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# Aquatic Synthesis for Voyageurs National Park

Information and Technology Report
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**Front cover:** Aerial photo looking east over Namakan Lake, Voyageurs National Park.

# Aquatic Synthesis for Voyageurs National Park

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May 2003

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## Executive Summary

Voyageurs National Park (VOYA), which was established in 1975, contains significant aquatic resources with about 50% of its total area of 883 km$^2$ (341 mi$^2$) consisting of aquatic habitats. In addition to the Park's 30 named lakes, there are numerous wetlands including hundreds of beaver ponds. Due to the Park's size and location in the drainage basin, aquatic resources within the Park are particularly susceptible to activities and developments that occur outside its' boundary. This is particularly true in regard to the water quality and aquatic communities in the four large lakes that comprise 96% of the Park's total lake area of 34,400 ha (133 mi$^2$). Because most Park activities center on the lakes, particularly the large lakes, resource managers need to have knowledge and understanding of VOYA's aquatic resources to effectively preserve, in an unimpaired condition, the ecological processes, biological and cultural diversity, and history of the northwoods, lakecountry border shared with Canada.

The purpose of this synthesis is threefold: (1) to provide a complete and integrated account of what is known about the aquatic ecosystem of VOYA, including the entire Rainy Lake and Namakan Reservoir basins, their hydrological inflows and outflows, as well as the other aquatic habitats and communities that actually occur within the Park's boundary; (2) to provide pertinent comparisons from other areas to help park managers better understand the results of research and monitoring efforts within the Park; and (3) to identify needs and potential opportunities for filling gaps in the existing knowledge base.

### Drainage Basin Characterization

The area encompassing VOYA has a continental climate, characterized by moderately warm summers and long, cold winters. As has been documented for other areas in the Northern Hemisphere, air temperatures since VOYA's establishment have been above average and there has been a long-term pattern of later freeze, earlier breakup, and shorter duration of ice-cover. Average annual precipitation in VOYA is 24 inches (62 cm), 30% of which is in the form of snow. During the period from 1948 to 2002, there has been a downward trend in precipitation of – 0.31 inches/decade.

Most of the Rainy Lake watershed, including VOYA, is in the Superior Province (3.6-2.5 billion years old) of the Canadian or Precambrian Shield. The Precambrian Shield features in VOYA are some of the most complete and extensive in the United States and are not evident in any other U.S. National Park.

Pleistocene glaciation, the last of which occurred during the Wisconsin ice age that spanned from 50,000 to 10,000 years ago, formed most of the surficial features seen in the Park today. Glacial quarrying and deposition created most of the lakes and streams in the Rainy Lake watershed. As the glaciers retreated north, the melt water formed glacial Lake Agassiz, which covered much of the Rainy Lake watershed. Lake Agassiz, which was last present in the Park about 9,900 years ago filled the region's many lake basins, removed glacial till from many of the bedrock knolls through wave action, and left gray clay deposits in the lower areas of parts of the region. These sediments are unusually rich in soluble minerals and as a result specific conductance measurements in rivers and lakes from these areas are significantly higher than from areas with extensive granitic bedrock exposure.

Water flow through the Rainy Lake drainage, which is part of the Hudson Bay watershed, is generally northwesterly along the International Boundary. The Rainy Lake watershed can be divided into two sub-basins, which includes the 19,270 km$^2$ (7,440 mi$^2$) area above the outlet of Namakan Reservoir at Kettle Falls and the 19,320 km$^2$ (7,460 mi$^2$) area draining directly to Rainy Lake below Kettle Falls. Overall, about 70% of the Rainy Lake basin lies in Ontario and 30% in Minnesota. Based on long-term flow records, about 8.3 billion m$^3$ (2.2 trillion gallons) of water move through the Rainy Lake watershed annually.

Lake levels in the Park's large lakes have been controlled by a hydroelectric dam at the outlet of Rainy Lake and by regulatory dams on Namakan Lake's two main outlets since the early 1900s. In the 1980s, because of its concern about the effects of the regulated lake levels on the aquatic ecosystem, VOYA implemented a research program to 1) assess the effects of regulated water levels on the aquatic ecosystem, and 2) develop alternatives to the existing water management program (1970 rule curves). The species and biological communities investigated were generally found to be adversely effected by the 1970 rule curves, and in particular, by the changes in timing and magnitude of the fluctuations in water levels on Namakan Reservoir. VOYA and other U.S. and Canadian representatives used these and other research results to develop a consensus on how the waters of Rainy Lake and Namakan Reservoir should be managed. In 1993, this group submitted their recommendations to the International Joint Commission (IJC). In 2000, after further analysis and review, the IJC instituted a new (2000 rule curves) hydrologic regime more closely approximating that with which the species and communities in these waters evolved, particularly on Namakan Reservoir. VOYA and the other natural resource agencies are continuing some long-term monitoring and also developing new programs to determine whether the 2000 rule curves are providing the anticipated biological effects.

Rainy Lake, which covers 92,110 ha (227,604 ac), is composed of three geographically distinct basins. The North Arm and Redgut Bay are located entirely in Ontario while the South Arm is divided between Ontario and Minnesota. About 14,738 ha (36,418 ac) or 67% of the South Arm is located within the Park boundary. The three basins in Namakan Reservoir that are located in or at least partially within the Park boundary are Kabetogama, Namakan, and Sand Point lakes. Kabetogama Lake is the largest of these lakes with a surface area of 10,425 ha (25,760 ac). Namakan Lake has a total area of 10,170 ha (25,130 ac), 49% of which is located within the Park boundary. Sand Point Lake has a total area of 3,580 ha (8,869 ac), 59% of which is located within the Park boundary. The Park's 26 interior lakes, 19 of which are located on the Kabetogama Peninsula, range in area from 8 ha to 305 ha. Mukooda and Shoepack lakes are the only interior lakes that have total areas greater than 100 ha.

Limnological surveys have shown that surface waters in the Park are generally of high quality. All the Park lakes except Kabetogama Lake and three shallow, interior lakes are characterized by stable thermal stratification throughout the warm season with mixing only occurring before and after the period of seasonal ice cover. The stratified large lakes have abundant dissolved oxygen throughout the water column and are low in dissolved solids and alkalinity. In the majority of the interior lakes, however, dissolved oxygen concentrations within the hypolimnion fall to levels where members of freshwater fish communities exhibit symptoms of distress.

Light penetration in most VOYA lakes is not regulated by factors related to algal productivity, but by other factors such as stain or color associated with dissolved and colloidal materials. The most significant exception is Kabetogama Lake, which experiences significant mid- to late summer blue-green algae blooms.

The relatively shallow waters of Kabetogama Lake, Sullivan Bay in Kabetogama Lake, and Black Bay in Rainy Lake have different water chemistry (higher nutrients, chlorophyll-*a*, specific conductivity, alkalinity, pH and lower Secchi depth) than the other three large lakes. The primary reason for the differences in water chemistry is that these waters receive inflows from an area west and south, which is overlain by calcareous drift and Lake Agassiz sediments. Sand Point Lake receives most of its inflow from the southeast via the Vermilion and Loon Rivers. Namakan and Rainy lakes, which lie near the eastern and northern boundaries of the Park, receive water that drains a large area of bedrock and thin noncalcareous drift.

Reflective of the area's geology, all of VOYA's lakes have alkalinities characteristic of soft water lakes. All of the interior lakes have alkalinities lower than the large lakes except O'Leary, Little Trout, and Mukooda lakes. Chlorophyll-*a* concentrations in the interior lakes, which were positively correlated with total phosphorus concentrations, were similar to those in the less-productive large lakes. Based on Trophic State Indices determined with chlorophyll-*a* concentrations, the majority of the Park lakes would be classified as mesotrophic. Kabetogama Lake and eight relatively shallow, interior lakes would be classified as eutrophic.

## Biological Communities

Surveys and studies of the Park's lakes have produced genera and species lists and in some instances estimates of relative abundance for phyto- and zooplankton, zoobenthos, aquatic vegetation, fish, and reptiles and amphibians. Interpretation of the survey results, particularly for the plants and invertebrates, however, is hampered by disparities in survey methods and taxonomic expertise of the investigators. A consistent observation, however, has been that the relative abundance of phyto- and zooplankton and benthic invertebrates exhibited a pattern similar to that of primary productivity with densities in Kabetogama Lake being about 2 to 3 times greater than in Namakan, Sand Point, and Rainy lakes, which were approximately the same.

VOYA contains significant wetland resources, a large proportion of which are the result of beaver activity. Overall, beaver activity has resulted in a substantial accumulation of chemical elements that become available for plant growth when dams fail and meadows are formed. A well-designed study that showed that macrophyte communities in the Park's regulated lakes were significantly different than in a large, unregulated lake was a key factor in the Park's attempt to get rule curves that approximated a more natural hydrologic regime.

The Park's fish populations and communities, because of their ecological importance as well as their utilization by Park visitors, have been and continue to be the most intensively studied and monitored biological community. Not unexpectedly, the most emphasis has been placed on those species harvested by anglers. A variety of sampling methods are used to monitor the fish, while creel surveys are used to monitor fishing activity and harvest.

While the number of fish species in the large lakes range up to 40, less than 10 species are present in the majority of the interior lakes. Also, sixteen fish species have been found in the Park's small streams and numerous beaver ponds; however, geological barriers, stages of beaver pond succession, and environmental filters such as hypoxia result in significant variation in species richness and distribution, as well as abundance in these habitats.

While most of the 54 fish species found in the Park are believed to have originated from the Mississippi glacial refugium, on-going debates about post-glacial dispersion patterns and a long history of unrecorded or poorly recorded introductions makes delineation of pre-settlement distributions and identification of non-native fish species in the Rainy Lake watershed and the Park difficult if not impossible. This is particularly true for all the Centrarchids except the rock bass and pumpkinseed that are commonly recognized as being native to the area. Rainbow smelt, which is definitely an exotic species, first appeared in VOYA in 1990.

Sport fishing has traditionally been and continues to be the principal visitor activity in VOYA, with nearly 760,000 angler-hours typically being expended on the large lakes during the summer season. Total summer angling harvests commonly exceed 90,000 kg with walleye and northern pike comprising about 50 – 60% and 25 –38% of the catch, respectively. Because walleye harvests have consistently exceeded target levels, the Minnesota and Ontario natural resource agencies have implemented more restrictive size and creel limits and established sanctuaries in an attempt to reduce angling harvest.

Results from the standardized gill net sampling program, conducted on the Park's large lakes since 1983, have shown that while there was significant variation in year-class strength, the fluctuations within the species were similar in the three Namakan Reservoir basins. This similarity suggests that hydrological conditions and other environmental factors in those basins are having similar affects on reproduction and survival of the fish species. While the magnitudes of the fluctuations in Rainy Lake gill net catches were similar to those in Namakan Reservoir, the fluctuations did not correspond to those observed for Namakan Reservoir catches.

Tagging, which has been used to assess fish movement and exploitation in Rainy and Kabetogama lakes, has shown that there are discrete walleye stocks in the three Rainy Lake basins and in the different basins in Namakan Reservoir. Based on physical-tagging and genetic data, two spawning populations of northern pike in Kabetogama Lake exhibit spawning-site and natal-site fidelity.

The combined efforts of the Park, state and provincial agencies, and independent researchers have produced a significant amount of information about the area's fishery resources, particularly the top predators that support the recreational fisheries. Long-term monitoring programs still need to be designed and implemented that will supplement current programs, but more importantly, that will provide information on the fish community and its structure, including the species that are non-terminal predators. Fisheries managers must have and understand such information if they wish to sustain optimal fishery yields.

## Mercury and Other Contaminants

Mercury concentrations in Park lake water are low, but Hg concentrations in zooplankton, fish, and fish-eating wildlife are high due to food-chain bioaccumulation. Consumption advisories have been imposed on the majority of the Park's lakes due to the health risks posed to humans by Hg-contaminated fish. Although there has been an extensive amount of research on Hg in VOYA, it remains one of the most serious and scientifically challenging contaminant threats to the Park and Nation's aquatic resources. Contaminants other than Hg in fish from the Park waters, primarily the large lakes, are generally low with no discernable trends by lake. Elevated levels of organochlorines and PCBs, however, have been found in herring gulls and other fish-eating birds. These may pose a threat to bald eagles because they commonly prey on the herring gulls.

## Conclusion

Although numerous aquatics-related studies and surveys have been done in VOYA, many questions still need to be answered if the USNPS is to "understand, maintain, restore, and protect the inherent integrity of the natural resources, processes, systems, and values of the Park". Because of the sporadic and uneven nature of much of the work that has been done, we have limited knowledge of temporal and spatial variation in water quality and biological communities; species occurrences and distributions, particularly for lower trophic levels; biotic interactions; and functions and processes. Interior lakes, beaver ponds, and other aquatic habitats, which are integral components of the Park's aquatic ecosystem, need to receive more attention. An integrated monitoring plan that focuses on providing an understanding of the complex network of physical, chemical, and biological factors that influence aquatic systems is needed so that observed changes can be understood and explained and the potential for future changes can be predicted.

# Aquatic Synthesis for Voyageurs National Park

**"…if stationary men would pay some attention to the districts on which they reside, and would publish their thoughts respecting the objects that surround them, from such materials might be drawn the most complete county-histories…Gilbert White 1788 The Natural History of Selborne "**

## Defining the System

Defining the aquatic ecosystem of Voyageurs National Park (hereafter referred to as VOYA or the Park) is complicated by the Park's location at the lower end of the 38,600 km$^2$ (14,900 mi$^2$) Rainy Lake basin, which is part of the headwaters of the Hudson Bay watershed (Figure 1). About 70% of the drainage is in Ontario, and the remainder in Minnesota. In general, the basin is forested and characterized by thin soils and frequent outcrops of Precambrian rocks. Lakes, ponds, and interconnecting streams and rivers comprise about 14% of the basin. Parks and wilderness areas compose 25% of the basin upstream from Voyageurs National Park. The Boundary Waters Canoe Area Wilderness in the Superior National Forest in Minnesota covers 4,387 km$^2$ (1,694 mi$^2$) while the Quetico Provincial Park in Ontario covers an additional 4,788 km$^2$ (1,849 mi$^2$).

VOYA contains significant aquatic resources with about 50% of its total area of 883 km$^2$ (341 mi$^2$) consisting of aquatic habitat types (Hop and others, 2001). In addition to the Park's 30 named lakes (Figure 2), there are numerous wetlands including hundreds of beaver ponds. While some flowing stream segments exist, their numbers are limited due to the Park's exceptionally high beaver density.

Due to the Park's size and location in the drainage basin, aquatic resources within the Park are particularly susceptible to activities and developments that occur outside its' boundary. This is particularly true in regard to the water quality and aquatic communities in the four large lakes that comprise 96% of the Park's total lake area. Three of these four large lakes are border waters shared with Ontario. Only 16% of Rainy Lake, 49% of Namakan Lake, and 58% of Sand

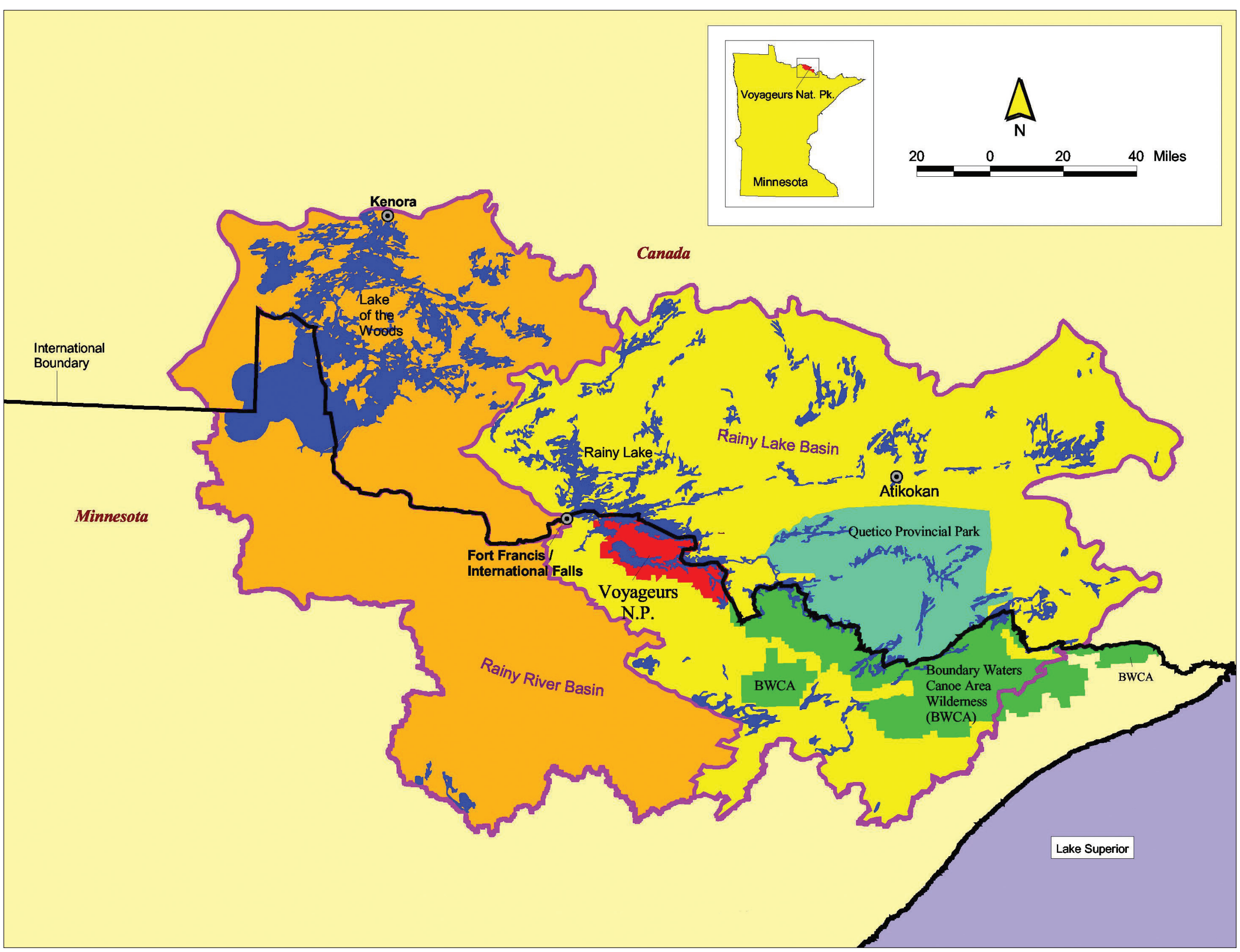



**Figure 1.** Lake of the Woods/Rainy Lake watershed.

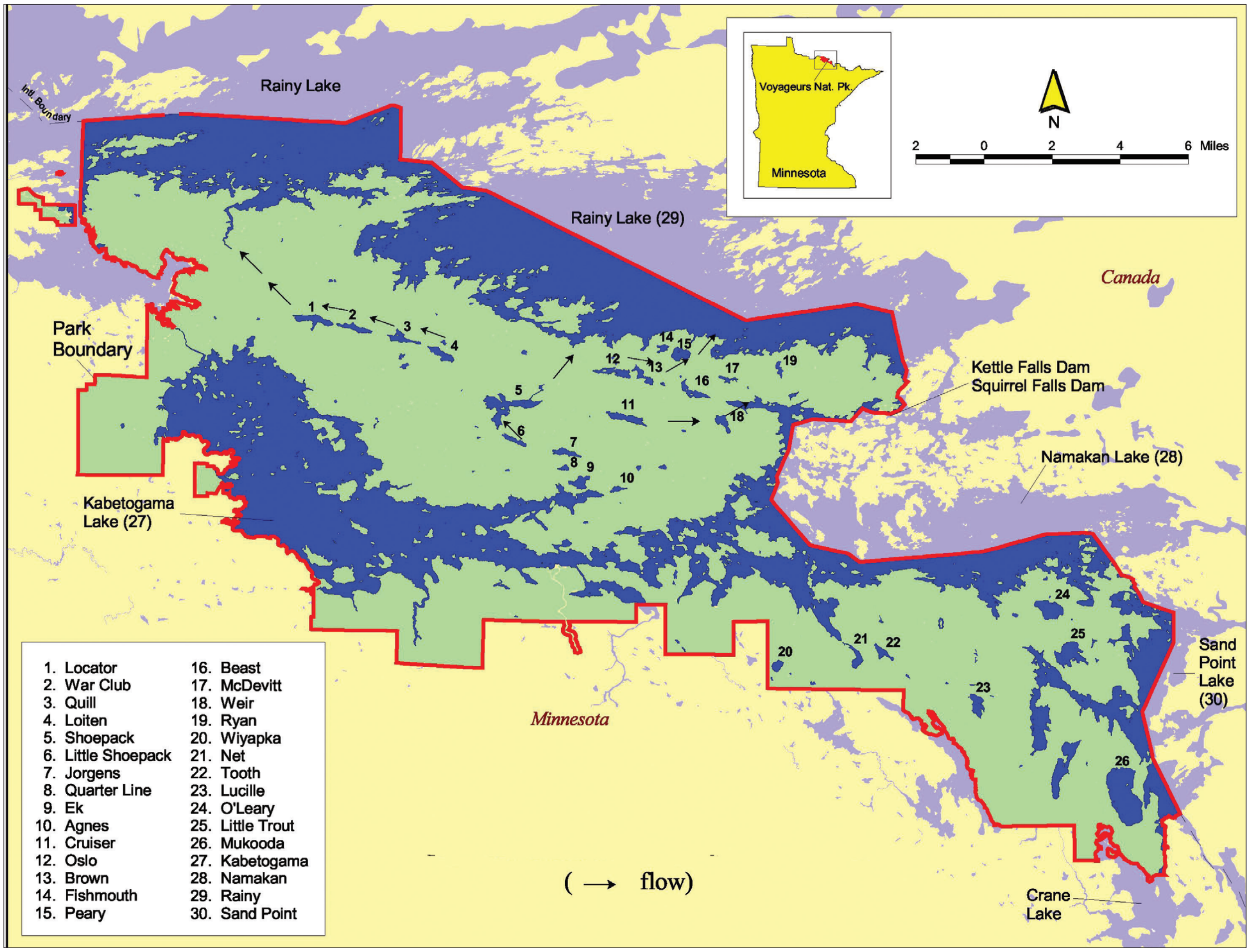



**Figure 2.** Lakes of Voyageurs National Park.

Point Lake are within the Park's boundary. An additional 9% of Rainy Lake is in Minnesota but is not included in the Park. Kabetogama Lake, the other large lake, lies entirely in the Park but is bordered by about 20 km (12.5 miles) of private land.

These lakes and the rivers that flow into them have traditionally been viewed as a hydrological system. For nearly a century, water managers have viewed these waters as an aquatic ecosystem, and have used the system to support a broad range of needs and activities, including power production, navigation, sanitation, domestic water supply, and recreation and other public purposes. A long history of cooperation has existed between the Minnesota Department of Natural Resources (MNDNR) and the Ontario Ministry of Natural Resources (OMNR) on the management of fisheries in the border lakes and the Rainy River. Heinselman (1996) provided an accurate and detailed description of the Boundary Waters ecosystem, including the origin of its landforms, its terrestrial and aquatic communities, and human impacts on the ecosystem. This synthesis report focuses on the aquatic ecosystem of VOYA, including the entire Rainy Lake and Namakan Reservoir basins, their hydrological inflows and outflows, as well as the other aquatic habitats and communities that actually occur within the Park's boundary. The information contained in this report should enable aquatic resource managers in the Park to identify factors that are or might influence the Park's aquatic resources.

# Drainage Basin Characterization

## Climate

The area encompassing VOYA has a continental climate, characterized by moderately warm summers with a mean July temperature of 66 °F (19 °C) and long, cold winters with a mean January temperature of 1.9 °F (-17 °C) (Figure 3; National Oceanic and Atmospheric Administration, 2002). The average annual temperature of 36.9 °F (2.8 °C) has been exceeded in 17 of the 23 years since 1980 (Figure 3). The frost-free season ranges from 110 to 130 days. Lakes are typically covered with ice five to six months of the year. Freeze-up typically occurs in

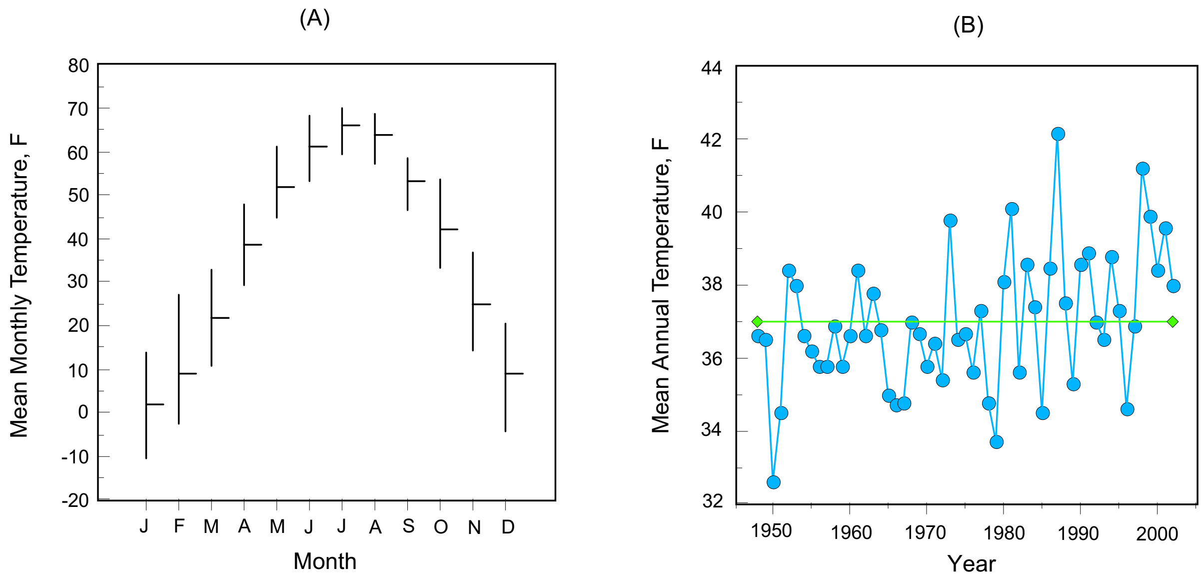



**Figure 3.** (A) Means and ranges in mean monthly temperatures, and (B) average yearly temperatures for International Falls, MN, 1948-2002. The horizontal lines in (A) represent the monthly mean and in (B) the average annual temperature. Data from National Oceanic and Atmospheric Administration (2002).

early to mid-November in the shallower small lakes and bays of the large lakes and extends into late November and early December in the deeper small lakes and main basins of the large lakes. Ice-out commonly occurs between early to mid-April and mid-May, with shallower waters becoming ice-free first. Comparisons of long-term ice-out records for Rainy Lake from 1930-2000 (mean = May 4) and Kabetogama Lake for 1952-2000 (mean = April 30) suggest that ice-out has occurred earlier in recent years (Figure 4). Earlier ice-outs have also been reported for lakes in Wisconsin (Anderson and others, 1996), which were attributed to regional climatic response to El Nino events, and in the Experimental Lakes Area in Ontario (Schindler and others, 1996). Long-term patterns of later freeze, earlier breakup, and shorter duration of ice cover have been observed around the Northern Hemisphere (Magnuson and others, 2000).

Average annual precipitation in VOYA is 24 inches (62 cm), 30% of which is in the form of snow (National Oceanic and Atmospheric Administration, 2002). The wettest and driest periods of the year are June through August and December through March, respectively (Figure 5). During the period from 1948 to 2002, there has been a downward trend in precipitation of – 0.31 inches/decade (Figure 5). Estimates of evapotranspiration from all surfaces in the basin have ranged from 46.5 cm to 49 cm (18 – 19 in), or about 65 to 72% of the mean annual precipitation (Ericson and others, 1976; International Rainy Lake Board of Control, IRLBC 1999). Evaporation from lake surfaces averages 63.5 cm (25 in) (International Rainy Lake Board of Control/International Lake of the Woods Control Board, IRLBC/ILWCB1984). Annual runoff has been estimated as 24.9 cm or 9.8 in (Ericson and others, 1976). A combination of snowmelt and rainfall results in inflow of streams to lakes typically being highest in May and June. Although heavy rains have a low probability of occurrence, they can cause significant runoff and high flow conditions at any time during the open water season. The most recent example of this occurred on June 9-10, 2002 when a 48-hour rainfall total of over 165 mm (6.5 in), which has a one percent probability of occurrence, resulted in flows in many of the tributaries to Rainy Lake being the highest of record (IRLBC 2002).

## Geology

Most of the Rainy Lake drainage, including VOYA, is underlain by Archean continental crust composed of greenstone, gneissic, migmatitic, granitic, meta-sedimentary, and schistose bedrock that is hard and resistant to erosion (Ojakangas and Matsch, 1982). The watershed is in the Superior Province (3.6-2.5 billion years old) of the Canadian or Precambrian Shield, which is exposed through about one-half of Canada and the northern portions of Minnesota, Michigan, and Wisconsin. Park rocks from the Wabigoon and Quetico subprovinces, which evolved during the birth of the North American continent, have been aged at 2.78 to 2.12 billion years (Harris, 1974; Ojakangas

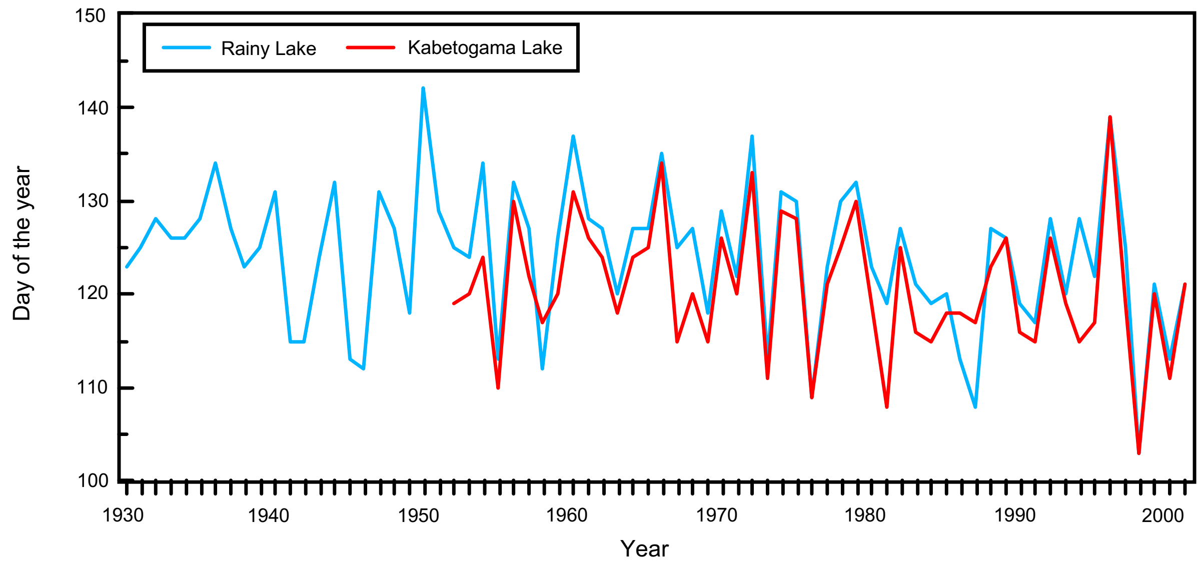



**Figure 4.** Ice-out dates for Rainy (1930-2001) and Kabetogama lakes (1952-2001). (International Falls Daily Journal).

and Matsch, 1982; Day, 1990; Day and others, 1990). The entire Precambrian Shield area has been stable for 500 million years and experiences fewer earthquakes and less violent geologic events than that of areas surrounding it (Geological Survey of Canada, 1999). The Precambrian Shield features in VOYA are some of the most complete and extensive in the United States and are not evident in any other U.S. National Parks.

The oldest geologic feature (2.78 billion years) in VOYA is a narrow band of greenstone that parallels the northwestern border of the Park, running in a southwesterly to northeasterly direction. It is part of a volcano plutonic belt known as the Wabigoon subprovince. Greenstones typically occur as long narrow belts since they were in essence volcanic island chains in an ocean, which later became bounded and intruded by granitic rocks on both sides. Greenstones get their name from the light to dark green color of the green metamorphic minerals chlorite, actinolite, and epidote that were produced when the volcanic rocks were metamorphosed. They are mainly basaltic volcanic rocks with lesser amounts of andesitic and rhyolitic volcanics and associated sedimentary rocks (graywackes, conglomerate, other detrital formations). They have been chemically and structurally reorganized by the addition of water and low-intensity metamorphism after the rocks were erupted and deposited (Ojakangas and Matsch, 1982; Day, 1990; Day and others, 1990; LeBerge, 1996).

The greenstone belt has many layers that were injected and deposited into oceanic waters and onto island arcs. The original layers were relatively horizontal, but now due to tectonic deformation are generally U-shaped, with the deepest and oldest volcanic features on the outside of the U (distorted pillow lavas, tuffs, lava flows and basalt) and the shallowest and youngest metavolcanic and metasedimentary features forming the central parts of the U (LeBerge, 1996).

The greenstone belt, which extends into Ontario, contains mineral concentrations of iron, gold, and other economically important minerals (Minnesota Geological Survey, 1969; LeBerge, 1996). Mineralized veins have been located on several of the Park islands in the belt, including Cranberry, Steamboat, and Grassy Island (Minnesota Geological Survey, 1969). During the 1890s the greenstone belt was prospected and mined for gold. The Little American mine on Little America Island produced $4,600 worth of gold in 1894-95. The last mining activity in the area now occupied by the Park occurred at the Little American mine in 1936-37 when the mine was re-opened and some diamond drilling was done (M. Graves, VOYA Cultural Resource Specialist, personal communication).

The majority of the Park's crust and also that of the Quetico Provincial Park in Ontario consist of rocks of a gneiss belt of the Quetico subprovince that developed about 2.7 billion years ago as the North American continent was growing larger. This belt of sedimentary rocks, which is 530 km long and has an average width of 24 km (Harris, 1970), consists chiefly of metasedimentary schists, various migmatitic rocks derived from ancient sedimentary materials, and granitoid intrusions (Day and others, 1990). These rocks probably formed shortly after the development of the greenstone belts to the north and south of the Park. Most of the rocks of the Kabetogama Peninsula

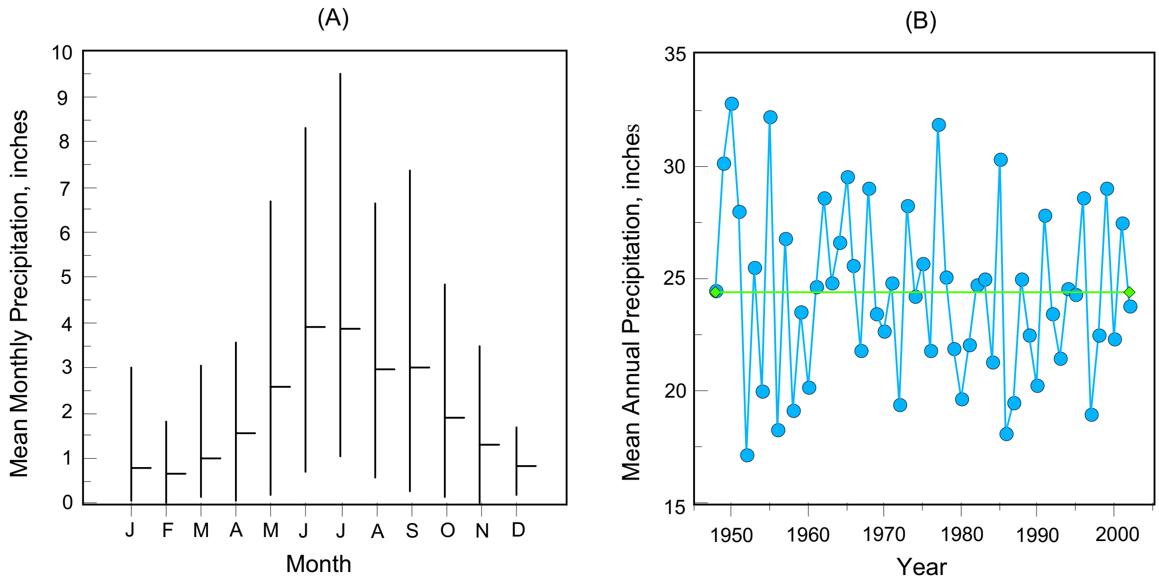



**Figure 5.** (A) Means and ranges in mean monthly precipitation, and (B) total yearly precipitation for International Falls, MN, 1948-2002. The horizontal lines in (A) represent the monthly mean and in (B) the average annual precipitation. Data from National Oceanic and Atmospheric Administration (2002).

and along the shores of Rainy and Namakan lakes are schists.

The rocks of the gneiss belt were formed deep in the crust during a period when geologic conditions were extremely unstable (Ojakangas and Matsch, 1982; LeBerge, 1996). They record a complicated geologic history that involved the development of an accretionary wedge along a margin where two plates of Earth's crust collided. The plates contained island arc systems and were made of oceanic crust. The wedge was made from sedimentary rocks eroded from the arc systems. As the plates collided, the sediments were squeezed and some were scraped off the plate and bent deep down under the crust of the other plate. As the bent plate reached depths in the crust where melting of the sediments and the crust occurred, materials become molten and intruded into the island arch margins and squeezed areas above. The collision of the plates caused folding, faulting, uplifting, melting, and intrusion of molten rock into the crust at great depths.

The most significant granitoid intrusion in the Rainy Lake watershed is the massive Vermilion Batholith, which occupies a significant portion of the Boundary Waters Canoe Area Wilderness, extending from Basswood Lake to Vermilion Lake and north and northwestward far into Quetico and VOYA parks. In VOYA, the granitoid intrusions occur primarily in the southeastern portion of the Park between Sand Point and Johnson lakes and west along the southern boundary to the southwest end of Kabetogama Lake. Small areas of granitic intrusions are also found in the Anderson Bay and Kempton Channel areas of Rainy Lake. There is a zone of migmatitic rocks lying along the contact zone between the schists and the granitoid intrusions.

After solidification of the granitic batholiths in this region of North America, the greenstones and granites were subjected to new stresses that caused movement along numerous faults. Great portions of the crust were moved up or down or horizontally relative to one another. The combination of folding, faulting, and intrusion that resulted from these movements caused regional mountain building - the Algoman Orogeny. The mountains were at least a few kilometers high. Boundaries between the Park's gneiss belt and the flanking greenstone belts to north and south are major fault zones from this era. The development of the greenstone-gneiss belts and subsequent mountain building in the Park and surrounding region occurred over a 50-100 million-year period around 2.7 billion years ago (Ojakangas and Matsch, 1982).

When continental growth stopped in this region of North American, the mountains and other features were a highland that slowly eroded to low relief during the next 2.5 billion years (Ojakangas and Matsch, 1982). The crust of the earth became thinner and uplifted as erosion proceeded and the Precambrian rocks that were originally much deeper in the earth were exposed. The exposed rocks provide evidence of the low-grade metamorphism that occurred at the margins of the gneissic belt and the high-grade metamorphism that occurred in central part of the belt. They also indicate how the partial melting of metasediments resulted in numerous granitic veins invading the older rocks. These mixtures of igneous and metamorphic rocks make up the migmatites common in the Park.

About 2.2 billion years ago, hundreds of northwest-trending dikes intruded into the earth's crust in an area from Cloquet, Minnesota at the south tip of Lake Superior to Kenora, Ontario 233 km northwest of the Park (Southwick and Day, 1983). These dark-brown dikes, which are made up of gabbro, diorite, and diabase formed when molten material from the mantle squeezed into fractures of the crust at great depth. Geologists believe the regional crust was being stretched when the dikes formed. They occur primarily along the southwestern edge of the Rainy Lake watershed (Sims and Mudrey, 1972). In the VOYA area, they occur at road-cuts in the west Kabetogama area and as outcrops along the Echo Bay Trail and Tom Cod Bay.

The final chapter of the Park's and regions geologic history was recorded during the Pleistocene ice age of the last two million years. During this period, four great ice sheets advanced and retreated across the region, the last occurring during the Wisconsin ice age that spanned from 50,000 to 10,000 years ago. Although these events were much different than the Precambrian events, they played an important role in molding the landscape. The region experienced repeated episodes of glaciation followed by ice-free periods (Zoltai, 1961; Prest, 1970; Pielou, 1991). Huge glaciers up to 10,000 feet thick scraped over bedrock that had been weathering and eroding in the area for billions of years. As the glaciers moved, they further eroded whatever was in their path, leaving behind signatures of their presence - polish, grooves, striations, gouge marks, and whalebacks distributed throughout the Park. Debris scraped and plucked from the bedrock was carried great distances from where it was picked up and deposited as till, moraines, erratics, drumlins, and outwash (Ojakangas and Matsch, 1982; Lusardi, 1997). During the Wisconsin period, ice from the Rainy Lobe and the St. Louis sublobe of the Des Moines Lobe came over the Park from different directions and deposited very different materials (Hobbs and Goebel, 1982). Sandy till in the area originated from ice sheets coming from the northeast. Later movement of an ice sheet from the west carried large amounts of clay materials in its load. These deposits are like footprints that retrace glacial movements (Zoltai, 1961; 1965).

Glacial quarrying and deposition, which may or may not have occurred in valleys created by earlier erosional events, created most of the lakes and streams in the Rainy Lake watershed (Zumberge, 1952). The Park's large lakes, Kabetogama, Namakan, and Rainy, lie in bedrock basins that cannot be related logically to a preglacial drainage system. The islands and headlands of these lakes typically consist of granite and pegmatite while the bottom of the bays is schist, which is more easily eroded (Zumberge, 1952).

As the glaciers retreated north, the earth's crust which had been depressed by their immense weight rebounded leaving a topography consisting of bare bedrock, bedrock covered with thin till deposits, and pockets of lake clays and other lacustrine components (OMNR, 1977). Most of the Rainy Lake watershed became ice-free about 11,000 to 12,000 years ago (Ojakangas and Matsch, 1982). During deglaciation, the formation, recession, and expansion of proglacial lakes was controlled by the position of the ice sheet margin, which alternately blocked or created drainage channels for the enormous amounts of melt water originating from the Laurentide ice. The melt water formed glacial Lake Agassiz that at its maximum extent inundated over 300,000 $km^2$ of northern Minnesota, Ontario, Manitoba, and Saskatchewan (Teller and Clayton, 1983). Lake Agassiz, which was extant from 12,500 to 7,500 years ago, covered much of the Rainy Lake watershed during several of its phases. Analysis of sediments from Cayou Lake, a small lake on the Kabetogama Peninsula, indicates that Lake Agassiz was last present in the Park during the Emerson Phase or about 9,900 years ago (Winkler and Sandford, 1998a).

The soils of the Rainy Lake watershed are the products of materials deposited by glaciers and Lake Agassiz that have been subsequently reworked and redeposited by water, wind, and wave action (OMNR, 1977; USNPS, 1994; Heinselman, 1996). Two basic soil associations, shallow upland forest soils and deep organic soils, occur throughout the region, typically with very abrupt transitions (Arneman, 1963). The upland associations, which are glacial in origin, consist primarily of coarse to fine textured noncalcareous sandy fill and decomposed igneous rock. The till that remains is generally less than 15 m thick (Ericson and others, 1976), and depending on slope and location commonly ranges in thickness from <1 m to 3 or more meters. If this material is derived from granite, it is typically quite acidic and low in nutrients and consequently, the productivity and diversity of the ecosystem it supports is low. In contrast, till and soils derived from metasedimentary and greenstone bedrock are moderately acidic and rich in nutrients, thus these areas support a more diverse and productive ecosystem.

The deep organic soils, which consist of coarse to fine textured forest soils, calcareous lacustrine clays, and organic materials, occur in lowland areas and marshy areas that are poorly-drained depressions surrounded by bedrock. The cool, wet and acidic environment prevent plants from disintegrating completely and the partially decomposed plants accumulate and eventually create a deep, spongy peat. While most peat lands in Minnesota have been created by this process of paludification, (Glaser, 1987), classical lake filling with its characteristic accumulation of sediments and sequence of development of various vegetation types has also occurred. The raised bogs contain plant species common to patterned peatlands including ericaceous shrubs, sedges, mosses, sundew, pitcher plants, and orchids. Runoff from these areas contributes to the tea color and low alkalinity observed in most of the Park lakes.

Lake Agassiz, in addition to filling the region's many lake basins and through wave action removing glacial till from many of the bedrock knolls, left gray clay deposits in the lower areas of much of the region. These deposits, which range from one to 10 m thick, are most extensive to the south and west of Kabetogama Lake and along the Wawiag River in Quetico Provincial Park. These clays occur at maximum elevations between 1250 and 1300 ft above sea level in VOYA (Heinselman, 1996). These sediments are unusually rich in soluble minerals and as a result specific conductance measurements in rivers and lakes from these areas are significantly higher than from areas with extensive granitic bedrock exposure (Figure 6; Ericson and others, 1976). Because of these higher concentrations of nutrients in inflows, primary productivity is higher in Kabetogama Lake and Black Bay of Rainy Lake than in the Park's other large lakes (Payne, 1991). These deposits also support unusual southern plant species that are unable to survive in the prevalent sterile, acidic soils of the region.

## Hydrology

Water flow through the Rainy Lake drainage is generally northwesterly along the International Boundary. Under average flow conditions, changes in flow initiated at the headwaters take about 21 days to reach the outlet of Rainy Lake. The waters drop about 135 m (443 ft) in the 338 km (210 miles) between these two points (IRLBC/ILWCB, 1984). Based on long-term flow records, about 8.3 billion $m^3$ (2.2 trillion gallons) of water move through the Rainy Lake watershed annually (Ericson and others, 1976).

Rainy Lake, the largest lake in the drainage, has a surface area of 921 $km^2$, 75% if which is in Ontario. The lake has three distinct basins: the North Arm, Redgut Bay, and the South Arm in which the Park and the remaining Minnesota portion of the lake are located. Namakan Reservoir lies immediately upstream of Rainy Lake and encompasses Namakan, Kabetogama, Sand Point, Crane, and Little Vermilion lakes. Namakan Reservoir has a surface area of 260 $km^2$,

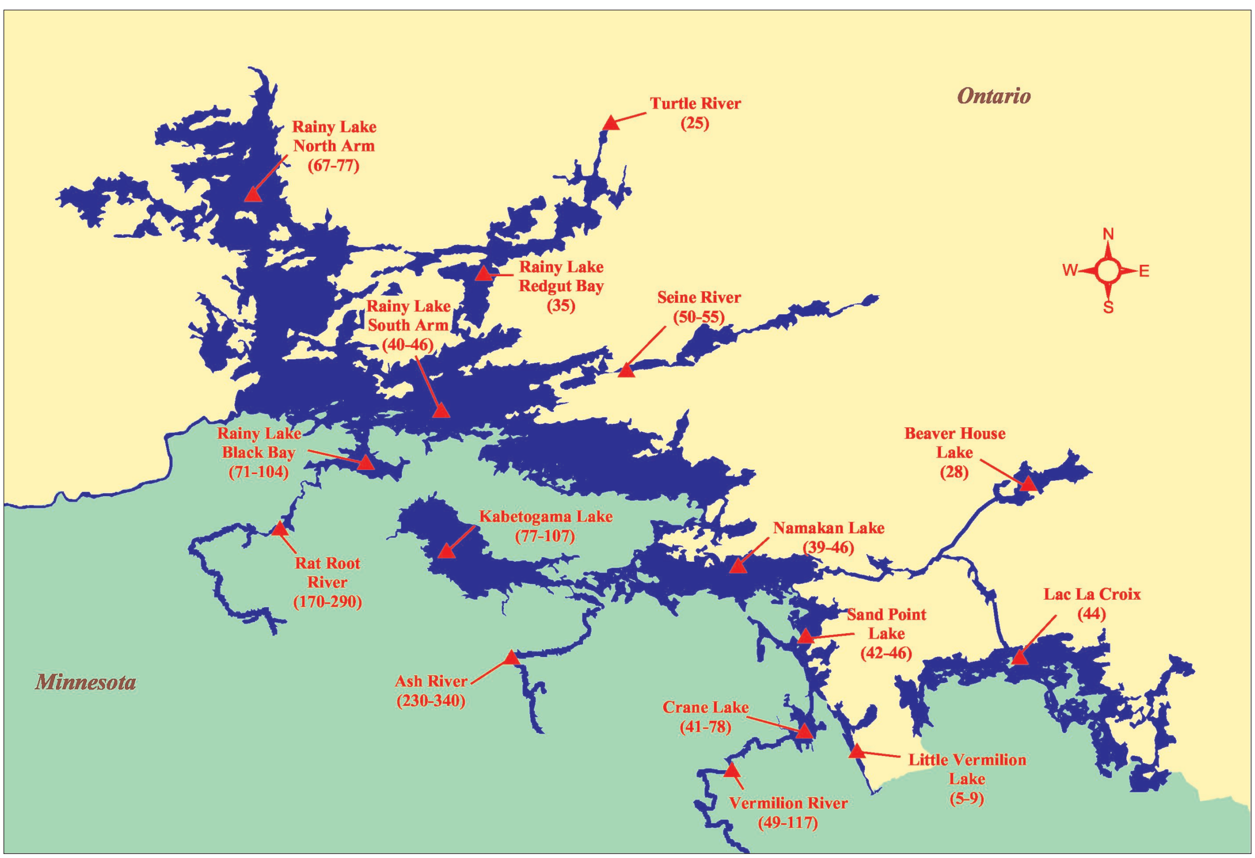



**Figure 6.** Specific conductance measurements (µS/cm) in lakes and rivers in and draining into Voyageurs National Park. Data sources are Ericson and others (1976), Sutton and others (1985), Payne (1991), Anderson and Heiskary (2001), and OMNR unpublished data.

77% of which is in Minnesota. The volume of Rainy Lake is about 3 times that of Namakan Reservoir. Based on their volumes and total annual discharges, water in Rainy Lake and Namakan Reservoir could theoretically be "flushed out" or have a residence time of 359 and 235 days, respectively.

The Rainy Lake watershed can be divided into two sub-basins, which includes the 19,270 $km^2$ (7,440 $mi^2$) area above the outlet of Namakan Reservoir at Kettle Falls and the 19,320 $km^2$ (7,460 $mi^2$) area draining directly to Rainy Lake below Kettle Falls. About 54% of the Namakan Reservoir drainage is in Minnesota and 46% in Ontario. For the area downstream from Kettle Falls, 6% of the drainage is in Minnesota and 94% in Ontario. The Namakan River, which is the largest single source of inflow to the Park with a mean discharge of 109 $m^3$/sec, and the Vermilion River with a mean discharge of 9 $m^3$/sec contribute about 80% of the inflow into Namakan Reservoir. Discharge from Namakan Reservoir into Rainy Lake, most of which occurs through the dams at Kettle and Squirrel Falls, has averaged about 146 $m^3$/sec or 51% of the outflow from Rainy Lake.

In addition to the regulated outflows at Kettle and Squirrel Falls, overflows occur at Bear Portage and Gold Portage that transfer water from Namakan Reservoir to Rainy Lake. Flow commences at Gold Portage, which connects Kabetogama Lake with Black Bay in Rainy Lake, when the water elevation of Namakan Reservoir reaches 339.39 m (1113.5 ft) and at Bear Portage when the elevation is 340.39 m (1116.8 ft) (IRLBC/ILWCB, 1984). Stream flow records from the USGS gaging station at Gold Portage, which was established in 1984, indicate that the average incidence of flow was 253 days per year under the International Joint Commission's (IJC) 1970 Order. Flow incidence is expected to increase to between 325 and 365 days per year under the IJC's 2000 Order. At the lower limit of summer levels, the capacity of these unregulated overflows can be approximately 60% of the specified minimum flow at Kettle Falls (IRLBC, 1999). However, from 1988 to 1999 the summer discharge through Gold Portage averaged 10.3% of the discharge at Kettle Falls while that of Bear Portage was only about 1%.

The Turtle River (mean discharge = 37 $m^3$/sec) and the Seine River (mean discharge = 48 $m^3$/sec) are the two principle tributaries that enter Rainy Lake below Kettle Falls. The outflow from these tributaries and Namakan Reservoir contribute about 81% of the outflow from Rainy Lake, which has averaged 286 $m^3$/sec for the period from 1923 to 1999. The Rainy Lake outflow provides nearly 70% of the inflow to Lake of the Woods. Historically, flows in the drainage have been highly variable (coefficient of variation ~ 33%) with no discernable trends either up or down (Figure 7). During the 27 years since VOYA was established both high (1985, 1996, 2001, 2002) and low (1980, 1987, 1998) discharges have occurred, but compared to long-term mean discharges the number of years that have been above and below average are about equal.

Outflows from the Park's interior lakes are divided equally with 13 discharging into Namakan Reservoir and 13 into Rainy Lake (Figure 2). There are three chains or series of interior lakes that discharge into Rainy Lake – Loiten, Quill, War Club, Locator; Little Shoepack and Shoepack; and Oslo,

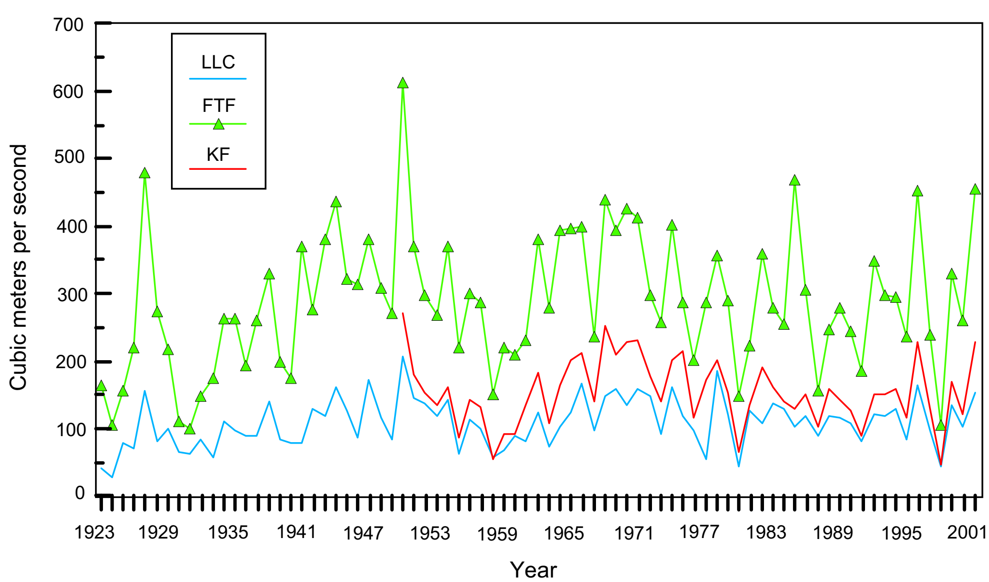



**Figure 7.** Mean annual discharge for the Namakan River at Lac La Croix (LLC), Kettle Falls (KF), and Rainy River at Fort Francis (FTF) gauging stations, 1923-2001.

Brown and Peary. The outflow from Cruiser Lake flows to Weir Lake, which then empties into Mica Bay on Namakan Lake. Some drainages are poorly defined due to the limited relief and the extensive networks of beaver impoundments. Consequently, under high water conditions the headwaters of some drainages could conceivably be connected.

While all the Park's interior lakes occupy distinct basins, water levels in several of them are held above the elevation of the natural sill height by beaver dams built on the lake outlets. As a result, rapid changes in water levels may occur if the dam is blown out by an extreme storm event. For example, in late July 2001 when the area received over 12.5 cm (5 in) of rain from one storm, the water level on Shoepack Lake dropped nearly 1.8 m (6 ft.) when the beaver dam on its outlet was blown out. Similar blowouts have occurred on Net Lake at least twice since the Park was established. The most recent, which occurred in 2001, dropped the water level over one meter. Storm related blowouts of dams controlling beaver ponds also occur frequently, contributing to the dynamic nature of those systems.

## Regulated Lake Levels

Lake levels in the Park's large lakes have been controlled by a hydroelectric dam at the outlet of Rainy Lake and by regulatory dams on Namakan Lake's two main outlets since the early 1900s. The latter dams control the lake levels in Namakan Reservoir, which includes Kabetogama, Namakan, Sand Point, Crane, and Little Vermilion lakes. While all these lakes existed as natural water bodies, the present day reservoirs are larger and are regulated to satisfy a variety of water users.

Since these are international waters, shared by Canada and the United States, the International Joint Commission (IJC) regulates them. Legally recognized water uses are navigation, sanitation, domestic water supply, power production, and recreation and other public purposes. While the dams are regulated by the IJC, they are owned and operated by private industry. Industry is responsible for the day-to-day operation of the dams, the IJC becomes involved only if it's rules are not, or cannot be followed.

In 1949, the IJC established its first Order defining when emergency conditions exist and prescribing the method of regulating lake levels to preclude the occurrence of such conditions on Rainy Lake and Namakan Reservoir (IRLBC/ILWCB, 1984). This Order was subsequently amended by Supplementary Orders in 1957 and 1970, with the latter being in effect at the time that VOYA was established. Although allowable annual fluctuations remained the same under this sequence of Orders, actual fluctuations on Namakan Reservoir tended to decrease (Figure 8). Under the 1970 Order, however, larger-than-natural fluctuations on Namakan Reservoir continued to be used to maintain less-than-natural fluctuations on Rainy Lake. The timing of the fluctuations was also altered with the regulated system, particularly on Namakan Reservoir.

Concerns about the effects of the regulated lake levels on the aquatic biota had been expressed ever since the dams were constructed (Sharp, 1941; Johnson and others, 1966; Chevalier, 1977; Osborn and others, 1981). However, the establishment of

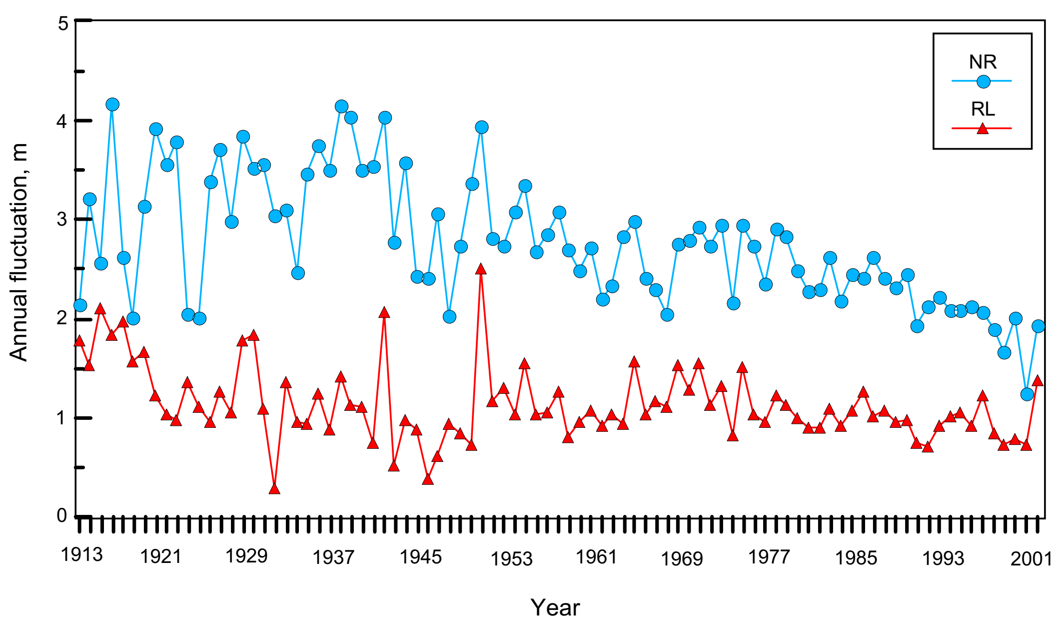



**Figure 8.** Annual fluctuations in water levels on Namakan Reservoir and Rainy Lake, 1913-2001.

VOYA, with its emphasis on restoring and preserving the natural environment, heightened the concern about the impacts of the regulated lake levels on the aquatic ecosystem (Cole, 1979; 1982). Because of those concerns, in 1983 the U.S. National Park Service (USNPS) started a research program to assess the impacts of the regulated lake levels on the Park's aquatic ecosystem and develop possible alternatives to the existing water management program (Kallemeyn, 1983). The research program included studies dealing with littoral vegetation (Meeker and Wilcox, 1989); benthic organisms (Kraft 1988); the fish community, particularly walleye and northern pike (Kallemeyn, 1987a; 1987b); shore and marsh nesting birds, particularly the common loon and red-necked grebe (Reiser, 1988); and aquatic furbearers, including beaver (Smith and Peterson, 1988; 1991), muskrat (Thurber and others, 1991), and river otter (Route and Peterson, 1988). Additional studies to obtain baseline information dealt with primary production in the large lakes (Kepner and Stottlemyer, 1988) and the relationship between lake levels and boat dock usability (Kallemeyn and Cole, 1990). A hydrological model was developed that could be used to assess the effects of alternative regulatory programs (Flug, 1986).

The species and biological communities that were investigated were generally found to be adversely affected by the existing water management programs, and in particular the greater-than-natural fluctuations in water levels on Namakan Reservoir (Kallemeyn and Cole, 1990; Kallemeyn, 1992; Kallemeyn and others, 1993). Impacts occurred throughout the year, with those in a particular season frequently the result of a combination of water level conditions that occurred in previous seasons. The plants and animals did not appear to have adjusted to the changes in the magnitude and timing of fluctuations since the dams were constructed, and in particular to the existing water management program. Management techniques that would provide a hydrologic regime more closely approximating that with which these species evolved appeared to present the best opportunity for overcoming these problems. Embracing this philosophy, the USNPS in 1990 developed and evaluated 13 alternative regulatory programs (Kallemeyn and Cole, 1990). Each alternative was analyzed with a hydrology model (Flug, 1986) to determine if the reservoir system could accommodate the alternative under both normal and extreme hydrologic conditions. The model also provided projections of hydropower production for each alternative.

Results from both the model analysis and environmental studies were then used in an impact assessment matrix to assess the potential effects of the various alternatives. Ranking factors were developed for various biological attributes along with hydropower production, navigation, flood control, archeological resources, public beaches, boat dock usability and susceptibility to ice damage, all of which could be affected by changes in the water management programs. The ranking factors were used to evaluate effects of the alternatives on the attributes, with the results then being entered into the matrix. The matrix, although based on simplifying assumptions about complex ecological and economic relationships, provided a means of integrating the information so that it could be used to facilitate discussions among various water users. As the USNPS analysis proceeded in 1990, concerns continued to be expressed about the existing water management program, particularly effects on navigation, flood control, power generation, and water access. Proponents for those uses felt the agency's preferred alternative did not adequately address their concerns and placed too much emphasis on ecosystem integrity.

In 1991, the Rainy Lake & Namakan Reservoir Water Level International Steering Committee, (RLNRISC) steering committee was formed to develop a consensus on how the waters of Rainy Lake and Namakan Reservoir should be managed. The RLNRISC consisted of U.S. and Canadian representatives from private industry, the public, and government. The pertinent U.S. agencies, including the USNPS, U.S. Fish and Wildlife Service (USFWS), and the MNDNR, recognizing the international implications of such a plan and the need to also address the concerns related to Namakan Reservoir, worked with their Canadian counterparts to establish the RLNRISC so that the concerns of both U.S. and Canadian water users could be addressed. Also, this committee was formed, as a result of a U.S. Federal Regulatory Commission (FERC) licensing action for the U.S. portion of the hydroelectric dam at the outlet of Rainy Lake. The license, which was issued in 1987, required the licensee to "develop a water-level plan for Rainy Lake to ensure the protection and enhancement of water quality, fish and wildlife, and recreational resources in Rainy Lake."

From 1991 to 1993, the RLNRISC implemented a program involving extensive analyses of data, discussions, public consultations, and reviews. The USNPS supported research studies and a study conducted by Cohen and Radomski (1993) were key elements in the deliberations. Boise Cascade Corporation provided hydrologic modeling results that were also a significant component of the evaluations (Acres International Limited, 1993). After two years of deliberation and extensive public involvement, the RLNRISC concluded that changes to the existing 1970 Order were warranted and in fact were necessary to improve both the environment and economy of the area. In November 1993, the RLNRISC officially submitted a final report containing specific proposals for new regulations for Rainy Lake and Namakan Reservoir to the IJC. In February 1994, Boise Cascade Corporation, who had been a member of the RLNRISC, submitted a statement to the IJC requesting that the 1970 Order be retained.

In April 1995, the IJC requested that its International Rainy Lake Board of Control (IRLBC) prepare a study plan to review its 1970 Supplementary Order for the regulation of Rainy Lake and Namakan Reservoir. The request was in response to the concerns expressed by the RLNRISC and other parties in the basin (IRLBC, 1999). Key areas for study identified in the final study plan were hydrologic modeling, inflow forecasting, flood risk assessment, navigation and the potential for ice-damage, the fishery and other environmental resource factors, and economic/social/recreation factors (IRLBC, 1999). Upon completion of the study, in which many of the environmental findings of the USNPS and the RLNRISC were substantiated, the IRLBC recommended to the IJC that the 1970 Supplementary Order be modified.

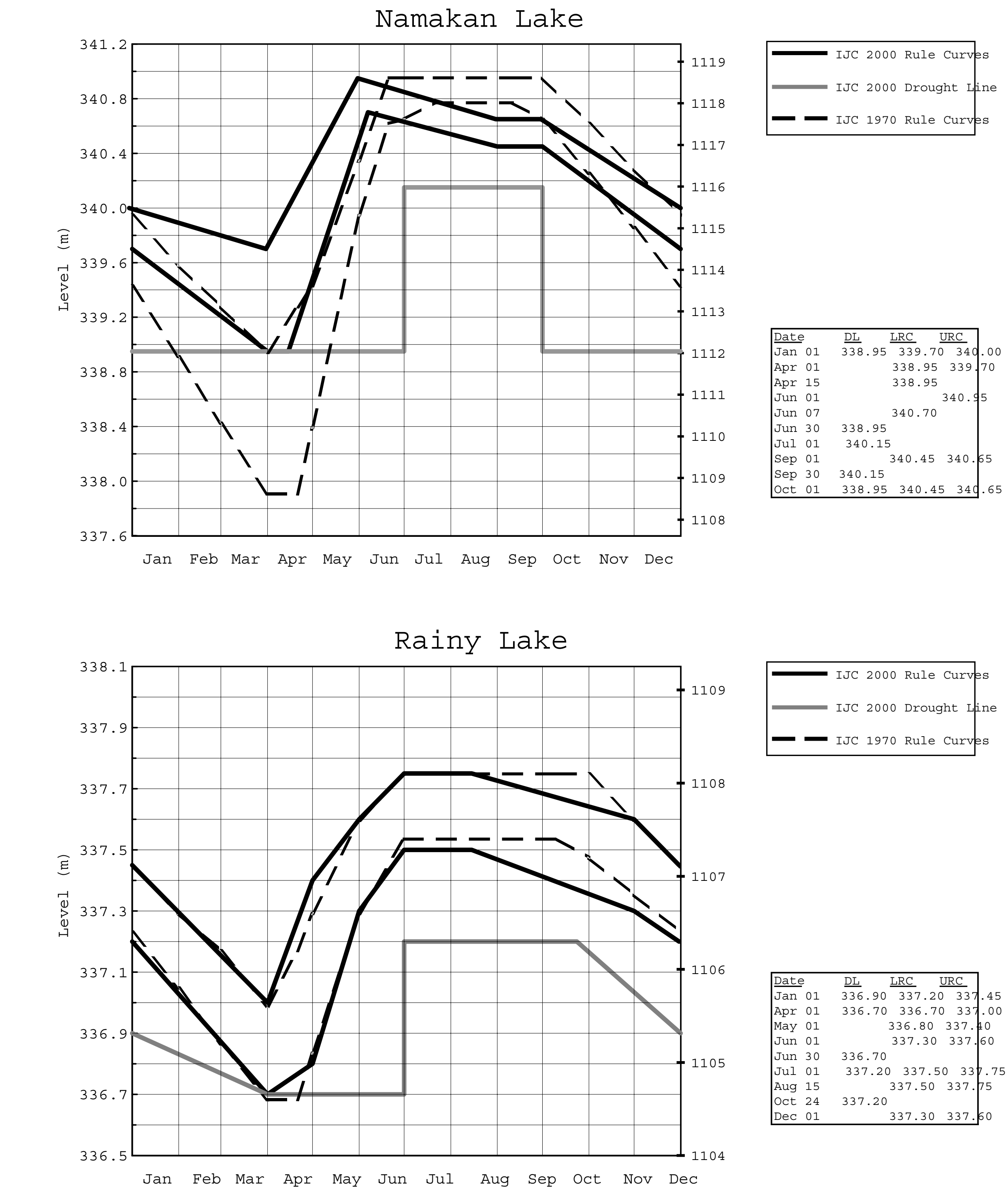
On January 6, 2000, the IJC issued a new supplementary order (the 2000 Order) for the management of Rainy Lake and Namakan Reservoir. The 2000 Order (1) essentially adopted the rule curves for Namakan Reservoir proposed by the RLNRISC, but with a wider band during the spring refill; (2) maintained the existing 1970 rule curves for Rainy Lake, but with a slightly wider band during the spring refill period and a modest drawdown in late summer and fall; and (3) required the dam owners to operate so as to normally target for levels in the middle of the rule curve bands (Figure 9). The 2000 Order also took into account improvements to water quality in the Rainy River that allow lower discharges under low-flow conditions than were previously desirable. Although restoration of more extreme periodic fluctuations in lake levels such as would occur in an unregulated system was discussed in the IRLBC (1999) report, such fluctuations were not included in the 2000 Order.

The section of the 2000 Order stating that it was subject to review after 15 years and that “the review shall, at minimum, consider monitoring information collected by natural resource management agencies and others during the interim that may indicate the effect of the changes contained in this Supplementary Order” was especially pertinent to the Park and other proponents of rule curve change. To facilitate the development of a monitoring program, the IJC contracted with the U.S. Geological Survey to organize and host a facilitated workshop. The goals of the workshop were to (1) define the scope of the monitoring program, (2) develop monitoring protocols for fisheries and other major components of the aquatic communities, and (3) identify possible funding mechanisms for implementation of the monitoring protocols. A binational workshop involving about 60 scientists and resource managers was held in International Falls, MN on January 11-12, 2000 (Kallemeyn, 2000).

Workshop participants did not develop the detailed monitoring protocols. However, the participants did identify approaches and provided general guidance that might be used by the resource managers and scientists who are ultimately charged with the development of such comprehensive monitoring plans. The participants unanimously called for the formation of a joint U.S. and Canadian coordinating committee to oversee the development and implementation of a long-term monitoring program. The goal of the committee would be to design a monitoring and assessment program that would accurately and reliably measure performance indicators, thereby allowing assessment of progress toward meeting the objectives of the program. Establishment of objectives and evaluation criteria is critical since without them there will be no means of determining in the allotted 15 years if the 2000 Order provided the anticipated environmental benefits.

It was recognized that implementation of such a long-term monitoring program would require long-term commitments not only from the natural resource agencies, but also from industry, other agencies, and the public concerned with these significant water resources, and that obtaining the financial resources needed to support the program would be a significant and ongoing challenge. While the natural resource agencies are willing to continue their existing programs, they don’t in most cases have the financial resources and in some cases the expertise to expand their programs into new areas. Most funding sources that are available to natural resource agencies are short-term in nature (<5 years) and would be more suited for supporting process-oriented research studies than long-term monitoring. While trying to obtain long-term funding to support the monitoring program, the coordinating committee must ensure that those aspects of resource agency programs that are essential to the success of the monitoring program are maintained.

Fortunately, the resource agencies have been able to continue their ongoing monitoring programs, particularly those dealing with the fish communities. VOYA has done some survey work relative to loons and beaver and has acquired two-year funding to support the development of a monitoring protocol for aquatic vegetation. The OMNR has provided some supplemental financial support for this effort and is procuring satellite photos that can be used in the vegetation analysis. VOYA has also obtained funding to




| Date | DL | LRC | URC |
|---|---|---|---|
| Jan 01 | 338.95 | 339.70 | 340.00 |
| Apr 01 | | 338.95 | 339.70 |
| Apr 15 | | 338.95 | |
| Jun 01 | | | 340.95 |
| Jun 07 | | 340.70 | |
| Jun 30 | 338.95 | | |
| Jul 01 | 340.15 | | |
| Sep 01 | | 340.45 | 340.65 |
| Sep 30 | 340.15 | | |
| Oct 01 | 338.95 | 340.45 | 340.65 |

| Date | DL | LRC | URC |
|---|---|---|---|
| Jan 01 | 336.90 | 337.20 | 337.45 |
| Apr 01 | 336.70 | 336.70 | 337.00 |
| May 01 | | 336.80 | 337.40 |
| Jun 01 | | 337.30 | 337.60 |
| Jun 30 | 336.70 | | |
| Jul 01 | 337.20 | 337.50 | 337.75 |
| Aug 15 | | 337.50 | 337.75 |
| Oct 24 | 337.20 | | |
| Dec 01 | | 337.30 | 337.60 |

**Figure 9.** Comparison of International Joint Commission 1970 and 2000 rule curves. Levels are in meters and feet above mean sea level.

assess the possible effects of the changes in reservoir operations on trophic-state indicators and mercury accumulation in fish and other components of the aquatic ecosystem. Thus, some work has been accomplished that is applicable to evaluating the effects of the 2000 Order, albeit in a piece-meal fashion.

The establishment of a broad-based ecological monitoring program, however, has not taken place. In 2002, VOYA and the Ontario and Minnesota natural resource agencies finally established a coordinating committee to guide the development and implementation of a long-term comprehensive ecological monitoring program. The committee is currently in the initial stages of planning and establishing a program, much of which will be funded from 2004 to 2006 by the USNPS. In February 2002, the OMNR sponsored a workshop to refine the monitoring priorities identified at the 2000 workshop (Kallemeyn, 2000) and to provide guidance to the newly established coordinating committee. Scope of works and study plans are to be developed in 2003 for those organisms and communities the committee has identified as being the "best bets" for assessing the effects of the 2000 rule curves. The actual studies and monitoring are to be initiated in 2004.

## Lake Morphometry and Drainage Area Characteristics

For consistency, this synthesis utilizes the morphometric values for the Park's four large lakes produced by the MNDNR/OMNR (1998). While generally similar to the MNDNR/OMNR values, other estimates that exist, for example, Chevalier, 1977; IRLBC/ILWCB, 1984; Kepner and Stottlemyer, 1988; and VOYA, unpublished data, exhibit considerable variation. The discrepancies among these morphometric values should be resolved by GIS analysis of the digitized maps that exist for the four lakes.

Morphometric characteristics of the Park's interior lakes were determined by planimetry analyses of bathymetric maps obtained from the MNDNR (VOYA/USGS, unpublished data). Drainage areas for the interior lakes were determined by planimetry of 1:24,000 scale U.S. Geological Survey topographic maps. The drainage area is the total land area, measured in a horizontal plane, enclosed by a topographic divide, from which direct surface runoff from precipitation normally drains by gravity into a wetland, lake, or river (Armantrout, 1988). The drainage area does not include the lake area. The percent littoral zone (LITT) is the proportion of the lake area less than 4.6 m deep. Formulas presented by Wetzel (1983) were used to calculate shoreline development ($D_L$) and volume ($V$) values for the interior lakes. Shoreline development ($D_L$) is the ratio of the length of the shoreline ($L$) to the circumference of a circle of an area equal to that of the lake. Volumes were estimated by summation of the frusta of a series of truncated cones of the depth strata identified on the MNDNR bathymetric maps. Insulosity ($A_i$) values are the percentage of the area within the lake shoreline occupied by islands (Hutchinson, 1957).

Morphometric values for the large lakes are presented in Table 1. Rainy Lake, which covers 92,110 ha (227,604 ac), is composed of three geographically distinct basins. The North Arm 34,590 ha (85,472 ac) and Redgut Bay 8,320 ha (20,559 ac) are located entirely in Ontario while the South Arm is divided between Ontario 27,300 ha (67,458 ac) and Minnesota 21,900 ha (54,115 ac). About 14,738 ha (36,418 ac) or 67% of the South Arm is located within the Park boundary. The South Arm is the deepest of the three basins, having maximum and mean depths of 49.1 m and 10.7 m, respectively. The mean depth for the whole lake is 9.9 m. The lake has 1,495 km of irregular shoreline and as a result it has a high $D_L$ value of 14.4. The insulosity value for Rainy Lake, which contains hundreds of islands, has not been determined.

The three basins in Namakan Reservoir that are located in or at least partially within the Park boundary are Kabetogama, Namakan, and Sand Point lakes. Kabetogama Lake is the largest of these lakes with a surface area of 10,425 ha (25,760 ac). Namakan Lake has a total area of 10,170 ha (25,130 ac), 4,987 ha (12,323 ac) of which is located within the Park boundary. Sand Point Lake has a total area of 3,580 ha (8,869 ac) of which 2,096 ha (5,179 ac) is located within the Park boundary. Kabetogama Lake is the shallowest of the three basins, with maximum and mean depths of 24.4 m and 9.1 m. Although Namakan Lake's mean depth exceeds that of Sand Point Lake, the latter contains the deepest spot in Namakan Reservoir and Rainy Lake. Shore development and insulosity values are 5.8 and 8.8% for Kabetogama Lake, 6.6 and 12.9% for Namakan Lake, and 7.2 and 2.8% for Sand Point Lake. Percent littoral zones in these basins range from 20% to 32%.

The Park's 26 interior lakes, 19 of which are located on the Kabetogama Peninsula (Figure 2), range in area ($A$) from 8 ha (Quarter Line Lake) to 305 ha (Mukooda Lake) (Table 1). Sixteen (61.5%) lakes have areas of less than 40 ha (99 acres), whereas eight have areas between 40 and 100 ha. In addition to Mukooda Lake, Shoepack Lake is the only interior lake that has a total area greater than 100 ha. The drainage area: lake surface area ratios of the interior lakes range from 2.4 to 57.2, with arithmetic means and medians of 12.2 and 7.6, respectively. There is a significant positive relationship between the area of the interior lakes and their individual drainage areas ($r^2 = 0.351$, $P = 0.001$, N =26). This relationship is important because generally lakes with larger drainage area: lake area ratios have higher ion concentrations as a result of increased input of materials to the lake on an areal basis (Lillie and Mason, 1983).

Maximum and mean depths in the interior lakes range from 2.4 and 1.5 m in Weir Lake to 29.0 m and

**Table 1.** Morphometric characteristics of 30 lakes in Voyageurs National Park, Minnesota. Littoral area (%) = proportion of lake <15 ft (4.6m) deep. Insulosity ($A_i$) = percentage of area within shoreline occupied by islands.

| Lake | Lake Area ($A$) (ha) | Watershed to Lake area ratio | Shore development ($D_L$) | Maximum depth ($z_m$) (m) | Mean depth ($z$) (m) | Littoral area (%) | Volume ($m^3x10^6$) | Insulosity ($A_i$) (%) | Renewal time (years) | MNDNR Lake class |
|---|---|---|---|---|---|---|---|---|---|---|
| Agnes | 12.9 | 57.2 | 1.8 | 5.5 | 2.5 | 85 | 0.3 | | 0.2 | 13 |
| Beast | 32.8 | 6.8 | 2.0 | 20.1 | 6.1 | 60 | 2.0 | 3.0 | 3.6 | 10 |
| Brown | 30.8 | 20.9 | 2.1 | 8.2 | 4.2 | 51 | 1.3 | | 0.8 | 10 |
| Crusier | 46.5 | 3.5 | 2.0 | 27.7 | 13.2 | 19 | 6.2 | | 15.4 | 3 |
| Ek | 36.0 | 7.1 | 1.6 | 5.8 | 2.4 | 85 | 0.8 | 0.1 | 1.3 | 13 |
| Fishmouth | 12.9 | 2.5 | 1.5 | 8.5 | 3.8 | 62 | 0.5 | | 5.9 | 10 |
| Jorgens | 24.7 | 7.0 | 1.8 | 5.8 | 3.0 | 77 | 0.7 | | 1.7 | 10 |
| L. Shoepack | 22.7 | 6.5 | 1.8 | 7.6 | 2.5 | 91 | 0.6 | 1.1 | 1.5 | 13 |
| L. Trout | 96.7 | 2.6 | 1.8 | 29.0 | 13.0 | 33 | 12.6 | 0.2 | 20.0 | 5 |
| Locator | 56.7 | 21.7 | 2.4 | 15.8 | 8.1 | 32 | 4.6 | | 1.5 | 10 |
| Loiten | 36.6 | 7.9 | 1.6 | 14.9 | 7.8 | 25 | 2.9 | | 4.0 | 10 |
| Lucille | 53.0 | 2.9 | 1.6 | 5.8 | 2.5 | 92 | 1.3 | 0.5 | 3.5 | 13 |
| McDevitt | 12.1 | 11.1 | 1.7 | 7.0 | 2.1 | 85 | 0.3 | | 0.8 | 13 |
| Mukooda | 305.0 | 2.5 | 1.3 | 23.8 | 12.2 | 20 | 37.4 | 0.5 | 19.9 | 5 |
| Net | 43.7 | 9.2 | 2.1 | 3.7 | 2.0 | 100 | 0.9 | | 0.9 | 12 |
| OíLeary | 78.5 | 3.5 | 1.2 | 17.1 | 7.1 | 33 | 5.6 | | 8.1 | 5 |
| Oslo | 42.5 | 11.6 | 2.4 | 11.0 | 4.7 | 62 | 2.0 | 4.1 | 1.6 | 10 |
| Peary | 45.3 | 18.8 | 1.4 | 4.6 | 2.6 | 100 | 1.2 | 0.9 | 0.6 | 12 |
| Quarter Line | 8.3 | 3.1 | 1.6 | 6.7 | 3.1 | 85 | 0.3 | | 4.0 | 13 |
| Quill | 34.4 | 16.1 | 1.9 | 14.0 | 6.9 | 27 | 2.4 | 1.6 | 1.7 | 10 |
| Ryan | 14.2 | 7.0 | 1.6 | 3.7 | 2.1 | 100 | 0.3 | | 1.2 | 14 |
| Shoepack | 123.8 | 16.1 | 2.4 | 7.3 | 2.9 | 82 | 3.6 | 2.3 | 0.7 | 13 |
| Tooth | 23.5 | 7.3 | 1.8 | 13.1 | 5.9 | 47 | 1.4 | | 3.2 | 10 |
| War Club | 36.8 | 22.7 | 1.9 | 12.2 | 5.8 | 41 | 2.2 | | 1.0 | 10 |
| Weir | 26.8 | 29.1 | 1.7 | 2.4 | 1.5 | 100 | 0.4 | | 0.2 | 17 |
| Wiyapka | 20.2 | 13.3 | 1.2 | 5.2 | 2.7 | 86 | 0.6 | | 0.8 | 13 |
| Kabetogama | 10425.0 | 196.7 | 9.0 | 24.3 | 9.1 | 30 | 948.7 | 8.8 | | 2 |
| Namakan | 10170.0 | 192.7 | 6.5 | 45.7 | 13.6 | 20 | 1383.1 | 11.5 | 0.6* | 2 |
| Rainy | 92100.0 | 41.9 | 14.4 | 49.1 | 9.9 | 35 | 9117.9 | | 1.0 | 2 |
| Sand Point | 3580.0 | 566.8 | 7.0 | 56.1 | 12.0 | 32 | 430.7 | 3.3 | | 2 |

* Renewal time is for Namakan Reservoir

13.2 m in Little Trout Lake and Cruiser Lake, respectively (Table 1). However, the depth distributions are heavily skewed with maximum depths being less than 15 m in 20 lakes and mean depths less than 5 m in 16 lakes. Mean to maximum depth ratios, which serve as an index of lake basin form, average 0.47 and range from 0.30 to 0.62. Significant positive relations exist between both log transformed maximum and mean depths and lake area. The relations are $\log_e z_m = 0.738 + 0.411 \log_e A$ ($r^2 = 0.241$, $P = 0.011$, N = 26), and $\log_e z = -0.125 + 0.435 \log_e A$ ($r^2 = 0.295$, $P = 0.004$, N = 26).

The percent littoral zone in the interior lakes ranges from 19 to 100%, with mean and median values of 65% and 69%, respectively (Table 1). $D_L$ values for the interior lakes are considerably lower than in the large lakes and range from 1.23 to 2.68 with a mean of 1.83 (Table 1). Insulosity ($A_i$) values range from 0.1 to 3.0% in the 10 interior lakes that contain islands (Table 1).

The theoretical water renewal time (= mean hydraulic residence time) is a useful system-level index that has similar ecological implications for rivers, lakes, and reservoirs (Søballe and Kimmel, 1987). Numerous factors important to aquatic ecosystem function are related to water movement including sedimentation rates, resuspension, dilution, nutrient supply, turbidity, and spatial and temporal variability. The residence time of water in lakes can have a significant effect on phytoplankton biomass and production (Søballe and Kimmel, 1987). However, because outflows from VOYA's interior lakes are not gaged and because no detailed studies have been conducted, it is only possible to develop order-of-magnitude hydrological comparisons of this important index at this time. Theoretical water renewal times ($\tau$ = the number of years required to replace a lake volume) for the interior lakes were calculated using a method described by Brunskill and Schindler (1971). Parameters needed for the calculations include land drainage area, lake surface area, lake volume, average precipitation (68 cm), lake evaporation (63.5 cm, IRLBC/ILWCB 1984), and evapotranspiration (49 cm, IRLBC, 1999). Estimates of $\tau$ for the interior lakes ranged from 0.3 to 37.7 years, with 21 of the 26 lakes having values of seven or less years (Table 1). Such values are typical in lakes (Wetzel, 1983). The three lakes with lake trout populations, Mukooda, Little Trout, and Cruiser, had the longest estimated retention times because of their relatively large volumes. Fishmouth Lake, a small and not exceptionally deep lake, had a relatively high retention value (11.1 years) because of its limited drainage area. Refining these estimates will require significant effort since the analytical techniques for determining water balances are complex and must be conducted over several years to allow for variations in climate (Wetzel, 1983).

The 30 lakes in the Park have been assigned by the MNDNR to lake classes using an ecological classification system developed by Schupp (1992) from data for 3,029 Minnesota lakes (Table 1). Parameters used to classify the lakes are lake area, maximum depth, shoreline length, percent littoral area (area of lake with depth <4.6m), Secchi disk transparency, and total alkalinity. The Park's four large lakes are in class 2, while eight interior lakes are in class 13 and 10 in class 10. There are three interior lakes in class 5, two in class 12, and one each in classes 3, 14, and 17. The principal feature distinguishing the Class 2 lakes is their large size. Of the two other predominant classes represented in the Park, lakes in Lake Class 10 tend to be larger and have a smaller proportion of littoral area than lakes assigned to Lake Class 13.

**Future Needs and Opportunities:** As previously indicated, the discrepancies among the morphometric values for the large lakes should be resolved by GIS analysis of the existing digitized maps. That analysis should also include determining the numbers and areas of islands and shoreline lengths. To help with future studies and long-term monitoring of the interior lakes, permanent benchmarks should be established at each lake so that changes in water levels and related morphological features can be determined. The MNDNR bathymetric maps for the interior lakes should be georectified and digitized so that they can be used in the Park's GIS. Aerial photos and satellite imagery should be obtained on a regular basis so that changes in wetland types and areas can be monitored.

## Physical, Chemical, and Trophic State Observations for VOYA Lakes

There has been significant spatial and temporal variation in the limnological surveys of the Park lakes, with the most extensive being those conducted by Hargis (1981), Payne (1991), and the VOYA/USGS long-term monitoring program. Hargis (1981) sampled the four large lakes and Ek Lake from 1978 to 1980, and a total of 19 other interior lakes in 1979 and 1980. From 1977 to 1984, the USGS in cooperation with the National Park Service, monitored water quality at 41 sites in the four major lakes, 19 small interior lakes, and 2 streams (Payne, 1991). Comparative sampling was done at seven of the large lake sites in 1999 (Payne, 2000). Beginning in 1981 for Kabetogama and Namakan Lakes and in 1983 for Rainy and Sand Point Lakes, water quality samples have been taken 11 times each summer from May through September by VOYA in cooperation with the USGS (VOYA/USGS, unpublished data). Additionally, a similar monitoring program has been conducted on each of the Park's 26 interior lakes for at least one full summer. Other surveys involving the large lakes include those of Kepner and Stottlemyer (1988) and the MNDNR's annual mid-July collection, which was initiated in 1983 (Eibler, 2001a, b). Kepner and Stottlemyer (1988) selected sampling sites that were located in proximity to those that were previously used by Hargis (1981) and Payne (1991). Additional limnological surveys of the interior lakes include those of Webster and Brezonik (1995), Whitman and others (2002), and a May 2000 sampling of 12 lakes by the Minnesota Pollution Control Agency. Cruiser, Loiten, Locator and Shoepack lakes, which were selected because they were considered to be susceptible to acidification by acid deposition, were part of USEPA's Long-Term Monitoring (LTM) program from 1978-1995 (Newell and others, 1987; Webster and Brezonik, 1995). Whitman and others (2002) monitored limnological conditions in Locator and Mukooda lakes in 1997 and 1998. Temporally, sampling frequency has ranged from bi-weekly (VOYA/USGS, unpublished data), to monthly (Hargis, 1981; Kepner and Stottlemyer, 1988; Whitman and others, 2000), to 2-4 times per year (Payne, 1991; Webster and Brezonik, 1995).

Interpretation of the results of the limnological surveys, particularly for the estimates of primary production, is complicated by the variety of sampling designs that have been used by the various investigators. In addition to the previously noted temporal and spatial variation, sample collection procedures have included surface grabs, individual samples from depths of one to five meters, as well as integrated samples from a variety of depths. Most of the investigators have assessed primary productivity by using spectrophotometry or fluorescence to determine chlorophyll-*a* concentrations, which provide a measure of phytoplankton biomass (Hargis, 1981; Kepner and Stottlemyer, 1988; Payne, 1991; USNPS, 1995; Whitman and others, 2002; Eibler, 2001a; 2001b; VOYA/USGS, unpublished data). The exception being Kepner and Stottlemyer (1988) who used the in situ $^{14}C$ method to determine production rates in the four large lakes in 1985 and 1986.

**Temperature, dissolved oxygen, and light:** Because of their known importance to biological processes (Wetzel, 1983), measurement of temperature, dissolved oxygen (DO) and light conditions have generally been included in the limnological surveys (Hargis, 1981; Kepner and Stottlemyer, 1988; Payne, 1991; Whitman and others, 2002; Minnesota Pollution Control Agency, unpublished data; VOYA/USGS, unpublished data). Most of these surveys have been limited, either spatially or temporally, and in some instances this has resulted in erroneous conclusions. For example, Kepner and Stottlemyer (1988) concluded that thermal stratification in the large lakes was infrequent and unstable based on sampling sites that did not include the deepest water in any of the basins. Long-term monitoring at sites that are located near each lake's deepest point, however, has shown that while stratification is infrequent and unstable in Kabetogama Lake, that is not the case in the other large lakes (VOYA/USGS, unpublished data).

Based on the results of the VOYA/USGS long-term monitoring program, all the Park's lakes are dimictic, except Kabetogama, Lucille, Net, and Ryan lakes, which would be identified as discontinuous cold polymictic under Lewis's (1983) classification system. The dimictic lakes are characterized by stable stratification throughout the warm season with mixing only occurring before and after the period of seasonal ice cover. Discontinuous lakes may be stratified for several days or weeks but mixing may occur at irregular intervals. Stratification will develop in Kabetogama Lake during extended periods of hot, still weather but it is usually short-lived since the first significant wind typically returns the lake to a nearly homogeneous state. When Kabetogama Lake does stratify, dissolved oxygen (DO) concentrations commonly fall to less than 4 mg/L at depths of more than 10 m. In the other large lakes, August hypolimnetic DO exceed 5 mg/L. Average epilimnion thicknesses in Sand Point, Namakan, and Rainy lakes in mid-August are 8, 12, and 13 m, respectively. Epilimnion temperatures, which typically peak in late July and early August, are similar in these lakes with mean mid-August epilimnion temperatures ranging from about 18 to 23 ºC (Figure 10). Mean hypolimnion temperatures have been consistently higher as well as more variable in Rainy and Namakan lakes than in Sand Point Lake (Figure 10). Fall turnover in Rainy and Namakan lakes typically has occurred in early to mid-October and in Sand Point Lake in late October or early November.

The long-term water temperature database, when combined with climatic and hydrologic data, serves as a useful tool in assessing changes in growth and survival of fish. During the past 20 years, significant variation has occurred in the number of growing degree days >10 ºC. Accumulated degree days >10 ºC for the surface to 10 m depth zone (~ epilimnion) in the large lakes have varied by 300 to 400 units (Figure 11). Preliminary analyses have found that these fluctuations in accumulated degree days in the lakes are positively correlated with air degree days ($r = 0.70$, $P = 0.002$). Also, there is some indication that the fluctuations are affected by summer discharge. Accumulated heat is apparently flushed downstream in years with high discharges. Some of the observed variations appear to coincide with El Nino and La Nina events and the global cooling that resulted from

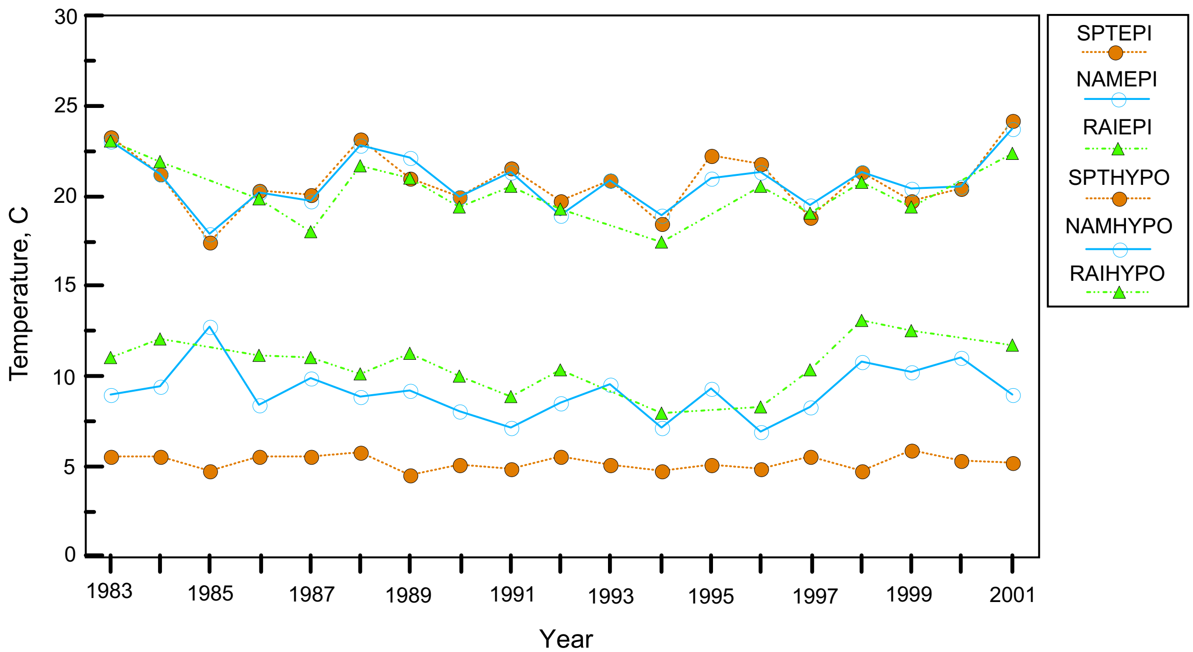



**Figure 10.** Mean epilimnion and hypolimnion temperatures in mid-August in Sand Point, Namakan, and Rainy lakes, 1983-2001.

the Mount Pinatubo eruption in 1991. However, more detailed analyses are needed to assess the effect of global climate trends and annual events on the lakes thermal environment.

Thermal stratification is dependent on several physical features including lake area, maximum depth, basin shape, water color, orientation to prevailing winds, and surrounding topographical features (Hutchinson, 1957). In VOYA's interior lakes, where stratification commonly develops within two weeks of iceout, epilimnion thicknesses in 18 of the 23 stratified lakes were four meters or less. In the other five lakes, which include the three deeper lakes with lake trout populations, the epilimnion was between 5 and 7 m thick. Monitoring from 1997 to 1999 for Locator and Mukooda lakes showed that epilimnion thicknesses were consistent from year to year. Mid-August temperatures in the epilimnion were relatively consistent and ranged from 21 to 24 ºC. Mean hypolimnion temperatures during this period were between 5 and 10 ºC in 15 lakes, between 10 and 15 ºC in 6 lakes, and >15 ºC in two lakes. Use of the colder water by fish, however, is restricted by low DO concentrations. DO levels in the meta- and hypolimnion were below 4 mg/L in 18 of the 23 lakes, and below 2 mg/L in 13 lakes. At such low DO levels, many members of freshwater fish communities start to exhibit symptoms of distress (Davis, 1975).

Fall turnover occurs when epilimnion temperatures cool sufficiently to equalize water density differences between the upper and lower portions of the lakes. A significant positive relationship was observed between fall turnover dates and mean depths in the interior lakes; turnover date (day of the year) = 250.378 + 4.683 (z, m) ($r^2$ = 0.692, $P$ = 0.000, N = 14). Thermoclines typically started to move downward in late August and early September so that in lakes with mean depths of <3 m turnover was usually complete by mid-September. In contrast, the three deepest interior lakes, Cruiser, Little Trout, and Mukooda, typically will not turnover until late October or early November. Observed turnover dates agreed quite closely with dates predicted by a model developed by Nurnberg (1988).

Light penetration in VOYA lakes has been measured primarily with a Secchi disk. Exceptions are Hargis (1981) who used a photometer to determine the percent light transmittance through the water column and Kepner and Stottlemyer (1988), who used a LiCor LI – 185B quantum sensor to measure Photosynthetically Active Radiation (PAR), which is a measure of light quantity important in aquatic primary production. A significant positive relationship exists between the light transmission readings from the 24 lakes sampled by Hargis (1981) and the mean Secchi disk values obtained from those lakes by VOYA/USGS. The equation relating Secchi disk visibility (S) to visible light transmittance (T) is: T = -12.041 + 17.393 (S, m) ($r^2$ = 0.831, $P$ = 0.000, N = 24).

A number of factors may influence the transmittance of light through surface water columns. Hargis (1981) found a significant negative relationship between transmittance and chlorophyll-*a*

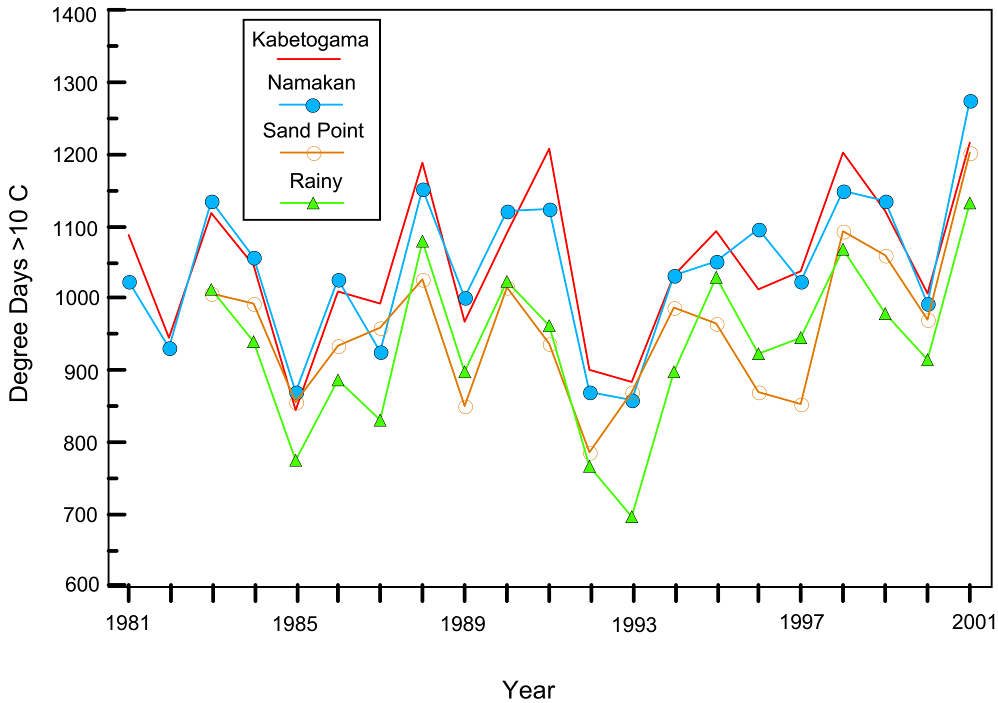



**Figure 11.** Accumulated degree days >10 °C in the surface to 10 m depth zone in Kabetogama, Namakan, Sand Point, and Rainy lakes, May 23-September 26, 1981-2001.

concentrations in 24 Park lakes; however, Kepner and Stottlemyer (1988) and Payne (1991) concluded that light penetration in most VOYA lakes was not regulated by factors related to algal productivity, but by other factors, particularly stain or color associated with organic materials. The most significant exception would be Kabetogama Lake, which experiences significant mid- to late summer algal blooms. Color associated with dissolved and colloidal materials have also been found to effect light transmittance in humic lakes in Wisconsin (Birge and Juday, 1934) and in northwestern Ontario (Schindler, 1971).

VOYA lakes have been separated into three management groups based on water clarity (Hargis, 1981). Transmittance values were <17% in low clarity lakes, were between 17 and 40% in medium clarity lakes, and were >40% in high clarity lakes. Five VOYA lakes were classified in the low clarity category; 11 were classified in the medium clarity category; and 8 were classified in the high clarity category. VOYA's four large lakes were classified as having medium clarity. In these lakes, Secchi disk readings for the low, medium, and high clarity categories would be <1.9 m, 1.9 to 2.9 m, and >3.0 m, respectively. Based on VOYA/USGS Secchi disk readings, three of the six lakes not sampled by Hargis would fall in the low clarity category and three in the high clarity group (Figure 12).

**Water chemistry:** The relatively shallow waters of Kabetogama Lake, Sullivan Bay in Kabetogama Lake, and Black Bay in Rainy Lake have different water chemistry than the other three large lakes (higher nutrients, chlorophyll-*a*, specific conductivity, alkalinity, pH and lower Secchi depth). One main reason for this is that they receive inflow from the Ash (Kabetogama Lake) and Rat Root Rivers (Black Bay) from an area west and south that is overlain by calcareous drift. Sand Point Lake receives most of its inflow from the southeast via the Vermilion and Loon Rivers. Namakan and Rainy lakes, which lie near the eastern and northern boundaries of the Park, receive water that drains a large area of bedrock and thin non-calcareous drift. The effect of these various inflows on the lakes water chemistry is reflected in the composition of the dominant cations. Although the order of cation concentrations in all the lakes is the typical Ca>Mg>Na>K observed in lakes in the temperate zone (Wetzel, 1983), there is a noticeable difference in the Ca to Mg ratio. In Sand Point Lake, Kabetogama Lake, and Black Bay the ratio is 1.7-1.8:1 while in Namakan Lake and Rainy Lake it is 2.2-2.3:1 (Payne, 1991).

Water quality for the Ash River site at the entrance to Sullivan Bay in Kabetogama Lake generally had poorer water quality compared to the other large lake sites (Figures 13-15). Samples collected during 1977-83 along Ash River indicated that commercial and residential development were not degrading Ash River water quality since high concentrations

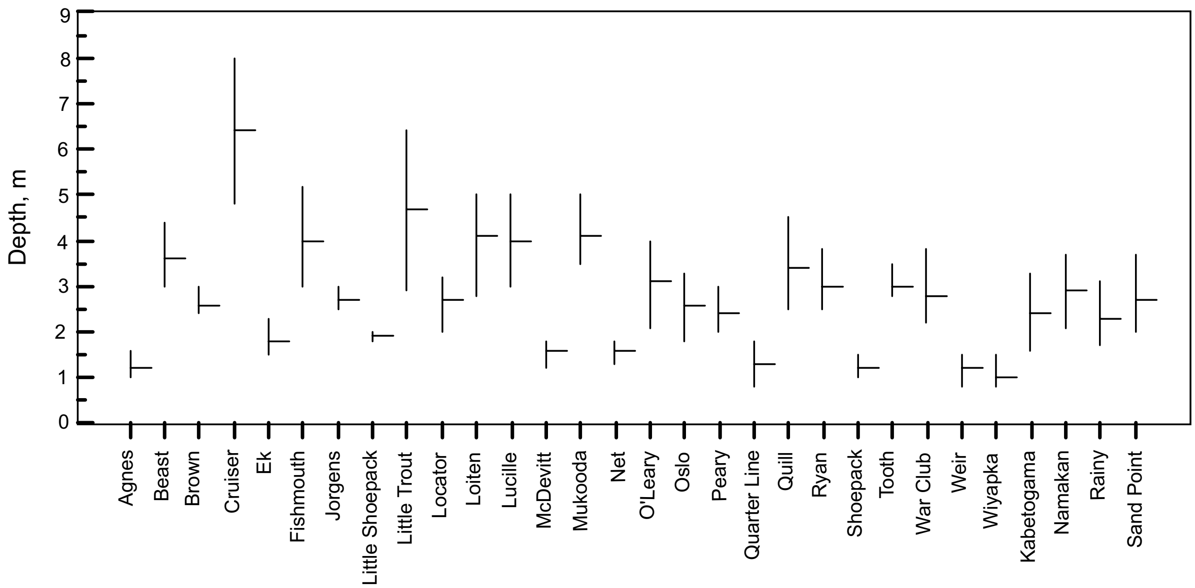



**Figure 12.** Means (vertical lines) and ranges (horizontal lines) of Secchi disk readings from 30 lakes in Voyageurs National Park, Minnesota.

of total phosphorus and chlorophyll-*a* were present upstream as well as downstream (Payne, 1991). Apparently, the degraded water quality was the result of inflow from the richer geological substrates.

Interquartile ranges for specific conductivity and alkalinity were narrow for all areas except Ash River, where they were markedly higher (Figure 13). Specific conductance and alkalinity in 1999 did not differ substantially from the 1977-1983 values, indicating fairly stable chemistry (Payne, 2000). The increased specific conductance in Sand Point Lake in 1999 may have been due to above-normal inflow from the Vermilion River in the summer of 1999 (Payne, 2000). A decrease in alkalinity in 1999 in Kabetogama Lake may have been due to above-normal inflow of relatively low alkalinity water from Namakan Lake (Payne, 2000).

The broad, shallow, sunny waters of Ash River at Sullivan Bay, and the shallow polymictic waters of Kabetogama Lake have higher nutrient concentrations (Payne, 1991). Total phosphorus (TP), total nitrogen, and chlorophyll-*a* levels have tended to be higher at these sites (Figures 14, 15), while transparency has been lower (Figure 15). Namakan, Rainy and Sand Point lakes, which undergo dimictic stratification and share a common flow system, generally had higher transparency and lower algal productivity (Figure 16; Payne, 1991). In general, the rankings of mean summer chlorophyll-*a* concentrations have been Kabetogama>Sand Point<>Rainy>Namakan (Hargis, 1981; Kepner and Stottlemyer, 1988; Eibler, 2001a; 2001b). The ranking would be similar for these lakes based on August chlorophyll-*a* concentrations from 1980 to 1983 and mid-July concentrations from 1990 to 2000 (Payne, 1991; Eibler, 2001a; 2001b). Mean summer concentrations in Kabetogama Lake (range 7.75 – 11.41 mg/m$^3$) were about 2 to 3 times those in the other large lakes (2.11 – 4.73 mg/m3). Peak chlorophyll-*a* concentrations in Kabetogama Lake, which are associated with blue-green algae blooms (cyanobacteria), typically occur in August and are commonly 5 to 6 times higher than spring and early summer levels and peak levels in the other large lakes.

The productivity data (carbon assimilation rates) collected from VOYA's large lakes showed similar rankings and patterns (Kepner and Stottlemyer, 1988). The mean volumetric carbon assimilation rate for Kabetogama Lake (29.4 mgC m$^3$ 4 hours) was about 2.2 times the mean rates for the other large lakes. Productivity peaks occurred earlier in Namakan and Rainy lakes (May or June) than in Kabetogama Lake (August). Greatly reduced productivity was observed in September and October, except in Kabetogama Lake.

Significant differences were observed in total phosphorus, chlorophyll-*a*, and Secchi disk transparency between 1977-83 and 1999 (Payne, 2000). Total phosphorus values from 1999 were lower than in 1977-83 in Black Bay and Kabetogama Lake. Total nitrogen concentrations in 1999 were lower than the 1977-83 median concentrations in all the major water bodies except Ash River (Figure 15). Chlorophyll-*a* concentrations at Kabetogama Lake, Ash River and Black Bay dropped 10 to 13 percent from the 1977-83 median values, and thus were similar to median concentrations in the less productive Namakan, Rainy

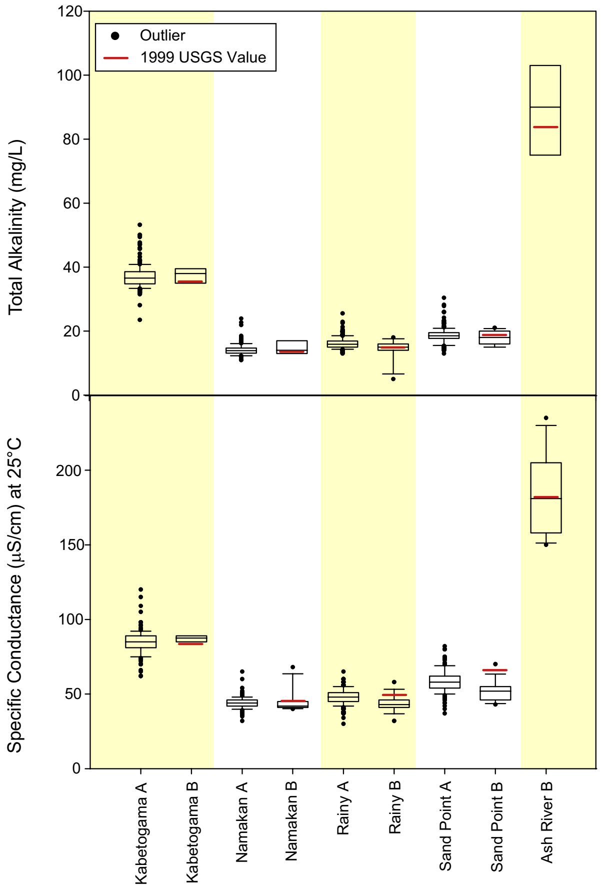



**Figure 13.** Comparison of total alkalinity and specific conductance data collected by VOYA/USGS personnel (unpublished) and the U.S. Geological Survey (Payne 1991) from selected lakes in Voyageurs National Park. A represents data collected by VOYA/USGS unpublished (bi-weekly May-September 1981-2000); B represents data collected from USGS (May and August 1977-1983).

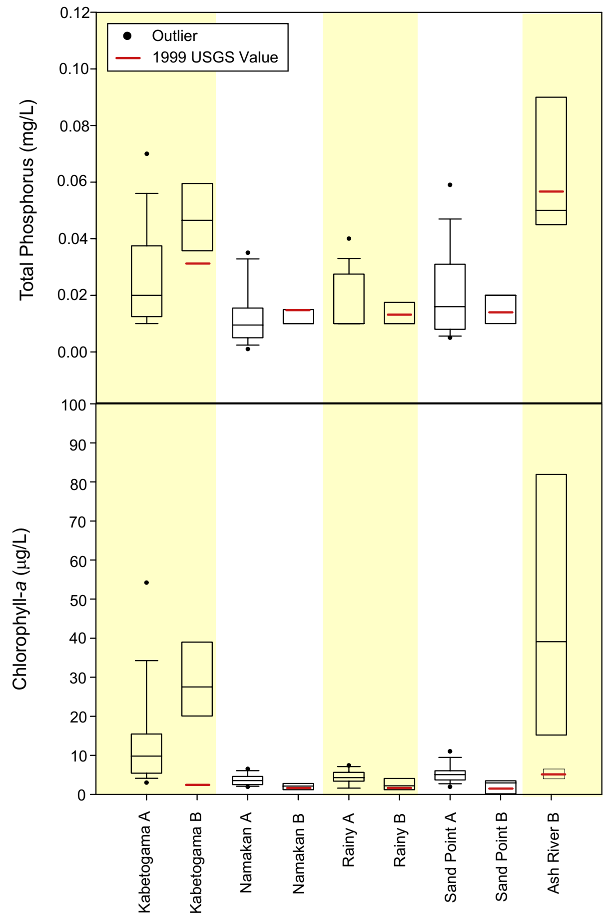



**Figure 14.** Comparison of total phosphorus and chlorophyll-*a* data collected by the the U.S. Geological Survey (Payne 1991) and the Minnesota Department of Natural Resources (Eibler 2001b,c and unpublished data) from selected lakes in Voyageurs National Park. A represents data collected by MNDNR (July and September 1983-2000; n=14-16). B represents data collected from USGS (August 1977-1983; n=4-7).

and Sand Point lakes. This decrease in algal biomass was reflected in the increase in 1999 Secchi disk transparency values at Black Bay, Kabetogama Lake, and Ash River. These changes were consistent with the VOYA/USGS and MNDNR long-term monitoring data that also indicated an increase in Secchi depth and a decrease in chlorophyll-*a* and total phosphorus after 1990 in Kabetogama Lake (Figure 16). Changes in water quality of VOYA large lakes after 1990 may be due to changes in water level fluctuation.

***Interior Lakes:*** Similar to VOYAs large lakes, the order of concentration of cations in the interior lakes is the typical Ca>Mg>Na>K observed in lakes in the temperate zone (Wetzel, 1983). Calcium to Mg ratios in the interior lakes ranged from 1.3-1.7:1 (Payne, 1991). The predominant anions were bicarbonates and sulfates (Payne, 1991). Reflective of the area's geology, all of the lakes within VOYA have alkalinities characteristic of soft water lakes (< 75 mg/L). Alkalinities (actually ANC) from the Park's 26 interior lakes ranged from 4.9 – 28 mg/L or 98 – 559 µeq/L (Payne, 1991; VOYA/USGS, unpublished data). All of VOYA's interior lakes had lower alkalinities than the large lakes except O'Leary, Little Trout, and Mukooda lakes. A comparison of May water chemistry values from 12 of the interior lakes sampled in 1982-84 (Payne, 1991) and 2000 (MPCA, unpublished data) shows that changes in ANC were slight and evenly divided between increases and decreases (Figure 17). Many of the interior lakes in VOYA have significant staining from bog drainage. Of the 12 lakes sampled by MPCA in 2000, only 3 could be classified as "clear" (< 21 Pt-Co units); the rest were above 20 Pt-Co units (range: 43-119) and would be classified as having some level of color. Sulfate was markedly lower in 2000 than in the early 1980's in 10 of the 12 lakes (Figure 17). The decrease is believed to be from decreased sulfate deposition.

Payne (1991) reported that TP ranges in the interior lakes were similar to those from the large lakes.

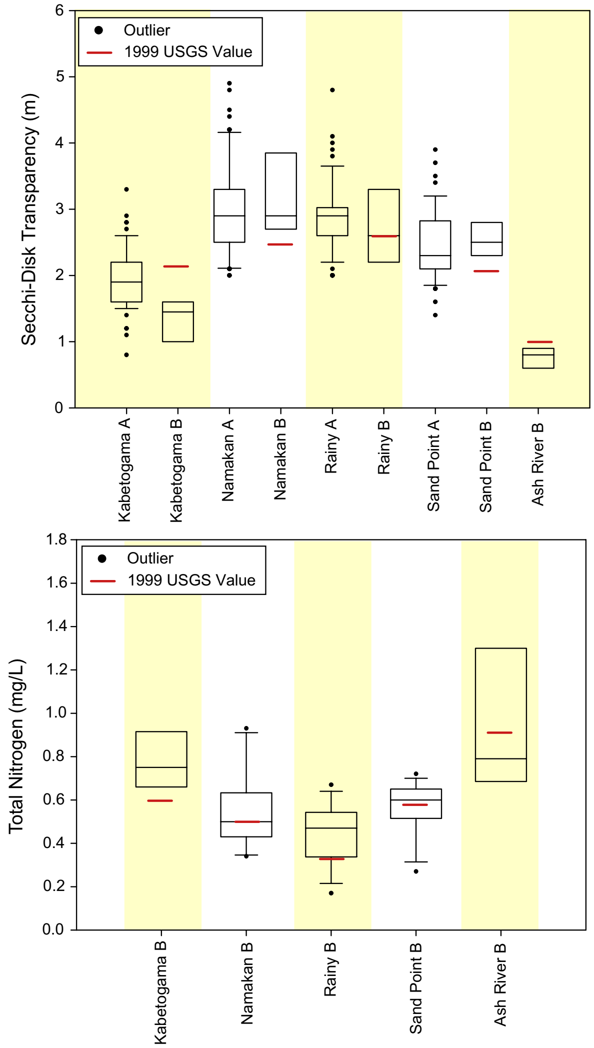



**Figure 15.** Comparison of Secchi disk transparency and total nitrogen data collected by VOYA/USGS personnel (unpublished) and the U.S. Geological Survey (Payne 1991) from selected lakes in Voyageurs National Park. Upper panel A represents data collected by VOYA/USGS unpublished (bi-weekly August 1981-2000); B represents data collected from USGS (August 1977-1983, n=4-7). Lower panel B represents data collected from USGS (May and August 1977-1983).

More significantly, he also found that TP concentrations decreased from May to August in most of the interior lakes. Changes in TP were related to the presence or absence of sharp thermal stratification, which is regulated by lake depth, basin shape, orientation, and fetch. TP concentrations decreased in stratified lakes and increased in un-stratified lakes during the summer. This suggests that internal cycling plays a major role in determining TP availability during the growing season. In 8 of the 12 lakes, TP concentrations in 2000 were lower than in the 1980s, however, the differences in most cases were less than 0.005 mg/L (Figure 18).

Chlorophyll-*a* concentrations in the interior lakes in spring and early summer were similar to those in the less-productive large lakes and ranged from 0.2 to 6.5 µg/L in May (Payne, 1991; VOYA/USGS, unpublished data) and from 0.8 to 4.8 µg/L in June (Hargis, 1981). August chlorophyll-*a* concentrations ranged from 10 to 18 µg/L in 7 interior lakes while in the remaining lakes they ranged from less than 0.1 to 5.2 µg/L (Payne, 1991; VOYA/USGS, unpublished data). Similar values were reported by Hargis (1981) for August (range 0.5 – 17.6 µg/L). Compared to the 1980s data (Payne, 1991), chlorophyll-*a* concentrations in the MPCA's 2000 samples changed in half the lakes by 50% to 450%, but the range of 1.3 – 6.5 µg/L remained basically unchanged (Figure 18). Chlorophyll-*a* concentrations in the interior lakes were positively correlated with total phosphorus concentrations ($r = 0.792$, $P = 0.000$) and negatively correlated with maximum ($r = -0.601$, $P = 0.001$) and mean depth ($r = -0.595$, $P = 0.001$).

***Water quality criteria:*** Ten large lake sites were sampled during August 1980 to determine water quality in the Park with respect to criteria established by the United States Environmental Agency for protection of freshwater aquatic life, drinking water, and recreation. Nearly all criteria were met (Payne, 1991). Oil and grease and phenols exceeded drinking water criteria at a few sites (3 at intensive-use sites). Sulfide concentrations at Black Bay, ammonia at Sullivan Bay, and PCB concentrations at one site in Kabetogama Lake exceeded criteria for protection of aquatic life. Resampling in August 1981 of the sites that had exceeded recommended levels in 1980 showed that all constituents had decreased, with most below recommended levels (Payne 1991).

In January 1995, the USNPS released Baseline Water Quality Data Inventory and Analysis: Voyageurs National Park that included information for 98 monitoring stations, based on data collected from 1967 to 1984 (USNPS, 1995). The USEPA's water-quality criteria (USEPA, 1986) were used to identify water quality problems within VOYA surface waters. Nine parameters were found to have exceeded screening criteria at least once during the study. Dissolved oxygen, pH, alkalinity, cadmium, copper, lead, and zinc all exceeded USEPA acute or chronic criteria for the protection of freshwater life. Cadmium, lead and nickel exceeded the respective USEPA drinking water criteria. Indicator bacteria (total coliform) concentrations exceeded the National Park Service's Water Resources Division (WRD) screening limit for primary-body contact recreation. Alkalinity and pH values are summarized below and the remaining parameters that exceeded USEPA's water quality criteria are shown in Table 2.

The pH was measured 458 times at 70 monitoring stations throughout the study area. Ninety-one

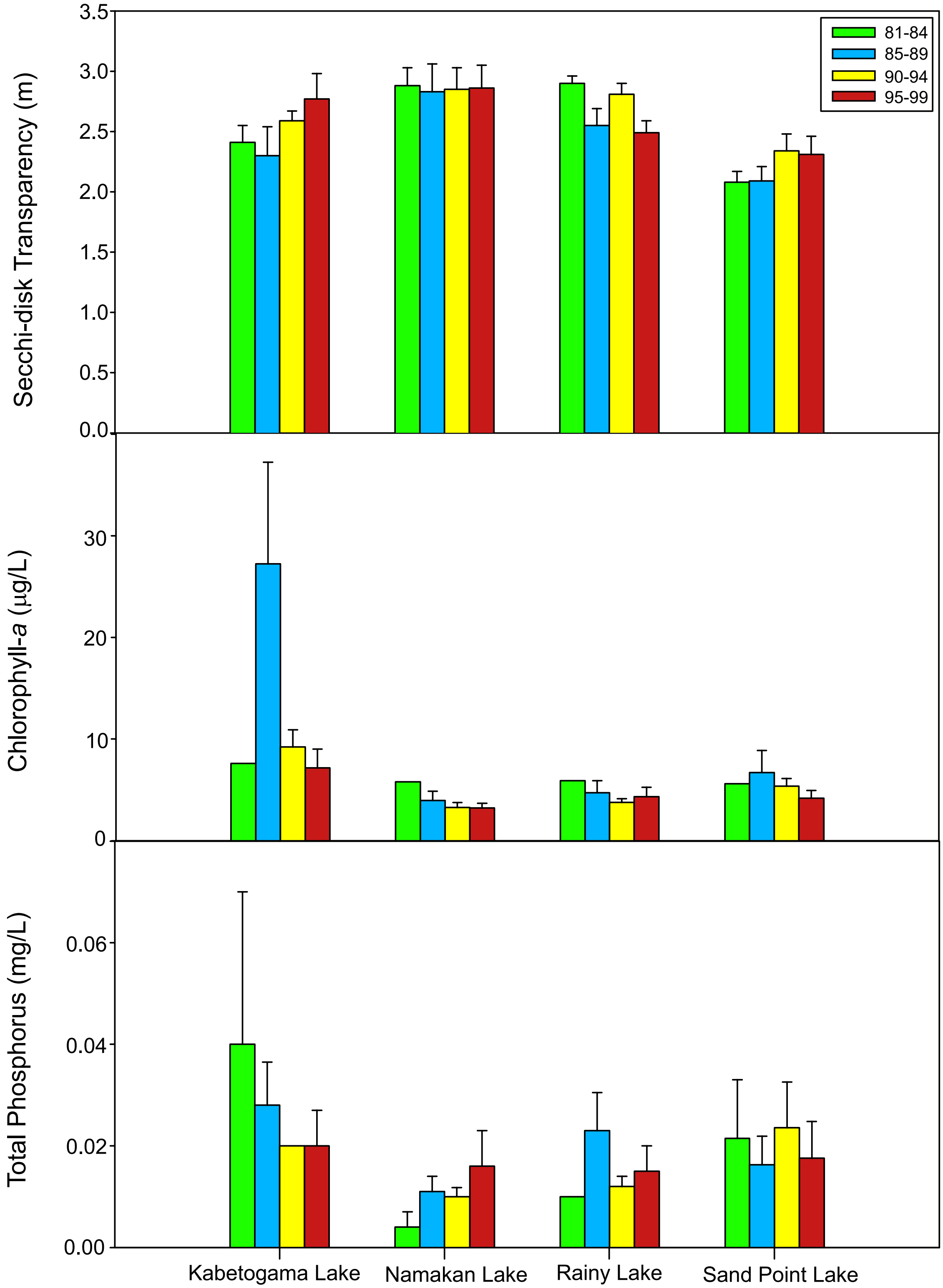



**Figure 16.** Comparison of Secchi disk transparency (VOYA/USGS July 1981-2000, unpublished data) and chlorophyll-*a* and total phosphorus (MNDNR annual September 1983 and July 1984-2000, Eibler 2001b,c and unpublished data), collected from selected lakes in Voyageurs National Park. The vertical lines represent standard errors.

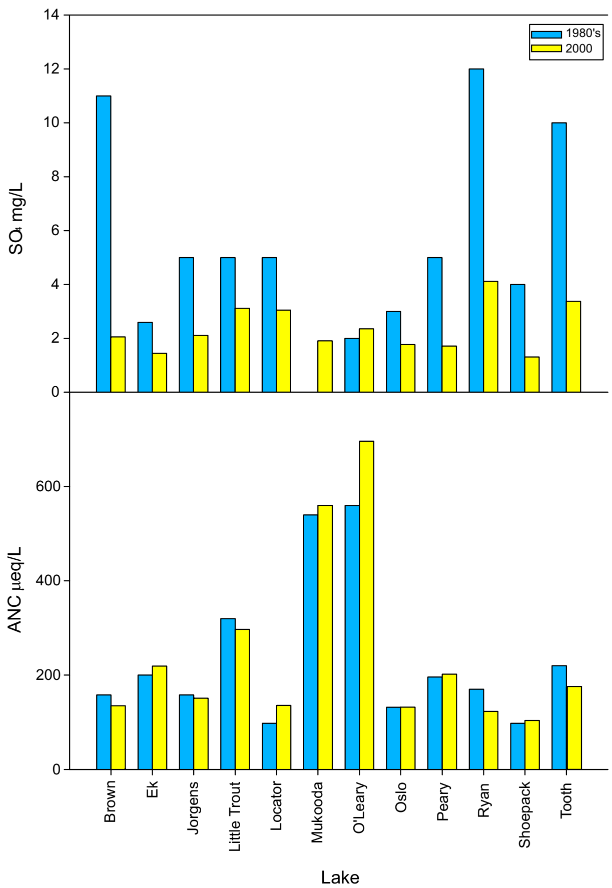



**Figure 17.** May sulfate and ANC concentrations in 12 interior lakes in Voyageurs National Park in the 1980s (Payne 1991) and 2000 (Minnesota Pollution Control Agency, unpublished data).

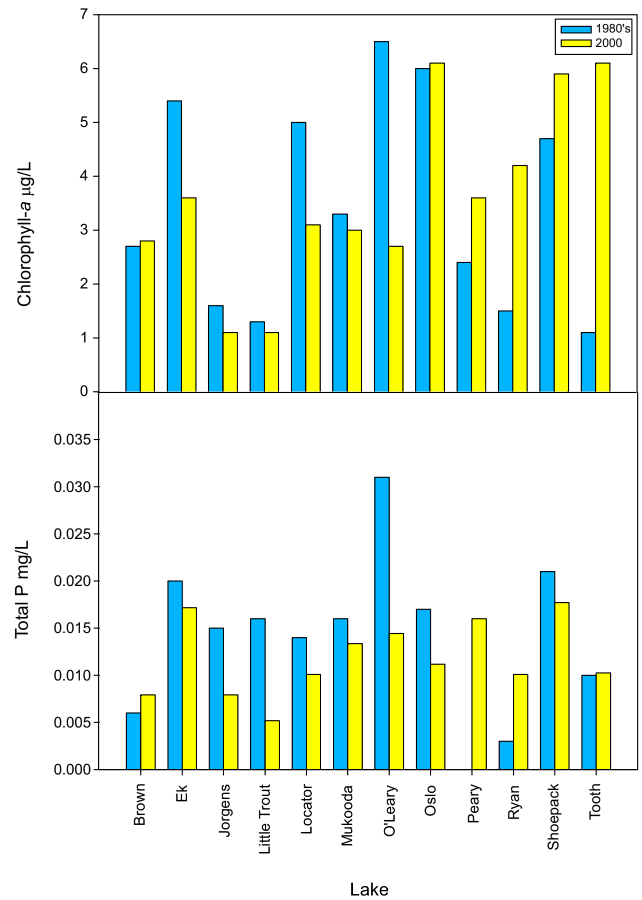



**Figure 18.** May chlorophyll-*a* and total phosphorus concentrations in 12 interior lakes in Voyageurs National Park in the 1980s (Payne 1991) and 2000 (Minnesota Pollution Control Agency unpublished data).

observations at 30 monitoring stations were outside the pH range of 6.5 to 9.0 (USEPA chronic criteria for freshwater aquatic life). Eight of the nine observations where the pH was greater than or equal to pH 9.0 occurred at Kabetogama Lake stations including four at Kabetogama Lake's Sullivan Bay outlet. Eighty-two observations at 25 monitoring stations were less than or equal to pH 6.5. Forty-three percent of the low pH values, including the lowest pH of 5.1, were measured at the Echo River station, which had a mean pH of 6.26.

Single total alkalinity was determined by low-level (less than 10 mg/L as $CaCO_3$) Gran Plot analysis at 10 monitoring stations on October 21, 1984. Of these, seven observations at seven small lakes within the Park boundary were below the MPCA's (1982) screening criteria of less than 200 µeq/L, indicating sensitivity to acid deposition.

The water quality inventory concluded that while the EPA criteria are important for identifying potential water quality problems, it is important to remember that criteria may have been exceeded due to any number of natural or anthropogenic factors. Results of this water quality inventory indicate that surface waters within the Park study area were generally of high quality with indications of some impacts from human activities, including atmospheric deposition.

***Sensitivity to Acid Precipitation:*** Payne (1991) applied a MPCA (1982) lake classification system to data he collected from 19 VOYA interior lakes from 1982 – 1984 to express lake sensitivity to acid precipitation. He found that 13 of the lakes could be classified as moderately sensitive (100 <alkalinity< 200 µeq/L as $CaCO_3$) and 2 of the lakes (Locator and Shoepack lakes) were extremely sensitive (> 0, < 100 µeq/L). Two of the remaining 4 lakes (Tooth and Little Trout lakes) were potentially sensitive (> 200, < 400 µeq/L). Mukooda and O'Leary were the only lakes classified as non-sensitive (> 400 µeq/L).

Regression analysis was used to analyze selected parameters from the data sets from Cruiser, Loiten, Locator and Shoepack lakes, the lakes included in the EPA's Long-Term Monitoring (LTM) program, to detect water quality trends and the relationship between atmospheric deposition and water quality.

**Table 2.** Number of measurements exceeding EPA water quality criteria[1] for selected sites in Voyageurs National Park.

| Station | Dissolved Oxygen | Total Cadmium | Total Copper | Total Lead | Total Nickel | Total Zinc | Total Coliform |
|---|---|---|---|---|---|---|---|
| Black Bay, Rat Root River Mouth | | 1/1& FA, DW | | 2/2& DW | | | |
| Echo River | | | 4/39 FA | | | | 1/1 |
| Kabetogama Lake, Ash River | | | 2/15 FA | 1/1& | | | |
| Kabetogama Lake, Sullivan Point | | 1/1& FA, DW | | 1/1& DW | | 1/15 FA | |
| Kabetogama Lake, Eks Bay | | 1/1& FA, DW | 1/14 FA | 1/14, FA 1/1&, DW | | | |
| Kabetogama Lake, Ek Lake | | | | 2/2& DW | | | |
| Kabetogama Lake, State Point | | | 1/15 FA | 2/2& DW | | 1/15 FA | |
| Kabetogama Lake, Gold Portage | | | | 1/1& DW | | 1/11 FA | |
| Namakan Lake, Red Pine Island | | 2/2& FA, DW | | | | | |
| Rainy Lake, Kettle Falls | | 1/1& FA, DW | 1/11 FA | 1/1& DW | | | |
| Rainy Lake, Kempton Channel | | | | 1/1& DW | | | |
| Rainy Lake, Saginaw Bay | | 2/2& FA, DW | | | | | |
| Rainy Lake, Neil Point | | 1/1& FA, DW | | | | 1/14 FA | |
| Sand Point Lake I | 1/7 FA | | | | | | |
| Sand Point Lake II | | | 1/13 FA | | 1/13 DW | 1/13 FA | |

[1]FA – Fresh Water Acute, DW – Drinking Water (U.S. EPA 1986)

&- Below detection limit observations, for which half the detection limit exceeded the edit criterion, were excluded from the criterion comparison for this parameter.

*Shaded box indicates no exceedences or parameter was not measured.

Precipitation-weighted mean concentrations of sulfate deposition were obtained from National Atmospheric Deposition Program for 1980 -1995 and analyzed for trend (NADP Fernberg, MN). Sulfate deposition showed a negative trend over the duration of the study (Figure 19) and showed a significant negative correlation ($p$ = 0.0000) with time (year). With all lakes combined, sulfate concentrations in the lakes also showed a negative trend over time (Figure 19, $p$ = 0.0000) and had a positive relationship with sulfate deposition ($p$ = 0.0000). Acid neutralizing capacity (ANC) showed a positive trend over time and had a negative relationship with sulfate deposition (Figure 20, $p < 0.001$). The pH also showed a generally positive trend over time but not as clearly as ANC (Figure 20). The pH had a negative relationship with sulfate deposition when lake was added to the model ($p$ = 0.0000). In all lakes except Cruiser Lake, ANC increased over time while sulfate deposition in the area decreased. ANC increased over 20 μeq/L in Loiten and Locator lakes while ANC in Shoepack Lake increased over 40 μeq/L (Figure 20). According to these data, only Shoepack Lake would have been classified as extremely sensitive based on the MPCA's standards at the beginning of the study; the other lakes would have been classified as moderately sensitive. At the end of the study, ANC in Shoepack Lake had increased enough so that all of the lakes were in the moderately sensitive category. Data from Payne (1991), Whitman and others (2002) and MPCA (unpublished) are included in Figures 19 and 20 for comparative purposes. Unlike the other three lakes, there was no relationship between ANC and sulfate deposition or lake sulfate concentration in Cruiser Lake. This may have been related to the smaller decreases in sulfate concentrations in Cruiser Lake compared to the other lakes, which could have resulted in undetectable increases in ANC. However, there was a significant relationship between sulfate deposition and lake sulfate concentrations for Cruiser Lake. Also, Cruiser Lake is quite different from the other three lakes in that it is deeper, more dilute and less productive and therefore could be expected to react differently to changes.

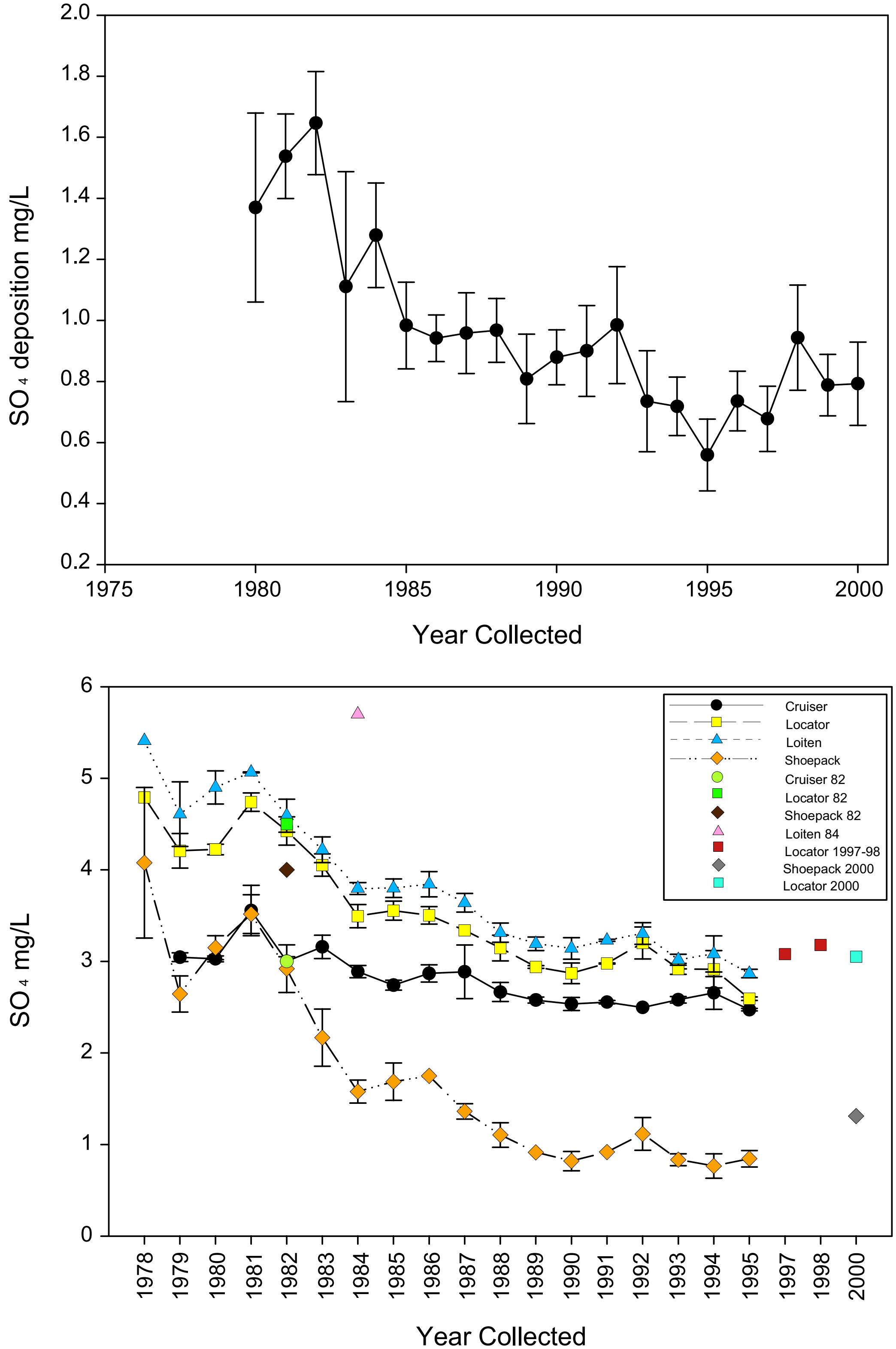



**Figure 19.** Precipitation-weighted mean concentrations of $SO_4$ deposition near Voyageurs National Park (NADP Fernberg, MN) and mean $SO_4$ by year in four interior lakes in Voyageurs National Park. Line connected data for the lakes are from Webster and Brezonik (1995), 1982 and 1984 data are from Payne (1991), 1997-98 data are from Whitman and others (2002), and 2000 data from the Minnesota Pollution Control Agency.

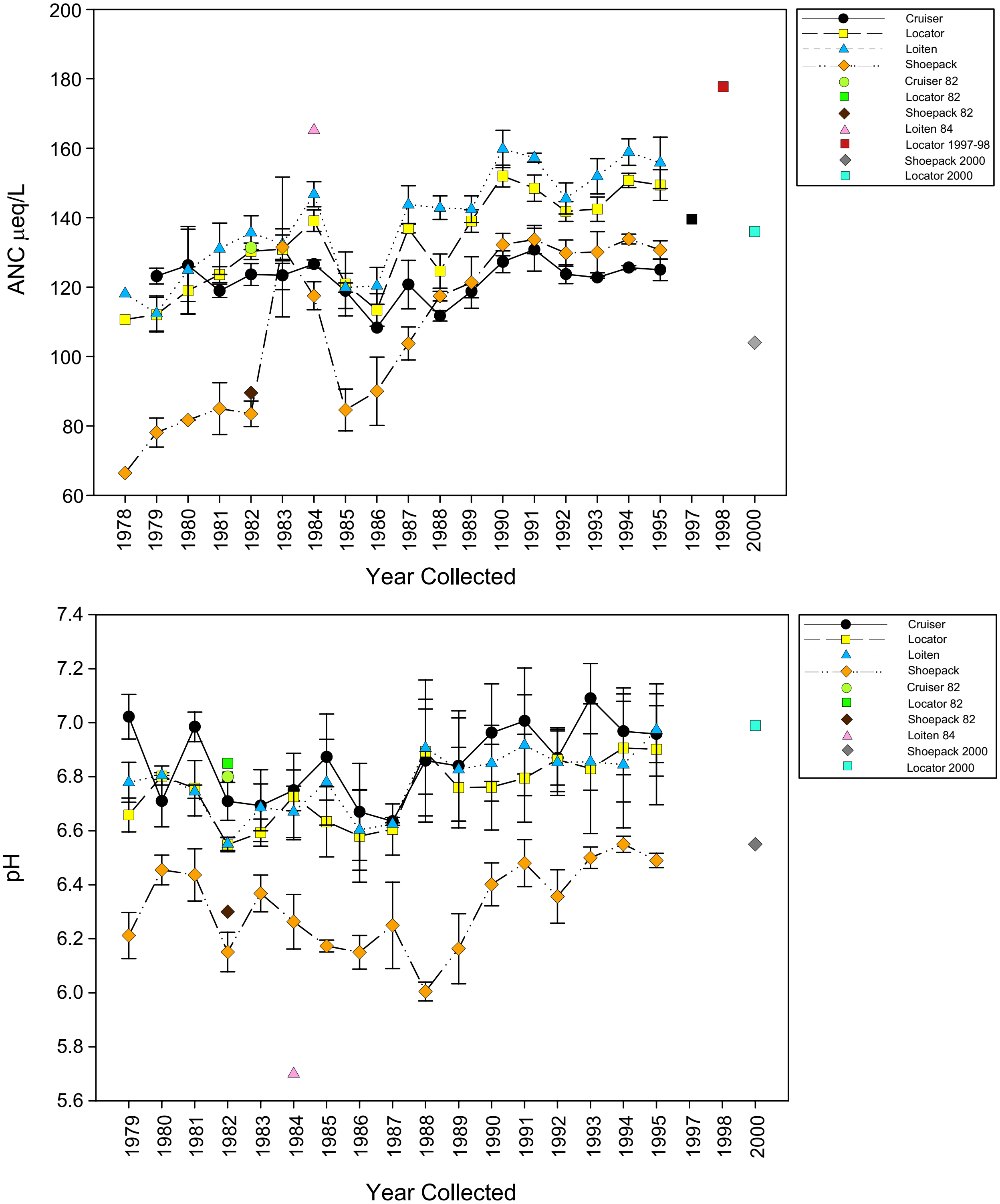



**Figure 20.** Mean concentrations of ANC and pH by year in four interior lakes in Voyageurs National Park. Line connected data for the lakes are from Webster and Brezonik (1995), 1982 and 1984 data are from Payne (1991), 1997-98 data are from Whitman and others (2002), and 2000 data from the Minnesota Pollution Control Agency.

**Trophic status:** Trophic status for each Park lake has been assessed on the basis of chlorophyll-*a* concentrations with Carlson's Trophic State Index (TSI; Carlson, 1977). The TSI places natural waters on a numerical gradient from 0 to 100, with each major division of 10 representing a doubling of algal biomass. While TSIs can also be developed using Secchi disk readings and total phosphorus concentrations, Carlson (1977) suggested that for the purposes of classification the chlorophyll-based index is the one best applied during summer months. Results, however, must be interpreted carefully since changes of less than 5 TSI units have been found to be indistinguishable from the inherent "noise" in the available data (Spacie and Bell, 1980). Even though they were originally developed to overcome such arbitrary divisions, TSI values are commonly divided with those less than 35 considered typical of oligotrophic conditions; those between 35 and 50 mesotrophic conditions; and higher values, eutrophic conditions (Walker, 1988).

Because the original TSI values reported by Hargis (1981) were miscalculated, they were recalculated using the chlorophyll-*a* values presented in his report. After the correction, the Hargis (1981) values and those reported by Payne (1991) were similar with differences of less than five TSI units occurring in 13 of the 22 possible comparisons of August samples. Kepner and Stottlemyer (1988) also reported similar TSI values for the Park's four large lakes. Although the proportion of lakes with TSI values >50 increased in August, the majority of the lakes sampled by Hargis (1981) and Payne (1991) still fell into the 35 to 50 or mesotrophic category (Figure 21). With the exception of two midsummer values from Rainy and Namakan lakes, all of the TSI values <35 reported by Hargis (1981) and Payne (1991) were from interior lakes. TSI values >50 occurred in Kabetogama Lake and in eight relatively shallow (mean depths <4.0 m) interior lakes (Hargis, 1981; Payne, 1991; VOYA/USGS, unpublished data). Based on chlorophyll-*a* measurements, trophic state indices from 1999 samples were lower than median values from 1977-83 at all the large lake sites (Payne, 2000). Lower concentrations of soluble inorganic nitrogen and ortho-phosphorus were also observed, suggesting that nutrient availability was limiting trophic levels in 1999.

Seasonally, TSI values increased from spring and early summer to late summer in about 60-65% of the lakes, decreased in about 30-32%, and remained the same in the rest (Hargis, 1981; Kepner and Stottlemyer, 1988; Payne, 1991; USGS/VOYA, unpublished data). In many instances, however, the changes within a lake were less than 5 TSI units. Similar increases were observed in monthly samples from May through September in 1997 and 1998 from Locator and Mukooda lakes (Whitman and others, 2002). Payne (1991) suggested that the observed changes could be due to a variety of factors including the availability of biologically active phosphorus and

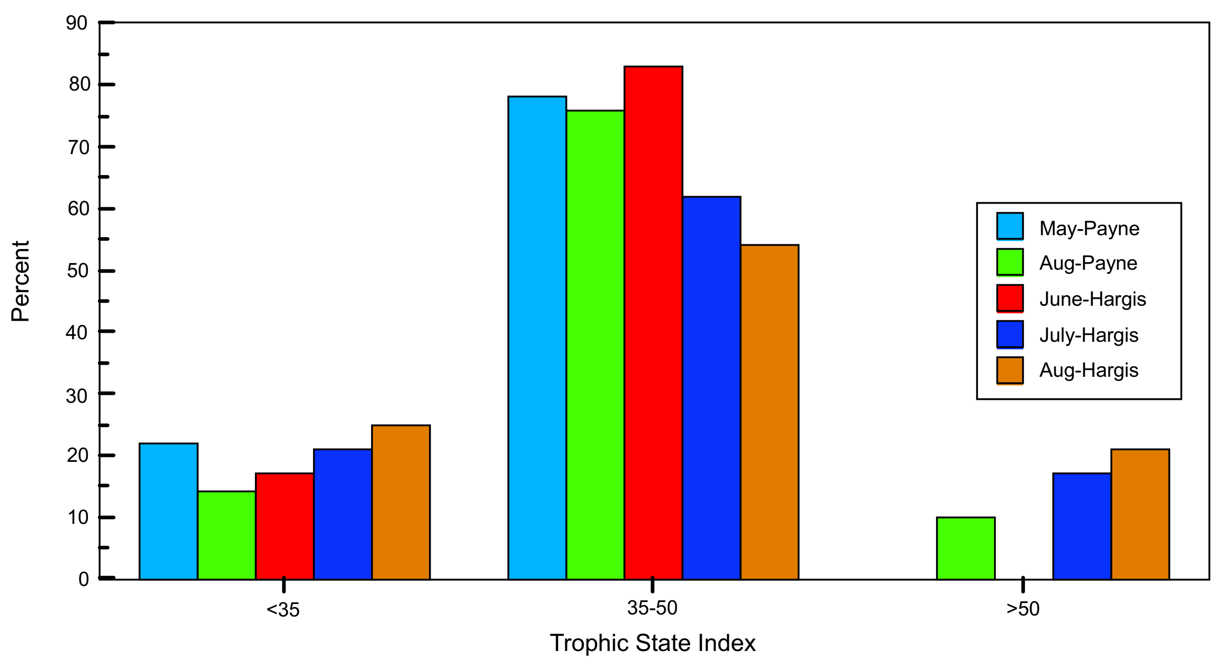



**Figure 21.** Seasonal distribution of trophic state indexes based on chlorophyll-*a* concentrations measured by Hargis (1981) and Payne (1991) in 22 Voyageurs National Park lakes.

trace-element nutrients, and zooplankton grazing.

**Future Needs and Opportunities:** Although a significant amount of information has been collected on the physical and chemical characteristics of the Parks lakes, there is still a need for more baseline data. A long-term monitoring program is needed to obtain the information required to determine if activities both within and out of the Park are affecting the Park's water quality. The monitoring program should include in addition to the major ions, nutrients, and other common limnological parameters, potential pollutants, and bacteriological monitoring in areas experiencing significant visitor use. Coordination with other parties conducting such work in the drainage should be an integral component of any program the Park may establish. A priority should be the development of a centralized database, including the existing models for the watershed that all the agencies and parties concerned with water quality in the drainage can utilize.

# Biological Communities

## Phytoplankton

The U.S. Geological Survey (USGS, 1981; 1982; Payne, 1991; USGS, unpublished data) identified and quantitatively analyzed phytoplankton from all the Park lakes. Samples were collected during May and August from the large lakes from 1978 to 1983 and from each of the interior lakes in one year between 1982 and 1984. Phytoplankton was identified to genera and the number of individual cells was recorded for the large lake samples and 12 interior lake samples collected during 1978-83. Samples collected in 1984 from the other 14 interior lakes were analyzed at a different laboratory where phytoplankton was identified to species and counts were made of "algal units". An algal unit being a discrete entity composed of a colony, filament, or single cell. This analytical difference precludes comparisons of densities. It is still feasible, however, to identify dominant genera.

Other studies and surveys involving phytoplankton have been conducted, but they usually only involved a few lakes or sampling sites. An ecosystems analysis of six sites proposed for facilities development in early Park planning documents included evaluation of phytoplankton communities (University of Minnesota, 1973; 1976). Hargis (1981) presented data on the percent composition of the phytoplankton standing crop in the Park's four large lakes and 10 interior lakes, although the methodology used and time of sampling was not given. Kepner and Stottlemyer (1988) presented a qualitative analysis of phytoplankton from August 1985 samples from the four large lakes. Phytoplankton from monthly samples from Locator and Mukooda lakes from 1997 and 1998 were analyzed to species and individual cell counts were done (Whitman and others, 2002).

The total number of phytoplankton genera in all the USGS samples was 79. The most common algal groups were the Chlorophyta (green algae), Bacillariophyceae (diatoms), Chrysophyceae (golden-brown algae), and Cyanophyta (blue-green algae, cyanobacteria) with 27, 21, 12, and 11 genera respectively. Three genera each of Cryptomonadineae and Pyrrophyta (dinoflagellates) and two genera of Euglenophyceae (euglenoid algae) were also identified. The average number of genera per sample was about 8 in the large lakes and 12 in the interior lakes. Comparison with the number of genera identified by Whitman and others (2002) in their more intensive surveys of Locator and Mukooda lakes suggests that the USGS surveys and analyses did not account for all the phytoplankton taxa. Whitman and others (2002) identified 41 and 47 genera from Locator and Mukooda lakes, while only 23 and 15 genera were reported by the USGS (1982). Such differences are not unusual and can result from differences in sampling and analysis effort and the taxonomic expertise of the investigator. In fact, wide disparities between data sets collected by different researchers often make comparisons of diversity indices practically useless (Harris, 1986). Obtaining a complete inventory of the Park's phytoplankton would require the services of a taxonomist rather than an ecologist since they typically identify significantly more species than the latter (Kalff and Knoechel, 1978).

Either blue-green algae (cyanobacteria) or diatoms most frequently dominated (>15% of the total cell count) the Park's large lake phytoplankton communities (Payne, 1991). Of the 38 genera identified as dominants in the May samples, 21 were diatoms, 12 were blue-green algae, 4 were green algae, and one was a Euglenoid. For the August samples, 37 of the 48 dominants were blue-green algae, 9 were diatoms, and 3 were green algae. The prevalent diatom genera were *Cyclotella*, *Asterionella*, *Stephanodiscus*, *Diatoma*, and *Melosira*. Common blue-green algae genera were *Anabaena*, *Aphanizomenon*, *Anacystis*, and *Gomphosphaeria*. *Oscillatoria, Dictyosphaerium,* and *Ankistrodesmus* were the green algae that were dominants.

Algal cell densities in the Park's large lakes in May were generally less than 10,000 cells/mL and frequently were less than 1000 cells/mL. The average May cell density (1978-83) in Kabetogama Lake was 2 to 3 times higher than in the other large lakes. During August, both Kabetogama Lake and Sand Point Lake were dominated by blue-green algae. However, the average cell density in Kabetogama

Lake was over 103,000 cells/mL while in Sand Point Lake it was only 4,850 cells/mL. In Namakan and Rainy lakes, where the dominants in August consisted of both blue-green algae and diatoms, the average densities were 20,760 and 2,420 cells/mL, respectively. Blue-green algal blooms in Kabetogama Lake, which were first reported in 1941 (Sharp, 1941), occur annually.

Other observations on the composition of the phytoplankton communities in the Park's large lakes were similar to those of Payne (1991). The University of Minnesota investigators (1973; 1976), who sampled primarily in bays and shallow water near areas being considered for development, found that algal populations varied during the summer months. Generally, diatoms were dominant in June, blue-green algae in July, and both groups in September. Black Bay in Rainy Lake and Sullivan Bay in Kabetogama Lake contained more phytoplankton than the other sites. They observed that the green algae, *Ulothrix*, was the dominant periphytic algae, although there were also some other periphytic green and blue-green algae present at some sites. The dominant groups identified by Hargis (1981) were blue-green algae and cryptomonads in Kabetogama Lake; diatoms, blue-green algae, and cryptomonads in Rainy and Sand Point lakes; and green algae, diatoms, and cryptomonads in Namakan Lake. Kepner and Stottlemyer (1988) only performed qualitative analysis on samples collected in August in 1985. They concluded that blue-green algae were prevalent in Kabetogama and Sand Point lakes and diatoms in Rainy Lake.

Cryptomonads and blue-green algae were the dominant algal groups in the phytoplankton samples collected from the Park's interior lakes (USGS, 1981; 1982; USGS, unpublished data). In the May samples, 19 of the 44 dominant genera were cryptomonads, 11 were blue-green algae, 6 were green algae, 5 were golden-brown algae, and 3 were diatoms. For the August samples, 23 of 43 genera were blue-green algae, 9 were cryptomonads, 6 were diatoms, 4 were green algae, and 1 was a golden-brown algae. The dominant cryptomonads were *Cryptomonas* and *Rhodomonas* while the primary blue-green dominants were *Anacystis*, *Gomphosphaeria*, and *Anabaena*. The green algae, *Crucigenia*, *Chlamydomonas*, and *Dictyosphaerium* were each dominant in two lakes. *Cyclotella* was the prevalent diatom genera, comprising 6 of the 9 cases where a diatom was a dominant. The golden-brown alga, *Ochromonas* was a dominant in 4 lakes. Hargis (1981) presented data on the percent composition of the phytoplankton standing crop in 10 interior lakes. Blue-green algae were the dominant phytoplankton group in 9 lakes, diatoms in 3 lakes, and green algae and cryptomonads in 2 lakes each. The dominant groups identified by the USGS and Hargis corresponded in about 50% of the cases in these 10 lakes.

Locator and Mukooda lakes, which were sampled in 1982 (USGS, 1982) and 1997-98 (Whitman and others, 2002), are the only interior lakes where it is feasible to compare results between years and surveys. Blue-green algae and diatoms were the dominant groups in Mukooda Lake in May in 1982 while blue-greens were dominant in August. The initial 1997 Mukooda Lake sample, which was taken in June, contained approximately equal proportions of yellow-green algae (Xanthophyceae), blue-green algae, green algae, and diatoms. In May of 1998, diatoms, green algae, and yellow-green algae were again dominant. In both the 1997 and 1998 August samples, blue-green algae, diatoms, and green algae were the dominant groups. In Locator Lake in 1982, blue-green algae were dominant in both May and August, being joined by diatoms in August. In 1997, the early summer sample contained about equal proportions of diatoms, blue-green algae, and green algae. In May of 1998, yellow-green algae and diatoms were the dominant groups. Dominants in August in 1997 were diatoms and green algae while in 1998 they were joined by yellow-green and blue-green algae as dominants. Thus, similarities as well as significant variation were observed in the phytoplankton communities in these two lakes. The most noticeable difference being the dominance by the yellow-green algae, which were not reported at all by the USGS (1982). Whether or not this was an actual difference in abundance or was due to a failure to identify members of this group is unknown.

Comparisons with cell densities in the large lakes were restricted to the 12 interior lakes that were sampled in 1982 and 1983 because a different counting method was used during 1984 in 14 lakes. May algal cell densities in the majority of the 12 lakes were less than 5,000 cells/mL, the primary exceptions being O'Leary (142,600 cells/mL) and Shoepack lakes (16,000 cells/mL). The primary contributor to these high densities was the blue-green algae, *Anacystis*, which comprised over 95% of the cells in both lakes. August cell densities in 10 of the 12 lakes were similar to the less productive large lakes. The two exceptions, O'Leary and Beast lakes had cell densities similar to those in Kabetogama Lake. *Aphanizomenon*, a blue-green algae, was the principle contributor to O'Leary Lake's relatively high cell count, while the main contributors in Beast Lake were the green algae, *Cosmarium*, and the blue-green algae, *Anacystis*.

Two attempts have been made to assess the possible effects of anthropogenic factors on productivity and the phytoplankton community. Because of concerns about the ecological effects of acid precipitation, the phytoplankton community's response to acidification was investigated in Kabetogama Lake in 1980 using in situ incubations of 72-hour duration (Hargis, 1981). Acidification altered the lake's water chemistry, which subsequently caused alterations in the phytoplankton community. Acidification caused chlorophyll-*a* concentrations to decrease and seemed to speed up the cycling dynamics of the phytoplankton population. It was hypothesized that these changes could have far-reaching influences on the aquatic food web. These findings were similar to those at numerous other locations, particularly the Experimental Lakes Area (ELA) that is operated by the Canadian Department of Fisheries and Oceans (Schindler, 1987). The ELAs close proximity (160 km NW of International Falls/Fort Francis) and its similar geology and climate make the findings from research conducted there especially applicable to aquatic issues in the Rainy Lake basin, including the Park.

The second study involved the use of a model to compare model-generated seasonal total phosphorus concentrations under different water management regimes, including projected natural conditions (Kepner and Stottlemyer, 1988). The predicted changes in total phosphorus were then used to assess possible changes in phytoplankton standing crop since there is a positive relationship between the two factors (Harris, 1986). Kepner and Stottlemyer (1988), while stressing that the model was uncalibrated, concluded that changes in the magnitude of the drawdown of Kabetogama Lake could effect nutrient concentrations and ultimately productivity. Restoration of more natural conditions (that is less drawdown than was occurring at the time) would lower total phosphorus and chlorophyll-*a* concentrations. The authors suggested that the model could be used to consider other questions germane to changes in lake trophic conditions. An example being changes in loading rates of total phosphorus resulting from changes in the human population in the basin. The study that was initiated by the USGS in 2001 of the effects of the new rule curves on trophic conditions in Rainy Lake and Namakan Reservoir will provide additional opportunities to utilize and test the applicability of the model.

**Future Needs and Opportunities:** While the surveys and studies that have been conducted have provided some information on the phytoplankton communities in the Park's lakes, more detailed work is needed. Seasonal and spatial variation needs to be determined so that the Park will have a basis for evaluating long-term changes and changes possibly associated with Park use and management actions. At present, our knowledge of the composition of the phytoplankton communities is limited due to the disparities in survey methods and taxonomic expertise of the investigators that have worked in the Park. A complete inventory will require more intensive surveys, both spatially and temporally, and the services of a recognized taxonomist(s). More detailed studies involving ecologists and limnologists are needed to assess both historical and current conditions and to identify causal mechanisms. Information gained from such work could be extremely valuable since phytoplankton and other species with short life cycles are sensitive indicators of environmental stress (Schindler, 1987).

## Zooplankton

Four investigations in the Park have involved sampling of the zooplankton community. The ecosystems analysis of six potential VOYA development sites that was previously mentioned also included evaluation of zooplankton communities (University of Minnesota, 1973; 1976). Hargis (1981) sampled zooplankton in 20 interior lakes and the four large lakes from 1978 to 1980. Zooplankton in all the Park's lakes were sampled during the period from 1981 to 1984, with the sampling repeated on Namakan and Rainy lakes in 1996 (VOYA/USGS, unpublished data). Whitman and others (2002) sampled Locator and Mukooda lakes in 1997 and 1998. The investigators used vertical net tows from a variety of depths to collect zooplankton. Mesh sizes of the nets used were 63 µm (University of Minnesota, 1973; 1976), 80 µm (Whitman and others, 2002), and 153 µm (Hargis, 1981; VOYA/USGS, unpublished data). Sampling frequency was primarily monthly except in the VOYA/USGS program where sampling was done bi- or triweekly. Due to financial limitations, however, sample analysis for the interior lakes was restricted to samples from May, late-July or early August, and late September or early October. Sampling was typically done at a site located at or near the deepest point in a lake; however, in the large lakes Hargis (1981) and VOYA/USGS (unpublished data) used multiple sites in some years. The analyses by the University of Minnesota (1973; 1976) and Whitman and others (2002) included rotifers and crustacean zooplankton, while only members of the latter group were identified and counted in the Hargis (1981) and VOYA/USGS (unpublished data) surveys. J. Novotny, U.S. Fish and Wildlife Service analyzed the samples collected during1981-84 by VOYA/USGS, and L. Last from the USGS-Lake Michigan Ecological Station analyzed the 1996 samples. L. Last also analyzed the samples collected from Locator and Mukooda lakes during 1997-98. Comparisons between years for the VOYA/USGS large lake samples were based primarily on 10 m vertical tows taken at one fixed station.

Because the focus was on inshore areas and embayments, the vertical tows of the University of Minnesota were from depths of less than 5 m in most instances. Rotifers, which were identified only to genus, were the dominant organisms at three sites, Neil Point and Black Bay on Rainy Lake, and State Point on Kabetogama Lake. *Keratella* spp. was the dominant genus. At Sullivan Bay on Kabetogama Lake, rotifers were dominant in June and September while copepods and cladocerans were dominant in July. Approximately equal proportions of cladocerans, copepods, and rotifers occurred in several embayments in the Kettle Falls area in July and September. Densities, however, were lower in September.

Locator and Mukooda lakes exhibited similar patterns of abundance in zooplankton even though densities were much higher in 1997 than in 1998 (Whitman and others, 2002). Highest densities of organisms occurred in June with reductions occurring throughout the remainder of the summer. The rotifers were the numerically dominant taxon group. *Conochilus unicornis*, *Kellicottia longispina*, and *Asplanchna* spp., which were the most common rotifers, are ubiquitous throughout the Great Lakes region. In Locator Lake, the most common crustacean zooplankton species were the copepod, *Diacyclops bicuspidatus thomasi*, and the cladoceran, *Bosmina longirostris*. They were joined in Mukooda Lake by *Daphnia galeata mendotae* and *Leptodiaptomus minutus*, other species commonly found in glacier-formed lakes.

In all, 38 species of crustacean zooplankton have been identified from the Park's lakes (Table 3). These consist of 7 cyclopoid and 7 calanoid copepod species and 24 cladoceran species. Twenty-six of the species are generally considered as limnetic forms; eleven (9 cladocerans and two copepods) as littoral or benthic forms, and one, *Ergasilus chautauguaensis*, is a copepod whose adult female stage is parasitic (Pennak, 1978). For the Park-wide surveys, Hargis (1981) only reported 15 species while the VOYA/USGS surveys reported 38. While distributions of more common species were similar in these surveys, there were some obvious exceptions. *Tropocyclops prasinus*, *Cyclops vernalis*, and *Chydorus sphaericus* were found in numerous lakes by VOYA/USGS but were not reported at all by Hargis (1981). The opposite was true for *Paracyclops fimbriatus poppei*, which Hargis (1981) indicated was present in 10 lakes. Other obvious discrepancies involved *Skisto diaptomus oregonensis* and *Diaptomus sicilis*, and the group of *Ceriodaphnia* species. Although uncertain, it appears the differences for these organisms could be the result of misidentification. *Skisto d. oregonensis* and *D. sicilis* were reported to occur in about the same number of lakes but Hargis (1981) only reported *D. sicilis,* while VOYA/USGS identified both species and found that *S. d. oregonensis* was the most widespread of the two. Complete resolution of these potential taxonomic questions would require analysis of samples from both surveys. Although this may not be possible, samples exist that could be used to confirm whether the initial VOYA/USGS identifications were correct.

Hargis (1981) reported 6 to 12 zooplankton species for individual VOYA lakes with the majority of the lakes having either 10 or 11 species. In the surveys conducted by VOYA/USGS, the number of species per VOYA lake ranged from 10 to 30 with most interior lakes having between 10 and 14 species and the large lakes more than 20. A comparison of the number of species identified in the 24 lakes that both Hargis (1981) and VOYA/USGS surveyed shows that more species were identified by VOYA/USGS in 18 lakes, whereas Hargis (1981) identified more species in three lakes and in the remaining three lakes the VOYA/USGS and Hargis (1981) surveys identified the same number of species. The numbers of species identified in the three surveys of Locator Lake were 11 (Hargis, 1981), 13 (VOYA/USGS), and 14 (Whitman and others, 2002). On Mukooda Lake, surveys by Hargis (1981), VOYA/USGS, and Whitman and others (2002) produced 10, 17, and 18 species, respectively. Although these estimates are similar to values reported for similar lakes in northwestern Ontario (Patalas, 1990), they should not be construed as representing the entire zooplankton species pool in these lakes. To obtain that information, a long-term sampling program will be required that addresses both the inter- and intraannual changes that zooplankton undergo (Arnott and others, 1998). Additionally, on the large lakes several sampling sites will be needed since the ability to detect zooplankton species is dependent on lake size (Patalas and Salki, 1993).

Fifteen of the 38 species comprised more than 10% of the zooplankton (= dominant) in at least one of the VOYA/USGS samples (Table 4). Of these, the most frequently occurring dominants were the copepods, *Diacyclops bicuspidatus thomasi*, *Tropocyclops prasinus*, and *Skisto diaptomus oregonensis*, and the cladocerans, *Bosmina longirostris*, *Diaphanosoma leuchtenbirgian*, and *Holopedium gibberum*. *Cyclops vernalis*, although occurring in 10 interior lakes, only reached dominant status in the large lakes. Seasonal variation in dominance was evident even for the most common species, particularly the copepods. For example, *D. b. thomasi* and *S. d. oregonensis* were dominant mainly in spring, while *T. prasinus* became more important in the fall. In the interior lakes, *D. leuchtenbirgian* was dominant almost exclusively in mid-summer. Analysis of Hargis's (1981) data produced similar patterns for the species both he and VOYA/USGS found to be widespread. The cladoceran that Hargis (1981) identified as *Diaptomus sicilis* was dominant in 10 lakes in June, 15 lakes in July, and 14 lakes in August. In comparison, *S. d. oregonensis* from the VOYA/USGS samples was dominant

**Table 3.** Crustacean zooplankton species distribution in Voyageurs National Park's interior and large lakes, 1978-80 (n=24 Hargis 1981), 1981-84 (n=30) and 1996 (n=2) (VOYA/USGS, unpublished data).

| Species | 1978-80 Interior | 1978-80 Large | 1981-84 Interior | 1981-84 Large | 1996 Large |
|---|---|---|---|---|---|
| *Diacyclops bicuspidatus thomasi* | 19 | 4 | 20 | 4 | 2 |
| *Mesocyclops edax* | 17 | 4 | 24 | 4 | 2 |
| *Mesocyclops sp.* | -- | -- | -- | 2 | 2 |
| *Tropocyclops prasinus* | -- | -- | 23 | 4 | 2 |
| *Ergasilus chautauguaensis* | -- | -- | 1 | 3 | 2 |
| *Cyclops vernalis* | -- | -- | 10 | 4 | 1 |
| *Eucyclops agilis montanus* | -- | -- | 1 | 2 | -- |
| *Macrocyclops albidus* | -- | -- | 1 | 1 | -- |
| *Diaptomus ashlandi* | -- | -- | 2 | 4 | 1 |
| *Skisto diaptomus oregonensis* | -- | -- | 21 | 4 | 2 |
| *Diaptomus sicilis* | 20 | 4 | 2 | 4 | 2 |
| *Lepto diaptomus minutus* | -- | -- | 9 | 4 | 2 |
| *Epischura lacustris* | 11 | 4 | 13 | 4 | 2 |
| *Limnocalanus macrurus* | -- | -- | 1 | 4 | 2 |
| *Paracyclops fimbriatus poppei* | 10 | -- | -- | -- | -- |
| *Daphnia parvula* | -- | -- | -- | 1 | -- |
| *Daphnia Catawba* | -- | -- | -- | -- | 1 |
| *Daphnia longiremis* | 4 | -- | 3 | 1 | 2 |
| *Daphnia pulicaria* | 6 | -- | 18 | 4 | 1 |
| *Daphnia galeata mendotae* | 16 | 4 | 22 | 4 | 2 |
| *Daphnia retrocurva* | 14 | 4 | 17 | 4 | 2 |
| *Bosmina longirostris* | 19 | 4 | 26 | 4 | 2 |
| *Eubosmina coregoni* | -- | -- | -- | -- | 2 |
| *Chydorus sphaericus* | -- | -- | 14 | 4 | 2 |
| *Diaphanosoma leuchtenbergian* | 19 | 4 | 23 | 4 | 2 |
| *Sida crystallina* | -- | -- | 2 | 2 | -- |
| *Ceriodaphnia lacustris* | 2 | -- | 17 | 4 | 2 |
| *Ceriodaphnia quadrangular* | -- | -- | 4 | 4 | 2 |
| *Ceriodaphnia reticulata* | 6 | -- | -- | -- | 1 |
| *Ceriodaphnia rotunda* | -- | -- | -- | -- | 1 |
| *Holopedium gibberum* | 20 | 4 | 25 | 4 | 2 |
| *Leptodora kindtii* | 13 | 4 | 9 | 4 | 2 |
| *Graptoleberis testudinaria* | -- | -- | -- | 2 | 1 |
| *Polyphemus pediculus* | -- | -- | 1 | 4 | 2 |
| *Alona gutatta* | -- | -- | 4 | 3 | -- |
| *Alona affinis* | -- | -- | -- | 2 | 1 |
| *Alona rustica* | -- | -- | -- | -- | 1 |
| *Ophryoxus gracilis* | -- | -- | -- | 1 | -- |
| *Eurycercus lamellatus* | -- | -- | -- | 1 | -- |

in 10, 9, and 5 lakes, respectively.

Jaccard's coefficient of community similarity was used to obtain an estimate of the similarity of the zooplankton communities and dominant species observed by Hargis (1981) and VOYA/USGS. This coefficient ranges from 100 for two communities or samples composed of identical species to 0 when they have no species in common. Coefficients calculated using only the VOYA/USGS data for all possible between lake comparisons (30 lakes, N = 435) were about normally distributed with the mode of the coefficients being between 40 and 59 (Figure 22). Lakes within this central group could generally be considered to be most representative for this lake region while those at the extremes would be least representative of the overall area. The majority of the coefficients were also in this range for the comparison of all species captured in individual lakes by Hargis (1981) and VOYA/USGS (Figure 22). However, the between-survey comparison did not produce coefficients <20 or >60 as were observed in the VOYA/USGS results. Comparisons of dominant species (= >10% of the

**Table 4.** Number of Voyageurs National Park interior (IL) and large (LL) lakes in which individual zooplankton species comprised more than 10% of the total catch in spring, summer, and fall plankton net catches (VOYA/USGS unpublished data).

| | Spring | | Summer | | Fall | |
|---|---|---|---|---|---|---|
| **Species** | **IL** | **LL** | **IL** | **LL** | **IL** | **LL** |
| *Diacyclops bicuspidatus thomasi* | 8 | 3 | 2 | -- | 5 | 1 |
| *Mesocyclops edax* | 5 | 3 | 1 | 1 | -- | -- |
| *Tropocyclops prasinus* | 6 | -- | 6 | -- | 19 | 2 |
| *Cyclops vernalis* | -- | 1 | -- | 1 | -- | 2 |
| *Skisto diaptomus oregonensis* | 10 | -- | 6 | 3 | 3 | 2 |
| *Diaptomus sicilis* | 1 | -- | -- | -- | -- | -- |
| *Lepto diaptomus minutus* | 3 | -- | 4 | -- | 3 | 1 |
| *Daphnia longiremis* | 1 | -- | 2 | -- | -- | -- |
| *Daphnia pulicaria* | 7 | -- | 2 | -- | 2 | -- |
| *Daphnia galeata mendotae* | 3 | 1 | 4 | 2 | 4 | 1 |
| *Daphnia retrocurva* | -- | -- | 4 | -- | 4 | -- |
| *Bosmina longirostris* | 14 | 4 | 20 | 2 | 18 | 1 |
| *Chydorus sphaericus* | -- | -- | 2 | -- | -- | 2 |
| *Diaphanosoma leuchtenbergian* | 1 | 1 | 12 | 3 | 0 | 3 |
| *Holopedium gibberum* | 12 | 1 | 12 | -- | 5 | -- |

population) in the early summer, mid-summer, and late summer to early fall collections from the two surveys generally produced lower similarity coefficients. Comparisons between species distributions in the more recent surveys from Locator, Mukooda, Namakan, and Rainy lakes and the earlier surveys showed that the Jaccard coefficients from the Hargis (1981) results were generally 10 to 20 points lower than comparable values from the VOYA/USGS data. These apparently consistent differences could be due to the previously mentioned differences in taxonomic resolution in the different surveys but actual interannual differences in the zooplankton populations may have also contributed.

Summer averages of crustacean zooplankton abundance (n = three sampling periods) from the Hargis (1981) and the VOYA/USGS surveys were positively correlated ($r$ = 0.626, $P$ = 0.002, N = 22). Densities were less than 20,000 organisms/m$^3$ in the majority of the lakes in each of the sampling periods and for the whole summer (Figure 23). The proportion of lakes with densities >20,000 organisms/m$^3$ peaked in the mid-summer VOYA/USGS survey and in the fall Hargis (1981) survey. High densities were observed in both surveys in Kabetogama, Weir, and Ek lakes. Other interior lakes with relatively high zooplankton densities included Shoepack, Little Shoepack, and War Club lakes (Hargis, 1981); and Net, Mukooda, O'Leary, Oslo, and Peary lakes (VOYA/USGS, unpublished data). Similar to algal abundance and productivity estimates, average zooplankton densities in Kabetogama Lake were typically two to three times higher than in the other large lakes.

Although there was considerable seasonal variation in the zooplankton communities in the large lakes, similar trends were observed in 1983 and 1984 (Figure 24). In 1983 in Kabetogama Lake, overall abundance of zooplankton increased relatively slowly up to mid-August when it more than doubled. High densities continued to be present until mid to late September when there was a significant decrease. A similar pattern of changes occurred in 1984 with the peak density again occurring in early September. In the other large lakes, densities either remained relatively consistent or slowly declined after peaking in early July. These seasonal patterns are directly attributable to seasonal fluctuations in the dominant groups or species of zooplankton (Figure 25). A combination of cladocera and relatively high numbers of copepods contributed to the higher values in early summer while in Kabetogama Lake, the late summer peak was directly attributable to a large build-up of cladocerans, particularly *Chydorus sphaericus*. Increases in copepod densities in September and October in the other large lakes were offset by decreases in cladocera, the result being an overall decrease in zooplankton density.

**Future Needs and Opportunities:** Further investigations, including a more detailed analysis of the existing zooplankton data, could conceivably provide a better understanding of the factors regulating the composition and abundance of the zooplankton communities in the Park's large lakes. Taxa exhibiting large site-specific variability can be sensitive indicators of change in an ecosystem, whereas taxa that exhibit large temporal variation can be studied to understand factors influencing seasonal or yearly variations (Kratz and others, 1987). As is the case with the phytoplankton, our knowledge of the composition of the

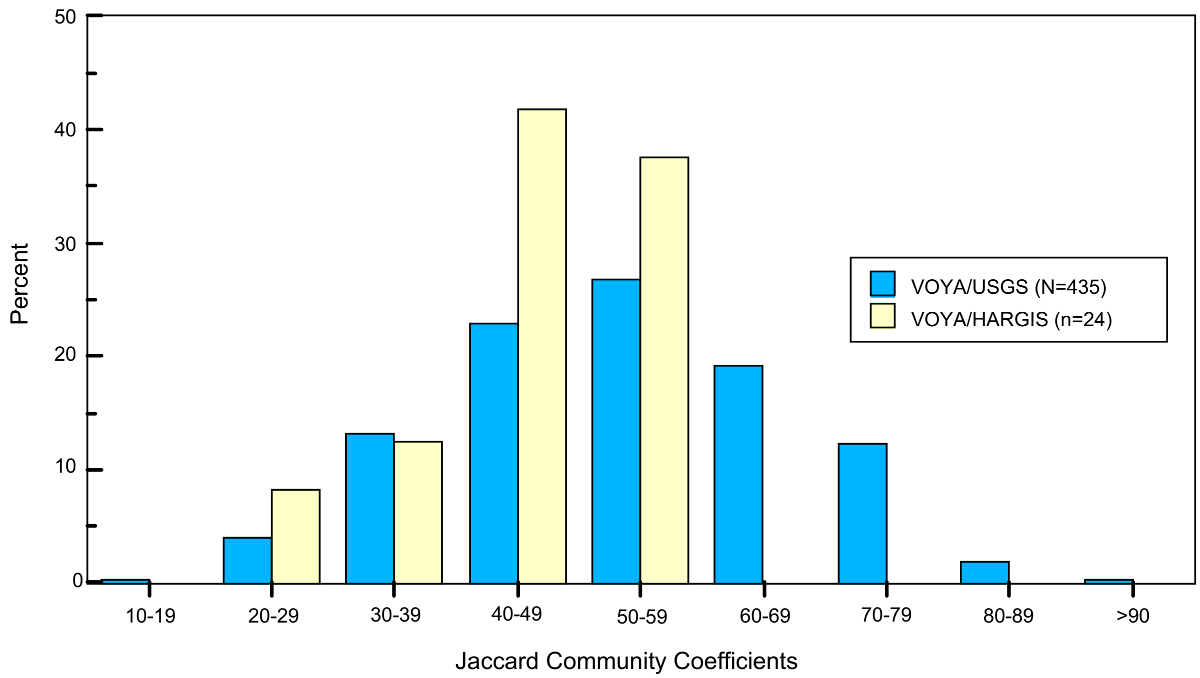



**Figure 22.** Distribution of Jaccard coefficients for comparisons of zooplankton communities in Voyageurs National Park lakes. VOYA/USGS represents all possible comparisons (30 lakes, N = 435) while VOYA/Hargis is a direct comparison for 24 lakes at two different time periods.

zooplankton communities is limited due to the disparities in survey methods and taxonomic expertise of the investigators that have worked in the Park. A complete inventory will require more intensive surveys, both spatially and temporally, and the expertise of a recognized taxonomist(s).

## Zoobenthos

The zoobenthos of VOYA is for the most part poorly understood because there has been no complete survey of the Park's aquatic environment. This is particularly true of the profundal zone in the large lakes and in the other aquatic habitats such as streams, beaver ponds, wetlands, and interior lakes. Our understanding of the zoobenthos rests primarily on qualitative observations of the large midge and mayfly hatches that traditionally occur and the results of six limited investigations and surveys. The ecosystems analysis of six potential Park development sites that was previously mentioned also included evaluation of the benthic communities (University of Minnesota, 1973; 1976) as did Whitman and others (2002) survey of Locator and Mukooda lakes. Kraft (1988) compared benthic communities in Kabetogama, Namakan, and Sand Point lakes with those in Rainy Lake to assess the effect of the greater than natural overwinter drawdown associated with the IJC's 1970 rule curves on littoral zone macroinvertebrates in Namakan Reservoir. A scuba survey was also used to assess the effect of the winter drawdown on Unionid mussels (W. L. Downing, Hamline University, St. Paul, MN, personal communication). Concerns about the possible invasion of the Park by the non-native rusty crayfish, *Orconectes rusticus*, led to a survey of crayfish in 16 Park lakes in 1993 and 1994 by VOYA/USGS. Additional sampling was conducted from 1999 to 2002 in Namakan Lake and the Johnson River. The opossum shrimp, *Mysis relicta,* and the phantom midges, *Chaoborus* spp, because of their importance in the aquatic food web, have been routinely sampled in the South Arm of Rainy Lake since 1998. Understanding the dynamics of these invertebrates could be key to understanding the trophic linkages and to predicting the impacts of the non-native rainbow smelt since *M. relicta* has been found to be one of their principle prey items.

Invertebrates were collected with an Ekman grab in the University of Minnesota (1973; 1976), Kraft (1988), and Whitman and others (2002) investigations. Littoral zone samples were taken at the potential development sites in June, July, and September (University of Minnesota, 1973; 1976), while in Locator and Mukooda lakes, monthly samples (June – September) were collected in both the littoral and limnetic zones (Whitman and others, 2002). Kraft (1988) sampled along transects at depths of 1, 2, 3, 4, and 5

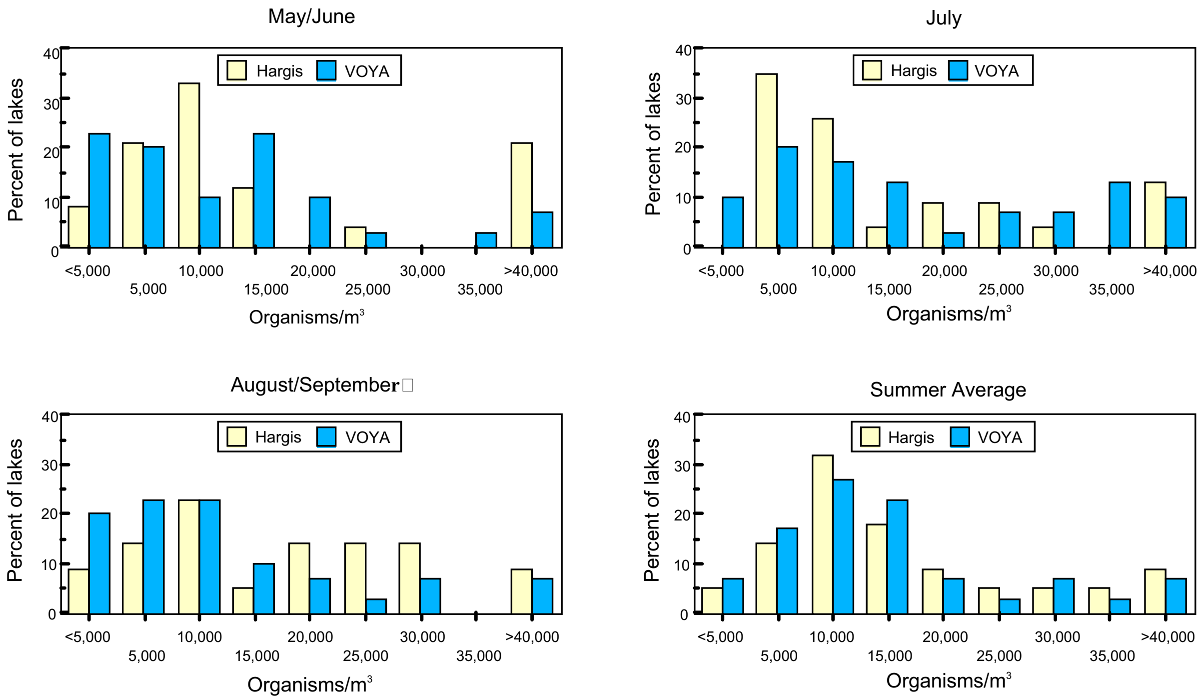



**Figure 23.** Distribution of zooplankton densities in lakes in Voyageurs National Park. Data from Hargis (1981, n = 24 lakes) and VOYA/USGS files (N = 30 lakes).

m. Sampling was confined to the summer except on Kabetogama Lake where samples were also collected throughout fall and winter. Invertebrates in these studies were typically identified to genus or higher taxonomic level and counted. For the mussel study, a 100 m transect line was run perpendicular to the shore and all living mussels within a meter on each side of the line were collected (W. L. Downing, Hamline University, St. Paul, MN, personal communication). Minnow traps baited with dead rainbow smelt were used in the crayfish surveys. Traps were set at 1, 2, and 3 m depths in all the lakes and additionally at 6 m in the Park's large lakes. Approximately equal numbers of sets were made in rock and vegetated habitats. *M. relicta* and *Chaoborus* spp. distribution and relative abundance have been assessed by vertical hauls with a 1.0 m diameter, 243 µm plankton net (Grossnickle and Morgan, 1979; Nero and Davies, 1982). Replicate samples (total vertical lifts) collected biweekly during daylight hours at eight fixed stations during the open water season provide a measure of relative abundance. Depths of the eight stations, which are equally distributed east and west of Brule Narrows in Rainy Lake, primarily exceed 30 m (range 25 – 46 m). The seasonal distribution in the South Arm of Rainy Lake has been assessed by sampling along 21 line transects arranged cross contour. Two samples were taken from each 10 m depth zone represented on each transect, that is 0 – 10, 10 –20, 20 – 30, and >30 m. All organisms were counted and total lengths were then determined from a representative subsample.

Benthos sampling by the University of Minnesota (1973; 1976) at the potential development sites yielded organisms that are characteristic of waters with good water quality. Because the bottom sediments in these areas varied from rocky to highly organic, the samples contained a variety of organisms, including amphipods, insects, mollusks, and worms. Midges (Chironomidae) were typically the most abundant organisms. The frequent occurrence of the amphipod, *Hyalella azteca*, and mayflies, caddisflies, and snails indicated that the sites generally had adequate amounts of dissolved oxygen. Site differences in the species of snails were primarily attributed to variation in the amount of aquatic plant growth, with *Physa* sp. being most common when there was significant vegetation.

Whitman and others' (2002) benthic surveys in 1997 and 1998 in Locator Lake produced 42 and 23 taxa, with approximately 74% and 52% being insects. Comparable figures for 1997 and 1998 from Mukooda Lake were 46 and 26 taxa, and 67% and 54% insects. Total invertebrate abundance in both lakes was significantly higher in the littoral zone than in the limnetic zone in both years. Diversity and species richness indices were also higher from the littoral zone except in 1997 when the Shannon-Wiener diversity index val-

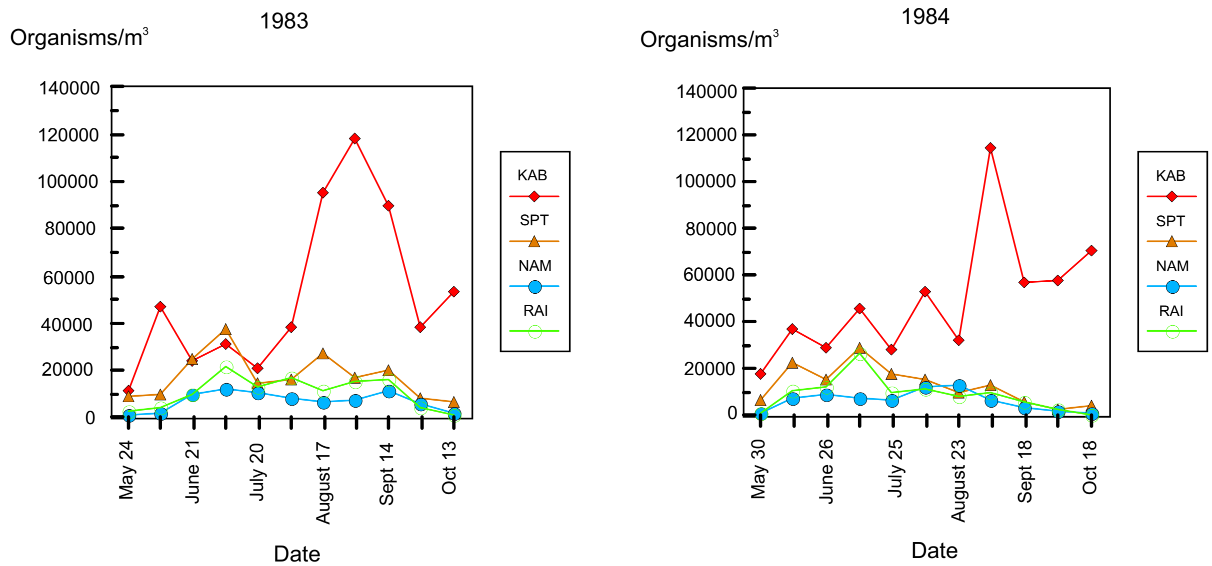



**Figure 24.** Seasonal variation in crustacean zooplankton densities in Kabetogama, Sand Point, Namakan, and Rainy lakes in Voyageurs National Park, Minnesota, 1983 and 1984 (VOYA/USGS unpublished data).

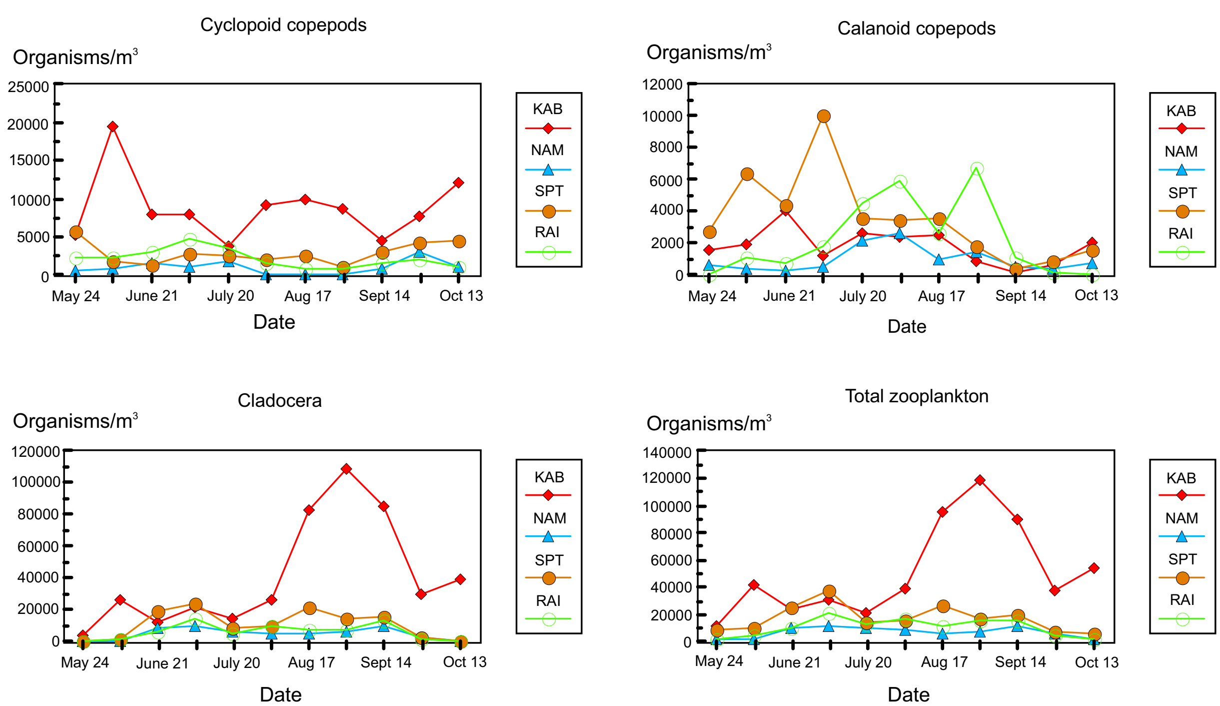



**Figure 25.** Seasonal variation in abundance of zooplankton taxonomic groups in Rainy, Kabetogama, Namakan, and Sand Point lakes in Voyageurs National Park, Minnesota, 1983 (VOYA/USGS unpublished data).

ues were slightly lower than in the limnetic zone. Dominant taxa in the two lakes were generally similar with chironomids and the amphipod, *Hyalella azteca* being predominant in the littoral zone. Caddisfly, mayfly, and dragonfly larvae were most abundant in the littoral zone. *Chaoborus* spp., chironomids, and oligochaets were the dominant taxa in the limnetic zone. The amphipod, *Diporeia* spp., which typically is confined to deep, summer-cold continental, glacial relict lakes (Bousfield, 1989), was collected only in Mukooda Lake.

Results from the Kraft (1988) study, which included 7 summer sampling periods, showed that the average density of benthic invertebrates exhibited a pattern similar to that of primary productivity and water chemistry with densities in Kabetogama Lake being about 2.7 times greater than in Namakan, Sand Point, and Rainy lakes, which were approximately the same. The three Namakan Reservoir lakes produced 33 taxa while Rainy Lake produced 30, 27 of which also were present in the Namakan Reservoir samples. Variations in the number of taxa per sampling period were greater in Namakan Reservoir than in Rainy Lake suggesting there was greater instability in the invertebrate community in the reservoir basins. The fact that Kabetogama Lake had the highest average number of taxa at 3, 4, and 5 m, but not at 1 and 2 m also suggests that the large winter drawdown in Namakan Reservoir reduced the number of taxa in the drawdown zone.

Under the 1970 Rule Curve, winter drawdown on Namakan Reservoir could dewater up to 25% of the reservoir bottom and cause a massive layer of ice to be in contact with the substrate for periods exceeding 100 days. These effects were found to extend to levels 2 to 3 m below summer pool elevation. Mean diversity values for invertebrates at depths of 1 and 2 m in Namakan Reservoir were significantly lower than in Rainy Lake but were not significantly different at 3, 4, and 5 m. Equitability values, which indicate the evenness of allotment of individuals among taxa, exhibited a similar pattern. Stranding and subsequent mortality, which were observed frequently in the winter samples, seemed to be a major contributing factor to the observed differences.

Individual taxa exhibited similar patterns, with densities of the alderfly (*Sialis* spp.), a species sensitive to lake level regulation (Grimas, 1961), and mayfly (*Hexagenia* spp.) being lower in the drawdown zone in Namakan Reservoir than in Rainy Lake. In contrast, chironomids, which quickly recolonize newly submerged areas (Cowell and Hudson, 1968), were more abundant at the Namakan Reservoir sites than in Rainy Lake, particularly in the dewatered zone. Isopods (*Asellus* spp.), which are also affected by regulation (Grimas, 1961), were collected regularly in Rainy Lake but never in Namakan Reservoir.

Kraft's (1988) study and the mussel survey indicated the drawdown on Namakan Reservoir may have reduced the numbers of snails and mussels and caused a shift in their distribution. Mussel densities in Kabetogama and Namakan lakes were lower than in Rainy Lake and they occurred only at depths exceeding 4 m. In Rainy Lake, mussels were primarily found at depths of less than 4 m, which is more typical of bivalves (Pennak, 1978). Snail densities at one meter in Namakan Reservoir were reduced from 54 to 88% (Kraft, 1988). Conceivably, the drawdown could limit the populations of these organisms either directly through death resulting from stranding or by forcing them to live in suboptimal habitats. Drawdown in other locations has resulted in the stranding of large numbers of clams (Kaster and Jacobi, 1978), and has caused Unionid mussels to virtually disappear (Samad and Stanley, 1986).

Three of the six Unionid mollusk species reported by Dawley (1947) as occurring in the Rainy River drainage in Minnesota have been collected in Park waters during the course of the various benthos studies. *Lampsilis radiata siliquoidea* and *Anodonta grandis* were collected in both Namakan and Kabetogama lakes and the latter species in Rainy, O'Leary, and Locator lakes by W. L. Downing (Hamline University, St. Paul, MN, personal communication). Investigators from the University of Minnesota (1973) observed *Anodontoides ferussacianus* in Black Bay in Rainy Lake. *Sphaerium* spp. and *Pisidium* spp. from the Sphaeridae or fingernail clam family, which were not reported by Dawley (1947), were collected both by the University of Minnesota (1973; 1976) and Whitman and others (2002). Additionally, those two surveys and the Kraft (1988) study produced 10 of the 16 snail species that were reported by Dawley (1947) from Lake Vermilion, which lies upstream from the Park in the Rainy Lake basin.

Three crayfish species, *Orconectes virilis*, *O. immunis*, and *Cambarus diogenes diogenes*, were collected by VOYA/USGS in the initial survey of the four large lakes and 12 interior lakes. All are considered to be native to northeastern Minnesota (Helgen, 1990). *O. virilis*, which is the dominant species of crayfish in Minnesota (Helgen, 1990), comprised about 99% of the catch in the large lakes and all except one of the specimens collected in the interior lakes. This species does not burrow, preferring instead to live amongst rocks and rubble in lakes and rivers. *O. immunis*, which was not caught in any interior lakes, comprised about one percent of the catch in Kabetogama, Rainy, and Namakan lakes. *O. immunis* typically is found in shallow, muddy-bottomed areas of lakes and ponds. The only specimen of *C. d. diogenes* caught was captured in Little Trout Lake. This species is a semi-terrestrial species that constructs burrows down to the water table.

The overall mean catch per trap (all depths, all habitats) in the large lakes were 2.75 in Kabetogama Lake, 2.30 in Rainy Lake, 1.88 in Namakan Lake, and 0.70 in Sand Point Lake. Mean catches generally were highest in the traps set at 3 and 6 m (Table 5). With the exception of Beast, Ek, and Jorgens lakes, catches in the interior lakes were considerably lower than in the large lakes (Table 5). Beast Lake in 1994 had an exceptionally high catch rate; however, when sampling was repeated in 1996 it was similar to those observed in the other interior lakes. This decrease would appear to have been due to expansion of the population of recently introduced smallmouth bass.

In 1999, the MNDNR collected rusty crayfish, *O. rusticus*, in Johnson Lake, which lies adjacent to the Park and drains into Namakan Lake. The concern relative to the possible invasion by this non-native species centers on its demonstrated potential to impact aquatic vegetation, fish eggs, and displacement of native crayfish (Lodge and others, 1994). To determine if this non-native species had spread throughout the Johnson River drainage, crayfish sampling was conducted in 1999 in Spring, Johnson, and Little Johnson lakes, the Johnson River between Little Johnson and Namakan lakes, and in Junction Bay in Namakan Lake. Sampling was repeated at the latter two sites from 2000 to 2002. Rusty crayfish were only captured in Johnson Lake with only *O. virilis* and *immunis* being collected at the other sites. Rusty crayfish are also present in Vermilion Lake, which also drains into the Park. Crayfish sampling in 1994 by MNDNR personnel in the Vermilion River between Vermilion and Crane lakes, however, produced only *O. virilis*. A rusty crayfish, however, was collected by the MNDNR in Crane Lake in 2002.

*Mysis relicta* is native to deep, cold, oligotrophic lakes in the northern states, the Great Lakes, and many Canadian lakes (Pennak, 1978). In the Park, *Mysis relicta* has been collected in Rainy and Namakan lakes and observed in zooplankton samples from Sand Point Lake. During the summer stratification period in Rainy Lake, *Mysis relicta* occurs primarily at depths >20 m and the highest densities occur at depths of >30 m during daylight hours (Figure 26). Hydroacoustic observations and depth stratified sampling on Rainy Lake has shown that *Mysis relicta* undergoes its characteristic vertical migration at night. Average densities for the eight fixed stations have been relatively consistent except for those west of Brule Narrows in 1998 when significantly higher numbers were observed (Figure 27). Similar ranges in densities were observed in Namakan Lake in 1998 when monthly sampling was done at three deepwater sites. Comparison of *M. relicta* densities is complicated by the variety of sampling methods used by different investigators, but it appears that densities in Rainy Lake on average are less than in the Great Lakes (Lasenby, 1991). Total lengths of juvenile *M. relicta* in Rainy Lake increase from about 4 mm to 12 to 14 mm by late September or at a rate approaching 2 mm/month (Figure 28). A relatively fast rate such as this usually occurs only in more productive waters; in meso-oligotrophic to oligotrophic lakes growth rates are typically 1 mm or less per month (Beeton and Gannon, 1991).

*Chaoborus* spp. has been collected in all the

**Table 5.** Mean crayfish catches (CPUE) in baited minnow traps set at depths from one to six m in 16 lakes in Voyageurs National Park, Minnesota, 1994.

| | Depth, m | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | one | | two | | three | | six | | Total | |
| Lake | trap sets | CPUE | trap sets | CPUE | trap sets | CPUE | trap sets | CPUE | trap sets | CPUE |
| Agnes | 6 | 1.00 | 6 | 0.17 | 6 | 0.00 | -- | -- | 18 | 0.39 |
| Beast | 12 | 9.83 | 12 | 13.67 | 12 | 13.83 | -- | -- | 36 | 12.44 |
| Brown | 6 | 0.67 | 6 | 1.00 | 3 | 0.00 | -- | -- | 15 | 0.67 |
| Ek | 6 | 1.83 | 6 | 6.67 | 6 | 7.83 | -- | -- | 18 | 5.44 |
| Jorgens | 6 | 4.00 | 6 | 2.17 | 6 | 1.00 | -- | -- | 18 | 2.39 |
| L. Trout | 12 | 0.42 | 12 | 0.17 | 12 | 0.17 | -- | -- | 36 | 0.23 |
| Locator | 12 | 0.92 | 12 | 0.50 | 12 | 1.17 | -- | -- | 36 | 0.86 |
| Mukooda | 12 | 0.08 | 12 | 0.25 | 12 | 0.25 | -- | -- | 36 | 0.19 |
| Peary | 6 | 0.83 | 6 | 0.50 | 6 | 0.50 | -- | -- | 18 | 0.61 |
| Quarterline | 6 | 0.50 | 6 | 0.00 | 6 | 0.00 | -- | -- | 18 | 0.17 |
| Quill | 12 | 0.00 | 12 | 0.00 | 12 | 0.25 | -- | -- | 36 | 0.17 |
| Shoepack | 12 | 0.42 | 12 | 0.08 | 12 | 0.08 | -- | -- | 36 | 0.19 |
| Kabetogama | 48 | 1.71 | 48 | 1.71 | 42 | 3.24 | 29 | 5.52 | 167 | 2.75 |
| Namakan | 48 | 0.96 | 48 | 1.48 | 48 | 2.23 | 32 | 3.34 | 176 | 1.88 |
| Rainy | 48 | 1.65 | 48 | 1.94 | 48 | 3.21 | 32 | 2.47 | 176 | 2.30 |
| Sand Point | 48 | 0.29 | 48 | 0.48 | 48 | 0.40 | 32 | 2.12 | 176 | 0.70 |

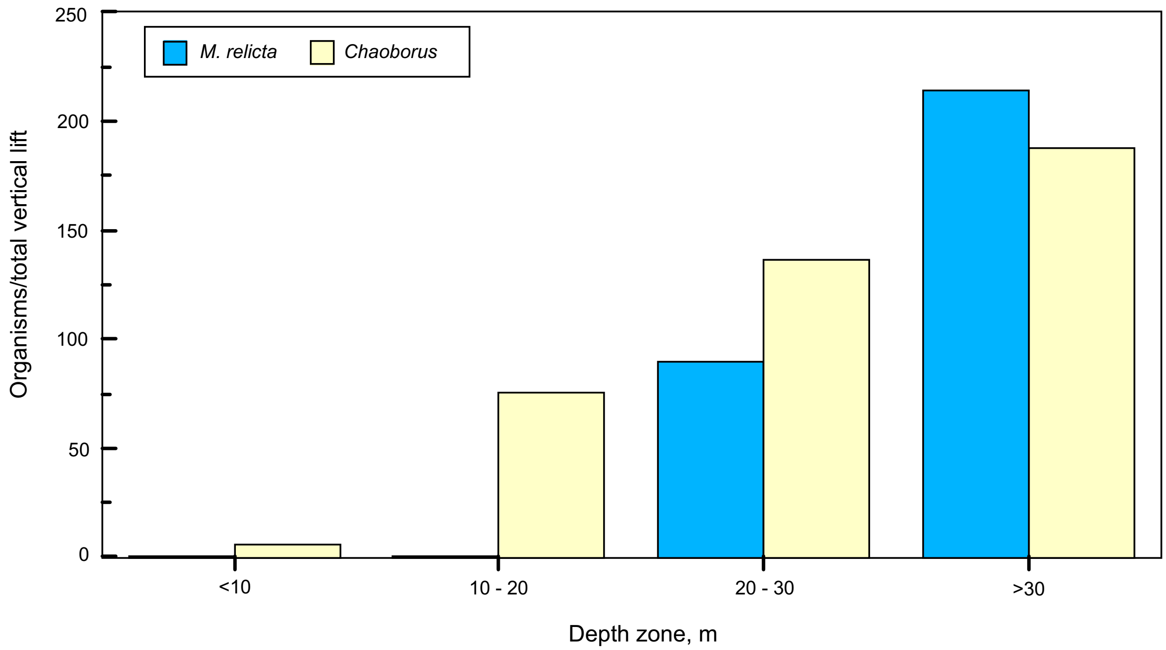



**Figure 26.** Depth distribution of *Mysis relicta* and *Chaoborus* spp. in Rainy Lake, August 19-30, 1999 (VOYA/USGS unpublished data).

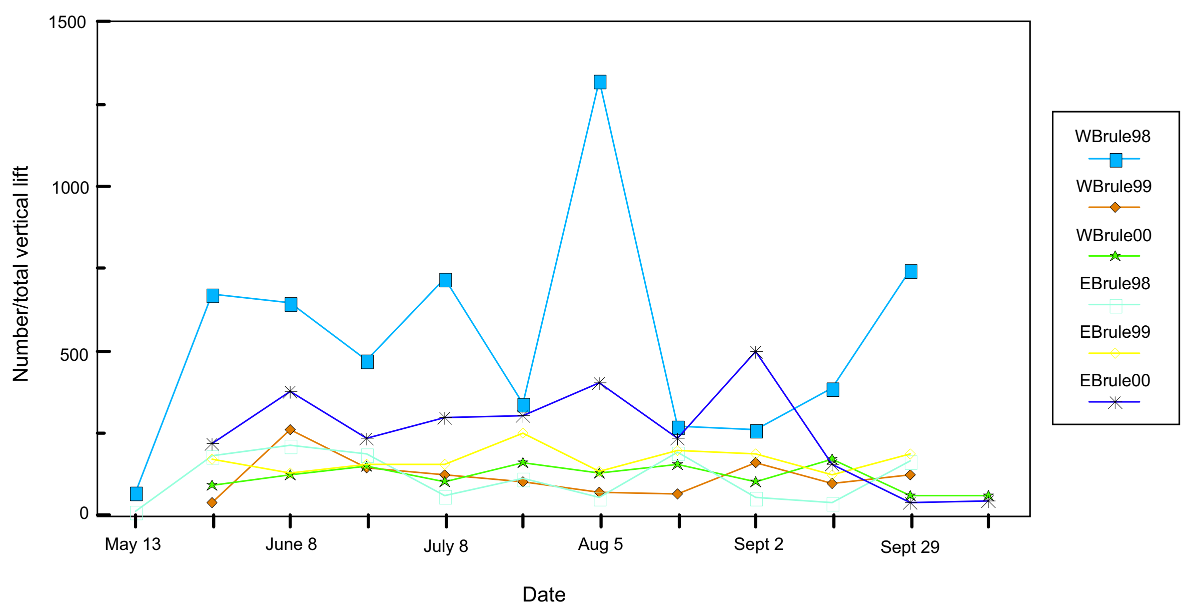



**Figure 27.** Comparison of number of *Mysis relicta* per total vertical lift from east and west of Brule Narrows, Rainy Lake, 1998-2000 (VOYA/USGS unpublished data).

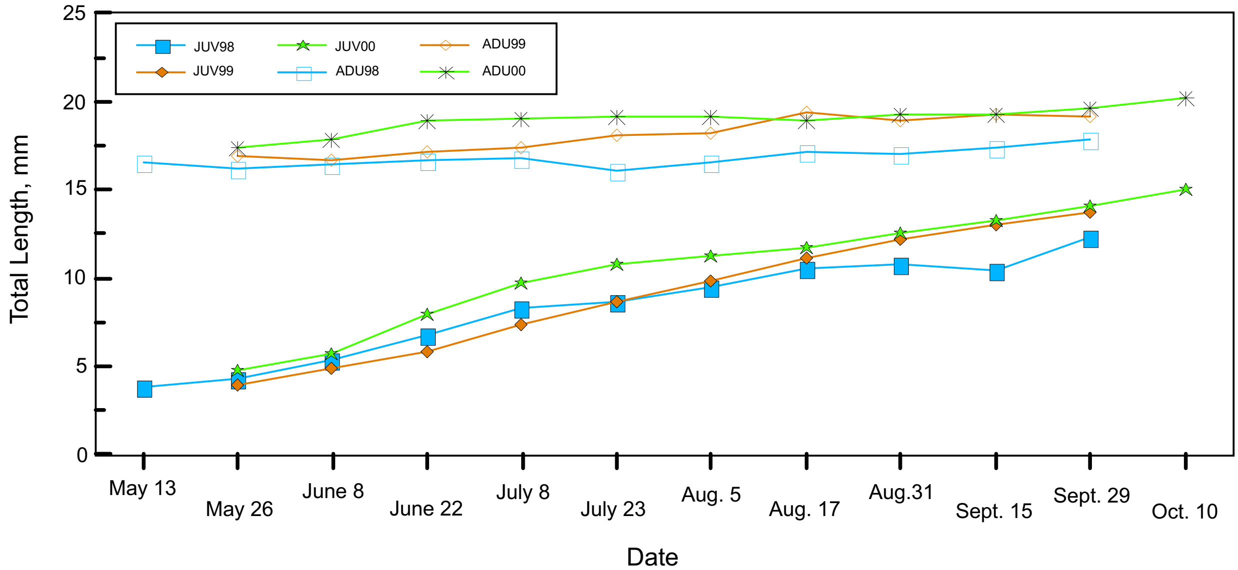



**Figure 28.** Mean total lengths of juvenile and adult *Mysis relicta* in Rainy Lake, 1998-2000 (VOYA/USGS unpublished data).

benthic surveys conducted in VOYA. Like *M. Relicta*, the fourth instar of *Chaoborus* spp. exhibit pronounced daily migratory movements, being confined to the bottom waters and mud during the day and migrating to the surface waters at night (Pennak, 1978). Daytime collections in Rainy Lake were greatest from depths >20 m (Figure 26). Two peaks in density occurred in Rainy Lake in both 1999 and 2000 (Figure 29). The June peak consisted primarily of relatively large organisms while the August peak contained much smaller organisms. Speculatively, the latter most likely was due to the recruitment of an instar that was susceptible to the mesh in the tow net. More detailed analyses, including determination of what species are involved, is needed to understand the observed patterns in density.

**Future Needs and Opportunities:** Given the limited amount of work that has occurred, the first priority should be a detailed inventory of the zoobenthos in the Park waters. This will require the expertise of recognized taxonomists. Then more detailed studies could be conducted to gain an understanding of the factors regulating the composition, abundance, and productivity of the benthic community. Monitoring and research is needed to determine if the 2000 rule curves are having the hypothesized effects on the benthic communities in the large lakes. Monitoring should also be continued to determine if and when non-native species such as the rusty crayfish invade the Park.

## Aquatic Vegetation/Wetlands

To date, about 820 vascular plant species have been collected and identified in the Park as the result of the studies referenced below and by others. Monson (1986), in particular, made a significant contribution to the development of this species database. Monson (1986) compiled pertinent vouchers from the Olga Lakela Herbarium, University of Minnesota-Duluth, and during his studies in 1982 –83, he added nearly 700 vouchers representing 375 species. Monson's 1982-83 collections added 45 species to the record assembled in 1949-55 by Lakela (1965). Monson (1986) combined his collections with those of Lakela (1965) and reported that the Park's flora included 602 species of vascular plants. Based on Gleason (1952), Fassett (1957), and Muenscher (1964), approximately 25% of the Park's plant species would be classified as aquatic species. Of the 85 genera represented in the aquatics group, *Carex* is best represented with 39 species. Other well-represented genera include 12 species of *Potamogeton* and 11 species of *Juncus*.

There are no federally listed endangered or threatened aquatic plant species in the Park. Aquatic plant species classified as endangered by the State of Minnesota that either occur or have been found in the past in the Park are *Subularia aquatica* and *Caltha natans*. Pigmyweed (*Tillaea aquatica*), a state listed threatened species, also occurs in the Park.

VOYA contains significant wetland resources. Because of the well-recognized ecological values of these wetland resources (Wilcox and Meeker, 1992; Mitsch and Gosselink, 1993), they have been included

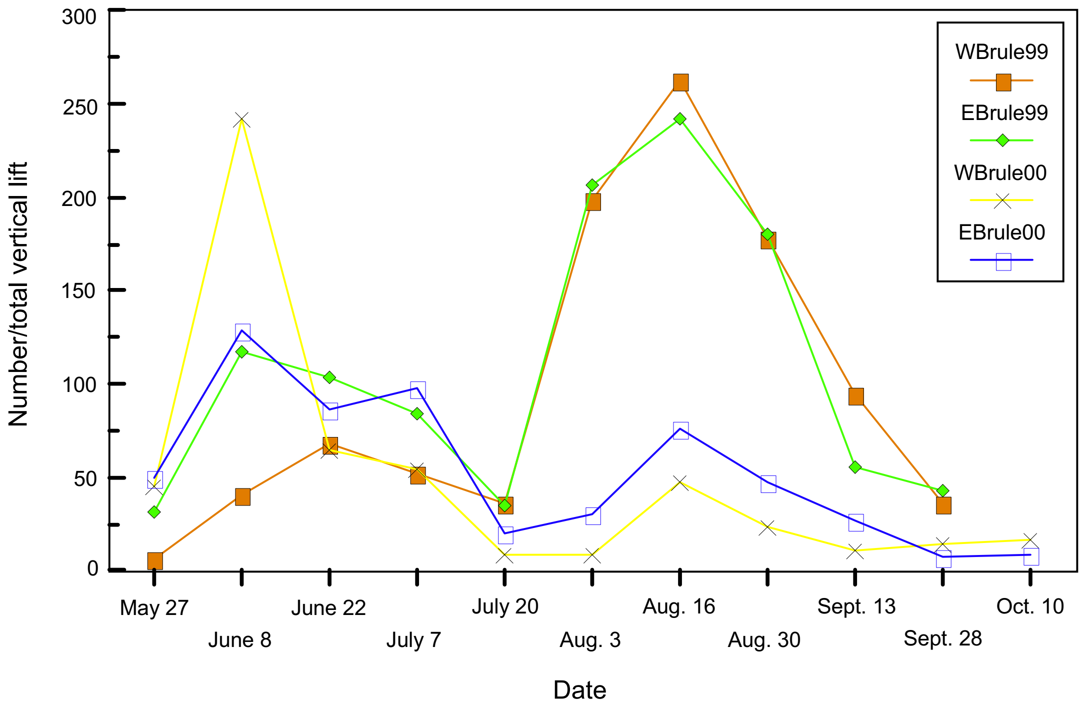



**Figure 29.** Mean number of *Chaoborus* spp. per total vertical lift from east and west of Brule Narrows, Rainy Lake, 1999-2000 (VOYA/USGS unpublished data).

in parkwide as well as site-specific plant community classification and mapping investigations. The three primary park wide investigations were conducted by Kurmis and others (1986), the U.S. Fish and Wildlife Service (USFWS), and Hop and others (2001). Kurmis and others' (1986) classification of the Park's vegetation includes 12 ecological types identified on the basis of moisture and nutrient gradients. The five of these associated with wet, edaphic conditions were white cedar – *Coptis*, black spruce – *Alnus*, black spruce – *Kalmia*, leatherleaf bog, and marsh. In contrast, the USFWS and the Hop and others (2001) studies used more detailed classification systems to identify and map the Park's wetlands. The USFWS as part of their National Wetlands Inventory (NWI) identified and mapped wetlands in the Park and adjoining areas. Wetlands were identified on aerial photographs based on vegetation, visible hydrology, and geography in accordance with Cowardin and others (1979) wetland classification guide. Based on an analysis of the digital versions of the NWI maps, 11,997 ha (29,646 ac) in the Park were classified as palustrine wetlands (W. Wold, GIS Specialist, VOYA, personal communication). These would include the vegetated wetlands traditionally called marsh, swamp, bog, fen, and in some instances small, shallow ponds (Cowardin and others, 1979). Portions of these wetlands lie within the Park's lacustrine system, which encompasses the permanently flooded interior lakes and the four large lakes.

Similar quantities and distributions of wetland communities were identified in the most recent parkwide analysis of the Park's plant communities (Hop and others, 2001). Based on aerial photo interpretation and ground truthing, Hop and others (2001) identified a total of 50 plant community types using the U.S. National Vegetation Classification system. About 50% of these were identified as bog, swamp, marsh, fens, and ponds. Together, these covered about 13,104 ha (32,380 ac) with about 4,168 ha (10,300 ac) located within the 33,027 ha (81,609 ac) encompassed by the Park's 30 named lakes.

The NWI survey showed that a significant portion (28%) of VOYA's wetlands is the result of beaver activity. Interpretation of a series of aerial photographs showed that between 1940 and 1986 the portion of the Kabetogama Peninsula impounded by beaver increased from <1% to 13% (Johnston and Naiman, 1990). Thus, in 1986, about 3,764 ha (9,300 ac) were covered by beaver impoundments that contained a mosaic of different wetland vegetation types (Naiman and others, 1988; Johnston and others, 1993). While changes in dominant vegetation types do occur in response to changes in hydrological conditions, long-term analysis has shown that the impounded areas continue to be dominated by wetland plants (Johnston and Naiman, 1990). Erickson (1994) found that species composition in these communities varied along complex hydrologic-nutrient availability gradients, that nitrogen and secondarily phosphorus limited plant growth in less productive meadows, and that the degree of nutrient limitation also varied along hydrological gradients. Interpretation of diversity-productivity relationships for these areas was found to be sensitive to plot size and required specification of the species-area relationship for the specific community (Pastor and others, 1996). Overall, beaver activity on the Kabetogama Peninsula has resulted in the substantial accumulation of chemical elements in the organic horizon of pond sediments (Naiman and others, 1994). These elements are available for vegetative growth when dams fail, ponds drain, and meadows are formed.

Mapping and identification of aquatic vegetation has been a component of the lake surveys conducted by the MNDNR in the Park's interior lakes (MNDNR, 1993). Mapping is done by cruising the shoreline, mid-lake reefs, and islands and determining the extent of the vegetation along the shoreline and its distance from shore. Visual observation, depth finders, and occasionally a grapple may be used to determine the extent of the bed. Major plant species are identified and mapped. In addition to the mapping, aquatic vegetation is identified in 6-m wide transects that run perpendicular to the shoreline out to the maximum depth of vegetation growth. The number of transects, which are evenly spaced around the lake, is based on lake area. The objective is to obtain as accurate a list as possible of the species that are present on each transect. Comparison of the results from different time periods can then be used to document changes in vegetation distribution. In addition to the mapping and transect sampling, biologists are also to record any other species they encounter.

Complete lake surveys of all 26 interior lakes were first conducted by the MNDNR in the early 1970s. In 1983, 14 of the lakes were resurveyed with two more being sampled for the second time in 1996 and 1999. Five lakes were subsequently surveyed for a third time between 1995 and 2000. Of the 76 plant taxa identified from all the surveys, 14 occurred in more than half of the 26 interior lakes (Table 6). Common cattail, yellow and white waterlily, largeleaf pondweed, and three-way sedge were the most frequently observed species. While the average numbers of taxa per lake in the first and second surveys were similar, 14.7 and 14.2, in the third survey the average rose to 23.4. Comparison of the vegetation composition in the first and second surveys using Jaccard's index produced an average similarity value of 34% with only three lakes having values of 50% or greater. For the five lakes that were surveyed three times, the average similarity value between the first and second surveys was 40.6%, between the first and third surveys 41.6%, and between the second and third surveys 44.6%. Index values from Mukooda Lake, which had the largest number of taxa in all three surveys, had similarity values of 29%, 66%, and 64% respectively. Whether the predominantly low values actually reflect changes in the plant communities or variability due to the observers is unknown. Since fishery biologists conduct the lake surveys and tend in most instances to focus on common species, there is little doubt that intensive surveys of these lakes by plant taxonomists would produce more species.

More site-specific investigations of aquatic vegetation in the Park were conducted by the University of Minnesota (1973; 1976), Monson (1986), Kallemeyn (1987b), and Wilcox and Meeker (1991; 1992). The University of Minnesota's ecosystems analysis of six potential Park development sites included the identification and mapping of emergent, floating, and visible submergent aquatic vegetation. In total, 34 aquatic plant taxa were identified at these sites. Results were generally qualitative, with comments usually restricted to assessments of the relative abundance of the predominant species. Possibly of more long-term value are the overlay maps in their reports that show where beds of dominant species were located in each of the embayments.

Assessment of the effects of the fluctuating water levels resulting from the IJC's 1970 rule curves, and subsequently their affect on northern pike spawning habitat was the objective of the Monson (1986), Kallemeyn (1987b), and Wilcox and Meeker (1991) studies. Monson (1986), based on comparisons of aquatic vegetation communities in Rainy, Kabetogama, Namakan, and Sand Point lakes, concluded there were no consistent significant differences between the lakes. His study, however, was hampered by poor sampling design and too few sampling points to obtain statistically valid data (Meeker and Wilcox, 1989). Limitations of his sampling method led to the exclusion of low-growing rosette forms such as *Sagittaria* spp. and *Isoetes* spp. and the rhizomatous *Eleocharis acicularis*, all of which were found by Wilcox and Meeker (1991) to be significant in explaining the effects of water level regulation. Monson (1986) concluded after presenting a brief review of factors affecting wild rice production that further research was needed to assess what factor or factors were applicable to the Park lakes.

To address the question of the altered hydrologic regimes, Wilcox and Meeker (1991) compared aquatic macrophyte communities in Rainy and Namakan lakes with those in Lac La Croix, an unregulated lake located 32 km upstream from Namakan Lake. Lac La Croix's mean annual fluctuation of 1.6 m fell between the 1.1 m and 2.7 m experienced by Rainy and Namakan lakes under the 1970 rule curve. Unlike, the regulated lakes, Lac La Croix's water level typically declined after early June rather than remaining stable,

**Table 6.** Aquatic plants identified in Minnesota Department of Natural Resources lake surveys of Voyageurs National Park's 26 interior lakes.

| Scientific name | Common name | # of lakes | Scientific name | Common name | # of lakes |
|---|---|---|---|---|---|
| *Acorus calamus* | Sweet Flag | 1 | *Nuphar microphyllum* | Little Yellow Waterlily | 18 |
| *Alisma trivale* | Water Plantain | 1 | *Nymphaea tetragona* | Little White Waterlily | 4 |
| *Alopecurus aequalis* | Foxtail | 3 | *Nymphaea tuberosa* | White Waterlily | 21 |
| *Andromeda glaucophylla* | Bog Rosemary | 1 | *Phalaris arundinacea* | Reed Canary Grass | 4 |
| *Brasenia schreberi* | Water Shield | 14 | *Phragmites communis* | Cane | 9 |
| *Calamagrostis canadensis* | Bluejoint | 3 | *Potamogeton amplifolius* | Largeleaf Pondweed | 20 |
| *Calla palustris* | Water Arum | 15 | *Potamogeton crispus* | Curled Pondweed | 1 |
| *Caltha palustris* | Marsh Marigold | 2 | *Potamogeton epihydrus* | Nuttall's Pondweed | 14 |
| *Carex spp.* | Sedge | 18 | *Potamogeton filiformis* | Pondweed | 4 |
| *Carex spp.* | Narrowleaf Sedge | 5 | *Potamogeton gramineus* | Variable Pondweed | 3 |
| *Ceratophyllum demersum* | Coontail | 10 | *Potamogeton illinoensis* | Illinois Pondweed | 1 |
| *Chara spp.* | Muskgrass | 3 | *Potamogeton natans* | Floatingleaf Pondweed | 9 |
| *Decodon verticillatus* | Swamp Loosestrife | 2 | *Potamogeton pectinatus* | Sago Pondweed | 1 |
| *Drepanocladus spp.* | Water Moss | 5 | *Potamogeton richardsonii* | Claspingleaf Pondweed | 3 |
| *Dulichium arundinaceum* | Three-way Sedge | 19 | *Potamogeton robbinsii* | Robbin's Pondweed | 1 |
| *Eleocharis acicularis* | Needlerush | 3 | *Potamogeton spirillis* | Snailseed Pondweed | 2 |
| *Eleocharis smallii* | Spikerush | 13 | *Potamogeton strictifolius* | Narrowleaf Pondweed | 6 |
| *Elodea canadensis* | Canada Waterweed | 3 | *Potamogeton zosteriformis* | Flatstem Pondweed | 2 |
| *Equisetum fluviatile* | Swamp Horsetail | 16 | *Potentilla palustris* | Swamp Fivefinger | 8 |
| *Eriocaulon septangulare* | Pipewort | 10 | *Ranunculus spp.* | Water Buttercup | 5 |
| *Eriophorum spp.* | Cottongrass | 2 | *Sagittaria spp.* | Arrowhead | 11 |
| *Heteranthera dubia* | Water Star-grass | 1 | *Sagittaria graminea* | Slender Arrowhead | 1 |
| *Hippuris vulgaris* | Marestail | 6 | *Sagittaria latifolia* | Arrowhead | 4 |
| *Hypericum virginicum* | Marsh St. John's-wort | 4 | *Sagittaria rigida* | Stiff Wapato | 6 |
| *Iris versicolor* | Blue Flag | 14 | *Scirpus spp.* | Bulrush | 3 |
| *Isoetes spp.* | Quillwort | 1 | *Scirpus acutus* | Hardstem Bulrush | 7 |
| *Juncus spp.* | Rushes | 4 | *Scirpus cyperinus* | Wool Grass | 9 |
| *Ledum groenlandicum* | Labrador Tea | 1 | *Scirpus pungens* | Threesquare | 1 |
| *Leersia oryzoides* | Rice Cutgrass | 2 | *Scirpus subterminalis* | Water Bulrush | 2 |
| *Lemna minor* | Lesser Duckweed | 1 | *Scirpus validus* | Softstem Bulrush | 3 |
| *Lobelia dortmanna* | Lobelia | 2 | *Sium suave* | Water Parsnip | 4 |
| *Megalondonta beckii* | Water Marigold | 1 | *Sparganium spp.* | Burreed | 1 |
| *Myrica gale* | Sweetgale | 14 | *Sparganium angustifolium* | Floatingleaf Burreed | 19 |
| *Myriophyllum spp.* | Water Milfoil | 11 | *Sparganium chlorocarpum* | Greenfruited Burreed | 3 |
| *Myriophyllum tenellum* | Leafless Water Milfoil | 2 | *Sparganium eurycarpum* | Giant Burreed | 4 |
| *Najas spp.* | Bushy Pondweed | 5 | *Typha latifolia* | Common cattail | 26 |
| *Nitella spp.* | Stonewort | 2 | *Utricularia spp.* | Bladderwort | 14 |
| *Nuphar luteum* | Yellow Waterlily | 24 | *Vallisneria americana* | Wild Celery | 5 |
| | | | *Zizania palustris* | Wild Rice | 14 |

and it exhibited greater year-to-year variability. Significantly, from the study design perspective, aquatic macrophytes were sampled along four depth contours selected to represent specific habitat types in the unregulated lake. The transects were established at altitudes relative to the mean high water levels, the rational being that the plant communities would be more likely to correspond to the long-term hydrologic regime. Species identification and percent cover estimations were made in twenty 1-m$^2$ quadrants on each transect. Importance values were calculated for each taxon as the sum of the relative frequency and relative mean cover on each transect.

A total of 109 taxa were sampled in the three lakes with Rainy Lake having a slightly greater species richness (76 taxa) than either Namakan Lake (72) or Lac La Croix (65). Species pools in the lakes were similar. The similarity index values were 61.0% between Rainy Lake and Lac La Croix, 66% between Rainy and Namakan lakes, and 70% between Lac La Croix and Namakan Lake. Because of the similarity in species pools, Wilcox and Meeker (1991) concluded differences in communities at various depths were a result of the different water-level regimes to which the lakes were exposed.

Naturally regulated Lac La Croix supported a more taxonomically diverse plant community at all depths; the greatest differences were evident in the plant assemblages from deeper water (Figure 30). The effect of the less than natural water level fluctuation on Rainy Lake was most obvious on transects that were never dewatered. Only four plant taxa were present at that depth (1.75 m), and they were all erect aquatics. On Namakan Lake, the effects were most apparent at the depth (1.25 m) that was exposed annually to the effects of desiccation and disturbance from ice formation in the sediments. Those conditions favored the establishment of low rosette and mat-forming plant species, neither of which provides much structural diversity in the water column. Wilcox and Meeker (1991) concluded the macrophyte communities of both regulated lakes would benefit from a hydrological regime approximating that of Lac La Croix. They suggested such conditions would provide a more natural and structurally diverse macrophyte community that would provide more diverse habitats for aquatic fauna (Wilcox and Meeker, 1992).

Kallemeyn (1987b) developed detailed

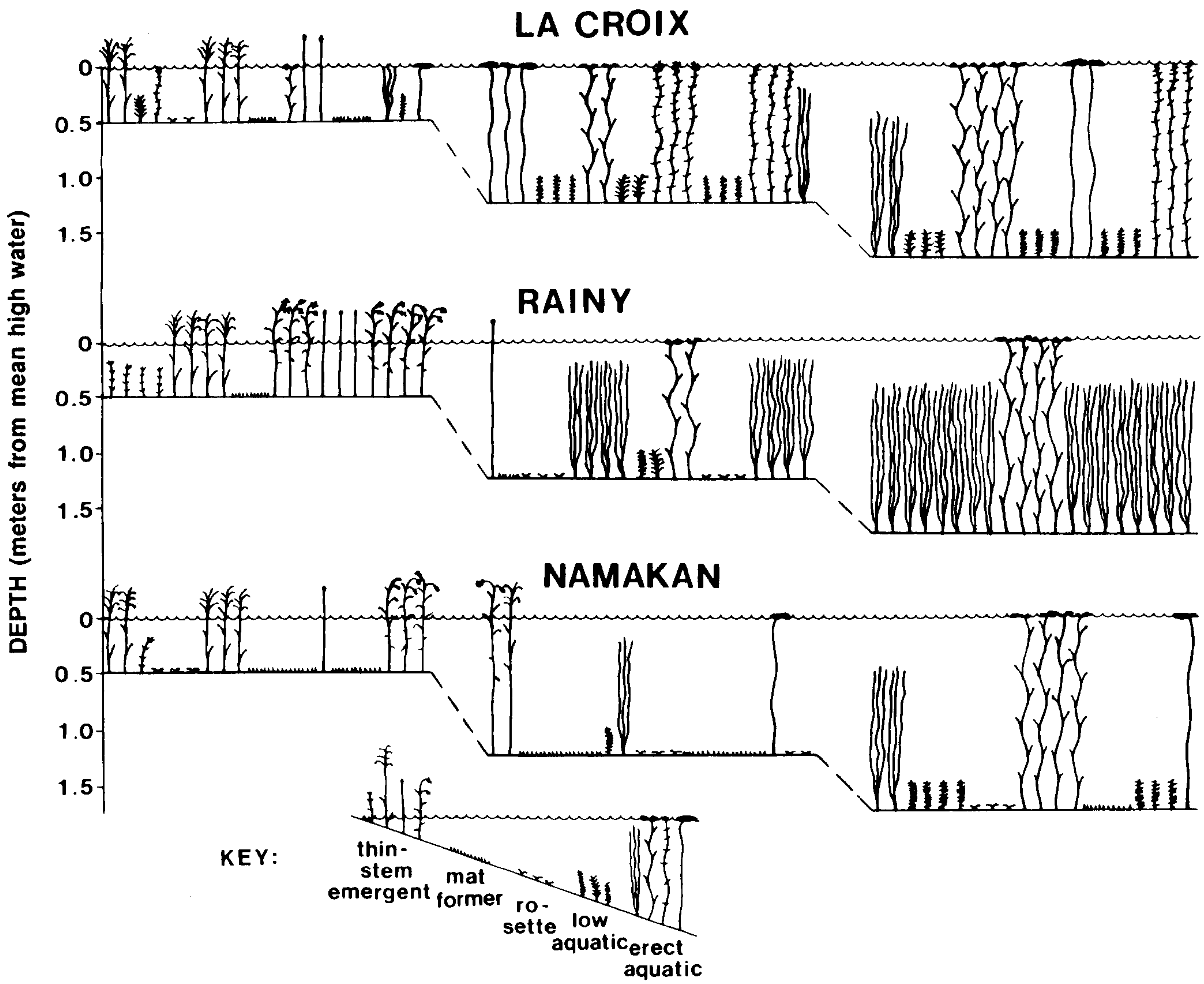



**Figure 30.** Schematic model showing cross-sections of the littoral zone of study sites in Lac La Croix, Rainy Lake, and Namakan Lake. The general structure of the 30 most important aquatic plant taxa are depicted at the water depths sampled along contours of 0.5, 1.25, and 1.75 m (adapted from Wilcox and Meeker 1992).

topographic maps of Daily Brook and Tom Cod Bay, the primary northern pike spawning areas in Kabetogama Lake. Then he identified and mapped the distribution of the emergent vegetation that might be available to the northern pike for spawning in the 3-week period following ice-out. Total areas of the two areas at 340.5 m (1117 ft) above mean sea level were about 60 ha (148 ac) and 82 ha (203 ac), of which 19% and 29%, respectively consisted of emergent vegetation or potential northern pike spawning habitat. The emergent vegetation, which consisted primarily of *Typha latifolia* and *Scirpus* spp., was restricted to substrate elevations above 339.86 m (1115 ft) above mean sea level by the high, stable summer water levels. Consequently, for the vegetation to be flooded during the preferred spawning period, water levels had to exceed the maximum levels allowed under the 1970 rule curve. When this occurred, reproductive success of the northern pike was higher.

Park management relative to aquatic vegetation and wetlands has focused primarily on the restoration of more natural hydrologic regimes to the large lakes (see the Regulated Lake Level section) and the control of exotic purple loosestrife (Szymanski and Johnson, 2000). Purple loosestrife, *Lythrum salicaria*, is believed to have been present when the Park was established in 1975. It is widespread outside the Park, including in several drainages that flow into the Park. From 1989 to 1997, the Park used a combination of manual plant and seed-head removal and chemical control on the 130 acres of purple loosestrife in the Tom Cod, Ranta Bay, and Moose Bay areas of Kabetogama Lake. This effort resulted in a significant reduction in the distribution and density of loosestrife in the infected area. Since 1998, manual removal and biological control using the beetles, *Galerucella calmariensis* and *G. pusilla* has been used in the control program. Beetles have been released at infected sites both within the Park as well as in small drainages that flow into the Park. In 2000, Park staff found loosestrife at several locations where it had not been noted for several years (Szymanski and Johnson, 2000).

**Future Needs and Opportunities:** Detailed inventories of aquatic plant communities in the interior lakes are needed, as are surveys to delineate distributions of endangered and threatened plant species. Monitoring and research is needed to determine if the 2000 rule curves are having the hypothesized effects on the aquatic vegetation. It is obvious that monitoring and control will continue to be needed for purple loosestrife, particularly since control efforts on established populations outside the Park are extremely limited or non-existent. Monitoring will also be necessary to detect whether other exotic plants such as Eurasian water milfoil have been introduced into the Park. Surveys should be conducted to determine if logging and associated activities outside the Park boundary are influencing bog/peatland areas that extend into the Park. The greatest potential would seem to be in the area west and south of Kabetogama Lake. While some of this area is protected by MNDNR East and West Rat Root River Peatland Scientific and Natural Areas (MNDNR, 1999), portions are located outside of the protected areas and are subject to logging, which conceivably could disrupt the water flow system and alter the plant communities (Glaser, 1987).

## Fish Communities/Fishing

The fish populations and communities, because of their ecological importance as well as their utilization by Park visitors, have been and continue to be the subject of numerous surveys, studies, and long-term fisheries assessment programs. MNDNR and VOYA/USGS personnel conduct assessment activities on the Minnesota portions of the large border lakes, while the OMNR conducts sampling in the Canadian portions of Rainy, Namakan, and Sand Point lakes. The MNDNR’s Large Lake Assessment program (Wingate and Schupp, 1985), that was designed to standardize sampling on Minnesota’s largest, most conspicuous walleye lakes, is used on Rainy and Kabetogama lakes, with some aspects of the program also being used on Namakan and Sand Point lakes. Under this program, which has been in effect since 1983, sampling is conducted annually using standardized equipment and procedures. Experimental gill netting, which is the backbone of this program, is done at fixed stations at the same time each year. Other sampling equipment used includes small-mesh gill nets, seines, trap nets, and an electrofishing boat. Each piece of equipment targets certain species. For example, experimental gill netting targets primarily walleye, northern pike, yellow perch, sauger, cisco, and white sucker; small-mesh gill nets target rainbow smelt; trap nets target black crappie; electrofishing targets young-of-the-year and yearling walleye and smallmouth bass; and seining targets young-of-the-year gamefish and minnows and other forage fish species. This program provides indices of abundance, size and age structure of populations, growth rates, condition indexes, sex ratios, and for some species maturity schedules. Gamefish species are aged using scales, otoliths, and cleithra. Lengths at age are computed from annuli on scales with growth being analyzed using the linear growth model, DISBCAL (Frie, 1982). The resulting data is used to establish fishing regulations and to assess the effects of other biological and environmental variables on reproductive success and year-class strength.

Although gill nets and other similar sampling methods are used by the OMNR, their fisheries assessments in the border lakes have not been conducted as frequently as MNDNR and VOYA/USGS assessments. The OMNR has in recent years implemented a standardized fall walleye index-netting program that provides results that can be compared with data from other Ontario lakes. In 2001, the OMNR and MNDNR collaborated on a gill netting program on Rainy Lake to determine the comparability of results from their two netting programs.

In addition to the fish sampling, angler creel surveys are conducted to measure fishing pressure and to obtain catch and harvest statistics on the large lakes. In Minnesota, pressure estimates are based on boat counts obtained with an aerial survey while the catch data comes from completed trip interviews conducted by creel clerks at lake accesses. Aerial surveys are also used in Ontario to determine fishing pressure. Interviews, however, are done using a randomized roaming survey with anglers actually being contacted while they are on the water fishing. Minnesota creel surveys were initially conducted on Rainy Lake and Namakan Reservoir in 1977-78 (Ernst and Osborn, 1980), on Kabetogama Lake in 1981, and again on all the lakes from 1983-90. Since then Rainy Lake was surveyed every year except 1991 while Kabetogama and Namakan lakes were surveyed in 1992-94 and all the Namakan Reservoir lakes in 1998-99. Creel surveys in Ontario are done less frequently with Rainy Lake typically being surveyed for two consecutive years out of every five. On Namakan and Sand Point lakes, the most recent OMNR creel surveys were completed in 1998. Results of the Minnesota surveys, most of which have been a joint effort of the MNDNR and VOYA/USGS, have been presented in a series of reports. Minnesota creel survey data referenced in this synopsis were taken from summary tables presented by Burri (2000) and Eibler (2002). The OMNR has also prepared reports summarizing the results of their surveys (Wepruk and others, 1992; Jackson, 1994; Elder, 2001).

Creel surveys of the Park's interior lake fisheries have been conducted using voluntary creel cards. This method, despite known weaknesses such as higher reporting rates by successful anglers, exaggeration of catches, misidentification of fish, and misreporting of sizes of fish (Fraidenburg and Bargmann, 1982; Essig and Holliday, 1991), is commonly used in remote lakes where light use makes on-site sampling impractical if not logistically impossible. Survey forms are distributed to Park visitors who use Park boats and canoes. In some years cards have been numbered so they could be tracked and response rates calculated. Unfortunately, the program has primarily been limited to lakes on the Kabetogama Peninsula so there is practically no information for the fisheries on lakes such as Mukooda and O'Leary lakes, which appear to receive a fair amount of use by anglers.

Much of the Rainy Lake/Namakan Reservoir fishery data is summarized in a joint publication of the MNDNR and OMNR called the Minnesota-Ontario Boundary Waters Fisheries Atlas (MNDNR/OMNR, 1998). This publication, which also includes extensive information from Lake of the Woods, is published about every five years. In addition to the most current data, the Atlas contains some of the historical or background information that exists for these fisheries and aquatic ecosystems. The document also presents potential yields for the border waters estimated using the Morphoedaphic Index or MEI, which is derived using the mean depth of the water body and the total dissolved solids concentrations (Ryder, 1965). This total potential yield estimate is partitioned into estimated yields for individual species on the basis of data from a series of lakes that have withstood moderate to heavy fishing pressure over time (OMNR, 1982). Using results from index netting, creel surveys, and sampling of angling and commercial catches, these potential yield estimates, which are considered "first order" estimates, are further refined to develop target harvest levels. The target is the management harvest objective that reflects actual stock status and is designed to achieve or maintain a healthy population with desirable fishery characteristics. Thus, targets may vary depending on whether the objective is to maximize yield, rehabilitate a depressed stock, or produce greater numbers of large or trophy fish. Potential yields and targets are allocated on the basis of the surface acreage of the border lakes that lie in Minnesota and Ontario.

Attempts to apply the MEI and other empirical production models to Kabetogama Lake were unsuccessful as the predictive models consistently produced yields lower than the actual yields that had been recorded (MNDNR, 1997). Because of this, potential and target yields for walleye were based on the mean of 14 harvest estimates from angler creel surveys conducted between 1977 and 1994.

Sampling of the other lakes in the Park under the MNDNR's Lake Survey program is less intense and is done less frequently. As previously indicated, complete lake surveys of all the 26 interior lakes were first conducted by the MNDNR in the early 1970s. In 1983, 14 of the lakes were resurveyed with two more being sampled for the second time in 1996 and 1999. Five lakes were subsequently surveyed for a third time between 1995 and 2000. Experimental gill nets and trap nets are the principle sampling methods used and the same data is gathered as is collected on the large lakes.

**The fish community:** Fifty-four fish species from 16 families have been identified in Park waters as a result of the various surveys and studies (Table 7). Additionally, the creek chub (*Semotilus atromaculatus*) and the river shiner (*Notropis blennius*) have been reported as occurring in Rainy Lake outside the Park (Underhill, 1957; Wepruk and others, 1992). The best-represented families are Cyprinidae (16 species), Centrarchidae (8 species), and Percidae (7 species).

The number of fish species ranges from 36 to 40 in the large lakes. In the 26 interior lakes, the number of species ranges up to 18 but in the majority of the lakes there are less than 10 species. Species richness is strongly correlated with the logarithms of the lake area ($r = 0.956$, $P = 0.000$), shore development ($r = 0.913$, $P = 0.000$), and maximum depth ($r = 0.678$, $P = 0.000$). While there is also a significant negative relation with lake elevation ($r = -0.564$, $P = 0.001$), this probably is more a reflection of the fact that all the large lakes occur at the lower elevations. Relations such as these are generally attributed to the increased habitat diversity in larger, deeper lakes with more complex shorelines (Tonn and Magnuson, 1982; Eadie and Keast, 1984; Eadie and others, 1986).

Yellow perch and northern pike are the most ubiquitous species, occurring in 27 and 23 lakes, respectively (Table 7). Other species that occur in 15 or more lakes include the white sucker, blacknose shiner, golden shiner, and Iowa darter. Walleye, the species most sought after by anglers, only occurs in the large lakes and in three interior lakes. Smallmouth bass, largemouth bass, sauger, and black crappie, which are also sought after by anglers, occur in 9, 9, 7, and 6 lakes, respectively. Lake trout are present in three interior lakes and are also occasionally reported in Rainy Lake with the most recent report being in 1988. Muskellunge are present in the two Shoepack lakes, Rainy Lake, and based on recent angler reports, Crane Lake. Studies evaluating the genetic composition and

**Table 7.** Fish species collected in Voyageurs National Park.

| Family | Scientific Name | Common Name | Abbreviation | # of Lakes |
|---|---|---|---|---|
| Petromyzontidae | *Ichthyomyzon unicuspis* | Silver lamprey | SIL | 4 |
| Acipenseridae | *Acipenser fulvescens* | Lake sturgeon | LKS | 4 |
| Hiodontidae | *Hiodon tergisus* | Mooneye | MOE | 2 |
| Cyprinidae | *Couesius plumbeus* | Lake chub | LKC | 1 |
| Cyprinidae | *Hybognathus hankinsoni* | Brassy minnow | BRM | 1 |
| Cyprinidae | *Luxilus cornutus* | Common shiner | CSH | 5 |
| Cyprinidae | *Margariscus margarita* | Pearl dace | PRD | 4 |
| Cyprinidae | *Notemigonus crysoleucas* | Golden shiner | GOS | 15 |
| Cyprinidae | *Notropis atherinoides* | Emerald shiner | EMS | 7 |
| Cyprinidae | *Notropis heterodon* | Blackchin shiner | BCS | 1 |
| Cyprinidae | *Notropis heterolepis* | Blacknose shiner | BNS | 19 |
| Cyprinidae | *Notropis hudsonius* | Spottail shiner | SPO | 6 |
| Cyprinidae | *Notropis volucellus* | Mimic shiner | MMS | 5 |
| Cyprinidae | *Phoxinus eos* | Northern redbelly dace | NRD | 9 |
| Cyprinidae | *Phoxinus neogaeus* | Finescale dace | FND | 9 |
| Cyprinidae | *Pimephales notatus* | Bluntnose minnow | BNM | 8 |
| Cyprinidae | *Pimephales promelas* | Fathead minnow | FHM | 8 |
| Cyprinidae | *Rhinichthys atratulus* | Blacknose dace | BND | 3 |
| Cyprinidae | *Rhinichthys cataractae* | Longnose dace | LND | 2 |
| Catostomidae | *Catostomus catostomus* | Longnose sucker | LNS | 1 |
| Catostomidae | *Catostomus commersoni* | White sucker | WTS | 19 |
| Catostomidae | *Moxostoma anisurum* | Silver redhorse | SLR | 2 |
| Catostomidae | *Moxostoma macrolepidotum* | Shorthead redhorse | SHR | 4 |
| Ictaluridae | *Ameiurus melas* | Black bullhead | BLB | 8 |
| Ictaluridae | *Ameiurus nebulosus* | Brown bullhead | BRB | 1 |
| Ictaluridae | *Noturus gyrinus* | Tadpole madtom | TPM | 4 |
| Esocidae | *Esox lucius* | Northern pike | NOP | 23 |
| Esocidae | *Esox masquinongy* | Muskellunge | MUE | 3 |
| Umbridae | *Umbra limi* | Central mudminnow | CNM | 2 |
| Osmeridae | *Osmerus mordax* | Rainbow smelt | RBS | 3 |
| Salmonidae | *Coregonus artedi* | Cisco | TLC | 8 |
| Salmonidae | *Coregonus clupeaformis* | Lake whitefish | LKW | 4 |
| Salmonidae | *Salvelinus namaycush* | Lake trout | LAT | 3 |
| Percopsidae | *Percopsis omiscomaycus* | Trout-perch | TRP | 4 |
| Gadidae | *Lota lota* | Burbot | BUB | 4 |
| Gasterosteidae | *Culaea inconstans* | Brook stickleback | BST | 5 |
| Gasterosteidae | *Pungitius pungitius* | Ninespine stickleback | NST | 4 |
| Cottidae | *Cottus bairdi* | Mottled sculpin | MTS | 3 |
| Cottidae | *Cottus cognatus* | Slimy sculpin | SMS | 6 |
| Centrarchidae | *Ambloplites rupestris* | Rock bass | RKB | 11 |
| Centrarchidae | *Lepomis cyanellus* | Green sunfish | GSF | 1 |
| Centrarchidae | *Lepomis gibbosus* | Pumpkinseed | PMK | 13 |
| Centrarchidae | *Lepomis macrochirus* | Bluegill | BLG | 4 |
| Centrarchidae | *Lepomis megalotis* | Longear sunfish | LES | 2 |
| Centrarchidae | *Micropterus dolomieu* | Smallmouth bass | SMB | 9 |
| Centrarchidae | *Micropterus salmoides* | Largemouth bass | LMB | 9 |
| Centrarchidae | *Pomoxis nigromaculatus* | Black crappie | BLC | 6 |
| Percidae | *Etheostoma exile* | Iowa darter | IOD | 15 |
| Percidae | *Etheostoma nigrum* | Johnny darter | JND | 14 |
| Percidae | *Perca flavescens* | Yellow perch | YEP | 27 |
| Percidae | *Percina caprodes* | Logperch | LGP | 5 |
| Percidae | *Percina shumardi* | River darter | RVD | 1 |
| Percidae | *Stizostedion canadense* | Sauger | SAR | 5 |
| Percidae | *Stizostedion vitreum* | Walleye | WAE | 7 |

degree of relatedness among muskellunge populations from throughout the Midwest have demonstrated that the populations in the Shoepack lakes are unique (Hanson and others, 1983; Fields and others, 1997). The muskellunge in Crane Lake most likely came down the Vermilion River from Lake Vermilion where a stocking program of Mississippi River strain muskellunge from Leech Lake has been in place since 1987 (J. Geis, MNDNR personal communication). Thirteen of the additional 19 species that have been reported in four or fewer lakes were found only in the large lakes.

The Park's small streams and numerous beaver ponds also support significant fish populations. Sixteen species have been found with the predominant fish species being northern redbelly dace, finescale dace, brook stickleback, and fathead minnow (Schlosser and Kallemeyn, 2000). Geological barriers, stages of beaver pond succession, and environmental filters such as hypoxia result in significant variation in species richness and distribution, as well as abundance in these habitats (Figure 31). Dispersal of early-life history stages of black crappie, smallmouth bass, yellow perch, and burbot from Kabetogama Lake contribute to higher species richness in some drainages. A *Phoxinus eos-neogaeus* gynogenetic complex of cyprinid fish has also been found in several of the small drainages of the Kabetogama Peninsula (Doeringsfeld, 1996; Schlosser and others, 1998). In these unisexual fish, the entire genomic constitution of the mother is inherited intact with sperm from one of the progenitor species only being needed to initiate cleavage (Dawley, 1989). The gynogenetic complex on the Kabetogama Peninsula, unlike other parthenogenetic vertebrate populations that commonly exhibit high degrees of clonal variation, contains only one clonal lineage (Elder and Schlosser 1995). This single clone is not highly

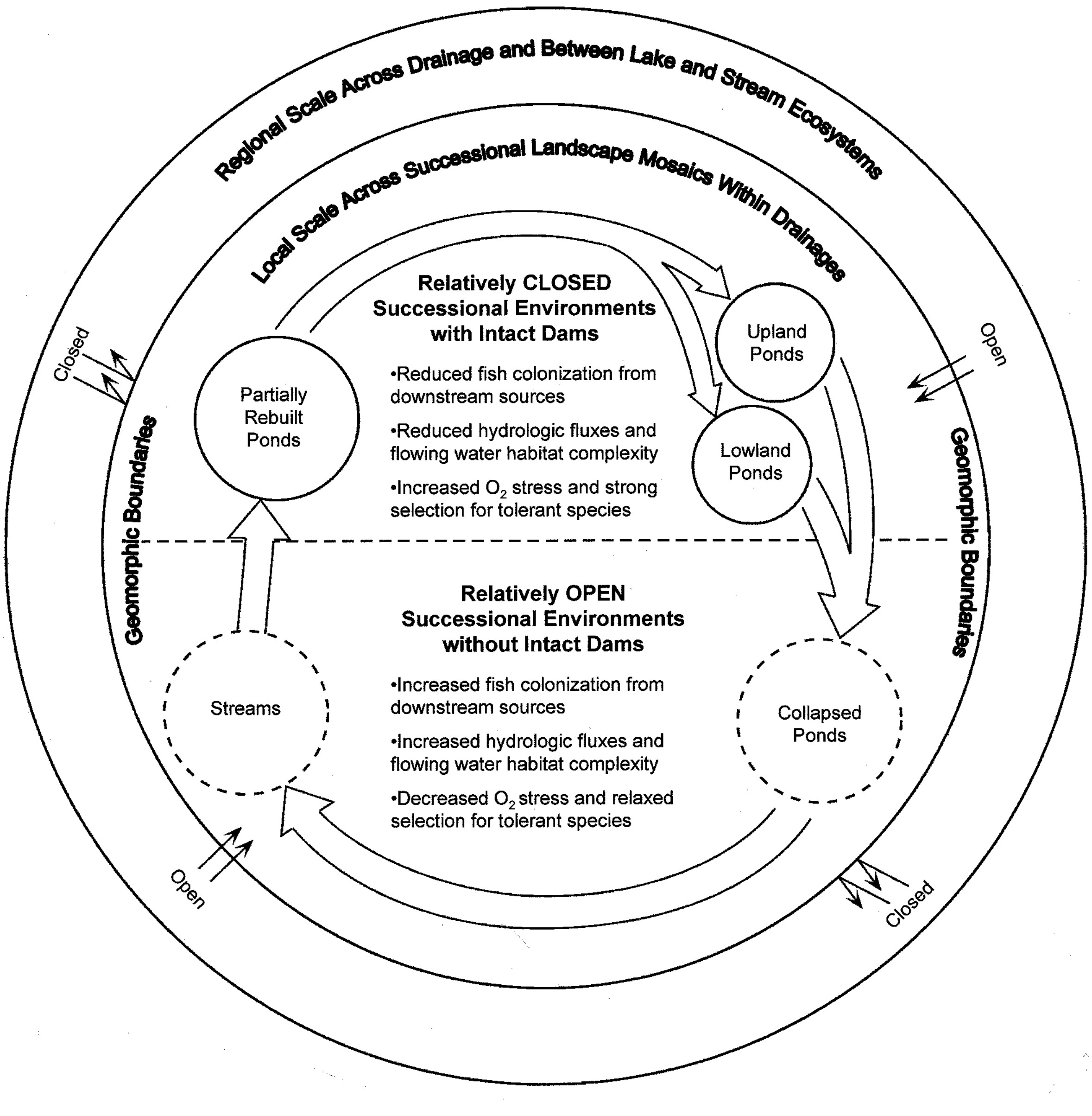



**Figure 31.** Conceptual framework suggesting how regional geomorphic boundaries and local succession influence fish assemblage attributes in north-temperate landscapes modified by beaver activity (from Schlosser and Kallemeyn 2000).

specialized, either in utilization of spatial resources or in body morphology, and is more common in the marginal and stressful environments associated with beaver pond succession (Schlosser and others, 1998). The temporal and spatial unpredictability of the environmental conditions to which it has been exposed has apparently resulted in a physiologically flexible clonal genotype, which occupies a broad ecological niche.

Most fish species in the Park are believed to have originated from the Mississippi glacial refugium, using corridors provided by the retreat of the Wisconsin ice sheet and the accompanying glacial Lake Agassiz (Crossman and McAllister 1986). Initially, fish could have moved upstream into the Hudson Bay watershed through the River Warren (today's Minnesota River), which drained southward into the Mississippi River. At a later stage, eastern outlets developed between Lake Agassiz and the ancestral Great Lakes. Of these, the most direct connection to the area now included in the Rainy Lake watershed appears to have been through the Dog-Kaministikwia and Kashabowie-Seine channels, which connected Lake Agassiz and Lake Superior during the Moorhead phase (Teller and Thorleifson, 1983). These may have provided an opportunity for fish that had earlier colonized the Great Lakes from the Mississippi and other refugia to move into the watershed. Fields and others' (1997) finding that yellow perch from Shoepack Lake were genetically indistinguishable from fish from Lake Michigan and the Mississippi River drainage in Minnesota would seem to support this concept. Johnny darter from Shoepack Lake and Rainy Lake, which were used to avoid the possible confounding effects of fish stocking, also clustered genetically with fish from the Mississippi River drainage (Fields and others, 1997). The degree to which these alternative corridors were used is subject to debate with some investigators suggesting that the Great Lakes spillway was actually more important than the Minnesota River spillway (Stewart and Lindsey, 1983). Crossman and McAllister (1986) suggested that 29 species that presently occur in northern Minnesota, northwestern Ontario, and eastern Manitoba could possibly have migrated by a pathway other than (or in addition to) Lake Agassiz. Of these, 25 occur in the Park lakes.

Currently, the dam at International Falls-Fort Frances, which was closed in 1909, prevents upstream migration of fish into Rainy Lake. Thus, even though fish can still conceivably move under high water conditions from the Mississippi River drainage to the Hudson Bay drainage via the Big Fork River they are precluded from moving upstream into the Rainy Lake watershed. The long-term implications of this are unknown but in addition to preventing the movement of new species, this fragmentation may adversely affect population viability of species that routinely moved between Lake of the Woods, the Rainy River, and Rainy and Namakan lakes. For example, mooneye, which are still common in the Rainy River downstream from the dam, have not been collected in gill net surveys in Namakan Lake since 1975. While only one mooneye has been collected in gill net surveys in Rainy Lake since 1959, 20 specimens were collected by the OMNR in 1993 from the lower Seine River, which flows into Rainy Lake (McLeod and Chepil, 1999). Downstream movements from the upper portions of the watershed are feasible as evidenced by the recent invasion of Rainy and Namakan lakes by exotic rainbow smelt. However, only two additional native species, brook trout (*Salvelinus fontinalis*) and shortjaw cisco (*Coregonus zenithicus*), occur upstream that are not already present in the Park. Thus, it is more likely future immigrants from upstream will be non-native or exotic species.

The on-going debate about post-glacial dispersal patterns and a long history of unrecorded or poorly recorded introductions makes delineation of pre-settlement distributions and identification of non-native fish species in the Rainy Lake watershed and the Park difficult if not impossible (Eddy and others, 1972). This is particularly true for all the Centrarchids except the rock bass and pumpkinseed that are commonly recognized as being native to the area. Although smallmouth and largemouth bass were present in the Mississippi refugium and the Great Lakes and could have conceivably colonized the Rainy Lake watershed, as did many other species, their presence in the border waters is generally attributed to stocking beginning at the turn of the 20th century. Their native range in Minnesota according to Eddy and Underhill (1974) and MacCrimmon and Robbins (1975) was restricted to the Mississippi River drainage and did not include the Rainy River drainage. However, possible contradictory evidence exists in the unpublished diaries of E. L. Brown (Minnesota Historical Society files), who reported observing bass in Deer Lake in the Bigfork River drainage in 1893, and in the Manitou River drainage off the North Arm of Rainy Lake in 1894. Unfortunately, Brown did not indicate what species he observed, but based on his other entries relative to fish; apparently, he was a knowledgeable observer of fish and wildlife. For example, in the Manitou reference he also indicated that rock bass were present. Another early reference to the presence of smallmouth bass in the Rainy Lake watershed was provided by I. W. Stevens (1927). He reported catching large numbers of smallmouth bass from a small lake adjacent to Lac La Croix in 1925, or well before widespread stocking of the species reportedly occurred in the border waters. The irresolvable question of course remains, were the bass these anglers apparently observed native or the result of some unrecorded introduction.

Further contradictory evidence was produced by a recent genetics study of smallmouth bass, which used both allozyme and mitochondrial DNA analyses (Fields and others, 1997). Based on the mitochondrial DNA analysis, smallmouth bass from Kabetogama and Rainy lakes were more closely related to populations from western Lake Superior (Brule Flowage, Chequamegon Bay) than they were to surrounding populations, including three others from within the Rainy River drainage. Fields and others (1997) suggested that this haplotype (Type B) may have evolved in an Atlantic or eastern Great Lakes refugium, and the northerly and westerly migration of smallmouth bass during recolonization resulted in it's appearance in several locations. They suggested that the presence of fish with other haplotypes in the other lakes in the Rainy River drainage might be due to the plantings of fish from more than one brood source. Their suggestion that the smallmouth bass in Kabetogama and Rainy lakes are possibly native conflicts with Bonde and others (1961) assertation that smallmouth bass were not present in Rainy Lake prior to 1921 when they were initially stocked. Also, Fields and others (1997) failed to mention the extensive bass-stocking program that was carried out in the border waters and other lakes in the Rainy Lake watershed by the MNDNR in the 1940s. This program is commonly believed to be the source of both the smallmouth and largemouth bass that now occupy many lakes in Quetico Provincial Park where bass were never stocked. Both species spread northward into the Ontario park and by the 1970s they were present in 58 lakes (Crossman, 1976). Given these conflicting views, the question still remains whether smallmouth bass in Kabetogama and Rainy lakes are native. More extensive application of the genetic methodology used by Fields and others (1997) could conceivably help resolve the status of the smallmouth bass in the Rainy River drainage.

In 1920, 230 fingerling largemouth bass were stocked in Kabetogama Lake with additional plantings made in the early 1940s and 1950s (MNDNR unpublished stocking records). These plants were apparently unsuccessful as today the species is rarely observed. During this period and continuing into the 1950s and 1960s, largemouth bass were stocked in 10 of the 26 interior lakes that are now part of the Park. However, when the initial lake surveys were conducted by the MNDNR between 1969 and 1972 largemouth bass were only found in two of the lakes. Presently, as a result of downstream movement and in one case, possible illegal stocking, they occur in seven interior lakes. Smallmouth bass populations were established in four interior lakes prior to the Park's establishment in 1972. In the early 1990s, as a result of an unauthorized introduction, they became established in Beast Lake.

The black crappie, another Centrarchid, is also problematic when it comes to determining whether it should be considered as a native species or not. The range of this species is commonly described as being southern Manitoba eastward to Quebec, over the eastern U.S., and south to Florida and Texas (Eddy and Underhill, 1974). Stewart and Lindsey (1983) suggested that the black crappie might have been one of the species that moved into the Lake Agassiz region from the Great Lakes. The species frequently was not reported by earlier workers (Eddy and others, 1972); however, it appears that it may be native in some lakes in northern Minnesota and northwestern Ontario and introduced in others. While the black crappie was collected from Lake of the Woods in the early 1900s (Evermann and Latimer, 1910), it reportedly was not present in Rainy Lake in the 1920s (Bonde and others, 1961). However, the black crappie was reported in commercial catch records from the mid-1930s, or prior to the early 1940s when the MNDNR records show they were first stocked. Also, commercial fishermen in Namakan Lake harvested black crappie as early as 1930. Whether these were native fish or immigrants from either native or introduced populations is unknown. OMNR records show that crappies were planted in Lac La Croix, which is upstream from the Park, in 1911 (Crossman, 1976). MNDNR records show that they were stocked in Kabetogama Lake in 1920, in Ek Lake in 1957, and in Jorgens Lake in 1942-45 and 1957. Black crappie were also stocked in Crane Lake in the period between 1930 and 1943. Also, MNDNR stocking records show that black crappie were stocked in Pelican Lake and other lakes that drain into Namakan Reservoir prior to 1940. Presently, black crappies occur in all the Park's large lakes and Ek and Mukooda lakes. Thus, while there may be some uncertainty whether crappie were present prior to known stocking events in the large lakes, there is no doubt they did not occur in the interior lakes.

Bluegill and green sunfish, two of the three other sunfish species that occur in the Park and surrounding area have been so widely introduced that most investigators have concluded that it is impossible to determine their original distribution (Eddy and others, 1972; Crossman and McAllister 1986). Their restricted distribution in the Park - large lakes and Mukooda Lake - suggests that they were not native to the area. MNDNR stocking records show that bluegill and sunfish were stocked in Agnes (1966) and Jorgens (1942-45, 1966) lakes and in Kabetogama Lake during the period between 1918 and 1943. Presently, they do not occur in either interior lake. Conceivably, the bluegill as well as the other Centrarchids that occur in Mukooda Lake entered through the short, relatively low gradient stream connecting it to Sand Point Lake. The origins of the green sunfish, which only occurs in Mukooda Lake, and of the bluegills in the large lakes are unknown. Both species could have immigrated from upstream since they are present in several lakes in the Quetico Provincial Park (Crossman, 1976) and in numerous lakes in the Minnesota portion of the Rainy Lake drainage.

The presence of the longear sunfish, which was first identified in Rainy Lake and Lake of the Woods in the 1960s and in Sand Point Lake in the 1980s, may be due to a natural expansion of the species range. An isolated population of the species was identified in Burditt Lake in the Rainy River district in Ontario in 1963 (Scott, 1963). Although it was located well outside the normal range of the species, it was not apparently the result of an artificial introduction (Gruchy and Scott, 1966). Since then, longear sunfish have been identified from nine locations in Quetico Provincial Park (Crossman, 1976) and from Hustler Lake in the Boundary Waters Canoe Area (J. C. Underhill, University of Minnesota, personal communication). Dr. Underhill suggested that a re-analysis of bluegill specimens in the James Ford Bell Museum at the University of Minnesota might reveal that earlier collectors confused the two species and that the longear sunfish may be more widespread than originally thought.

Brown bullheads, which were native to Lake of the Woods and historically were harvested commercially, were not detected in Rainy Lake until the 1970s and in Namakan Reservoir until 1981. Although there is some question relative to taxonomy, black bullheads have also been collected. While distribution maps in Scott and Crossman (1973) indicate that neither species occurred in the Rainy River drainage upstream of Lake of the Woods, more recent MNDNR lake surveys have identified bullheads in Vermilion, Pelican, and several other lakes upstream from the Park. The original source of these fish as well as those in the Park is unknown. Brown and black bullheads may have migrated downstream into the Park or been introduced illegally. In addition to the large lakes, bullheads have been collected in O'Leary (1972, 79, 82), Mukooda (1983), Agnes (1999), and Net (2000) lakes. Their presence in O'Leary Lake is noteworthy, because it predates the collections in Namakan Lake and because the lake was treated in 1961 with toxaphene to remove the native predators so that it could be managed as a stream trout lake. Rainbow trout (*Oncorhynchus mykiss*) stocking was discontinued after 10 years when it was found that the native predators as well as smallmouth bass and bullheads had entered the lake. Colonization of interior lakes by bullheads has occurred and is likely to continue, particularly if a low gradient outlet stream connects a lake to one of the large lakes.

The rainbow smelt (*Osmerus mordax*), which occurs in the Park, is definitely an exotic species. Rainbow smelt colonized numerous areas in the upper Rainy Lake watershed after being introduced by humans (Franzin and others, 1994) and first appeared in Rainy and Namakan lakes in 1990. Since then they have been collected in Kabetogama and Sand Point lakes. The greatest buildup of the species has occurred in Rainy Lake. Due to their intermediate trophic position – as consumers of zooplankton (including icthyoplankton) and as prey for top predators – rainbow smelt have the potential to introduce a wide array of ecological impacts from both direct and indirect effects (Kerfoot and Sih, 1987; Carpenter, 1988).

Historically there has been extensive stocking of both native and non-native species. The MNDNR has been stocking walleye for over 100 years (MNDNR, 1996) and millions have been stocked in Rainy, Kabetogama, and the other border lakes over the years. The OMNR also stocked walleye in the North Arm of Rainy Lake from 1932-1958 and 1985-1988 (McLeod and Gillon, 2000). Although many of the Minnesota walleye that were stocked originated from the Rat Root River, others conceivably came from other sources since fry and fingerlings were distributed statewide (McInerny and others, 1991). Walleye stocking continued in the Park up to 1996 with most of more recent plants containing fish from the Pike River, a tributary of Lake Vermilion (J. Eibler, MNDNR, personal communication). While these more recent plants did not produce an overall increase in abundance in Rainy Lake, in limited areas, particularly Black Bay and the Rat Root River, stocked fingerlings comprised between 8 and 11 percent of the catch in various gears (Eibler, 2001c). Whether these fish or fish from any of the earlier introductions had an effect on genetic variation is unknown. The Rainy Lake walleye population was one of 48 walleye populations in Minnesota, Wisconsin, and Illinois in which within and among population genetic variation was compared (Fields and others, 1997). Results from mitochondrial DNA and allozyme analyses showed that the Rainy Lake fish were similar to walleye populations from the upper Mississippi River and Lake Superior drainages, as well as those from other lakes in the Hudson Bay drainage. These results, however, do not conclusively prove that the stocked fish have had no effect since there are a variety of factors and conditions that may obscure the genetic identity of donor stocks (Fields and others, 1997). No similar analyses have been conducted on walleye from the other Park lakes.

With the exception of a muskellunge stocking in Kabetogama Lake in 1975, stocking of other species in the large lakes predated the establishment of the Park. Species stocked in the large lakes included lake whitefish, northern pike, yellow perch, sunfish, largemouth bass, black crappie, smallmouth bass, muskellunge, and catfish. Whether the introductions of native species had any effect or actually contributed to the populations is unknown. While a rebound in the Rainy Lake commercial fishery was attributed to the 1913-17 stocking of lake whitefish fry obtained from Lake Erie (Dodds, 1935), it could have also been due to the entry of a strong naturally produced year class into the fishery. A few muskellunge were captured in Kabetogama Lake after the 1975 stocking but since the mid-1980s there has been no evidence of the species. Conceivably, the muskellunge that have appeared in Crane Lake in recent years have moved downstream from Lake Vermilion where they have been stocked since 1984. Genetic effects of transfers of fish from other watersheds have not been evaluated.

As previously indicated, several of the interior lakes were stocked with various Centrarchid species prior to the Parks' establishment. While no authorized stocking has occurred in recent years, private parties have illegally introduced smallmouth bass into Beast Lake and largemouth bass into Quarterline Lake. Walleye were also transferred into Beast Lake illegally but there is no evidence that a population was established. Beast Lake, like O'Leary Lake, was treated by the MNDNR with toxaphene so that it could be managed as a stream trout lake. In 1980, this management practice was discontinued at the Parks' request. From 1995 to 1997, adult northern pike were stocked in Beast Lake in an attempt to re-establish a breeding population. The lake's carrying capacity would ultimately determine the population level of the progeny.

Since 1980, the planting of lake trout into Cruiser, Little Trout, and Mukooda lakes has been the only other legal stocking in the interior lakes. All of these lakes are believed to have contained native lake trout stocks. Supplementary stocking started in the 1940s in Cruiser and Mukooda lakes and in 1965 in Little Trout Lake. Fingerlings were stocked biannually in all three lakes from the mid-1960s until 1988, but since then only Mukooda and Little Trout lakes have been stocked. Prior to 1980 plants were made using a Marquette strain of lake trout. In the 1980s the MNDNR started using a strain collected near Isle Royale in Lake Superior and another from Gillis Lake, a small lake located in the Hudson Bay drainage in northeastern Minnesota. Since 1988 only the Gillis Lake strain has been used. Cruiser Lake received its only Gillis Lake fish in 1988; it has not been stocked since. Lake trout from the three lakes exhibited low genetic diversity, with the fish from Mukooda and Little Trout lakes having haplotypes similar to the Gillis Lake strain (Burnham-Curtis and others, 1997). Lake trout from Cruiser Lake also exhibited low diversity but unlike the other lakes, they contained the haplotype that appears in greater frequency in Lake Superior. Lake trout in Cruiser Lake are reproducing successfully and appear capable of maintaining their population without supplementation if angler extraction is regulated properly and the introduction of non-native species is avoided. Restoring self sustaining populations in Mukooda and Little Trout lakes will be more difficult due to the presence of numerous non-native fish species and well established winter fisheries.

Stocking continues to be used as a management tool by both the MNDNR and OMNR in waters outside the Park but within the Rainy Lake drainage. Conceivably, fish from these plants could move downstream into the Park, for example muskellunge from Vermilion Lake entering Crane Lake. Thus, some introductions may still pose a threat to Park fish populations even though more emphasis is being placed on the use of fish strains that will maintain the genetic integrity of the existing populations. These threats could be further reduced by adoption of the guidelines proposed to the MNDNR (Fields and others, 1997). The proposed guidelines incorporate nine Conservation Management Units (CMU) delineated on the basis of genetic analyses of six fish species from the three major drainages in Minnesota. Movement of fish between CMU's should be restricted since they encompass genetically distinct groups or populations. For the Park, the pertinent CMU is the Rainy River CMU, which encompasses the entire Rainy River drainage, including the Big Fork and Little Fork River drainages.

Possibly even more problematic as far as the Park meeting its management goal of maintaining native, self-sustaining fish populations (USNPS, 2002) are unauthorized fish introductions and/or the release or escape of baitfish or other non-native organisms from bait buckets. Illegal transfers of species that were legally introduced at some earlier time are unfortunately a common phenomenon that are extremely difficult to prevent (Rahel, 1997). Examples of this in the Park include the introduction of largemouth bass to Quarterline Lake and of smallmouth bass to Beast Lake. There is a high probability of bait bucket transfers between major watersheds because of high angler mobility, baitfish maintenance techniques, and long distance transfers by bait wholesalers (Ludwig and Leitch, 1996). Anglers not only move bait long distances but a large proportion of them commonly release any live bait they have left despite being told not to in the fishing regulation guidelines. Potential options for eliminating or minimizing bait bucket transfers range from outright prohibition of the use of live baitfish to less stringent limitations on their use (Litvak and Mandrak, 1993; Ludwig and Leitch, 1996). Educating anglers on the threat posed by bait bucket transfers would help but as long as live bait use is permitted the potential will remain for the introduction not only of non-native fish but other detrimental non-native aquatic species such as zebra mussels, rusty crayfish, and spiny water fleas.

**Sport and commercial fishing:** Sport fishing has traditionally been and continues to be the principal visitor activity in the Park. Based on the 12 creel surveys conducted between 1977 and 1999 that included all four of the Park's large lakes, the average number of angler hours expended in the summer season was 759,657 with a range 643,740 – 890,790 (Figure 32; Burri, 2000; Eibler, 2002). Historically, Kabetogama Lake received about 60% of the fishing pressure, Rainy Lake about 18%, Namakan Lake 16%, and Sand Point Lake 6%. In recent years, however, Kabetogama Lake's proportion decreased so that by 1998 and 1999, it received 39.1% and 42.4% while Rainy Lake received 37.9% and 37.1%, respectively (Burri, 2000; Eibler, 2002). Although the fishing pressure has increased on Rainy Lake, it continues to be less on a per hectare basis than that experienced by each of the three Namakan Reservoir basins (Figure 32). Based on creel surveys conducted in the 1990s on Minnesota's' 10 principle walleye lakes, Kabetogama Lake ranked 5th and Rainy Lake 9th in fishing pressure on a per acre basis (MNDNR, 1997).

The 1999 creel survey of the Namakan Reservoir lakes showed that Minnesota residents comprised between 58 and 77 percent of the anglers, with over 90% being from outside the local area (Burri, 2000). On Rainy Lake, Minnesota anglers again comprised 77% of the participants (Eibler, 2001a). However, about 53% of the Minnesota anglers were local or from within 30 miles of Rainy Lake. Non-resident anglers primarily came from Midwestern states, particularly Illinois, Wisconsin, and Iowa in both areas. A 1998 creel survey of the Ontario portion of Namakan and Sand Point lakes found that non-residents from the U.S. were the primary participants in the fishery, with anglers based in Minnesota making up 57% and 65% of the anglers contacted in Sand Point and Namakan lakes, respectively (Elder, 2001). Minnesota based anglers traditionally were the principal participants in the fishery of the Ontario portion of the South Arm of Rainy Lake. However, in 1994 effort by Minnesota-based anglers was reduced through the introduction of non-resident catch and release regulations (MNDNR/OMNR, 1998).

Since 1977 total summer angling harvests exceeded 90,700 kg (200,000 lbs) in 9 of the 12 years when creel surveys were conducted on all four of the large lakes (Figure 33). Highest reported catches occurred in 1978, 1989, and 1990 when the harvests exceeded 136,050 kg (300,000 lbs). Walleye and northern pike are the target of most anglers, typically comprising about 50 - 60% and 25 – 38% of the harvest by weight

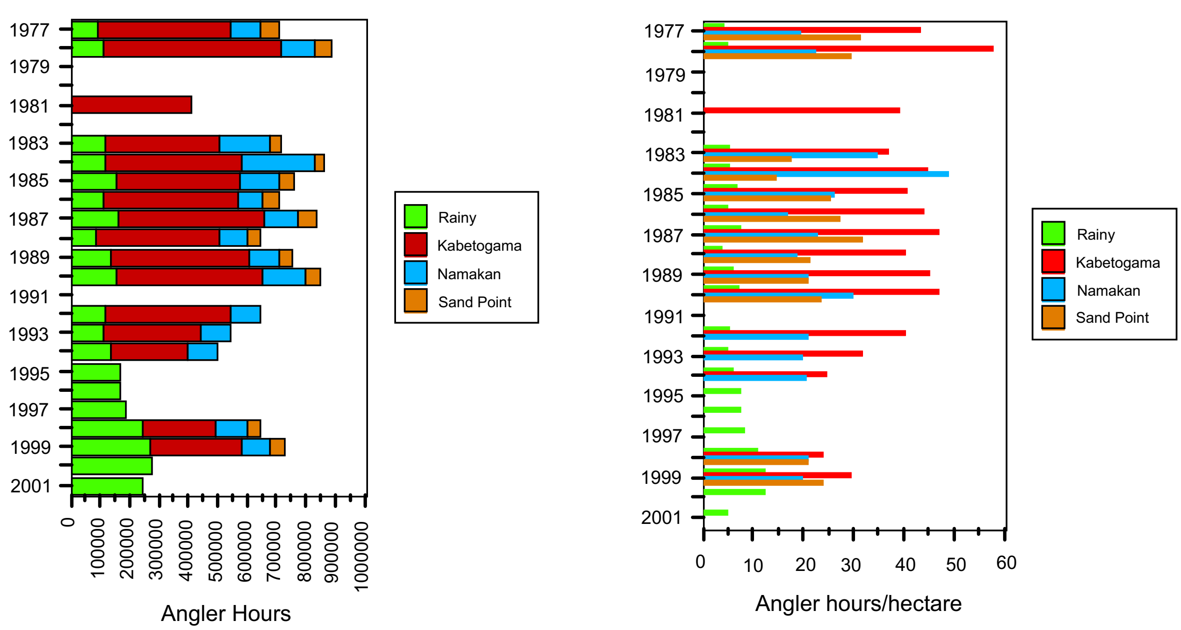



**Figure 32.** Summer angler hours and angler hours/hectare for Rainy, Kabetogama, Namakan, and Sand Point lakes, Minnesota, 1977-2001 (Burri 2000; Eibler 2002).

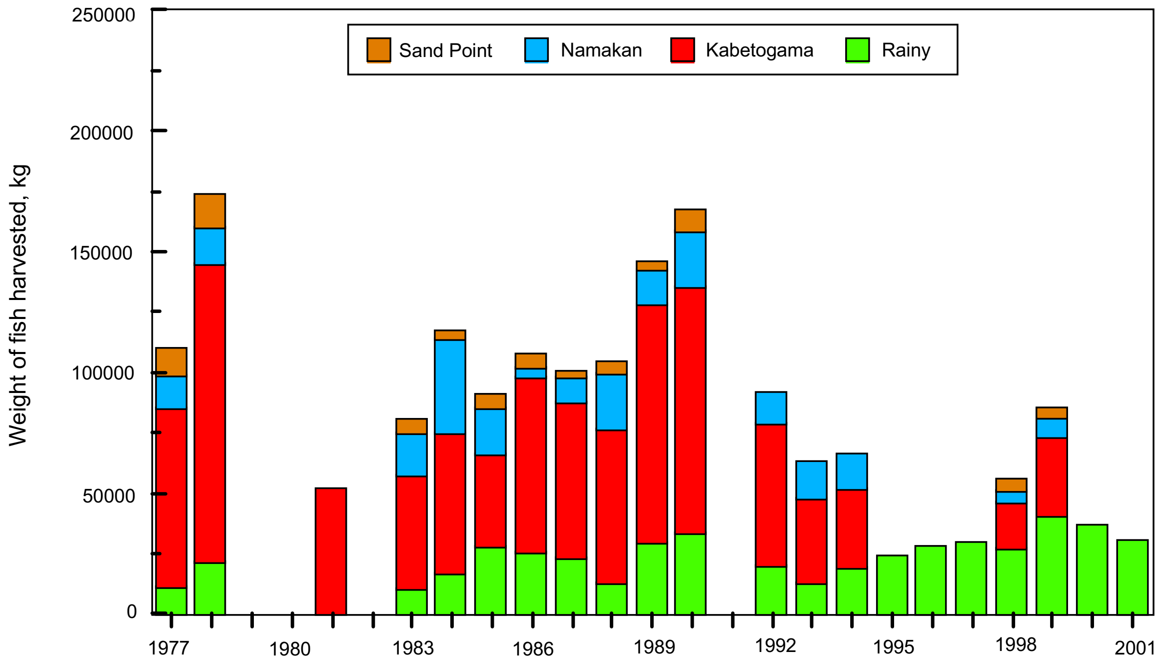



**Figure 33.** Summer harvest of fish by anglers from Rainy, Kabetogama, Namakan, and Sand Point lakes, Minnesota, 1977-2001 (Burri 2000; Eibler 2002).

(Figure 34). Other species commonly harvested by anglers from the large lakes include smallmouth bass, sauger, black crappie, and yellow perch. Anglers fishing the interior lakes may also catch muskellunge, largemouth bass, and lake trout.

Harvest rates for walleye in the large lakes have consistently been below the 0.3 walleye per angling hour defined by Colby and others (1979) as representing a good angler success rate (Figure 35). In relatively unproductive lakes, as in the Park and adjoining Ontario, harvest rates for walleye commonly fall as fishing pressure increases. In a study involving 76 lakes in Ontario, Minnesota, Wisconsin, and Colorado, catch rates declined rapidly as fishing pressure approached 10 hours/hectare and fell to less than 0.3 walleye per hour when angling pressure exceeded 20 hours per hectare (Baccante and Colby, 1991). With the exception of Rainy Lake, fishing pressure on the Park's large lakes has commonly exceeded the latter value (Figure 32). Although harvest rates on Rainy Lake have remained less than 0.3 since 1994, the year a 17 to 25 inch release slot limit was enacted, catch rates have increased and for the period from 1995 to 2000 averaged 0.43 walleye/hr (range 0.24-0.55, Eibler 2001a). In 1998 the MNDNR imposed a 13 to 17 inch (33 cm – 43 cm) harvest slot limit with a size limit of one fish over 23 inches (58 cm) allowed to be kept on Kabetogama, Namakan, and Sand Point lakes. Catch rates in 1998 and 1999 were 2 to 4 times the harvest rates but only on Sand Point Lake in 1999 did the catch rate exceed 0.3 walleye/hr (Burri, 2000).

Total walleye harvests from the large lakes have fluctuated significantly with coefficients of variation calculated from the annual harvests from 1977 to 1994 being about 36% for Namakan Lake, 44% for Kabetogama Lake, 46% for Rainy Lake, and 76% for Sand Point Lake (Table 8). Based on 10 creel surveys conducted on Kabetogama, Namakan, Rainy, and Sand Point lakes from 1977 to 1990, average harvests were 46,659, 10,258, 9,453, and 4,040 kg, respectively. During this period, yields on a per hectare basis were consistently higher from the Namakan Reservoir basins, particularly Kabetogama Lake. Creel surveys of the four lakes in 1998 and 1999 found that total harvest had approximately doubled on Rainy Lake (20,576 kg) while on Kabetogama Lake they had fallen to less than 20% of the 1977-90 average harvest. Average harvest in 1998-99 from Namakan Lake was about 30% of the 1977-90 average while from Sand Point Lake it was 55%. The decreases in the Namakan Reservoir basins in combination with the increase in Rainy Lake resulted in all four lakes having similar yield values (Table 8; Burri, 2000; Eibler, 2002).

The walleye harvests from 1977 to the early 1990s in both the Minnesota and Ontario portions of the South Arm of Rainy Lake consistently exceeded target levels and in some cases the MEI estimates of potential yield. Although commercial walleye harvest was eliminated in 1985 in Minnesota and by 1991 in

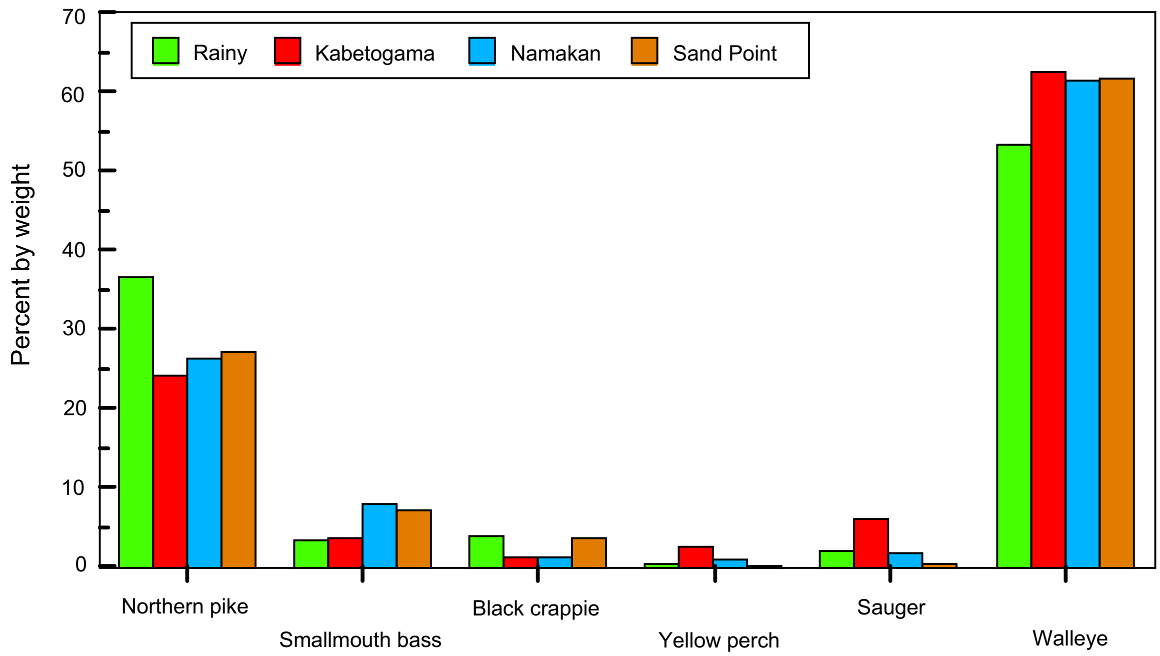



**Figure 34.** Composition of summer angling catches from Rainy, Kabetogama, Namakan, and Sand Point lakes, Minnesota, 1977-2001 (Burri 2000; Eibler 2002).

Ontario, harvests continued to exceed target levels. As a result, both the OMNR and the MNDNR implemented more restrictive regulations in an attempt to reduce the angling harvest. To date, the size and creel limits, sanctuaries, and restrictions on harvest by Minnesota-based anglers implemented by the OMNR appear to have been more successful in reducing harvests. Walleye harvests in Ontario averaged 12,700 kg (27,900 lbs) from 1990-1996, which is below the potential yield, but slightly above the target level of 11,200 kg (24,600 lbs) (MNDNR/OMNR, 1998). Despite the implementation of a 43.2 – 63.5 cm (17 to 25 inch) release slot limit in 1994, walleye harvests in the Minnesota portion of Rainy Lake continued to increase in the late 1990s as a result of increased fishing effort and catch rates. The combined effect of the Ontario and Minnesota regulations has been to reduce the average overall harvest from the South Arm from 39,456 kg (87,000 lbs) prior to 1994 to 26,304 kg (58,000 lbs) since then (Eibler, 2001a). Because of the continued increases in the Minnesota portion of the South Arm, the MNDNR in 2001 widened the release slot to 43.2 – 71.1 cm (17 to 28 inches). In 2002, the daily walleye bag limit was reduced from six to four fish.

Harvests of walleye from the Minnesota portion of Namakan and Sand Point lakes, the other border lakes the Park shares with Ontario, also consistently exceeded target and potential yield levels from 1977 to 1994. Harvest during the same period from the Ontario portion of the lakes was below target levels with the Namakan Lake harvest having been divided approximately equally between the sport and commercial fishery with each taking about 2,600 kg per year. The situation was similar on Sand Point Lake with the Ontario harvest being about 87% of the potential yield of 1,400 kg (3,000 lbs) while the Minnesota harvest exceeded the estimated potential yield of 3,200 kg (7,100 lbs) by 62%. Lake-wide, the harvest level exceeded the potential yield by 32%. Following imposition in 1998 of the harvest slot limit on all the Namakan Reservoir basins, harvests in 1998 and 1999 in the Minnesota portion of both Namakan and Sand Point lakes were approximately equal to the estimated potential yield, while in Kabetogama Lake they were well below the potential yield. Walleye harvests from the Ontario portions of the lakes in 1998 continued to be below target levels (Elder, 2001).

Kabetogama Lake, the most productive of the large lakes, generally produced the highest yields of walleye through 1994. Based on returns from tagged walleye, the exploitation rate was 23% in both 1984 and 1985 (Kallemeyn, 1990a). This level of exploitation resulted in an average harvest for the two years of about 46,000 fish weighing 32,337 kg (71,400 lbs). Since 1994, however, both fishing pressure and harvest have fallen so that in 1998 and 1999 yields were the lowest ever recorded and were similar to those of the less productive lakes (Figure 35; Burri, 2000). Conceivably, both the presence of several year classes

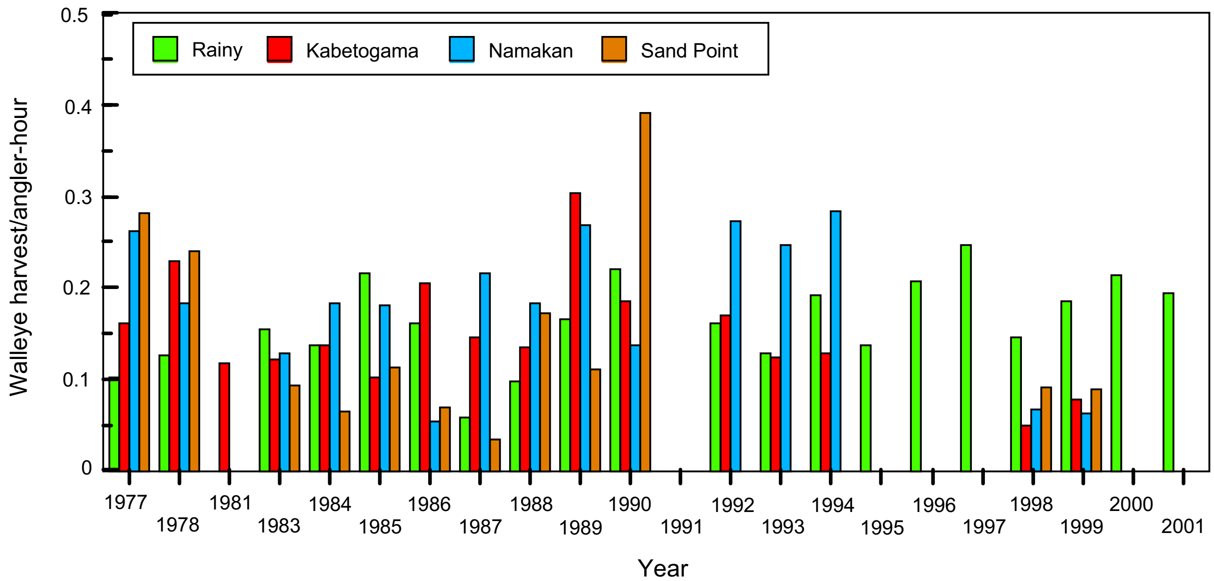



**Figure 35.** Number of walleye harvested per angler-hour during the summer fishery in Rainy, Kabetogama, Namakan, and Sand Point lakes, Minnesota, 1977-2001 (Burri 2000; Eibler 2002).

of below average strength (Eibler, 2001b), as well as the implementation of the harvest slot limit in 1998 could have contributed to the low harvest levels in 1998 and 1999.

Assessment of the effectiveness of the regulations implemented to control walleye harvest has been hampered by several factors such as infrequent creel surveys, no surveys of winter harvest or hooking mortality, as well as movement of fish between the Minnesota and Ontario portions of the lakes (Bonde and others, 1961). Inclusion of these factors could provide a significantly different view of the effect of angling on fish in these lakes. An analysis for the South Arm of Rainy Lake that included estimates of unsurveyed harvests and hooking mortality rather than just the open water harvest suggested that additional sport fishing regulations may be needed (Radomski, 2000). Hooking mortality alone could have a significant effect since it has been found to range up to 10% with live bait (Payer and others, 1987).

Analyses addressing these factors and attempts to identify safe harvest levels of walleye have been ongoing. A compendium published by the MNDNR (1997) provided a preliminary look at methods for estimating safe harvest levels to prevent overexploitation of walleye in Minnesota's large walleye lakes, including Kabetogama and Rainy lakes. Empirical models that rely on physical or limnological indices of productivity were used to estimate total fish yield. The first-order predictions of yield provided by the models didn't compare favorably with the historical yields from some lakes, including Kabetogama Lake. The compendium demonstrated that a more scientific approach would be needed to determine the safe harvest levels for these large lakes. In response to this, Gangl (2001) conducted a more detailed analysis of the Minnesota large lake walleye database, attempting to identify the best means of estimating total mortality from catch curves, obtaining more accurate estimates of natural and fishing mortality, and examining the dynamics of mortality of walleye. He also examined the potential to use biological characteristics, termed biological performance indicators (BPI), to monitor exploitation of walleye in the large lakes. Neither Kabetogama nor Rainy Lake was found to exceed the identified threshold levels, suggesting that their walleye populations have not been overexploited. Gangl (2001) concluded, however, that because the BPIs' are also influenced by environmental factors, managers must incorporate their personal knowledge of the biology of the system into any management decisions based on these indices.

The OMNR has also been attempting to develop methods of identifying safe rates of fishing for walleye. Lester and others (2000) assessed life history variation in Ontario walleye populations and found that there was a significant amount of inter-population variability, much of which was associated with climate and other environmental properties. They concluded that measurement of key environmental variables, particularly growing degree-days, could supply first-order estimates of safe levels of exploitation. An analysis of the relationship between preferred light and temperature conditions for walleye determined that changes in water clarity may have a dramatic effect on the supply of walleye habitat, and thereby, the production of

**Table 8.** Estimated total summer angler harvest (kg) and harvest/hectare (kg/ha) of walleye from the Minnesota waters of Rainy, Kabetogama, Namakan, and Sand Point lakes, 1977-2001. Data from Burri (2000) and Eibler (2002).

| | Rainy | | Kabetogama | | Namakan | | Sand Point | |
|---|---|---|---|---|---|---|---|---|
| **Year** | **Kg** | **Kg/ha** | **Kg** | **Kg/ha** | **Kg** | **Kg/ha** | **Kg** | **Kg/ha** |
| 1977 | 5581 | 0.26 | 38843 | 7.72 | 10773 | 2.16 | 9578 | 4.57 |
| 1978 | 7559 | 0.35 | 78054 | 7.49 | 10366 | 2.07 | 7603 | 3.63 |
| 1981 | --- | | 24631 | 2.37 | --- | | --- | |
| 1983 | 7812 | 0.36 | 26451 | 2.53 | 9549 | 1.92 | 1541 | 0.74 |
| 1984 | 9509 | 0.44 | 36730 | 3.52 | 17380 | 3.49 | 1569 | 0.75 |
| 1985 | 16957 | 0.77 | 28033 | 2.69 | 15365 | 3.08 | 3974 | 1.89 |
| 1986 | 7969 | 0.36 | 52604 | 5.04 | 1829 | 0.37 | 3429 | 1.64 |
| 1987 | 6009 | 0.27 | 41726 | 4.00 | 8370 | 1.68 | 937 | 0.45 |
| 1988 | 2971 | 0.13 | 32151 | 3.08 | 6817 | 1.37 | 2844 | 1.36 |
| 1989 | 11826 | 0.54 | 78182 | 7.50 | 10510 | 2.11 | 1509 | 0.72 |
| 1990 | 18346 | 0.84 | 53819 | 5.17 | 11620 | 2.33 | 7421 | 3.54 |
| 1992 | 11606 | 0.53 | 45749 | 4.39 | 12195 | 2.44 | --- | |
| 1993 | 7184 | 0.33 | 25654 | 2.47 | 11658 | 2.34 | --- | |
| 1994 | 11813 | 0.54 | 19480 | 1.87 | 12031 | 2.41 | --- | |
| 1995 | 11277 | 0.52 | --- | | --- | | --- | |
| 1996 | 16227 | 0.74 | --- | | --- | | --- | |
| 1997 | 20033 | 0.92 | --- | | --- | | --- | |
| 1998 | 17309 | 0.78 | 6228 | 0.59 | 3254 | 0.65 | 1858 | 0.89 |
| 1999 | 23844 | 1.09 | 11632 | 1.12 | 3043 | 0.61 | 2619 | 1.24 |
| 2000 | 27626 | 1.27 | --- | | --- | | --- | |
| 2001 | 20052 | 0.92 | --- | | --- | | --- | |

walleye (Lester and others, 2002)

A Minnesota management perspective was provided by Eibler (2001c) for the South Arm of Rainy Lake walleye fishery. Based on the results of an analysis using several biological indicators used to measure population stress, he concluded that despite the increased Minnesota harvest the health of the population was improving. The positive indicators he identified included reduced growth rates due to increased population density, reduced variability in abundance, increased age at maturity, and reduced annual mortality. Similar observations from the Ontario portion of the South Arm of Rainy Lake suggest this is a basin wide phenomenon (D. McLeod, OMNR, personal communication). To what extent this is dependent on the reduced Ontario harvest is unknown.

While Gangl's (2001) and Eibler's (2001c) analyses did address the potential effect of changes in walleye yield on several growth-related parameters, they did not address the effects on walleye condition or forage fish consumption. Long-term changes in condition (relative weight) of walleye and northern pike are being assessed by comparing values from fish collected during the annual fall gill netting surveys (L. Kallemeyn, USGS, unpublished data). Preliminary results from Kabetogama and Rainy lakes suggest that there may be some reduction in growth and decrease in relative weights of walleye. Additional analyses are needed, however, to determine what factors are contributing to these changes. Analysis of the effects on forage fish consumption, which could be done by coupling population models with energetic modeling techniques, would provide a broader ecological perspective to the management of the fish community (Luecke and others, 1994).

Northern pike harvests from the Minnesota portion of the large lakes have fluctuated even more than those of the walleye (Table 9). Coefficients of variation calculated from the annual yields of northern pike from 1977 to 1994 were about 98% for Namakan Lake, 56% for Kabetogama Lake, 53% for Rainy Lake, and 62% for Sand Point Lake. Based on the 10 creel surveys conducted on the four large lakes from 1977 to 1990, Kabetogama Lake consistently produced the largest quantity of northern pike weight-wise, and also the highest yields on a per hectare basis. Although Rainy Lake had the second highest average total harvest during that period, Namakan Lake and Sand Point Lake had higher yields per hectare in 9 of the 10 years. Rankings for the four lakes for northern pike harvests and yields in 1998 and 1999 were about the same even though the actual harvest in each of the Namakan Reservoir basins decreased while it increased in Rainy Lake.

Prior to 1990, the combined harvests of northern pike in the South Arm of Rainy Lake by the sport, commercial, and subsistence fisheries consistently exceeded the estimated potential yield (MNDNR/OMNR, 1998). The OMNR has been able

**Table 9.** Estimated total summer angler harvest (kg) and harvest/hectare (kg/ha) of northern pike from the Minnesota waters of Rainy, Kabetogama, Namakan, and Sand Point lakes, 1977-2001. Data from Burri (2000) and Eibler (2002).

| | Rainy | | Kabetogama | | Namakan | | Sand Point | |
|---|---|---|---|---|---|---|---|---|
| **Year** | **Kg** | **Kg/ha** | **Kg** | **Kg/ha** | **Kg** | **Kg/ha** | **Kg** | **Kg/ha** |
| 1977 | 5905 | 0.27 | 31120 | 2.98 | 2668 | 0.54 | 1906 | 0.91 |
| 1978 | 12549 | 0.57 | 32441 | 3.12 | 2503 | 0.50 | 3946 | 1.88 |
| 1981 | --- | | 13604 | 1.30 | --- | | --- | |
| 1983 | 2600 | 0.12 | 13531 | 1.30 | 5021 | 1.01 | 3403 | 1.62 |
| 1984 | 6130 | 0.28 | 12648 | 1.21 | 16986 | 3.41 | 853 | 0.43 |
| 1985 | 11236 | 0.52 | 10334 | 0.99 | 4033 | 0.81 | 1566 | 0.75 |
| 1986 | 16504 | 0.75 | 11405 | 1.10 | 1923 | 0.38 | 2054 | 0.98 |
| 1987 | 13545 | 0.62 | 11738 | 1.12 | 1775 | 0.36 | 692 | 0.33 |
| 1988 | 7293 | 0.34 | 15876 | 1.52 | 11565 | 2.32 | 919 | 0.44 |
| 1989 | 13067 | 0.59 | 12168 | 1.17 | 2387 | 0.48 | 1746 | 0.83 |
| 1990 | 11901 | 0.50 | 22050 | 2.12 | 6082 | 1.22 | 831 | 0.39 |
| 1992 | 4097 | 0.19 | 8022 | 0.77 | --- | | --- | |
| 1993 | 4224 | 0.19 | 6264 | 0.61 | 2400 | 0.48 | --- | |
| 1994 | 4029 | 0.18 | 8411 | .81 | 980 | 0.20 | --- | |
| 1995 | 9155 | 0.41 | --- | | --- | | --- | |
| 1996 | 10239 | 0.47 | --- | | --- | | --- | |
| 1997 | 8417 | 0.38 | --- | | --- | | --- | |
| 1998 | 9321 | 0.43 | 10128 | 0.98 | 1299 | 0.26 | 1235 | 0.59 |
| 1999 | 14602 | 0.66 | 15421 | 1.48 | 2509 | 0.50 | 558 | 0.27 |
| 2000 | 7983 | 0.37 | --- | | --- | | --- | |
| 2001 | 7191 | | --- | | --- | | --- | |

to reduce harvests to a level below the potential yield through reductions in non-resident angling effort, buy-outs of commercial fishing quotas, the establishment of fish sanctuaries in prime northern pike spawning habitat, and the implementation of a size regulation that restricts daily catch and possession of fish greater than 70 cm (27.5 inches). To improve population structure and fishing quality, the target harvest level has been reduced to the potential yield level (12,400 kg, 27,300 lbs). The combined angling and commercial harvests of northern pike in Minnesota waters in the late 1970s and in the 1980s also exceeded the potential yield in most years. The commercial harvest up until 1985 and the buyout of the commercial walleye licenses, composed between 24% and 56% of the northern pike harvest. In 1992, a target harvest level for northern pike of 12,200 kg (27,000 lbs) was established, which was 23% greater than the potential yield level. This northern pike harvest level was established in an attempt to divert harvest away from the walleye stock. With the exception of the period from 1992-94, the angling harvest of northern pike continued to fluctuate around the potential yield level of 10,000 kg (22,000 lbs) (Table 9). In 1998, in response to this and some evidence of potential for over-harvest the target level was reduced by 2,200 kg so that it would equal the potential yield level (MNDNR/OMNR, 1998).

Northern pike harvests on Namakan and Sand Point lakes during the late 1970s and the 1980s also frequently exceeded the target harvest levels, which were set at the estimated potential yields of the lakes. However, in the 1990s harvests in both lakes were consistently below the target levels. In recent years, the Ontario fishery on Sand Point Lake harvested about 61% of its 1,042 kg (2,300 lb) target, while in Minnesota about 85% of the 1,450 kg (3,200 lb) target was harvested (Table 9). Comparable values for Namakan Lake, which in Ontario included a commercial fishery, were 46% of the 3,034 kg (6,700 lbs) Ontario target and 85% of the 2,944 kg (6,500 lb) Minnesota target (Table 9).

Harvests of northern pike from Kabetogama Lake in 10 of the 16 years in which creel surveys were conducted were generally between 9,060 kg and 15,850 kg (20,000 – 35,000 lbs) (Table 9). Harvests in 1977, 1978, and 1990 were well above the target, while from 1992 to 1994 they were well below it. From 1983 to 1985, anglers and spearers harvested 16.3% of 2,309 northern pike tagged in 1983 (Miller and others, 2001). In 1998 and 1999, the harvests were 67% and 103% of the 14,946 kg (33,000 lb) target level. These fluctuations as well as some of those observed in the other Namakan Reservoir basins were most likely associated with strong or weak year classes that were caused by exceptionally high or low spring water levels (Kallemeyn, 1987b). The 1987 and 1988 year classes, which should have been a major component of the harvest in the early 1990s, were the two weakest year classes produced in Kabetogama Lake since

1980 (Eibler, 2001b).

Harvests of smallmouth bass and black crappie, while extremely variable, have consistently been below potential yield and target levels in both the Minnesota and Ontario portions of all the large lakes. As a result, both species have in the past frequently been promoted as alternative sport fish. In 1998, however, target levels in the South Arm of Rainy Lake were re-adjusted in response to changing management objectives (MNDNR/OMNR, 1998). Because of the popularity of black crappies as well as its highly variable recruitment, the target levels were reduced to 6,200 kg (13,600 lbs) in Ontario and 4,900 kg (10,900 lbs) in Minnesota. The Ontario target for smallmouth bass was reduced to 4,400 kg (9,715 lbs) with the focus being on improving the quality of the fishery. In Minnesota the smallmouth bass target was increased to 3,500 kg (7,800 lbs) so that the total allowable harvest of it and black crappies remained at the combined potential yield for the two Centrarchid species.

Target levels for black crappie and smallmouth bass, which are set at the combined potential yield for the two Centrarchids in Namakan and Sand Point lakes, have not been exceeded. Although the fishing effort directed at smallmouth bass in the Ontario portions of the two lakes has increased, there has been no concomitant increase in harvest (Elder, 2001). In the Minnesota portion of the lakes the effort directed at smallmouth bass has decreased (Burri, 2000). While summer harvests of black crappie in both lakes are typically well below target levels, there is a winter fishery on the Minnesota portion of Sand Point Lake that harvests an unknown but apparently substantial number of black crappie. About one-half of Ontario's Centrarchid harvest from Sand Point Lake has consisted of black crappie that were harvested commercially with the remainder being smallmouth bass that were taken by angling.

During the 1990s, smallmouth bass and black crappie together comprised from 3.0 (1993) to 14.6 (1990) percent of the total angling harvest by weight in Kabetogama Lake (Burri, 2000). Except in 1994, the yield of smallmouth bass was 3 to 7 times that of the crappie. As in the other large lakes, harvests have in most years been below potential yield and target levels.

Sauger, yellow perch, and rock bass are generally a minor component of the sport fishery in Rainy Lake and the Namakan Reservoir lakes due to few individuals attaining a size large enough to be desirable to anglers. The principle exception being in Kabetogama Lake where sauger and in a few years, yellow perch reach sizes that are acceptable to anglers. Together, these two Percids from 1978 to 1990 comprised between 6.2 and 15.5% of Kabetogama Lake's total harvest (average = 10.6%, n = 8). It was also in this period when catches exceeded potential yield and target levels in half of the years. From 1992-1999, a period when they presumably might have been targeted more by anglers due to lower walleye catches; they unexpectedly comprised only 6.6% of the total harvest on average. Harvests of both species were below target levels throughout this latter period.

Attempts to monitor angler use of the interior lakes have been hampered by low return rates of the voluntary creel forms. In 1989, only 37.2% of the survey forms distributed by Park rangers and 45.5% of those distributed at visitor centers were returned (Kallemeyn, 1990b). A similar return rate of 46.3% was obtained in 2000 (Broschart, 2001). Thus, all conclusions relative to this fishery must be viewed with caution. Based on returns from 1982, 1989, 1990, 1991, 1996, 1999, and 2000, angler hours peaked in 1990 at about 1550. In 1991, they fell to about 500 hours, a level that has remained relatively constant since. Many of the anglers fishing in the interior lakes in the summer practice catch and release. Annual reported catch rates of northern pike have ranged from about 0.70 to 0.35 fish per hour. Largemouth bass catch rates, which have ranged from 0.30 to 0.90 fish per hour, were relatively high in the 1980s survey years, fell to lower levels in 1990-91, and then recovered in the last three survey years. Other species reported by anglers include muskellunge, yellow perch, black crappie, and rock bass.

The magnitude of the winter harvest by angling and spearing from the Park lakes is generally unknown. While the MNDNR has counted fish houses on Rainy and Kabetogama lakes in December and January annually since 1971, no creel surveys have been done. The mean number of houses on Rainy Lake increased about 3 times, rising from about 60 to 70 in the 1970s to nearly 250 in 2000 (Eibler, 2000a). The fishery on Rainy Lake is focused in the area outside the Park with over 80% of the houses being in the Sand Bay area. Most of the houses on Kabetogama Lake, which historically have been primarily used for spearing northern pike, are located in shallower bays such as Irwin Bay and Tom Cod Bay (Eibler, 2000a). The mean number of houses for Kabetogama Lake was 67 in the 1970s, 32 in the 1980s, and 45 in the 1990s. From 1983 to 1987, spearers on Kabetogama Lake accounted for 25 (6.4%) of the 392 tag returns from northern pike that were tagged in 1983.

The only estimates of winter harvest from the Park's interior lakes were obtained in 2002 for Mukooda and Little Trout lakes (Burri, 2003). A winter creel survey produced estimates of fishing pressure for Mukooda and Little Trout lakes of 1,588 and 97 angler-hours, and for lake trout harvest of 0.78 and 0.27 kg/ha, respectively. While lake trout harvests from both lakes were below projected yields derived from thermal habitat models, the Mukooda Lake harvest did exceed the potential yield estimate that was based on the morphoedaphic index (Siessenop, 2000).

Another fishery for which there is no harvest data is the fall sport gill net fishery for whitefish and cisco. This activity is permitted by the MNDNR on all the large lakes in the Park from the second Friday of October through the first Sunday of December. Each licensee is limited to one gill net 100’ x 3’ with 1.75” stretch mesh. Nets, which cannot be set in any water deeper than six feet, must be tended at least once every 24 hours. Whitefish and ciscoes taken in this fishery may not be bought or sold. The number of people participating in this fishery in the Park is unknown. Statewide, the number of licenses issued has been slowly declining with 923 licenses having been sold in 2000 (Roy Johannes, MNDNR, personal communication).

Commercial fishing in both the Minnesota and Ontario portions of the large lakes has been reduced significantly since the authorization of the Park in 1971. About five fishermen and their helpers were active during the period from 1971 to 1984 in the Minnesota portion of Rainy Lake. Average annual commercial harvest during this period was 36,174 kg (79,872 lbs) with walleye comprising 20% of the catch, northern pike 8.9%, lake whitefish 39.5%, and other species 31.6% (Figure 36). This latter group consisted primarily of suckers, burbot, and cisco. Initially after the 1985 buyout of the walleye licenses by the MNDNR, two fishermen continued to fish but since 1988 only one fisherman has been active. Since 1985 the fishery has been directed at lake whitefish, which have comprised 84.2% of the average annual harvest of 11,353 kg (25,068 lbs). By-catch of the other species has been 15.2% of the total harvest with walleye and northern pike taken incidentally each comprising 0.3% of the harvest. The majority of the lake whitefish harvested in the 133 mm (5.25 in) stretch mesh gill nets are from 457 to 559 mm (18 – 22 in long) and from 7 to 9 years old (Eibler, 2000b). Based on a catch curve analysis, which included fish up to 25 years old, annual mortality was estimated as 26% (Eibler, 2000b). The MNDNR in the late 1990s, because of concerns about the potential effect of rainbow smelt on the lake whitefish population, reduced the commercial quota to 11,430 kg (25,240 lbs).

As indicated earlier, the OMNR has taken similar steps to reduce or eliminate commercial harvest of walleye and northern pike in the South Arm of Rainy Lake. While small amounts of northern pike and black crappie are still harvested commercially and in the First Nation subsistence fishery, the lake whitefish

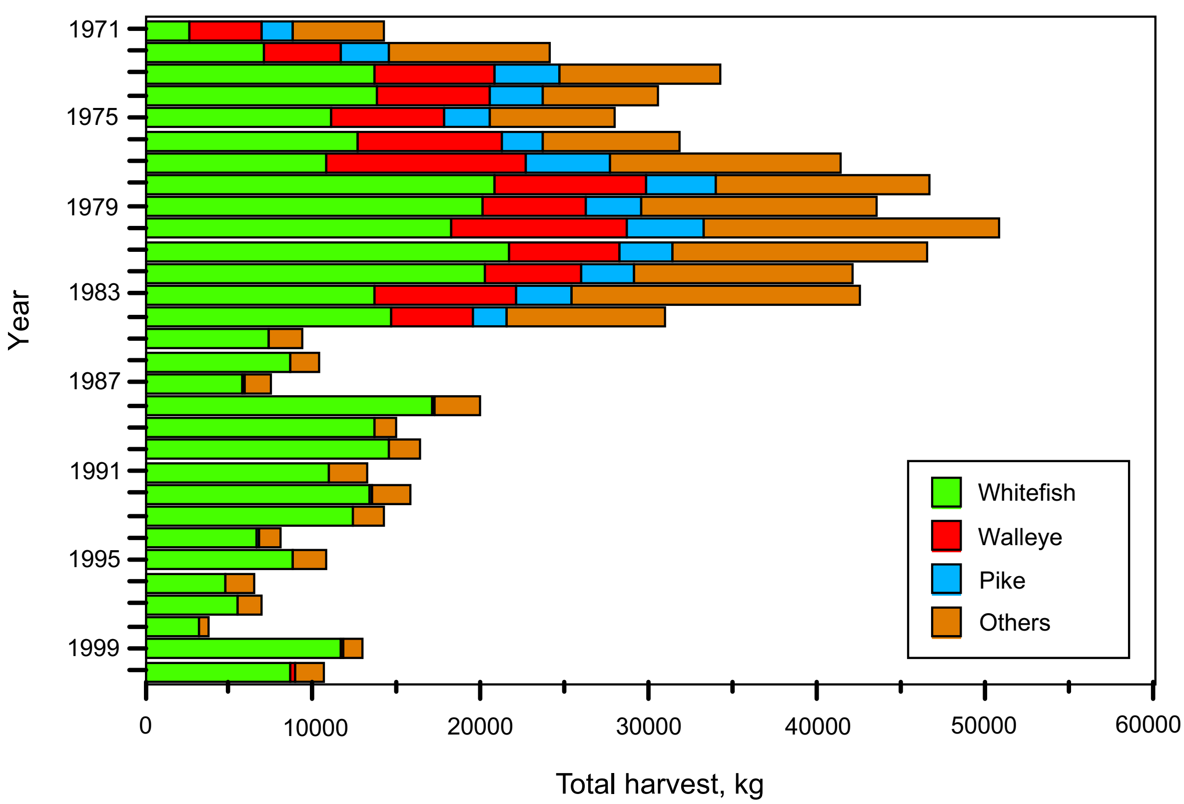



**Figure 36.** Commercial fish harvest from the Minnesota portion of the South Arm of Rainy Lake, 1971-2000 (Eibler 2000b; MNDNR unpublished data).

is the primary species being harvested. Commercial whitefish quotas have been reduced by over 50% since 1986 through buyouts. The average harvest of lake whitefish from 1990-96 of 13,800 kg (30,300 lbs) was just below the potential yield of 14,855 kg (32,800 lbs) (MNDNR/OMNR, 1998). Long-term monitoring has shown the population has normal growth, maturity, and age and size distributions. Mean ages and the age composition in the catch have improved, with fish from 5 to 22 years old being present. Like the MNDNR, the OMNR is concerned about the effect of the rainbow smelt and as a result has reduced the target level to the potential yield level (MNDNR/OMNR, 1998).

Commercial fishing in the Minnesota portion of Namakan Lake since 1946 has been restricted to lake whitefish with a by-catch of cisco, burbot, and suckers. Fishing activity and harvest of lake whitefish have declined since the Park's authorization in 1971. In the 1970s, the average annual harvest of lake whitefish was 1,937 kg (4,277 lbs), in the 1980s 1,298 kg (2,866 lbs), and in the 1990s 144 kg (318 lbs). Fishing was only conducted in six years in the latter period. Recent harvests have consistently been well below the target harvest level of 1,359 kg (3,000 lbs).

In 2002, the entire commercial fishery on the Ontario portions of Namakan and Sand Point lakes was bought out by the OMNR. Prior to that, commercial harvest of lake whitefish from the Ontario portion of Namakan Lake had been reduced as the target level had been lowered to the potential yield level of 2,900 kg (6,400 lbs) (MNDNR/OMNR, 1998). Consequently, average harvests declined from 9,110 kg (20,115 lbs) in the 1970s to 8232 kg (18,177 lbs) in the 1980s to 3157 kg (6971 lbs) in the 1990s. As indicated earlier, commercial harvests of walleye and northern pike had consistently been below target levels. Long-term harvests by the Ontario commercial lake sturgeon fishery were almost identical to the whole lake's potential yield of 400 kg (994 lbs). Currently, there is no known harvest of lake sturgeon from the Minnesota waters and the target level is set at zero.

No commercial fishing is allowed in the Minnesota portion of Sand Point Lake. Prior to the 2002 buyout there were commercial quotas for lake whitefish, black crappie, and lake sturgeon in the Ontario portion of the lake. Harvests of lake whitefish had averaged about 65% of Ontario's 1,042 kg (2,300 lbs) target level. The Ontario fishery, as was the case for Namakan Lake, had harvested lake sturgeon at the 200 kg (400 lbs) potential yield level for the whole lake. The current target harvest level for lake sturgeon in Minnesota is zero.

Commercial fishing for gamefish in Kabetogama Lake was terminated in 1926. Commercial fishing for lake whitefish, cisco, and burbot continued up until 1959 when the two Coregonid species were declared unfit for human consumption due to heavy parasite loads. The only commercial-type activity since then occurred in the 1970s when a rough fish removal program resulted in the harvest of 11,050 kg (24,400 lbs) of white suckers (Eibler, 2001b).

**Fish populations:** The standardized gill net sampling program that has been conducted on the Park's large lakes since 1983 has provided useful indicators of the species composition and relative abundance of some species in the fish community. This data is particularly important since a positive relationship has been found between the net catches and angler catches (Eibler, 2001c). Variation in abundance between years, which is expressed as the coefficient of variation (CV), may also serve as an index or early warning of increased fishing pressure (OMNR, 1983). Also, the gill net sampling program has produced significant autecological information for walleye, sauger, yellow perch, northern pike, smallmouth bass, and black crappie, the principle species in the sport fishery. For these species, the resulting data has been used to determine relative abundance, age and size composition, relative year class strengths, growth and mortality rates, body condition, and age at first maturity. These parameters are important in assessing the status of the populations and for analyzing the effects of exploitation and environmental conditions.

While 25 fish species have been captured in the fall gill net catches, the three Percid species and white sucker, cisco, and northern pike have composed over 90% of the catch in Kabetogama, Namakan, and Sand Point lakes (Table 10). Black bullheads, the dominant species in Rainy Lake, replaced cisco in this dominant group. Walleye have been the dominant species in Kabetogama and Namakan lakes while cisco have been dominant in Sand Point Lake. Catches of the remaining species have been low and irregular. Although catches have varied from year to year, the CVs for walleye and northern pike catches from 1983 to 2000 in the four large lakes were below the 40 and 45 thresholds for concern suggested by the OMNR (1983) (Table 10). Based on a decline in CVs from 41 to 22 from gill netting results from the periods 1970 to 1981 and 1994 to 2000, Eibler (2001c) concluded that the Rainy Lake walleye population has become more stable. The CV values for smallmouth bass have exceeded the recommended threshold of 50; however, the high CV values might indicate that the gill net is not an effective tool for sampling smallmouth bass. The CV was 49 for smallmouth bass from fall electrofishing surveys on Rainy Lake (1991 to 2000) that specifically targeted smallmouth bass, while the CV was 82 from gill net catches during the same period.

**Table 10.** Mean catch per unit of effort of fish in annual gill net surveys in Kabetogama, Namakan, Sand Point, and Rainy Lakes, 1983-2000. Coefficient of variation in parentheses. t = trace.

| Species | Kabetogama | | Namakan | | Sand Point | | Rainy | |
|---|---|---|---|---|---|---|---|---|
| Lake sturgeon | | | 0.04 | (114) | 0.03 | (136) | 0.01 | (424) |
| Mooneye | | | | | | | t | (424) |
| Common shiner | | | t | (424) | | | | |
| Golden shiner | | | 0.01 | (247) | 0.01 | (291) | | |
| Longnose sucker | | | | | | | 0.01 | (424) |
| White sucker | 5.32 | (32) | 1.61 | (28) | 2.04 | (36) | 2.57 | (30) |
| Silver redhorse | 0.01 | (424) | 0.01 | (424) | | | | |
| Shorthead redhorse | 0.08 | (141) | 0.04 | (156) | 0.06 | (117) | 0.02 | (159) |
| Black bullhead | | | 0.37 | (204) | 0.23 | (114) | 8.62 | (123) |
| Brown bullhead | | | | | | | 0.78 | (424) |
| Northern pike | 2.07 | (37) | 1.44 | (34) | 1.85 | (29) | 2.22 | (37) |
| Rainbow smelt | t | | 0.01 | (424) | | | | |
| Cisco | 4.14 | (63) | 5.26 | (41) | 9.14 | (40) | 0.83 | (99) |
| Lake whitefish | 0.01 | (193) | 0.08 | (94) | 0.08 | (96) | 0.04 | (136) |
| Burbot | 0.14 | (79) | 0.08 | (121) | 0.06 | (97) | 0.03 | (187) |
| Slimy sculpin | | | | | | | t | (424) |
| Rock bass | 0.32 | (74) | 0.81 | (45) | 0.87 | (42) | 1.15 | (47) |
| Pumpkinseed | | | t | (424) | | | | |
| Bluegill | 0.01 | (291) | 0.02 | (219) | 0.17 | (168) | | |
| Smallmouth bass | 0.33 | (55) | 0.36 | (59) | 0.23 | (69) | 0.40 | (63) |
| Largemouth bass | | | | | 0.02 | (243) | | |
| Black crappie | 0.33 | (101) | 0.23 | (83) | 1.19 | (52) | 0.24 | (94) |
| Yellow perch | 5.79 | (51) | 5.08 | (36) | 3.92 | (38) | 5.14 | (46) |
| Sauger | 4.22 | (30) | 2.49 | (29) | 1.33 | (22) | 3.03 | (30) |
| Walleye | 10.29 | (26) | 7.46 | (36) | 8.95 | (21) | 5.11 | (38) |
| TOTAL | 33.06 | | 25.40 | | 30.18 | | 31.18 | |

An index of relative year class strength for walleye, sauger, yellow perch, and northern pike has been determined by summing the gill net catch per unit of effort (CPUE) for each year class at ages 2, 3, and 4. These ages were used because they typically represent age groups that are fully recruited to the gill nets and comprise the majority of the gill net catches (VOYA/USGS, unpublished data). The CPUE sums for each species showed that there was significant variation in the strength of the year classes but also that fluctuations in year class strength within the species were similar in the three Namakan Reservoir basins (Figure 37). This similarity in fluctuations in year class strength across basins suggests that hydrological conditions and other environmental factors in the three Namakan Reservoir basins are having similar affects on reproduction and survival of the fish species. The CPUEs for northern pike, whose year class strength is positively correlated with mean water levels during the three weeks following ice-out in all three basins (Kallemeyn, 1987b), provide the strongest supporting evidence of the strong influence of hydrological conditions on the year class strengths of fish species. Additional evidence of the significant affects that hydrological conditions can exert on the year class strengths of fish species was reported for walleye in Kabetogama, Rainy, and Sand Point lakes (Kallemeyn, 1987a). Chevalier (1977) also found a positive relation between water levels at spawning time for walleyes and subsequent year class strength in Rainy Lake. Comparisons between hydrological and climatological conditions and yellow perch and sauger year class strength, although less definitive, suggest that year class strength is positively related to temperature and negatively related to discharge and spawning season water levels during their first year of life (K. Holmberg, University of Minnesota, personal communication). It is critically important to gain a better understanding of the influences of hydrological conditions on fish productivity in the Park lakes in order to provide sound biological and ecological information for the successful management of the Park's fisheries resources.

Gill net catches in Rainy Lake showed magnitudes of fluctuations similar to those in Namakan Reservoir, but there was little correspondence with the Namakan Reservoir catches. An earlier, more-detailed analysis of gill net catch data from four sites in Rainy Lake showed that there were differences in the extent of species interaction and population fluctuations

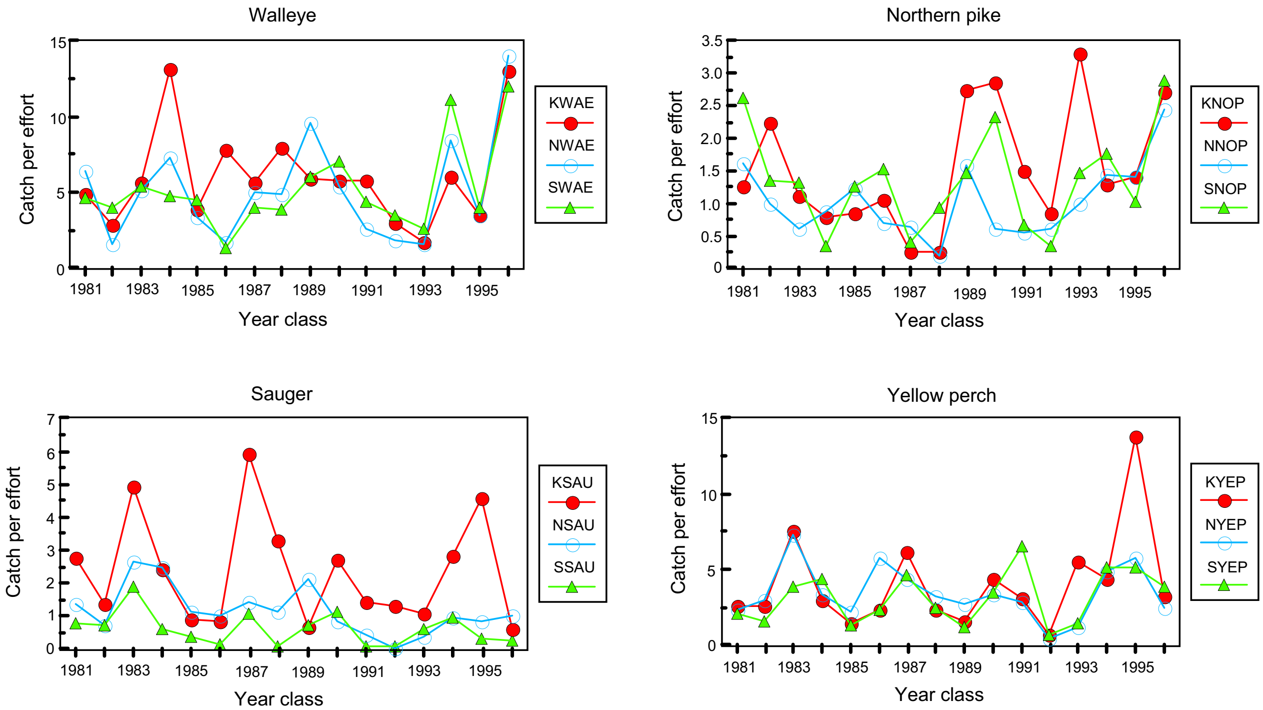



**Figure 37.** Sum of gill net catch per unit of effort (CPUE) at ages 2, 3, and 4 for 1981-96 year classes of walleye, northern pike, sauger, and yellow perch from Kabetogama, Namakan, and Sand Point lakes, Minnesota. Data compiled from large lake surveys conducted annually by the MNDNR and VOYA/USGS, 1983-2000.

among locations (Cohen and others, 1993). The authors concluded that because of these differences in large lakes it may be necessary to identify local fish communities and to address management problems locally. Although this can be done for fisheries regulations, it is not feasible for factors such as water levels that are not location specific.

The standardized seining that is done annually on Rainy and Kabetogama lakes also has contributed to our understanding of the relationships between environmental conditions and recruitment and growth of young-of-the-year fish, including both the primary predators and several prey species. Generally, first year growth was positively correlated with temperature (measured as degree days >10 ºC) and in some instances negatively correlated to both inter- and intraspecific species density (Warner, 1994; Eibler, 2001b; 2001c; VOYA/USGS, unpublished data). A positive correlation has been shown to exist between the rate of growth of fish during their first growing season and increased survival and year class strength (Toney and Coble, 1979; Post and Evans, 1989). A significant positive relationship was observed between the length of age-0 walleye and recruitment success of walleye in Kabetogama Lake for the period 1983 to 1993 (Warner, 1994). Also, analyses of long-term data have shown similar positive relationships for walleye in both Rainy and Kabetogama lakes (Eibler, 2001b; 2001c).

The seining program, while primarily designed to obtain information on age-0 of walleye and some other game fish, also provides relative abundance and growth data for many cyprinids and other species that are not collected by the other sampling methods. In addition to the routine analyses of abundance and growth, the data is currently being used to analyze long-term temporal and spatial patterns in littoral zone biodiversity in the large lakes (L. Kallemeyn, USGS, unpublished data). Since many of these fish are utilized as prey by a variety of birds and mammals, results of these analyses may also prove valuable to researchers investigating the distribution and productivity of those organisms.

Sampling methods such as electrofishing and trapnetting have been used in the large lake program, particularly on Rainy Lake, to gather information on species such as smallmouth bass and black crappie that are not sampled efficiently with the gill nets or seines. The same parameters can be determined from the catches in these accessory gears. For example, spring trap netting in Black Bay in Rainy Lake, which was initiated in 1992, has shown that there is considerable variation in year class strength in black crappie with stronger than normal year classes having been produced in 1994 and 1995 (Eibler, 2001c). Monthly trap netting from June through August 1983-88 on

Kabetogama Lake produced similar results for black crappie (VOYA/USGS, unpublished data). There was a positive relationship between catches of one-year old crappies in the trap nets and seine catches of age-0 from the previous year, with the strongest year class during this period occurring in 1987. Year class strength estimates from fall electrofishing catches of age-0 walleye on Rainy Lake were positively correlated with estimates derived from gill net catches (Eibler, 2001c). Also, electrofishing results were used to develop an index of year class strength for smallmouth bass in Rainy Lake (Eibler, 2001c). Unfortunately, electrofishing data from Kabetogama Lake has limited value because of the poor visibility there resulting from the heavy blue-green algae blooms that occur in late summer and early fall.

Smallmesh gill netting is another sampling method that has been used routinely since 1992 on Rainy and Namakan lakes. Sixty-one meter (200 ft) nets containing 30.5 m each of 9.5 mm (0.375 in) and 12.7 mm (0.50 in) mesh were used, primarily to obtain an index of abundance for rainbow smelt. Rainbow smelt catches, which contain primarily yearling and older fish, peaked in 1996 on Rainy Lake (Figure 38). Catches of rainbow smelt in Rainy Lake have consistently been higher than in Namakan Lake. Cisco catches in the smallmesh gill nets, which consist mainly of age-0 and yearling fish, peaked in 1998 and 1999 in Rainy Lake (Figure 38).

Through the use of standardized methodology, the large lake program provides extensive and useful information on some of the fish species, particularly the game fish on which the program was designed to focus. However, the large lake program does have some limitations. It does not effectively sample the entire fish community or all of the habitat zones. Typically, the pelagic and deepwater zones have not been sampled, although in 1996, 1997, and 2000 the deepwater zone was sampled in Rainy and Namakan lakes (Eibler, 2001c; VOYA/USGS, unpublished data). For other species such as cisco and suckers, which are captured by gill netting, ages usually are not determined so it is difficult to relate the results to biological or environmental factors. Unfortunately, the nonprobability fixed station sampling designs used limits statistical inferences to the sites sampled and restricts other potential uses of the data (Wilde and Fisher, 1996). Given these types of limitations, it is conceivable that significant changes in the fish community could go undetected. A more uniform and intensive sampling program that utilizes multiple sampling methods is needed to ensure that changes in the Park's fish community are detected and managed.

Although standard sampling methods are used in the Park's interior lakes, analyses are hampered by low sampling frequency and in some lakes limited gill net sets. The interior lakes are not sampled frequently because the MNDNR rates most of the lakes as a low priority due to the fish communities not being actively managed, and the perception that the lakes receive limited fishing pressure. Consequently, assessments of the status of fish populations in the interior lakes are dependent on comparisons of current survey data with results of earlier surveys and summarized gill net

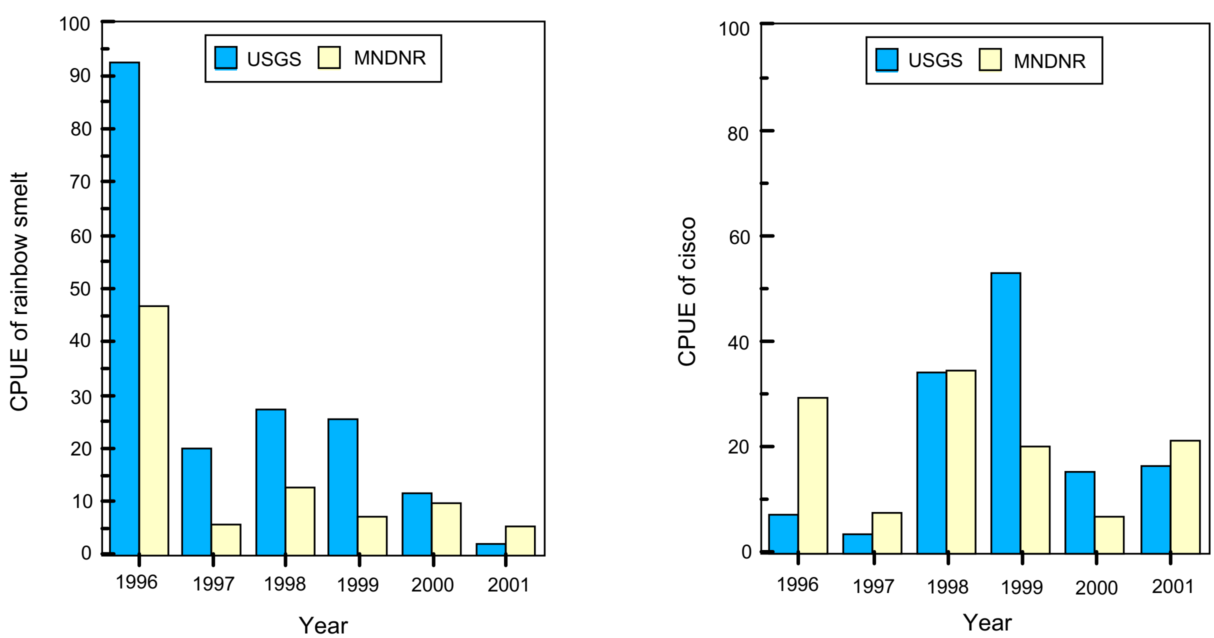



**Figure 38.** Catch per unit of effort (CPUE) of rainbow smelt and cisco in VOYA/USGS and MNDNR September smallmesh gill net sets in Rainy Lake, 1996-2001.

catch per unit of effort from Minnesota lakes of the same lake classes. The CPUE values from the Park's lakes are compared to intraclass quartiles developed for Minnesota lakes with values falling within the interquartile range being viewed as normal for that lake class. Values that fall above the third quartile or below the first quartile may be considered unusual, meriting more detailed examination (Schupp 1992). This approach, though statistically conservative, is particularly applicable when lakes are assessed infrequently.

Based on the most recent gill net surveys of the Park's interior lakes, mean catches of about 67% of the fish species were within or above the interquartile range. In comparison to the ranges for the various lake classes, 33% of the northern pike CPUE values were within the interquartile range, 56% were above it, and 11% were below. Comparison of yellow perch CPUE values showed that 45% of the values were within the interquartile range, 20% were above it, and 35% were below. For white sucker, 92% were below the interquartile range and 8% were above it. It is noteworthy that significant portions of the CPUE values are from surveys conducted in the 1970s and 1980s. Conceivably, significant changes may have occurred in the intervening years in species abundance and composition of the fish communities. Given the current sampling regime, such changes are likely to continue to go undetected, or if detected could not be explained due to the paucity of information that exist on the interior lakes. Thus, it will be extremely difficult to judge whether management actions are necessary to ensure the long-term well being of the interior lakes' fishery resources.

**Autecology/synecology:** In addition to the relatively long-term fisheries assessment activities, numerous studies and surveys have been conducted to address specific fisheries issues. These have included both autecological and synecological studies. The former deals with the study of single species and the latter with the study of the interrelationships of species. The fisheries issues addressed in these studies have included the effects of water level management on reproductive success, population size, effects of non-native species on native fish and other aquatic organisms, taxonomy and genetics, and landscape effects on species distributions. Frequently, data collected in the long-term monitoring programs has been incorporated into these studies.

***Reproduction:*** Specific studies addressing the questions related to species maturity, the time and location of spawning, and fecundity have been limited primarily to walleye and northern pike. Estimates of maturity have been obtained for the primary species collected in the large lake gill net surveys and from sampling walleye in the Rat Root River (Eibler 2001c) and northern pike and walleye in Kabetogama Lake during the spawning season (Kallemeyn, 1987b; 1990a). Based on walleye captured in gill nets, mean ages at first maturity for females in Rainy and Kabetogama lakes have been similar and ranged from 4 to 5.5 years. The mean age of first maturity for walleye males in Kabetogama Lake has been between 3 and 4 years while in Rainy Lake, it has been between 4 and 4.5 years. In 1984 and 1985 in Kabetogama Lake, walleye males first entered the spawning run at age 3 and females at age 4 (Kallemeyn, 1990a). Both male and female northern pike entered the spawning run at age 2 in Kabetogama Lake (Miller and others, 2001).

The Rat Root River and Kabetogama Lake surveys also provided some information on the time and location of species spawning. Additionally, information on walleye and northern pike spawning habitat availability was collected during some earlier spawning season surveys (Osborn and others, 1978; Osborn and Ernst, 1979). Spawning of northern pike and walleye typically occurs within two to three weeks of ice-out, with degree of activity being influenced by climatic and hydrological conditions. If flooded vegetation isn't available due to low water levels, northern pike will not spawn and instead will reabsorb their eggs. A reconnaissance of potential smallmouth bass spawning habitat in Kabetogama Lake was conducted in 1960 by the MNDNR (Scidmore, 1960).

Fecundity, or the number of gametes produced, has only been determined for northern pike from Kabetogama Lake (VOYA/USGS, unpublished data). The number of eggs produced by the Kabetogama Lake fish was generally similar to values reported for similar size northern pike from populations in Houghton Lake, MI (Carbine, 1944), Oahe Reservoir, SD (June, 1971), and Lac La Ronge, Sask. (Koshinsky, 1979). Females from all these populations would produce about 35,000 eggs when they are 635 mm long (25 in) and 65,000 eggs when they reach 762 mm (30 in).

***Population estimates:*** Managers of the walleye fisheries in the Park's lakes have had to rely on relative abundance estimates obtained from the annual gill net surveys since only two attempts have been made to estimate actual population sizes. Population estimates for walleye in Kabetogama Lake age 3 or older, computed from creel survey and resort tag returns, were 162,446 (95% confidence limits, 128,542 – 205,138) in 1984 and 168,916 (95% confidence limits, 139,902 – 203,882) in 1985 (Kallemeyn, 1989). Radomski (2000) used virtual population analysis (Pope, 1972) to estimate walleye abundance in the Minnesota portion of the South Arm of Rainy Lake for the years 1983 to 2000. The estimates for walleye age 2 and older, which ranged from 87,000 in 1987 to 281,000 in 2000, generally increased throughout this period. Radomski (2000), however, suggested that these estimates must be viewed with caution since there are many shortcomings in this model that could conceivably result in the population size being over or underestimated.

***Movement/exploitation:*** Tagging has been used to assess fish movement and exploitation in Rainy and Kabetogama lakes. Tag returns from walleye tagged during the spawning season indicate that there are discrete walleye stocks in the three major arms of Rainy Lake (MNDNR/OMNR, 1998). Walleye tagged in the North Arm of Rainy Lake remained in that basin, as did walleye tagged in Red Gut Bay. Walleye tagged at six sites in the South Arm of Rainy Lake in 1959 moved freely between Minnesota and Ontario waters but remained in that basin (Bonde and others, 1961). Overall, 10.6% of the 1,439 walleyes that were tagged were caught in the sport and commercial fisheries. Walleye introduced in the North Arm of Rainy Lake from Namakan Lake exhibited a greater propensity to move out of the basin than did fish that originated there (McLeod and Gillon, 2000). Northern pike from the North Arm of Rainy Lake also remained in that basin (MNDNR/OMNR, 1998).

Tag returns from 4,294 walleye in Kabetogama Lake in 1984 and 1985 suggest that there are also separate stocks in the different basins in Namakan Reservoir. Of the 1,340 tags returned by anglers, 1,329 were from fish caught in Kabetogama Lake, 10 from Namakan Lake, and one from Rainy Lake (VOYA/USGS, unpublished data). Over 90% of the walleye were caught within 10 kilometers of the site where they were tagged. First year exploitation of the tagged fish was 24% after a tag loss correction factor of 24.2% was applied (Kallemeyn, 1989). Exploitation rates for fish less than 480 mm long was about twice that of fish longer than that length (Kallemeyn, 1990a). Based on tag returns through 1993, total exploitation was 15.5% for the walleye tagged in 1984 and 19.5% for fish tagged in 1985.

Based on physical-tagging and genetic data, two spawning populations of northern pike in Kabetogama Lake exhibit spawning-site and natal-site fidelity (Miller and others, 2001). Northern pike marked at Tom Cod Creek and Daley Brook exhibited high fidelity to these spawning areas with straying rates of only 1.3% and 4.8%, respectively. Tag returns from anglers, all of which were from within Kabetogama Lake, showed that the year-round ranges for fish from the two sites overlapped, so that lack of dispersal could not completely explain the high fidelity to spawning sites. Genetic analysis of fish from the two spawning populations also indicated low levels of gene flow between the populations. This reproductive isolation would only be expected if most individuals first spawn at the site of their own birth and subsequently return to that site. Based on these results, management of discrete spawning populations within lakes may be more appropriate for a larger number of species and locations than is commonly practiced. The exploitation rate of the tagged pike from 1983 to 1985 by anglers and spearers was 17% for tagged fish from Tom Cod Creek and 15% for those tagged at Daley Brook. A fisherman returned three tags he had found on Anchor Island in Rainy Lake. Conceivably, an avian predator or scavenger could have transported the fish there since they were less than 475 mm long when tagged.

***Feeding habits/trophic ecology:*** Food habits studies conducted in the Park have focused on determining the feeding habits of native species as well as the impacts that introduced non-native largemouth bass and rainbow smelt might have on the aquatic communities, and in particular native fish species. Native species investigated in Kabetogama Lake include age-0 walleye (Levar, 1986) and age-0 and yearling yellow perch (Lindgren, 1986). Food habits of several native species and exotic rainbow smelt from Rainy Lake have been studied (VOYA/USGS, unpublished data) as have feeding habits of northern pike and non-native largemouth bass in several interior lakes (Soupir, 1998; Soupir and others, 2000).

Age-0 walleye in Kabetogama Lake relied heavily on fish as forage in both 1984 and 1985, however changes occurred in the species composition of their diet (Levar, 1986). These changes reflected a major change in the abundance of food organisms, particularly the abundance of age-0 yellow perch. In 1984, the age-0 walleye were opportunistic feeders and foraged on whatever fish species were available within their preferred size range. Darters were the main species utilized but the diet also contained smallmouth bass and black crappie. Walleye did not utilize age-0 yellow perch as prey until mid-August. A three-fold increase in age-0 yellow perch abundance from 1984 to 1985 resulted in the age-0 walleye feeding on them almost exclusively, thereby reducing the predation pressure on the other species. Thus, high densities of age-0 yellow perch serve as a predation buffer and can influence the population dynamics of the alternative prey species as well as that of the walleye (Forney, 1974).

Selection of food items by age-0 yellow perch in Kabetogama Lake appeared to be controlled by availability of prey in the environment (Lindgren, 1986). While zooplankton was the dominant food item throughout the summer of 1985, the composition in the perch's diet shifted from copepods to cladocerans as the season progressed, thus, reflecting changes in the zooplankton community. Yearling yellow perch exhibited a transition from zooplankton and amphipods to larger invertebrates such as decapods and aquatic insects, particularly corixids. Their limited utilization of fish was probably due to most of them being less than 100 mm long. Yellow perch in other populations don't usually convert to a fish diet until they reach a length of about 140 to 160 mm (Keast, 1977).

To determine if non-native largemouth bass adversely affect indigenous northern pike through food-resource competition and diet overlap, seasonal food habits of allopatric and sympatric assemblages of the two species were investigated in six of the Park's interior lakes (Soupir, 1998; Soupir and others, 2000). Results from stable isotope analysis for $\delta^{15}N$, which provides a measure of an organism's trophic position based on its long-term assimilated diet (Hesslein and others, 1993), indicated the two species were at the top of the food web and that they utilized similar energy sources in these lakes (Soupir, 1998). Significant differences, however, were found in the proportions of food types in the diets of the two species, with the largemouth bass consuming a greater diversity of food items. Fish, particularly yellow perch, were of high importance in the northern pike diet in both sympatric assemblages and allopatric populations in all seasons. In contrast, largemouth bass ingested a relatively high proportion of insects during all seasons, regardless of allopatry or sympatry. Both species consumed age-0 largemouth bass, however, no northern pike were found in largemouth bass stomachs. Although there was some biologically significant diet overlap in the sympatric assemblages, at current densities it did not appear that the largemouth bass were limiting the well being of the northern pike through food-resource competition. Bioenergetics' modeling simulations conducted to depict low yellow perch availability due to high largemouth bass and northern pike competition resulted in small differences in pike growth (Soupir, 1998). These results indicate that removal of the largemouth bass would likely have little influence on the northern pike populations. The removal of the allopatric largemouth bass populations in Quill and Loiten lakes, however, could have a significant affect on the aquatic communities since neither lake contained northern pike or any other large piscivore prior to the introduction of the largemouth bass.

Stable isotope and food habits analyses have also been used to assess the influence of the exotic rainbow smelt on the aquatic food web in Rainy and Namakan lakes (Sorensen and others, 2001; VOYA/USGS, unpublished data). Food web linkages were examined by measuring stable isotope ratios in aquatic plants and animals including various forage fish and two game fish species, northern pike and walleye. The $\delta^{13}C$ change per trophic level was found to be 1‰ to 2‰, while for $\delta^{15}N$ it was 2‰ to 3‰. The trophic position for both game fish, as measured by $\delta^{15}N$, was about 3.6 while it was 3.6 for rainbow smelt in Rainy Lake and 2.9 in Namakan Lake. Assuming an enrichment value of 3.4‰ for $\delta^{15}N$ from food to consumer, the isotope analyses suggested that rainbow smelt do not constitute a significant portion of the diets of walleye and northern pike. A comparison of the stable isotope results with results derived from stomach analysis indicates reasonable agreement for northern pike but a significant difference for walleye. Rainbow smelt comprised 14% and 50% of northern pike and walleye stomach contents by weight during the summer of 1996 in Rainy Lake. The inconsistencies between the results of stable isotope and stomach content analyses for walleye may be due to seasonal changes in diets for which the "snapshot" survey of stomachs could not account.

The invertebrate *Mysis relicta* was the dominant food item in 1,079 rainbow smelt stomachs examined from 1996 to 1999, and occurred in 55 to 90% of the stomachs. In August and September, the rainbow smelt preyed almost exclusively on *M. relicta*. Rainbow smelt also preyed on other groups of organisms including zooplankton, amphipods, insects, and fish. The fish typically occurred in the diet most frequently in early summer when large numbers of newly hatched fry were available. Unfortunately, sampling during the early spring period when cisco and lake whitefish fry are most likely to be utilized by the rainbow smelt has not been feasible due to ice conditions.

***Behavior:*** To further address the question of whether northern pike or nonindigenous largemouth bass have an advantage when they compete for food under low light intensities, large tanks were used in a controlled laboratory test to assess differences in feeding behavior of the two predators using yellow perch as prey (Savino and others, 1999). The feeding behavior of the two predators was evaluated both singly and in combination with each other under low light intensities. Largemouth bass captured fewer prey in tests containing northern pike than when alone. Northern pike capture rate did not change significantly in the presence of largemouth bass, but they did capture more prey than the largemouth bass when the predators were tested together. Number of captures did not change with light intensity. Because aggressive interactions appeared to be related to size, specifically differences in weight, northern pike were in most instances the aggressor. Thus, the results of this laboratory study supported the findings of the field study

(Soupir 1998) that northern pike are the better competitor in feeding and aggressive interactions with largemouth bass.

**Alternative sampling programs:** Sampling methods other than those previously mentioned have been used in some instances. Domeier (1989) fished commercial minnow traps concurrently with the conventional beach seine to determine their relative efficiencies for measuring the presence, relative abundances, and size composition of age-0 gamefishes in Kabetogama Lake. The traps were less effective than the seine at measuring relative abundance of fish species within the community; however, they appeared to be more successful at monitoring temporal and spatial changes in abundance of some species, particularly yellow perch and smallmouth bass. Minnow traps may be a preferred alternative for certain types of studies because they can be used in areas where seining is not feasible and they require minimal labor for deployment.

The invasion of the Park by the rainbow smelt precipitated the need for identifying and testing sampling methods that could be used to assess and monitor the smelt population as well as other members of the pelagic fish community with which smelt might interact (Duffy and others, 1994). Basically, new sampling methods were necessary because none of the traditional fish sampling methods used in ongoing assessment programs on Rainy Lake or the other large lakes efficiently sampled the pelagic fish community. Both bottom and midwater trawling have been tested since they both are commonly used in the Great Lakes to monitor prey fish abundance. Bottom trawling conducted monthly from June through September from 1995 to 1997 on Rainy Lake did not prove to be a good means of monitoring rainbow smelt; however, bottom trawling appeared to have potential for monitoring some bottom-oriented species, including trout-perch, darters, sauger, burbot, and sculpin that are seldom sampled in the other gears being used.

Integrated hydroacoustic and midwater trawl surveys have proven to be a valid means of assessing the distribution, density, and biomass of pelagic fish in the Great Lakes (Argyle, 1982; Heist and Swenson, 1983; Brandt and others, 1991), and in smaller lakes like Rainy Lake where rainbow smelt occur (Burczinsky and others, 1987; Kim and LaBar, 1991). Pilot surveys conducted in 1996 (Fleischer and others, 1996) demonstrated the efficacy of the integrated hydroacoustic and midwater trawl survey method for sampling rainbow smelt in Rainy Lake. The pilot surveys also proved that such assessments could be done during daylight hours due to the reduced light transmission in Rainy Lake. Based on the survey results, the standing crop of rainbow smelt in the South Arm of Rainy Lake in 1996 was similar to those in Lakes Huron and Michigan and Lake Oahe, a Missouri River reservoir. The surveys also demonstrated that the rainbow smelt exhibited a patchy distribution. The integrated acoustic – trawl surveys should become a standard part of the sampling program for VOYA lakes.

**Future Needs and Opportunities:** The importance of the fish community and fishery dictate that Park management needs to develop a plan for the long-term management of fish and aquatic resources within VOYA. Although there is USNPS (2001) policy on fisheries management, specific long-term goals and objectives for the Park are needed. The long-term goals and objectives should be incorporated in the plan, which should also present existing information and ongoing activities, clarify agency roles and responsibilities, identify additional opportunities for cooperative management, list key issues, describe desired future conditions, and list prioritized project statements. The plan should be more comprehensive than the individual MNDNR lake management plans, which tend to focus primarily on management of game fish. Also, the Park needs to ensure that it has **in house** fisheries expertise to address aquatic resource management issues.

The combined efforts of the MNDNR, OMNR, VOYA/USGS, and independent researchers have produced a significant amount of information about the area's fishery resources, particularly the top predators that support the recreational fisheries. Given the extent of the water resources and the shared jurisdictions, those collaborative efforts must continue to provide the information needed to ensure the long-term sustainability of the shared resources. Efforts to calibrate or standardize sampling techniques used by the various agencies should continue. New programs using stratified-random sampling designs are needed for the nearshore and deepwater fish communities and for comparison with the traditional fixed-station sampling program. Comparisons of netting results from the fixed-stations with those from randomly chosen sites over a number of years could enhance utilization of the existing large, gill net survey database. Implementation of these new programs will strengthen the agencies ability to detect long-term changes in the overall fish community, which in the case of human induced disturbances are likely to be gradual and incremental (Lester and others, 1996)

Much remains to be learned about the fish community and the fishery. For example, our knowledge of whether fish stocks are shared in the Minnesota/Ontario border lakes or the degree to which they are shared is limited because few studies have been carried out to delineate individual stocks.

Although tagging studies could provide this information, there are inherent limitations that must be dealt with in interpreting their results. In addition to movement and distribution information, tagging studies could also provide much needed information on exploitation and critical habitat, particularly spawning areas. This information could prove extremely useful in allocating harvests between jurisdictions and, where necessary, for protecting or restoring key habitats.

Because fish diversity, recruitment and productivity is dependent to a great extent on land/inland water ecotones (Naiman and others, 1989), their maintenance or restoration should be a high priority. The identification of littoral spawning/nursery habitats and their effect on recruitment must be a significant component of any attempt to evaluate the effects of the IJC's 2000 rule curves. Also, there is a need to identify littoral spawning/nursery habitats for those species that utilize streams and tributaries so that management actions can be taken to prevent land use activities that might adversely affect them. Littoral zone coarse woody debris, which is an important substrate for many plant and animal species in forest-lake ecotones (Bowen and others, 1995; France, 1997a), needs to be inventoried, especially since it represents a persistent class of aquatic habitat that accumulates over many centuries (Guyette and Cole, 1999). Existing beaver survey data and counts of abandoned houses should be included in the inventory since they can be an important habitat resource in small boreal lakes (France, 1997b).

It is not unexpected that monitoring has focused on fish species that are managed for recreational harvest, with only limited information being collected on other species. Traditional sampling programs have provided only limited information on pelagic or deep-water fish species, exceptionally large fish such as lake sturgeon, and species characteristically lumped as non-game fish. Only limited attempts have been made to identify processes influencing population and community dynamics, including interconnections with other ecosystem components. Consequently, there is a great deal of uncertainty about what the effects of management actions taken to regulate harvest are on the remainder of the fish community and piscivorous birds or wildlife. For example, no means exist to assess whether changes in walleye or northern pike population characteristics as a result of management actions affect prey populations, or alternatively if prey availability affected the response of the predators. The need for information on aquatic resource interactions has been heightened by the invasion of the rainbow smelt. Long-term monitoring programs need to be designed and implemented that will supplement current programs, but more importantly that will provide information on the fish community and its structure, including the species that are non-terminal predators. Fisheries managers must have and understand such information if they wish to sustain optimal fishery yields (Evans and others, 1987).

More detailed information about the large lake fisheries also would be required to implement an "active" management style such as is used on Mille Lacs Lake, MN. Implementation of a similar program would require: (1) data that would provide estimates of population size, exploitation rate, and the biological status of the stock; (2) harvest tactics (regulations) to achieve safe exploitation rates; and (3) procedures for monitoring and enforcement of the catch limits such as creel surveys (Gangl, 2001). Because of the data requirements, implementation of such a program would probably be limited to more intensive fisheries such as those on Rainy and Kabetogama lakes.

More frequent monitoring of all the Park's interior lakes is needed, particularly those receiving significant use. Monitoring at no more than 5-year intervals (preferably more often) with multiple gear types will provide presence-absence data that can be used to assess changes in community composition, species richness, and biodiversity (Jackson and Harvey, 1997). Additionally, this type of program would be especially useful for detecting invading species. To reduce the effect of sampling mortality in these small lakes, non-lethal sampling methods should be investigated or developed. Both before and after a management practice is implemented, surveys should be conducted annually for several years so that the effectiveness of the management action can be determined. Also, additional studies are needed on the interior lakes to assess the effects of non-native fish on native fish species and other aquatic organisms, the effectiveness of the removal of non-native species, and to identify or develop creel surveys that will provide accurate estimates of fishing pressure and harvest.

## Reptiles and Amphibians

Analysis of the herpetofauna of VOYA has been extremely limited. In 1988, reptiles and amphibians were collected with pitfall traps, dip nets, and from seines and trap nets being used in the fisheries program (Palmer, 1988). In all 7 amphibian and 3 reptile species were collected (Table 11). Additionally, after consultation of the herpetological collection of the James Ford Bell Museum of Natural History at the University of Minnesota and various literature sources, an additional 10 amphibian species and 3 reptile species were identified as likely to occur in the Park (Table 11).

**Future Needs and Opportunities:** A more detailed inventory of the Park's herpetofauna by the USGS

**Table 11.** Reptile and amphibian species collected in Voyageurs National Park, Minnesota (VOYA), species collected in adjoining areas (AA), and species that may appear based on existing range maps (MA) (adapted from Palmer 1988).

| Common name | Scientific name | VOYA | AA | MA |
|---|---|---|---|---|
| Blue-spotted salamander | *Ambystoma laterale* | X | | |
| Tiger salamander | *Ambystoma t. tigrinum* | | X | |
| Redbacked salamander | *Plethodon c. cinereus* | | X | |
| Jefferson salamander | *Ambystoma jeffersonianum* | | X | |
| Mudpuppy | *Necturus maculosus* | | X | |
| Spotted salamander | *Ambystoma maculatum* | | | X |
| Central newt | *Notophthalmus viridescens louisianensis* | X | | |
| American toad | *Bufo a. americanus* | X | | |
| Canadian toad | *Bufo h. hemiophrys* | | | X |
| Gray treefrog | *Hyla v. versicolor* | X | | |
| Copes gray treefrog | *Hyla chrysocelis* | | | X |
| Spring peeper | *Pseudacris crucifer crucifer* | X | | |
| Boreal chorus frog | *Pseudacris triseriata* | | X | |
| Green frog | *Rana clamitans* | | X | |
| Northern Leopard frog | *Rana pipiens* | X | | |
| Mink frog | *Rana septentrionalis* | | X | |
| Wood frog | *Rana sylvatica* | X | | |
| Snapping turtle | *Chelydra s. serpentina* | X | | |
| Western painted turtle | *Chrsemys picta belli* | X | | |
| Ringneck snake | *Diadophis punctatus edwardsi* | | | X |
| Redbelly snake | *Storeria o. occipitomaculata* | | X | |
| Eastern garter snake | *Thamnophis s. sirtalis* | X | | |
| Red-sided garter snake | *Thamnophis sirtalis parietalis* | | | X |

Biological Resource Division is being conducted (J. Schaberl, VOYA, personal communication). This inventory will provide an opportunity to determine distribution and range borders within the Park and if malformed frogs are present as has been observed in other locations in recent years. A survey should be conducted to determine what kind and how many frogs and turtles are currently being harvested under the authority of the MNDNR fishing regulations.

## Mercury and Other Contaminants

Mercury (Hg) contamination affects hundreds of rivers, lakes, and reservoirs in the Great Lakes states, including the waters of VOYA. Initial surveys of Hg in fish from Minnesota lakes in the 1970s found excessively high levels in Rainy and Crane lakes (Minnesota Department of Health, 1977). These results and the results of a survey and analysis of hair and blood samples from Crane Lake residents and summer visitors prompted the establishment of an early consumption advisory. The rate of change of Hg concentrations (1930s and 1970s to the late 1980s) was found to be an increase of 3 to 5% per year (Swain and Helwig, 1989). Based on that rate of change, Sorensen and others (1990) determined that the proportion of lakes with concentrations greater than 1 µg/g in standard sized northern pike (55 cm) would rise from 2% to 45 %.

Surveys in the 1980s and 1990s by numerous agencies and investigators have found high Hg concentrations in fish from nearly all of the Park's 30 lakes (Minnesota Pollution Control Agency, 1985; Swain and Helwig, 1989; MNDNR 1994; Sorensen and others, 2001). Because Hg concentrations in fish are commonly size and age dependent (Glass and others, 2001), concentrations in standard sized fish are used for comparisons between lakes and years. Estimated Hg concentrations for standard sized northern pike from eight small Park lakes (range 374-4486 ng/g) were all higher than for Rainy (339 ng/g), Namakan (362 ng/g) and Kabetogama (141 ng/g) Lakes. The Hg concentrations in standard length northern pike from Ryan and Tooth lakes were the highest observed for the state of Minnesota (Sorensen and others, 2001). An inverse relationship between fish Hg concentrations and lake size was observed for 16 lakes in the Park and surrounding area (Sorensen and others, 2001). Similar relationships have been reported for Canadian Shield lakes (Bodaly and others, 1993) and for 80 Minnesota lakes (Glass and others, 1999). These results have caused consumption advisories to be extended to the majority of the Park lakes due to the health risks posed to humans by Hg-contaminated fish. Hg contamination in fish may influence a large proportion of Park visitors since approximately 70% engage in fishing while visiting the Park.

As a result of the elevated Hg concentrations in fish, Park waters and biota have been included in numerous studies. Some of the studies were Park-specific and others dealt with Hg throughout northern Minnesota. Results from these studies indicate that Hg is currently widespread in the Park's aquatic ecosystem. In addition to fish, elevated Hg concentrations have been documented in water (Sorensen and others, 1990), lake sediments (Meger, 1986; Glass and others, 1992; Engstrom and others, 1999), zooplankton and aquatic plants (Glass and others, 1992; Sorensen and others, 2001), benthic organisms (Sorensen and others, 2001), piscivorous birds (Zicus and others, 1988; Ensor and others, 1992; 1993; Derr, 1995; Giovengo, 1997; Evers and others, 1998), bald eagles (Bowerman 1993), and river otter (Route and Peterson 1988). In 2000, multidisciplinary studies focusing on Hg concentrations and cycling in the Park's interior lakes were initiated by personnel from the Minnesota Pollution Control Agency; Water, Mineral, and Biological Divisions of the USGS; and University of Wisconsin-Lacrosse. The overall goal of these studies is to identify the ecosystem processes or factors causing the observed variation in Hg in these small lakes.

Most of the Hg contamination in the Park and other mid-continental lakes is derived from atmospheric deposition, with three-quarters of this airborne Hg being generated by human activities (Sorensen and others, 1990; Glass and others, 1991; Swain and others, 1992). Geological sources of Hg in northeastern Minnesota are negligible compared to atmospheric sources (Swain and others, 1992). Emissions from the pulp and paper mills in the area were believed to be the source of much of the Hg found in lichens in the Park (Bennett and Wetmore, 1997). Monitoring of total wet Hg deposition from 1990 to 1995 at VOYA and five other sites in Minnesota and North Dakota showed that the Park and a station located near Ely, MN had significantly lower average values for concentration and deposition than the other stations, three of which were located further south in Minnesota (Glass and Sorensen, 1999). Deposition at all of the stations increased about 8% per year over the study period. There was a consistent seasonal pattern with higher precipitation and Hg deposition rates in the warm season accounting for 77% of the total annual wet deposition. A similar pattern was observed in concentrations and total amounts of Hg in organic litter and soil along a gradient extending from northwestern Minnesota to eastern Michigan (Nater and Grigal, 1992).

Analyses of lake sediment cores have provided additional information on deposition rates of Hg in the aquatic ecosystem. A study of the stratigraphy of Hg in the sediments of Crane and Kabetogama lakes provided some of the first evidence that the Hg problem was of relatively recent origin (Meger, 1986). Analysis of the core samples showed that Hg flux to the sediments had doubled since 1880. Subsequent studies of cores from other lakes in the region, including several in the Park, verified these findings (Henning and others, 1989; Engstrom and Swain, 1997; Engstrom and others, 1999). Based on an analysis of $^{210}Pb$ dated cores from 50 lakes from throughout Minnesota, total Hg concentrations increased from low background levels in pre-industrial sediments (pre-1860) to maximum values sometime during the 20$^{th}$ century (Engstrom and others, 1999). The Hg flux ratios of modern (36 µg m$^2$ year) to pre-industrial (10 µg m$^2$ yr) accumulation for lakes in northeastern Minnesota, including the Park lakes, averaged 3.6 (Engstrom and others, 1999). Hg concentrations in the sediments in five Park lakes (Little Trout, Locator, Loiten, Shoepack, Tooth), which exhibited the lowest and most consistent sediment accumulation rates of the 50 lakes, peaked around 1980. Since then, there has apparently been a consistent decline in Hg accumulation and concentration in the lake sediments. This decrease, which represents 15-20% of peak Hg loading, may have been due to a reduction in the use of mercuric fungicides by the local paper mills (Engstrom and others, 1999).

Although total Hg accumulation apparently decreased, the methylated portion of total-Hg (%MeHg) increased by a factor of 2-3 between 1940 and 1970 in 12 of 14 sediment cores from northeastern Minnesota lakes, including four from within the Park (Engstrom and others, 1999). The authors suggested that this increase, which was most likely due to increased deposition of other atmospheric contaminants, particularly sulfate and nitrate, multiplied the biological effect of the Hg being deposited.

The water management programs for Rainy Lake and Namakan Reservoir may also be influencing the biological effect of Hg. The creation of reservoirs is known to cause a substantial increase in Hg concentrations throughout the food web (for example Bodaly and others, 1984); however, the length of time that initial reservoir affect lingers and the effects of subsequent water level manipulations and fluctuations is not as well documented or understood (Ramsey, 1990). Based on annual analysis of Hg concentrations in age-0 yellow perch from Sand Point Lake during the 1990s, it appears that Hg levels are positively related to annual water level fluctuations (J. Sorensen, University of Minnesota-Duluth, personal communication). These preliminary data suggest that the reduction in water level fluctuations with the IJC's new rule curves could significantly reduce Hg accumulation in the biota of the reservoir system. A study has been initiated to test the fit of the current prediction and to determine which environmental variables, in combination, are the most reliable for predicting Hg concentrations in fish.

Studies have been conducted on the partitioning and bioavailability of Hg in the Park waters and other waters in northeastern Minnesota (Sorensen and others, 1990; Glass and others, 1992; Sorensen and others, 2001). Sorensen and others (1990) observed wide variation in Hg concentrations in the lake sediments, plankton, lake water, and standard sized (55 cm) northern pike from 80 northern Minnesota lakes. Through bioaccumulation, Hg concentrations increased from 2.5 ng/L in water to 88ng/L in zooplankton to 450 ng/g in adult northern pike (Sorensen and others, 1990). Similar patterns in biomagnification have been observed in the aquatic food webs in Kabetogama, Sand Point, Crane, and Rainy lakes (Glass and others, 1992; Sorensen and others, 2001). Hg concentrations in Rainy Lake increased from less than 20 ng/g (wet weight) in the lower trophic levels to between 30 and 90 ng/g in prey fish to 359 and 1114 ng/g in walleye and northern pike, the top level predators (Figure 39). Hg concentrations in the exotic rainbow smelt were similar to those in the native prey species and have apparently not caused an increase in concentrations in the major piscivores in Rainy Lake (Sorensen and others, 2001). In fact, Hg concentrations in standard sized northern pike and walleye in Rainy Lake in 1996 were significantly lower than values observed in previous years (Figure 40). In a recently completed study of over 50 lakes in northern Minnesota, similar decreases in Hg concentrations were observed in both walleye and northern pike in over 50% of the lakes (Glass and others, 1999). An explanation for these reductions is not readily apparent since monitoring has shown that wet Hg deposition in NE Minnesota continued to gradually rise during the 1990s (Glass and Sorensen, 1999; Berndt, 2002). It is conceivable that the effect of the increased deposition was mediated by deposition of other atmospheric contaminants (Engstrom and others, 1999), and in-lake processes, including water level fluctuations such as has been observed in Sand Point Lake.

Studies of Hg in birds in the Park have focused primarily on piscivorous species such as the common loon (Ensor and others, 1992; Evers and others, 1998), red-necked grebe, common merganser, hooded merganser (Zicus and others, 1988; Derr, 1995), and herring gull which composes a significant portion of the diet of some bald eagles in the Park (Giovengo, 1997). Blood, feather tissue, and in some instances eggs were analyzed in the majority of the species to assess the degree of Hg contamination. Adult birds typically contained significantly higher Hg concentrations than juveniles. Based on feather tissue analysis for adults, common loons contained significantly higher Hg concentrations than the other piscivorous species, in which Hg concentrations were similar (Derr, 1995; Evers and others, 1998). Hg concentrations from both adult and juvenile common loons from the Park were generally at the median of values from nine areas in

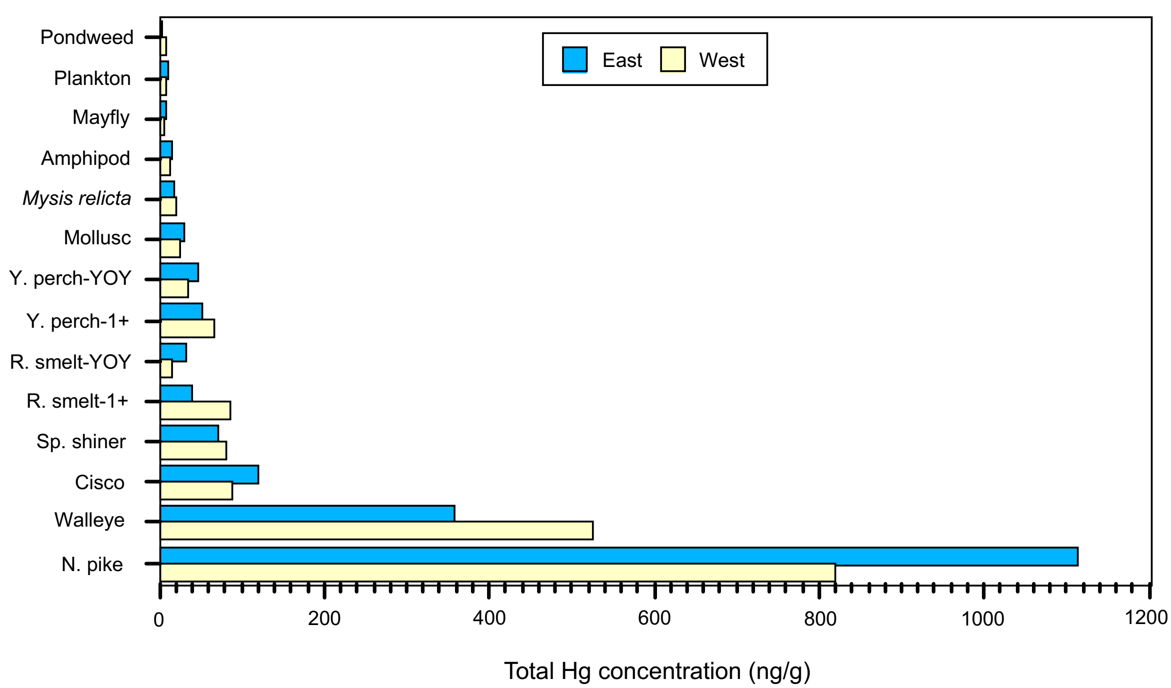



**Figure 39.** Mean total mercury concentrations in aquatic biota from east and west of Brule Narrows, Rainy Lake, 1996-97 (Sorensen and others 2001).

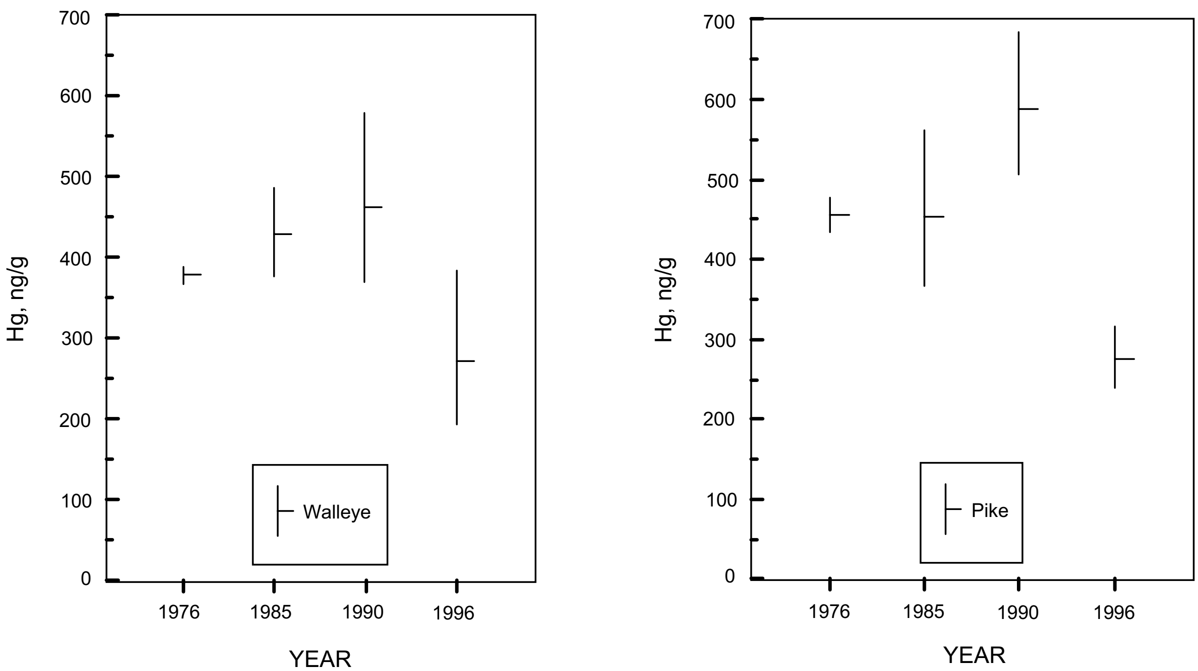



**Figure 40.** Comparison of mean total mercury concentrations (+SE) in standard sized walleye (39 cm) and northern pike (55 cm) from Rainy Lake, Minnesota, 1976-1996 (Sorensen and others 2001).

the Great Lakes region (Evers and others, 1998). Concentrations in the piscivorous species were higher than in common goldeneye, a non-piscivore species (Zicus and others, 1988; Derr, 1995).

Comparisons of Hg concentrations in herring gulls with those in the other piscivorous birds are limited to values obtained from eggs, since carcasses and livers were analyzed from adults and chicks rather than feathers and blood (Giovengo, 1997). Hg concentrations in eggs from 5 herring gull colonies at the Park were 0.10, 0.33, and 0.44 µg/g for Rainy Lake, 0.22 µg/g for Namakan Lake, and 0.25 µg/g for Kabetogama Lake (Giovengo, 1997). In comparison, Derr (1995) found mean Hg concentrations in eggs from common merganser, hooded merganser, red-necked grebe, and common goldeneye of 0.68, 0.50, 0.16, and 0.13 µg/g, respectively. A composite sample of common merganser eggs collected in the Park in 1989 had an Hg concentration of 0.36 µg/g (Ensor and others, 1993). Geometric mean Hg concentrations in eggs collected in 1981 in northern Minnesota from hooded merganser and common goldeneye were 0.45 and 0.11 µg/g, respectively (Zicus and others, 1988). Hg concentrations in herring gull chick carcasses (range 0.04 – 0.29 (µg/g) were significantly lower than in both the eggs and adult carcasses (Giovengo, 1997). Mean concentrations in herring gull adults from Rainy (2 sites), Namakan, and Kabetogama lakes were 1.91, 0.78, 0.46, and 0.71 µg/g, respectively (Giovengo, 1997).

Thus, elevated Hg levels have been observed in some of the Park's bird species, but it is unknown whether or not the populations are being adversely affected. While feather Hg concentrations in several of the species exceeded levels that have been shown to affect the reproductive success of mallards (Heinz, 1979), egg Hg concentrations were consistently below levels found to impair reproduction of other bird species (for example, Fimreite, 1971; Heinz, 1979). Derr (1995), because of these apparently contradictory results as well as some other confounding factors, concluded that the three target species she studied were probably not being impacted by current levels of Hg contamination. However, Derr (1995) did suggest that if Hg contamination continued to increase, Hg concentrations in the populations might ultimately reach effect thresholds. A similar situation appears to exist for common loons. To date, feather concentrations of Hg in common loons have not exceeded the 20 µg/g concentration considered to be the toxic effects threshold (Scheuhammer and Bond, 1991). However, the loon populations may be at risk from forage fish with Hg residues >0.3 µg/g, the concentration Barr (1986) associated with impaired loon reproduction. Hg residues of >0.3 µg/g in loon forage fish continue to be widespread in the Park (Sorensen and others, 1990; Glass and others, 1992; Sorensen and others, 2001). No studies have been conducted to determine if Hg exposure is affecting loon survival, reproduction or behavior.

High Hg residues also have been a concern for bald eagles because they prey extensively on fish and gulls, both of which are known to have elevated Hg residues. Eaglet breast feathers from VOYA contained a mean total Hg residue that was 2 to 6 times higher than residues in samples from the Great Lakes and from the Upper and Lower peninsulas of Michigan (Bowerman, 1993). Nest and foraging locations appeared to affect Hg uptake as the highest concentrations in both eaglets and fish were found in Sand Point Lake (Giovengo, 1997). Whether these elevated Hg residues are adversely affecting VOYA's eagles is unknown. Assessing the effects of Hg residues has been complicated by the presence of organochlorine compounds (Frenzel, 1985; Bowerman 1993). Information on additive or synergistic effects of organochlorines and Hg is sparse, thus, the effects of Hg on bald eagle reproduction cannot be stated with certainty (Grim and Kallemeyn, 1995). Conceivably, results from the contaminant analyses of eaglet samples collected from VOYA during the 1990s (W. W. Bowerman, Clemson University, personal communication) could provide additional information on the effects of Hg on eagle productivity. Preliminary results from this investigation showed that mean Hg concentrations declined in eaglet feathers from 20.2 µg/g in 1985-89 samples to 7.8 µg/g in 1999 samples (Bowerman, 2000). The results of these analyses could be supplemented with existing Hg data from fish that has been collected by other agencies during this period.

The river otter (*Lutra canadensis*) is the only mammal from the Park that has been tested for Hg contamination. Hg concentrations in fur samples from five otter from Kabetogama Lake ranged from 3.3 to 5.4 µg/g, while the range was 28 to 75 µg/g for six samples from Rainy Lake (Route and Peterson, 1988; Ensor and others, 1993). Thus, the fur samples seem to reflect the relative Hg concentrations in fish and other prey in the two lakes, even though the otter, particularly males, moved extensively between the large and small lakes in the Park (Route and Peterson, 1988). The Hg residues, particularly from Rainy Lake, significantly exceeded residues considered as normal in fur (1 – 5 µg/g) and from otter from industrialized portions of Wisconsin (Sheffy and St. Amant, 1982).

In addition to the surveys and studies of Hg in various components of the aquatic ecosystem, investigations have been conducted on mechanisms regulating Hg bioaccumulation in fish and of possible mitigation methods and strategies for reducing Hg contamination in lakes and rivers (Rapp and Glass, 1995; Austin, 1996). Sand Point Lake and the St. Louis River estuary of Lake Superior, both of which have significant Hg contamination in the aquatic food chain, were used for the field-testing. Ten littoral area enclosures (4 m X 10 m) were used in Sand Point Lake. Monitoring ambient Hg concentrations in biotic compartments in the enclosed areas and adjacent non-enclosed areas as a function of changed conditions and/or applied treatments to the enclosed area was used to develop and evaluate various hypotheses on the mechanistic pathways for Hg bioaccumulation. Ecosystem functions such as primary productivity, growth rate of top-level consumers, water quality, and Hg accumulation in biota were measured as endpoints. Hypotheses that were evaluated included (1) the effects of adding Hg chelators, precipitants, and absorbents, (2) the effects of adding micronutrients and bioactive organic carbon, and (3) alteration of the concentrations of bioaccumulative Hg from atmospheric wet deposition inputs, sediment diffusion, water column degassing, and changing demethylation rates.

Twenty-nine replicated pilot tests were conducted over four years at the two locations with the results being evaluated based on the hypotheses that Hg chemical activity was the controlling factor (Rapp and Glass, 1995). Micronutrient additions of selenite were found to significantly reduce Hg concentrations in age-0 yellow perch and black crappie. In the Sand Point Lake enclosures, Hg concentrations in the age-0 yellow perch were reduced by 72%. Addition of aquatic vegetation to the enclosures increased Hg concentrations in age-0 yellow perch and was a significant mechanism for transferring bioaccumulated Hg from one growing season to the next. This finding may prove to be especially important since it has been hypothesized that the 2000 IJC rule curves may result in significant changes in the aquatic vegetation, particularly in Namakan Reservoir.

Results of tests of various Hg binding agents, covering sediment with clean sand, water aeration, wet deposition changes, mesocosm isolation from ambient water, and water level and temperature variations were less conclusive. While findings from these treatments did provide some incite into bioaccumulation mechanisms and the assessment of possible mitigation alternatives, more specifically they indicated that the solution to the wide spread Hg problem is pollution prevention, through the reduction of Hg usage and emissions, rather than after-the-fact mitigation.

In comparison to the work that has been done with Hg, sampling for other contaminants has been relatively limited. Sampling was done in 1980 to determine water quality in the Park's large lakes with respect to established water-quality criteria (Payne, 1991). Concentrations of carbamate insecticides, chlorinated herbicides, organochlorine insecticides, organophosphorus insecticides, and triazine herbicides were within recommended limits except for one exceedence of the PCB criteria in Kabetogama Lake.

Other items that exceeded criteria in some of the 1980 samples included oil and grease, phenols, sulfide, and ammonia. Resampling in 1981, however, showed that concentrations for all of these including the PCBs in samples were within the recommended limits.

Contaminants other than Hg in fish from the Park waters, primarily the large lakes, are generally low with no discernable trends by lake (OMNR unpublished date 1985; MNDNR, 1994; Giovengo, 1997). Observed concentrations were typically below detection limits or within acceptable criteria levels. Based on hazard assessments conducted to determine the potential for adverse effects on bald eagles in Michigan (Giesy and others, 1995), fish collected from the Park did not have PCB or DDE concentrations high enough to pose a threat to the bald eagles (Giovengo, 1997). Contrarily, herring gulls, which are an important prey item of some bald eagles in the Park contained elevated concentrations of contaminant residues (Bowerman, 1993; Grim and Kallemeyn, 1995). A composite of seven herring gull eggs collected by Park personnel in 1989 contained the second highest concentration of organochlorines and PCBs observed in a survey of contaminants in several wildlife species in Minnesota (Ensor and others, 1993). Herring gulls collected in 1993 from several Park colonies also contained significantly higher concentrations of PCBs and DDE than did fish collected at the same time (Giovengo, 1997). This and elevated concentrations of PCBs in common merganser eggs collected in the Park at the same time caused Ensor and others (1993) to recommend that the effects of elevated contaminant residues in fish eating birds in the Park be investigated. Organochlorine residues in plasma from Park eaglets, which Giovengo (1997) attributed to the use of herring gulls as prey, were higher than in eaglets from other inland populations in the Great Lakes basin but were lower than residues in eaglets from the Great Lakes (Bowerman, 1993). Productivity and reproductive success of bald eagles from the Great Lakes and the Park were significantly less than that of bald eagles from the inland populations (Bowerman, 1993). Thus, even though PCB and DDT use ceased in North America, concentrations of the compounds apparently remained high enough to affect reproduction of bald eagles in the Great Lakes and the Park. Preliminary results from a comparison between 1987-92 and 1999 concentrations of these contaminants in eaglet plasma showed that a decrease had occurred (Bowerman, 2000). Mean concentrations of PCBs declined from 47 ng/g in 1987-92 to 2 ng/g in 1999 while mean concentrations of DDE declined from 20 ng/g to 6 ng/g during the same periods.

Whether chemical contamination is having a direct affect on the Park's herring gulls and other aquatic associated wildlife remains unknown. Although residues of PCB and DDE were low in common goldeneye and hooded merganser from northern Minnesota, there was evidence of eggshell thinning when compared to values for eggs prior to the use of DDT (Zicus and others, 1988). Eggshell thinning (up to 4% below a pre-1947 mean value) observed in two of five herring gull colonies in the Park (Giovengo, 1997) was well below the 15 – 20% level considered as critical (Keith and Gruchy, 1972). Ensor and others (1993) considered the elevated PCB levels they found in mink and river otter in their Minnesota survey to be a cause for concern. However, whether such levels occur in Park animals remains unknown since their sample did not contain animals from the Park.

**Future Needs and Opportunities:** Although there has been an extensive amount of research on Hg, it remains one of the most serious and scientifically challenging contaminant threats to the Park and Nation's aquatic resources (Krabbenhoft and Weiner, 1999). Because of the environmental threat it poses, particularly to human health via the consumption of contaminated fish, it remains a high research priority for the U.S. Geological Survey and other government agencies as well as the scientific community at large. The overall goal of a proposed research agenda for the U.S. Geological Survey is to provide scientific information needed by resource managers and environmental planners to identify and evaluate options for reducing exposure of humans and wildlife to this highly toxic metal (Krabbenhoft and Weiner, 1999).

The Park, because of existing historical and environmental information, has provided and should continue to provide opportunities for research that address both local and national information needs. For example, the Hg studies currently being conducted in the Park's interior lakes address some components of both the regional assessments and ecosystem investigations segments of the proposed U.S. Geological Survey research program. This multidisciplinary effort is attempting to identify and interpret how lake chemistry and watershed features influence aquatic Hg cycling and fish-Hg residues in the Park's interior lakes. The objective of one portion of the study is to determine the influence of trophic structure on Hg concentrations in northern pike. The recently initiated study to assess the effect of changes in reservoir management on Hg accumulation in fish and other components of the aquatic ecosystem may also provide information of both local and international importance. Another ecosystem-related study relative to Hg in the Park would involve determining the impact of forest fires, both prescribed and wild, on the movement of Hg within a watershed. Such a study could prove to be extremely valuable since it would not only deal with the aquatic system but would also provide information on Hg in the Park's terrestrial environment about which we currently know very little.

The Park also could contribute to the wildlife exposure and effects component of the U.S. Geological Survey's proposed research program by serving as a field site for assessing the toxicological significance of methyl-Hg exposure to fish-eating wildlife. Past work has shown that in addition to fish some wildlife species in the Park are accumulating significant quantities of Hg, but whether the accumulation is affecting the individuals or populations remains unknown. Field studies are needed to determine the effects of Hg on wildlife species, particularly in regard to effects on reproduction, which is the most sensitive biological endpoint. Additionally, the effect on fish reproduction, which is basically an unknown (Wiener and Spry, 1996; Hammerschmidt and others, 2002), need to be determined. Studies should also be conducted that include species that prey on aquatic organisms such as emerging aquatic insects and crayfish, which may contain significant quantities of Hg (Headon and others, 1996; Tremblay and others, 1996; Tremblay and Lucotte, 1997). For this assessment to be successful, a more thorough analysis of Hg residues in the Park's predator and prey communities will be necessary since our current knowledge is limited to a relatively few species. An assessment of Hg residues in aquatic insects will need to include both detritivores-grazers (dipterans, ephemeropterans, trichopterans) and predators (heteropterans, coleopterans, odonates) since the latter group typically have higher Hg concentrations due to their feeding habits (Tremblay and others, 1996). Results of these analyses could then be used to assess the relationship between local sediment contamination and the transfer of contaminants from the sediments into the aquatic insects and subsequently into the terrestrial food web (Custer and others, 1998). Cavity nesting birds, particularly tree swallows (*Tachycineta bicolor*), which prey on aquatic insects, are frequently used as indicators of local contamination (Custer and others, 2001).

Given the scale of the Park's Hg problem, monitoring of atmospheric deposition of Hg should be reinstated as part of the Park's regular air quality monitoring program. Regular monitoring of Hg residues in fish also is needed to provide timely and if necessary accurate consumption advisories. The monitoring data could prove extremely valuable when incorporated into some of the previously suggested studies.

Surveys to determine current levels of contaminants other than Hg are needed since most of the existing data is more than a decade old. The analysis of the backlog of plasma samples from bald eagles will provide an assessment of long-term trends in contaminant levels. Also, analysis of these samples may provide an indication of changes in contaminant residues in the prey base since concentrations in the eaglets reflect local inputs. Similar long-term analyses should be done for other species known to accumulate organochlorines and other contaminants.

## Paleoecology/Climate Change

Paleoecological analyses of a 713 cm sediment core collected in 1993 from the Park's Cayou Lake provide a chronology of ice sheet recession and advance, the formation of the regional proglacial lakes, and late-glacial and Holocene vegetation and limnological changes at the site (Winkler and Sandford, 1998a, b). Cayou Lake, which is located about 1 km south of Quill Lake and drains into Kabetogama Lake, has a radiocarbon-date of 10,620 + 180 years before present (BP) based on the basal organic sediments. The dry-mass sedimentation rate for the 20$^{th}$ century for Cayou Lake was 0.34 kg/m$^2$/year, which although higher than the 0.08 to 0.21 range recorded for five other Park lakes, was within the range of normal variation observed in a regional group of lakes (D. R. Engstrom, University of Minnesota, personal communication). The lake was inundated by Glacial Lake Agassiz during the Emerson Phase (about 9,900 BP).

Climatic reconstructions based on pollen assemblages from the start of the 10,620 ± 180 year period covered by the Cayou Lake core showed that January, July, and annual temperatures increased, becoming warmest and driest just before 6,000 (BP) (Davis and others, 2000). At that time, January and annual temperatures were 2.0 °C and 1.5 °C warmer than the predicted modern values, while precipitation reached its Holocene minimum. After 6,000 BP, the climate at VOYA became more moist and cool with temperatures gradually declining to their current values. Modern precipitation values were reached by 4000 BP.

The pollen analysis indicated that the vegetation changed from an initial cold and dry spruce-popular parkland (10,620 BP) to an even colder steppe landscape of very sparse spruce trees and scrub willow around 10,000 BP (Winkler and Sanford, 1998b). Following the retreat of Glacial Lake Agassiz, a boreal forest of spruce, jack pine, alder, and willow surrounded Cayou Lake. By 9,000 BP, this forest was replaced by a northern-conifer/hardwood forest dominated by jack and red pine. White pine did not become an important component of the forest until about 6,200 BP. From 4,000 BP up until recent logging, the pines persisted and spruce, fir, tamarack, cedar, and sphagnum bog increased. Swain (1981), using sediment cores from Cruiser and Little Trout lakes, identified a similar forest composition for the last 1,000 years. Charcoal peaks observed in the three lakes suggest that fires were important in accelerating some of the vegetation changes (Swain, 1981; Winkler and Sanford, 1998b).

Detailed analyses by Winkler and Sanford (1998b) of diatoms and cladocerans provided evidence of changes in limnological conditions in Cayou Lake, particularly as Glacial Lake Agassiz expanded into the site. They found that during that period, the diatom community was dominated by a distinctive association, which today is found only in high Arctic lakes and in newly formed proglacial and ice-recessional lakes near Glacier Bay, Alaska. The presence of this group suggests the lake was probably more alkaline than at any other time. Changes in the algal community following the recession of Glacial Lake Agassiz indicated that while there were changes in the lake's trophic status, the lake remained relatively alkaline and nutrient rich up until 4,000 BP. In response to the cooler and wetter climate, the diatom flora increasingly was dominated by species that could tolerate the more acidic conditions in the lake. Based on the last 110 years of the sediment core, the advent of logging early in the 20th century was accompanied by an increase in diatoms that are found more often in nutrient-rich water. Since 1930, however, the lake has again become more acidic and there have been significant changes in the diatom community. Despite having been protected within the Park since 1971, diatom changes have continued to occur, suggesting that atmospheric inputs of industrial elements and acids are affecting the lake's chemistry and biota (Winkler and Sanford, 1998b).

Winkler and Sanford (1998b) also provided detailed incite into the changes in Cayou Lake's biotic community through their analysis of the cladocera. Changes in species composition, size within particular species, and body morphology of cladocerans can all serve as indicators of changes in the invertebrate and vertebrate predators that feed on them. Changes observed in the cladocerans suggest that until Glacial Lake Agassiz inundated Cayou Lake only invertebrate predators were present. With that inundation, however, coldwater fish such as whitefish and lake trout probably entered the lake and preyed on the invertebrate predators. During the mid-Holocene warm period, new limnetic cladocerans invaded the lake and a shift occurred in the body morphology of one species that indicated a higher level of fish zooplanktivory, presumably by recent fish invaders such as yellow perch and cyprinids. About 4,000 BP as the climate cooled, a new cladocerans assemblage became dominant that is typical of an assemblage that occurs when the major fish predators are yellow perch and minnows, the dominant fish species in Cayou Lake. While the latter assemblage has continued to be predominant, two cladoceran species have disappeared in the last 20 years. While the cause of these disappearances is unknown, they are reminiscent of the intermittent recruitment success of these species in the mid-Holocene warm period.

Based on their analyses of historic climate changes at VOYA and parks located along the shores of the Great Lakes, Davis and others (2000) concluded that greenhouse gas-induced temperature changes would be more extreme at VOYA and other sites distant from the Great Lakes. Predicted increases in temperature (1 – 2 °C) and decreases in summer soil moisture (2-4 cm) (Kattenburg and others, 1996), suggest that the mid-Holocene period may serve as an analog for future warming (Davis and others, 2000). Winkler and Sanford (1998a) provided some predictions on what may result if the climate change produces warm and dry conditions similar to what occurred in the mid-Holocene. Terrestrially, they projected the forests would become more open and eventually prairie would expand near the Park. If the warming were accompanied by more moisture there would be increased growth of deciduous trees on the uplands and alder and other trees and shrubs in the Park's wetlands. Production of nitrogen by alder will stimulate growth of aquatic plants and algae, thereby increasing the sedimentation rate in lakes and ponds. Consequently, lakes will fill in faster and become shallower, and the character of the Park's wetlands will be altered. Winkler and Sanford (1998a) also predicted that despite their relative remoteness and their location in a national park, the lake's biological and chemical characteristics would likely continue to be altered by local, regional and extra-regional anthropogenic activities.

In addition to these relatively site-specific predictions, there are numerous other reports and papers that provide pertinent predictions on the potential effects of global climate change on aquatic habitats and organisms (Regier and others, 1990; McKnight and others, 1996; Schindler, 1998a; Stefan and others, 2001; McGinn, 2002). These sources indicate that responses of boreal lakes such as those in VOYA will involve complex interactions between the effects of climate on temperature, hydrology, lake catchments, and in-lake processes. Modeling results suggest that epilimnetic temperatures will increase, particularly in early spring and fall, and there will be longer periods of anoxia in the hypolimnion (Stefan and others, 1996). Warming will have a negative impact on coldwater fish in northern lakes such as those in VOYA (Stefan and others, 2001). Conversely, conditions for warmwater species will improve. Conceivably such changes in the Park lakes will benefit non-native warmwater species such as largemouth bass while adversely affecting native cool- and coldwater species. Based on paleolimnological records as well as recent research and modeling results, changes in physical conditions forced by climate change also can be expected to alter other components of the biotic communities in the Park's aquatic ecosystem (De Stasio and others, 1996; Winkler and Sanford, 1998b).

**Future Needs and Opportunities:** While the Park's aquatic ecosystem is not immune to the effects of climate change and some other anthropogenically induced alterations, it and in particular it's small, interior lakes is relatively lightly affected compared to other waters in the region. Because of this, it provides an opportunity for an assessment of both past and future change. Further paleolimnological studies could provide data on long-term patterns of diverse components of the ecosystem at a diversity of spatial and temporal scales, which subsequently could be used to pose questions about climatic, terrestrial, and limnological processes (Fritz, 1996). Paleolimnological techniques could be used to gain a more thorough understanding of the scale, timing, and effects of Glacial Lake Agassiz on the Park's water resources. More specifically, analyses of sediment cores from the Park's large lakes could conceivably provide a better understanding of changes in limnological conditions and biotic communities resulting from their conversion from natural lakes to dam-controlled impoundments. On Rainy Lake, the sediment layer resulting from the Steep Rock mine breakout into the Seine River in May of 1951 could serve as a known reference point in ageing the sediments. Paleolimnological analyses might also be used to assess the effect on the invertebrate community of the introduction of largemouth bass into Quill and Loiten lakes since previously no large piscivore had been present in the lakes.

## Conclusion

The Park's large lakes, even though they are designated as "Outstanding Resource Value Waters" by the state of Minnesota (MPCA, Ch. 7050.0180), continue to be threatened by a variety of anthropogenic factors. As some of the proceeding information has shown, the Park's water resources have been and continue to be directly affected by fishing, reservoir operations, invasions and introductions of non-native species, and inputs of persistent contaminants. Like other boreal waters and landscapes (Schindler, 1998a; 1998b), the Park's resources are also likely being exposed to stressors such as climate warming, acidic precipitation, and stratospheric ozone depletion. Although logging and mining within the Park boundary ceased with its authorization in 1971, logging and mining may contribute to Park water quality problems as long as they are actively pursued within the Rainy Lake drainage (Weeks and Andrascik, 1998). Wood deposits from the earlier logging era may still be affecting water quality in Hoist Bay in Namakan Lake. Other potential threats to water quality include emissions from outboard motors and snowmobiles and human wastewater discharges from both inside and outside of the Park. Recreational home development within the watershed, particularly in areas adjoining the Park, disturbs riparian areas and likely increases nutrient inputs. Lakeshore development has resulted in a significant reduction in littoral vegetation in some parts of Minnesota (Radomski and Goeman, 2001). Because of important interactions that occur between some of these stressors, they cannot be treated in isolation (Schindler, 1998b).

Although numerous studies and surveys have been done that addressed some of these issues, as the previously presented future needs and opportunity sections suggest many questions still need to be answered if the USNPS is to "understand, maintain, restore, and protect the inherent integrity of the natural resources, processes, systems, and values of the Park" (USNPS, 2001). Because of the sporadic and uneven nature of much of the work that has been done, we have limited knowledge of temporal and spatial variation in water quality and biological communities; species occurrences and distributions, particularly for lower trophic levels; biotic interactions; and functions and processes. Interior lakes, beaver ponds, and other aquatic habitats, which are integral components of the Park's aquatic ecosystem, need to receive more attention, particularly those lakes receiving more use as a result of the Park's boats on interior lakes program. This and additional information on the "natural" backgound values for the Park's water resources will be needed to detect whether changes are natural or human-induced and if the latter, whether intervention is necessary. To separate anthropogenically induced change from natural variation will require an **aggressive, long-term commitment** to qualitative and quantitative scientific observation (Stottlemyer, 1987). Such data is invaluable for detecting environmental trends or events and for putting the present into perspective (Stow and others, 1998). Hopefully, implementation of the USNPS's new Park Vital Signs Monitoring program will result in more consistent support than has been available to date.

As suggested previously, Park management needs to develop a plan that identifies goals and objectives for the long-term management of fish and aquatic resources within VOYA. Obviously, one of those goals must be the development and implementation of a monitoring plan that addresses both the biotic and abiotic components of the Park's aquatic ecosystem. An integrated monitoring plan that focuses on providing an understanding of the complex network of physical, chemical, and biological factors that influence

**Table 12.** Parameters that should be incorporated in an integrated monitoring program of Voyageurs National Park's aquatic ecosystem. For the Biota group, X represents monitoring of species richness and relative abundance/biomass while XXX would also include more detailed monitoring of life history and population parameters, areal coverage, and for fish, exploitation.

| *Monitoring Parameters* | *Interior Lakes* | *Large Lakes* | *Wetlands Beaver ponds* | *Streams* |
|---|---|---|---|---|
| **Climate** | | | | |
| --Temperature | X | X | X | X |
| --Precipitation | X | X | X | X |
| --Wind | X | X | X | X |
| --Solar radiation | X | X | X | X |
| --Snow cover | X | X | X | X |
| **Atmospheric Deposition** | | | | |
| --Ozone | X | X | X | X |
| --Nutrients | X | X | X | X |
| --pH | X | X | X | X |
| --$SO_4$ | X | X | X | X |
| --Contaminants | X | X | X | X |
| **Physical Attributes** | | | | |
| --Hydrology | X | X | X | X |
| --Tributary inflows | X | X | | |
| --Discharge | X | X | | X |
| --Retention time | X | X | | |
| --Water level fluctuations (magnitude/timing) | X | X | X | |
| --Water source (ground water/surface flow) | X | X | X | X |
| --Ice formation/cover | X | X | | |
| --Ice scour | | X | | X |
| --Substrate type (littoral, profundal, soil) | X | X | X | X |
| --Large woody debris | X | | X | X |
| --Areal coverage | X | X | X | |
| --Nutrient supply | X | X | X | X |
| --Beaver dam numbers and condition | X | | X | X |
| **Water Quality** | | | | |
| --Temperature | X | X | X | X |
| --Transparency | X | X | X | X |
| --Dissolved oxygen | X | X | X | X |
| --Conductivity | X | X | X | X |
| --Acid neutralizing capacity | X | X | X | X |
| --Nutrients (TP, TN) | X | X | X | X |
| --Calcium, Sulfate | X | X | X | X |
| --pH | X | X | X | X |
| --Chlorophyll-*a* | X | X | X | |
| --Contaminants | X | X | | |
| --Coliform bacteria | X | X | | |
| **Biota** | | | | |
| --Macrophytes | X | XXX | XXX | |
| --Phytoplankton/sessile algae | XXX | XXX | XXX | XXX |
| --Zooplankton | X | XXX | | |
| --Zoobenthos | X | XXX | XXX | XXX |
| --Amphibians | X | X | XXX | X |
| --Fish | XXX | XXX | X | X |
| --Aquatic birds/furbearers | X | XXX | XXX | X |
| --Exotic/rare species | X | X | XXX | X |

aquatic systems is needed so that observed changes can be understood and explained and the potential for future changes can be predicted (Table 12; Hunsaker and Carpenter, 1990; Hicks and Brydges, 1994). The monitoring program should provide information that can be used to address issues such as biological integrity, the non-degradation of water quality from both local and more widespread stressors, the IJC 2000 rule curve changes, and changes in fish and other biotic communities. The Park's monitoring efforts should as much as possible complement existing programs being conducted by the MNDNR, OMNR, and other parties. Provisions need to be made for peripheral programs that can be used to identify causes of the changes that have been detected.

Although they are not necessarily pristine, water resources within national parks such as those within VOYA, because of their relatively protected status, are ideal locations for the establishment of long-term monitoring programs. Such programs can, if properly designed, not only identify changes that have occurred but can also provide context for determining impacts and ecological processes (Hermann and Stottlemyer, 1991). VOYA's interior lakes, because they and their watersheds lie entirely within the Park, would be excellent locations for long-term monitoring. Although monitoring should be done on all the interior lakes, Locator, Mukooda, Cruiser, Shoepack, and Loiten lakes would be logical choices for intensive monitoring because of the results that are available from past monitoring efforts (Webster and others, 1993; Whitman and others, 2002). Sampling on these lakes should be done annually while the remaining interior lakes could be broken into groups of 5 or 6, with each group sampled every four to five years. Sampling should be done at least three times during the open water season based on the degree of seasonal variation observed in the previous surveys. Physical-chemical conditions should be monitored along with phytoplankton, zooplankton, benthic macroinvertebrates, amphibians, and fish (Table 12). Aquatic vegetation composition, distribution, and abundance should be assessed every four to five years.

Annual monitoring of the large lakes will be necessary if the Park wishes to assess the effects of the landscape level changes occurring in the drainage basin, including changes resulting from the 2000 rule curves. Fortunately, the monitoring of climatological and hydrological parameters is already being done by other agencies. Monitoring a variety of taxa and different ecological parameters will improve or lend more weight to the overall assessments findings and will provide a broader, ecosystem perspective of the fish community and fishery (Table 12; Karr 1994). It is essential, given the importance of the fishery, that the MNDNR's large lake program be maintained and where possible, improved upon through the use of randomized sampling designs in all principle habitats. Creel surveys should be done annually on all the large lakes.

Remote sensing, including satellite imagery analysis, can be an important complement to the ground-based monitoring programs that have traditionally been used in the Park (Kloiber and others, 2002). Remote sensing procedures can be used to assess landscape scale changes in aquatic vegetative cover in the large lakes and also the wetlands associated with the Park's numerous beaver ponds. The procedures can also be used to monitor ice cover duration (Magnuson and others, 2000), chlorophyll concentrations and water transparency (Stadelmann and others, 2001; Kloiber and others, 2002), and land use changes in the watershed that may affect the Park's water quality.

In developing monitoring plans, VOYA must not ignore or forget the large body of knowledge and understanding that already exists (Minns and others, 1996). Many of the sampling and monitoring protocols that have been developed by other agencies (USEPA-Environmental Monitoring and Assessment Program; USGS-National Water-Quality Assessment, and Biomonitoring of Environmental Status and Trends; Canadian Department of Fisheries and Oceans-Experimental Lakes Area, National Science Foundation-North Temperate Lakes, Long-term Ecological Research program; MNPCA-Lake Assessment Program) could be used in designing a monitoring plan for the Park. In recent years, efforts by many resource management agencies and ecological societies to develop a scientific basis for ecological monitoring and trend detection have resulted in numerous publications and books that Park staff could use for guidance (for example, Moore and Thornton, 1988; Busch and Sly, 1992; Loeb and Spacie, 1994; Dixon and others, 1998; Simon, 1999).

Lastly, because of the Park's hydrologically complex and politically sensitive environment, another component that will be critical to the success or failure of the Park's efforts to protect and manage its water resources will be its ability to successfully interact with other jurisdictions, agencies, and personnel in the watershed. Effective communication will be needed to overcome conflicting values and objectives and to establish common goals for protecting the watershed and the Park's water resources.

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12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*) Voyageurs National Park (VOYA) in northern Minnesota contains significant aquatic resources, including 30 lakes and numerous wetlands. This synthesis contains an integrated account of what is known about the aquatic resources of VOYA; compares VOYA resources to those of other areas; and identifies opportunities and needs for future studies and surveys. Surveys and studies in VOYA have identified fifty-four fish species from 16 families, 820 vascular plant species, and 7 amphibian and 3 reptile species (higher numbers probably occur). Estimates of relative abundance for phyto- and zooplankton vary among VOYA lakes and depths surveyed. The VOYA fish populations and communities have been the most intensively studied. Twenty-eight percent of VOYA wetlands are the result of beaver activity. Mercury contamination and its' food-chain bioaccumulation in VOYA are of particular concern. An integrated monitoring plan is needed in VOYA to provide continuous data and information on the complex physical, chemical, and biological factors that influence aquatic systems. Resource managers in VOYA will use this information to understand and explain observed changes and to predict the potential for future changes.

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