JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 51, No. 1 AMERICAN WATER RESOURCES ASSOCIATION February 2015

TROPHIC STATE IN VOYAGEURS NATIONAL PARK LAKES BEFORE AND AFTER IMPLEMENTATION OF A REVISED WATER-LEVEL MANAGEMENT PLAN[1]

Victoria G. Christensen and Ryan P. Maki[2]

ABSTRACT: We compiled Secchi depth, total phosphorus, and chlorophyll *a* (Chl*a*) data from Voyageurs National Park lakes and compared datasets before and after a new water-level management plan was implemented in January 2000. Average Secchi depth transparency improved (from 1.9 to 2.1 m, $p = 0.020$) between 1977-1999 and 2000-2011 in Kabetogama Lake for August samples only and remained unchanged in Rainy, Namakan, and Sand Point Lakes, and Black Bay in Rainy Lake. Average open-water season Chl*a* concentration decreased in Black Bay (from an average of 13 to 6.0 μg/l, $p = 0.001$) and Kabetogama Lake (from 9.9 to 6.2 μg/l, $p = 0.006$) between 1977-1999 and 2000-2011. Trophic state index decreased significantly in Black Bay from 59 to 51 ($p = 0.006$) and in Kabetogama Lake from 57 to 50 ($p = 0.006$) between 1977-1999 and 2000-2011. Trophic state indices based on Chl*a* indicated that after 2000, Sand Point, Namakan, and Rainy Lakes remained oligotrophic, whereas eutrophication has decreased in Kabetogama Lake and Black Bay. Although nutrient inputs from inflows and internal sources are still sufficient to produce annual cyanobacterial blooms and may inhibit designated water uses, trophic state has decreased for Kabetogama Lake and Black Bay and there has been no decline in lake ecosystem health since the implementation of the revised water-level management plan.

(KEY TERMS: eutrophication; chlorophyll; phosphorus; trophic state index; Voyageurs National Park; water-level fluctuations.)

Christensen, Victoria G. and Ryan P. Maki, 2015. Trophic State in Voyageurs National Park Lakes before and after Implementation of a Revised Water-Level Management Plan. *Journal of the American Water Resources Association* (JAWRA) 51(1): 99-111. DOI: 10.1111/jawr.12234

INTRODUCTION

The implementation of a water-level management plan can alter the magnitude and timing of water-level fluctuations. Water-level fluctuations can affect phosphorus accumulation rates (Hambright *et al.*, 2004), water clarity (Hoyer *et al.*, 2005), and alter biological communities (Benson, 1973; Baxter, 1977; Kimmel and Groeger, 1986; Prosser, 1986; Paillisson and Marion, 2011). Water-level fluctuation also may be an important factor contributing to accelerated eutrophication (Hambright *et al.*, 2004) and thus may affect a lake's trophic state.

United States federal requirements for fishable and swimmable waters have resulted in numerous efforts to classify a lake's trophic state (e.g., Carlson and Simpson, 1996). Trophic State Indices (TSI) were originally developed by Carlson (1977) and were computed from measurements of Secchi depth or concen-

[1]Paper No. JAWRA-13-0232-P of the *Journal of the American Water Resources Association* (JAWRA). Received October 25, 2013; accepted May 29, 2014. **Discussions are open until six months from print publication**.

[2]Hydrologist (Christensen), U.S. Geological Survey, 2280 Woodale Drive, Mounds View, Minnesota 55112; Aquatic Ecologist (Maki), National Park Service, Grand Rapids, Minnesota 55744 (E-Mail/Christensen: vglenn@usgs.gov).

trations of total phosphorus (TP) or chlorophyll *a* (Chl*a*). The significance of the TSI is that it is a simple numeric index that can be related to the traditional typological scheme of Naumann (1919), which classifies water bodies as oligotrophic, mesotrophic, and eutrophic. Increases in eutrophication result in increased trophic state, which typically is considered less desirable than lower trophic state. However, TSI does not indicate whether a lake system's change in trophic state is natural or anthropogenic.

Changes in TSI have been attributed to fluctuations in water levels in individual lotic systems (Li *et al.*, 2012) and lake systems (Leira and Cantonati, 2008), and water levels can affect all components of an ecosystem (Kallemeyn *et al.*, 1993). Water-level fluctuations are natural patterns that ensure biodiversity and productivity (Gafny and Gasith, 1999), and although extreme events and conditions can have deleterious effects (Bond *et al.*, 2008; Wanzen *et al.*, 2008), decreases in water-level fluctuation have been a focal point for research in the lakes and reservoirs of Voyageurs National Park (Figure 1). In these lakes, the regulation of water levels has removed much of the hydrologic variability the lakes would experience under natural conditions (Kallemeyn *et al.*, 1993). Effects on fish communities (Sharp, 1941; Johnson *et al.*, 1966; Chevalier, 1977; Osborn *et al.*, 1981) and littoral zone biota (Cole, 1979, 1982) are particular concerns in Voyageurs National Park.

Voyageurs National Park is on the border between the United States and Canada, is approximately 50% water covered, and visitor activities are almost exclusively water based. Rainy Lake and Namakan Reservoir were natural lakes before they were dammed in the early 1900s (Kallemeyn *et al.*, 2003). Namakan Reservoir consists of five large lakes (Namakan, Kabetogama, Sand Point, Crane, and Little Vermilion). Because Rainy Lake and Namakan Reservoir are shared by the United States and Canada, they are governed by the International Joint Commission (IJC), which establishes rules on dam operation.

Before the IJC implemented the first water-level management plan in 1949 (Kallemeyn *et al.*, 2003), the lake levels were controlled by the private sector for multiple uses with a hydroelectric dam at the outlet of Rainy Lake and by dams at Namakan Reservoir's main outlets. Prior to 1949, annual fluctuation was greater on Rainy Lake and Namakan Reservoir, but Namakan in particular, where water-level fluctuations were considered extreme compared to the more natural conditions on the nearby unregulated Lac la Croix (Meeker and Harris, 2009). The 1949 order was updated in 1957 and again in 1970. The 1970 order allowed larger-than-natural fluctuations on Namakan Reservoir to maintain less-than-natural fluctuations on Rainy Lake (Kallemeyn *et al.*, 2003). The 1970 water-level management plan was later determined to be detrimental to the ecosystem. Fluctuating water levels negatively affected macrophyte communities (Wilcox and Meeker, 1991), benthic organisms (Kraft, 1988), beaver (Smith and Peterson, 1991), muskrats (Thurber *et al.*, 1991), otter (Route and Peterson, 1988), aquatic birds (Reiser, 1988), and fish (Kallemeyn *et al.*, 1993). One particularly damaging aspect of the 1970 water-level management plan was the winter drawdown for Namakan Reservoir that affected aquatic vegetation and benthic macroinvertebrates through desiccation and ice scraping along the lake bed during and after the drawdown (Kraft, 1988; Wilcox and Meeker, 1991).

Kallemeyn *et al.* (1993) proposed a water-level management plan that more closely approximated the magnitude and timing of natural fluctuations in lake levels with which the plant and animal species of the system evolved. The National Park Service (NPS) developed 13 alternative management plans (Kallemeyn and Cole, 1990). The alternatives were analyzed with a hydrologic model (Flug, 1986) to determine if each alternative was sufficient for hydropower production at the Rainy Lake dam and feasible under extreme high-flow and low-flow conditions.

As a compromise between competing needs of environmental and economic interests and in an effort to improve the water quality and the overall health of the ecosystem, the IJC implemented an order in January 2000 to change the water-level management plan for the private sector dams that regulate Rainy Lake and Namakan Reservoir. New water levels (Figure 2) or rule curves (maximum and minimum allowable water levels) were intended to restore a more natural water regime and improve water quality and trophic state. The new water-level management plan was expected to reduce the amount of shoreline area that was dried and rewetted each year based on a 1-m reduction in annual water-level fluctuation for Namakan Reservoir. In addition, maintaining a higher volume of water in Namakan Reservoir would cause a dilution effect. No substantial change was expected for Rainy Lake, as the change to the 2000 Rainy Lake rule curves was minimal when compared to Namakan Reservoir. Early evidence pointed to lower Chl*a* concentrations and trophic state of the Park's lakes after implementation of the 2000 water-level management plan (Christensen *et al.*, 2004); however, aquatic systems likely take longer periods of time to fully adapt to changes in hydrologic regime than available in the Christensen *et al.* (2004) dataset. In 2015 or soon after, the IJC will initiate a review during which they will decide whether to change the current rules governing dam operation based, in part, on whether the rules are benefiting the ecosystem of these water bodies (L. Kallemeyn, W.R. Darby, E. Eaton, K. Peter-

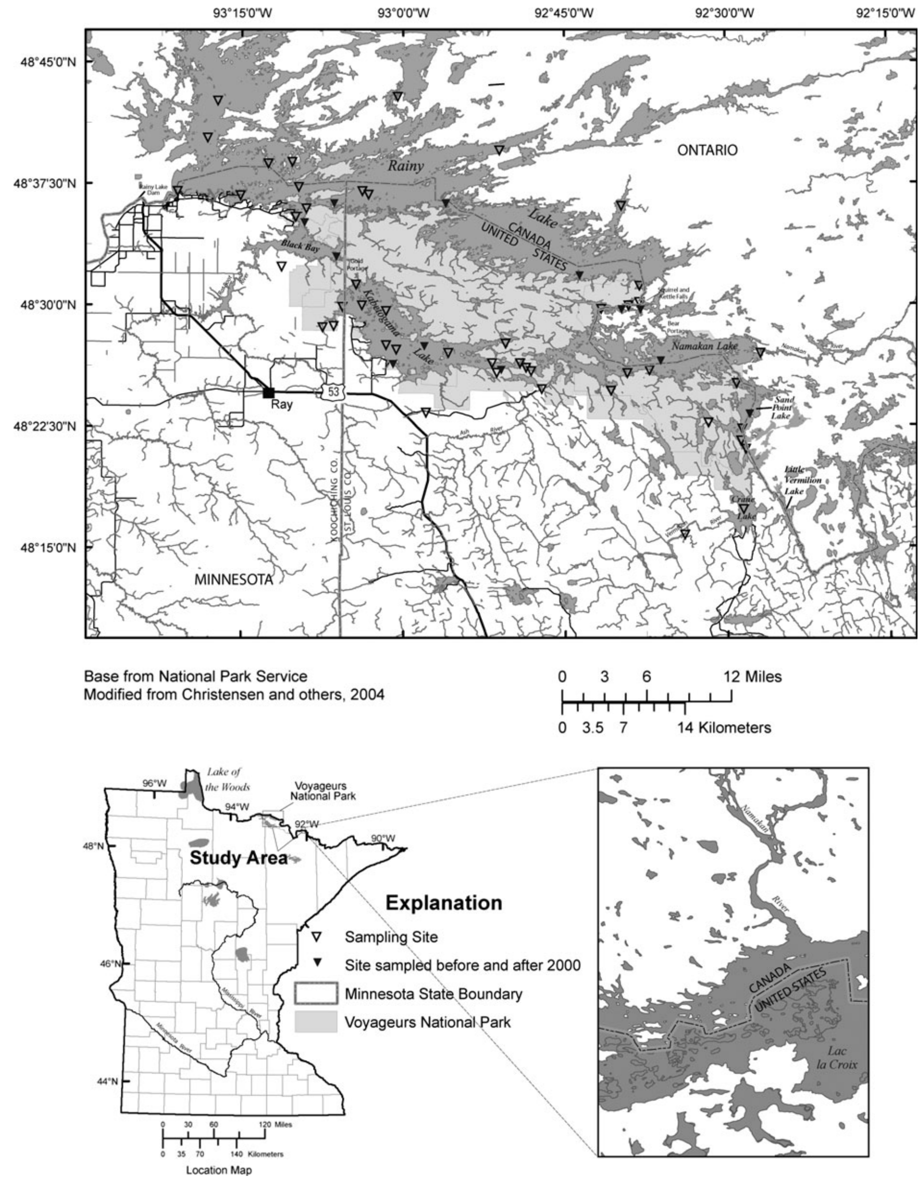

FIGURE 1. Map Showing Lakes and Sampling Sites in Voyageurs National Park.

son, K. Smokorowski, and J. Van den Broeck, "Plan of Study for the Evaluation of the IJC 2000 Order for Rainy and Namakan Lakes and Rainy River," unpublished report for the International Joint Commission by the 2000 Rule Curve Assessment Workgroup, 2009). Therefore, it was critical to assess Secchi depth, TP, Chl*a*, and trophic state conditions now that an extended period of time (14 years) had passed since the implementation of the 2000 water-level management plan.

To assess the 2000 water-level management plan and prepare for adaptive management, the U.S. Geological Survey (USGS) and the NPS evaluated changes in the trophic state of Voyageurs National Park's (also called "the Park") large lakes. The specific objective of this study was to assess and interpret changes in trophic state for Rainy, Kabetogama, Namakan, and Sand Point Lakes before and after implementation of the 2000 water-level management plan. The novelty of this study is that it provides insight into the relation between water-level management and long-term records of trophic state conditions.

Study Area

Voyageurs National Park (Figure 1) was established in 1975 "to preserve, for the inspiration and enjoyment of present and future generations, the outstanding

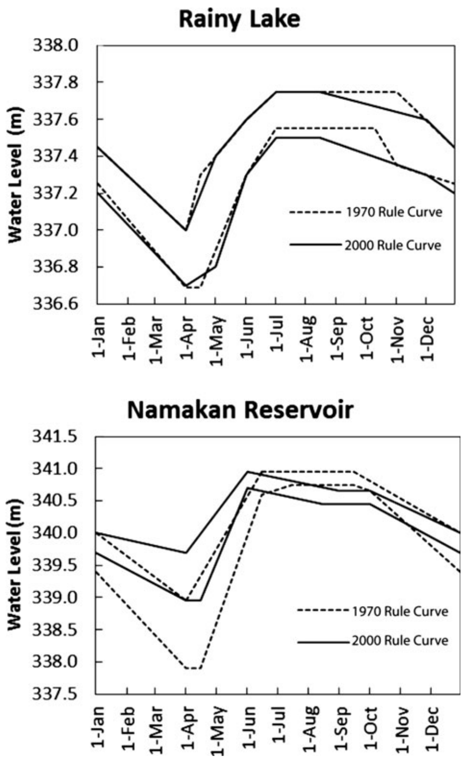

FIGURE 2. Rule Curves for Water-Level Management for Rainy Lake and Namakan Reservoir. The 1970 and 2000 curves show maximum and minimum water levels that are allowed throughout the year. Water levels are in meters above the datum of the U.S. Coast and Geodetic Survey of 1912.

scenery, geological conditions, and waterway system which constituted a part of the historic route of the voyageurs" (public law 97-405). Visitor use in the Park includes boating along scenic waterways, fishing, and swimming. Aquatic systems support much of the Park's major fauna, including fish, waterfowl, loons, eagles, beavers, and moose. With two large reservoirs and 26 smaller interior lakes, water quality is an essential element of the Park environment with respect to both the health of its ecosystem and visitor enjoyment.

Rainy Lake (including Black Bay) and Namakan Reservoir (consisting of Kabetogama, Namakan, Sand Point, Little Vermilion, and Crane Lakes) are natural lakes that are hydrologically connected (Figure 1). The hydrology of the system is complex, but water generally flows in a northwesterly direction. Major inputs to the system include the Namakan River, which flows into Namakan Lake; the Vermilion River, which flows into Crane Lake; and the Ash River, which flows into Kabetogama Lake. The Rat Root River also contributes to the system, flowing into Black Bay, a eutrophic bay that is considered a separate water body for the analyses in this report. Black Bay is largely enclosed (Figure 1) and, in terms of water quality, is a statistical outlier (Maki *et al.*, 2005) when compared to other parts of Rainy Lake.

Water flows out of the Namakan Reservoir into Rainy Lake at three locations — (1) through the dams at Squirrel Narrows and Kettle Falls at the northwest end of Namakan Lake, (2) at Bear Portage on the north-central side of Namakan Lake, and (3) at Gold Portage at the west end of Kabetogama Lake. The flows are regulated at Squirrel Narrows and Kettle Falls, and unregulated overflows occur at Bear Portage and Gold Portage (Figure 1). Gold Portage connects Kabetogama Lake with Black Bay in Rainy Lake and can be the equivalent of approximately 60% of the lower rule curve limit during the summer months (International Rainy Lake Board of Control, 1999). Bear Portage is considered a minor outflow, accounting for about 1% of the outflow from Namakan Reservoir during 1988-1999 (Kallemeyn *et al.*, 2003).

Most of Voyageurs National Park is underlain by Archaen continental crust composed of greenstone, gneissic, magmatic, granitic, meta-sedimentary, and schistose bedrock that is resistant to erosion (Ojakangas and Matsch, 1982). The Rainy Lake watershed is part of the Canadian Shield, which is exposed throughout northern Minnesota (Kallemeyn *et al.*, 2003). Coarse to fine textured forest soils, lacustrine clays, and other organic material occur in depressions in the surrounding bedrock. These lowland marshy areas contribute to the tea color and low alkalinity of the Park's lakes (Kallemeyn *et al.*, 2003). Rainy Lake, Namakan Lake, and Sand Point Lake receive most of their inflows from areas of exposed bedrock (Payne, 1991; Kallemeyn *et al.*, 2003). The watershed of the Namakan River, which supplies most of the inflow to Namakan Lake, is characterized by thin deposits of Rainy lobe drift (Payne, 1991), which is sandy with little clay (Hobbs and Goebel, 1982). Kabetogama Lake and Black Bay receive inflow from an area that is overlain by calcareous glacial drift from the Des Moines lobe (Payne, 1991), which generally is clay rich and carbonate rich (Woodruff *et al.*, 2002). Crane Lake receives most of its inflow from the Vermilion River, which drains areas covered by both Des Moines lobe drift and Rainy lobe drift (Payne, 1991).

Rainy Lake covers 92,110 ha, whereas the five Namakan Reservoir lakes cover approximately 26,000 ha combined (Kallemeyn *et al.*, 2003). Of the Namakan Reservoir lakes, Kabetogama Lake and Little Vermilion Lake are the largest and smallest, respectively (Table 1). Depths vary with Sand Point Lake being the deepest lake (both maximum depth and average depth), Kabetogama Lake having the shallowest average depth (Kallemeyn *et al.*, 2003), and Little Vermilion having the shallowest maximum depth (Table 1; 16 m). Black Bay in Rainy Lake also is very shallow, with a maximum depth of only 5 m.

TABLE 1. Surface Area and Maximum Depth of Lakes Comprising Rainy and Namakan Reservoirs.

Lake	Surface Area (ha)	Maximum Depth (m)
Rainy (including Black Bay)	92,110[1]	46[2]
Black Bay	—	5[2]
Namakan Reservoir	26,000[1]	56[2]
Crane	1,182[2]	24[2]
Kabetogama	10,425[1]	24[1]
Little Vermilion	521[2]	16[2]
Namakan	9,739[2]	46[2]
Sand Point	3,580[1]	56[2]

Notes: ha, hectares; m, meters; —, no data.
[1]Kallemeyn *et al.* (2003).
[2]Minnesota Department of Natural Resources (2013a, b).

About 73% of the land in Rainy Lake watershed is publicly owned and managed by federal, state, or county entities (Natural Resources Conservation Service, 2012). The major land-cover types are forest, wetland, water, and shrub, accounting for 97.6% of the watershed (Natural Resources Conservation Service, 2012). Residential and commercial land-cover types account for 0.6% of the watershed. No major changes in land use within Park boundaries have occurred since 1975. Serieyssol *et al.* (2008) provided evidence that land-use change (e.g., logging activities) was the most significant stressor to Voyageurs National Park lakes, based on diatom assemblages in sediment cores. However, this effect was evident prior to 1975 and climate warming, not land use, was the prominent stressor in recent decades.

The climate near Voyageurs National Park is continental with moderately warm summers and long cold winters. The frost-free season ranges from 110 to 130 days (Kallemeyn *et al.*, 2003). Average snowfall is 172 cm, average temperature is 2.9°C, and average rainfall is 61 cm (Minnesota Climatology Working Group, 2010). Evaporation from lake surfaces averages 63.5 cm (International Rainy Lake Board of Control and International Lake of the Woods Control Board, 1984). The lakes generally are ice covered from mid-November to mid-April or May (Kallemeyn *et al.*, 2003).

The relatively shallow Kabetogama Lake and Black Bay in Rainy Lake have different water chemistry than Sand Point, Namakan, and Rainy Lakes (Kallemeyn *et al.*, 2003), and substantial water-quality differences occur between the bays, mid-lake, and shoreline areas of Lake Kabetogama (Christensen *et al.*, 2011). Kabetogama Lake and Black Bay have higher specific conductance, nutrient, and Chl*a* concentrations (Kallemeyn *et al.*, 2003) than the other large lakes in the Park.

METHODS

Secchi depth, TP, Chl*a*, site location, and sampling method data were compiled for 75 sites that have been part of a variety of research efforts on the Park's large lakes from 1977 through 2011. Most samples were collected by either NPS or USGS personnel. Additional samples were collected by other groups, such as Rainy River Community College and the Minnesota Pollution Control Agency. All samples were collected during the open-water season, from May to October, with only two exceptions, a March 1977 sample and a November 1978 sample from Rainy Lake. For most sites, samples were collected twice per month except in May and October, when ice or cold weather prevented sample collection. For Rainy Lake, Black Bay, and Kabetogama Lake, the period of 1977-1983 was an exception when only May and August samples were collected. For this reason, additional statistics were completed for May and August.

The quality assurance of the 75-site dataset was extensive and included checking for duplicate entries, verifying location, evaluating the comparability of laboratory methods, and conversion into common units. To attain a dataset that would be representative of trophic conditions, sites were eliminated (1) if exact latitude and longitude was not recorded, (2) if located near inflows or otherwise not representative of lake conditions, or (3) if samples were not collected both before and after 2000. Sufficient data from Crane or Little Vermilion Lakes, which lie outside Park boundaries, were not available prior to the water-level management plan change and did not allow for a meaningful statistical comparison of Secchi depth, TP, or Chl*a*. Black Bay, a statistical outlier for water-quality among the areas of Rainy Lake (Maki *et al.*, 2005), is assessed separately in order not to confound the assessment of the remainder of Rainy Lake. The resulting dataset included 12 sites from five water bodies (Table 2; Figure 1).

All samples were collected from the euphotic zone. Light penetration (Secchi depth) was measured at each site with a Secchi disk (U.S. Environmental Protection Agency, 2014). Water samples were collected with a Van Dorn sampler (for TP analysis) or a 500-ml to 1-l polyethylene sample container (for Chl*a* analysis). Samples were stored on ice and transported to a field laboratory for filtration or preservation within recommended holding times. TP was analyzed by colorimetry (U.S. Environmental Protection Agency, 1993) or persulfate digestion (American Public Health Association, 1999). Chl*a* was analyzed by fluorometry (Arar and Collins, 1997) or spectrophotometry (Ameel *et al.*, 1998).

TABLE 2. Lakes Sites Used for the Computation of Trophic State, Voyageurs National Park.

Lake	Location	Site Indicator Used in Previous Reports	Decimal Latitude	Decimal Longitude
Sand Point	S of Burnt Is	Site 7	48.38801	–92.46548
Namakan	Squirrel Narrows	NSN	48.49609	–92.66183
Namakan	E of Blackstone Is	Site 14	48.44319	–92.6062
Namakan	Mouth Namakan R	Site 20	48.4525	–92.44611
Kabetogama	N of Meadwood Bay	Site 11, Meadwood#2, K2	48.43528	–92.85472
Kabetogama	Mid-lake	Site 17, KS_KA	48.45574	–93.011
Kabetogama	At Gappas Landing	Site 8	48.44167	–93.02139
Rainy	Brule Narrows	Site 5	48.60535	–92.93179
Rainy	Dryweed Is	DWI[1]	48.61576	–93.11209
Rainy	Minitaki Is	MTI[1]	48.53129	–92.73487
Black Bay	Near RLVC	Payne2, BB Site 1	48.58639	–93.15778
Black Bay	E end Black Bay	Site 16	48.55111	–93.1075

Notes: S, south; N, north; E, east; Is, island; R, river; RLVC, Rainy Lake Visitor's Center.
[1]Latitude and longitude were estimated based on detailed site descriptions.

Previous investigations (Christensen *et al.*, 2004, 2013) established justification for combining the results from the different analytical methods. Secchi depth, TP, and Chl*a* data collected by the USGS or as part of USGS/NPS partnerships are available electronically (U.S. Geological Survey, National Water Information System. Accessed 2012, http://waterdata.usgs.gov/nwis). Data collected by Rainy River Community College, the Minnesota Pollution Control Agency, and other agencies are available on file at the Voyageurs National Park Headquarters, International Falls, Minnesota.

Trophic state index was determined following techniques established by Carlson (1977) on the basis of Chl*a*. Chlorophyll *a* is the most appropriate indicator of trophic state in these lakes (Payne, 1991) because (1) data from Voyageurs National Park did not match Carlson's (1977) regression that relates Chl*a* to TP and (2) soluble organic substances that color some of the Park's water bodies affect the indices computed from Secchi-disk transparency. However, Secchi depth and TP comprised longer records for statistical analysis and thus are reported. Carlson's TSI equation has been simplified (Payne, 1991) and the form used in this article was as follows:

$$\mathrm{TSI(Chl}a) = [9.81 \times \ln(\mathrm{Chl}a)] + 30.6$$

where TSI(Chl*a*) is the trophic state index based on chlorophyll-*a* concentrations in micrograms per liter (μg/l).

Sites within lakes were combined for the analysis of Secchi depth, TP, and Chl*a* changes. The practice of combining lake sites has been a common approach for researchers (Welch *et al.*, 1992; Burns *et al.*, 1997; Wei *et al.*, 2000; Kagalou *et al.*, 2003; Raateoja *et al.*, 2005; Duan *et al.*, 2007; Xu *et al.*, 2010), although trophic state also has been based on a single site (Bachmann *et al.*, 2002; Gotdyn *et al.*, 2003; Noges *et al.*, 2003; Yang *et al.*, 2012). Combining sites allowed for increased temporal coverage of the data; in other words, the data for each water body included more than one site and more samples collected throughout the study period, which increased the period of record (Table 3, column 1).

Wilcox rank sum tests and one-sided seasonal tests (Helsel and Hirsch, 1992) were used to test for differences in Secchi depth, TP, Chl*a*, trophic state, and ice-out dates before and after implementation of the 2000 water-level management plan. The non-normally distributed data, and in some cases small sample sizes (e.g., 9 Chl*a* samples at Black Bay; Table 3), justified the use of nonparametric tests (Helsel and Hirsch, 1992). One-sided tests were justified due to the hypothesis that TSI would decrease, TP would decrease, and Secchi depth would increase after the implementation of the 2000 water-level management plan. A two-sided test was used to evaluate ice-out dates. All statistical tests used a significance value of 0.05.

RESULTS AND DISCUSSION

Open-water season Secchi depth and TP differences between 1977-1999 and 2000-2011 were not significant ($p > 0.05$) for Sand Point, Namakan, Kabetogama, Rainy Lake, or Black Bay (Table 3). Chl*a* decreased after implementation of the 2000 water-level management plan in Black Bay (from an average of 13 to 6.0 μg/l; $p = 0.001$) and Kabetogama Lake (from an average of 9.9 to 6.2 μg/l, $p = 0.006$). Chlorophyll *a* was similar before and after implementation of the 2000 management plan for Namakan and Rainy Lakes; data were not available to evaluate Chl*a* for Sand Point Lake (Table 3).

TABLE 3. Open-Water Season Descriptive Statistics for Secchi Depth, Total Phosphorus, and Chlorophyll *a* in Voyageurs National Park Lakes.

	Secchi Depth		Total Phosphorus		Chlorophyll *a*	
Lake (Years of Sample Collection)	**1977-1999**	**2000-2011**	**1977-1999**	**2000-2011**	**1977-1999**	**2000-2011**
Black Bay (1977-1983, 1996-1997, 2001-2011)						
Average (*n*)	1.0 (33)	0.9 (151)	0.042 (15)	0.043 (103)	**13 (9)**	**6 (96)**
Range	0.3-1.8	0.2-1.8	0.020-0.071	0.019-0.104	**5.6-26**	**0.8-27.2**
Standard deviation	0.34	0.3	0.02	0.02	**7.57**	**5.13**
Kabetogama (1977-1999, 2000-2011)						
Average (*n*)	2.3 (202)	2.4 (177)	0.025 (43)	0.03 (131)	**9.9 (21)**	**6.2 (117)**
Range	1.1-4.5	1.1-4.8	0.005-0.066	0.010-0.150	**1.2-26.4**	**0.08-67.3**
Standard deviation	0.57	0.62	0.01	0.02	**6.64**	**8.13**
Namakan (1978-1999, 2000-2011)						
Average (*n*)	2.8 (236)	2.9 (138)	0.015 (31)	0.012 (80)	2.5 (12)	2.1 (48)
Range	1.5-4.9	1.5-5.0	0.00-0.040	0.003-0.029	0-5.60	0.5-9.6
Standard deviation	0.62	0.66	0.01	0	1.89	1.38
Rainy (1977-1983, 1996-1999, 2001-2011)						
Average (*n*)	2.8 (96)	2.6 (204)	0.010 (15)	0.012 (64)	2.3 (10)	2 (58)
Range	1.8-4.8	1.0-4.6	0.005-0.020	0.007-0.038	0-4.9	0.2-4.5
Standard deviation	0.55	0.51	0	0	1.46	1.07
Sand Point (1984-1999, 2000-2011)						
Average (*n*)	2.3 (166)	2.3 (127)	— (0)	0.014 (34)	— (0)	3.18 (30)
Range	1.3-3.9	1.3-4.6	—	0.009-0.024	1.3-11.2	—
Standard deviation	0.52	0.61	—	0	1.9	—

Notes: Bold type indicates values that are statistically different before and after 2000, at a *p*-value of 0.05; —, no data.

Three previous studies of the Park's large lakes included sampling in May and August (Payne, 1991; Christensen *et al.*, 2004, 2011). May sampling was intended to capture conditions as soon after ice-out as possible and before the onset of summer stratification periods. August sampling was intended to obtain samples at a time of maximal thermal stratification, maximum recreation use, and high algal productivity (Payne, 1991). In addition, assessing seasonal variability is important because Precambrian Shield lakes may have higher TP concentrations in the spring and fall and lower concentrations during the summer months (Clark *et al.*, 2010). Therefore, because most data compiled for this study were collected in May or August, comparisons of data covering the open-water season (Table 3) were followed by comparisons of data collected in May (Figure 3) and August (Figure 4).

Secchi depth transparency during August was greater after implementation of the 2000 water-level management plan for Kabetogama Lake (from an average of 1.9-2.1 m, $p = 0.020$). Differences in Secchi depth for the remaining lakes (May, August, Figures 3 and 4) were not significant ($p > 0.05$) before and after 2000. No TP changes in any of the lakes were significant for May or August samples. Chlorophyll *a* decreased significantly after implementation of the 2000 water-level management plan in Black Bay for May samples (from an average of 6.6 to 3.8 µg/l, $p = 0.028$) and August samples (from an average of 18.1 to 9.7 µg/l, $p = 0.006$) and for Kabetogama Lake in August (from an average 15.2 to 9.8 µg/l, $p = 0.006$). Changes in May and August Chl*a* for the remaining lakes (no pre-2000 data for Sand Point Lake) were not significantly ($p > 0.05$) different before and after implementation of the 2000 management plan.

The TSI(Chl*a*) values were calculated for August only for Namakan Lake, Kabetogama Lake, Rainy Lake, and Black Bay to limit the variability due to timing of sample collection. August TSI values were used partly because historical TSI values were available for August for comparison (Hargis, 1981; Kepner and Stottlemyer, 1988; Payne, 1991; Christensen *et al.*, 2004). The TSI(Chl*a*) values decreased significantly in Black Bay ($p = 0.006$) and Kabetogama Lake ($p = 0.006$) from 1977-1999 to 2000-2011 (Table 4). The TSI (Chl*a*) differences were not significant ($p > 0.05$) before and after implementation of the 2000 management plan for Namakan and Rainy Lakes. To place the TSI (Chl*a*) into context with previous research, comparisons were made of average August TSI(Chl*a*) with data from other studies (Table 4).

Using Carlson's index (Carlson, 1977), the Park's lakes can be assigned one of the four traditional lake types (Table 5). The TSI(Chl*a*) values in 2000-2011 indicate that Sand Point, Namakan, and Rainy Lake are oligotrophic; Kabetogama Lake is mesotrophic to eutrophic; and Black Bay is eutrophic. This is an improvement over conditions during 1977-1999 in which Kabetogama Lake and Black Bay had higher TSI(Chl*a*) values that put them solidly in the eutrophic category.

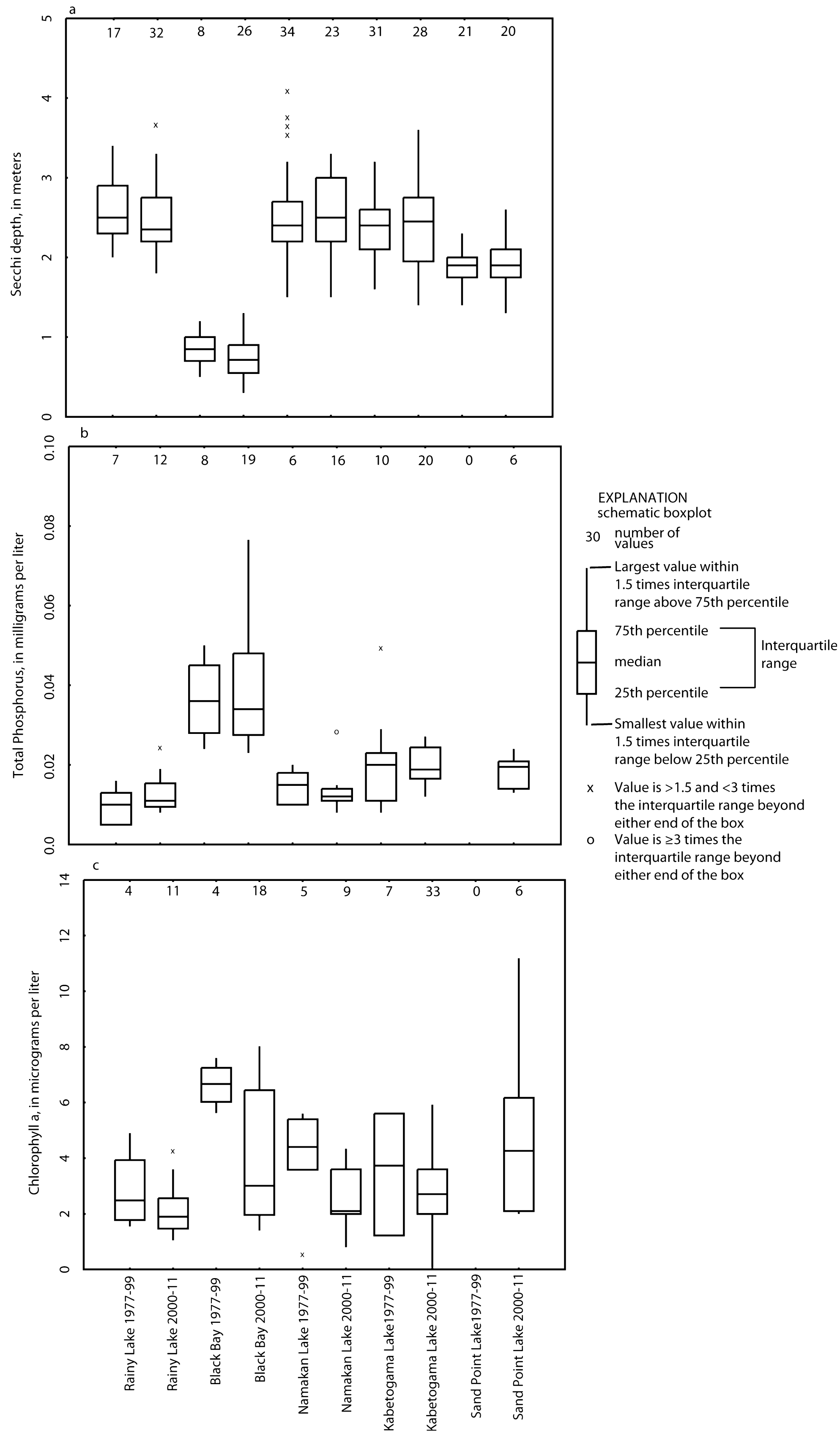

FIGURE 3. Secchi Depth, TP, and Chl*a* Results from Samples Collected during May, 1977-2011.

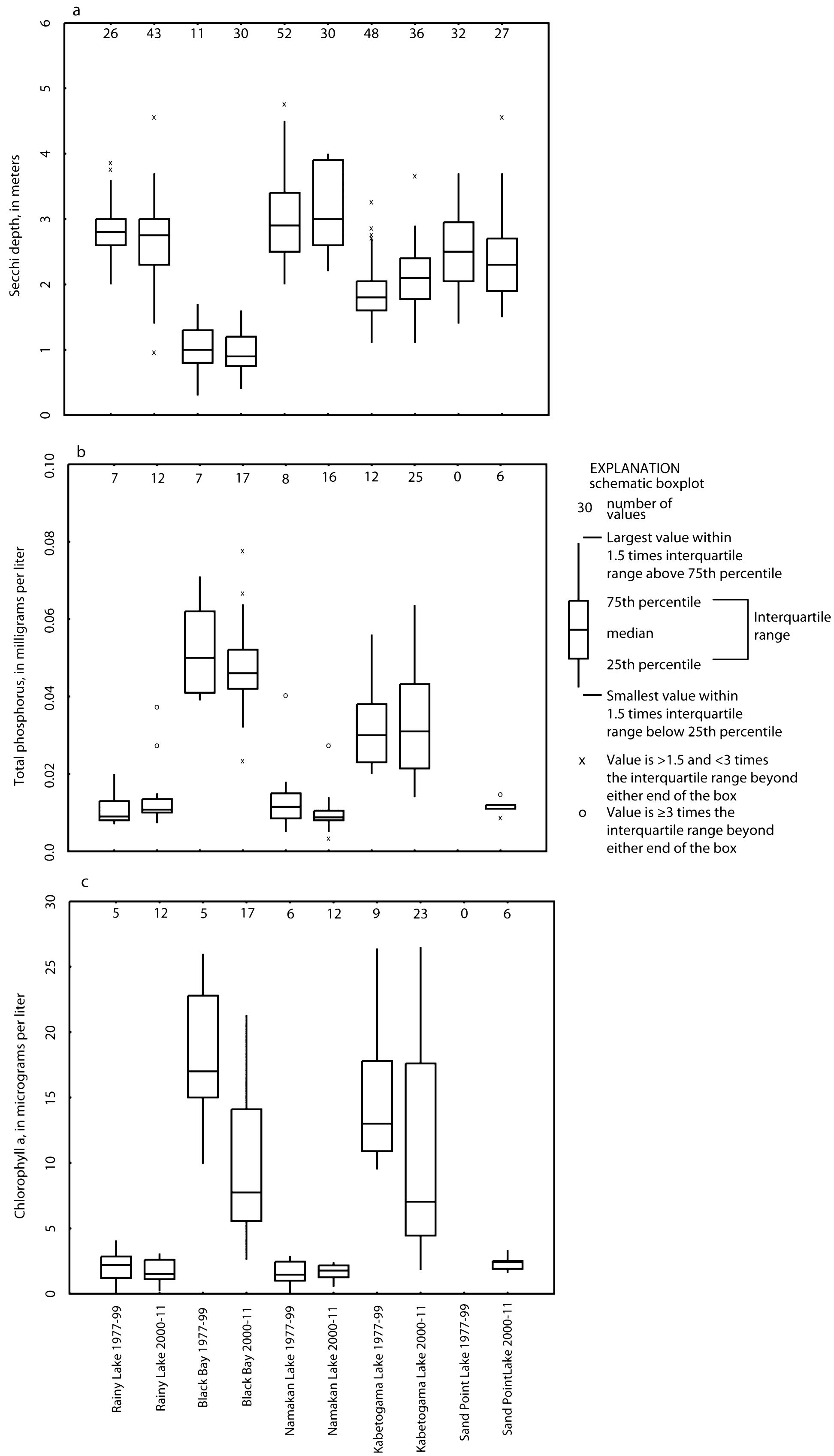

FIGURE 4. Secchi Depth, TP, and Chl*a* Results from Samples Collected during August, 1977-2011.

TABLE 4. Average August Trophic State Index Values Based on Chlorophyll-*a* Analyses in Voyageurs National Park Lakes.

Water Body	1979 Hargis (1981)	1979-1983 Payne (1991)	1985 Kepner and Stottlemyer (1988)	1986 Kepner and Stottlemyer (1988)	1977-1999 (current study)		2001-2003 Christensen *et al.* (2004)	2000-2011 (current study)
Sand Point	46	36	54	45	—		30	39 ± 2.5
Namakan	44	35	41	46	36 ± 4.6		32	35 ± 4.4
Rainy	53	39	43[1]	46[1]	39 ± 5.1	**2000 Rule Curve Change**	27	34 ± 7.6
Kabetogama	65	58	58	64	**57 ± 3.6**		53	**50 ± 7.4**
Black Bay	—	60	—	—	**59 ± 3.7**		48	**51 ± 6.3**

Notes: —, no data; bold indicates a statistically significant change at a p-value < 0.05; values for current study include the standard deviation.
[1]No distinction made between Rainy Lake and Black Bay.

TABLE 5. Carlson's Index of Trophic State.

Trophic Class[1]	TSI
Oligotrophic	<40
Mesotrophic	40-50
Eutrophic	50-70
Hypereutrophic	70+

Note: TSI, trophic state index.
[1]Carlson (1977).

Samples from previous episodic studies (Table 4) were collected at sites other than the longer term monitoring sites that provided most of the data compiled for this study, and Chl*a* concentrations can be quite variable throughout a large water body; therefore, some of the differences among studies (Table 4) may be influenced by spatial variability (Christensen *et al.*, 2004). The combination of shorter term studies (Table 4), however, provides a longer term dataset to reduce the likelihood of only evaluating data collected during extreme hydrologic events, as occurred with the conditions during the Christensen *et al.* (2004) study with excessive precipitation in 2001 and 2002 and drought conditions in 2003.

Additional evidence for pre-2000, as well as pre-settlement, TSI conditions is available from sediment core analyses on Kabetogama Lake (Kling, 2005) and Namakan Lake (Serieyssol *et al.*, 2008). A sediment core collected from Kabetogama Lake (Kling, 2005) confirms an increase in eutrophication through time. Sediment cores collected from Namakan Lake show evidence of anthropogenic effects, from logging to water-level manipulation (Serieyssol *et al.*, 2008). The evidence from those coring studies underscores the importance of the decreasing eutrophic conditions in Kabetogama Lake under the 2000 Rule Curves and may indicate that this decrease will help re-establish natural conditions in keeping with the NPS mission of maintaining resources in an unimpaired condition for current and future generations.

Extreme hydrologic events have affected water levels, which have exceeded the upper rule curves at times after 2000 (Christensen *et al.*, 2004, 2011). To determine if observed water-levels changed according to the prescribed rules, Christensen *et al.* (2011) demonstrated that observed water-level fluctuations during 1970-1999 were significantly greater (p = 0.001) than observed water-level fluctuations during 2000-2009 for the Namakan Reservoir system. This significant fluctuation decrease after the implementation of the 2000 water-level management plan occurred despite extreme hydrologic events.

In addition to hydrological factors, trophic conditions are affected by climate, morphometric (shape of the lake), and optical factors (Vollenweider, 1968). Climate conditions were assessed with ice-out dates. The nearby Great Lakes had a significant downward trend in ice coverage during 1973-2010 (Wang *et al.*, 2012). Ice-out dates for Kabetogama Lake (1952-2013) and Rainy Lake (1932-2013) were compiled to determine if changes in water quality of Voyageurs lakes could be due to changes in climate. Kabetogama Lake's average ice-out occurred on April 29 (±9.2 days) and Rainy Lake's average ice-out occurred on May 3 (±8.6 days). Although differences in ice-out dates on Kabetogama and Rainy Lakes between 1977-1999 and 2000-2011 were not statistically significant, the earliest ice-out dates occurred after 2000 in both lakes. However, because trophic state changed in some lakes but not others, climate change would be an unlikely explanation for changes in water quality after 2000 because the lakes are close together.

Lake morphometry and Secchi depth were important for assessing the potential effect of a new hydrologic regime on the trophic state of Voyageurs National Park lakes, because individual lakes with different depths and shapes may respond differently to the water-level changes. Kabetogama Lake is a shallow polymictic lake, and resuspension and internal cycling of nutrients are likely (Christensen *et al.*, 2011). Kabetogama Lake is threatened with eutrophication and yearly algal blooms (Kallemeyn *et al.*, 2003), which have been a concern to water managers due to high cyanotoxin levels (Christensen *et al.*, 2011). Despite the likely internal nutrient loading, August TSI(Chl*a*) decreased and August Secchi depth increased in Kabetogama Lake concurrently with the 2000 change in rules governing dam operation, representing a positive change in the lake's water quality. An increase in water clarity favors submerged macrophyte growth, as opposed to phytoplankton dominance (Scheffer, 2004), which is favorable for ecosystem health. The ecological significance of the increase in Secchi depth is that it may represent a decrease in phytoplankton density during the season when most blooms occur on Kabetogama Lake and Black Bay. The decrease in TSI(Chl*a*) for Black Bay may have been due to the change in the quality of the water flowing in from Kabetogama Lake at Gold Portage.

Rainy Lake also may respond differently to the 2000 water-level management plan than the other large lakes. Rainy Lake receives approximately 51% of its water volume from Namakan Reservoir (Kallemeyn *et al.*, 2003) and the other 49% from various tributaries, mainly on the north side of the lake. It was predicted that changes observed in Rainy Lake after 2000 would be minimal as compared to those in the Namakan Reservoir lakes because the bulk of the change in Rainy Lake is due to the changes in the inflow water it received from Namakan Reservoir and because the change in water-level fluctuation was not expected to be as great in Rainy Lake as Namakan Reservoir.

SUMMARY AND CONCLUSIONS

Few studies exist which compare water-level changes to TSI. This study not only provides the comparison of water-level changes to TSI, but also is a rare long-term record of water levels and TSI. Although nutrient inputs from inflows and internal sources promote cyanobacterial blooms and may inhibit designated water uses in Kabetogama Lake and Black Bay of Rainy Lake, the TSI in these water bodies decreased under the 2000 rules governing dam operation. Rainy and Namakan Lakes did not show significant differences in TSI, and data were not available for the remaining lakes. The major change that occurred concurrently with the 2000 change in rules governing dam operation is an improvement in the water quality of Kabetogama Lake and Black Bay. In 2015 or soon after, the IJC will decide whether to extend or change the current rules governing dam operation based, in part, on whether the rules are benefiting the ecosystem of these water bodies. By being well-informed, resource managers will be able to make recommendations to the IJC that will best protect the aquatic resources of Voyageurs National Park. The following conclusions are made:

After the implementation of the 2000 water-level management plan

1. Secchi depth increased (from 1.9 to 2.1 m, $p = 0.020$) in Kabetogama Lake for August samples and remained unchanged in the other four lakes.
2. Open-water season Chl*a* concentrations decreased in Black Bay of Rainy Lake (from an average of 13 to 6.0 μg/l, $p = 0.001$) and Kabetogama Lake (from 9.9 to 6.2 μg/l, $p = 0.006$). Chlorophyll-*a* concentrations did not change in Namakan and Rainy Lakes.
3. Trophic state index (TSI) values (based on Chl*a*) decreased for all water bodies, with significant decreases in Black Bay of Rainy Lake from 59 to 51 ($p = 0.006$) and Kabetogama Lake from 57 to 50 ($p = 0.006$) between 1977-1999 and 2000-2011. TSI values did not change significantly in Namakan and Rainy Lakes.
4. TSI based on Chl*a* indicated that Sand Point, Namakan, and Rainy Lakes are oligotrophic, whereas Kabetogama is mesotrophic to eutrophic and Black Bay is eutrophic.

The increase in water clarity, as shown by Secchi depth increases, favors submerged macrophyte growth — as opposed to phytoplankton dominance, which is favorable for ecosystem health. In addition, the trophic state indices indicate no decreases in lake ecosystem health since the water-level management plan changed in 2000, and the two most eutrophic water bodies have improved. Confounding effects such as climate or extreme hydrologic events are unlikely to have caused this result. However, lake morphometry and factors related to surface geology may have affected the different response that these lakes have had to the new hydrologic regime.

LITERATURE CITED

Ameel, J., E. Ruzycki, and R.P. Axler, 1998. Analytical Chemistry and Quality Assurance Procedures for Natural Water Samples (Sixth Edition). Central Analytical Laboratory, Natural Resources Research Institute Technical Report NRRI/TR–98/03, revised annually.

American Public Health Association, 1999. Standard Methods for the Examination of Water and Wastewater (21st Edition). American Public Health Association, Washington, D.C.

Arar, E.J. and G.B. Collins, 1997. U.S. Environmental Protection Agency Method 445.0 — In Vitro Determination of Chlorophyll a and Pheophytin a in Marine and Freshwater Algae by Fluorescence, Revision 1.2. U.S. Environmental Protection Agency, National Exposure Research Laboratory, Office of Research and Development, Cincinnati, Ohio.

Bachmann, R.W., C.A. Horsburgh, M.V. Hoyer, L.K. Mataraza, and D.E. Canfield, 2002. Relations between Trophic State Indicators and Plant Biomass in Florida Lakes. Hydrobiologia 470:219-234.

Baxter, R.M., 1977. Environmental Effects of Dams and Impoundments. Annual Review of Ecology and Systematics 8:255-283.

Benson, N.G., 1973. Evaluating the Effects of Discharge Rates, Water Levels, and Peaking on Fish Populations on the Missouri River Main Stem Impoundments. *In*: Man-Made Lakes: Their Problems and Environmental Effects, W.C. Ackerman, G.F. White, and E.B. Worthington (Editors). Geophysical Monograph 17, American Geophysical Union, Washington, D.C., pp. 683-689.

Bond, R.B., P.S. Lake, and A.H. Arthington, 2008. The Impacts of Drought on Freshwater Ecosystems: An Australian Perspective. Hydrobiologia 600:3-16.

Burns, N.M., J. Deely, J. Hall, and K. Safi, 1997. Comparing Past and Present Trophic States of Seven Central Volcanic Plateau Lakes, New Zealand. New Zealand Journal of Marine and Freshwater Research 31(1):71-87.

Carlson, R.E., 1977. A Trophic State Index for Lakes. Limnology and Oceanography 22(2):361-369.

Carlson, R.E. and J. Simpson, 1996. A Coordinator's Guide to Volunteer Lake Monitoring Methods. North American Lake Management Society, Madison, Wisconsin, 96 pp.

Chevalier, J.R., 1977. Changes in Walleye (*Stizostedion vitreum vitreum*) Population in Rainy Lake and Factors in Abundance, 1925-75. Journal of the Fisheries Research Board of Canada 34:1696-1702.

Christensen, V.G., R.P. Maki, and R.L. Kiesling, 2011. Nutrient Cycling and Relation to Changes in Water Levels in Kabetogama Lake, Voyageurs National Park, Northern Minnesota. U.S. Geological Survey Scientific Investigations Report 2011-5096, 50 pp. http://pubs.usgs.gov/sir/2011/5096/, *accessed* January 2013.

Christensen, V.G., R.P. Maki, and R.L. Kiesling, 2013. Evaluation of Internal Loading and Water Level Changes: Implications for Phosphorus, Algal Production, and Nuisance Blooms in Kabetogama Lake, Voyageurs National Park, Minnesota, USA. Lake and Reservoir Management 29:1-14.

Christensen, V.G., G.A. Payne, and L.W. Kallemeyn, 2004. Effects of Changes in Reservoir Operations on Water Quality and Trophic-State Indicators in Voyageur's National Park, Northern Minnesota, 2001-03. U.S. Geological Survey Scientific Investigations Report 2004-5044, 42 pp. http://pubs.usgs.gov/sir/2004/5044/, *accessed* January 2013.

Clark, B.J., A.M. Paterson, A. Jeziorski, and S. Kelsey, 2010. Assessing Variability in Total Phosphorus Measurements in Ontario Lakes. Lake and Reservoir Management 26:63-72.

Cole, G.F., 1979. Mission-Oriented Research in Voyageurs National Park. Proceedings Second Conference on Scientific Research in the National Parks 7:194-204.

Cole, G.F., 1982. Restoring Natural Conditions in a Boreal Forest Park. *In*: Transactions of the 47th North American Wildlife and Natural Resources Conference, Kenneth Sabol (Editor). Wildlife Management Institute, Washington, D.C., pp. 411-420.

Duan, H., Y. Zhang, B. Zhang, K. Song, and Z. Wang, 2007. Assessment of Chlorophyll-a Concentration and Trophic State for Lake Chagan Using Landsat TM and Field Spectral Data. Environmental Monitoring and Assessment 129:295-308.

Flug, M., 1986. Analysis of Lake Levels at Voyageurs National Park. U.S. National Park Service, Water Resources Division, Fort Collins, Colorado, Report 86-5.

Gafny, S. and A. Gasith, 1999. Spatially and Temporally Sporadic Appearance of Macrophytes in the Littoral Zone of Lake Kinneret, Israel: Taking Advantage of a Window of Opportunity. Aquatic Botany 62:249-267.

Gotdyn, R., T. Joniak, K. Kowalczewska-Madura, and A. Kozak, 2003. Trophic State of a Lowland Reservoir during 10 Years after Restoration. Hydrobiologia 506-509:759-765.

Hambright, K.D., W. Eckert, P.R. Leavitt, and C.L. Schelske, 2004. Effects of Historical Lake Level and Land Use on Sediment and Phosphorus Accumulation Rates in Lake Kinneret, Environmental Science and Technology 38:6460-6467.

Hargis, J.R., 1981. Ecological Analysis of the Plankton Communities of Voyageurs National Park. University of Minnesota-Duluth, Duluth, Minnesota, Final Report, National Park Service contract no. CX–6000–8–R133.

Helsel, D.R. and R.M. Hirsch, 1992. Statistical Methods in Water Resources. Elsevier Science Publishers, Amsterdam, 522 pp.

Hobbs, H.C. and J.E. Goebel, 1982. Geologic Map of Minnesota: Quaternary Geology. University of Minnesota, Minnesota Geological Survey, St. Paul, Minnesota, scale 1:500,000.

Hoyer, M.V., C.A. Horsburgh, D.E. Canfield, Jr., and R.W. Bachmann, 2005. Lake Level and Trophic State Variables among a Population of Shallow Florida Lakes and within Individual Lakes. Canadian Journal of Fisheries and Aquatic Sciences 62:2760-2769.

International Rainy Lake Board of Control, 1999. Final Report, Review of the IJC Order for Rainy and Namakan Lakes. Submitted to the International Joint Commission, Winnipeg, Manitoba, 169 pp.

International Rainy Lake Board of Control and International Lake of the Woods Control Board, 1984. Briefing Paper. Submitted to the International Joint Commission, Winnipeg, Canada, 41 pp.

Johnson, F.H., R.D. Thomasson, and B. Caldwell, 1966. Status of Rainy Lake Walleye Fishery, 1965. Minnesota Department of Conservation, Division of Game and Fish, St. Paul, Minnesota, Section of Research and Planning Investigational Report 292.

Kagalou, I., E. Papasterigiadou, G. Tsimarakis, and D. Petridis, 2003. Evaluation of the Trophic State of Lake Pamvotis Greece, a Shallow Urban Lake. Hydrobiologia 506-509:745-752.

Kallemeyn, L.W., Y. Cohen, and P. Radomski, 1993. Rehabilitating the Aquatic Ecosystem of Rainy Lake and Namakan Reservoir by Restoration of a More Natural Hydrologic Regime. *In*: Restoration Planning for the Rivers of the Mississippi River Ecosystem, L.W. Hesse, C.B. Stalnaker, N.G. Benson, and J.R. Zuboy (Editors). U.S. Department of the Interior, Washington, D.C., National Biological Survey Biological Report 19, pp. 432-448.

Kallemeyn, L.W. and G.F. Cole, 1990. Alternatives for Reducing the Impacts of Regulated Lake Levels on the Aquatic System of Voyageurs National Park, Minnesota: National Park Service. International Falls, Minnesota, 99 pp.

Kallemeyn, L.W., K.L. Holmberg, J.A. Perry, and B.Y. Odde, 2003. Aquatic Synthesis for Voyageurs National Park. U.S. Geological Survey Information and Technology Report 2003-0001, 95 pp.

Kepner, R. and R. Stottlemyer, 1988. Physical and Chemical Factors Affecting Primary Production in the Voyageurs National Park System. Great Lakes Area Resource Studies Unit Technical Report 29, Michigan Technological University, Houghton, Michigan.

Kimmel, B.L. and A.W. Groeger, 1986. Limnological and Ecological Changes Associated with Reservoir Aging. *In*: Reservoir Fisheries Management Strategies for the 80's, G.E. Hall and M.J. Van Den Avyle (Editors). Southern Division American Fisheries Society, Bethesda, Maryland, Reservoir Committee, pp. 103-109.

Kling, H.J., 2005. Paleolimnological Investigation of Kabetogama Lake Cyanobacteria Blooms and Other Indications of Increased Trophic Status. National Park Service Great Lakes Inventory and Monitoring Network Report GLKN/2005/18.

Kraft, K.J., 1988. Effect of Increased Winter Drawdown on Benthic Macroinvertebrates in Namakan Reservoir, Voyageurs National Park. U.S. Department of the Interior, Washington, D.C., National Park Service Research-Resources Management Report MWR-12.

Leira, M. and M. Cantonati, 2008. Effects of Water-Level Fluctuations on Lakes: An Annotated Bibliography. Hydrobiologia 613:171-184.

Li, Y., H. Liu, J. Hao, N. Zheng, and X. Cao, 2012. Trophic States of Creeks and Their Relationship to Changes in Water Level in Xixi National Wetland Park, China. Environmental Monitoring and Assessment 184:2433-2441.

Maki, R.P., C. Holbeck, and L.W. Kallemeyn, 2005. Tapping Volunteer Effort to Spatially Characterize the Water Quality of Rainy Lake and the Namakan Reservoir. North American Lake Management Society Meeting, Madison, Wisconsin.

Meeker, J.E. and A.G. Harris, 2009. Wetland Vegetation Monitoring — Voyageurs National Park. National Park Service, Fort Collins, Colorado, Natural Resources Technical Report NPS/NRPC/WRD/NRTR — 2009/202.

Minnesota Climatology Working Group, 2010. Monthly Climate Summaries, International Falls WSO Airport. http://www.hprcc.unl.edu/cgi-bin/cli_perl_lib/cliLIST.pl?mn4026+mn, *accessed* May, 2010.

Minnesota Department of Natural Resources, 2013a. Lakefinder. http://www.dnr.state.mn.us/lakefind/index.html, *accessed* June, 2013.

Minnesota Department of Natural Resources, 2013b. The DNR Data Deli. http://deli.dnr.state.mn.us/, *accessed* June, 2013.

Natural Resources Conservation Service, 2012. Rapid Watershed Assessment Rainy Lake (MN) HUC: 09030003, 19 pp. http://www.mn.nrcs.usda.gov/technical/rwa/Assessments/reports/rainy_lake.pdf, *accessed* September, 2012.

Naumann, E.C.L., 1919. Some Aspects of the Ecology of the Limnoplankton, with Special References to the Phytoplankton. Svensk Botansk Tidskrift 13(2):129-163.

Noges, P., T. Noges, L. Tuvikene, H. Smal, S. Ligeza, R. Kornijow, W. Peczula, E. Bécares, F. García-Criado, C. Alvarez-Carrera, C. Fernández-Aláez, C. Ferriol, M.R. Miracle, E. Vicente, S. Romo, E. van Donk, W. Van de Bund, J.P. Jensen, E. Gross, L.A. Hansson, M. Gyllström, M. Nykänen, E. de Eyto, K. Irvine, D. Stephen, S. Collings, and B. Moss, 2003. Factors Controlling Hydrochemical and Trophic State Variables in 86 Shallow Lakes in Europe. Hydrobiologia 506(1):51-58.

Ojakangas, R.W. and C.L. Matsch, 1982. Minnesota's Geology. University of Minnesota Press, Minneapolis, Minnesota.

Osborn, T.C., D.B. Ernst, and D.H. Schupp, 1981. The Effects of Water Levels and Other Factors on Walleye and Northern Pike Reproduction and Abundance in Rainy and Namakan Reservoirs. Minnesota Department of Natural Resource, Division of Fish and Wildlife, St. Paul, Minnesota, Section of Fisheries Investigational Report 374.

Paillisson, J.M. and L. Marion, 2011. Water Level Fluctuations for Managing Excessive Plant Biomass in Shallow Lakes. Ecological Engineering 37:241-247.

Payne, G.A., 1991. Water Quality of Lakes and Streams in Voyageur's National Park, Northern Minnesota, 1977-84. U.S. Geological Survey Water-Resources Investigations Report 88-4016, 95 pp.

Prosser, N.S., 1986. An Overview of Reservoir Fisheries Problems and Opportunities Resulting from Hydropower. *In*: Reservoir Fisheries Management Strategies for the 80's, G.E. Hall and M.J. Van Den Avyle (Editors). Southern Division American Fisheries Society, Bethesda, Maryland, Reservoir Committee, pp. 238-249.

Raateoja, M., J. Seppälä, H. Kuosa, and K. Myrberg, 2005. Recent Changes in Trophic State of the Baltic Sea along SW Coast of Finland. Ambio 34(3):188-191.

Reiser, M.H., 1988. Effects of Regulated Lake Levels on the Reproductive Success, Distribution, and Abundance of the Aquatic Bird Community in Voyageurs National Park, Minnesota. U.S. Department of the Interior, Washington, D.C., National Park Service Research-Resources Management Report MWR-13.

Route, W.T. and R.O. Peterson, 1988. Distribution and Abundance of River Otter in Voyageurs National Park, Minnesota. U.S. Department of the Interior National Park Service Research-Resources Management Report MWR-10.

Scheffer, M., 2004. Ecology of Shallow Lakes. Kluwer Academic Publishers, Boston, Massachusetts.

Serieyssol, C.A., M.B. Edlund, and L.W. Kallemeyn, 2008. Impacts of Settlement, Damming, and Hydromanagement in Two Boreal Lakes: A Comparative Paleolimnological Study. Journal of Paleolimnology 42:497-513, doi: 10.1007/s10933-008-9300-9.

Sharp, R.W., 1941. Report of the Investigation of Biological Conditions in Lakes Kabetogama, Namakan, and Crane as Influenced by Fluctuating Water Levels. Minnesota Department of Conservation, Division of Game and Fish, St. Paul, Minnesota, Section of Fisheries Investigational Report 30.

Smith, D.W. and R.O. Peterson, 1991. Behavior of Beaver in Lakes with Varying Water Levels in Northern Minnesota. Environmental Management 15:395-401.

Thurber, J.W., R.O. Peterson, and T.D. Drummer, 1991. The Effect of Regulated Lake Levels on Muskrats, *Ondatra zibethicus*, in Voyageurs National Park, Minnesota. Canadian Field-Naturalist 105:34-40.

U.S. Environmental Protection Agency, 1993. Method 3651, Determination of Phosphorus by Semi-Automated Colorimetry. U.S. Environmental Protection Agency, Cincinnati, Ohio, 17 pp.

U.S. Environmental Protection Agency, 2014. Using a Secchi Disk or Transparency Tube. http://water.epa.gov/type/rsl/monitoring/155.cfm, *accessed* March, 2014.

Vollenweider, R., 1968. The Scientific Basis of Lake and Stream Eutrophication, with Particular Reference to Phosphorus and Nitrogen as Eutrophication Factors. Technical Report OAS/DSI/68.27, Organization for Economic Cooperation and Development, Paris, France.

Wang, J., X. Bair, H. Hu, A. Clites, M. Colton, and B. Lofgren, 2012. Temporal and Spatial Variability of Great Lakes Ice Cover, 1973-2010. Journal of Climate 25:1318-1329.

Wanzen, K.M., K.O. Rothhaupt, M. Mortl, M. Cantonati, L.G.-Toth, and P. Fischer, 2008. Ecological Effects of Water-Level Fluctuations in Lakes: An Urgent Issue. Hydrobiologia 613:1-4.

Wei, B., N. Sugiura, and T. Maekawa, 2000. Evaluation of Trophic State of Eutrophicated Lake and Biotic Response from Algal Community Level. Environmental Technology 21(9):1047-1053.

Welch, E.B., R.P. Barbiero, D. Bouchard, and C.A. Jones, 1992. Lake Trophic State Change and Constant Algal Composition following Dilution and Diversion. Ecological Engineering 1:173-197.

Wilcox, D.A. and J.E. Meeker, 1991. Disturbance Effects on Aquatic Vegetation in Regulated and Un-regulated Lakes in Northern Minnesota. Canadian Journal of Botany 69:1542-1551.

Woodruff, L.G., W.F. Cannon, C.L. Dicken, and S. Pimley, 2002. Bedrock and Soil Geochemistry from Voyageurs National Park, Minnesota. U.S. Geological Survey Open-File Report 02-196.

Xu, Y., Q. Cai, X. Han, M. Shao, and R. Liu, 2010. Factors Regulating Trophic Status in a Large Subtropical Reservoir, China. Environmental Monitoring and Assessment 169:237-248.

Yang, J., X. Yu, L. Liu, W. Zhang, and P. Guo, 2012. Algae Community and Trophic State of Subtropical Reservoirs in Southeast Fujian, China. Environmental Science and Pollution Research International 19(5):1432-1442.