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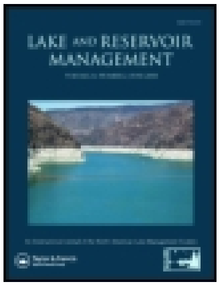

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Evaluation of internal loading and water level changes: implications for phosphorus, algal production, and nuisance blooms in Kabetogama Lake, Voyageurs National Park, Minnesota

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Abstract

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Hydrologic manipulations have the potential to exacerbate or remediate eutrophication in productive reservoirs. Dam operations at Kabetogama Lake, Minnesota, were modified in 2000 to restore a more natural water regime and improve water quality. The US Geological Survey and National Park Service evaluated nutrient, algae, and nuisance bloom data in relation to changes in Kabetogama Lake water levels. Comparison of the results of this study to previous studies indicates that chlorophyll *a* concentrations have decreased, whereas total phosphorus (TP) concentrations have not changed significantly since 2000. Water and sediment quality data were collected at Voyageurs National Park during 2008–2009 to assess internal phosphorus loading and determine whether loading is a factor affecting TP concentrations and algal productivity. Kabetogama Lake often was mixed vertically, except for occasional stratification measured in certain areas, including Lost Bay in the northeastern part of Kabetogama Lake. Stratification, higher bottom water and sediment nutrient concentrations than in other parts of the lake, and phosphorus release rates estimated from sediment core incubations indicated that Lost Bay is one of several areas that may be contributing to internal loading. Internal loading of TP is a concern because increased TP may cause excessive algal growth including potentially toxic cyanobacteria.

Key words: algal blooms, chlorophyll, eutrophication, internal load, phosphorus, Voyageurs National Park, water levels

Voyageurs National Park, Minnesota, established in 1975, is about 50% water covered, and most recreational use of the park is water based. Visitors boat, fish, and swim along scenic water ways, and aquatic systems support fish, waterfowl, loons, eagles, beavers, and moose; therefore, water quality is an essential element of the Voyageurs National Park environment with respect to the health of its ecosystem and visitor enjoyment.

The International Joint Commission (IJC) is the international body that sets the rules for dam operation on waters shared by the United States and Canada. Rule curves (IJC 2001) indicate bands of permitted maximum and minimum water levels allowed throughout the year (Christensen et al. 2004). Dam operators have had to maintain lake levels on Rainy Lake and the Namakan Reservoir system, the 2 large reservoirs in Voyageurs National Park (Kallemeyn 2000), in accordance with a series of IJC rule curves beginning in 1949 (Kallemeyn et al. 2003). The 1949 Rule Curves and rule curves modified in 1970 allowed greater than natural fluctuations in water levels. After multiple detrimental ecosystem effects were attributed to the 1970 Rule Curves and formally presented to the IJC (Kallemeyn et al. 2003), new rule curves were implemented on 6 January 2000. The new rule curves were expected to restore a more natural water regime that would reduce annual water level fluctuation on Namakan Reservoir by 1 m. In addition, the new rule curves were expected to lower phosphorus loading into the Namakan Reservoir system (which includes

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Kabetogama Lake), by (1) lessening the effects of drying and rewetting sediments from fluctuating water levels, (2) reducing nutrient inputs resulting from decaying littoral vegetation, and (3) reducing nutrient concentrations because of increased volume (Kepner and Stottlemyer 1988).

A 1977–1984 study indicated that Kabetogama Lake and Black Bay in Rainy Lake were eutrophic, having high algal productivity that produced cyanobacteria blooms (Payne 1991). Although chlorophyll *a* (Chl-*a*) concentrations were significantly lower in 2001–2003 (Christensen et al. 2004), total phosphorus (TP) concentrations did not decrease, and Kabetogama Lake still experienced yearly cyanobacterial blooms (Kallemeyn et al. 2003). Phosphorus release from bottom sediments has been determined to be a substantial nutrient source in several lakes in Minnesota (Larsen et al. 1981) and across the United States (Welch and Spyridakis 1972, Mueller and Ruddy 1993). Although sediment commonly acts as a sink for nutrients and other substances, changes in water levels or stratification patterns may release phosphorus from the bottom sediment into the water column. Increased release of phosphorus into the water column further stimulates the growth of algae and cyanobacteria causing nuisance algal blooms. Algal bloom decay leads to oxygen depletion, which can cause fish mortality or further liberate toxic substances and phosphorus bound to oxidized bottom sediments (Chorus and Bartram 1999).

Analysis of a lead-210 dated sediment core from Kabetogama Lake provided evidence that the lake gradually has shifted to a higher trophic state, particularly since the 1960s (Kling 2005). The proportion of Chrysophytes, which generally are representative of more oligotrophic conditions, decreased as diatoms became more prevalent, indicating increased nutrients and production. Cyanobacterial compositions have shifted with a decrease in diversity of *Anabaena*-dominated blooms, accompanied by more consistent pulses of *Aphanizomenon* akinetes. This apparent shift may be indicative of changing light conditions in the lake because *Anabaena* are adapted to relatively high light conditions and *Aphanizomenon* are adapted to relatively low light conditions (de Nobel et al. 1998).

Recent studies and collected data show that TP has remained higher and nuisance blooms continue to occur more often in Kabetogama Lake than in the other large lakes of Voyageurs National Park, leading us to believe that internal loading may be a factor in the Kabetogama Lake response to water level changes. We present data to (1) assess the effects of the implementation of the water level changes on in-lake TP concentrations and algal productivity, and (2) assess whether internal loading is a factor influencing TP concentrations and algal productivity in Kabetogama Lake.

Study site

Kabetogama Lake is one of 5 hydrologically connected natural lakes that make up the Namakan Reservoir system (Kabetogama, Namakan, Sand Point, Crane, and Little Vermilion; Fig. 1). Water flows from the Namakan Reservoir system (hereinafter referred to Namakan Reservoir) into Rainy Lake at 3 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 (Fig. 1).

Lake levels of Namakan Reservoir have been controlled by regulatory dams since the early 1900s (Kallemeyn et al. 2003). Most discharge from Namakan Reservoir into Rainy Lake occurs at Squirrel Narrows and Kettle Falls (Kallemeyn et al. 2003). When the Namakan Reservoir level reaches an elevation of 339.39 m above the North American Vertical Datum of 1988 (NAVD88), water begins to spill over into Rainy Lake at Gold Portage (International Rainy Lake Board of Control, International Lake of the Woods Control Board 1984). Pre-2000 Rule Curve streamflow records (1984–1998) for Gold Portage (site Q8, USGS station 05129290; Fig. 1) indicate that water flowed through Gold Portage, on average, 253 d/yr (USGS 2013). Operating Namakan Reservoir at the IJC-mandated midpoint water level of the 2000 Rule Curves results in flow through Gold Portage for about 325 d/yr. If Namakan Reservoir were operated at the maximum levels allowed by the IJC, flow would be expected through Gold Portage 365 d/yr (Kallemeyn et al. 2003), resulting in more water from Kabetogama Lake entering Black Bay (Fig. 1). Bear Portage is not a major outflow, and during 1988-1999 it accounted for $\sim$1% of the outflow from Namakan Reservoir (Kallemeyn et al. 2003).

Changes in hydrology (Flug 1986, Kallemeyn and Cole 1990) were anticipated to occur following implementation of the 2000 Rule Curves. Increased outflow at the west end of Kabetogama Lake likely would result in more inflow of water at the east end of Kabetogama Lake (from Namakan Lake). Evidence of Namakan Lake water entering Kabetogama Lake was documented during 1977–1984 (Payne 1991) and again during 2008–2009 (Christensen et al. 2011). In addition to the 1 m reduction in annual water level fluctuation, the timing of hydrologic events in Namakan Reservoir was expected to change under the 2000 Rule Curves, with peak lake-surface elevations and peak outflow occurring in late May to early June rather than late June to early July.

Morphologically, Kabetogama Lake is typical of lakes located on rocks of the Precambrian shield. Gray clay deposits left over from the glacial Lake Agassiz in the lower areas of

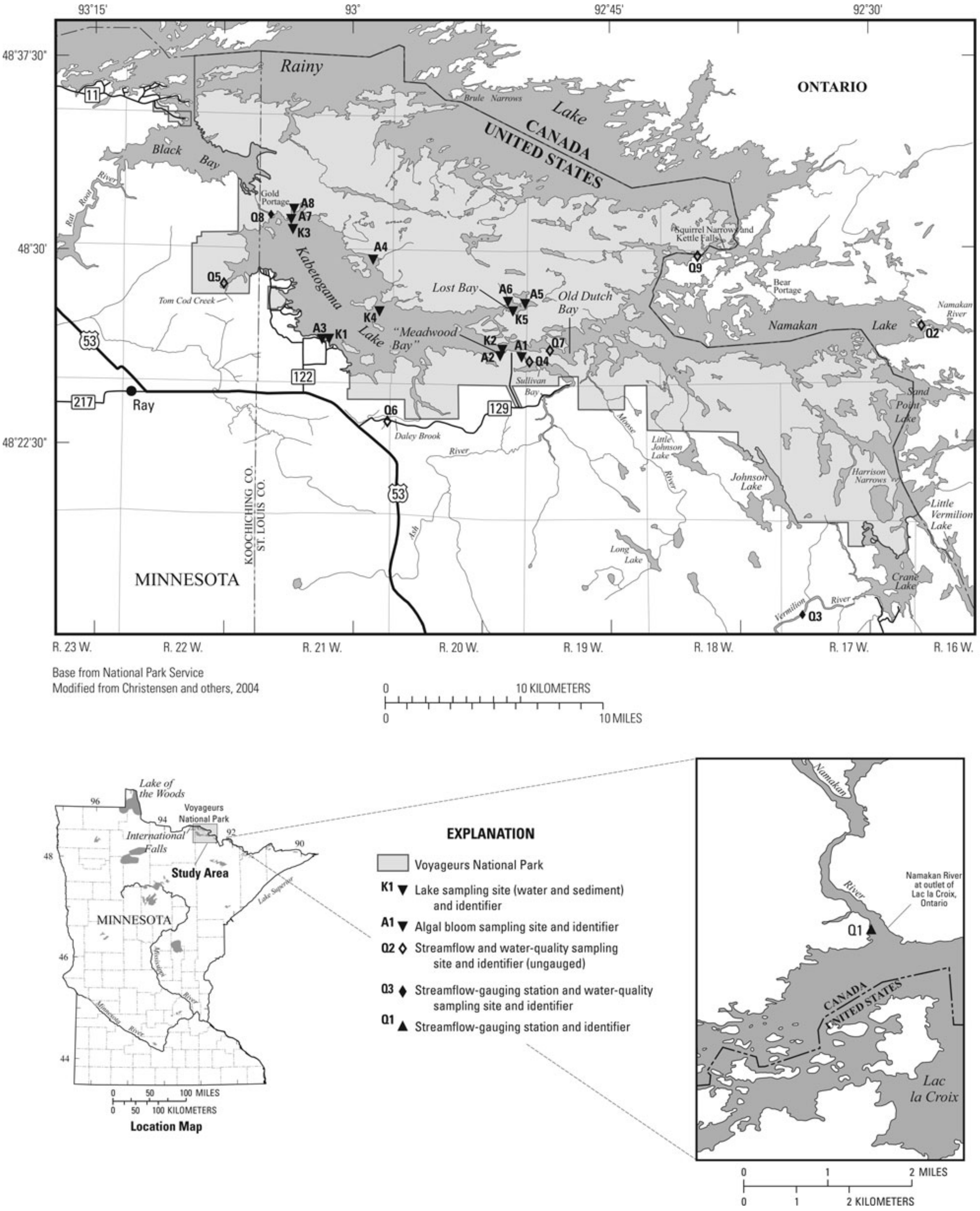

Figure 1.-Location of Voyageurs National Park, MN, sampling sites, and streamflow-gauging stations.

the region are prevalent in the area southwest of Kabetogama Lake. These sediments are unusually rich in soluble minerals (Kallemeyn et al. 2003).

The climate in the Kabetogama Lake area is continental with moderately warm summers and long, cold winters. The frost-free season ranges from 110 to 130 d (Kallemeyn et al. 2003). Average snowfall for the International Falls climate station is 172 cm, average temperature is 2.9 C, and total annual precipitation is 61 cm (Minnesota Climatology Working Group 2010). The lake typically is ice covered for about 5 or 6 months per year, with ice-up occurring in mid- to late November and ice-out occurring in late April (Minnesota Climatology Working Group 2009).

Dry conditions were reported in most of northeastern Minnesota during 2008–2009 (Minnesota Climatology Working Group 2009); however, annual precipitation measured at International Falls in 2008 (70 cm) and 2009 (65 cm) were above the annual average of 61 cm for the period of record (1906–2010). Winter snowpack values for 2007–2008 (243 cm) and 2008–2009 (319 cm) were substantially greater than the average of 172 cm for the period of record (1905–2010).

Kabetogama Lake, the largest and shallowest of the 5 Namakan Reservoir Lakes, covers 10,425 ha and has a maximum depth of about 24 m and a mean depth of about 9 m (Kallemeyn et al. 2003). Kabetogama Lake has irregular shorelines with numerous rock outcrops and islands. During the open water season, the water column of Kabetogama is mixed most of the time, even in the deepest parts of the lake. Thermal stratification occurs infrequently in Kabetogama Lake (Christensen et al. 2004). When thermal stratification does occur, dissolved oxygen (DO) concentrations <4 mg/L below the thermocline have been documented (Christensen et al. 2004).

The southwest shore is a potential source of nutrients to Kabetogama Lake (Payne 1991, Christensen et al. 2004). The southwest shore of Kabetogama Lake is not part of the park and, therefore, the shore is open for development, and numerous homes, cabins and resorts have been built along the roughly 19 km of shoreline. Residential and commercial areas on Ash River (Fig. 1), which flows into Kabetogama Lake from the south, also are a potential source of nutrients (Payne 1991).

Methods

The sampling design for this study of Kabetogama Lake consisted of several components. US Geological Survey (USGS) and National Park Service (NPS) personnel sampled 5 lake sites, 9 inflow or outflow sites, and 8 nuisance bloom sites (Table 1). Streamflow measurements (sites Q1, Q3, Q7-9) and water quality samples for sites K1 and K5 were collected only in May and August to correspond with historical sample collection dates. Samples from the remainder of the lake, inflow, and outflow sites generally were collected monthly during the open water season. Samples were collected from algal blooms as they occurred. Bottom sediment samples were collected at lake sites in May and August only.

Streamflow measurements were made consistent with previous studies (Christensen et al. 2004, 2011), according to methods described in Turnipseed and Sauer (2010) and Mueller and Wagner (2009). In 2011, the narrows between Kabetogama and Namakan lakes was outfitted with an acoustic Doppler velocity meter to continuously measure the direction and magnitude of flow between these 2 water bodies.

Vertical profiles of specific conductance, pH, water temperature, and DO concentration were recorded; Secchi depth was measured at the lake sites (K1–K5, Fig. 1), and lake water samples were collected from the euphotic zone and near the sediment–water interface every 2 weeks during 2008–2009. Water quality data collection methods were consistent with previous studies (Christensen et al. 2004, 2011) and followed standard USGS techniques (Wilde and Radtke 1998). Water samples collected at the lake, inflow, and outflow sites were analyzed for nutrients and Chl-*a* by the USGS National Water Quality Laboratory in Denver, Colorado, and the Natural Resources Research Institute Laboratory in Duluth, Minnesota. Method information, long-term method detection levels, and method detection limits for the 2 laboratories are given in Christensen et al. (2011).

Areas with visible algae accumulation (sites A1-A8, Table 1) were sampled to determine total microcystin concentration. Samples were collected according to methods described in Graham et al. (2008) and analyzed at the USGS Kansas Organic Geochemistry Research Laboratory in Lawrence, Kansas. Samples were analyzed by enzyme-linked immunosorbent assay (ELISA) with Abraxis ELISA kits.

Immediately following the collection of water quality samples at sites K1-K5, sediment samples were collected using a stainless steel Eckman dredge grab sampler. We collected the upper ~4 cm of bottom sediment and sent samples to Test America Laboratory, Arvada, Colorado, for analysis of ammonia (method 350.1), total Kjeldahl nitrogen (method 351.2), nitrite plus nitrate (method 353.2), orthophosphorus (method 365.3), and TP (method 365.3; USEPA 1983). These methods for water have been extended to analysis of nutrients in sediment samples. A sediment sample of 10 g was added to 200 mL of deionized water and distilled; the distillate was analyzed in the same manner as distillates from water samples.

Table 1.-Sampling sites in and near Voyaguers National Park, Minnesota

Site name	Site number (Fig. 1)	US Geological Survey identification number
Lake sites		
Kabetogama Lake near Gappas Landing near Ray, MN	K1	482642093011901
Kabetogama Lake at mouth of Meadwood Bay near Ray, MN	K2	482607092511701
Kabetogama Lake at Cemetary Island near Ray, MN[1]	K3	483012093035001
Kabetogama Lake near Grave Island near Ray, MN	K4	482731092574701
Kabetogama Lake at Lost Bay near Ray, MN	K5	482747092503001
Inflow or outflow sites		
Namakan River at outlet of Lac La Croix, ON, Canada[2]	Q1	05128000
Namakan Lake at mouth of Namakan River, ON, Canada	Q2	482709092264601
Vermilion River near Crane Lake, MN[2]	Q3	05129115
Kabetogama Lake, Sullivan Bay Narrows, near Ash River, MN[2]	Q4	482554092500301
Kabetogama Lake, mouth of Tom Cod Creek, near Ray, MN[1]	Q5	482846093073001
Daley Brook at Co. Rd. 129 near Kabetogama, MN	Q6	05129287
Kabetogama Lake, east end, near Old Dutch Bay, MN	Q7	482611092483801
Gold Portage outlet from Kabetogama Lake near Ray, MN[1,2]	Q8	05129290
Namakan Lake at Squirrel Narrows, near Kettle Falls, MN	Q9	482946092394301
Algal bloom sites		
Kabetogama Lake, Sullivan Bay NW, near Ash River, MN	A1	482542092493701
Kabetogama Lake at Ash River Landing near Ash River, MN	A2	482604092511801
Kabetogama Lake near Kabetogama Visitor Center near Kabetogama, MN	A3	482640093013901
Kabetogama Lake at Ellsworth Rock Garden near Kabetogama, MN	A4	482947092584401
Kabetogama Lake at Ek Lake Trail near Ash River, MN	A5	482804092494701
Kabetogama Lake at Eks Bay near Ash River, MN	A6	482808092504901
Kabetogama Lake west of Bald Rock Bay near Ray, MN	A7	483118093033601
Kabetogama Lake at Bald Rock Bay near Ray, MN	A8	483146093032201

[1] Algal samples also collected at this site
[2] US Geological Survey streamflow-gauging station

In addition to bottom sediments, sediment cores were collected under anoxic conditions to determine phosphorus release from sediments at sites K1, K3, K4, and K5. Sediment cores were collected with a Wildco Model 191-A12 stainless steel box corer (box size: 150 × 150 × 230 mm) fitted with an acrylic sleeve. Box cores and 4–6 cm of overlying water were brought onto the deck of the boat, and 4 replicate push cores were subsampled from each box core using 4 cm diameter, 30 cm long thin-walled polycarbonate tubes. Push cores and overlying water were capped on the top and bottom with tight-fitting polyvinyl chloride caps to maintain anoxic conditions. After collection, push cores were transported to the lakeside field laboratory, and ambient anoxic water was replaced with water collected at depth from the same site as the core. The ambient water temperature was maintained in an environmental chamber, and water remained anoxic throughout sample collection.

Initial nutrient concentrations were measured from overlying water from one of the replicate cores after 1 h in the environmental chamber. After incubation for 24 h, overlying water was decanted from the remaining cores, filtered through 0.45 micron disk filters, and frozen until analysis for dissolved phosphorus and nitrate. Penn et al. (2000) described phosphorus-release rates in anoxic cores as constant for about the first 7 d, and therefore a 24 h incubation period was deemed sufficient. Phosphorus release rates (mg/m^2/d) for Kabetogama Lake locations were calculated as the difference between final and initial concentrations scaled to sediment surface area and duration of incubation. Frequent instrument calibration and other quality-assurance procedures were used to ensure reliable and high-quality data. The quality-assurance plan for this study followed USGS guidelines (Brunett et al. 1997) and are described in more detail in Christensen et al. (2011).

Table 2.-Instantaneous streamflow measurements or streamflow from gauging-station records for sites affecting Voyaguers National Park, Minnesota, 2008–2009.

[Streamflow is reported in m^3/s; — indicates not measured]

Site name	Site number (Fig. 1)	US Geological Survey identification number	May 2008	May 2009	August 2009
Namakan River at outlet of Lac La Croix, Ontario, Canada[1]	Q1	05128000	405	376	106
Vermilion River near Crane Lake, MN[1]	Q3	05129115	90.6	56.6	11.2
Kabetogama Lake, east end, near Old Dutch Bay[2]	Q7	482611092483801	30.3	[−86.0]	[−70.2]
Gold Portage outlet from Kabetogama Lake near Ray, MN[1,3]	Q8	05129290	15.6	12.0	14.6
Namakan Lake at Squirrel Narrows, near Kettle Falls, MN	Q9	482946092394301	368	374	—

[1] US Geological Survey streamflow-gauging station

[2] Negative streamflow (in brackets) indicates water flowing out of Kabetogama Lake toward Namakan Lake

[3] Water elevations for May 2008, May 2009, and August 2009 were 340.49, 340.396, and 340.531 m above the US Coast and Geodetic Survey of 1912, respectively

Results

Streamflow and water levels

Water generally flows through Voyageurs National Park from the southeast to the northwest along the United States and Canadian border. Water from the Namakan and Vermilion rivers provide about 80% of the inflow to Namakan Reservoir (Christensen et al. 2004). The hydrologic system is complex however, and it is difficult to determine how much of the flow from these 2 sources is transported into Kabetogama Lake through the narrows near Old Dutch Bay (site Q7, Fig. 1). Water also flows into Kabetogama Lake from Ash River, Tom Cod Creek, and Daley Brook to the south, and from a few other minor tributaries.

During streamflow measurements made in May 2008, May 2009, and August 2009 (Table 2) and continuous measurements during 2011–2012, water flowed in an unpredictable pattern in both directions between Kabetogama Lake and Namakan Lake. In May 2008, water flowed west from Namakan Lake to Kabetogama Lake. During May and August 2009, water flowed east, from Kabetogama Lake to Namakan Lake. During 2011, flow was generally toward Kabetogama Lake in the winter months and toward Namakan Lake in the summer months. The variability in flow direction complicates the computation of nutrient loads. Based on the volume of water flowing between Kabetogama and Namakan lakes through the narrows near Old Dutch Bay in 2008 and 2009, the narrows near Old Dutch Bay is the largest potential external input of nutrients to Kabetogama Lake; however, the unpredictable direction and magnitude of the flow between Kabetogama and Namakan lakes demonstrates that Kabetogama Lake also may be a substantial source of nutrients to Namakan Lake.

Requisite maximum and minimum water levels for Namakan Reservoir (International Rainy Lake Board of Control 1999) were compared to actual water levels (DeWolfe M, Lake of the Woods Secretariat, 20 Apr 2010, written comm.) for Namakan Reservoir at Gold Portage on the west end of Kabetogama Lake and at Squirrel Narrows and Kettle Falls on the northern side of Namakan Lake (Fig. 2). During 2008, the maximum rule curve water levels were exceeded from 12 May through 7 July 2008 by as much as 0.329 m (15 Jun 2008; Fig. 2). Minor exceedances also occurred on a few days in fall 2008 and spring 2009 (8–23 Oct 2008 and 17–27 May 2009; Fig. 2). Water levels were not lower than the minimum rule curve during the study period.

To put 2008–2009 water levels into historical context, Kabetogama Lake levels for the period of record were obtained (DeWolfe M, Lake of the Woods Secretariat, 20 Apr 2010, written comm.). The annual maximum and minimum lake levels by year and the annual difference (Fig. 3) indicate a change in the mid-1980s when dam operators started to target the middle of the rule curve rather than the extremes (Meeker and Harris 2009). Wilcox rank-sum tests (Helsel and Hirsch 1992) were performed on the 2 datasets (1970–1999 and 2000–2009) to test the significance (p-value of 0.05) of the differences in water level fluctuation. The 1970–1999 water level fluctuations were significantly greater (p-value $= 0.001$) than water level fluctuations during 2000–2009. The difference in the annual water level

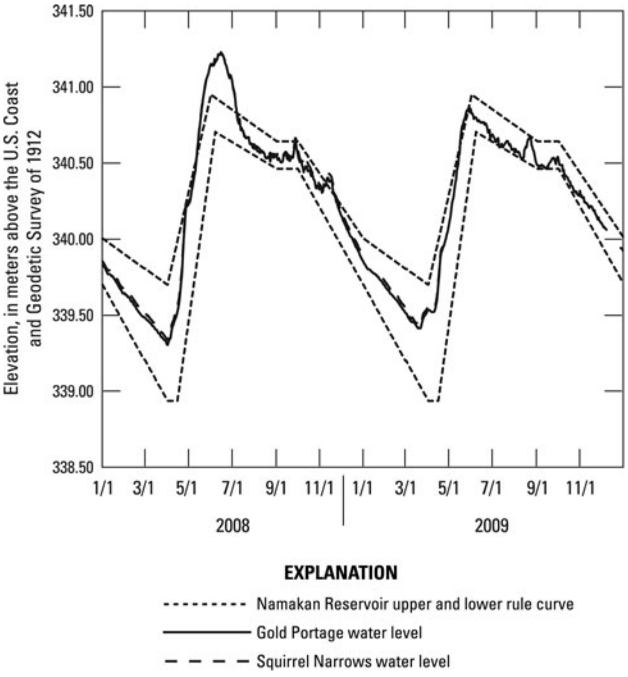

Figure 2.-International Joint Commission 2000 Rule Curves and lake levels for Namakan Reservoir, Voyageurs National Park, MN, 2008–2009.

fluctuations between the 2 time periods seems to be the result of a substantial increase in the minimum water level from the 1970–1999 period to the 2000–2009 period.

Total phosphorus, chlorophyll a*, and microcystin concentrations in water samples*

Near-surface TP concentrations (Fig. 4) from Kabetogama Lake were generally lower in the spring than in the summer. One sample from Grave Island (site K4, 14 Jul 2009: TP = 0.149 mg/L; Fig. 4D) was unusually high. A clean (no detections) field blank sample on this date did not indicate contamination; however, we cannot rule this out because the concentration is extremely high when compared to samples collected at this site during the past (e.g., Christensen et al. 2004).

Chl-*a* concentrations varied seasonally, with peak concentrations normally occurring in late summer (Christensen et al. 2011). Kabetogama Lake sites near Gappas Landing (site K1), at Meadwood Bay (site K2), at Cemetary Island (site K3), and at Lost Bay (site K5) maintained low Chl-*a* concentrations (<11 μg/L) during 2008–2009 (Fig. 5). One sample collected at Grave Island (site K4) had a Chl-*a* concentration of 31.8 μg/L (Fig. 4).

Total microcystin concentration was measured in 14 lake samples during 2008–2009. All samples were collected when visible algal growth was present, with the exception of one sample in 2008 collected at Gold Portage (site Q8). Samples collected from Kabetogama Lake in 2009 had total microcystin concentrations as high as 110 μg/L. Of the bloom samples analyzed, 78% (11 of 14) had detectable microcystin concentrations and 50% (7 of 14) of the samples contained concentrations that exceeded the World Health Organization (WHO) guideline of 1 μg/L in finished drinking water (WHO 2003). Two samples (8 Sep 2008 at site A2, and 10 Sep 2009 at site A5) were in the WHO high risk category (concentrations >20 μg/L; Chorus and Bartram 1999) for recreational exposure.

Comparison of pre- and post-2000 total phosphorus and chlorophyll a *concentrations in water samples*

Several studies conducted before 2000 provide a baseline for comparison to data collected after the implementation of the 2000 Rule Curves (Hargis 1981, Kepner and Stottlemyer 1988, Payne 1991, 2000). Most of the pre-2000

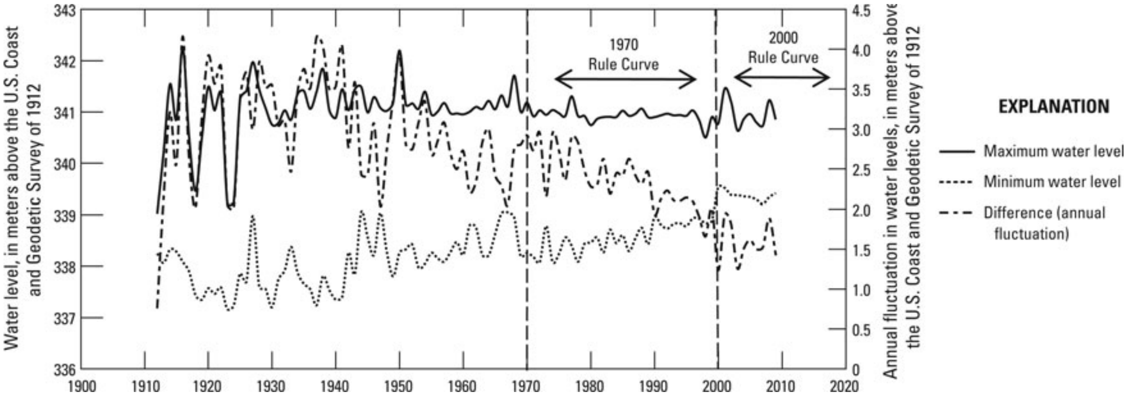

Figure 3.-Minimum and maximum annual water levels and fluctuations, Kabetogama Lake, Voyageurs National Park, MN, 1912–2009.

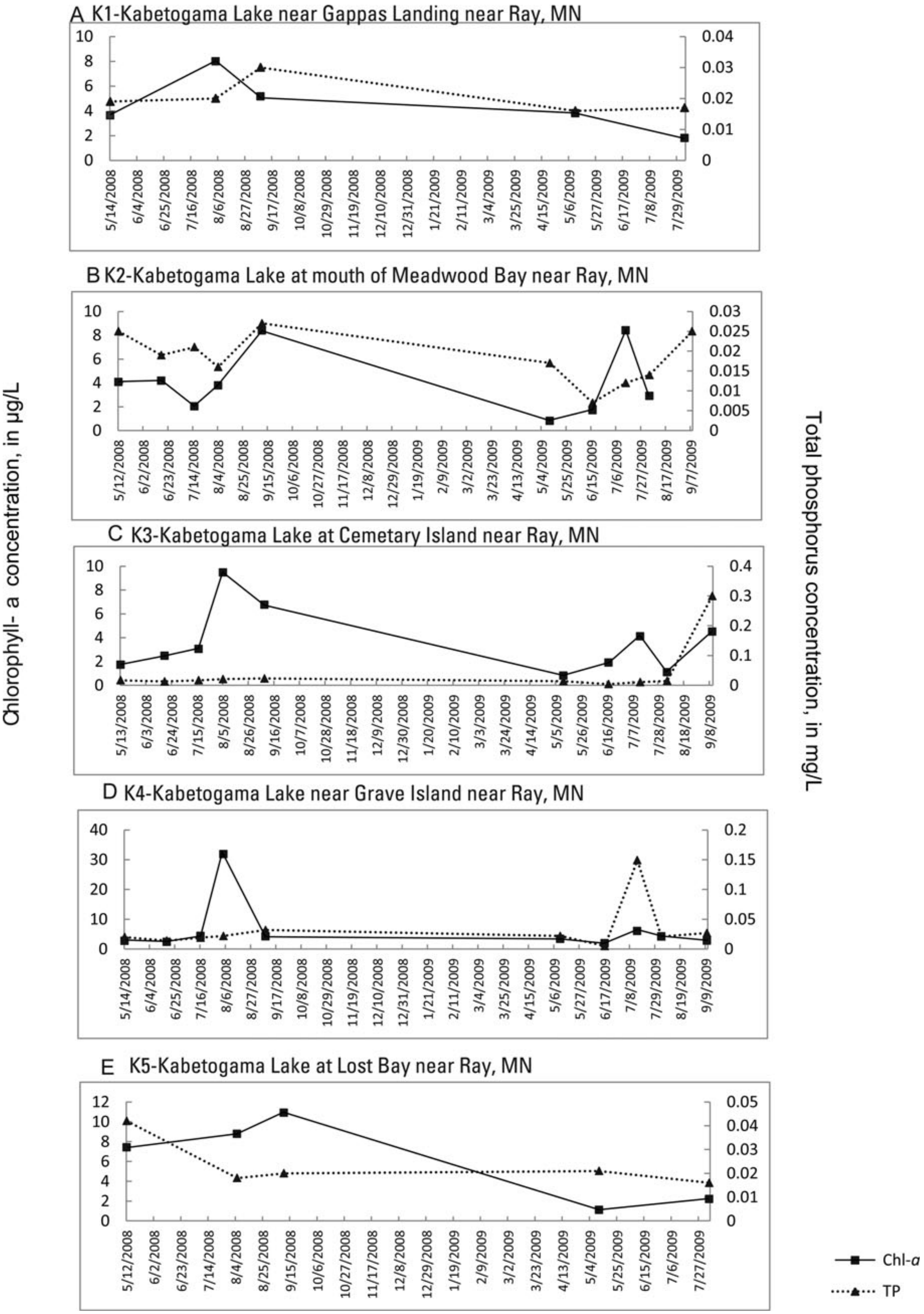

Figure 4.-Total-phosphorus (TP) and chlorophyll-*a* (Chl-*a*) concentrations for near-surface water samples, Voyageurs National Park, MN, 2008–2009, for selected Kabetogama Lake sites.

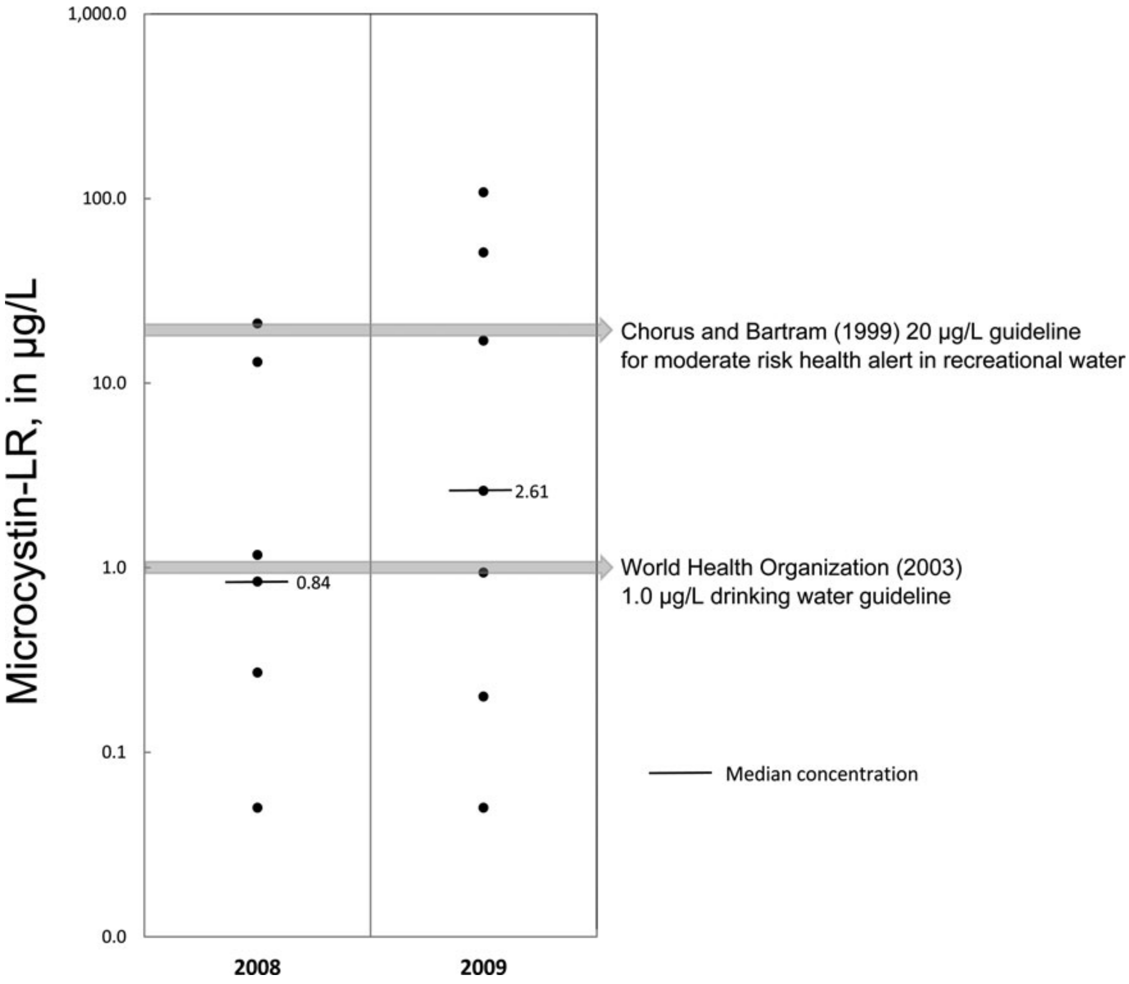

Figure 5.-Microcystin concentrations in water samples from Kabetogama Lake, Voyageurs National Park, MN, 2008–2009.

data were collected during May and August; therefore, May and August data from 2008–2009 (Christensen et al. 2011) and from 2001-2003 (Christensen et al. 2004) were compared with data from the pre-2000 studies (1978–1983). Because not all sites were sampled during the baseline studies, changes in Kabetogama Lake were evaluated using data from Meadwood Bay (site K2). Wilcox rank-sum tests indicated no statistical difference in TP concentrations between the 2 periods (Fig. 6). Additional analysis was attempted by separating the May and August data, but no statistical difference for TP concentrations was determined.

Chl-*a* concentrations were lower after 2000 than before 2000, regardless of laboratory analytical method, and the difference in Chl-*a* concentrations between the periods was statistically significant (p-value = 0.04; Fig. 6). Chl-*a* concentrations before 2008 were determined using both the fluorometric method (Arar and Collins 1997) and the spectrophotometric method (Ameel et al. 1998). The fluorometric method is more sensitive than the spectrophotometric method (Ameel et al. 1998); however, the spectrophotometric method has been shown to overestimate Chl-*a* concentrations (Rivera et al. 2005). Chl-*a* data collected after 2008 were analyzed with the spectrophotometric method only. Christensen et al. (2004) compared pre-2000 and post-2000 Chl-*a* data for which the same analytical methods were used and also documented lower Chl-*a* concentrations after the implementation of the 2000 Rule Curves.

Stratification, characteristics of lake-bottom sediments, and internal loading

DO profiles for August 2008 indicated that 4 of 5 lake sites reached a DO of <4 mg/L (Fig. 7). The profile on Lost Bay was incomplete (the cable used by the field team was too short), and the DO reached a minimum of 6 mg/L at a depth

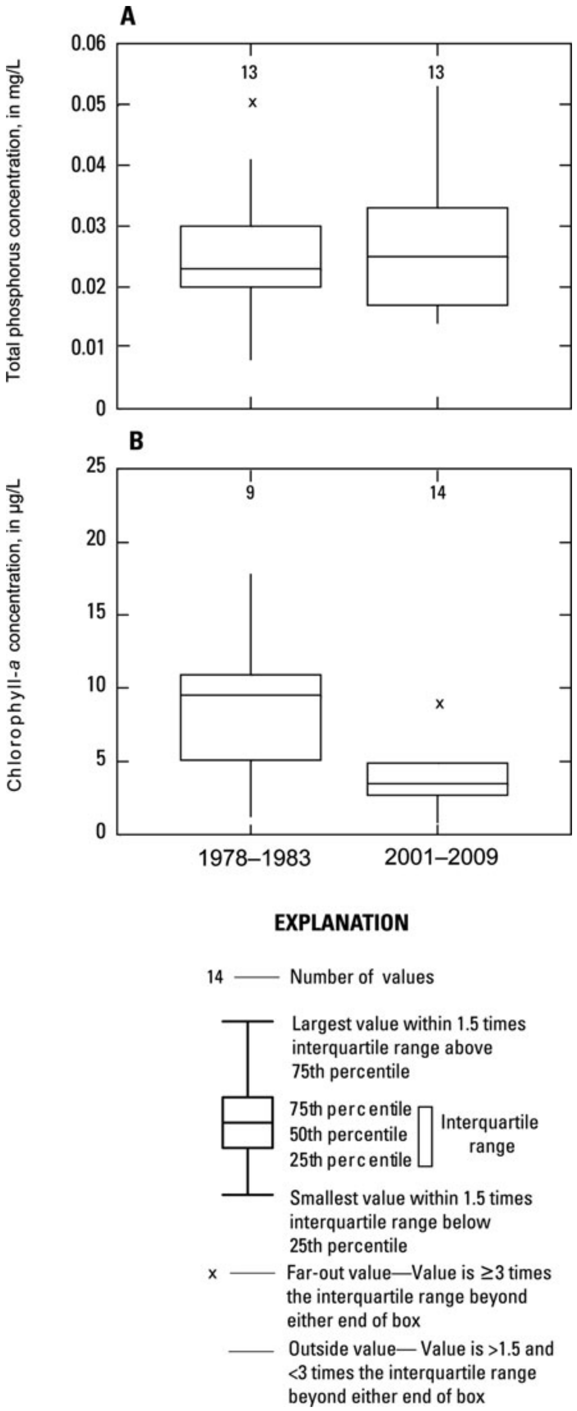

Figure 6.-Boxplots comparing historical Kabetogama Lake baseline concentrations (1978–1983) to 2001–2003 and 2008–2009 concentrations in water samples collected during May and August. (A) total phosphorus; (B) chlorophyll-*a*.

of 7 m. DO profiles for August 2009 clearly show that the 2 deepest sites, near Grave Island and in Lost Bay (sites K4 and K5), are anoxic at depth, whereas DO remains >8 mg/L for the other 3 sites (K1, K2, and K3; Fig. 7).

Of the 5 Kabetogama Lake sites, Grave Island (site K4, Fig. 1) had the highest mean concentration of ammonia in sediment, whereas Lost Bay (site K5) had the highest mean concentration of nitrite plus nitrate, total Kjeldahl nitrogen, orthophosphorus, and TP in sediment (Table 3). Grave Island and Lost Bay are the 2 deepest lake sites sampled, with depths of about 15 and 12 m, respectively. Deeper areas of the lake may have little or no oxygen during summer stratification (Christensen et al. 2011), and release rates from deep anoxic areas are likely to be maximum release rates (Penn et al. 2000).

Phosphorus release rates (Fig. 7) measured from bottom sediment incubated cores varied widely and were highest at Cemetary Island in 2009 (site K3, 44 mg/m^2/d) and Grave Island (site K4, 20 mg/m^2/d in 2008 and 33 mg/m^2/d in 2009). Part of the variability may be attributed to collection dates; 2008 and 2009 samples were collected in August, with the exception of the sample collected in Lost Bay, which was collected in May.

Discussion

Understanding the effect of water level on water quality in lakes and reservoirs is an important component of lake and reservoir management. Alteration, degradation, and eutrophication of surface water may favor cyanobacterial dominance and increase the risk of toxins in the water. Based on the total microcystin concentrations determined in this study, the risk of toxins in Kabetogama Lake may be a concern for residents who use it as a source for drinking water and for park visitors who use the lake for contact recreation. This study aimed to determine if water quality changed following implementation of the 2000 Rule Curves and to determine if internal loading was a factor for the eutrophic Kabetogama Lake.

The difference in TP concentrations in samples collected from Meadwood Bay (site K2) in Kabetogama Lake before and after implementation of the 2000 Rule Curve was not statistically significant, whereas the difference in Chl-*a* concentrations was statistically significant (Fig. 6). A possible explanation for relatively unchanged TP concentrations may be changes in residence time or the combined effects of internal and external loading. Residence time reflects the time it takes for water to move through a system. The movement of water through a system affects water chemistry and the biology of organisms inhabiting them (Wetzel 2001), and a change in residence time may affect phosphorus concentrations. With all other variables equal, a lake with a smaller volume would have a shorter residence time than a lake with a larger volume. Changes in dam operation associated with the 2000 Rule Curves would affect the residence time in Kabetogama Lake; however, because Kabetogama Lake

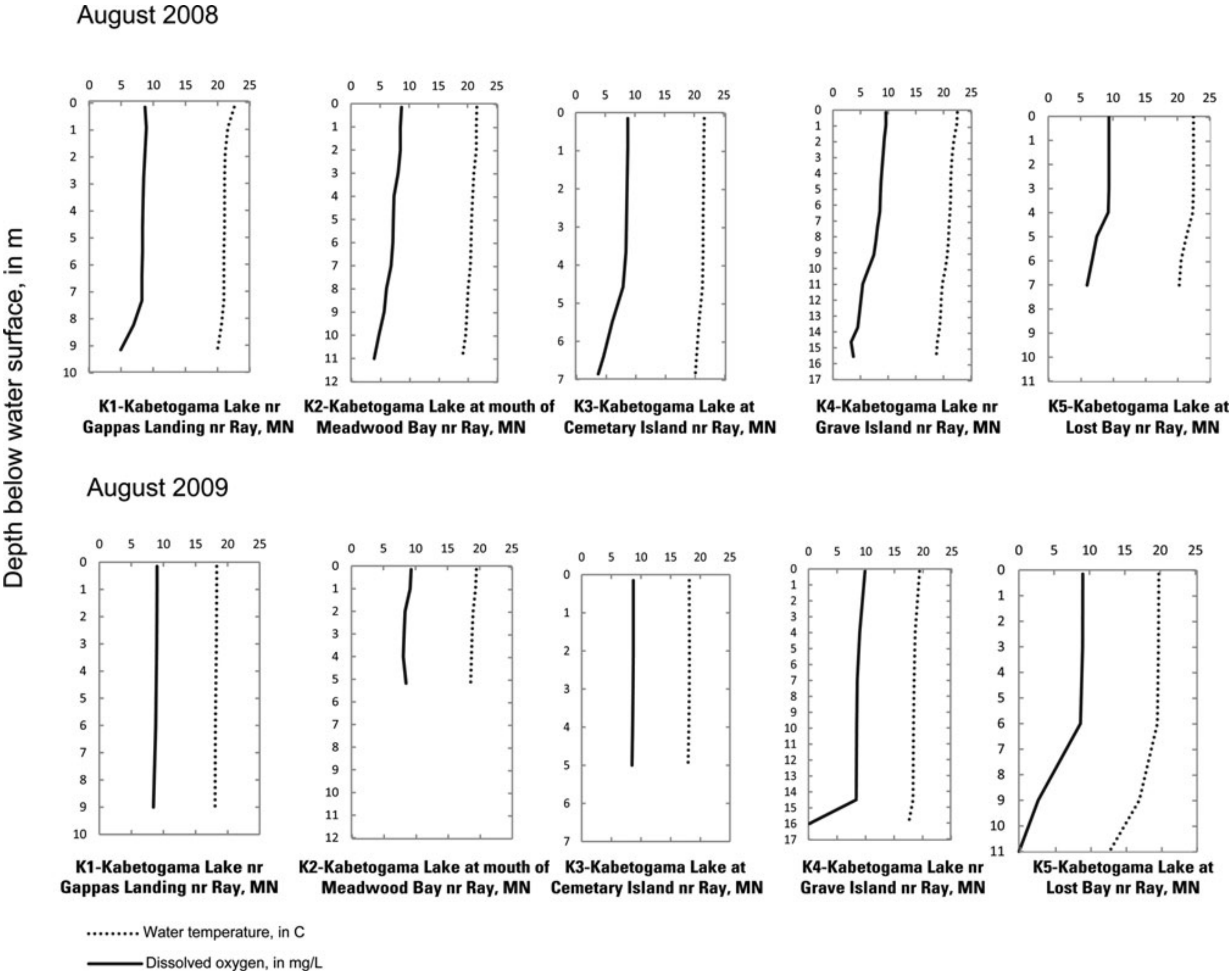

Figure 7.-Dissolved oxygen and water temperature profiles at 5 Kabetogama Lake sites, Voyageurs National Park, MN, 2008–2009.

has 2 outlets and multidirectional flow between lakes of the system, Kabetogama Lake may act like a backwater area to the larger Namakan Reservoir. Residence times were not calculated for Kabetogama Lake because of the complex hydrology of Voyageurs National Park. A shallow depth for a specific lake means less water volume, dilution, and assimilative capacity from external loads (Vollenweider 1975).

The combined effects of internal and external loading also may explain the lack of difference in water column TP concentrations before and after 2000. Nutrient availability may be affected by the difference in annual water level fluctuations because this seems to be the result of an increase in the minimum water level. An increased minimum water level may reduce drying and rewetting and thus nutrient inputs from sediment in the nearshore area. The variation in the volume of phosphorus released from the deeper sediments during stratification and the annual variation in external phosphorus loads may be substantial enough to mask any change in phosphorus concentrations.

Internal loading of phosphorus in Kabetogama Lake is indicated by (1) concurrent TP and Chl-*a* concentration peaks that occur at Meadwood Bay, Cemetary Island, and Grave Island, which may indicate increased algal production in response to phosphorus loading; (2) the difference in phosphorus concentrations between water samples collected at the surface and the water samples collected near the sediment–water interface (sediment–water interface samples are described in Christensen et al. 2011); (3) the stratification of deep lake sites, such as Lost Bay; (4) the high nutrient concentrations in bottom sediment samples; and (5) the elevated phosphorus release rates from the bottom sediment at sites near Cemetary Island and Grave Island observed during sediment core incubations.

Table 3.-Concentrations of nutrients in bottom-sediment samples from Kabetogama Lake, Voyageurs National Park, Minnesota, 2008–2009.

[All units in mg/kg; — indicates no data]

Date	Ammonia	Total Kjeldahl nitrogen	Nitrite plus nitrate	Orthophosphorus	Total phosphorus
Kabetogama Lake near Gappas Landing near Ray, MN (site K1, Fig. 1, 482642093011901)					
5/14/2008	1.8	5800.00	—	0.9	760
8/4/2008	9.0	7100.00	4	1.2	90
5/13/2009	3.9	2300.00	3	1.0	550
Mean	**4.9**	**5100.00**	**4**	**1.0**	**470**
Kabetogama Lake at mouth of Meadwood Bay near Ray, MN (site K2, Fig. 1, 482607092511701)					
5/12/2008	0.2	2.40	—	0.2	120
Kabetogama Lake at Cemetary Island near Ray, MN (site K3, Fig. 1, 483012093035001)					
5/13/2008	3.0	6100.00	6	1.6	890
8/5/2008	7.2	11, 000.00	7	1.8	820
5/11/2009	2.1	6800.00	1	1.2	700
8/5/2009	11	760.00	12	2.0	760
Mean	**5.8**	**6200.00**	**7**	**1.7**	**790**
Kabetogama Lake near Grave Island near Ray, MN (site K4, Fig. 1, 482731092574701)					
5/14/2008	3.2	5900.00	14	2.1	1,000
8/4/2008	12	1000.00	8	1.9	190
5/11/2009	5.4	12, 000.00	13	1.8	760
8/5/2009	53	7100.00	6	1.7	740
Mean	**18**	**6500.00**	**10**	**1.9**	**670**
Kabetogama Lake at Lost Bay near Ray, MN (site K5, Fig. 1, 482747092503001)					
5/12/2008	1.6	11, 000.00	2	1.3	820
8/5/2008	5.7	10, 000.00	10	2.6	920
5/11/2009	7.6	6300.00	33	2.5	780
Mean	**5.0**	**9100.00**	**15**	**2.1**	**840**

Annual internal phosphorus loads typically are higher for dimictic lakes, such as Namakan Lake, because of the extent and duration of anoxic conditions during stratification; however, internal loads in dimictic lakes typically manifest as a pulse during spring and fall turnovers. In contrast, for polymictic lakes, such as Kabetogama Lake, the frequent mixing between the deep pools and the shallow main lake may allow TP to be more immediately bioavailable throughout the ice-free season.

Water samples collected near the sediment–water interface during August when bottom waters were anoxic from Lost Bay (site K5), in particular, had substantially higher nutrient concentrations than water samples collected at the water surface (Christensen et al. 2011). The Lost Bay site also had the highest average concentrations for 4 of the 5 nutrients analyzed in bottom sediments (Table 3). These data indicate that phosphorus release may be particularly substantial in deeper areas such as Lost Bay.

Similar effects of internal loading on water quality observed in Kabetogama Lake also have been documented in other lakes (Harris 1986, Nurnberg 2009). Nurnberg (2009) found that internal loading from bottom sediments represented the main summer TP load to several lakes, and that the internal loads had measurable effects on water quality. The phosphorus release rates observed in this study (-0.6 to 44 mg/m^2/d; Fig. 8) were within the ranges of release rates determined in other studies of North American lakes (Callendar 1982, Nurnberg 1984, 2009, Penn et al. 2000, Borges et al. 2009). Nurnberg (1984) reported values for annual internal phosphorus load from 54 oxic and 33 anoxic lakes in North America and Europe. When Nurnberg's (1984) internal phosphorus loads are converted to release rates, they range from -3.7 to 0.5 mg/m^2/d for oxic lakes and from 2.95 to 11.5 mg/m^2/d for anoxic lakes.

One issue with comparing phosphorus release rates with those in the literature is that several different methods may be used to estimate phosphorus release. For example, *in situ* flux and core incubations (Nurnberg 2009) may be used, and different temperatures may be used for core incubations (Callendar 1982); therefore, the phosphorus release rates of other studies are used as a general guide for comparison.

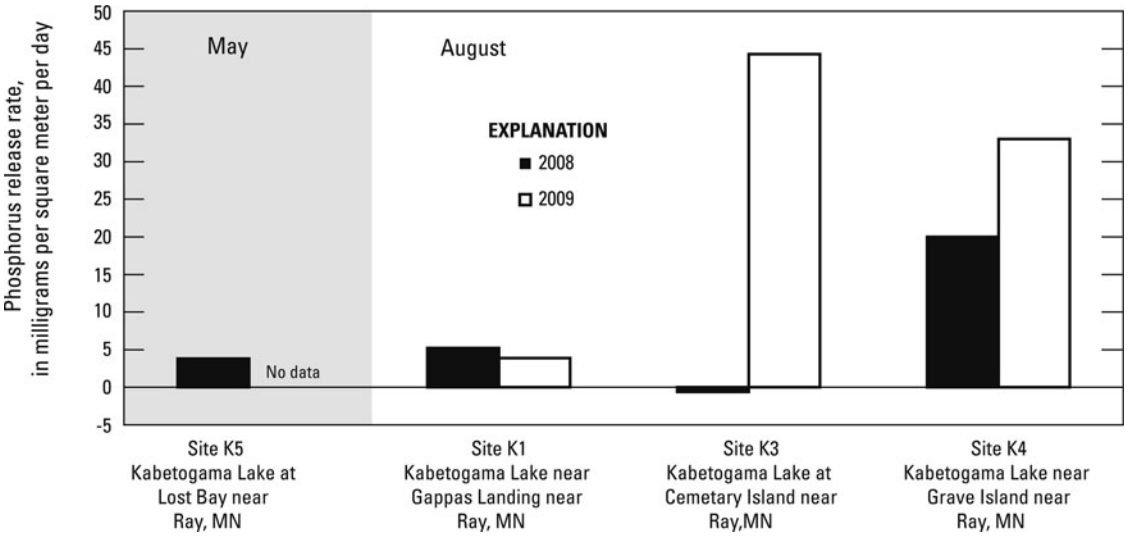

Figure 8.-Phosphorus release for selected sites in Kabetogama Lake, Voyageurs National Park, MN, 2008–2009.

Although samples collected during 2008 and 2009 were insufficient to determine the total internal phosphorus load for Lake Kabetogama, calculated phosphorus release rates indicate that (1) internal phosphorus loading may be substantial when the lake is stratified, and (2) internal loading may be an important source of phosphorus to the overlying water through mixing or vertical cyanobacterial transport. The assumption is that the mechanism involved in Kabetogama Lake is the release of phosphorus incorporated into iron hydroxides under anoxic conditions.

These results may help Voyageurs National Park personnel assess water quality changes that occurred concurrently with changes in IJC rules governing dam operation in 2000. Because of our study's intense focus on Kabetogama Lake, researchers and managers may better understand the effect of the new hydrologic regime on the unique situation in one of the park's most eutrophic lakes. To fully assess the consequences of the change in water level management, future studies might focus on residence time and documenting the exchange of water between Namakan and Kabetogama lakes.

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Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

References

Ameel J, Ruzycki E, Axler RP. 1998. Analytical chemistry and quality assurance procedures for natural water samples. 6th ed. Central Analytical Laboratory, Natural Resources Research Institute Technical Report NRRI/TR–98/03 [revised annually].

Arar EJ, Collins GB. 1997. US 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. Cincinnati (OH): US Environmental Protection Agency, National Exposure Research Laboratory, Office of Research and Development.

Borges AC, Sanders CJ, Santos HLR, Araripe DR, Machado W, Patchineelam SR. 2009. Eutrophication history of Guanabara Bay (SE Brazil) recorded by phosphorus flux to sediments from a degraded mangrove area. Mar Pollut Bull 58(11):1739–1765.

Brunett JO, Barber NL, Burns AW, Fogelman RP, Gilles DC, Lindwin RA, Mack TJ. 1997. A quality-assurance plan for district ground-water activities of the U.S. Geological Survey. US Geological Survey; Open-File Report 97–11.

Callendar EC. 1982. Benthic phosphorus regeneration in the Potomac River Estuary. Hydrobiologia. 92:431–446.

Chorus I, Bartram J, editors. 1999. Toxic cyanobacteria in water—a guide to their public health consequences, monitoring and management. World Health Organization. ISBN 0–419–23930–8.

Christensen VG, Maki RP, Kiesling RL. 2011. Relation of nutrient concentrations, nutrient loading, and algal production to changes in water levels in Kabetogama lake, Voyageurs National Park, northern Minnesota, 2008-09. US Geological Survey Scientific Investigations Report 2011–5096.

Christensen VG, Payne GA, Kallemeyn LW. 2004. Effects of changes in reservoir operations on water quality and trophic-state indicators in Voyageur's National Park, northern Minnesota, 2001–03. US Geological Survey Scientific Investigations Report 2004–5044.

de Nobel WT, Matthijs HCP, VonElert E, Mur LR. 1998. Comparison of the light-limited growth of the nitrogen-fixing cyanobacteria *Anabaena* and *Aphanizomenon*. New Phytol. 138:579–587.

Flug M. 1986. Analysis of lake levels at Voyageurs National Park. Ft. Collins (CO): National Park Service; Water Resources Division Report 86-5.

Graham JL, Loftin KA, Ziegler AC, Meyer MT. 2008. Cyanobacteria in lakes and reservoirs—toxin and taste-and-odor sampling guidelines (ver. 1.0). US Geological Survey techniques of water-resources investigations. Book 9, Chap. A7, Section 7.5. Available online only from: http://pubs.water.usgs.gov/twri9A/

Hargis JR. 1981. Ecological analysis of the plankton communities of Voyageurs National Park. University of Minnesota-Duluth; Final Report; National Park Service contract no. CX–6000–8–R133.

Harris GP. 1986. Phytoplankton ecology: structure, function, and fluctuation. London (UK): Chapman Hall.

Helsel DR, Hirsch RM. 1992. Statistical methods in water resources: Amsterdam (Netherlands): Elsevier.

[IJC] International Joint Commission. 2001. Order prescribing method of regulating the levels of boundary waters, Washington, DC.

International Rainy Lake Board of Control, International Lake of the Woods Control Board. 1984. Briefing paper submitted to the International Joint Commission. Winnipeg (MB).

International Rainy Lake Board of Control. 1999. Review of the IJC Order for Rainy and Namakan Lakes. Final report, submitted to the International Joint Commission. Winnepeg (MB).

Kallemeyn LW. 2000. Proceedings of the Rainy Lake-Namakan Reservoir ecological monitoring workshop; 11–12 Jan 2000; International Falls, MN. Washington (DC): Report to International Joint Commission.

Kallemeyn LW, Cole GF. 1990. Alternatives for reducing the impacts of regulated lake levels on the aquatic ecosystem of Voyageurs National Park, Minnesota. International Falls (MN): National Park Service.

Kallemeyn LW, Holmberg KL, Perry JA, Odde BY. 2003. Aquatic synthesis for Voyageurs National Park. US Geological Survey Information and Technology Report 2003–0001.

Kepner R, Stottlemyer R. 1988. Physical and chemical factors affecting primary production in the Voyageurs National Park system. Houghton (MI): Michigan Technological University; Great Lakes Area Resource Studies Unit Technical Report 29.

Kling H. 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.

Larsen DP, Schults DW, Malueg KW. 1981. Summer internal phosphorus supplies in Shagawa Lake, Minnesota. Limnol Oceanogr. 26(4):740–753.

Meeker JE, Harris AG. 2009. Wetland vegetation monitoring—Voyageurs National Park. Fort Collins (CO): National Park Service, Natural Resources Technical Report NPS/NRPC/WRD/NRTR—2009/202.

Minnesota Climatology Working Group. 2009. Minnesota's historical lake ice-out dates. State Climatology Office- DNR Waters; [cited 19 May 2010]. Available from: http://climate.umn.edu/doc/ice_out/ice_out_historical.htm

Minnesota Climatology Working Group. 2010. Monthly climate summaries, International Falls WSO Airport; [cited 5 May 2010]. Available from: http://www.hprcc.unl.edu/cgi-bin/cli_perl_lib/cliLIST.pl?mn4026+mn

Mueller DK, Ruddy BC. 1993. Limnological characteristics, nutrient loading and limitation, and potential sources of taste and odor problems in Standley Lake, Colorado. US Geological Survey Water-Resources Investigations Report 92–4053.

Mueller DS, Wagner CR. 2009. Measuring discharge with acoustic Doppler current profilers from a moving boat. US Geological Survey Techniques and Methods 3A–22.

Nurnberg GK. 1984. The prediction of internal phosphorus load in lakes with anoxic hypolimnia. Limnol Oceanogr. 29(1):111–124.

Nurnberg GK. 2009. Assessing internal phosphorus load—problems to be solved. Lake Reservoir Manag. 25:419–432.

Payne GA. 1991. Water quality of lakes and streams in Voyageur's National Park, northern Minnesota, 1977–84. US Geological Survey Water-Resources Investigations Report 88–4016.

Payne GA. 2000. Water quality of lakes in Voyageurs National Park, northern Minnesota, 1999. US Geological Survey Water-Resources Investigations Report 00–4281.

Penn MR, Auer MT, Doerr SM, Driscoll CT, Brooks CM, Effler SW. 2000. Seasonality in phosphorus release rates from the sediments of a hypereutrophic lake under a matrix of pH and redox conditions. Can J Fish Aquat Sci. 57:1033–1041.

Rivera C, Zapata A, Pinilla G, Donato J, Chaparro B, Jimenez, P. 2005. Comparison of spectrophotometric and fluorometric measurements of chlorophyll-a. Acta Biologica Colombiana. 10(2):95–103.

Turnipseed DP, Sauer VB. 2010. Discharge measurements at gaging stations. US Geological Survey Techniques and Methods; Book 3, Chap. A8.

[USEPA] US Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. Washington (DC): EPA–600/4–79–020.

[USGS] US Geological Survey. 2013. National Water Information System database; [cited 14 Feb 2013]. Available from: http://waterdata.usgs.gov/mn/nwis/

Vollenweider RA. 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweiz Z Hydrol. 37:53–84.

Welch EB, Spyridakis DE. 1972. Dynamics of nutrient supply and primary production in Lake Sammamish, Washington. In: Franklin JF, Dempster LJ, Waring RH, editors. A symposium on Research on Coniferous Forest Ecosystems, Bellingham (WA): Northwest Scientific Association, p. 301–315.

Wetzel RG. 2001. Limnology lake and river ecosystems. 3rd ed. San Diego (CA): Elsevier.

Wilde FD, Radtke DB. 1998. National field manual for the collection of water-quality data. US Geological survey techniques of water-resources investigations; Book 9, Chap. A6.

[WHO] World Health Organization. 2003. Cyanobacterial toxins—microcystin-LR in drinking water. Geneva (Switzerland): World Health Organization.