
SC	64	64	76	69	69	96	79	54
pH	7.1	7.8	8.0	8.4	7.6	8.0	7.9	7.0
Temp	16.9	18.1	18.0	23.2	22.5	23.0	22.9	11.5
Secchi	1.8	4.25	4.3	1.9	2.8	2.1	3.9	bottom

Appendix D. Field and Laboratory Results for Pictured Rocks National Lakeshore, 2011.

Multiprobe measurements for pH, specific conductance, dissolved oxygen, and temperature are reported from 1.0 m depth. Results in **bold font** indicate values less than the laboratory reporting limit (also known as the method quantitation limit or MQL). Blank cells indicate that no results are available. Abbreviations used are as follows (units of measurement are in parentheses):

Alk	Alkalinity (mg/L $CaCO_3$)
Ca^{+2}	Calcium (mg/L)
Cl^{-}	Chloride (mg/L)
DOC	Dissolved Organic Carbon (mg/L)
Mg^{+2}	Magnesium (mg/L)
K^{+}	Potassium (mg/L)
SiO_2	Silicate (mg/L)
Na^{+}	Sodium (mg/L)
SO_4^{-2}	Sulfate (mg/L)
NH_4-N	Ammonium-Nitrogen (µg/L)
NO_3+NO_2-N	Nitrate+Nitrite (µg/L)
TN	Total Nitrogen (µg/L)
TP	Total Phosphorus (µg/L)
TN - Hypolimnion	Bottom TN (µg/L)
TP - Hypolimnion	Bottom TP (µg/L)
chl-*a*	Chlorophyll-*a* (µg/L)
DO	Dissolved Oxygen (mg/L)
SC25	Specific Conductance (µS/cm)
pH	pH (standard units)
Temp	Temperature (°C)
Secchi	Secchi Depth (m)
Water Level	Water Level (m)
TSI(chl-*a*)	Trophic State Index calculated from chlorophyll-*a* concentration
TSI(TP)	Trophic State Index calculated from TP concentration
TSI(Secchi)	Trophic State Index calculated from Secchi depth

Appendix D. Pictured Rocks National Lakeshore, 2011.

Parameter	Month/Yr	Grand Sable	Legion	Beaver	Little Beaver	Chapel	Miners	Duplicate	Duplicate Location
Alk	7-8/11	53	**ND**	81		95	166	82	Beaver
Ca^{+2}	7-8/11	14.4	0.5	24.2		21.7	36.8	23.6	Beaver
Cl^{-}	7-8/11	0.6	0.3	0.5		0.7	2.0	0.5	Beaver
DOC	7-8/11	7.1	2.7	4.2		11.3	5.7	4.3	Beaver
Mg^{+2}	7-8/11	5.5	0.2	5.4		11.0	19.0	5.4	Beaver
K^{+}	7-8/11	0.9	**0.3**	0.6		0.7	0.7	0.6	Beaver
SiO_2	7-8/11	4.6	**ND**	6.7		3.9	6.5	6.8	Beaver
Na^{+}	7-8/11	0.9	**0.1**	0.9		0.6	1.4	0.9	Beaver
SO_4^{-2}	7-8/11	5.1	2.0	6.6		7.3	7.8	6.7	Beaver
NH_4-N	6/11	**7.4**	11.7	8.6		9.6	19.6	12.4	Legion
NH_4-N	7-8/11	**5.9**	**4.8**	**3.8**		**6.6**	10.2	**2.0**	Beaver
NH_4-N	8-9/11	**4.8**	**6.4**	**4.1**		**7.9**	**7.7**	**6.6**	Chapel
NH_4-N	average	6.0	7.6	5.5		8.0	12.5		
NO_3+NO_2-N	6/11	51.3	28.7	**3.4**		32.4	251	29.5	Legion
NO_3+NO_2-N	7-8/11	**4.2**	**3.3**	9.0		9.7	166	**6.9**	Beaver
NO_3+NO_2-N	8-9/11	**2.2**	**2.2**	**2.6**		**2.5**	155	**2.0**	Chapel
NO_3+NO_2-N	average	19.3	11.4	5.0		14.8	191		
TN	6/11	361	207	212		407	496	218	Legion
TN	7-8/11	323	219	248		491	521	236	Beaver
TN	8-9/11	306	231	241		368	377	343	Chapel
TN	average	330	219	233		422	465		
TP	6/11	11.0	4.3	9.9		9.0	9.7	6.3	Legion
TP	7-8/11	12.4	7.0	10.0		12.5	14.5	8.9	Beaver
TP	8-9/11	10.8	8.7	12.1		12.0	16.4	10.6	Chapel
TP	average	11.4	6.7	10.7		11.1	13.5		
TN - Hypolimnion	7-8/11	543	263	230		3565	na	235	Beaver
TP - Hypolimnion	7-8/11	36.7	16.5	16.3		20.4	na	17.1	Beaver

Appendix D. Pictured Rocks National Lakeshore, 2011 (continued).

Parameter	Month/Yr	Grand Sable	Legion	Beaver	Little Beaver	Chapel	Miners	Duplicate	Duplicate Location
chl-a	6/11	2.5	0.66	2.72		1.46	0.46	0.51	Legion
chl-a	7-8/11	1.79	0.78	1.29		1.59	3.28	1.43	Beaver
chl-a	8-9/11	1.68	0.79	1.8		0.63	1.51	1.88	Chapel
chl-a	average	1.99	0.74	1.94		1.23	1.75		
DO	6/11	9.3	9.4	9.3		10.4	10.5		
DO	7-8/11	8.6	8.2	9.1		8.6	9.6		
DO	8-9/11	8.8	8.7	8.8	9.1	7.2	9.3		
DO	average	8.9	8.7	9.0	9.1	8.7	9.8		
SC	6/11	113	9	166		170	305		
SC	7-8/11	118	9	171		193	318		
SC	8-9/11	118	10	174	162	218	341		
SC	average	116	9	170	162	194	321		
pH	6/11	7.9	5.2	8.1		8.0	7.8		
pH	7-8/11	8.4	5.3	8.5		8.1	8.2		
pH	8-9/11	8.1	5.1	8.2	8.3	8.2	8.0		
pH	average	8.1	5.2	8.3	8.3	8.1	8.0		
Temp	6/11	17.4	18.1	17.2		18.6	11.3		
Temp	7-8/11	24.1	24.1	24.0		22.0	17.5		
Temp	8-9/11	22.1	22.1	21.7	21.3	22.4	15.6		
Temp	average	21.2	21.4	21.0	21.3	21.0	14.8		
Secchi	6/11	2.97	7.45	3.70		2.68	2.35		
Secchi	7-8/11	3.10	5.83	4.48		2.75	2.35		
Secchi	8-9/11	2.95	6.10	4.05	1.45	3.43	3.00		
Secchi	10/11	2.66							
Secchi	average	2.90	5.97	4.27	1.45	3.09	2.68		
Water Level	6/11	0.26	-1.235	-0.93		-1.96	-0.97		
Water Level	7-8/11	0.51	-1.27	-1.025		-2.025	-1.105		
Water Level	8-9/11	0.37	-1.41	-1.055		-2.625	-1.145		
Water Level	average	0.38	-1.31	-1.00	1.45	-2.20	-1.07		

Appendix D. Pictured Rocks National Lakeshore, 2011 (continued).

Parameter	Month/Yr	Grand Sable	Legion	Beaver	Little Beaver	Chapel	Miners	Duplicate	Duplicate Location
TSI (chl-a)	6/11	40	27	40		34	23		
TSI (chl-a)	7-8/11	36	28	33		35	42		
TSI (chl-a)	8-9/11	36	28	36		26	35		
TSI (chl-a)	average	37	28	37		32	33		
TSI (TP)	6/11	39	25	37		36	37		
TSI (TP)	7-8/11	40	32	37		41	43		
TSI (TP)	8-9/11	38	35	40		40	44		
TSI (TP)	average	39	31	38		39	41		
TSI (Secchi)	6/11	44	31	41		46	48		
TSI (Secchi)	7-8/11	44	35	38		45	48		
TSI (Secchi)	8-9/11	44	34	40	55	42	44		
TSI (Secchi)	average	44	33	40	55	44	47		

Appendix E. Field and laboratory results for Indiana Dunes National Lakeshore, 2011.

Multiprobe measurements for pH, specific conductance, dissolved oxygen, and temperature are reported from 0.5 m depth. Results in **bold font** indicate values less than the laboratory reporting limit (also known as the method quantitation limit or MQL). Blank cells indicate that no results are available. Abbreviations used are as follows (units of measurement are in parentheses):

Alk	Alkalinity (mg/L $CaCO_3$)
Ca^{+2}	Calcium (mg/L)
Cl^{-}	Chloride (mg/L)
DOC	Dissolved Organic Carbon (mg/L)
Mg^{+2}	Magnesium (mg/L)
K^{+}	Potassium (mg/L)
SiO_2	Silicate (mg/L)
Na^{+}	Sodium (mg/L)
SO_4^{-2}	Sulfate (mg/L)
TSS	Total Suspended Solids
NH_4-N	Ammonium-Nitrogen (µg/L)
NO_3+NO_2-N	Nitrate+Nitrite (µg/L)
TN	Total Nitrogen (µg/L)
TP	Total Phosphorus (µg/L)
chl-*a*	Chlorophyll-*a* (µg/L)
DO	Dissolved Oxygen (mg/L)
SC25	Specific Conductance (µS/cm)
pH	pH (standard units)
Temp	Temperature (°C)
Secchi	Secchi Depth (m)
T-tube	Transparency Tube (cm)
Water Level	Water Level (m)
TSI(chl-*a*)	Trophic State Index calculated from chlorophyll-*a* concentration
TSI(TP)	Trophic State Index calculated from TP concentration
TSI(Secchi)	Trophic State Index calculated from Secchi depth

Appendix E. Indiana Dunes National Lakeshore, 2011.

Parameter	Month/Yr	Long	Middle Lagoon	Duplicate	Duplicate Location
Alk	8/11	108	81	77	Middle Lagoon
Ca^{+2}	8/11	29.6	15.4	15.3	Middle Lagoon
Cl^{-}	8/11	48.9	85.0	84.7	Middle Lagoon
DOC	8/11	10.3	5.5	5.7	Middle Lagoon
Mg^{+2}	8/11	8.6	12.3	12.4	Middle Lagoon
K^{+}	8/11	0.9	0.9	1.0	Middle Lagoon
SiO_2	8/11	6.4	5.9	6.1	Middle Lagoon
Na^{+}	8/11	27.0	47.8	48.4	Middle Lagoon
SO_4^{-2}	8/11	1.7	13.1	13.2	Middle Lagoon
NH_4-N	5/11	11.1	16.0	10.5	Middle Lagoon
NH_4-N	7/11	14.9	10.0	9.9	Middle Lagoon
NH_4-N	9/11	14.6	**3.7**	17.6	Long
NH_4-N	average	13.6	9.9		
NO_3+NO_2-N	5/11	**3.0**	8.9	**2.7**	Middle Lagoon
NO_3+NO_2-N	7/11	11.3	66.2	67.9	Middle Lagoon
NO_3+NO_2-N	9/11	**5.7**	**2.6**	**5.4**	Long
NO_3+NO_2-N	average	6.7	25.9		
TN	5/11	524	327	533	Middle Lagoon
TN	7/11	664	477	409	Middle Lagoon
TN	9/11	637	382	629	Long
TN	average	608	395		
TP	5/11	16.9	10.2	16.0	Middle Lagoon
TP	7/11	17.5	21.0	12.9	Middle Lagoon
TP	9/11	23.0	11.1	22.7	Long
TP	average	19.1	14.1		

Appendix E. Indiana Dunes National Lakeshore, 2011 (continued).

Parameter	Month/Yr	Long	Middle Lagoon	Duplicate	Duplicate Location
chl-a	5/11	0.9	0.7	0.5	Middle Lagoon
chl-a	7/11	1.4	1.4	1.5	Middle Lagoon
chl-a	9/11	4.7	1.5	5.4	Long
chl-a	average	2.3	1.2		
DO	5/11	8.1	8.1		
DO	7/11	0.2	11.6		
DO	8/11	2.0	11.2		
DO	9/11	3.4	8.5		
DO	average	3.4	9.8		
SC	5/11	354	620		
SC	7/11	393	481		
SC	8/11	309	375		
SC	9/11	351	440		
SC	average	352	479		
pH	5/11	7.3	7.9		
pH	7/11	6.6	9.8		
pH	8/11	7.2	9.3		
pH	9/11	6.9	8.1		
pH	average	7.0	8.8		
Temp	5/11	14.3	13.0		
Temp	7/11	24.0	31.8		
Temp	8/11	21.2	25.5		
Temp	9/11	18.3	17.4		
Temp	average	19.4	21.9		

Appendix E. Indiana Dunes National Lakeshore, 2011 (continued).

Parameter	Month/Yr	Long	Middle Lagoon	Duplicate	Duplicate Location
Secchi	5/11		2.1		
Secchi	7/11	0.35	bottom		
Secchi	8/11	0.58	bottom		
Secchi	9/11		bottom		
Secchi	average	0.465			
T-tube	5/11	>120	>120		
T-tube	7/11	60.75	>120		
T-tube	8/11	50.00	>120		
T-tube	9/11	73.00	>120		
T-tube	average	76.00	>120		
Water Level	5/11	-81.09	-5.63		
Water Level	7/11	-81.13	-5.58		
Water Level	8/11	-81.10	-5.43		
Water Level	9/11	-81.06	-5.63		
Water Level	average	-81.10	-5.57		
TSI (chl-a)	5/11	30	27		
TSI (chl-a)	7/11	34	34		
TSI (chl-a)	9/11	46	34		
TSI (chl-a)	average	37	32		
TSI (TP)	5/11	45	38		
TSI (TP)	7/11	45	48		
TSI (TP)	9/11	49	39		
TSI (TP)	average	47	42		
TSI (Secchi)	5/11		49		
TSI (Secchi)	7/11	75			
TSI (Secchi)	9/11	68			
TSI (Secchi)	average	71	49		

Appendix F. Field and laboratory results for Sleeping Bear Dunes National Lakeshore, 2011.

Multiprobe measurements for pH, specific conductance, dissolved oxygen, and temperature are reported from 1.0 m depth. Results in **bold font** indicate values less than the laboratory reporting limit (also known as the method quantitation limit or MQL). Blank cells indicate that no results are available. Abbreviations used are as follows (units of measurement are in parentheses):

Alk	Alkalinity (mg/L $CaCO_3$)
Ca^{+2}	Calcium (mg/L)
Cl^{-}	Chloride (mg/L)
DOC	Dissolved Organic Carbon (mg/L)
Mg^{+2}	Magnesium (mg/L)
K^{+}	Potassium (mg/L)
SiO_2	Silicate (mg/L)
Na^{+}	Sodium (mg/L)
SO_4^{-2}	Sulfate (mg/L)
NH_4-N	Ammonium-Nitrogen (µg/L)
NO_3+NO_2-N	Nitrate+Nitrite (µg/L)
TN	Total Nitrogen (µg/L)
TP	Total Phosphorus (µg/L)
TN - Hypolimnion	Bottom TN (µg/L)
TP - Hypolimnion	Bottom TP (µg/L)
chl-*a*	Chlorophyll-*a* (µg/L)
DO	Dissolved Oxygen (mg/L)
SC25	Specific Conductance (µS/cm)
pH	pH (standard units)
Temp	Temperature (°C)
Secchi	Secchi Depth (m)
Water Level	Water Level (m)
TSI(chl-*a*)	Trophic State Index calculated from chlorophyll-*a* concentration
TSI(TP)	Trophic State Index calculated from TP concentration
TSI(Secchi)	Trophic State Index calculated from Secchi depth

Appendix F. Sleeping Bear Dunes National Lakeshore, 2011.

Parameter	Month/Yr	Manitou	Florence	Narada*	Shell	Bass (N)	Otter	Tucker	North Bar	Loon	Round	Duplicate	Duplicate Location
Alk	7-8/11	125	56	161	105	105	130	118	151	132	119	126	Otter
Ca^{+2}	7-8/11	25.8	14.2	40.7	26.2	26.1	33.4	30.4	38.2	34.2	25.2	31.9	Otter
Cl^{-}	7-8/11	0.7	0.9	10.4	1.3	6.6	8.4	1.0	4.9	9.2	18.0	8.4	Otter
DOC	7-8/11	6.2	6.4	7.8	11.1	9.3	4.4	13.4	3.5	4.3	8.6	4.6	Otter
Mg^{+2}	7-8/11	15.6	6.1	12.0	14.5	9.9	13.8	10.7	14.9	12.3	16.6	13.0	Otter
K^{+}	7-8/11	0.5	0.7	0.5	0.5	1.0	0.8	**0.1**	0.7	0.7	0.6	0.7	Otter
SiO_2	7-8/11	2.8	**0.3**	10.2	7.4	1.8	4.7	3.6	6.8	6.3	6.4	4.6	Otter
Na^{+}	7-8/11	1.2	0.5	5.7	1.5	3.1	4.4	0.7	1.8	6.0	11.1	4.2	Otter
SO_4^{-2}	7-8/11	10.9	4.5	4.2	26.8	4.3	9.4	5.6	12.6	11.4	10.5	9.5	Otter
NH_4-N	6-7/11	11.3	17.2		57.0	32.3	27.1	19.3	26.6	14.3	28.3	32.0	Bass (N)
NH_4-N	7-8/11	11.5	24.6		34.7	21.8	22.8	16.8	27.1	16.0	49.2	21.8	Otter
NH_4-N	9-10/11	10.3	25.2	9.3	53.7	14.8	56.0	9.0	75.6	18.2	66.7	56.0	Shell
NH_4-N	average	11.0	22.3	9.3	48.5	23.0	35.3	15.0	43.1	16.1	48.0		
NO_3+NO_2-N	6-7/11	9.8	14.1		20.6	16.7	296	13.9	360	70.3	14.5	16.6	Bass (N)
NO_3+NO_2-N	7-8/11	174	76.0		175	110	250	49.8	357	11.0	46.5	261	Otter
NO_3+NO_2-N	9-10/11	**5.5**	16.9	**6.9**	13.1	**7.9**	129	**7.7**	229	16.9	12.7	12.7	Shell
NO_3+NO_2-N	average	63.2	35.7	6.9	69.6	44.8	225	23.8	315	32.7	24.6		
TN	6-7/11	547	596		838	686	634	773	679	350	731	742	Bass (N)
TN	7-8/11	534	606		973	721	580	805	658	319	829	591	Otter
TN	9-10/11	541	672	483	1087	740	570	868	657	438	957	1108	Shell
TN	average	540	625	483	966	716	595	815	665	369	839		
TP	6-7/11	15.0	13.0		10.6	8.6	8.5	17.8	11.2	9.9	10.6	12.0	Bass (N)
TP	7-8/11	11.8	10.1		12.6	8.7	7.6	12.9	9.8	9.2	11.1	7.8	Otter
TP	9-10/11	14.4	13.9	13.3	18.7	12.0	9.6	13.6	14.9	11.4	16.7	16.3	Shell
TP	average	13.7	12.3	13.3	14.0	9.8	8.6	14.7	12.0	10.1	12.8		
TN - Hypolimnion	7-8/11	1934	664	497	986	1648	587	789	932	720	797	602	Otter
TP - Hypolimnion	7-8/11	76.7	12.2	2421	17.4	19.9	9.4	13.4	25.4	21.6	16.0	9.5	Otter

Appendix F. Sleeping Bear Dunes National Lakeshore, 2011 (continued).

Parameter	Month/Yr	Manitou	Florence	Narada*	Shell	Bass (N)	Otter	Tucker	North Bar	Loon	Round	Duplicate	Duplicate Location
chl-a	6-7/11	2.2	2.4		1.7	1.8	1.7	3.9	1.6	1.2	2.3	1.9	Bass (N)
chl-a	7-8/11	1.4	2.7		1.8	1.3	1.3	2.6	0.6	1.2	1.7	1.0	Otter
chl-a	9-10/11	1.4	3.0	0.9	2.3	1.4	1.8	1.7	2.5	1.8	2.9	1.9	Shell
chl-a	average	1.7	2.7	0.9	1.9	1.5	1.6	2.7	1.6	1.4	2.3		
DO	6-7/11	10.4	9.2		9.6	9.6	10.5	10.5	9.6	9.7	10.2		
DO	7-8/11	9.1	8.4		8.8	9.0	10.3	9.2	9.0	9.0	8.5		
DO	9-10/11	9.2	9.0	9.8	10.1	10.0	10.1	9.7	10.8	9.4	9.6		
DO	average	9.5	8.9	9.8	9.5	9.5	10.3	9.8	9.8	9.4	9.4		
SC	6-7/11	255	121		271	226	296	224	333	318	307		
SC	7-8/11	246	125		258	222	282	231	317	296	308		
SC	9-10/11	240	127	333	258	206	281	248	324	303	314		
SC	average	247	124	333	262	218	286	234	325	305	310		
pH	6-7/11	8.7	8.4		8.4	8.5	8.5	8.4	8.4	8.4	8.7		
pH	7-8/11	8.7	8.4		8.7	8.7	8.6	8.4	8.3	8.5	8.6		
pH	9-10/11	8.7	8.5	8.0	8.5	8.7	8.4	8.2	8.4	8.3	8.4		
pH	average	8.7	8.4	8.0	8.5	8.6	8.5	8.3	8.4	8.4	8.5		
Temp	6-7/11	23.6	23.6		20.9	22.0	22.0	21.3	23.3	23.9	22.3		
Temp	7-8/11	25.1	26.2		28.4	27.9	26.9	28.7	26.3	27.1	26.4		
Temp	9-10/11	21.1	20.2	17.6	17.2	16.9	15.8	17.3	15.2	17.5	17.6		
Temp	average	23.3	23.3	17.6	22.2	22.2	21.5	22.4	21.6	22.8	22.1		
Secchi	6-7/11	2.88	3.18		3.33	4.03	3.44	2.23	4.10	2.35	3.65		
Secchi	7-8/11	3.00	2.50		2.45	2.95	2.83	2.55	2.25	3.98	4.80		
Secchi	9-10/11	3.25	2.18	4.03	2.83	3.48	4.50	2.43	3.25	4.62	3.05		
Secchi	average	3.04	2.62	4.03	2.87	3.49	3.59	2.40	3.20	3.65	3.83		

Appendix F. Sleeping Bear Dunes National Lakeshore, 2011 (continued).

Parameter	Month/Yr	Manitou	Florence	Narada*	Shell	Bass (N)	Otter	Tucker	North Bar	Loon	Round	Duplicate	Duplicate Location
Water Level	6-7/11	-0.945	-0.89		-0.42	-0.495	-0.75	-0.45	-1.29	-0.61	-1.03		
Water Level	7-8/11	-1.025	-0.97		-0.57	-0.78	-0.75	-0.60	-1.43	-0.70	-1.07		
Water Level	9-10/11	-1.15	-1.20	-0.75	-0.75	-1.41	-0.785	-0.80	-0.99	-0.72	-1.16		
Water Level	average	-1.04	-1.02	-0.75	-0.58	-0.90	-0.76	-0.62	-1.24	-0.68	-1.09		
TSI (chl-a)	6-7/11	38	39		36	36	36	44	35	32	39		
TSI (chl-a)	7-8/11	34	40		37	33	33	40	25	32	36		
TSI (chl-a)	9-10/11	34	42	30	39	34	36	36	40	36	41		
TSI (chl-a)	average	35	40	30	37	35	35	40	33	34	39		
TSI (TP)	6-7/11	43	41		38	35	35	46	39	37	38		
TSI (TP)	7-8/11	40	37		41	35	33	41	37	36	39		
TSI (TP)	9-10/11	43	42	41	46	40	37	42	43	39	45		
TSI (TP)	average	42	40	41	42	37	35	43	40	38	41		
TSI (Secchi)	6-7/11	45	43		43	40	42	48	40	48	41		
TSI (Secchi)	7-8/11	44	47		47	44	45	47	48	40	37		
TSI (Secchi)	9-10/11	43	49	40	45	42	38	47	43	38	44		
TSI (Secchi)	average	44	46	40	45	42	42	47	44	42	41		

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