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Natural Resource Stewardship and Science

Water Quality Monitoring Protocol for Inland Lakes

Great Lakes Inventory and Monitoring Network, Version 1.2

Natural Resource Report NPS/GLKN/NRR—2022/2349



ON THE COVER
Overlooking Chapel Lake at Pictured Rocks National Lakeshore, Michigan.
NPS / J. ELIAS

Water Quality Monitoring Protocol for Inland Lakes

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Natural Resource Report NPS/GLKN/NRR—2022/2349

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Revision History Log

The following table lists all edits and amendments to this document since the original publication date. Information entered in the log must be complete and concise. Users of this standard operating procedure will promptly notify the project manager and/or the Great Lakes Network (GLKN) data manager about recommended and required changes. The project manager must review and incorporate all changes, complete the revision history log, and change the date and version number on the title page and in the header of the document file. For complete instructions, please refer to Revising the Protocol, SOP #13.

Revision log:

Revision Date	Previous Ver. #	New Ver. #	Author	Location in Document and Concise Description of Revision	Reason for Change
5/01/2015	1.0	1.1	David VanderMeulen, GLKN	Updated the NPS contact author, dropped and added index lakes, added information about continuous monitoring and differentiated it from discrete monitoring, added details concerning deployment, operation, and data management for thermal arrays, removed references to VSIMS, and added information about Aquarius Informatics and data certification, added information about the use of web-based data summaries and reporting, updated personnel section to reflect that many park staff are paid by GLKN to implement water quality monitoring at their respective parks, removed information about estimated startup costs, updated estimated annual cost of equipment, supplies, salaries, analytical costs, and total estimated annual costs, added or updated references, fixed a handful of grammatical errors throughout, and deleted Tables 15, 16, and 18.	To clarify and update protocol narrative based on changes that have occurred since Version 1.0 was published in 2008
3/2021	1.1	1.2	Alexander Egan, GLKN	Fixed grammatical errors; updated website links as needed; highlighted lakes with new thermal arrays and explained reasons for additions; updated metadata to refer to general NPS/DOI standards instead of particular websites; updated annual costs; changed secchi disc process to include a second full reading by a second person and taking the mean of two readings in SOP #6; included a new peer-reviewed SOP #14 with references in protocol body.	To clarify and update protocol narrative based on changes that have occurred since Version 1.1 was published in 2015

Abstract

The Great Lakes Inventory and Monitoring Network (GLKN) developed this protocol to track basic limnological parameters and changing water quality over time at six national parks in the western Great Lakes. Water quality for inland lakes was ranked during strategic planning among the most fundamental ecological indicators for GLKN to monitor. The core suite of parameters includes pH, specific conductance, dissolved oxygen, temperature, lake level, and water clarity. The advanced suite of parameters includes nitrogen and phosphorous species, dissolved organic carbon, major ions, dissolved silica, and chlorophyll-*a*. This protocol describes each park's water resources, summarizes historical knowledge of water quality studies, explains sampling design and methods, and outlines steps for data handling, analysis, and reporting. Standard operating procedures give details on how each process is accomplished. The overall goal is to develop a program for monitoring water quality on inland lakes that will contribute to an understanding of the health of aquatic ecosystems and provide insights on likely water resources issues within each park.

Acknowledgments

We would like to thank S. Magdalene and D. Engstrom for discussions early in the planning process for this protocol. Thanks also go to the following Great Lakes Inventory and Monitoring Network staff: E. Beever for drafting sections on analysis of data, M. Hart for drafting the data management portion of the protocol, S. Sanders for text on reporting, and T. Ledder for discussion related to field methods, sampling handling, and quality assurance/quality control.

We relied heavily on the monitoring protocols of others, especially those of the Greater Yellowstone Network, San Francisco Area Network, and Southwest Alaska Inventory and Monitoring Network.

Finally, we would like to acknowledge the many reviewers who provided valuable comments on earlier versions of this protocol.

Introduction

Inland lakes are important and valuable resources at six of the parks of the Great Lakes Network: Apostle Islands National Lakeshore (APIS), Indiana Dunes National Park (INDU), Isle Royale National Park (ISRO), Pictured Rocks National Lakeshore (PIRO), Sleeping Bear Dunes National Lakeshore (SLBE), and Voyageurs National Park (VOYA). The Great Lakes Network (hereafter, GLKN or the network) parks encompass a variety of aquatic habitats and biota, including 129 named lakes, totaling nearly 41,000 ha (101,000 acres) (Lafrancois and Glase 2005).

This protocol addresses monitoring of inland lakes to assess change in basic limnological parameters, including those mandated by the National Park Service (detailed below), for the purpose of tracking changes in water quality over time.

1.1 Rationale for Selecting This Resource to Monitor

Water quality is generally high throughout GLKN parks, though threats exist from atmospheric deposition, urban and agricultural runoff, wastewater discharges and seepage from septic systems, recreational use, and other anthropogenic impacts. Network lakes listed as impaired under Section 303(d) of the Clean Water Act are only so designated because of fish consumption advisories (Ledder 2003). All lakes in the State of Michigan have fish consumption advisories (FCAs) for mercury (MDCH 2004), as do most lakes in VOYA (MPCA 2006, NPS WRD 2012) and Lake George, at INDU (NPS WRD 2012). In addition, Siskiwit Lake, at ISRO, has a FCA for polychlorinated biphenyls (PCBs) and Big Glen Lake, at SLBE, has a FCA for PCBs and chlordane. When lagoons are connected to Lake Superior, they are under FCAs for PCBs (NPS WRD 2012); however, these lagoons are sometimes isolated from the lake. All waterbodies within INDU, ISRO, PIRO, and SLBE are designated Outstanding State Resource Waters, and all those in VOYA are designated Outstanding Resource Waters. Lake Superior waters within APIS boundaries are designated Outstanding Natural Resource Waters by the state, and Lake Superior as a whole is designated as federal Outstanding Resource Waters (Ledder 2003).

Although the water quality of most inland lakes is currently relatively good at GLKN parks, conditions can change quickly. It is important to detect change as early as possible, in order to maximize the potential for effective management actions. Park lakes are used extensively by visitors for fishing, boating, swimming, and other recreational activities. The four large lakes at VOYA are impounded for generating hydropower; the levels are controlled through an international agreement (The International Joint Commission). Because the preservation of lake water quality and quantity is of utmost importance to park managers, researchers, and the general public, monitoring basic water quality ranked among the highest of the Network's vital signs (Route 2004).

1.2 Key Variables of Interest

A national review panel assembled by the National Park Service–Water Resources Division (NPS-WRD) recommended a suite of five parameters be measured across all NPS monitoring networks (NPS 2002). In addition to these five mandated parameters (temperature, pH, specific conductance, dissolved oxygen, and flow/water level) we added a measure of water clarity (Secchi depth or transparency tube depth) to our core suite. The core suite was ranked highest among potential vital

signs for aquatic systems of GLKN parks, although it was recognized that these measurements were less diagnostic of water quality degradation than biotic communities and other water quality variables, such as nutrient concentrations.

Inputs of excess nutrients, invasion and spread of exotic species, and contaminants from atmospheric fallout and surface runoff, and how these stressors affect the chemical and biological functions of lakes are key issues of concern. By monitoring an advanced suite of parameters (nitrogen and phosphorus species, dissolved organic carbon, major ions, dissolved silica, and chlorophyll-*a*), we will provide data for a more thorough understanding of changes in lakes over time.

1.2.1 Temperature

Water temperature exerts a major influence on the activity, growth, distribution, and survival of aquatic biota. Fish, insects, zooplankton, phytoplankton, and other aquatic organisms all have preferred temperature ranges for optimal health and reproduction. Temperature is also important because of its influence on water chemistry and physical processes, such as evaporation, oxygen (and other gas) diffusion rates, chemical reaction rates, particle settling velocities (via viscosity), and the stability of thermal stratification. Temperature, via its effect on water density, also acts to structure deeper lakes into distinct layers with profound physical and chemical differences that create a diversity of habitats for organisms (e.g., Wetzel 2001).

1.2.2 Specific Electrical Conductivity (EC25 or SC25)

Electrical conductivity is a measure of the capacity of water to conduct an electrical current. Specific conductivity (called EC25 or SC25) is the "raw" conductivity normalized to unit length and cross-section at 25°C. This normalization eliminates its temperature dependent variability and makes it a good estimator and surrogate measure of the concentration of total dissolved ions in the water. The magnitude of SC25 is controlled largely by geology (rock types) in the watershed, which determines the chemistry of the watershed soil and ultimately the lake. The size of the watershed relative to the area of the lake (Aw:Ao ratio) also affects SC25, with a larger ratio indicating that relatively more water drains into the lake because of a larger catchment area and has more contact with soil before reaching the lake. Increased SC25 may indicate a number of sources of pollutants, such as wastewater from sewage treatment plants or on-site septic systems, urban runoff from roads (especially road salt), agricultural runoff, and atmospheric deposition. Increased conductivity from runoff into soft waters can be a major stressor to salmonids, shoreline and nearshore plants, and other aquatic organisms. Conductivity is an important indicator of polluted runoff that may contain excess nutrients, organic matter, pathogenic microbes, heavy metals, and organic contaminants. SC25 increases naturally due to evaporative salt concentration and respiration, which increases bicarbonate and carbonate concentrations. It is also an excellent 'tracer' of water masses in the lake, as well as tributary and groundwater inflows.

1.2.3 pH

The pH value is the negative logarithm of the hydrogen ion (H^+) activity in the water. At higher pH levels, fewer free hydrogen ions are present; a change of one pH unit (e.g., pH 7 to pH 8) reflects a tenfold change in the concentrations of the hydrogen ion. A closely related parameter is the alkalinity or acid-neutralizing capacity (ANC,) which is a measure of the buffering capacity of the water. The

pH of water determines the solubility and biological availability of chemical constituents such as nutrients (phosphorus, nitrogen, and carbon) and heavy metals (e.g., lead, copper, cadmium). pH is generally used to set water quality criteria for lakes and streams because of its potential impacts to the life cycle stages of aquatic macroinvertebrates and certain salmonids that can be adversely affected when pH levels are above 9.0 or below 6.5 (Stednick and Gilbert 1998). The mobility of many metals is also enhanced by low pH and can be important in assessing mining impacts. Estimating the toxicity of ammonia, aluminum, and some other contaminants requires accurate pH values. Daily and seasonal variability in pH is associated with natural changes in biological photosynthesis and respiration, as well as inputs from runoff and atmospheric deposition (e.g., Schindler 1988, Schindler et al. 1985). When nutrient pollution results in higher algal and plant growth (e.g., from increased temperature or excess nutrients), pH levels may increase, as allowed by the buffering capacity of the lake. Although these small changes in pH are not likely to have a direct impact on aquatic life, they greatly influence the availability and solubility of all chemical forms in the lake and may aggravate nutrient problems.

1.2.4 Dissolved Oxygen (Concentration and % Saturation)

Dissolved oxygen (DO) is a measure of the amount of oxygen in solution. Oxygen solubility is controlled largely by water temperature and the partial pressure of oxygen within gases in contact with the solution. Its concentration in any stratum of water is determined by the net difference between its sources and its sinks. Oxygen transfer from the atmosphere to the water and from one depth to another depends on its diffusion rate, which is highest in the upper, turbulent wind-mixed layer (epilimnion) and very low in the hypolimnion. The largest source of O_2 is the atmosphere, but phytoplankton and macrophyte photosynthesis produce O_2 during daylight hours and tributaries can contribute significant DO to specific layers of water. The major sink for DO is respiration by animals, plants, and microbes, occurring throughout the day. Because photosynthesis is light dependent, and surface mixing is largely dependent on wind energy and morphometry (in the sense of wave height and fetch), DO levels can vary throughout the day, season, and with depth. Temperature controls the potential O_2 saturation, although water can supersaturate from high turbulence (e.g., waterfalls) or photosynthesis from algal blooms in hypereutrophic lakes.

A DO level >1 mg/L is generally accepted as a chronic minimum for most aquatic animals; 5 mg/L is a chronic minimum for the maintenance and survival of most aquatic organisms and is a common regulatory criterion for supporting a cold-water fishery. As water becomes warmer it can hold less DO. If the water becomes too warm, even if 100% saturated, O_2 levels may be suboptimal for many species of trout. Mid-summer may be a critical time for some fish because epilimnetic water is too warm for them, and while hypolimnetic water may be an optimal temperature, it may have too little oxygen.

1.2.5 Lake Level

Accurate lake level measurements are highly recommended as per NPS monitoring guidelines (NPS 2002) and are needed primarily because of their importance in defining the spatial extent of littoral zones. These shallow water areas provide critical habitat for many aquatic organisms and are nursery areas for both planktivorous and piscivorous fish at various stages of their life cycles. Accurate

volumetric estimates, hydrologic budgets, heat budgets and mass balance budgets for chemical compounds and oxygen also require accurate lake levels. In reservoirs and lake level-controlled systems such as Lake Kabetogama in VOYA, lake levels and discharge from the lake are controversial management issues (Kallemeyn et al. 2003). Fluctuations in lake level are also important in terms of nearshore development, wetland conservation and function (Mitsch and Gosselink 2000), and nutrient and mercury cycling (Christensen et al. 2004).

1.2.6 Water Clarity

Although not a mandated parameter, GLKN has included a measure of water clarity (Secchi depth and/or transparency tube depth) in the core suite of parameters because of its fundamental importance to whole-lake ecology, ease of measurement, and the fact that it will always be measured along with core suite profiles. Light penetration, for which water clarity is a surrogate, is an important regulator of rate of primary production and plant species composition, including the balance between phytoplankton and macrophyte production in shallow lakes (e.g., Moss et al. 1996). Water clarity provides a visual measurement that relates directly to the aesthetic perceptions of the public. Secchi depth can also be an effective indicator of non-algal suspended sediment loading from agricultural and urban runoff and from shoreline erosion (Swift et al. 2006, Holdren et al. 2001, Preisendorfer 1986). Secchi depth transparency has a long history of use in lake monitoring programs as an excellent indicator of trends in phytoplankton biomass (e.g., WOW 2005, Goldman 1988), and is an integral component of Upper Great Lakes States Monitoring programs (e.g., WDNR 2005; MPCA 2005a, MDEQ 2004, 2001).

1.2.7 Major Ions

- Cations—calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^{+}), and potassium (K^{+})
- Anions—$SO4^{-2}$, Chloride (Cl^{-}), and alkalinity ($CaCO_3$)

The chemical composition of a lake is a function of land use, climate, and basin geology. Each lake has an ion balance of the three major anions and four major cations (Table 1). The ionic concentrations influence the lake's ability to assimilate pollutants (e.g., acidification) and maintain nutrients in solution. For example, calcium carbonate ($CaCO_3$) in the form known as marl can precipitate phosphate, thereby removing this important nutrient from the water. High Ca^{+2} and Mg^{+2} directly reduce the bioavailability and toxicity of many heavy metals, and indirectly affect mercury cycling (e.g., Horne and Goldman 1994, Driscoll et al. 1994, Driscoll et al. 1995).

Table 1. Ion balance typical for fresh water in the upper Midwest (Wetzel 2001, Horne and Goldman 1994).

Ion Type	Major Ion	Percent
Cations	Ca^{+2}	63%
	Mg^{+2}	17%
	Na^{+}	15%
	K^{+}	4%
	other	< 1%
Anions	HCO_3^{-}	73%
	SO_4^{-2}	16%
	Cl^{-}	10%
	–	–
	other	< 1%

Bicarbonate and carbonate ions, which are estimated by alkalinity, dominate the major anions. Alkalinity directly estimates the majority of the buffering capacity of the water and is used to estimate sensitivity to acid precipitation. Sulfate concentrations provide a measure of the potential accumulation of sulfur due to acidic deposition of SO_x compounds and are important for assessing acid deposition effects. Sulfate is also a critical parameter for understanding and modeling mercury cycling because sulfate-reducing bacteria in anoxic environments are the primary source of methyl mercury, the major fraction involved in the bioaccumulation of mercury in food webs (e.g., Driscoll et al. 1994). Chloride (Cl^{-}) is a particularly good indicator of wastewater plumes as well as inputs and accumulation of road salt. It may be used as a tracer, as it moves through soil without significant absorption or adsorption.

The concentration of the major ions and their relative ratios influence the species of organisms that can best survive in a lake, in addition to affecting many important chemical reactions that occur in the water. Zebra mussels (*Dreissena polymorpha*), for example, require levels of calcium typically higher than those found in Lake Superior water, though this exotic species has invaded several inland lakes at SLBE. Humans can have profound influences on the characteristics of lake chemistry, including ion concentrations. Modification of natural shoreline vegetation and increasing the amount of impervious surfaces surrounding a lake cause increased runoff, which can carry chloride and potassium from the use of road salt.

1.2.8 Dissolved Silica (SiO_2)

Silica is considered an essential micronutrient for microorganisms and diatom algae. These organisms use silica to form shells and other protective structures. Diatoms are capable of using large amounts of silica and may be growth-limited when silica is in short supply.

1.2.9 Dissolved Organic Carbon (DOC)

Dissolved organic carbon (DOC) is usually the largest fraction of organic material in the open waters of lakes. (Exceptions generally involve hypereutrophic lakes with intense blooms of algae or an abundance of aquatic plants that die off in the fall.) It is derived primarily from decomposing material in the watershed that is leached into stream and groundwater inputs and washed in from wetlands with abundant sphagnum mosses (Wetzel 2001, Schindler and Curtis 1997). Typically, a lesser amount is contributed by algae, both from extracellular leakage and via decomposition; concentrations may be high following intense algae blooms. DOC plays important roles in freshwater ecosystems , including 1) affecting acid-base chemistry and metal cycling (e.g., copper, mercury, aluminum), and potential toxicity; 2) acting as a source of energy and nutrients to the microbial food chain, thereby influencing nutrient availability; 3) attenuating UV-B radiation; 4) attenuating PAR (photosynthetically active radiation) and thereby regulating primary production; and 5) influencing the heat budget of the lake by absorbing sunlight (Gergel et al. 1999, Schindler and Curtis 1997). Anthropogenic stressors, such as global warming, ozone losses, acidification, and intensive logging are cause for concern as they may be altering the concentration and distribution of DOC, resulting in adverse effects on lakes.

1.2.10 Nutrients (Total Phosphorus [TP], Total Nitrogen [TN], Nitrate+Nitrite-N [NO_3+NO_2-N], and Ammonium-N [NH_4-N])

Nitrogen and phosphorus are the two most influential nutrients in terms of regulating phytoplankton and aquatic macrophyte growth. Excessive inputs of nutrients can lead to excessive algal growth and eutrophication (Wetzel 2001, Horne and Goldman 1994) and are the most important threat to Upper Midwest lakes (MPCA 2004a; MDEQ 2004; WDNR 2005).

Nutrients are carried into a waterbody primarily through surface runoff and percolation through the surrounding rocks and soils. Bioavailable forms of phosphorus and nitrogen (dissolved phosphate, nitrate, and ammonium) are typically highest in the spring due to snowmelt runoff and the mixing of accumulated nutrients from the bottom during spring turnover. Concentrations typically decrease in the epilimnion during summer stratification, as nutrients are taken up by algae and eventually transported to the hypolimnion when the algae die and settle out. When stratified, any input of nutrients into the upper lake water may trigger a bloom of algae. In less productive systems, such as many of those in GLKN parks, significant amounts of available nitrogen may be deposited during rainfall or snowfall events (wet deposition) and through the less obvious deposition of aerosols and dust particles (dry deposition). Nitrogen and phosphorus in dry fallout and wet precipitation may come from dust, fine soil particles, and fertilizer from agricultural fields.

1.2.11 Chlorophyll-a

The concentration of chlorophyll-*a*, the primary photosynthetic pigment in all green plants including phytoplankton, is a nearly universally accepted measure of algal biomass in the open waters of lakes (e.g., Wetzel 2001, Wetzel and Likens 2000). However, it may also be important to examine the algal community microscopically on occasion, because the mix of species can influence chlorophyll-*a* concentration, as different algal groups have different proportions of chlorophyll-*a* versus other pigments. Hence, chlorophyll-*a* is not always an accurate measure of biomass, and the mix of species may influence lake management decisions. Chlorophyll-*a* concentrations are expected to be dynamic,

reflecting changes in algal abundance through the ice-free growing season. Consistent and directional trends in chlorophyll-*a* concentrations are good indicators of change in a lake's trophic status (Wetzel 2001, Carlson and Simpson 1996, Horne and Goldman 1994).

1.3 Background and History; Description of Resource

Several efforts have been undertaken in recent years to organize and synthesize aquatic resource data from GLKN parks. Most recently, Lafrancois and Glase (2005) published a summary and synthesis of information from over 600 studies. This synthesis will help guide management, future research, and monitoring efforts. The authors noted that much of the existing research in Great Lakes area parks was from short-term projects conducted by many different people without common methods or objectives, and that a comprehensive, network-wide analysis of the available information for use in identifying and addressing large-scale water resource issues had not been done previously.

Ledder (2003, 2005) summarized relevant numeric water quality standards in addition to compiling lists of designated uses for parameters of interest to the water quality monitoring project. Her summaries included relevant water quality criteria, waterbodies that are listed under section 303(d) of the Clean Water Act, and waterbodies with Outstanding Resource Waters designation.

Historical water quality data for inland lakes of the parks consist of lake profile data (temperature, dissolved oxygen, specific conductivity, pH, and Secchi depth) as well as various other physical, chemical, and biological (chlorophyll-*a*) parameters (Table 2). See Lafrancois and Glase (2005) for a more complete listing of aquatic research and monitoring efforts in GLKN park units. The Natural Resources Research Institute (NRRI) at the University of Minnesota–Duluth analyzed water quality data collected between 1997 and 2003 from lakes at SLBE, PIRO, and APIS (Axler et al. 2006). Other in-depth analyses of water quality data at ISRO and VOYA have been published recently (Kallemeyn et al. 2003, Kallemeyn 2000).

Table 2. Summary of water quality data available for inland lakes at Great Lakes Network parks.

Park	Source	Period of Record	Water Quality Parameters (Lakes)
APIS	Rose (1988)	1983	USGS–Outer Island Lagoon; 2x/summer; core suite, anion, cations, nutrients
	Rose (1988)	1984	USGS–Michigan Island Lagoon; 2x/summer; core suite, anion, cations, nutrients
	Balcer and McCauley (1989)	1986–1989	fecal bacteria, nutrients, sediment composition, core suite (Lake Superior, lagoons)
	MTU (1997)	1996	Michigan, Outer, Stockton Islands Lagoons; core suite, chlorophyll, nutrients, zooplankton, benthos; June, July, Aug.
	Axler et al. (2006)	2005	Michigan, Outer, Stockton Islands Lagoons; core suite, chlorophyll, nutrients, zooplankton, benthos; June, Aug., Oct.

[1] NRRI-CAL = Natural Resources Research Institute Central Analytical Laboratory

[2] MPCA = Minnesota Pollution Control Agency

Table 2 (continued). Summary of water quality data available for inland lakes at Great Lakes Network parks.

Park	Source	Period of Record	Water Quality Parameters (Lakes)
INDU	Arihood (1975)	1973–1974	chemical, organic, bacteriological; ground and surface waters
	Hardy (1983)	1978–1980	core suite, periphyton, bacteriological
	NPS	1990–2000	alkalinity, NH4, Cl, SC25, dissolved oxygen, NO_3, NO_2, pH, TP, hardness, turbidity
	Whitman et al. (1995)	1991	core suite, bacteriological
	Simon et al. (1997)	–	pH, conductivity. major ions, nutrients, morphometry; (4 lakes)
ISRO	Stottlemeyer (2000)	1980–1996	–
	Kallemeyn (2000)	1995–1997	summarized data, core and advanced
	NRRI CAL[1]	1996	Secchi, core suite, chlorophyll, nutrients, major ions
	–	1997	SC25, DOC, color- 32 lakes
	Gorski (2002)	1998–1999	DOC and Hg
PIRO	Handy and Twenter (1985)	1979–1981	once/year (Chapel, Beaver, Kingston, Grand Sable), temp, SC25, pH, and advanced suite
	Loope (1998)	–	review of six inland lakes
	Kamke (1987)	–	4 lakes (Chapel, Beaver, Kingston, Grand Sable)
	PIRO (1998)	1970–2002, intermittent	lake profiles (core parameters) and field notes only 1998 and 1999 multiple/year, the rest once/year
SLBE	Last et al. (1995)	1994–1995	core suite, chlorophyll-*a*
	SLBE	1997–2003	Secchi, profiles, water chemistry
	Murphy (2001, 2002)	2000–2002	core suite, turbidity, nutrients, major ions; inland lakes and rivers
VOYA	Payne (1991)	1977–1984	chlorophyll, Secchi, TN, TP, alkalinity, cations, anions (Rainy, Sand Pt., Namakan, Kabetogama, 19 interior, 2 streams); USGS & NPS
	Newell (1987) Webster (1995)	1978–1995	USEPA-LTM; (Cruiser, Loiten, Locator, Shoepack)
	Hargis (1981)	1978–1980	core suite, chlorophyll, % light transmittance (Rainy, Sand Pt., Namakan, Kabetogama, Ek 1978–1980; 19 interior lakes1979–1980)
	VOYA/USGS	1981/1983	1981 Namakan and Kabetogama, 1983 Rainy and Sand Pt. 11xs/summer, 26 interior lakes at least once

[1] NRRI-CAL = Natural Resources Research Institute Central Analytical Laboratory

[2] MPCA = Minnesota Pollution Control Agency

Table 2 (continued). Summary of water quality data available for inland lakes at Great Lakes Network parks.

Park	Source	Period of Record	Water Quality Parameters (Lakes)
VOYA (cont.)	Eibler (2001)	1983–2000	chlorophyll, Secchi, alkalinity (Kabetogama, Rainy, maybe Namakan and Sand Pt.); MNDNR; 1x/summer
	Whitman (2001)	1997–1998	chlorophyll, pH, ANC, SO_4 (Locator and Mukooda)
	Kepner (1988)	NA	(Rainy, Sand Pt., Namakan, Kabetogama)
	Payne (2000)	1999	Rainy, Sand Pt., Namakan, Kabetogama
	MPCA[2]	2000	(12 lakes)
	Kallemeyn et al. (2003)	2003	chlorophyll and TP (Rainy, Sand Pt, Namakan, Kabetogama)
	NRRI CAL[1]	2002	chlorophyll and TP (Rainy, Sand Pt, Namakan, Kabetogama)

[1] NRRI-CAL = Natural Resources Research Institute Central Analytical Laboratory

[2] MPCA = Minnesota Pollution Control Agency

The National Park Service–Water Resources Division (NPS-WRD) retrieved data from several EPA databases, including STOrage and RETrieval System (STORET), and summarized these data for national park units (NPS 1999 [APIS], 1997 [SLBE], 1995a [ISRO], 1995b [PIRO], 1995c [VOYA], 1994 [INDU]). Summaries include exceedance data, by station.

1.3.1 Water Quality Monitoring Efforts by Parks

Water quality monitoring programs conducted by the parks vary widely, and in most parks, have changed over time. Park funding and turnover of personnel have fluctuated, and the parks are not always able to continue monitoring programs on schedule. A brief synopsis of park water quality monitoring programs follows.

Until 1988, water quality studies at APIS were largely synoptic rather than routine monitoring efforts. At that time, Michigan Technological University established a monitoring program that the park has attempted to continue, conducting routine monitoring with a multi-parameter sonde every two to three years at five sites in Lake Superior and in three lagoons. More intensive physical, chemical, and biological monitoring was conducted by different research groups at the same sites in 1996 and 2004.

Intensive and extensive water quality studies have been conducted at INDU over the years (Lafrancois and Glase 2005). Researchers often focused on contaminants from industrial waste, although basic water quality parameters were also measured. From 1990 through 2000, the park monitored alkalinity, ammonium, chloride, specific conductance, dissolved oxygen, nitrate, nitrite, pH, total phosphorus, hardness, and turbidity of Long Lake. The park conducts routine bacteriological monitoring at Lake Michigan beach sites.

Two long-term water quality monitoring projects have occurred at ISRO—one at the Washington Creek gaging station, and the other a study of the Wallace Lake watershed. A number of additional inland lakes have been studied intensively for short periods of time, although no long-term water quality monitoring has been conducted on ISRO's inland lakes.

Most of the inland lakes at PIRO have been sampled at least once, with few lakes receiving greater attention in the form of synoptic studies. Beginning in 1994, annual data were collected, once in mid-summer, on six lakes with a multi-parameter sonde. For the first three years (1994–1996), nitrate, phosphate, and chlorophyll-*a* were also measured.

Prior to 2001, most water quality sampling at SLBE was conducted as part of synoptic studies to address particular concerns in a given lake or stream (e.g., nutrient loading downstream from a fish hatchery). However, park staff have conducted water quality monitoring routinely in most lakes of the park since 2001. Parameters typically measured were Secchi depth; profiles of temperature, dissolved oxygen, specific conductance, and pH; and less routinely, total dissolved solids, sulfate, calcium hardness, total hardness, total nitrogen, total phosphorus, nitrate, ammonium, alkalinity, true color, and chlorophyll-*a*. Bacteriological monitoring is also conducted weekly at beach sites from mid-May through mid-September.

The four large, regulated lakes at VOYA have been monitored for the past 25 years, every two weeks from May until October. Parameters measured in this program are temperature and dissolved oxygen profiles, alkalinity, pH, conductivity, and Secchi depth. Chlorophyll-*a* has also been measured on these lakes since 2000. Inland lakes of the park have not received the same continuous monitoring effort, though many intensive project-based studies have been conducted. Kallemeyn et al. (2003) analyzed and summarized historical water quality data of inland lakes.

1.3.2 Description of Parks' Inland Lakes

The inland lake resources of GLKN parks are astounding, numbering in the thousands. Lakes greater than one hectare number in the hundreds, with VOYA alone containing nearly 300 (Table 3).

Table 3. Number of lakes >1 hectare in six Great Lakes Network parks. Number of inland lakes between 1 and 10 hectares in parentheses. Data from the National Hydrologic Database.

Park	Number of Inland Lakes >1 Hectare (1–10 ha)
Apostle Islands National Lakeshore	11 (10)
Indiana Dunes National Park	8 (8)
Isle Royale National Park	77 (59)
Pictured Rocks National Lakeshore	24 (10)
Sleeping Bear Dunes National Lakeshore	24 (7)
Voyageurs National Park	299 (268)

The water chemistry of inland lakes varies widely across the Network. Lakes in SLBE are underlain by limestone, and hence have relatively high pH values (most lakes >8.0), high buffering capacity (alkalinity of most lakes >125 mg/L), and high conductivity values (many lakes SC25>300 µS/cm).

Pictured Rocks National Lakeshore contains a meromictic lake (Chapel Lake), >42 m deep, and a naturally acidic lake (Legion Lake), with pH values generally <5.0 and alkalinity near zero (Loope 1998). Some lakes at VOYA are underlain by granitic bedrock of the Canadian Shield, while others are underlain by thick calcareous drift. The differences in water chemistry within this park are great; some lakes are poorly buffered, some are well-buffered, some have noxious blooms of blue-green algae, and some are oligotrophic (Kallemeyn et al. 2003).

Accessibility of lakes also varies across the network, which affects the types of stressors influencing the lakes' water quality. Many park lakes require substantial time and effort to gain access. For example, Lake Manitou (SLBE) requires a boat ride across Lake Michigan waters and then a portage of approximately 4 km (2.5 mi); Lake Desor (ISRO) requires approximately an hour of boat transportation on Lake Superior followed by a steep off-trail bushwhack portage of approximately 1.6 km (1 mi). Lakes such as these receive little recreational pressure and no developmental effects. The primary stressors are likely due to atmospheric deposition and global climate change. The large lakes at VOYA receive houseboat use and are therefore at risk from inputs of excess nutrients from gray water discharge and failing sewage holding tanks. Many lakes within the network are located alongside of roads, accessed via boat ramps, and contain developed areas of shoreline. These lakes are affected by stressors such as road salt, runoff, oil and gas, failing septic tanks, invasive species, as well as the same atmospheric threats that face remote lakes.

With this monitoring protocol, we hope to encompass the variety of existing lake conditions and stressors affecting the lakes. The sampling design and methods of field sampling are described in the following sections (2.0 Sample Design, and 3.0 Field Methods).

1.4 Measurable Objectives

Our overall goal is to develop a program for monitoring water quality in inland lakes that will contribute to an understanding of the health of aquatic ecosystems and provide insights on likely water resources issues in park units of the Great Lakes Network.

Our specific objective is to monitor basic limnological parameters that describe water quality of select inland lakes in order to describe the current status and trends (i.e., magnitude and direction of change) of these lakes. We will examine parallel trends across lakes within park units and across the network as a whole and compare our results with other regional datasets.

1.5 Quality Assurance and Quality Control

Quality control is the planned and systematic pattern of all actions, or controls, necessary to provide adequate confidence that a project outcome optimally fulfills expectations. Quality assurance is a program for the systematic monitoring and evaluation of the various aspects of a project to ensure that standards of quality are being met. Together, quality assurance/quality control (QA/QC) is a significant part of any monitoring program. It is a broad management concept of maintaining the

ability to provide reliable information, requiring the complete integration of field and laboratory systems of sample collection and analysis. QA/QC incorporates peripheral but essential operations such as survey design, equipment preparation, maintenance tasks, data handling, and personnel training. The objective of QA/QC is to ensure that the data generated by a project are meaningful, representative, complete, precise, accurate, comparable, and scientifically defensible (O'Ney 2005a).

This protocol includes QA/QC procedures that must be followed, beginning with field preparations, through the collection of data, to the final analyses and reporting of results. See standard operating procedure (SOP) #12 for QA/QC details.

2.0 Sample Design

2.1 Rational For Selecting This Sampling Design

As we developed our sampling design, we explored the advantages and disadvantages of randomly selecting lakes for monitoring versus a nonrandom selection of lakes. We also considered the sampling designs of Minnesota, Wisconsin, and Michigan—three of the four states in which network parks are located. These three states have the greatest numbers of lakes of the lower 48 states, and all three have active water quality monitoring programs.

In the following paragraphs, we describe random, or probabilistic, and nonrandom, or targeted, selection of lakes for monitoring; we summarize the water quality monitoring programs of the three states; and we explain our design for discrete and continuous long-term monitoring of water quality of inland lakes in the Great Lakes Network.

2.1.1 Random Versus Nonrandom Selection of Lakes

Historically, monitoring programs for lakes have focused on either representative lakes or on specific lakes of particular interest. Examples of lakes selected for particular reasons include:

- Lakes with outstanding resource value—for example, the Lake Tahoe, California-Nevada program (Goldman 1988, Jassby et al. 2003), Lake Michigan (Madenjian et al. 2002), Crater Lake, Oregon (LaBounty and Larson 1996);
- Lakes representative of a class of lake types, for example, meso-oligotrophic (e.g., Castle Lake, California; Jassby et al. 1999, Goldman et al. 1989), eutrophic (Clear Lake, California; Suchanek et al. 2002), acid-sensitive Canadian shield lakes (Schindler et al. 1985, Schindler 1988);
- Lakes within a geographic area, for example, lakes and reservoirs of the southeastern U.S. (Reckhow 1988), lakes of the northeastern United States (Messer et al. 1991), long-term ecological research of North Temperate Lakes (Magnuson et al. 2006, Magnuson et al. 1984), recreational lakes in Vermont (Smeltzer et al. 1989);
- Economically important lakes under heavy anthropogenic stress, for example, Lake Mendota, Wisconsin (Lathrop et al. 1996); Lake Washington, Washington (Edmonson et al. 1956); Lake Okeechobee, Florida (Steinman et al. 2001); Lake Minnetonka, Minnesota (Barten 2004); Lake Mead, Nevada-Arizona (Paulson and Baker 1983, LaBounty and Horn 1997); Lake Tahoe, California-Nevada (Jassby et al. 1999).

Such nonrandom selection of lakes in a monitoring program allows results to be used in answering specific questions about a particular lake or suite of lakes. The main disadvantage of this design, however, is that inferences cannot be extended to lakes beyond those that are sampled.

Beginning with concerns about the potential degradation of soft-water lakes throughout the U.S. due to acidic deposition, the U.S. Environmental Protection Agency (EPA) initiated the development of a framework for probabilistic design and sampling. The approach has now moved beyond the acid-rain question to provide an approach that allows quantitative (i.e., with known statistical confidence) descriptions of aquatic resources.

A probabilistic, randomized sampling scheme is particularly well suited to examining large populations of lakes, to groups of lakes that have little prior information, and where one wishes to characterize populations or groups with a particular degree of statistical confidence. The advantage of a random design is that probabilistic statements can be made about differences in means. This ability to make statistical inferences to a large population of lakes from a relatively small number that are actually sampled makes the randomized method appear preferable because a comparison between groups of lakes or a trend over time can be justified with confidence limits. An important disadvantage of the randomized design is that in order to make useful probabilistic statements about responses in a larger population of lakes within a few years, the number of lakes in the sampling program must be relatively large (20% to 30% of the total population of lakes; e.g., Loeb 2002).

2.1.2 Current Lake-Monitoring Programs of States Within the Great Lakes Region

It is important that GLKN develops a program for monitoring water quality that is comparable with and acceptable to other regional monitoring programs, especially the states. Monitoring programs in Minnesota, Wisconsin, and Michigan have been in existence for many years, and all three have undergone changes in the past few years to enable the states to more efficiently comply with their assessment and reporting responsibilities for the federal Clean Water Act (see http://www.pca.state.mn.us/publications/reports/strategicplan.html for Minnesota, Wisconsin Water Monitoring | Wisconsin DNR for Wisconsin, and http://www.michigan.gov/deq/0,1607,7-135-3313_3686_3731---,00.html for Michigan).

The three state programs use different strategies in their attempt to maximize the efficiency of their monitoring and assessment programs, although all are fundamentally similar in that a set of sentinel or index lakes is sampled on a regular basis. Index lakes were selected nonrandomly, for different reasons among states. In brief, all three states involve volunteers to monitor Secchi depth, which is an established indicator of either algal biomass or suspended sediment (Carlson and Simpson 1996). All three states are also developing additional volunteer programs to collect water samples for chlorophyll-*a* and/or nutrients.

In Minnesota, the DNR samples all large lakes (>200 ha) on a 10-year cycle. Volunteers collect Secchi depth data on medium-sized lakes (40–200 ha). In addition, the Minnesota Pollution Control Agency (MPCA) conducts more intensive seasonal diagnostic studies at an unspecified number of lakes, based on need as indicated by either Secchi data or Landsat 7 satellite imagery (Kloiber et al. 2002a, 2002b). Wisconsin DNR monitors 65 index lakes and 110 randomly selected lakes (without replacement) annually, on a six-year rotation (WDNR 2005). In addition, volunteers measure Secchi depth on approximately 600 lakes. This volunteer program includes collection of water samples for nutrients and chlorophyll-*a* on a subset of lakes. Michigan's program is similar to Wisconsin's in that it includes both index and randomly selected lakes, but Michigan's program uses a 15-year rotation. Michigan volunteers monitor Secchi depth, total phosphorus, and chlorophyll-*a* on more than 300 lakes.

Wisconsin and Michigan are collaborating with Minnesota regarding the use of satellite imagery to supplement the transparency database. This technique has the potential to generate historical Secchi estimates, because past images and their spectral data are potentially available. In the future, the

network may find it useful to participate in this satellite imaging analysis of Secchi transparency to supplement lake data in remote areas.

2.1.3 Great Lakes Network Design

The network examined the monitoring programs of the three states and weighed the advantages and disadvantages of different sampling designs. A summary of several sampling designs is included in Table 4. Consistency of the network's monitoring design and protocol with neighboring state programs is desirable to facilitate data comparisons and allow statistical inferences using regional data.

The selection of lakes to include in the GLKN monitoring program must be based on the questions of interest, without jeopardizing the safety of field personnel. Development of detailed monitoring questions was an important initial phase that preceded the identification of target populations and subsequent development of sample designs. Question development was an iterative process with input from park managers, GLKN staff, and cooperating scientists. Our monitoring questions relate to individual lakes, lakes aggregated within each park, and lakes across the network and region. As we began to develop the protocol, it became clear that we would not be able to address the questions regarding the general health of the lakes in a park or across parks in a statistically adequate manner while staying within our budget. Answering questions about all lakes within a park or all lakes across the network requires either a complete census of lakes or a random selection of lakes, which allows inference to the entire population of lakes. A complete census of lakes is not feasible, as the network contains well over 1,000 lakes (Table 5). A random selection of lakes is not desirable because many lakes are inaccessible and would require more than a day of off-trail, backcountry travel to reach.

This realization led to the design that will best provide for assessments of individual lakes. We will address questions at broader spatial extents through comparisons of trends across lakes. (See section 4, below—Data Management, Analysis, and Reporting, and SOP #9—Data Analysis, for more details).

We selected lakes at each park such that they are spatially distributed throughout each park and span gradients of chemical and physical parameters, visitor use, and watershed area. Some lakes are of particular interest to a park. If lakes are connected via stream or channel, we selected the downstream lake, as it serves as an integrator of its drainage system. The lakes included in the sampling design (Table 6), referred to as "index lakes", will be sampled annually. Additional lakes will be sampled on a longer rotation at some parks as funding permits.

Continuous water temperature profile data will be collected from a subset of index lakes across four parks (ISRO, PIRO, SLBE and VOYA) with a significant number of inland lakes >1 ha (Table 6). This monitoring will address specific park management questions such as availability of suitable habitat to support cold-water fisheries, or to assess regional trends in the timing of ice on and ice off and other climate change driven phenomena. Details regarding GLKN water temperature profile techniques can be found in Standard Operating Procedure #14: Moored Temperature Arrays.

Table 4. Summary of different types of sampling designs.

Parameter	Random	Stratified	Systematic	Non-random
Lake	Sampled lakes are chosen randomly from geographic area	Randomly chosen from each geographic region (state, county, ecoregion) or within some other classification e.g., (recreational, beneficial use, drainage type, trophic status, surface area, max. depth)	Sample every lake along a transect, using a randomly chosen starting point	Choose lake based on convenience, access, proximity, or interest
Site	Randomly chosen from within the lake area	Randomly selected from within regions of lake	Sample at equidistant sites along transect of lake (distance selected a priori), starting with a randomly chosen point	Sample at the dam, over the deepest part of the lake, or other location based on interest
Depth	Randomly chosen	Randomly chosen within each depth region (e.g., epilimnion, hypolimnion, photic zone)	Sample at preset intervals, starting with a randomly chosen depth	Sample at the surface, at preset intervals surface to bottom, or at discreet depth for particular interest
Date	Randomly chosen	Randomly chosen within each season, month, or limnological period	Sample every two weeks, starting with a randomly chosen date	Sample on chosen day for reasons of convenience
Time	Randomly chosen	Randomly chosen within each diel period (e.g., morning, afternoon, evening), or some other division of day	Sample every two hours, starting with a randomly chosen time	Sample times based on convenience

Table 5. Summary of numbers of lakes and ponds in the six Great Lakes Network parks with inland lake resources, classified by size (surface area).

Park	Size Class (ha)	Named Lakes	Unnamed Lakes	TOTAL >1 ha
APIS	>1000	0	0	–
	100–1000	0	0	–
	10–100	1	0	–
	1–10	2	7	10
	<1	1	65	–
	Total	**4**	***76***	**–**
INDU	>1000	0	0	–
	100–1000	0	0	–
	10–100	0	0	–
	1–10	2	7	9
	<1	0	49	–
	Total	***1***	***56***	**–**
ISRO	>1000	0	0	–
	100–1000	5	0	–
	10–100	22	0	–
	1–10	15	45	87
	<1	0	189	–
	Total	***42***	***234***	**–**
PIRO	>1000	0	0	–
	100–1000	2	0	–
	10–100	5	0	–
	1–10	7	10	24
	<1	2	96	–
	Total	***16***	***106***	**–**
SLBE	>1000	1	0	–
	100–1000	3	0	–
	10–100	11	2	–
	1–10	6	1	24
	<1	6	3	–
	Total	***27***	***6***	**–**

Table 5 (continued). Summary of numbers of lakes and ponds in the six Great Lakes Network parks with inland lake resources, classified by size (surface area).

Park	Size Class (ha)	Named Lakes	Unnamed Lakes	TOTAL >1 ha
VOYA	>1000	4	0	–
	100–1000	3	1	–
	10–100	19	8	–
	1–10	3	265	299
	<1	0	237	–
	Total	***29***	***511***	**–**

Table 6. Index lakes in the Great Lakes Network's sampling design. Maximum depth (Z_{max}) is included when known.

Park	Lake Name	Area (ha)	Z_{max} (m)
APIS	Outer Island Lagoon	22	1.7
	Total	**–**	***1***
INDU	Middle Calumet Lagoon	32	3.0
	Total	**–**	***1***
ISRO	Siskiwit	1635	46
	Desor	428	14
	Richie [a]	216	11
	Feldtmann	186	3
	Sargent	143	14
	Harvey	55	4
	Beaver	20	5
	Ahmik	10	3
	George	3.8	3
	Total	**–**	***9***
PIRO	**Beaver** [a]	310	10
	Grand Sable [a]	255	26
	Chapel	28	42

[a] Lake where thermal arrays are deployed, also shown in bold font.

Table 6 (continued). Index lakes in the Great Lakes Network's sampling design. Maximum depth (Z_{max}) is included when known.

Park	Lake Name	Area (ha)	Z_{max} (m)
PIRO (cont.)	Trappers	20	2
	Legion	14	10
	Miners	5	4
	Total	**–**	***6***
SLBE	**Manitou** [a]	104	14
	Florence	32	8
	Shell	41	4
	Bass (Leelanau County) [a]	38	7
	Loon	37	20
	North Bar	12	10
	Total	**–**	***6***
VOYA	**Shoepack** [a]	124	7
	Little Trout [a]	97	29
	Locator	57	16
	Cruiser	47	28
	Peary	45	5
	Ek	36	6
	Brown	31	8
	Ryan	14	4
	Mukooda [a]	305	24
	Total	**–**	***9***

[a] Lake where thermal arrays are deployed, also shown in bold font.

Apostle Islands National Lakeshore—Outer Lagoon is included in the sampling design. There are two other island lagoons and one mainland site that were monitored by GLKN from 2007–2012, but they are periodically connected to and flushed by Lake Superior. This connection creates high inter and intra-variability in water quality and is exceedingly problematic when assessing long term trends. Outer lagoon is shallow and may not always meet the EPA criterion of a lake (>1 m in depth; Baker et al. 1997), depending primarily on Lake Superior water level, but is of particular interest to the park because of recent evidence of high mercury levels throughout the food chain (J. Wiener, pers. comm.), and to park partners due to the presence of a rare diatom species (*Semiorbis hemicyclus*) not found in any other lakes monitored in the network (M. Edlund, pers. comm). Outer Lagoon, and the

two lagoons and mainland site previously monitored essentially comprise the park's inland lakes, as the remaining lentic waterbodies are transient beaver ponds.

Indiana Dunes National Park—Middle Calumet Lagoon is an interdunal lagoon and the only lake included in the sampling design. Lake George, a constructed lake, was sampled in 2006, but was deemed unsuitable because it is more of a lotic than lentic environment. Long Lake, which is shallow and polymictic, was monitored from 2006 to 2012. However, monitoring was discontinued in 2013 due to lowering water levels, which is causing the lake to transition to a wetland marsh. Additional interdunal lagoons may be added to the sampling design in the future, depending on preliminary sampling results, budget, and interest to the park.

Isle Royale National Park—We ordinated historical lake chemistry data (nonmetric multidimensional scaling via PCORD; McCune and Mefford 1999) and compared our results with those of Carlisle (2000; in Crane et al. 2006), who used both chemical and physical data, to determine types of lakes on the island. We then selected nine lakes, some from each quadrant of the ordination plots, ensuring they spanned the spatial extent of the island. The lakes also spanned gradients of recreational use, surface area, depth, and watershed area. The number of lakes selected is restricted largely by budget. Continuous (1-hour intervals) year-round surface to bottom (1-meter intervals) water temperature data (referred to as a thermal array hereon) will be collected from Lake Richie at the same site where discrete monitoring will take place. This water temperature data will help to address park management concerns about availability of suitable habitat for cisco (*Coregonus artedi*), which historically was present in the lake but has not been documented since 1929 (Hubbs and Lagler 1949). As the park has concerns that water quality sampling may disrupt successful nesting of common loons (*Gavia immer*), an endangered species in Michigan, we will work with park staff to ensure water quality sampling personnel are trained in recognizing loon behaviors and avoid undue stress on nesting loons. In future years, additional lakes may be sampled on a rotational basis as funding permits.

Pictured Rocks National Lakeshore—Seven sites on six lakes are included in the sampling design, spanning the spatial extent of the park. The selected lakes span gradients of surface area, depth, watershed area, and recreational use. If two or more lakes are connected (e.g., Beaver and Little Beaver lakes), we selected the downstream lake as an integrator of that system. A thermal array will be deployed at Grand Sable and Beaver Lakes at our discrete monitoring sites. Water temperature data from these arrays will allow for assessment of suitable habitat for salmonids (historically stocked in the lake but not in recent years) and help to answer basic limnological questions related to changes in the timing of ice on/off, depth, timing, and strength of thermal stratification. Additional lakes beyond the six index lakes may be sampled on a rotational basis, as time and funding permits. No lakes in the Inland Buffer Zone are included, nor were they considered, because the park does not own the land surrounding them. The network will explore the possibility of sharing data with partners conducting monitoring of lakes in the Inland Buffer Zone.

Sleeping Bear Dunes National Lakeshore—Six lakes were selected as index lakes, based primarily on results of ordinations of past lake chemistry data (as described above for Isle Royale National Park). The lakes span the spatial extent of the park, as well as distance from roads and gradients of

recreational use, surface area, and depth (watershed size is currently not known). A thermal array will be deployed in Manitou and Bass Lakes at our discrete monitoring sites. Data from these arrays will be used to answer limnological questions related to changes in the timing of ice on/off, depth, timing, and strength of thermal stratification, and will be compared with climatological data collected by a nearby weather station operated and maintained by the network. Lakes that are partially within park boundaries but are actively monitored by other organizations were not considered so as to avoid duplication of effort. We will share data and expertise with these other organizations. Additional lakes beyond the index lakes may be sampled on a rotational basis, as funding permits.

Voyageurs National Park—Eight lakes were selected as index lakes based largely on a classification of lakes (Schupp 1992). Mukooda Lake was sampled in 2006 and permanently added to the index lakes in 2016, making nine total index lakes. The lakes have a long history of data collection, span a gradient of recreational pressure, and are spatially dispersed across the park. We selected downstream lakes when one or more are connected via surface stream or channel. A thermal array will be deployed at Little Trout, Shoepack, and Mukooda Lakes at our discrete monitoring sites. This water temperature data will help to address park management concerns about availability of suitable habitat for lake trout (*Salvelinus namaycush*). The population of lake trout has been in decline recently (MNDNR 2010) and no lake trout were found during a 2014 survey by the Minnesota Department of Natural Resources staff in 2014 (R. Maki, pers. comm.). Water quality monitoring at the four large lakes (Namakan, Rainy, Sand Point, and Kabetogama) is currently base-funded by the park. Staff at VOYA conduct water quality monitoring of these lakes annually, twice a month, using methods comparable to those employed by network staff. Therefore, the network excluded these lakes from the design. In 2006, we initially sampled 22 inland lakes (excluding the four large lakes) and we will continue monitoring the index lakes shown in Table 6 on an annual basis. Additional lakes will be sampled on a longer rotation as time and funding permits.

2.1.4 Legal Designations of Lakes Within the Great Lakes Network

All of the inland lakes in INDU, ISRO, PIRO, SLBE, and VOYA are designated as Outstanding Natural Resource Waters by their respective states. Many of these same lakes, however, are listed as impaired under section 303(d) of the Clean Water Act (CWA). All lakes in ISRO, PIRO, SLBE, and most lakes in VOYA are listed due to fish consumption advisories for mercury (NPS WRD 2012, MDCH 2004, MPCA 2006). Additionally, Siskiwit Lake (ISRO) is listed due to fish consumption advisories for PCBs (NPS WRD 2012). Little Sand Bay and Julian Bay (APIS) are intermittently connected to Lake Superior; when connected to the Great Lake, these lagoons are included on the 303(d) list for fish consumption advisories for PCBs (NPS WRD 2012).

NPS-WRD has advised that newly developed monitoring protocols include the water quality variables that have caused resource waters to be designated as impaired on the 303(d) list (Irwin 2008). GLKN has monitoring protocols for bioaccumulative contaminants, focused on bald eagles (*Haliaeetus leucocephalus*) (Route et al. 2009) and mercury in fish or other aquatic organisms (Wiener et al. 2009). We expect to monitor inland lakes in the network through these protocols on bioaccumulation.

2.2 Frequency of Sampling

For discrete monitoring a trade-off exists between the number of lakes sampled within a given year and the number of repeat visits made within a year. The same trade-off exists for continuous monitoring as periodic site visits are necessary to maintain, calibrate, and download data from sensors (i.e., thermal arrays). Variability of lake characteristics within a season is often high and may be comparable to the variability between years for some parameters, even for pristine lakes with no apparent long-term trends (e.g., Goldman et al. 1989).

Because of this seasonal variability, for discrete monitoring most state water quality programs collect data several times during the ice-free season, which usually extends from approximately May through October in the upper Midwest. Frequently collected data aid in understanding important issues, such as the onset of blooms of noxious algae and temporal patterns in temperature and dissolved oxygen.

Studies of annual and seasonal means of chlorophyll and total phosphorus concentrations in north temperate lakes spanning a range of trophic states (Hanna and Peters 1991, Marshall et al. 1988, Marshall and Peters 1989) led to the following conclusions:

- Sampling a single site per lake each visit was adequate to detect intra- or interannual trends; relatively little overall precision was gained by sampling multiple sites within a lake.
- Several visits within a year or within the open water season were required to characterize annual water quality as indicated by chlorophyll-*a*. Three to seven observations produced a coefficient of variation of 20% in oligotrophic lakes; 10 visits were needed for the same precision in more productive lakes.
- Differences between surface sampling and integrated euphotic-zone sampling were relatively small (also supported by Knowlton and Jones [1989]). (In the GLKN region, only Michigan uses the euphotic zone sampling scheme and only for chlorophyll-*a*.)
- Sampling effort should be directed to more visits over the course of a season rather than increasing replication on a sampling date, given that characterizing seasonal or annual means is the goal.

Analyses of Vermont's Lay Monitoring Program data for total phosphorus (TP), chlorophyll-*a*, and Secchi depth (Smeltzer et al. 1989) showed Secchi depth had the lowest variance of the three measures and therefore provided the most powerful ability to detect change over time. Chlorophyll-*a* was the most variable and TP was intermediate. The coefficient of variation (CV) of the long-term mean declined as a function of number of samples per year and the number of years of sampling for each variable, however increasing the sampling frequency beyond approximately four times per year yielded diminishing returns. Smeltzer et al. (1989) also found that 10 years of TP or chlorophyll-*a* data would not provide a sufficiently precise baseline against which a 20% change could be statistically detected (t-test, $p<0.05$ with a power of 80%) (Figure 1). A 10-year baseline of Secchi data, collected once or twice a month, would permit a future 20% change to be detected (Figure 2). Larger changes (e.g., 40%) would be detectable for all three variables, after collection of 10 years of monitoring data.

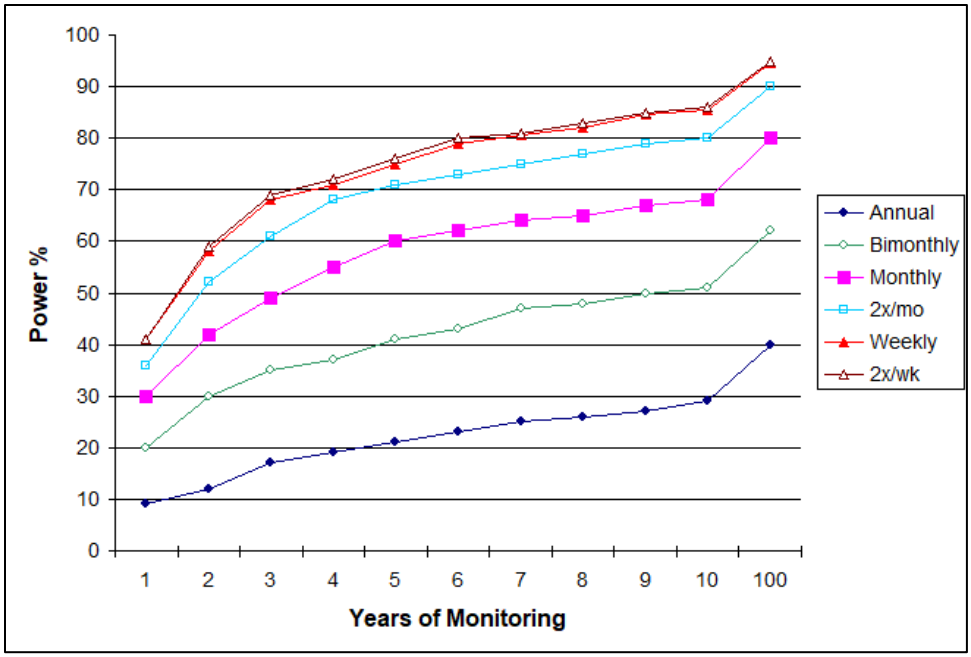


Figure 1. Trend analysis of long-term monitoring of total phosphorus in summer (Smeltzer et al. 1989).

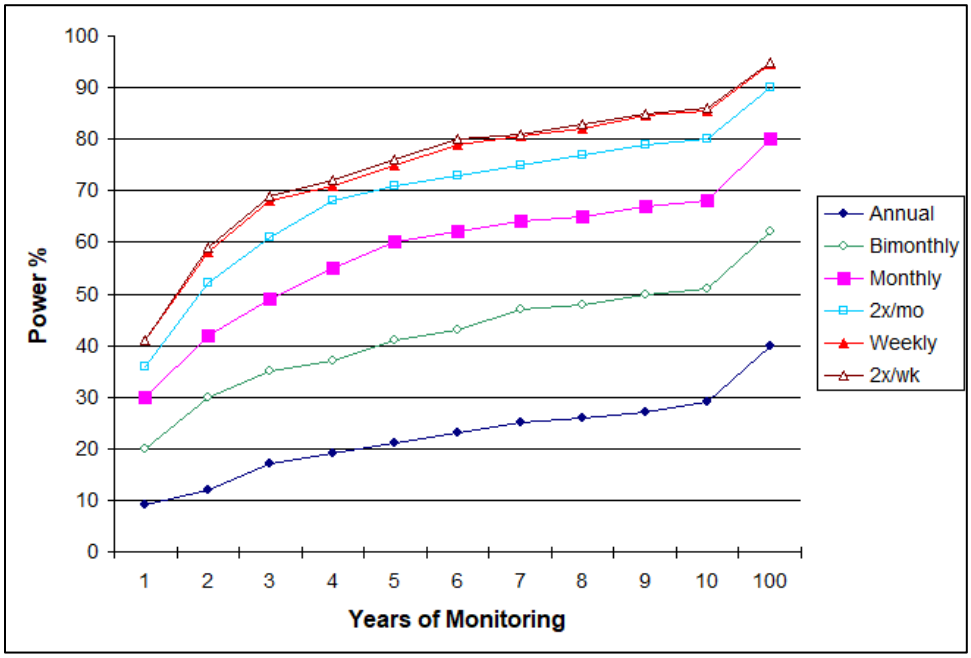


Figure 2. Trend analysis of long-term monitoring of Secchi depth in summer (Smeltzer et al. 1989).

Analysis of Minnesota Secchi data from many sets of lake data yielded a similar result to Vermont's (Heiskary and Lindbloom 1993). Ten years of monthly Secchi data will allow detection of a change of 20% for a given year from the 10-year baseline when $\alpha = 0.10$ and power $(1-\beta) = 0.90$ (MPCA 2005a, 2005b). It is reasonable to expect somewhat less detectable trends in TP and chlorophyll-*a*, based on Minnesota's climatic similarities with Vermont and a similar abundance of glacial lakes in

coniferous and mixed hardwood/coniferous watersheds, although detection levels cannot be precisely verified at this time.

Analyses of select data sets from Pictured Rocks and Sleeping Bear Dunes national lakeshores shows a wide range in the amount of time required to detect change in dissolved oxygen (G. Host, unpublished data). One can expect to detect a trend in percent saturation of dissolved oxygen in defined depth strata after four to 19 sampling years (Table 7).

Table 7. Number of years required to detect a change in dissolved oxygen (DO) saturation in different Great Lakes Network lakes and depth strata. Calculations assume ά = 0.1, power (1−β) = 0.80, rate of change = 20%, and sampling frequency of three times during the open water season. CV = coefficient of variation.

Lake (Park)	Depth Stratum (m)	Mean (% DO)	CV	# Years
Florence (SLBE)	1–3	96.8	0.051	4
Manitou (SLBE)	1–3	95.3	0.072	5
Manitou (SLBE)	6–7	87.8	0.065	5
Chapel (PIRO)	6–7	7.86	0.455	19

Sampling frequency requires a pragmatic compromise among statistical rigor, logistics, and cost. For our discrete monitoring the network will visit each sampling lake three times during the open water season when lakes are likely to be stratified. Analyses of existing data, such as those described above, help us understand the limitations of our sampling design. We do not expect to be able to detect changes in most variables after only a few sampling years and realize that it may take many years to detect changes in some highly variable parameters. Given our sampling frequency, we expect even the least variable parameter to require more than 10 years of monitoring data before we will be able to detect a 20% change with 80% power.

2.3 Location of Sites

A single sampling site, typically located in the deepest part of the lake, will be the routine location for measuring all water quality variables. Thermal arrays will be deployed at the same locations as the discrete sampling sites in lakes where both monitoring activities take place. Sampling the deepest part of the lake allows sampling every possible depth to the bottom and has a long history in limnology. Except for shallow lakes, this type of sampling ignores the littoral zone and always avoids the nearshore zone, as well as embayments and other features related to morphometry. In reservoirs, or in some lakes in which water levels are partially controlled, spatial variation across the length of the system, from inlet to outlet, typically forms major physical, chemical, and biological gradients that are important for understanding and managing the system (e.g., Wetzel 2001). Because the network will not be sampling any large reservoirs, this spatial heterogeneity is not an issue for characterizing overall trends over time. Hanna and Peters (1991) have shown that a single sampling site per lake is adequate to characterize phosphorus and chlorophyll concentrations, given that each site is visited several times within a season.

2.4 Depths of Sampling

The depths of sampling for laboratory analyses of water chemistry varies widely among monitoring programs, ranging from multiple discrete depths and high frequency research programs, to the EPA-EMAP, EPA-NSWS (National Surface Water Survey), and EPA-NES (National Eutrophication Survey) snapshot surveys (Paulsen et al. 1998, Messer et al. 1991), in which water is collected at a single depth (primarily <1 m). In some EPA surveys, bottom water has been collected if the lake was thermally stratified. Some programs use a pump with an inlet tube that is raised and lowered to provide an integrated sample. The State of Michigan steadily lowers a glass bottle to twice the Secchi depth, collecting a single sample that integrates over the entire euphotic zone (MDEQ 1997). This integrated sample is used for chlorophyll-a in an attempt to provide a better coupling between Secchi transparency and chlorophyll-estimated algal biomass (MDEQ 2001, 2004). Although conceptually reasonable, this procedure is questionable in that it adds some logistical difficulty to collecting the sample, it means that nutrients and chlorophyll are collected from different water masses, it potentially introduces errors associated with the qualitative nature of the bottle-filling process, and the euphotic zone is not necessarily twice the Secchi depth (Davies-Colley and Vant 1988, Lind 1979). In Minnesota and Wisconsin, a vertically integrated sample from 0–2 m is collected using a 2-m-long plastic pipe. This type of sampler reduces the contribution of algae surface scums (MPCA 2004a, 2004b) and collects an integrated column of water into a single sample. The main advantage of this integrated tube sampling device is that a larger stratum of water in the epilimnion is sampled, which reduces the effect that surface algal scums can exert on the seasonal chlorophyll means.

None of these techniques has achieved general acceptance among the community of limnologists. Because of its simplicity, many programs use a surface dip as a primary sample, assuming that the epilimnion is completely mixed and that the surface sample is a good estimator of epilimnetic conditions. Such assumptions are not always valid, particularly on warm, calm days when multiple thermal (and therefore chemical and biological) gradients may form for periods of hours to days (e.g., Moss 1998, WOW 2005).

Intensive sampling at multiple depths can best allow for calculating whole-lake nutrient budgets, if combined with morphometric data (lake shape, area, volume, maximum and mean depth, shoreline development, percent littoral zone). However, Carlson and Simpson (1996) pointed out that this method may miss significant gradients, and that sequential sampling, with a randomized starting depth, can correct for this potential bias. Research programs that use such a costly sampling program, however, typically have background data and infer gradients from core suite profiles to best select sampling depths to minimize this source of error.

After considering all of the above sampling strategies, the network decided to use a 0–2 m integrating tube sampler, following the protocol used by Wisconsin and Minnesota (WDNR 2004) and many other states. We will collect a near-bottom sample (ca. 1 m from bottom) via Van Dorn sampler during mid-summer, when lakes are stratified, for analysis of TP.

2.5 Timing of Sampling

For our discrete monitoring we will attempt to visit a given lake at approximately the same time of day each time we sample to minimize variation due to diurnal fluctuations. Temperature sensors on our thermal arrays collect data every hour year-round.

3.0 Sampling Methods

This section summarizes the information presented in greater detail in the standard operating procedures (SOPs) #1 (Pre-Season Preparation), #6 (Field Measurements and Water Sample Collection), #7 (Processing Water Samples and Analytical Laboratory Requirements), and #11 (Post-Season Procedures). The section ends with an overview of quality assurance and quality control (QA/QC) procedures, which pertain to all aspects of sampling. The details of QA/QC are presented in SOP #12.

3.1 Field Season Preparations and Equipment Setup

(Summary of SOP #1: Pre-Season Preparations)

All details of field work need to be planned well in advance. Checklists help ensure that personnel, equipment, and supplies will be prepared in a timely and orderly manner.

Table 8 summarizes which of the SOPs contain key checklists of equipment and supplies for water sampling. Field personnel should check the inventory of equipment and supplies against these lists to verify that no necessary equipment or supply is missing. All equipment, meters, and probes should be checked to verify that they are functioning properly. If needed, replacement equipment or supplies should be ordered well in advance of the onset of sampling, to allow time for inspection, pilot-testing, and calibration of replacements.

Table 8. Checklists of equipment and supplies for monitoring water quality of inland lakes.

Checklist	Location
Safety equipment and supplies	SOP #2
Decontamination equipment and supplies	SOP #5
Field equipment and supplies	SOP #6
Laboratory equipment and supplies	SOP #7

Table 9 provides general guidance for activities conducted prior to the field season. Additional considerations are as follows:

1) Copies of field information on waterproof paper should be kept in two types of 3-ring binders: a project binder and a site binder. The project binder should contain reference information relevant to general field sampling procedures with tabs identifying each procedure for easy access during field work, including QA/QC reminders, copies of all SOPs relating to safety, decontamination, sample collection and processing, copies of equipment instructions and troubleshooting, calibration logs (may be a separate binder), extra field forms, safety data sheets (SDSs) for field supplies that contain hazardous chemicals or materials, and analytical service request and chain-of-custody forms. Site binders should contain reference information specific to each sampling station, including a complete

description of and directions to the monitoring site, location coordinates, maps, and photos, copies of previous field forms, and data tables summarizing all previous measurements of field variables and analytical laboratory results. A summary of field sampling procedures, SDSs, and site descriptions should be taken along on each sampling trip, and thoroughly reviewed beforehand.

Table 9. Checklist of activities to be conducted prior to sampling inland lakes.

Activity	Approximate Date	Responsible Person
Prepare calendar of planned field trips	Before 1 Feb.	Project manager
Review sampling methods	Jan.–Feb.	Project manager
Review checklists of equipment and supplies	Jan.–Feb.	Project manager or crew leader
Charge/replace batteries	Feb. and prior to each sampling day	Field personnel
Clean and test equipment, repair or replace as needed	Jan.–Feb. and prior to each sampling day	Project manager or crew leader
Prepare equipment blanks	Feb.	Project manager or crew leader
Check expiration dates of reagents and calibration standards	Feb.	Crew leader
Contract for lab analyses	Jan.–Feb.	Project manager
Prepare list of items to be ordered; order supplies	Jan.–Feb.	Crew leader
Train field personnel	Jan.–Feb.	Project manager
Obtain permission for site access, if necessary	Feb.	Project manager or crew leader
Confirm current research and collection permits	Jan.–Feb.	Project manager
Check field vehicle for safety equipment and supplies	Feb. and prior to each sampling day	Crew leader
Update site binders	Jan.–Feb.	Project manager or crew leader
Prepare headers on field data forms, chain of custody forms, analytical service request forms; bottle labels	Prior to each sampling round	Crew leader

Table 9 (continued). Checklist of activities to be conducted prior to sampling inland lakes.

Activity	Approximate Date	Responsible Person
Review sample collection, processing, and documentation information	Feb. (Refer to SOPs #6 & 7)	Project manager and all crew personnel
Notify contract analytical laboratory of planned sample shipments	Prior to each sampling round and day of shipment	Crew leader
Make travel reservations and arrangements as needed	Feb. and prior to each sampling round	Project manager and crew leader
Provide supervisor with field trip and check-in schedule	Prior to each sampling round	Crew leader

2) Field personnel should be adequately experienced or trained in using field and water quality sampling equipment. This experience is best obtained through a combination of classroom and hands-on training while pilot-testing equipment at a nearby waterbody. Personnel should be familiar with the instruction manuals, particularly with regard to calibration and maintenance procedures.
3) Meters, probes, and sensors should undergo appropriate annual, weekly, and daily calibration. (See section 3.5, Table 13 for calibration frequencies and acceptance criteria.)
4) Conduct field reconnaissance, if necessary.
5) Pack all field gear to minimize shock and vibration during transport. Pack gear into organized and labeled boxes or cartons, to facilitate inventory and management of supplies.
6) Inspect motorized field vehicles to verify that they are tuned up and working properly. Ensure that vehicles meet space, power, and towing requirements.

3.2 Details of Taking Field Measurements and Collecting Samples

(Summary of SOP # 6: Field Measurements and Water Sample Collection)

3.2.1 Sequence of Activities During Field Workday

This subsection provides a general overview of all sampling tasks, while the next subsections contain more detailed descriptions of particular tasks. Following is the sequence of activities during any given field day:

1) Review the checklist of field gear.
2) Create a new field form for each monitoring station, printed on waterproof paper.
3) Sample bottles and labels should be prepared in advance and placed in a cooler.
4) Conduct daily calibration of appropriate meters and probes.

5) Inspect motorized field vehicles at the beginning of every field day, including all safety and directional lights, oil, gasoline, and tire air pressure levels.

6) Drive to boat landing. Load boat with sampling gear, launch boat, and navigate to monitoring site. Set up a clean workspace on the boat for sampling.

7) Refer to description of monitoring station location, directions, and photo to verify correct location. Verify coordinates on GPS unit.

8) Measure field water quality variables, conduct sampling, and/or deploy sensors per SOP #6. Collect water sample from the highest nutrient depth last, which is usually the bottom sample.

9) Be sure that all samples are correctly labeled and preserved on ice.

10) Navigate to benchmark and measure water level relative to marker, per SOP #4.

11) Verify that the field form is completely filled out, and initial the form.

12) If sampling from more than one monitoring station in a day, go back to step 7.

13) Upon return to shore, inspect boat, trailer, and all equipment that has come into contact with the water for invasive species. Follow procedures for decontamination of equipment per SOP #5.

14) After returning to the office or lab, clean sampling equipment per SOP #6. Rinse sensors with deionized water and perform calibration re-checks, as detailed in SOPs #6 and #12.

15) Conduct sample processing per SOP #7. Refrigerate or freeze samples, as required. Conduct in-house laboratory work and package samples for sending to contract analytical laboratory.

16) Enter or import data into NPSTORET or Aquarius as soon as possible after collecting field data and receiving results of laboratory analyses.

3.2.2 Arrival at Monitoring Site—Recording Field Information

Waterproof field forms should be prepared ahead of time, labeled with the project and station IDs. Field sampling information forms are used to record the physical and chemical water quality variables measured at the time of sample collection. Field forms should be utilized for both routine and non-routine monitoring (e.g., if only a subset of data is collected, or if additional monitoring occurs at a lake beyond the typical three visits per season). In addition to recording the field variables, any samples collected for laboratory analyses must be so indicated. Documentation should include calibration data for each instrument, field conditions at the time of sample collection, visual observations, and other information that might prove useful in interpreting these data in the future.

Upon arrival at the sampling station, record general observations of the appearance of the water (e.g., water color and odor) and other information related to water quality and water use (e.g., fishing and swimming).

General observations should include information that will be useful in interpreting water quality information, such as:

- *Water appearance*. General observations on water may include color, unusual amount of suspended matter, debris, or foam.
- *Weather*. Recent meteorological events that may have impacted water quality include heavy rains, cold front, lack of precipitation, or heavy precipitation.
- *Biological activity*. Excessive macrophyte, phytoplankton, or periphyton growth. The observation of water color and excessive algal growth is important in explaining high chlorophyll-*a* values. Other observations to note include fish, birds, or spawning fish.
- *Unusual odors*. Examples include hydrogen sulfide, mustiness, sewage, petroleum, chemicals, or chlorine.
- *Watershed or in-lake activities*. Shoreline, inlet stream, or drainage-basin activities or events such as bridge construction, shoreline mowing, new construction, high densities of fast-moving boats or personal watercraft close to shore.
- *Other things related to water quality and lake uses*. If the water quality conditions are exceptionally poor, note that standards are not met in the observations (for example, dissolved oxygen is below minimum criteria). Uses may include swimming, wading, boating, fishing, irrigation pumps, or navigation. This type of information may be used in evaluating standards compliance.

While at each monitoring site, the information recorded on field data sheets should include:

- Date
- Time of arrival
- Names of field team members
- GPS coordinates, to verify location
- Current weather (air temperature, wind speed and direction, wave height) and relevant notes about recent weather (storms or drought)
- Observations of water quality conditions
- Description of any photographs taken
- Multiprobe (model), calibration date, and field measurements of core suite variables
- List of samples collected and collection times for advanced suite variables or quality assurance samples and method of collection (e.g., integrating tube or grab)
- Whether any samples were not collected, and reason
- Water level measurement
- Any other required metadata for NPSTORET or Aquarius data entry
- Time of departure

All entries should be made clearly. If an incorrect entry is made, a single heavy line should be drawn through the incorrect entry and the correction made. All corrections should be initialed and dated. The completed field forms will be maintained in chronological order by station, copied into project

binders and the originals maintained on file indefinitely. Field data are reviewed annually by network personnel (see SOP #8, Data Entry and Management, for details).

3.2.3 Measurement of Field Parameters

Field measurements must be collected from an undisturbed area, and multiprobe instruments must be allowed to stabilize (Table 10). Take a replicate reading for every 10 readings; values should agree within 10% or the acceptance criteria in Table 10, whichever is larger. Use a Secchi disk and/or transparency tube to measure the water clarity. Deploy, retrieve, and/or download data from the thermal array, if applicable (see SOP #14, Moored Temperature Arrays), but work with arrays last so sediment and water column disturbance do not influence sonde or sample collection data.

Table 10. Typical sensor performance specifications (Penoyer 2003).

Sensor	Expected Range	Reporting Resolution [a]	Estimated Bias	Stabilization Criteria
Temperature	−5°C to 45°C	0.01°C	± 0.15°C	Thermistor: ± 0.2°C Glass: ± 0.5°C
Specific Conductivity (SC25)	0 to 2000 µS/cm	µS/cm (range dependent)	± 0.5% of reading + 1 µS/cm	≤100 µS/cm: ± 5% >100 µS/cm: ± 3%
pH	1 to 14 units	0.01 unit	±0.2 units	± 0.1 standard unit
Dissolved Oxygen (Conc.)	0 to 50 mg/L	0.01 mg/L	0 to 20 mg/L: ± 0.2 mg/L 20 to 50 mg/L: ± 0.6 mg/L	± 0.3 mg/L
Dissolved Oxygen (% sat.)	0% to 200%	0.1%	ca. ± 2 %	± 2%
Depth – Z (pressure sensor)	0 to >100 m	0.1 m	ca. 0.1 m	0.1 m

[a] Resolution specifications are supplied by the manufacturers of the measuring meters. They are not necessarily closely related to real-world (outdoor) precision or bias and are sometimes more related to the number of significant figures reported rather than how accurate the extra significant figures are. This is why we will control measurement sensitivity in the actual outdoor measuring environment at least once a year by calculating alternative measurement sensitivity (AMS; see Irwin 2008 for more details on AMS).

3.2.4 Collection of Water Samples

Collect water sample(s) with an integrated sampling tube for 0–2 m samples and Van Dorn for near-bottom samples. In the field data sheet, record information related to the sample collection, including:

1) Lake name and site identification code.
2) Sample date, time, and depth.
3) The amount of sample collected.
4) Whether duplicate samples for quality control were collected at this site.

5) Any additional notes or observations pertinent to this sample or location for this sampling period.

Always keep the following in mind:

- Sample containers should be labeled in indelible ink with, at a minimum, the station name, date and time of collection, and preservation method, if applicable.
- To ensure the integrity of the sample, be aware of possible sources of contamination. Contamination introduced during each phase of sample collection and processing is additive and usually is substantially greater than contamination introduced elsewhere in the sample handling and analysis process.
- Use appropriate procedures and quality-assurance measures that ensure sample representativeness and integrity and that meet study criteria. The degree to which a sample can be considered representative of a waterbody depends on many interrelated factors including temporal and spatial homogeneity of the waterbody, sample size, and the method and manner of sample collection.

3.3 Post-Collection Sample Processing

(Summary of SOP #7: Processing Water Samples and Analytical Laboratory Requirements)

Upon return to the office or home base, conduct in-house laboratory work, prepare and ship sample bottles, clean and prepare equipment for storage, and enter or import data from field forms into an approved database.

3.3.1 In-house Laboratory Work

Upon return from the field, keep sample bottles refrigerated prior to processing or analysis.

Process samples according to SOP #7 and specific laboratory instructions. If any of the water quality analyses are done in-house (for example, alkalinity titrations), conduct these procedures as soon as possible after returning from field work, ensuring that the maximum holding times for these variables are not exceeded. Store processed samples in the refrigerator or freezer, as appropriate, until shipping to the contract laboratory.

3.3.2 Shipping Samples to Contract Laboratory

Prior to shipping samples, notify the laboratory of how many samples of what type and when to expect shipment. Ensure that laboratory personnel will be available to receive the shipment. Check that the sample bottles are correctly labeled according to the protocols of the contract laboratory and that caps are securely tightened. Complete the analytical services request and chain-of-custody forms provided by the laboratory. Pack samples carefully in the shipping container according to laboratory protocols, to prevent bottle breakage, shipping container leakage, and sample degradation.

Table 11 summarizes the variety of methods, detection limits, preservation techniques, and holding times for water samples addressed by this protocol. Methods conform to those used by Minnesota, Wisconsin, and Michigan for state certification of environmental laboratories involved in Clean Water Act or drinking water sample analysis (MDH 2005, WSLH 2003, MDEQ 2005). They are also

used by EPA-funded research projects of natural waters in the upper midwestern United States. Refer to SOP #6 for additional details regarding sample collection and preservation.

The selection of a contract laboratory will include criteria regarding the laboratory's ability to provide method limits of quantitation (ML) adequate for the dilute, oligotrophic lakes included in this monitoring protocol. Desired MLs and method detection limits (MDL) for water chemistry parameters are based on examination of historical data, the occurrence of low nutrient lakes in several of the parks, and the MDLs achievable using the standard water chemistry methods that research limnologists currently use. See SOP #12 for details regarding analytical detection levels required for GLKN water quality monitoring.

Table 11. Example range of analytical methods, method detection limits (MDLs), containers, preservation methods, and holding times. Source: National Environmental Methods Index website (https://www.nemi.gov/home/). This list is not an endorsement of any particular method or laboratory for any particular analyte. Rather, it is to be used as a reference for the range of analytical methods available for each analyte. There are surface water conditions (pH, turbidity, other elements) that make a particular method unsuitable for a particular situation. As GLKN is monitoring surface water, the methods listed were chosen as representative of the lower range of detection limits. APHA = Clesceri et al. (1998).

Analyte	Analytical[1]	Method #	Det. Limit	Vol. (mL)	Filter	Preservation	Sample Bottle[2]	Hold Time
Alkalinity	Titrimetry	310.1 EPA-NERL	10 mg/L	–	–	4ºC	–	14 days
	Spec. auto.	310.2 EPA-NERL	10 mg/L	–	–	4ºC	–	14 days
	Titrimetry	NFM USGS-OWQ	0.01 meg/L	–	*Note 4*	None	–	none
Calcium	ICP	3120B APHA	10 ug/L	–	*Note 3*	pH<2 HNO_3	P or G	6 mos
	Titrimetry	215.2 EPA-NERL	0.5 mg/L	–	*Note 3*	4ºC	–	6 mos
	FAA	I-3152 USGS-NWQL	0.1 mg/L	250	*Note 3*	pH<2 HNO_3	P	180 days
Chloride	IC	300.0 EPA-NERL	0.02 mg/L	–	–	4ºC	P or G	28 days
	Colorimetry	325.2 EPA-NERL	1 mg/L	–	–	4ºC	–	28 days
	Titrimetry	4500-Cl APHA	0.15 mg/L	100	–	4ºC	P or G	28 days
Chlorophyll-*a*	Spect.	10200 APHA	2 ug/L	≤1 L	*Note 4*	Freeze filter	P	30 days
DOC	Spect.	415.3 EPA	0.018 mg/L	125	*Note 3*	pH<4 H_2SO_4	G	28 days
	Spect.	0-1122-92 USGS	0.1 mg/L	–	–	4ºC	AG	–
K	ICP	3120B APHA	0.3 mg/L	–	*Note 3*	pH<2 HNO_3	P or G	6 mos
	FAA	3111B APHA	5 ug/L	–	*Note 3*	pH<2 HNO_3	P or G	6 mos

[1] CIE-UV= capillary ion electrophoresis with UV detection, FAA = flame atomic absorption, FIA = flow injection analysis, IC= ion chromatography, ICP = inductively coupled plasma, Spec. auto = spectroscopy with autoanalyzer

[2] P = plastic (polypropylene), G=glass, AG=amber glass

[3] 0.45 µm membrane filter. Pre-filter for dissolved portion analysis.

[4] 0.45 µm glass fiber filter.

[5] USGS 2003= Patton and Kryskalla (2003)

Table 11 (continued). Example range of analytical methods, method detection limits (MDLs), containers, preservation methods, and holding times. Source: National Environmental Methods Index website (https://www.nemi.gov/home/). This list is not an endorsement of any particular method or laboratory for any particular analyte. Rather, it is to be used as a reference for the range of analytical methods available for each analyte. There are surface water conditions (pH, turbidity, other elements) that make a particular method unsuitable for a particular situation. As GLKN is monitoring surface water, the methods listed were chosen as representative of the lower range of detection limits. APHA = Clesceri et al. (1998).

Analyte	Analytical[1]	Method #	Det. Limit	Vol. (mL)	Filter	Preservation	Sample Bottle[2]	Hold Time
Mg	ICP	3120B APHA	20 ug/L	–	*Note 3*	pH<2 HNO_3	P or G	6 mos
	FAA	3111B APHA	0.5 ug/L	–	*Note 3*	pH<2 HNO_3	P or G	6 mos
Na	ICP	3120B APHA	30 ug/L	–	*Note 3*	pH<2 HNO_3	P or G	6 mos
	FAA	3111B APHA	2 ug/L	–	*Note 3*	pH<2 HNO_3	P or G	6 mos
NH_4-N	Selective elec.	4500-NH_3E	0.08 mg/L	–	–	4ºC/pH2,0ºC	–	24 h/28 d
	Colorimetry	350.2 EPA-NERL	0.08 mg/L	–	–	pH<4 H_2SO_4	–	28 days
	Titrimetry	4500-NH_3 APHA	5 mg/L	–	–	4ºC/pH2,0ºC	–	24 h/28 d
SiO_2	ICP	3120B APHA	20 ug/L	–	*Note 3*	pH<2 HNO_3	P or G	6 mos
	Spect.	4500- SiO_2 D APHA	0.04 mg/L	–	*Note 3*	No, 4ºC	P	28 days
	FIA-Spect.	4500- SiO_2 F APHA	0.78 ug/L	–	*Note 3*	No, 4ºC	P	28 days
SO_4	IC	4110C APHA	75 ug/L	–	*Note 3*	pH<4 H_2SO_4	P or G	–
	CIE-UV	D6508 ASTM	0.1 mg/L	–	*Note 3*	pH<4 H_2SO_4	–	ASAP
	Spect.	37512 EPA-NERL	0.5 mg/L	–	*Note 3*	pH<4 H_2SO_4	P or G	28 days

[1] CIE-UV= capillary ion electrophoresis with UV detection, FAA = flame atomic absorption, FIA = flow injection analysis, IC= ion chromatography, ICP = inductively coupled plasma, Spec. auto = spectroscopy with autoanalyzer

[2] P = plastic (polypropylene), G=glass, AG=amber glass

[3] 0.45 µm membrane filter. Pre-filter for dissolved portion analysis.

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Analyte	Analytical[1]	Method #	Det. Limit	Vol. (mL)	Filter	Preservation	Sample Bottle[2]	Hold Time
TP	Spect.	I-2606 USGS-NWQL	0.001 mg/L	125 mL	–	MgCl 4ºC	BrownP	30 days
	Alkaline P	USGS 2003	0.01 mg/L	120 ml	*Note 5*	4ºC /H_2SO_4	–	48 h/30 d
	ICP	200.7 EPA-NERL	60 ug/L	–	–	pH<2 HNO_3	P	6 mos
TN	Alkaline P	USGS 2003	0.03 mg/L	120 ml	*Note 5*	4ºC /H_2SO_4	–	48 h/30 d
	Titrimetry	4500-N	0–100 mg/L	–	–	4ºC	AG	7 days
	Combustion	440.0 EPA-NERL	0.1 mg/L	–	–	Filter	–	100 days

[1] CIE-UV= capillary ion electrophoresis with UV detection, FAA = flame atomic absorption, FIA = flow injection analysis, IC= ion chromatography, ICP = inductively coupled plasma, Spec. auto = spectroscopy with autoanalyzer

[2] P = plastic (polypropylene), G=glass, AG=amber glass

[3] 0.45 µm membrane filter. Pre-filter for dissolved portion analysis.

[4] 0.45 µm glass fiber filter.

[5] USGS 2003= Patton and Kryskalla (2003).

3.3.3 Equipment Cleaning and Storage

Clean all sample collection and storage containers and labware in a 0.1N HCl acid bath followed by deionized water rinses per SOP #7. Monitoring equipment should be cleaned and packed for storage. Keep equipment and supplies properly organized and labeled so they can easily be inventoried using the checklists.

3.3.4 Data Entry and Management

Download, enter, or import field and laboratory data into appropriate spreadsheets and databases as soon as possible to minimize error, per SOP #8. Refer to the instrument manufacturer's instruction manual for details on downloading data from field data loggers.

3.4 End of Field Season Procedures

(Summary of SOP # 11: End-of-Field Season Procedures)

When sensor probes are to be stored for extended periods of time, thoroughly clean sensors, remove batteries, and store the sonde according to specific instructions in SOP #11 and the manufacturer's manual. Store calibration standards and electrolyte solutions in a temperature-controlled environment. Ensure that containers are dated upon receipt and upon opening; observe expiration dates.

3.5 Quality Assurance/Quality Control

The objective of quality assurance/quality control (QA/QC) is to ensure that the data collected for a project are meaningful, representative, complete, precise, accurate, comparable, and scientifically defensible (O'Ney 2005a). It is a broad management concept requiring the complete integration of field and laboratory systems of sample collection and analysis. The QA/QC procedures that pertain to sample collection and processing are focused on: 1) ensuring that any given field or laboratory measurement accurately represents the water resource at the time the sample was collected, 2) ensuring that water quality data are comparable across all sampling dates, and 3) verifying that no contamination has been introduced to the sample at any time. These activities range from instrument calibration, to specification of field methods and laboratory detection limits, to analysis of sample blanks and spikes. Table 12 summarizes the QA/QC procedures pertaining to sampling methods that will be followed in this protocol.

One important aspect in the accuracy and precision of a water quality monitoring program is the correct selection of probes for measuring field variables and their subsequent calibration and maintenance schedule. Table 10 (above) lists typical field sensor performance specifications that should be expected from monitoring equipment for this protocol. Table 13 summarizes the ideal calibration frequency and minimum acceptance criteria for these sensor probes. The reality of logistical constraints at back country sites may preclude calibration and checks of calibration at the ideal frequency. Calibration logs for multi-parameter sondes will be maintained and will document the frequency of calibration and calibration checks. Ensure calibration standards are not used beyond expiration dates. Refer to SOP #6 for guidelines on potential field measurement problems.

The detection limits for water quality variables specified in Table 11 are based on examination of historical data and the occurrence of dilute concentrations of water quality variables in natural waters. Many commercial laboratories do not routinely analyze samples using these lower detection limits, even if they have the proper instrumentation, because their primary workload is wastewater-related with much higher concentrations. Therefore, the process of selecting a contract analytical laboratory will include consideration of whether the lab has experience analyzing naturally dilute waters.

Quality Control (QC) involves specific tasks undertaken to determine the reliability of field and laboratory data. It is accomplished internally by routine analysis of blanks, duplicates, and spikes in the day-to-day operation of a laboratory, or externally by incorporating field-originated blanks, duplicates, and spikes into the set of the samples collected during a water quality survey. We will include the following QA/QC routines:

1) Equipment blanks prior to the field sampling, to ensure no extraneous sources of contamination are introduced into the samples.
2) Submit duplicate water samples, at the rate of approximately 10%, so that the reported data are precise, or the results of analyses are reproducible.
3) Document the sensitivity of multiprobes through an estimation of the limits of detection known as alternative measurement sensitivity (AMS).
4) Replicate multiprobe field measurements at the rate of approximately 10%. Calculate the relative percent difference to document precision of the multiprobe.

Table 12. Summary of QA/QC procedures pertaining to sampling methods.

Procedure	Description/Reason
Instrument calibration logs	Each instrument must have a calibration log. Calibration schedule must be observed, using fresh calibration standards.
Project binder	Containing: checklist of QA/QC reminders, copies of decontamination, sample collection and processing SOPs, copies of equipment calibration and troubleshooting instructions, ASR and COC forms, blank field forms.
Site binders	Containing: GPS coordinates for verification of correct sampling location, table of previous field measurements to compare with new measurements, map and directions to site.
Field forms	Field forms are the only written record of field measurements, so copies are placed in project binders and originals must be kept on file indefinitely.
Field instrument methods	Require consistent measurement methods and detection limits
Sample preservation and minimum holding time	Water samples are maintained as close to sampling conditions as possible.

Table 12 (continued). Summary of QA/QC procedures pertaining to sampling methods.

Procedure	Description/Reason
Chain-of-custody	A chain-of-custody includes not only the form, but all references to the sample, including information that allows tracing the sample back to its collection and documents the possession of the samples from the time they were collected until the sample analytical results are received.
Laboratory methods	Require consistent analytical methods and detection limits

Table 13. Ideal calibration frequencies and acceptance criteria for field instruments.

Parameter	USEPA Method	Minimum Calibration Frequency and QC checks	Acceptance Criteria	Corrective Actions
Temperature: thermometer	170.1	Annually, 2-point check with NIST thermometer	±1.0ºC	Re-test with a different thermometer; repeat measurement
Temperature: thermistor	170.1	Annually, 2-point check with NIST thermometer	±1.0ºC	Re-test with a different thermometer; repeat measurement
Specific Conductance (SC25)	120.1	Daily, prior to field mobilization; calibration check prior to each round of sampling; 10% of the readings taken each day must be duplicated or a minimum of 1 reading if fewer than 10 samples are read.	± 5% RPD 10%	Re-test; check low battery indicator; use a different meter; use different standards; repeat measurement
pH	150.1	Daily, prior to field mobilization (two buffers should be selected that bracket the anticipated pH of the water body to be sampled with an independent third buffer selected to check instrument performance in that range);	± 0.05 pH unit	Re-test; check low battery indicator; use different standards; repeat measurement; don't move cords or cause friction/static
	150.1	Calibration check w/ third buffer prior to each round of sampling	± 0.1 pH unit	Re-test; check low battery indicator; use different standards; repeat measurement; don't move cords or cause friction/static
	150.1	10% of the readings taken each day must be duplicated or a minimum of 1 reading if fewer than 10 samples are read.	RPD 10%	Re-test; check low battery indicator; use different standards; repeat measurement; don't move cords or cause friction/static

Table 13 (continued). Ideal calibration frequencies and acceptance criteria for field instruments.

Parameter	USEPA Method	Minimum Calibration Frequency and QC checks	Acceptance Criteria	Corrective Actions
Dissolved Oxygen	360.1	Daily, prior to field mobilization, check at the field site if elevation or barometric pressure changed since calibration	0.2 mg/L concentration or ±10% saturation	Re-enter altitude; re-test; check low battery indicator; check membrane for wrinkles, tears, or air bubbles; replace membrane; use a different meter; repeat measurement; allow more time for stabilization
Depth	–	Daily, prior to field mobilization, check at the field site. Check annually against commercially purchased brass sash chain labeled every 0.5 m to ensure that it reads zero at the surface and varies <0.3 m for depths <10 m and no more than 2% for greater depths.	± 0.1 m	Retest, check low battery indicator; repeat measurement; use with accurately calibrated line
Transparency tube	–	Transparency tubes have a 100- or 120-cm scale; ensure tube is clean	± 1.0 cm for transparency tube	Transparency tube
Marked lines (e.g., Secchi, Van Dorn)	–	Check markings annually against brass sash chain. If lines are heated (for decontamination) check prior to each round of sampling.	± 1%, 0–10 m ± 2%, >10 m	Re-mark line.

4.0 Data Handling, Analysis, and Reporting

4.1 Metadata Procedures

Metadata allows potential data users to evaluate the quality and usefulness of the data based on an understanding of the complete process under which it was collected and maintained. In this respect, all of the protocol documentation, including standard operating procedures (SOPs), is part of a dataset's metadata. A reference to the appropriate version of these documents is part of the metadata for any particular element of a dataset. Although perhaps obvious, all data must have an associated value for the date and time they were collected.

Most of the remaining metadata will be recorded directly in the protocol-specific databases and tables. We will enter or import all required metadata for NPSTORET and Aquatic Informatics' Aquarius database; the data and metadata will ultimately be moved to the EPA STORET database or for Aquarius maintained by NPS-WRD staff in Ft. Collins, Colorado.

For metadata associated with geospatial data, we will abide by Executive Order 12906, which mandates that every federal agency document all new geospatial data it collects or produces using the Federal Geographic Data Committee (FGDC) Content Standard for Digital Geospatial Metadata (CSDGM; www.fgdc.gov/metadata/contstan.html). All GIS data layers will be documented with applicable FGDC and NPS metadata standards. The network will also generate FGDC-style metadata for non-spatial datasets that meet this standard, absent only the geospatial-specific elements. A metadata record will be created, compliant with a standard approved by NPS and DOI. The metadata record shall include taxonomic metadata elements that permit potential users to discover and use the dataset efficiently and effectively.

For more details on the Great Lakes Network's overall strategy for metadata generation, management, and distribution see chapter 8, Data Documentation, of GLKN's Data Management Plan (Hart and Gafvert 2006) and the appendices of that document.

4.2 Overview of Database Design

The NPS-WRD has established a policy that all I&M water quality monitoring data will be made compatible with, and be uploaded to, the EPA's STORET database. The WRD developed a Microsoft Access database tool, NPSTORET, which duplicates most of the EPA data and table structures in, to facilitate easier movement of I&M networks' water quality data into EPA Water Quality Exchange (WQX) framework. We will use NPSTORET as the primary data entry tool and data transfer mechanism to WRD. In addition, GLKN uses Aquatic Informatics' Aquarius system for storage and visualization of continuously monitored water quality data from automated loggers (i.e., water temperature data from thermal arrays).

The network will maintain one master copy of NPSTORET at the Ashland office on a central server. This is the only copy of NPSTORET that can be used to export data to other locations (WRD). Additional copies of NPSTORET can be used by network staff or cooperators, but they can only be used as a conduit for data entry and the importation of data to GLKN's master version of NPSTORET. For analysis, the data from the master copy of NPSTORET must be used. The network

will continue to improve tools for automating analysis and visualization of the information contained in the NPSTORET and Aquarius datasets.

4.3 Data Entry, Verification, Certification, and Editing

Detailed instructions for the data entry procedures for this protocol are given in SOP #8, Data Entry and Management. As described above (Section 3, Field Methods), three general classes of water quality data are collected. The first is field observations and measurements that are recorded on data sheets in the field. These field sheets will be entered into a digital file. The second class of data is the results of testing performed by contract analytical laboratories. The last class of water quality data is digital data that have been collected by multiprobe sondes and other field data loggers. GLKN will develop formatting routines to be applied to the digital files prior to importation of data into NPSTORET or Aquarius.

Data verification starts with the QA/QC steps that are outlined in the SOPs associated with this protocol. If data being imported into NPSTORET do not pass a QA/QC test, NPSTORET prompts the user to make corrections and re-import the data. Data that are outside the expected rate of change for a parameter based on previous records for that parameter will be flagged for further review by an expert.

Quality assurance/quality control checks are performed as data are imported into NPSTORET or Aquarius and again when the data are transferred to WRD. The network's water quality data records are regarded as being in provisional status until they are returned to GLKN from WRD or are accepted by WRD without changes after the final QA/QC steps. Once returned to GLKN by WRD, and after appropriate documentation is completed, the dataset is officially considered certified. Only qualified users who have been trained and given edit permissions are allowed to edit data in NPSTORET or Aquarius. These procedures protect the integrity of the data and allow the history of each data record to be traced.

4.4 Data Archival Procedures

Data archiving serves two primary functions: it provides a source to retrieve a copy of any dataset when the primary dataset is lost or destroyed, and it provides a data record that is an essential part of the QA/QC process. The unedited files are the original data for digital data. The archival of the printed data forms for this protocol is described in SOP #8.

The network will create duplicate files of all digital data at the earliest opportunity. At least two complete copies of any water quality dataset are required by WRD, including digital replicas (scanned versions) of hard copy data sheets. Digital field data that are entered directly into a field computer or collected from a data logger will be backed up to a second medium at the earliest possibility. The data files on field computers and loggers must not be erased until the integrity of these data files are verified on the duplicate storage medium.

The network's master version of NPSTORET is maintained on a central server in the Ashland Office that is backed up daily and backed up off-site weekly. Complete details of the GLKN Server archiving procedure are found the Infrastructure chapter of GLKN's Data Management Plan (Hart

and Gafvert 2006); the general strategy for data archiving is also described in this plan and its appendices.

4.5 Quality Assurance and Quality Control Pertaining to Data Entry and Management

Quality assurance and quality control procedures are crucial during every step of data entry and data management. Details of such QA/QC regarding data management are provided in SOP #8 and are summarized below in Table 14.

Table 14. Summary of QA/QC procedures pertaining to data management.

Procedure	Description
Instrument calibration logs	Each instrument must have a calibration log.
Field forms	Field forms are the only written record of field measurements, so copies are placed in project binders and originals must be kept on file indefinitely.
Estimating precision	The precision measurement is calculated using the Relative Percent Difference (RPD) between duplicate sample results per analyte. Precision estimates should be performed within 7 days of receipt of laboratory results.
Electronic data entry	Approximately 10% of electronic data entries should be spot checked on a random basis for errors. If errors are found, another 10% are spot checked.
Data archiving	Program sampling data and associated records are archived in boxes and stored at the GLKN Ashland office. Boxes are numbered consecutively by year, project, and station number.
Data validation	Data validation is the process that determines whether data collection quality control objectives were met.
Data validation reports	Data validation reports provide a narrative that discusses any deviations from QA/QC procedures and the impacts of those deviations.
Data verification	Data verification demonstrates that a data set will qualify as credible data.
Data certification	Data certification demonstrates that data are complete for the period of record; 2) they have undergone and passed the quality assurance checks; and 3) that they are appropriately documented and in a condition for archiving, posting and distribution as appropriate.
Data verification reports	Data verification reports document the results of the data verification procedure.
Data qualification codes	Data must be fully qualified before uploading to the Water Resources Division

4.6 Routine Data Summaries

Brief characterizations of the data from each lake, across each NPS unit in which sampling occurred and for the network as a whole, will be performed following each sampling year after all QA/QC procedures have been completed. For each water quality variable, these descriptive statistics may include mean, median, maximum, and minimum values by lake; and these same values with the addition of skew, kurtosis, and measures of variability (e.g., coefficient of variation, standard error, 95% confidence intervals) among lakes within each NPS unit. These broader-extent analyses can inform managers whether anomalous values recorded from a given lake (or even across all lakes within one park) were also observed at broader spatial extents that year (e.g., across a given park, or in other parks). Given the relevant legislation (e.g., Clean Water Act of 1972), it may be of interest to the individual parks and to other entities to assess the proportion of measurements during a time period or across a domain (at a single point in time) that exceed specific water quality criteria or pre-determined thresholds. As with nearly all percentage data, arcsine transformations must be performed on those percentage data before statistical analyses can be performed. However, back-transformed values will be used for graphical presentation and other reporting.

In addition to these descriptive statistics, analytical approaches may also include estimation of interannual change, graphic approaches (e.g., comparison of mean and variability in a parameter in the current year versus past years), and occasionally qualitative analysis (Guthery et al. 2001), as well as modeling, correlational analyses, and various parametric and nonparametric analyses.

4.7 Methods for Long-Term Trend Analysis

After at least three sampling seasons of monitoring data are collected at a given lake, more intensive analyses of change may be performed for each lake. In addition to repeated-measures, time-series, regression, and non-parametric equivalents of various methods such as Mann-Kendall, monitoring data may also be evaluated through Monte Carlo simulation analyses, Bayesian analyses, and comparisons of period means. For the latter-most approach, one is often interested in comparing values before and after an important event (e.g., change in management policy, remarkable anthropogenic disturbance, natural catastrophe, drought), and considers years within each of the two periods as replicates. The seasonal Kendall test is one of several preferred nonparametric tests for evaluating interannual trends in water quality (Hirsch et al. 1991). The test, which accounts for intra-annual variability, has been used widely for more than 15 years, and usually requires five to ten years of data. In the test, one can define “seasons” as months, quarters, ice-on/off periods, by limnological stratification, or by any other criterion. The examination of interannual change is subsequently performed on each of the seasons; the average of all the seasons’ slopes becomes the final trend line. Trends in parameters that are analyzed with respect to biotic and abiotic covariates that may affect water quality will be examined, although cause-effect relationships may be investigated more thoroughly by NPS partners and collaborators (e.g., USGS-WRD, university investigators).

In addition to analyzing each variable separately, several abiotic indicators of water quality that are not correlated and that naturally could be considered a homogeneous group of parameters could be analyzed collectively through multivariate ordinations (e.g., nonmetric multi-dimensional scaling) of resource conditions through time, following West and Yorks (2002). This approach effectively

integrates information across many indicators and can suggest whether water quality at individual lakes is moving in the same direction in multidimensional ordination space. Furthermore, joint plots can be overlaid on the ordination, and can suggest which variables correlate most strongly to the direction of changes. Multivariate analyses can help suggest cause-and-effect relationships and are useful as hypothesis-generating tools. Multivariate ordinations are also useful for relating water-quality conditions with abundance or presence data from many species (e.g., diatoms) (McCune and Grace 2002).

See SOP #9 for additional details on data summaries and analyses.

4.8 Reporting Schedule

One of the network's main goals is to ensure that the results and knowledge acquired through the water quality monitoring program are shared with all appropriate parties, especially the parks and their natural resource managers. We will strive to provide park managers with clear, meaningful products in a timely manner to convey our findings. Because our monitoring data will be of interest to a broader community, we will also provide our reports to the states, the NPS I&M Division, and when appropriate, submit them to peer-reviewed journals for publication. We will also present our findings orally and in poster format at regional meetings, such as the Western Great Lakes Research Conference, the St. Croix Research Rendezvous, or the Lake of the Woods Research Conference.

As mentioned above, routine data summaries will be conducted annually for lakes and parks that are sampled within that year. The summaries will be compiled from data that has been uploaded to the EPA's STORET database or the Aquarius database by NPS-WRD. Hard copy or web-based summary reports will be produced periodically, after the data is certified, with the primary audience being the parks.

More comprehensive reports, with analyses of trends, will occur after three or more seasons of sampling. For stations that are located where no previous monitoring has occurred, three sampling periods are the minimum needed to establish a time series sufficiently powerful to detect meaningful levels of change (e.g., 20%) through time.

The target audience of the analysis and synthesis reports will be the parks, the network, both regional and Servicewide I&M, and the broader scientific community. Drafts of these reports will be reviewed internally and sent to the parks, and possibly outside sources, for further review. The extent of review will depend on how analytically complicated the methods are and the gravity of inference and recommendations.

4.9 Report Format with Examples of Summary Tables and Figures

Both annual summaries and reports that include detailed analyses on trends should adhere to Servicewide I&M reporting guidelines for Natural Resource Data Summary reports (for annual summaries) and Natural Resource Reports (for detailed analysis reports). Refer to the Natural Resource Publications Management website for the most up-to-date guidelines and formats. Reports should include tables and figures appropriate for the data and for the intended audience.

4.10 Moored Temperature Array Continuous Data Reporting

Data from moored arrays will be housed in the Aquatic Informatics Aquarius system that is maintained by NPS WRD. This system is separate from NPSTORET, which cannot be used to maintain continuous data. Aquarius allows us to store, perform QA/QC procedures, and make data available to the public in a single platform.

Data downloads from arrays will typically occur twice per year, at the beginning and end of field season. The data are uploaded to Aquarius as soon as possible after return from the field, QA/QC checked, errors rectified, and made available to the public through the NPS Aquarius Web Portal at: https://irma.nps.gov/aqwebportal/. For more details on array data management, please see SOP #14.

5.0 Personnel Requirements and Training

5.1 Roles and Responsibilities

The water quality monitoring program at the network is staffed by a project manager (GLKN aquatic ecologist, GS/11) and two assistant project managers (GLKN aquatic ecologists, GS/9s). The project manager and the assistant project managers are permanent full-time employees. The assistant project managers primarily focus on leading fieldwork for separate water quality monitoring protocols (inland lakes or large rivers) during the field season, but also have many overlapping responsibilities throughout the year. The assistant project managers will each supervise at least one seasonal crew member at the GS/4 or GS/5 level, and along with the crew members may be stationed at one of the parks.

The field crews will work on this water quality monitoring project for a limited number of pay periods per year and may spend the remaining part of their time on other network or park projects. The network will explore the possibility of sharing seasonal positions with the parks. When a park has an aquatic person on staff, the network will make use of such existing staff expertise on the crew when possible, paying for the time spent on I&M monitoring activities, and will provide the same training to the park person as to the rest of the crew members. The field crews will monitor water quality in both rivers and lakes; the responsibilities, training, and qualifications of the crew are the same for both protocols.

5.1.1 Project Manager

The role of the project manager is to serve as a liaison among other related water quality monitoring projects conducted by partners (e.g., state monitoring programs), park staff, other network staff (field personnel, data manager), contracted analytical laboratories, and other GLKN project managers. The individual will coordinate with resource management staff at the parks to ensure parks are informed of monitoring activities. Specific responsibilities of the project manager include the following:

- Coordinate field schedules and availability of supplies with field personnel.
- Develop a training program for field personnel.
- Develop, document, and oversee the implementation of standard procedures for field data collection and data handling.
- Coordinate logistics with park staff.
- Develop QA/QC measures for the project, supervise staff training, and conduct quality assurance checks of field sampling techniques at least once, mid-season, with each field crew.
- Contract with analytical laboratories for analysis of water samples, ensure lab results meet program needs (e.g., QA/QC procedures, meaningful minimum detection limits for dilute waters, adequate reproducibility of replicate samples).
- Supervise or perform data entry, verification, and validation.
- Summarize data and analyze data, prepare reports.
- Serve as the main point of contact concerning data content.

The project manager will also work closely with the data manager in the following capacities:

- Complete project documentation (i.e., metadata) in appropriate databases.
- Develop data verification and validation measures for quality assurance.
- Establish and implement a procedure to officially certify water quality datasets.
- Ensure staff are trained in the use of database software and quality assurance procedures.
- Coordinate changes to the field data forms and the user interface for the project database.
- Identify sensitive information that requires special consideration prior to distribution.
- Manage the archival process to ensure regular archival of project documentation, original field data, databases, reports and summaries, and other products from the project.
- Define how project data will be transformed from raw data into meaningful information and create data summary procedures to automate and standardize this process.
- Establish meaningful liaisons with state counterparts to promote sharing of data on a timely basis.

5.1.2 Assistant Project Managers

Assistant project managers are largely responsible for implementing the inland lakes and large rivers water quality monitoring protocols. Specific responsibilities include:

- Assist with coordination of field schedules and supplies.
- Supervising and training field personnel.
- Coordinate logistics with park staff.
- Help ensure all aspects of QA/QC are met.
- Perform data entry, verification, and validation.
- Train other staff in the use of database software.
- Assist with data analysis and report writing.

5.1.3 Field Personnel (Field Crew Member/Leader)

The role of field personnel is to conduct all field work related to the monitoring project. Field personnel will include both a crew leader and a crew member. The crew leader is responsible for contacting the parks prior to each sampling event to ensure logistical requirements will be met. Crew leaders and crew members may be park staff that coordinate with their respective parks and the network project manager. Responsibilities for network or park crew leaders and crew members include the following:

- Complete all training for field sampling, sample handling, and boat operation, if required by park.
- Complete all phases of field season preparation.
- Collect data and samples according to developed protocols.
- Pack and ship samples to analytical laboratory.
- Maintain accurate field and office notes.

- Ensure that all QA/QC procedures are implemented.
- Maintain and calibrate equipment according to protocols and manufacturers' directions.
- Communicate progress and accomplishments with the project manager during and after sampling at each park unit and report any deviations from sampling protocols.
- Download, enter, and verify data into databases as required.
- Maintain documentation of important details of each field data collection period, including explanations of all deviations from standard procedures.
- Maintain hard copies of data forms and send original data forms to archive on a regular basis.
- Represent the National Park Service and the network in a professional manner, and assist in maintaining positive communication among the network, park staff, and the public.

5.1.4 Data Manager

The data management aspect of the monitoring effort is the shared responsibility of the data collectors first, then the project manager, and finally the network data manager. Typically, field personnel are responsible for data collection, data entry, data verification, and validation. The data manager is responsible for data archiving, data security, dissemination, and database design. The data manager, in collaboration with the project manager, also develops data entry forms and other database features (as part of quality assurance) and automates report generation.

5.2 Crew Qualifications

The crew leader must have a bachelor's or advanced degree in biology, chemistry, or other related physical or biological science. Field experience is mandatory and laboratory experience is preferred. Prior leadership experience and good decision-making skills are highly desirable, as is experience with boats, motors, and canoes.

Crew members should have a background in biology, chemistry, or other related physical or biological science, although an undergraduate degree is not required. Prior field experience, including that with boats, motors, and canoes, is highly desirable and laboratory experience is preferred.

All crew members must be physically fit, able to work long hours in inclement weather, and able to carry heavy loads. Sampling at some parks may involve camping for several days at a time and portaging between lakes.

5.3 Training Procedures

Prior to data collection, field personnel must become familiar with the use, calibration, and maintenance of all meters and probes planned for use in the monitoring project. A combination of classroom and field training will be required prior to each field season. Personnel who were previously trained for this monitoring project will participate in a review of all methods and techniques. Specific details of the training procedures are covered in SOP #2 and will include:

- Basic limnological concepts and field sampling techniques.
- Review of all SOPs for the project.

- Calibration, operation, and maintenance of all field and laboratory meters and probes used in the project.
- Methods for sample collection.
- Methods for cleaning equipment.
- Methods for handling and preserving samples.
- Completion of field data forms, sample labels, chain of custody forms, analytical service request forms.
- Data entry procedures.
- Completion of field and calibration logbooks.
- Use of GPS equipment.
- Park-specific training requirements (e.g., boat operation, navigation, radios).
- NPS-specific training (e.g., computer use, credit card, travel).

6.0 Operational Requirements

6.1 Annual Workload and Field Schedule

The annual workload and schedule for the monitoring of water quality in inland lakes must be viewed within the context of the other planned water quality monitoring activities. We prepared the estimated workload and schedule for monitoring of inland lakes and large rivers together, but we anticipate additional related protocols in the future (e.g., wadeable streams). As these additional protocols become part of the GLKN monitoring program, the workloads are likely to change.

Parks with inland lakes are APIS, INDU, ISRO, PIRO, SLBE, and VOYA. We will monitor water quality at each selected index lake three times during the open water season (May to October). We likely will deploy and maintain thermal arrays in one or more inland lakes at ISRO, PIRO, SLBE, and VOYA, which typically requires at least two additional days in the field above and beyond the usual three monitoring days per lake each season. The time it takes to conduct field work is always weather dependent, and this is especially true at parks where travel on Lake Superior or Lake Michigan is required (SLBE, ISRO, and APIS). Sampling can be delayed and field crews can be stranded for days when wind and waves prohibit boat travel. We estimate sampling to take from one day at INDU, to as much as 10 or more days at VOYA and ISRO, including travel time. Initial estimates of time required to sample at each park (explained in more detail, below, under staff salaries) assume minimal weather-related delays.

6.2 Facility and Equipment Needs

At each park, the field crew will need a facility with a sink and counter-top space where they can calibrate instruments, clean and store equipment, and process samples. They will also need a refrigerator and freezer for storing samples prior to shipment to an analytical laboratory, and secure space for storing a boat, motor and gasoline, canoe, and other field equipment. Availability of needed space varies across park units, but all park units with inland lake resources can meet the basic necessities with the exception of APIS, which does not have laboratory space. The network office is located near APIS, however, and can provide the needed laboratory space.

6.3 Budget Considerations

6.3.1 Equipment and Supplies

Costs associated with purchase of equipment and supplies related to fieldwork and laboratory activities are now associated with replacing equipment as it wears out or becomes obsolete, or when supplies need to be replenished. Some of the parks already had some of the necessary sampling gear and equipment when this protocol was first implemented and continue to replace gear and equipment as necessary. When possible, we will coordinate with the parks in the use of their equipment. Sampling at APIS, ISRO, and the islands of SLBE requires large boats for travel on the Great Lakes. The network owns two boats, with motors, trailers, and other necessary equipment, appropriate for use on Lake Superior at APIS and ISRO. SLBE owns boats appropriate for traveling to North and South Manitou islands and will provide transportation for water quality field crews as necessary. The network and VOYA jointly own a boat, motor, and trailer to be shared by park and network staff at that park. Boats or canoes appropriate for inland lakes are available to the network at all the parks,

though network-owned crafts may be required in the future. The network purchases supplies related to monitoring under this protocol, and for some parks provides funds to help cover fuel costs and boat operator salaries when parks assist in transporting network staff. Annual expenses related to equipment, supplies, and fuel expenses typically range from $10,000 to $15,000.

6.3.2 Staff Salaries

From 2011 to 2014 annual salary expenses related to inland lake water quality monitoring at six network parks ranged between $190,000 and $215,000, taking into account the following:

- annual salaries for the network project manager and assistant project manager,
- six-to-eight pay periods for a network seasonal crew member duty stationed at ISRO,
- six-to-ten pay periods for a VOYA permanent crew leader shared with the network, and
- Various salary expenses for park staff at four parks who conduct inland lake monitoring work for the network.

The project manager's annual salary is divided between the I&M Division and WRD, with the majority of salary typically assigned to WRD. The network data manager's salary is covered entirely by the I&M Division and is not reflected in the annual salary expenses above. The salary estimates include staff time for project management, training, pre-season preparation, sampling, processing samples, packing and shipping samples, data entry, analysis, reporting, and other various tasks associated with the monitoring effort.

6.3.3 Vehicles and Travel

We expect travel expenses to be approximately $7,500 annually. This estimate includes GSA vehicles and travel (lodging and per diem), and is based on the following assumptions:

1) GSA vehicles will be shared with other monitoring projects or parks, when possible.
2) Park housing will be available at ISRO, VOYA, SLBE, and PIRO.
3) The program manager will travel to network parks on a rotational basis to assist with monitoring activities and provide oversight on water quality monitoring activities for the network
4) Park staff that serve as crew leaders will work with the project manager and assistant project managers and will occasionally travel to other parks as needed.

6.3.4 Analytical Laboratory Costs

Monitoring guidelines established by WRD include strong recommendations for selecting an analytical laboratory that has been accredited by the federal National Environmental Laboratory Accreditation Program (NELAP). The network will assess the differences in detection and reporting limits among NELAP-approved, state accredited, and research laboratories, along with other criteria, prior to selecting a contract laboratory. The laboratory selected by GLKN must be able to detect and report concentrations appropriately low such that changes in water quality variables can be detected early in the naturally dilute waters occurring throughout the network. The laboratory selected must meet the detection limits outlined in SOP #12 and have a rigorous QA/QC plan.

For the purpose of estimating a budget for monitoring water quality of inland lakes, we use the costs quoted by CT Laboratories and the St. Croix Watershed Research Station, which are the two analytical laboratories that currently process network water samples (Table 15). The estimates from the other laboratories are included as examples of what our costs might be if we selected one of them instead.

Table 15. Estimates of laboratory costs for analysis of water quality parameters.

Parameter	CT Laboratories	Natural Resources Research Institute	St. Croix Watershed Research Station	Central Michigan University
Alkalinity	**$10** [a]	$12	$4	$6
DOC	**$18** [a]	$18	$15	–
Cl	**$8** [a]	$23 (Cl w/ SO_4)	$10	$5
SO_4	**$8** [a]	$23 (Cl w/ SO_4)	$10	$7
Na, K, Mg, Ca	**$32** [a]	$23	NA	–
TP	$18	$28 (dual TP and TN)	**$32** (dual TP and TN) [a]	$7
TN	$18 (as TKN)	$28 (dual TP and TN)	**$32** (dual TP and TN) [a]	–
NH_4-N	$12	$11	**$32** (dual w/ NO_3/NO_2-N) [a]	$1
NO_3+NO_2-N	$12	$12	**$32** (dual w/ NO_3/NO_2-N) [a]	$10.50
Chlorophyll-*a*	$27	$34	**$16** [a]	$13
SiO_2	**$9** [a]	–	$10	–

[a] Cost reflects per sample prices for 2015, also shown in bold font.

We expect to measure nutrients (TP, TN, NO_3+NO_2-N, NH_4-N) and chlorophyll-*a* each sampling visit, or three times per survey-year, one near-bottom TP sample per year, and the remaining parameters once per survey-year. Annual estimated laboratory analysis costs associated with inland lake monitoring (samples, duplicates, and equipment blanks) are typically about $15,000 but may be higher if funding is available and additional lakes are monitored.

6.3.5 Total Estimated Annual Costs

Annual monitoring costs (Table 16) at the six parks with inland lake resources are high—more than the network receives from WRD (approx. $150,000). Monitoring water quality of large rivers (Magdalene et al. 2008), diatoms (Ramstack et al. 2008), and wadeable streams (protocol in preparation) are not included in these estimates, putting the total cost of monitoring water quality well beyond the funding WRD provides. Because of the importance of water quality to GLKN parks, the network is contributing substantial I&M funds to implement these water quality monitoring protocols.

Table 16. Total estimated annual costs for monitoring water quality at GLKN inland lakes.

Item	Cost
Annual equipment and supplies	$10,000–$15,000
Salary and benefits	$190,000–$215,000
Travel	$7,500
Laboratory analyses	$15,000
Total	**$222,500–$252,500**

6.4 Procedures for Revising and Archiving Previous Versions of the Protocol

As our water quality monitoring program matures, revisions to both the protocol narrative and specific standard operating procedures (SOPs) are likely. Documenting changes and archiving copies of previous versions of the protocol and SOPs are essential for maintaining consistency in the collection of data and for appropriate interpretation of the data summaries and analyses. The NPSTORET database contains a field for each monitoring component that identifies which version of the protocol was being used when the data were collected.

The rationale for dividing a sampling protocol into a protocol narrative with supporting SOPs is based on the following:

- The protocol narrative is a general overview of the protocol that gives the history and justification for doing the work and an overview of the sampling methods but does not provide all methodological details. The protocol narrative will only be revised if major changes are made to the protocol.
- The SOPs are specific step-by-step instructions for performing a given task. They are expected to be revised more frequently than the protocol narrative.
- Usually, when a SOP is revised, it is not necessary to revise the protocol narrative to reflect the specific changes made to the SOP.

All versions of the protocol narrative and SOPs will be archived.

The steps for changing the protocol (either the protocol narrative or the SOPs) are outlined in Procedures for Revising the Protocol, SOP #13. Each SOP contains a Revision History Log that must be updated each time a SOP is revised, to explain why the change was made and to assign a new version number to the revised SOP. The new version of the SOP or protocol narrative should then be archived in the appropriate folder of the GLKN database structure.

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The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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