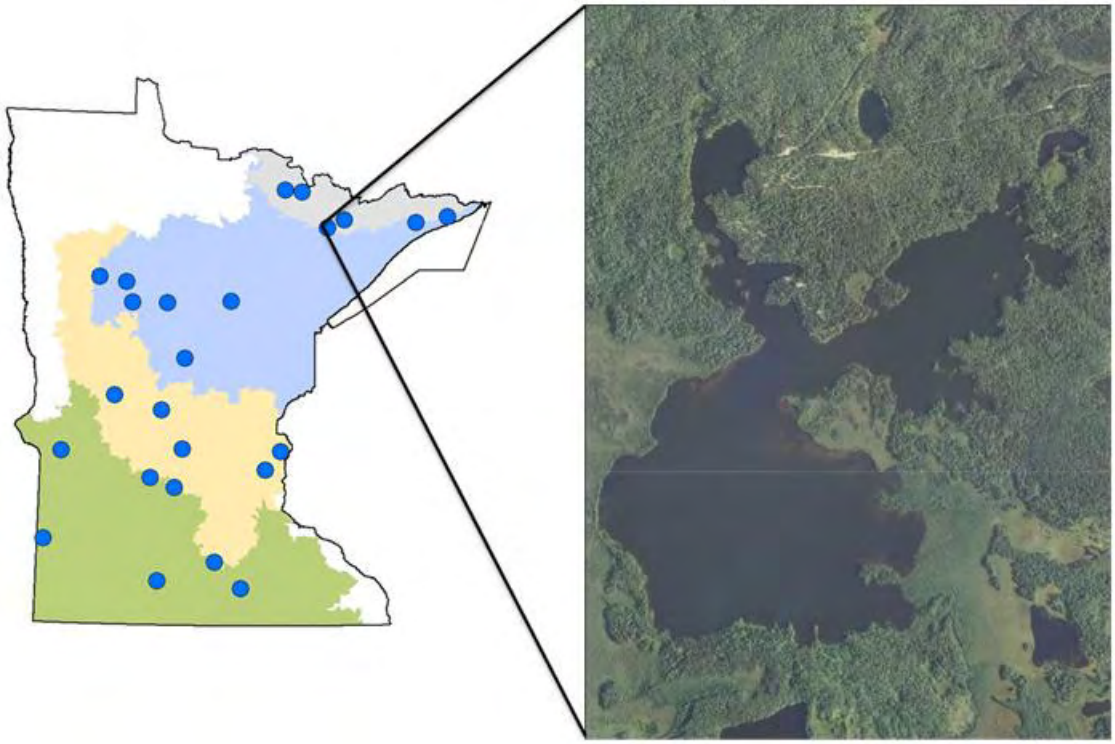
Sentinel Lake Assessment Report
Bear Head Lake (69-0254)
Saint Louis County, Minnesota



Minnesota Pollution Control Agency
Water Monitoring Section
Lakes and Streams Monitoring Unit
&
Minnesota Department of Natural Resources
Section of Fisheries

January, 2012

Minnesota Pollution Control Agency
520 Lafayette Road North
Saint Paul, MN 55155-4194
http://www.pca.state.mn.us
651-296-6300 or 800-657-3864 toll free
TTY 651-282-5332 or 800-657-3864 toll free
Available in alternative formats

Minnesota Pollution Control Agency

Minnesota
DEPARTMENT OF NATURAL RESOURCES

Contributing Authors

Jesse Anderson, MPCA
Ray Valley, Don Klick, MDNR

Editing

Steve Heiskary and Dana Vanderbosch, MPCA
Peter Jacobson MDNR

Sampling

Jesse Anderson, Brittany Story, Alex Jackson, Don Carlson, Andrew Streitz, Matt Lindon, Dereck Richter, Mike Kennedy - MPCA
Jen Westlund, Joe Mirau, Mike Tezak, Matt Klesser, Mark Panstar, Jody Popesh, Bear Head Lake State Park - MDNR
Don Klick, Doug Thompson, Duane Williams, Ray Valley, Ethan Karppinen, Cindy Tomcko, Rod Pierce, Kim Strand, Shannon McNamara - MDNR
Anne Tim (USFS)

2008-10 Lake Assessment of Bear Head Lake (69-0254) Saint Louis County, Minnesota
Minnesota Pollution Control Agency
Water Monitoring Section
Lakes and Streams Monitoring Unit
&
Minnesota Department of Natural Resources
Section of Fisheries

wq-2slice69-0254

The MPCA is reducing printing and mailing costs by using the Internet to distribute reports and information to wider audience. For additional information, see the website:
www.pca.state.mn.us/water/lakereport.html

This report was printed on recycled paper manufactured without the use of elemental chlorine (cover: 100% post-consumer; body: 100% post-consumer)

Contents

List of Tables ii
List of Figures iii
Executive Summary 1
Introduction 4
History 4
Background 5
  Lake Morphometric and Watershed Characteristics 5
  Precipitation and Climate Summary 10
Methods 12
  Fisheries and Aquatic Plants 12
Results and Discussion 13
  Fisheries Assessment 13
  Aquatic Plant Assessment 21
  Water Quality 27
  Zooplankton 35
Trophic Status Trends 40
Modeling 41
303(d) Assessment and Goal Setting 44
References 45
Appendix A 47

List of Tables

Table 1. Bear Head Lake and watershed morphometric characteristics..... 5
Table 2. Bear Head Lake watershed ecoregion land use comparison..... 9
Table 3. Fish species captured during past fisheries surveys in Bear Head Lake. 17
Table 4. Bear Head Lake fish stocking history 17
Table 5. Common species observed during previous transect surveys..... 24
Table 6. Percent frequency of occurrence of aquatic plant species 25
Table 7. Bear Head Lake 2008-2010 summer- mean water quality data. 27
Table 8. Bear Head Lake cation, anion, and total organic carbon measurements..... 27
Table 9. Summary of 2008-2010 Bear Head Lake temperature data..... 28
Table 10. 2008 zooplankton data from all Sentinel lakes..... 37
Table 11. MINLEAP model results for Bear Head Lake 43
Table 12. BATHTUB model results for Bear Head Lake 43
Table 13. Eutrophication standards by ecoregion and lake type 44

List of Figures

Figure 1. MDNR map of Sentinel lakes and major land types 3
Figure 2. Bear Head Lake watershed 6
Figure 3. Bear Head Lake watershed land use 7
Figure 4. Bear Head lake depth contours 7
Figure 5. Minnesota ecoregions as mapped by EPA 8
Figure 6. Bear Head Lake level elevations in 2008 and 2010; MDNR data 9
Figure 7. 2008 monitoring season rainfall based on records for Babbitt, MN 10
Figure 8. 2009 monitoring season rainfall based on records for Babbitt, MN 10
Figure 9. 2008-2009 Minnesota water year precipitation and departure from normal 11
Figure 10. Historical catch per unit effort of the major fish species 18
Figure 11. Length frequency histogram of walleye captured. 19
Figure 12. Length at age of major game fish species in Bear Head Lake 20
Figure 13. Length frequency histogram of northern pike captured. 21
Figure 14. Cover of aquatic vegetation in Bear Head Lake 22
Figure 15. Number of aquatic plant species surveyed. 23
Figure 16. 2008 and 2010 Bear Head Lake average daily water temperatures 28
Figure 17. 2008 Bear Head Lake dissolved oxygen and temperature profiles 29
Figure 18. Bear Head Lake 2008-10 spring, summer, and fall temperature profiles 30
Figure 19. Bear Head Lake 2008-10 total phosphorus, chlorophyll-a and Secchi depth 32
Figure 20. 2008-10 average Bear Head Lake total phosphorus concentrations 33
Figure 21. 2008-2010 monthly comparisons of total phosphorus concentrations 33
Figure 22. Algal composition for Bear Head Lake in 2008 34
Figure 23. Algal composition for Bear Head Lake in 2009 34
Figure 24. Mean monthly zooplankton densities and biomass 36
Figure 25. Zooplankton biomass and density in Bear Head Lake, 2008-2010 38
Figure 26. Cladoceran and copepod counts in Bear Head Lake, 2008-2010 39
Figure 27. Bear Head Lake TSI values from 2008-2010 40

Executive Summary

The Minnesota Pollution Control Agency (MPCA) is working in partnership with the Minnesota Department of Natural Resources (MDNR) on the Sustaining Lakes in a Changing Environment (SLICE) Sentinel Lakes Program. The focus of this interdisciplinary effort is to improve understanding of how major drivers of change such as development, agriculture, climate change, and invasive species can affect lake habitats and fish populations, and to develop a long-term strategy to collect the necessary information to detect undesirable changes in Minnesota Lakes (Valley 2009). To increase our ability to predict the consequences of land cover and climate change on lake habitats, SLICE utilizes intensive lake monitoring strategies on a wide range of representative Minnesota lakes. This includes analyzing relevant land cover and land use, identifying climate stressors, and monitoring the effects on the lake's habitat and biological communities.

The Sentinel Lakes Program has selected 24 lakes for long-term intensive lake monitoring (Figure 1). The "deep" lakes typically stratify during the summer months. "Shallow" lakes are defined as mixing continuously throughout the summer. "Cold Water" lakes are defined as lakes that either harbor cisco, lake whitefish, or lake trout and are the focus of research funded by the Environment and Natural Resources Trust Fund (ENTF). "Super sentinel" lakes also harbor cold-water fish populations and research on these lakes is also funded by the ENTF.

Bear Head Lake is located in St. Louis County within the Kawishiwi River watershed (Figure 2), part of the Rainy River basin. Bear Head Lake is located approximately 10 miles east of Tower, MN, within Bear Head Lake State Park. The entire shoreline of Bear Head Lake, and most of its watershed, is included within the State Park. Bear Head is a moderately deep lake and the water column routinely stratifies by late spring. Bear Head is a seepage lake and therefore has no surface water inlets or outlets. The lake is surrounded by primarily coniferous forested land. In 2008-2010 water quality data on Bear Head Lake were collected by the MPCA and State Park staff. MPCA staff sampled Bear Head monthly from May through October in 2008-2009 and 'seasonally' – May, July, and October - in 2010.

Bear Head Lake supports a relatively simple fish community. The fish community is mostly composed of cool-water species such as walleye, northern pike, yellow perch, and white sucker. Statistically, each of these populations do not show significant trends in any direction over the whole data record; however, in the last two decades white sucker have been trending downward; while the abundance of northern pike and other warm water species such as bluegill and black crappie have been trending upward. Electrofishing results during 2008 and 2011 also show a significant largemouth bass population in the lake. This mirrors statewide trends in these species. Warm water fish species have been increasing over time in northeast Minnesota lakes due presumably in part to warming water temperatures. Continued warming will affect the composition of Bear Head's fishery with continued increases in warm water species, such as sunfish and bass likely. Significant increases in warm water species could result in eventual declines in cool-water species including walleye, white sucker, and yellow perch.

Still, at this time, size and age structure of most major game species in Bear Head Lake appears balanced with a relatively large number of large, old individuals in each population. Despite little quantitative information on angler harvest, size and age indicators suggest low to modest levels of angler harvest.

Enhancing the resilience of Bear Head's fish community will require fisheries management that seeks to maintain a balance of predator and prey communities under changing lake thermal regimes and angler harvest patterns.

Epilimnetic dissolved oxygen (DO) concentrations exceeded 5 milligrams per liter throughout the 2008 field season, at concentrations needed to sustain a productive cool and warm water fishery. The hypolimnion started becoming anoxic in early July, and DO concentrations reached their minimum in the water column, at a depth of 6 meters (m) (20 feet), in mid-August. Hypoxic conditions started to decline by early September, coinciding with cooling water temperatures, wind mixing, and the change in seasons.

Total phosphorus (TP) concentrations did not change significantly between years, averaging 13 micrograms per liter (µg/L) in 2008, 14 µg/L in 2009, and 15 µg/L in 2010. Likewise, changes in concentration from spring through fall were minimal as well. Chlorophyll-*a* (chl-*a*) concentrations provide an estimate of the amount of algal production in a lake. During 2008-10, chl-*a* levels were moderate in Bear Head and indicated mesotrophic conditions. Secchi disk transparency averaged 3.0 m from 2008-10. Bear Head has a slight bog stain originating from incompletely dissolved organic matter arising from forest and wetland runoff. At high concentrations "bog stain" may limit transparency; however at the modest concentrations observed in Bear Head its impact is rather minimal and transparency is highly correlated with algal productivity. The low alkalinity and ion concentrations indicate Bear Head has very soft water. This is a function of the thin soils, exposed bedrock and minimal amounts of carbonate in the soils and parent material. Collectively, these data indicate that Bear Head has excellent water quality.

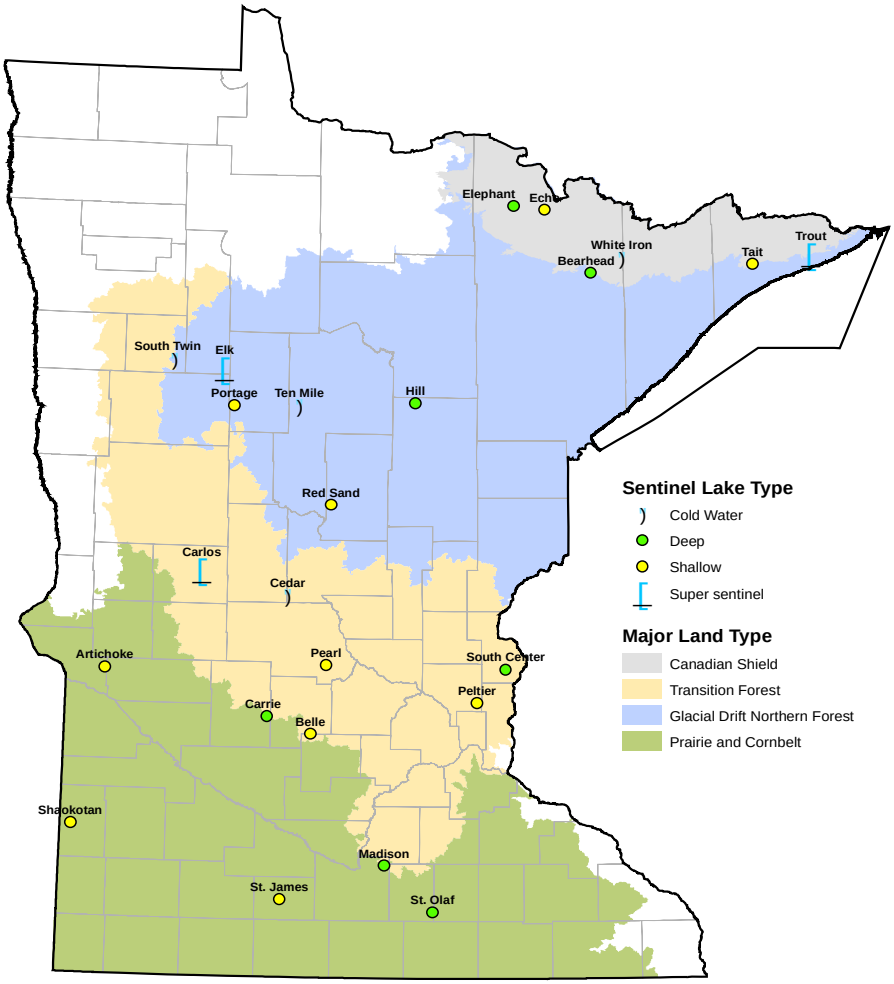
Various algal forms were evident from spring through fall; however, blue green algae were dominant in late summer in 2008 and 2009, which is normal for mesotrophic lakes. Chlorophyll-*a* concentrations were low, however, and nuisance levels of blue greens were not observed. The zooplankton community over the three year period of record was dominated by copepods. Zooplankton density tended to be highest in the spring, and slowly declined throughout the season. Zooplankton density and biomass were very low in Bear Head compared to other Sentinel lakes in the region. A possible explanation for the low densities and biomass could be predation by sunfish and other planktivorous fish. *Daphnia* zooplankton are a key driver for maintaining clear-water regimes in lakes and overgrazing by overly abundant planktivore fish can impair the resilience of lakes. This heightens the importance of managing for a balanced food-web in Bear Head Lake.

Two empirical water quality models, BATHTUB and MINLEAP, were run on Bear Head Lake using data from 2008-2010. MINLEAP predicts a TP loading rate of about 116 kilograms (kg) per year entering Bear Head Lake from its small forested watershed. The model predicts approximately 65 percent of the TP will be retained in the lake, a reasonable estimate given the lake's small watershed, volume, and relatively long residence time (estimated at ~ 4 years). The BATHTUB model provides a further basis for estimating water and nutrient budgets for Bear Head Lake using a combination of runoff and TP export coefficients based on land use in the watershed. Because groundwater cannot be modeled with BATHTUB, and no streams enter the lake, modeled sources of TP to the lake were minimal and included wet and dry atmospheric deposition, and direct runoff to the lake from the surrounding forests and wetlands. Human-caused sources of TP to the lake, such as wastewater, were estimated only for the park's two restroom / shower buildings, since the waste is treated with an on-site septic system. BATHTUB estimated an annual TP load to Bear Head Lake of 135 kg, very similar to the results from the MINLEAP model. The relative contribution of

TP from wastewater was estimated at 1.8 kg per year (<2 percent of the lake's TP load based on BATHTUB's estimate), and was calculated from water use data provided by the park, and the assumption the facilities are well maintained and up to code.

Bear Head Lake is meeting water quality standards for those waters that support a cool and warm water fishery in Minnesota's Northern Lakes and Forests Ecoregion. In summary, water quality in Bear Head Lake is excellent and relatively stable and reflective of the lake's State Park setting and small forested watershed.

Figure 1. MDNR map of Sentinel lakes and major land types. "Deep" lakes stratify during the summer. "Shallow" lakes are defined here as those that mix continuously throughout the summer. "Cold Water" lakes are those that either harbor cisco, lake whitefish, or lake trout and are the focus of research funded by the Environmental Trust Fund (ETF). "Super sentinel" lakes also harbor cold-water fish populations and research on these lakes is also funded by the ENTF.



Introduction

This report provides a relatively comprehensive analysis of physical, water quality, and ecological characteristics of Bear Head Lake in Saint Louis County Minnesota (MN). This assessment was compiled based on Minnesota Department of Natural Resources (MDNR) surveys of the lake's fish community and aquatic plant communities, Minnesota Pollution Control Agency (MPCA), and Bear Head Lake State Park water quality monitoring, and analysis of various other sources of data for the lake. The water quality assessment focuses on data collected during the 2008-2010 seasons. Water quality data analyzed includes all available data in STORET, the national repository for water quality data. Further detail on water quality and limnological concepts and terms in this report can be found in the *Guide to Lake Protection and Management*: (http://www.pca.state.mn.us/water/lakeprotection.html).

History

(Compiled with assistance from MDNR Bear Head Lake State Park manager Jen Weslund, and the MDNR website http://www.dnr.state.mn.us/state_parks/bear_head_lake/index.html)

Early logging

At the turn of the 20th century, logging was the major activity around Bear Head Lake. In the early 1900s a sawmill was built on the south side of the lake which remained in operation until 1911. Between 1911 and 1913, several fires swept the area and consumed the forest inside the park boundary. A few seasonal cabins were located on the lake's southern shore in the 1920s. The original MDNR fish survey in 1961 noted huge quantities of wood slabs from old sawmill operations covering the bottom of much of the shoal water area, especially the bays.

Lakeshore development

After early logging activities, little was recorded about the area until 1961 when the Minnesota Legislature created the park. The initial 1961 MDNR fish survey noted six cabins along the lake. Walleye catches in gill nets are the highest recorded (15 per net) despite no stocking in the years leading up to the survey. Walleye stocking becomes routine after this date up to present-day. The campground and associated recreational facilities were first established in the 1970s, and now are the only developed portion of the lakeshore.

Present day

Land use within the watershed has remained unchanged since the early 1900s. Silvicultural activity continues in the vicinity, but outside park boundaries. In 2010 Bear Head Lake State Park won the title of "America's Favorite Park" and a $100,000 gift in a nationwide campaign. The money will be used to build a trail center at the park.

Background

Lake morphometric and watershed characteristics

Bear Head Lake is located in St. Louis County within the Rainy River Headwaters watershed (Figure 2), part of the Rainy River Basin. Bear Head Lake is located approximately 10 miles east of Tower, MN, within Bear Head Lake State Park. The entire shoreline of Bear Head Lake, and most of its watershed, is included within the State Park boundaries (Figure 2). The park also includes portions of Eagles Nest Lake #3, and four other small lakes- including two designated trout lakes.

Bear Head is a moderately deep lake and the water column routinely stratifies by late spring. Bear Head is a seepage lake and therefore has no surface water inlets or outlets. The lake is surrounded by primarily coniferous forested land (Figure 3). Large wetland complexes are located adjacent to the lake's main southern basin. Watershed boundaries were not validated in the field and there may be some uncertainty as to precise direction of flow for some portions of the watershed. If more precise delineation was needed in the future, actual field observation and measurements may be needed. Quaternary geology includes thin unconsolidated materials (gravel and boulders) over bedrock (Ericson et. al., 1976). The lake has a small watershed, made up of forest, wetlands, and water (principally the lake itself; Figure 3). Most of the lakeshore is undeveloped and managed by MDNR. The developed portions of the lakeshore are limited to areas of the north shore associated with the State Park (campground, swimming beach, picnic grounds, and boat ramp).

Bear Head Lake's morphometric characteristics are summarized in Table 1. Bear Head is a moderately sized lake covering 266 hectares (659 acres). The lake has a mean depth of 4.2 m (13.8 feet), a maximum depth of 14 m (46 feet), and 56 percent of the lake is considered littoral. The lake is separated into three distinct basins (Figure 4). The west basin is the shallowest, the eastern basin is slightly larger and more variable in depth, and the central basin is the largest and has a more uniform depth of 4.5-6 m (15-20 feet). The lake's maximum depth is located near the boundary of the central and east basins.

Percent littoral area refers to that portion of the lake that is 4.6 m (15 feet) or less in depth, which often represents the depth to which rooted plants may grow in the lake; on Bear Head this is limited to near-shore areas, particularly the west and southeast shorelines. Lakes with a high percentage of littoral area and non-rocky substrates often have extensive rooted plant (macrophyte) beds. These plant beds are a natural part of the ecology of these lakes and are important to maintain and protect. The volume of Bear Head Lake was estimated at 9,094 acre-feet, and the residence time was estimated at four years, reflective of the lake's moderate depth and seepage hydrology.

Table 1. Bear Head Lake and watershed morphometric characteristics

	Lake ID	Lake Basin hectares (acres)	Littoral Area (%)	Total Watershed Area hectares (acres)	Watershed: Lake	Max. Depth meters (feet)	Mean Depth meters (feet)	Lake Volume acre-ft
Bear Head	69-0254	266 (659)	56	1,101 (2,722)	4.1 : 1	14 (46)	4.2 (13.8)	9,094

Lake bathymetry based on original surveys in 1960

Figure 2. Bear Head Lake watershed



Figure 3. Bear Head Lake watershed land use

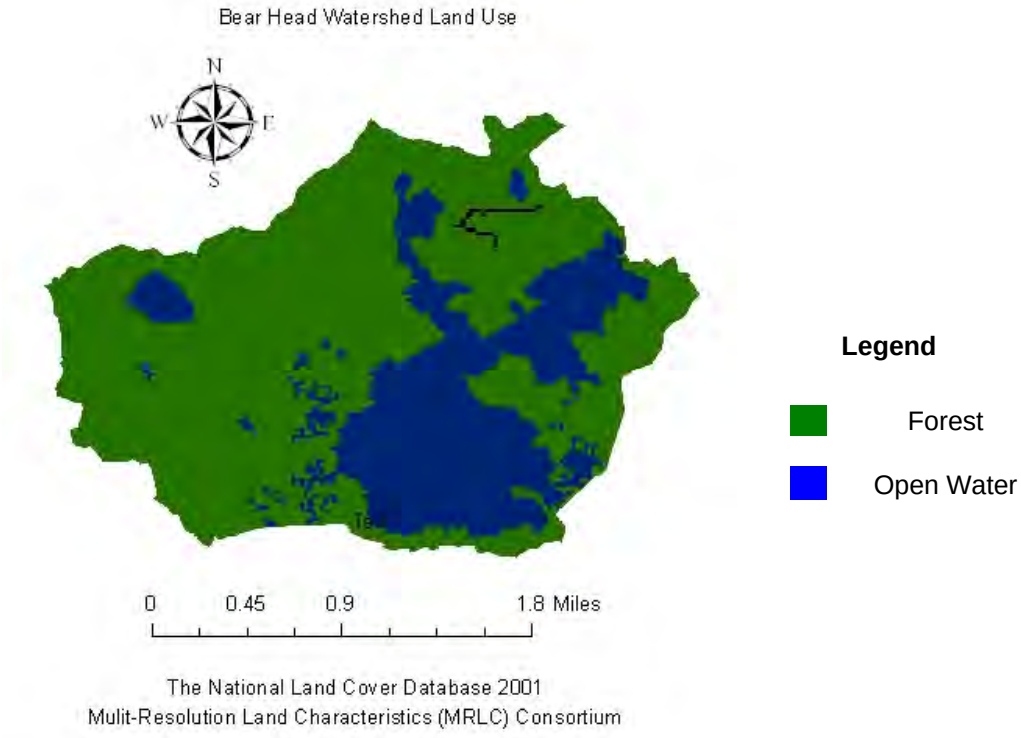
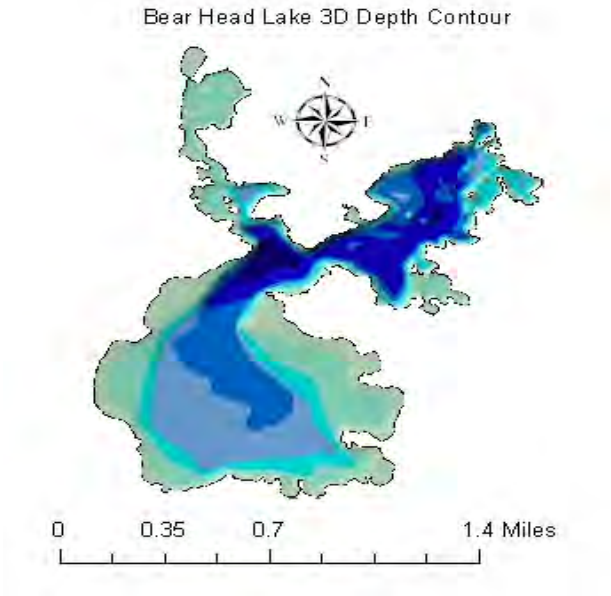


Figure 4. Bear Head lake depth contours



Ecoregion and Land Use Characteristics

Minnesota is divided into seven regions, referred to as ecoregions, as defined by soils, land surface form, potential natural vegetation and land use (Omernik 1987). Data gathered from representative, minimally impacted (reference) lakes within each ecoregion serve as a basis for comparing the water quality and characteristics of other lakes. Bear Head Lake lies within the Northern Lakes and Forest (NLF; Figure 5) ecoregion. NLF values will be used for land use (Table 2) and summer-mean water quality comparisons. Additionally, the NLF ecoregion will be used for model applications. Omernik level III and IV ecoregions provided a basis for the "land type" delineations noted in Figure 1. This step was taken prior to selection of the Sentinel lakes and provided a means to most closely characterize geomorphological differences in lake condition. In the NLF ecoregion this allowed for differentiation between the "Canadian Shield" lakes and "Glacial Drift Northern Forest" lakes.

Since land use affects water quality, it has proven helpful to divide the state into regions where land use and water resources are similar. Land use within the Bear Head Lake watershed is nearly all forest and open water. There has been little change in land use since 1969 (Table 2), primarily because most of the watershed is within Bear Head Lake State Park (Figure 2).

Figure 5. Minnesota ecoregions as mapped by United States Environmental Protection Agency

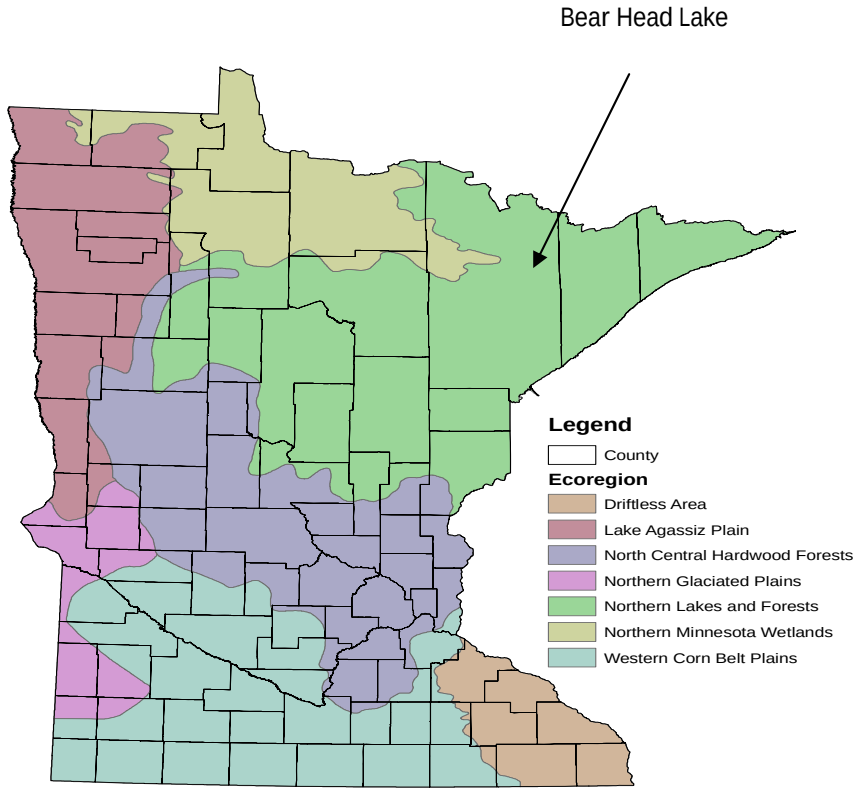


Table 2. Bear Head Lake watershed ecoregion land use comparison. Typical (interquartile) range based on NLF ecoregion reference lakes noted for comparison (Heiskary and Wilson 2005).

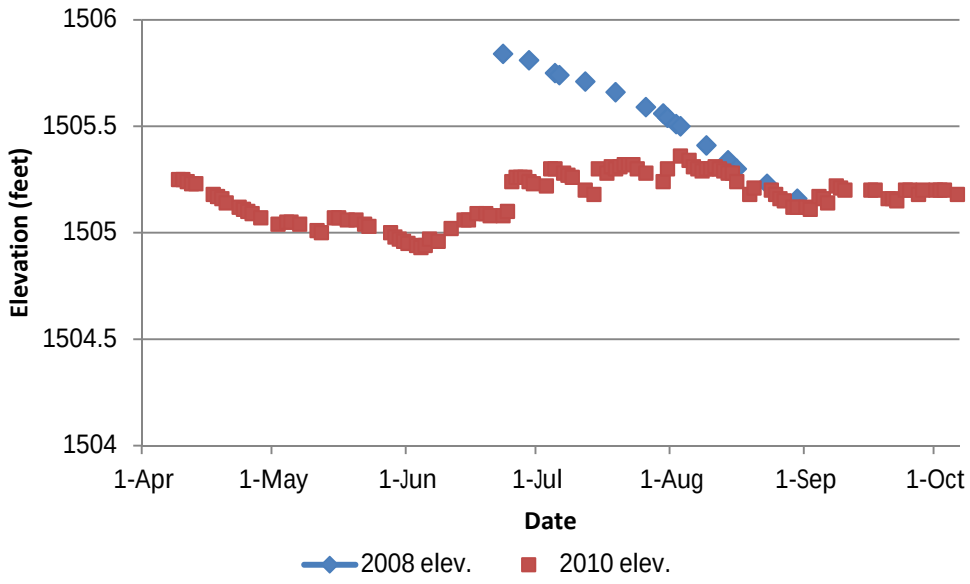
Land use (%)	Bear Head $(2001)_1$	NLF ecoregion	Applicable $(1969)_2$	Applicable $(1991)_3$
Developed	<1	0 - 7	<1	<1
Cultivated (Ag)	0	< 1	0	0
Pasture & Open	<1	0 - 6	<1	<1
Forest	74	54 - 81	74	74
Water & Wetland	25	14 - 31	25	25

[1]National Land Cover Database www.mrlc.gov/index.php
[2]Minnesota Land Management Information Center www.lmic.state.mn.us/chouse/metadata/luse69.html
[3]Minnesota Land Cover 1991-1992:MAP www.lmic.state.mn.us/chouse/land_use_DNRmap.html

Lake Level

The MDNR Division of Waters began lake level monitoring on Bear Head in 2008, with several instantaneous readings. In 2010, the MDNR installed instrumentation that recorded the lake level; average daily values are shown in Figure 6 (data from 2009 are not available). Levels in 2008 were consistently higher, because it was a wetter year (see below). In 2010, the total fluctuation in water level was approximately 0.4 feet. Bear Head appears to have a very low sill, with water flowing out of a wetland that maintains a rather stable water level.

Figure 6. Bear Head Lake level elevations in 2008 and 2010; MDNR data



Precipitation and Climate Summary

Climate and precipitation records for the 2008-2009 field seasons varied considerably. Rain gage records from Babbitt (a long-term climate station seven miles southeast of Bear Head Lake) show four 2.5 centimeter (cm; 1 inch) plus rain events during the 2008 field season and one during 2009 (Figures 7 and 8). Large rain events will increase runoff into the lake and may influence in-lake water quality and lake levels. Precipitation records for the 2008 water year (October 2007 through September 2008) showed conditions were wetter than average near Bear Head Lake (Figure 9). Precipitation for the 2009 and 2010 water years were near and slightly below normal, respectively.

Figure 7. 2008 monitoring season rainfall based on records for Babbitt, MN; State Climatology Office data

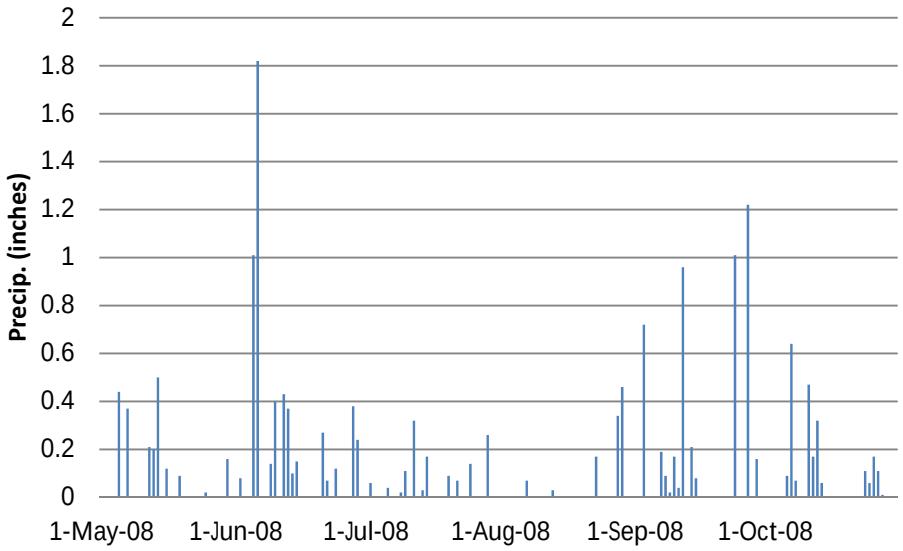


Figure 8. 2009 monitoring season rainfall based on records for Babbitt, MN; State Climatology Office data

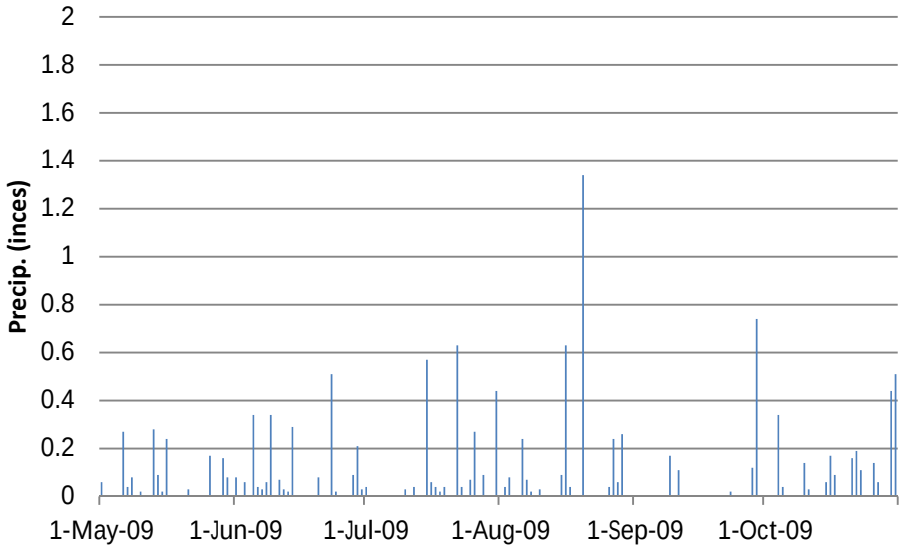
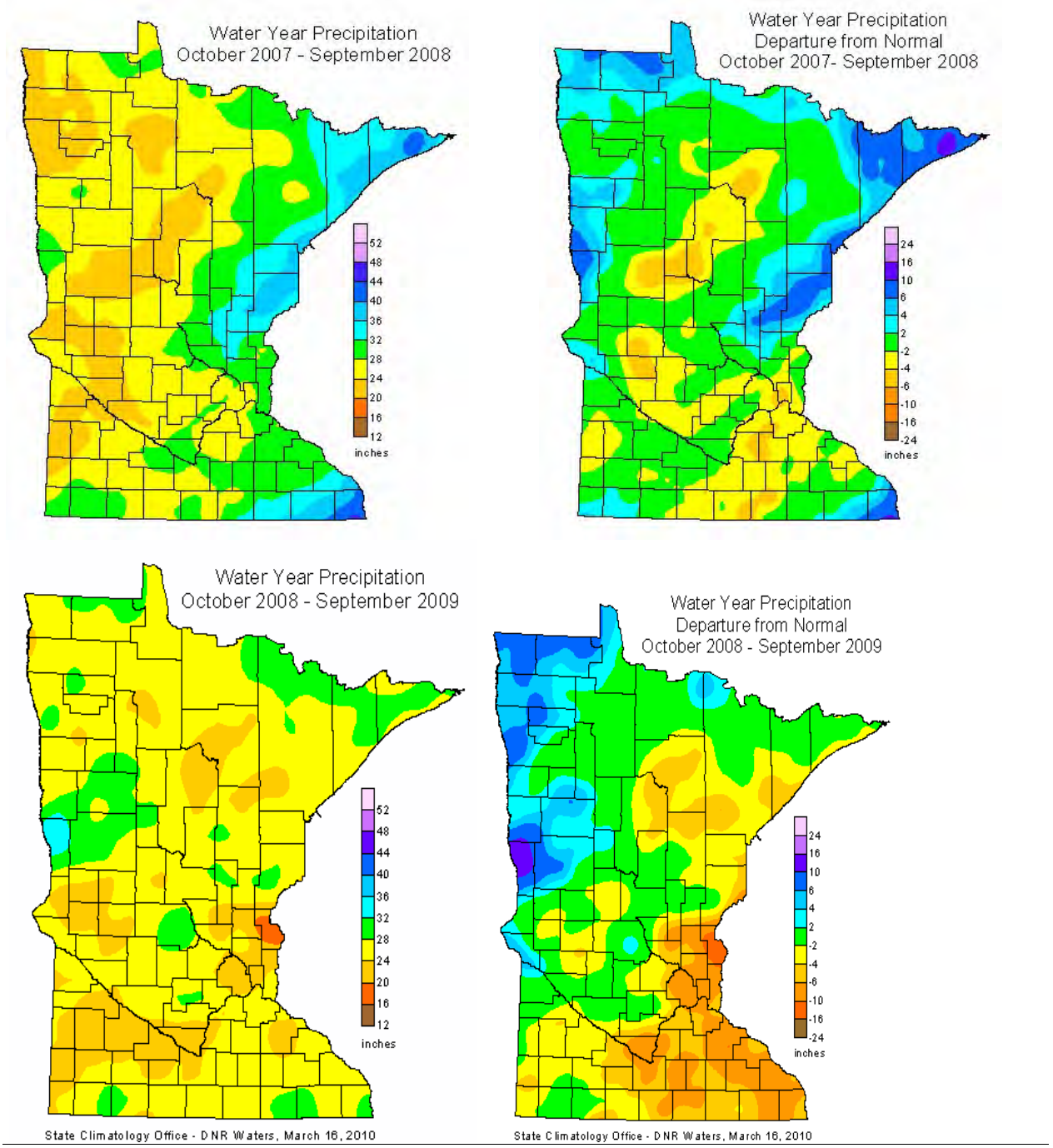


Figure 9. 2008-2009 Minnesota water year precipitation and departure from normal; State Climatology Office data



Methods

Fisheries and aquatic plants

Frequency of occurrence of aquatic plant species was assessed using the point-intercept method (Madsen 1999). This method entailed visiting sampling points on a grid within the vegetated zone of the lake, throwing a two-sided rake over one side of the boat at each point, raking the bottom approximately 1 m, then retrieving the rake and identifying all species present, and recording the depth. Survey points were spaced approximately 80 m (0.7 points per littoral acre).

Most recent fisheries surveys follow guidelines outlined by MDNR Special Publication 147 (1993; Manual of Instructions for Lake Survey). Near-shore non-game fish surveys were also completed on each Sentinel lake following methods described by Drake and Pereira (2002).

Water quality

In 2008-2010 water quality data on Bear Head Lake were collected by the MPCA. Staff sampled Bear Head monthly from May through October in 2008-2009 and 'seasonally' – May, July, and October - in 2010. Samples were collected at the lake's maximum depth, in the north-central portion of the lake (MPCA site # 101; Figure 2). MPCA lake surface samples were collected with an integrated sampler, a poly vinyl chloride (PVC) tube 2 m (6.6 feet) in length, with an inside diameter of 3.2 cm (1.24 inches). Zooplankton samples were collected with an 80 micrometer (µm) mesh Wisconsin zooplankton net. Phytoplankton (algae) samples were taken with an integrated sampler. Depth TP samples were collected with a Kemmerer sampler. Temperature and DO profiles and Secchi disk transparency measurements were also taken by MPCA and MDNR State Park staff (park staff collected data in 2008 and 2010). Sampling procedures were employed as described in the MPCA Standard Operating Procedure for Lake Water Quality document, which can be found here: http://www.pca.state.mn.us/publications/wq-s1-16.pdf .

Laboratory analysis was performed by the Minnesota Department of Health using United States Environmental Protection Agency (EPA)-approved methods. Samples were analyzed for nutrients, color, solids, pH, alkalinity, conductivity, chloride, metals, and chl-a. Phytoplankton samples were analyzed at the MPCA using a rapid assessment technique.

Zooplankton

Zooplankton samples were collected monthly from ice-out (May) through October 2008-2010. Two replicate vertical tows were taken at each sampling event. The net was lowered to within 0.5 m of the bottom and retrieved at a rate of approximately 0.5 m per second. Contents were rinsed into sample bottles and preserved with 100 percent reagent alcohol. Analysis was conducted by MDNR personnel.

Each zooplankton sample was adjusted to a known volume by filtering through 80 micrograms per liter (µg/L) mesh netting and rinsing specimens into a graduated beaker. Water was added to the beaker to a volume that provided at least 150 organisms per 5-milliliter aliquot. A 5-milliliter aliquot was withdrawn from each sample using a bulb pipette and transferred to a counting wheel. Specimens from each

aliquot were counted, identified to the lowest taxonomic level possible (most to species level), and measured to the nearest .01 millimeter using a dissecting microscope and an image analysis system. Densities (#/liter), biomass (µg/L), percent composition by number and weight, mean length (millimeter), mean weight (µg) and total counts for each taxonomic group identified were calculated with the zooplankton counting program ZCOUNT (Charpentier and Jamnick, 1994 in Hirsch, 2009).

Results and Discussion

Fisheries assessment

MDNR fisheries managers utilize netting survey information to assess the status of fish communities and measure the efficacy of management programs. Presence, absence, abundance, physical condition of captured fishes, and community relationships among fish species within survey catch information also provide good indicators of current habitat conditions and trophic state of a lake (Schupp and Wilson, 1993). This data is stored in a long-term fisheries survey database, which has proven valuable in qualifying and quantifying changes in environmental and fisheries characteristics over time.

Three fisheries lake surveys and 12 fish population assessments have been done on Bear Head Lake, dating back to 1961. Gill nets (3 to 12 sets) were used during most of these investigations. Trap nets (6 to 20 sets) were used during eight of these investigations. Most gill netting and trap netting was done in early June to September. Shoreline seining was done during the lake surveys in 1961, 1983, 1999, 2008, and 2009. Electrofishing targeting largemouth bass was done in 2008 and 2010. The median total catch of fish in the gill nets (all species combined) in all investigations on Bear Head Lake of 30 fish/net (29 lbs/net) is typical for Lake Class 7. This lake class is one of the more productive in northeast Minnesota, in terms of gill net catches of fish. See Figure 10 for a summary of standard gill net and trap net catches on Bear Head Lake.

Fish community status and trends

Bear Head Lake supports a relatively simple fish community. The fish community is mostly composed of cool-water species such as walleye, northern pike, yellow perch, and white sucker (Table 3). Statistically, each of these populations do not show significant trends in any direction over the whole data record; however, in the last two decades white sucker have been trending downward; while the abundance of northern pike and warm water species such as bluegill and black crappie have been trending upward (Figure 10). Electrofishing results during 2008 and 2011 also show a significant largemouth bass population in the lake (long-term trends in abundance are unknown).

Warm water fish species have been increasing over time in northeast Minnesota lakes due presumably in part to warming water temperatures. Continued warming will affect the composition of Bear Head's fishery with continued increases in warm water sunfish and bass likely. Although the population of cold water burbot is presumably small in Bear Head, the species will not likely persist in Bear Head Lake if current climate warming trends persist (Jacobson et al. 2010). Over the long-term in Bear Head, we may also expect slow declines in cool-water walleye, white sucker, and yellow perch perhaps due to negative interspecific interactions with largemouth bass and other centrarchids (Fayram et al. 2005).

Still, at this time, size and age structure of most major game species in Bear Head Lake appears balanced with a relatively large number of large, old individuals in each population. Despite little quantitative information on angler harvest, size and age indicators suggest low to modest levels of angler harvest.

Individual species assessments

Walleye

The median catch of walleye in all investigations on this lake of 6.4/gill net was near the median for Lake Class 7. Walleye sizes over the long-term have averaged 15.0 inches, which was in the third quartile for this lake class (Figure 11). A few 30 inch walleye weighing 12 pounds each have been captured in recent investigations. Fifty-seven percent of the walleye captured in 2004 were age five or older, higher than the average of 43 percent of walleye age five or older in past investigations on this lake. Walleye growth has been slower than normal by area standards (in the first quartile) for ages one and two and normal (in the second quartile) for ages three and older (Figure 12).

Walleye fry (over 3,500,000) and "bass" fingerlings (a total of 950) were stocked from 1928 through 1947. The initial fisheries lake survey in 1961 showed high numbers of walleye (15.0/gill net) despite no stocking from 1948-1961; thus a robust naturally reproducing walleye population was present at the time that Bear Head State Park was founded (Figure 10).

Despite an abundant natural walleye population, small walleye fingerlings were stocked in 7 of 16 years from 1961 through 1976 at the average rate of 0.11 lb/littoral acre (104 fingerlings/littoral acre) for each stocking (Table 4). In 1961, in addition to the fingerlings stocked that year, walleye fry were stocked at the rate of 5,391 fry/littoral acre.

Assessments in 1969, 1974, and 1977 captured an average of 5.5 walleye/gill net, which was in the second quartile for this lake class. Age analysis of walleye captured in 1974 and 1977 showed that from 1969 through 1976 a total of 39 walleye were captured from four fingerling-stocked year classes for an average of 9.8 walleye per fingerling-stocked year class. In contrast, a total of 15 walleye were captured from four non-stocked year classes for an average of only 3.8 walleye per non-stocked year class. Thus it appears that stocked year classes were about 2.5 times as strong as non-stocked year classes.

Walleye fry were stocked annually from 1977 through 1981 at the average rate of 2,075 fry/littoral acre. Assessments in 1980 and 1983 captured an average of 10.4 walleye/gill net, which was in the fourth quartile for this lake class. One strong year class (1977) and one weak year class (1979) were produced during this period of annual fry stocking.

Walleye fry were stocked biennially from 1983 through 2009 at the average rate of 947 fry/littoral acre. Eight assessments from 1984 through 2004 captured an average of 7.1 walleye/gill net, which was in the third quartile for this lake class. Age analysis of walleye captured in these assessments showed that from 1982 through 2003 a total of 222 walleye were from eleven fry-stocked year classes for an average of 20.2 walleye per fry-stocked year class. In comparison, a total of 155 walleye were from eleven non-stocked year classes for an average of 14.1 walleye per non-stocked year class. Thus, it appears that fry-stocked year classes were, on average, 43 percent stronger than non-stocked year classes. Strong year classes during this period occurred in 1983, 1989, 1995, and 2001, all of which were stocked. Weak year classes occurred during 1982, 1992, 1996, 1998, and 2000, none of which were stocked, and in 1985 and 2003, which were stocked. Li et al. (1996a,b) documented suppressed natural reproduction in years

adjacent to stocked years. Since stocking has been continuous over the past several decades in Bear Head, the reproductive viability of the "wild" walleye population in the lake in the absence of stocking is unknown.

Yellow perch

The median catch of yellow perch in all investigations on this lake of 8.4/gill net was in the fourth quartile for this lake class; however, perch numbers have declined in recent investigations in 2004 (4.0/gill net) and 2008 (0.6/gill net; Figure 10).

Across the state, perch abundance in gill nets has declined dramatically since 1993 (D.S. Staples, unpublished data). Perch are a forage species for walleye, largemouth bass, black crappie and northern pike. Maintenance of high walleye populations through stocking along with increases in warm-water largemouth bass and crappie populations due to warming water temperatures, and increasing abundance of northern pike may depress yellow perch populations in the future.

Bluegill

Bluegill were first captured in Bear Head Lake in gill nets in the 1969 investigation but did not show up in trap nets until the 1993 investigation. Their numbers have increased over time, with the highest catch (38.5/trap net) occurring in 1999 (Figure 10). These numbers are extremely high compared with lakes similar to Bear Head. Bluegill are large in Bear Head averaging 6.2 inches over the long term; the largest bluegill (caught in a gill net) was a very large 9.5 inches. But, bluegill grow slowly in Bear Head. At the development of the fourth annulus, Bear Head bluegill were 3.4 inches long compared to the Tower area Lake Class 7 mean of 5.4 inches (n=989; SE=0.04). Bluegill recruitment is relatively low and 45 percent of the bluegill captured in 2009 was age seven from the 2002 year class.

Low but stable recruitment, coupled with a relatively high proportion of old individuals in the population (regardless of growth rates) is good from a fisheries management perspective; yet unusual given the popularity of bluegill as a sport fish, the usual ease of catching them, and presumed high angling pressure from state park visitors. To maintain a quality bluegill fishery within Bear Head Lake, angler harvest, especially of large individuals should be kept low.

Black crappie

Another warm water species, black crappies were first captured in the 1989 gill net investigation. Crappie numbers then increased to a high of 14.2/trap net in 1995 (Figure 10). The 2009 crappie catch of 2.4/trap net was in the second quartile for this lake class. Like bluegill, the average crappie size in past investigations was large (9.6 inches) with a 14.3-in crappie being caught in 2004. Growth of crappies captured in 2009 was normal by area standards (Figure 12).

In 2010, black crappie abundance (0.8/trap net) was the lowest ever recorded since they appeared in the lake, and was below the lake's historical median (2.4/trap net). Crappie trap net catch per unit effort (TN CPUE) also fell below the 25th percentile value for Lake Class 7 (1.7); however, vulnerability of black crappie to trap nets is known to be variable and changes in these numbers may not reflect changes in the actual population in Bear Head Lake (McInerny and Cross 2008). Crappie ranged in length from 6.7 inches to 13.4 inches and was composed of five different year classes.

Northern pike

The median catch of northern pike in all investigations on this lake of 1.9/gill net was in the second quartile for this lake class (Figure 10). The 2008 catch of northern (5.7/gill net) was the highest catch of all investigations on this lake. Pike sizes have averaged 20.3 inches in gill nets. The largest pike, caught in a trap net was 37 inches and many large individuals are present in the population (Figure 14).

Pike growth in 2008 was normal by area standards (Figure 12, Figure 13). Like bluegill, northern pike are aggressive fish and highly susceptible to angler harvest. Overabundance of small northern pike (i.e., "hammer handles") is common where harvest of large northern pike is high (MDNR 2008). Thus, for continued quality northern pike populations, angler harvest of large individuals should be limited.

Largemouth bass

Largemouth bass numbers are under represented by gill net and trap net catches, as bass are known to be "net shy" to passive gears. Moderate numbers of young-of-year largemouth bass have been captured in shoreline seining throughout Bear Head's surveyed history. Largemouth numbers were high in 2008 spring electrofishing, where 41.4/hour of electrofishing were captured. A very wide range of sizes of largemouth bass were captured in the 2008 electrofishing, ranging from 4 inches to 19 inches (mean 10.5 in). In 2010, spring electrofishing was also conducted and sampled largemouth bass at a CPUE of 28.4/hour. In 2010, bass ranged in length from 7.2 inches to 18.1 inches with a mean of 12.4 inches. In 2010, eight year classes were identified compared to seven year classes in 2008. In 2010, growth was slightly above average. At the development of the fourth annulus, Bear Head largemouth bass were 10.5 inches long compared to the Tower area mean of 9.7 inches (n=531; SE=0.09). Largemouth bass will continue to be a prominent predator in Bear Head Lake and may interact negatively with walleye primarily through predation, but also competition for similar prey (Fayram et al. 2005).

Table 3. Fish species captured during past fisheries surveys in Bear Head Lake. Thermal guilds were classified by Lyons et al. (2009) and environmental tolerances were categorized by Drake and Pereira (2002).

Common name	Species name	Trophic guild	Thermal guild	Environmental tolerance[a]	First sampled
Northern pike	*Esox lucius*	Predator	Cool	Neutral	1961
Black crappie	*Pomoxis nigromaculatus*	Predator	Cool-warm	Neutral	1993
Walleye	*Sander vitreus*	Predator	Cool-warm	Neutral	1961
Largemouth bass	*Micropterus salmoides*	Predator	Warm	Neutral	1961
Burbot	*Lota lota*	Predator	Cold	Neutral	1989
White sucker	*Catostomus commersonii*	Omnivore	Cool-warm	Tolerant	1961
Central mudminnow	*Umbra limi*	Insectivore	Cool-warm	Neutral	2009
Iowa darter	*Etheostoma exile*	Insectivore	Cool	Intolerant	2009
Yellow perch	*Perca flavescens*	Insectivore	Cool-warm	Neutral	1961
Hybrid sunfish	*Lepomis spp.*	Insectivore	Warm	Neutral	1961
Bluegill sunfish	*Lepomis macrochirus*	Insectivore	Warm	Neutral	1992
Green sunfish	*Lepomis cyanellus*	Insectivore	Warm	Neutral	2008
Pumpkinseed sunfish	*Lepomis gibbosus*	Insectivore	Warm	Neutral	1983

Table 4. Bear Head Lake fish stocking history

Year	Species	Total no.	Life stage
1928-1947 (intermittent)	Walleye	5,535,00	Fry
1928-1947 (intermittent)	"Bass"	950	Fingerlings
1961-1976 (intermittent)	Walleye	39,000 per stocking	Fingerlings
1961	Walleye	2,000,000	Fry
1977	Walleye	500,000	Fry
1978	Walleye	1,000,000	Fry
1979	Walleye	1,000,000	Fry
1980	Walleye	1,000,000	Fry
1981-2009 (biennially)	Walleye	350,000	Fry

Figure 10. Historical catch per unit effort of the major fish species of Bear Head Lake, St. Louis Co. Dashed lines represent the first and third quartiles for gear and species specific catches in all Class 7 lakes. The solid lines represent the long-term lake average.

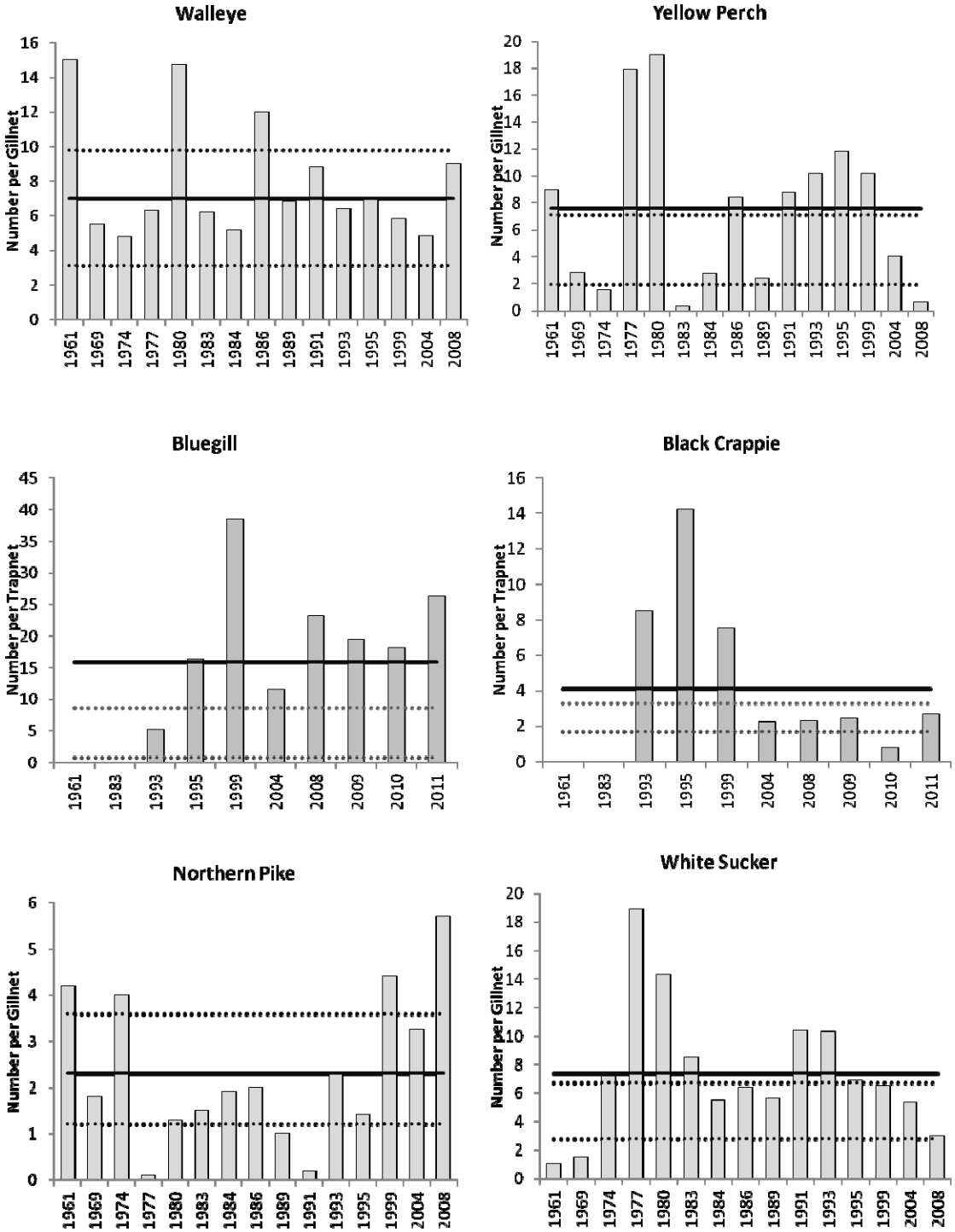


Figure 11. Length frequency histogram of walleye captured during the last gill net evaluation in 2008 in Bear Head Lake, St. Louis Co.

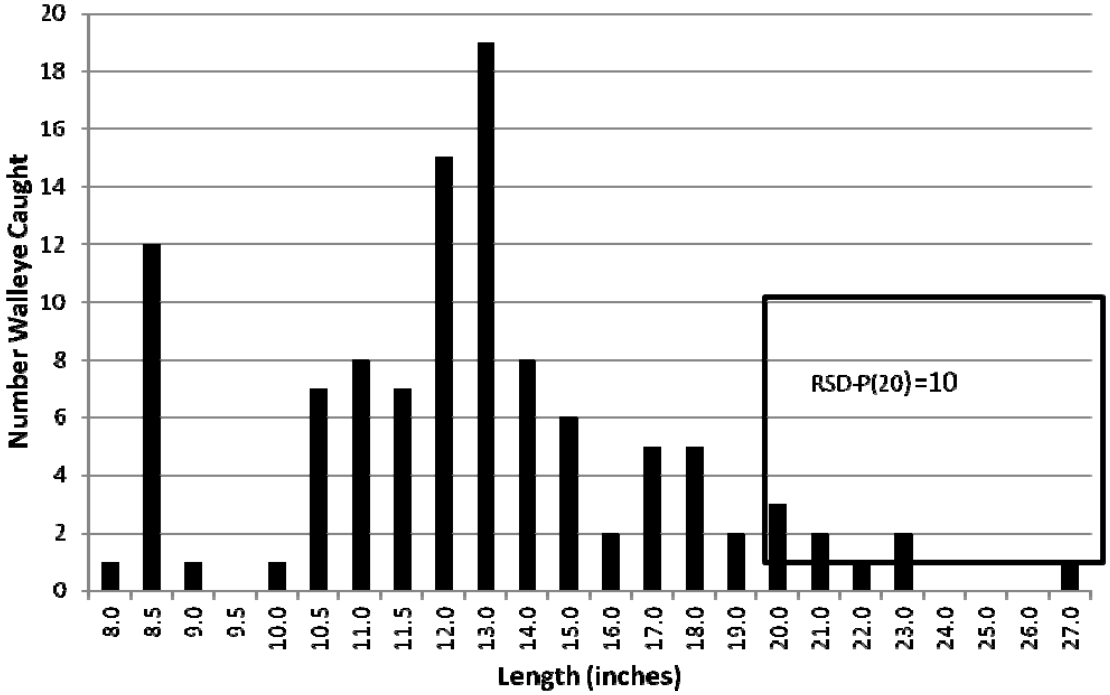


Figure 12. Length at age of major game fish species in Bear Head Lake, St. Louis Co.

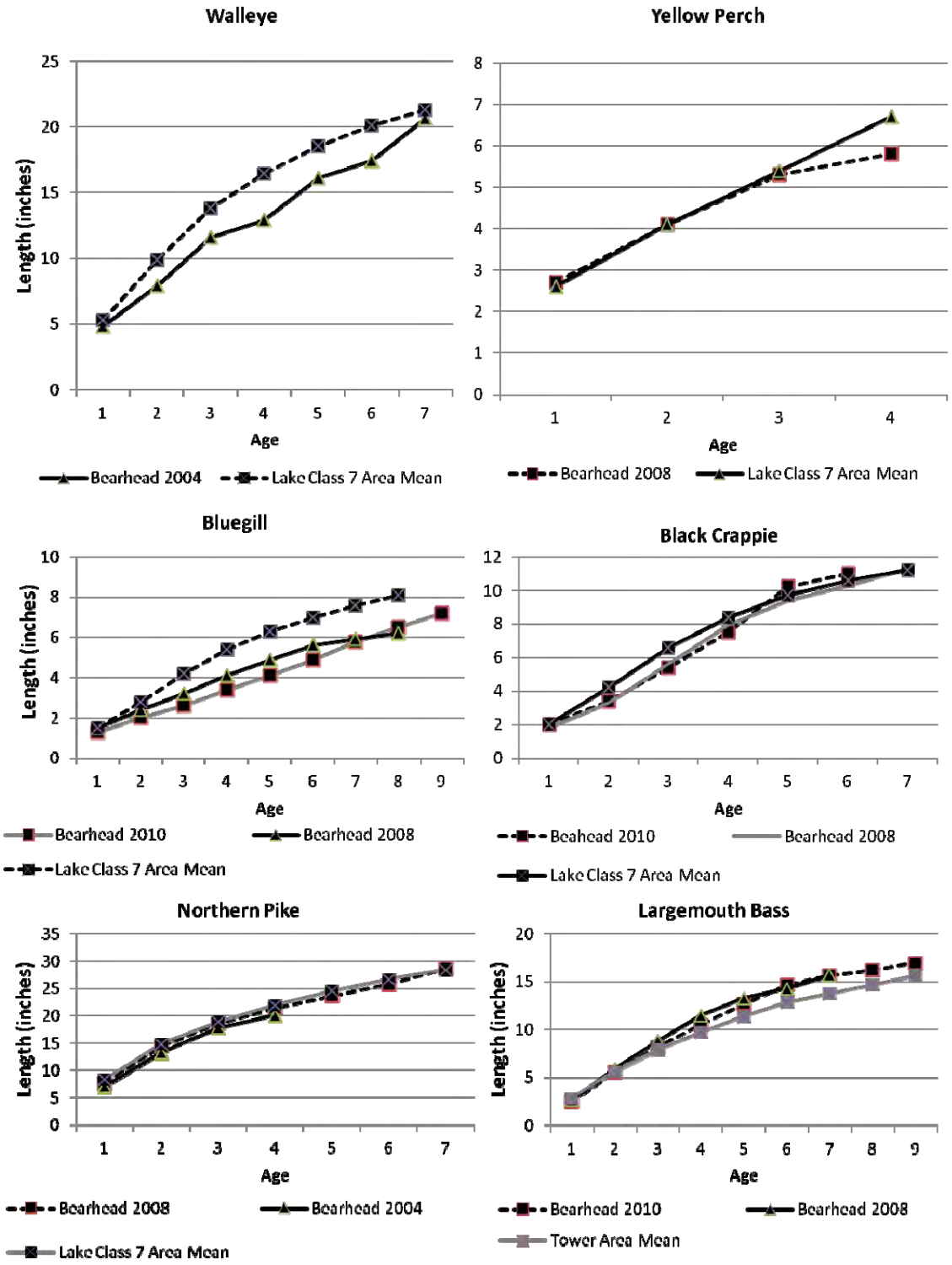
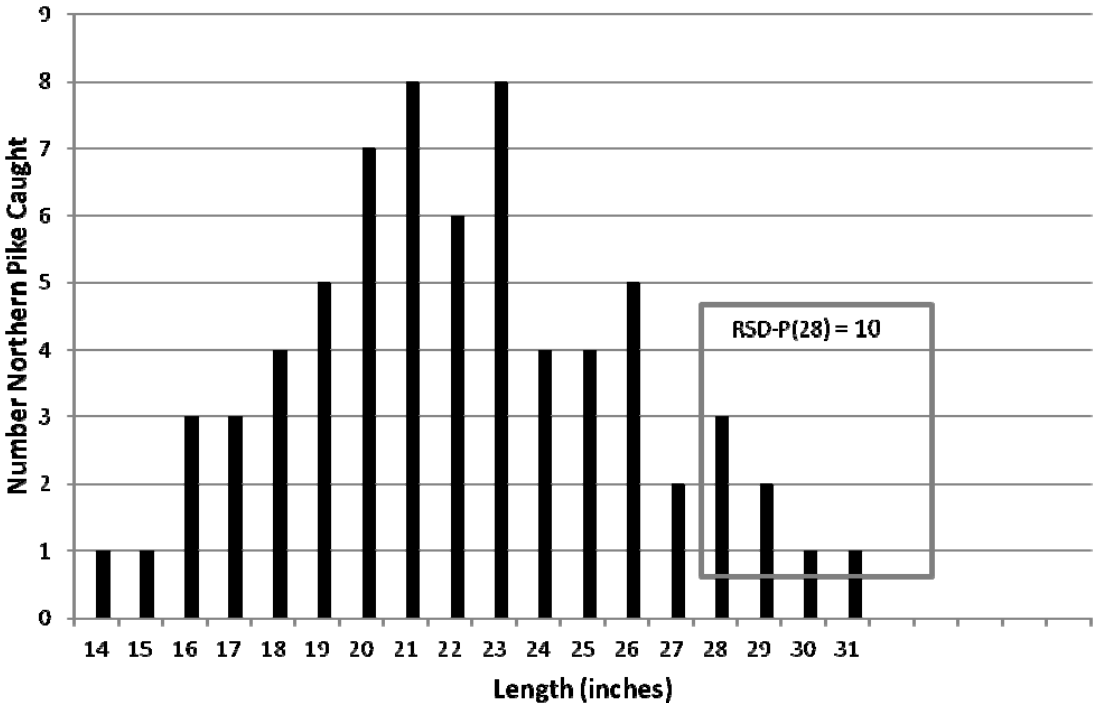


Figure 13. Length frequency histogram of northern pike captured during the last gill net evaluation in 2008 in Bear Head Lake, St. Louis Co.



Aquatic plant assessment

Near-shore and submersed aquatic plants are abundant and diverse in Bear Head Lake (Table 5,

Table 6, Figure 14, Figure 15). The stained soft-water, large shallow areas, and organic sediments of Bear Head Lake create a unique environment for rare aquatic plants. In fact, survey crews recently sampled 13 species identified as highly intolerant by Milburn et al. (2007) and two species listed by the state of Minnesota as species of special concern (American shore plantain and Vasey's pondweed; Table 6). An Index of Biotic Integrity developed by Beck et al. (2010) rates Bear Head Lake at 71-74 out of a possible 100.

Because Bear Head Lake's shoreline is owned by the State Park, there is little threat of damage of aquatic plants by near-shore development activities. Increased motorized recreation in shallow areas, introduction of non-native species, and climate change pose the greatest threat to the biodiversity of aquatic plants in the lake. Efforts to minimize non-climate stressors by local lake managers will be important to enhance the resilience of Bear Head Lake's aquatic plant community to uncontrollable changes in the climate.

Figure 14. Cover of aquatic vegetation in Bear Head Lake, St. Louis Co. assessed via point-intercept vegetation surveys in July 2010 and mapped with indicator kriging. Areas of green represent where vegetation occurred with high probability.

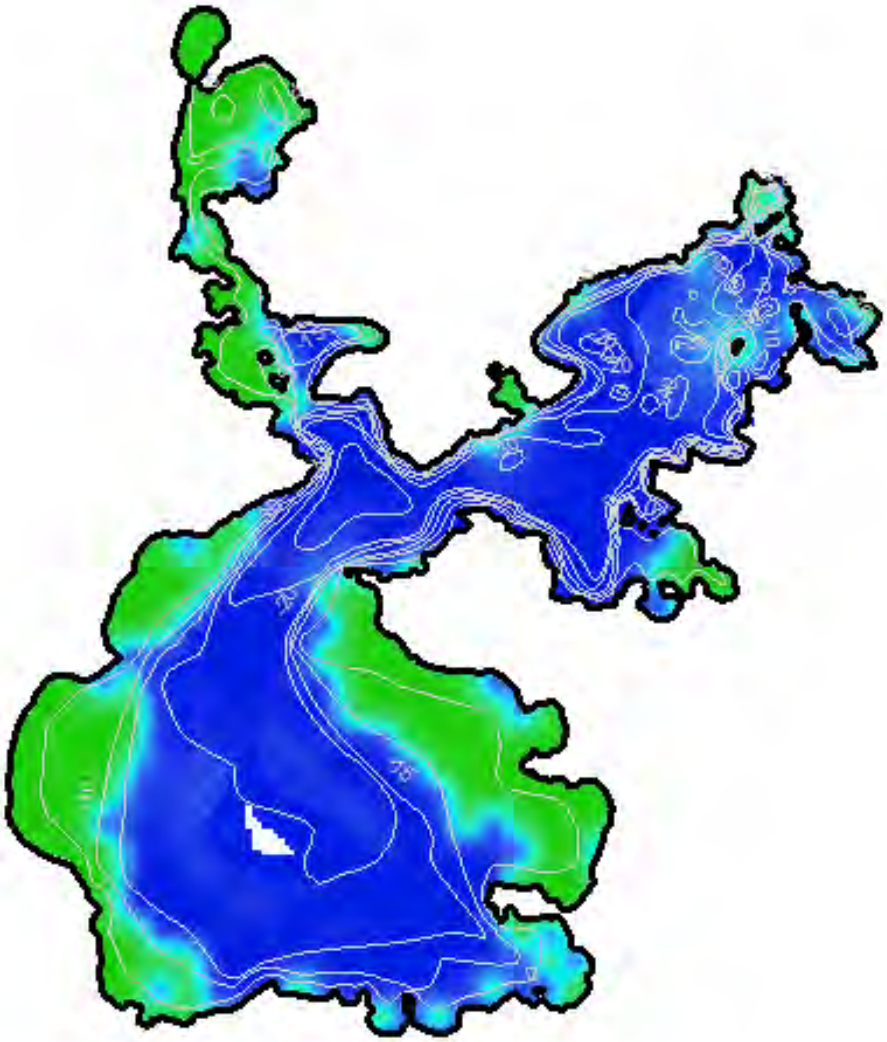


Figure 15. Number of aquatic plant species surveyed at each point during point intercept surveys in July 2010 on Bear Head Lake, St. Louis Co.

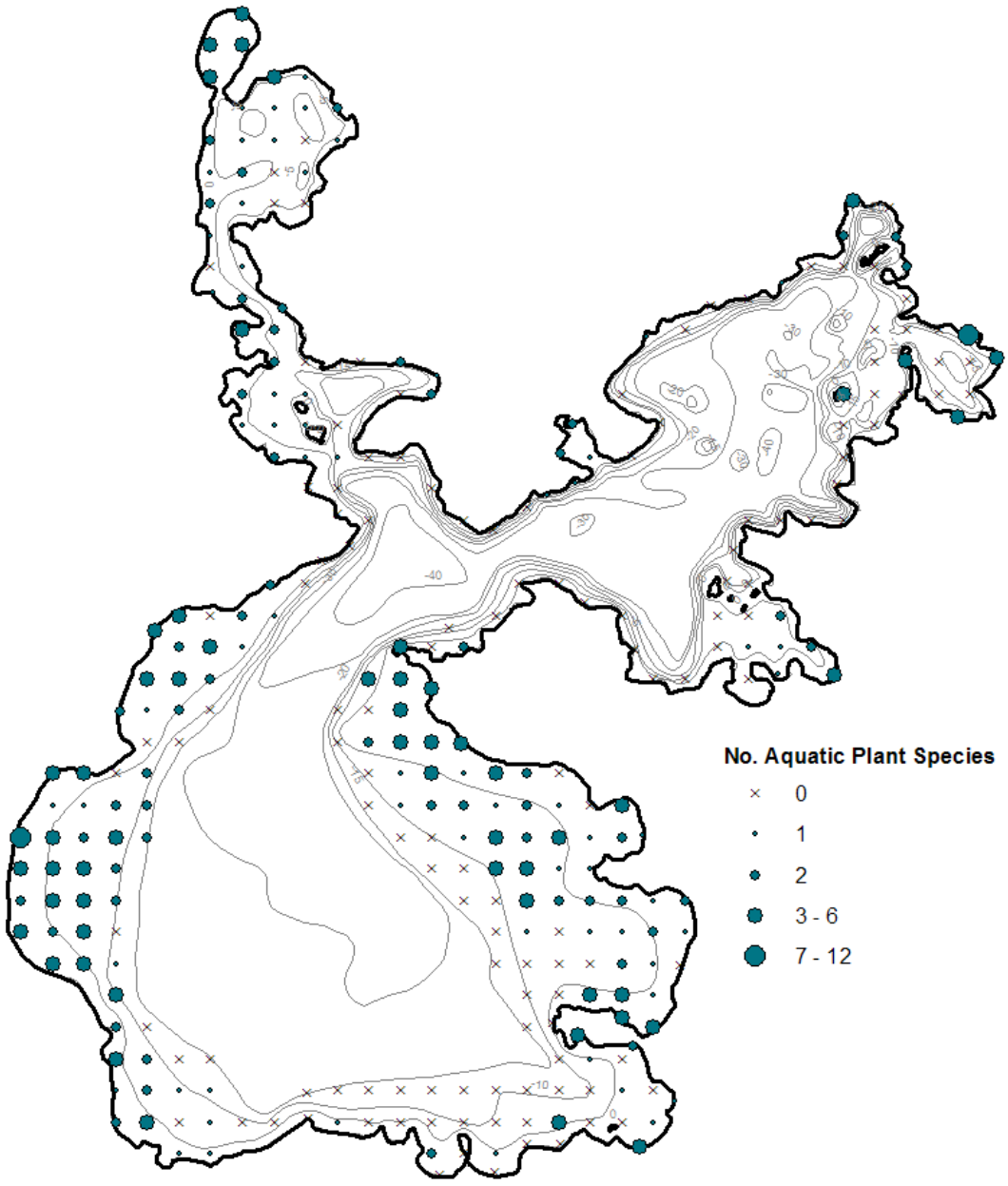


Table 5. Common species observed during previous transect surveys. Species documented were either labeled as "common" at any transect or found at ≥ 10 percent of the transects. The aquatic plant surveys in 1961 and 1983 were rapid assessments of vegetative cover and likely missed many other common species.

Date	Common name	Species name	Growth form
6/20/1961	Spikerush	*Eleocharis palustris*	Emergent
	Arrowhead	*Sagittaria sp.*	Emergent
	Quillwort	*Isoetes spp.*	Submersed
9/06/1983	Sedge	*Carex spp.*	Emergent
	Horsetail	*Equisetum sp.*	Emergent
	Blue Flag	*Iris versicolor*	Riparian
	Yellow waterlily	*Nuphar variegatum*	Floating leaf
	White waterlily	*Nymphaea odorata*	Floating leaf
	Variable pondweed	*Potamogeton gramineus*	Submersed
8/25/1999	Leather leaf	*Chamaedaphne calyculata*	Riparian
	Marsh St. John's-wort	*Hypericum virginicum*	Riparian
	Blue Flag Iris	*Iris versicolor*	Riparian
	Water Horehound	*Lycopus americanus*	Riparian
	Labrador Tea	*Ledum minor*	Riparian
	Sweetgale	*Myrica gale*	Riparian
	Reed Canary Grass	*Phalaris arundinacea*	Riparian
	Swamp fivefinger	*Potentilla palustris*	Riparian
	Marsh skullcap	*Scutellaria epilobiifolia*	Riparian
	Skullcap	*Scutellaria lateriflora*	Riparian
	Green-fruited burreed	*Sparganium chlorocarpum*	Emergent
	Sweet Flag	*Acorus calamus*	Emergent
	White waterlily	*Nymphaea odorata*	Floating leaf
	Floating-leaf pondweed	*Potamogeton natans*	Floating leaf
	Broad-leaved cattail	*Typha latifolia*	Emergent
	Coontail	*Ceratophyllum demersum*	Submersed
	Variable-leaf pondweed	*Potamogeton gramineus*	Submersed
	Common water starwort	*Callitriche verna*	Submersed
	Watermoss	*Drepanocladus sp.*	Submersed
	Canada waterweed	*Elodea canadensis*	Submersed
	Spikerush	*Eleocharis palustris*	Submersed
	Quillwort	*Isoetes sp.*	Submersed
	Alternate-flower milfoil	*Myriophyllum alterniflorum*	Submersed
	Dwarf Water milfoil	*Myriophyllum tenellum*	Submersed
	Large-leaf pondweed	*Potamogeton amplifolius*	Submersed
	Ribbon-leaf pondweed	*Potamogeton epihydrus*	Submersed
	Variable-leaf pondweed	*Potamogeton gramineus*	Submersed
	White-stem pondweed	*Potamogeton praelongus*	Submersed

Date	Common name	Species name	Growth form
	Coiled pondweed	*Potamogeton spirillus*	Submersed
	Narrow-leaf pondweed	*Potamogeton spp.*	Submersed
	Robbins' pondweed	*Potamogeton robbinsii*	Submersed
	Arrowhead group	*Sagittaria spp.*	Submersed
	Common bladderwort	*Utricularia vulgaris*	Submersed
	Water celery	*Vallisneria americana*	Submersed

Table 6. Percent frequency of occurrence of aquatic plant species at depths ≤ 15 feet sampled during point-intercept surveys on 20 July 2008, 3 August 2009, 26 July 2010, and 15 August 2011 at Bear Head Lake, Bear Head State Park, MN.

Common name	Species name	Growth form	Frequency (%) 2008	2009	2010	2011
All rooted plants			61.8	58.7	61.1	62.8
Robbins' pondweed[a]	*Potamogeton robbinsii*	Submersed	18.5	20.1	21.9	16.8
Canada waterweed	*Elodea canadensis*	Submersed	17.8	11.3	11.8	16.8
Variable-leaf pondweed	*Potamogeton gramineus*	Submersed	10.2	9.5	4.5	10.4
Muskgrass	*Chara sp.*	Submersed	9.5	1.8	4.2	1.0
Coontail[b]	*Ceratophyllum demersum*	Submersed	9.5	9.5	5.6	8.1
White waterlily	*Nymphaea sp.*	Floating-leaf	9.1	6.9	16.0	18.4
White-stem pondweed	*Potamogeton praelongus*	Submersed	7.6	4.0	0	3.9
Large leaf pondweed	*Potamogeton amplifolius*	Submersed	5.1	5.1	4.5	4.8
Stoneworts	*Nitella sp.*	Submersed	5.1	11.7	7.3	9.1
Alternate-flower watermilfoil[a]	*Myriophyllum alterniflorum*	Submersed	3.6	2.6	1.4	3.9
Water marigold[a]	*Megalodonta /Bidens beckii*	Submersed	3.3	2.2	0.7	1.3
Ribbon-leaf pondweed[a]	*Potamogeton epihydrus*	Submersed	2.9	3.6	1.7	7.1
Flat-stem pondweed	*Potamogeton zosteriformis*	Submersed	2.5	0.4	0.3	0
Narrow-leaf pondweed	*Potamogeton sp.*	Submersed	2.2	0	0	1.0
Dwarf watermilfoil[a]	*Myriophyllum tenellum*	Submersed	1.8	0.4	1.4	5.2
Bushy pondweed	*Najas flexilis*	Submersed	1.8	0	1.7	1.9
Burreed	*Sparganium sp.*	Emergent	1.8	0	0	0
Bulrush	*Scirpus sp.*	Emergent	1.8	0	0	0
Wild celery	*Vallisneria americana*	Submersed	1.5	3.6	3.8	4.8
Bladderwort	*Utricularia sp.*	Submersed	1.1	0.7	0.3	1.6
Watershield	*Brasenia schreberi*	Floating-leaf	1.1	0.7	3.8	3.2
Spikerush	*Eleocharis sp.*	Emergent	1.1	0	3.5	4.2
Floating-leaf pondweed	*Potamogeton natans*	Floating-leaf	1.1	1.1	2.1	1.6
Arrowhead	*Sagittaria sp.*	Emergent	1.1	2.2	3.1	1.9
Floating-leaf burreed	*Sparganium sp.*	Floating-leaf	1.1	0.7	0	3.9

Common name	Species name	Growth form	Frequency (%) 2008	2009	2010	2011
Sedge	*Carex sp.*	Emergent	0.7	1.1	1.0	6.8
Three-way sedge[a]	*Dulichium arundinaceum*	Emergent	0.7	1.1	1.0	1.9
Swamp horsetail	*Equisetum fluviatile*	Emergent	0.7	0	0	0
Yellow waterlily	*Nuphar sp.*	Floating-leaf	0.7	0.4	1.7	2.3
Cattail	*Typha sp.*	Emergent	0.7	0	1.4	1.6
Horsetail	*Equisetum sp.*	Emergent	0.4	1.1	1.4	1.3
Blue flag iris	*Iris versicolor*	Emergent	0.4	0.4	2.8	3.6
Water smartweed	*Polygonum amphibium*	Emergent	0.4	0	0.7	0.3
Water buttercup	*Ranunculus sp.*	Submersed	0.4	0	0	1.3
Vasey's pondweed[a,c]	*Potamogeton vaseyi*	Submersed	0	7.3	8.3	8.1
Spikerush	*Eleocharis smallii*	Emergent	0	2.6	0	0
Naiad	*Najas sp.*	Submersed	0	2.2	0	0
Illinois pondweed	*Potamogeton illinoensis*	Submersed	0	0.7	2.4	3.6
Leafy pondweed	*Potamogeton foliosus*	Submersed	0	0.7	0	0
Pipewort[a]	*Eriocaulon aquaticum*	Emergent	0	0.7	1.0	2.3
Quillwort[a]	*Isoetes sp.*	Emergent	0	0.7	1.0	0
Needlerush	*Eleocharis accicularis*	Submersed	0	0.4	0	0
Needlerush	*Eleocharis sp.*	Submersed	0	0.4	1.7	0.3
Clasping-leaf pondweed	*Potamogeton richardsonii*	Submersed	0	0.4	0	1.3
Filamentous algae			0	0	0.7	1.6
American shore plantain[a,c]	*Littorella uniflora*	Submersed	0	0	0.4	0
Giant burred	*Sparganium eurycarpum*	Emergent	0	0	2.1	5.2
Floating-leaf burreed[a]	*Sparganium fluctuans*	Floating-leaf	0	0	3.5	0
Narrow-leaf cattail[d]	*Typha angustifolia*	Emergent	0	0	0.4	0
Bottle-brush sedge	*Carex comosa*	Emergent	0	0	0	0.3
Leather-leaf[a]	*Chamaedaphne calyculata*	Emergent	0	0	0	3.9
Water moss	*Drepanocladus sp.*	Free floating	0	0	0	1.0
Waterwort[a]	*Elatine sp.*	Submersed	0	0	0	1.0
Rush	*Juncus sp.*	Submersed	0	0	0	2.9
Northern milfoil	*Myriophyllum sibiricum*	Submersed	0	0	0	0.3
Reed canary grass[d]	*Phalaris arundinacea*	Emergent	0	0	0	1.6
Wool grass	*Scirpus cyperinus*	Emergent	0	0	0	0.3
Max depth of veg growth (ft)[e]			12.2	13.0	9.2	9.3

[a]Species intolerant to turbidity (Conservatism values > 7) as described by Milburn et al. (2007) and Beck et al. (2010).
[b]Species tolerant to turbidity (Conservatism values > 7) as described by Milburn et al. (2007) and Beck et al. (2010).
[c]State listed as a species of Special Concern.
[d]Non-native
[e]Depth of 95% of all plant occurrences

Water quality

Standard summer-mean water quality data for 2008, 2009, and 2010 are presented in Table 7, and raw data results are provided in Appendix A. In addition, major cations, anions, and total organic carbon were analyzed on three sample dates, and those values and typical ranges as derived from the National Lakes Assessment (NLA) database for Minnesota are summarized in Table 8. The NLA was a statistically-based survey of the nation's lakes administered by the EPA in 2007. The typical range provided in Table 8 is based on 64 Minnesota lakes that were included in that NLA study and is intended to provide a state-wide perspective.

Table 7. Bear Head Lake 2008-2010 summer- mean water quality data. Typical range based on 32 NLF ecoregion reference lakes (Heiskary and Wilson 2008) noted for comparison. A value of half the detection limit was substituted for those values reported as less than the detection limit. 2010 values reflect the July sample only.

Parameter	Bear Head Lake 2008 Site 101	Bear Head Lake 2009 Site 101	Bear Head Lake 2010 Site 101 (July only)	NLF
Total phosphorus (µg/L)	13.7	14.0	15.0	14 - 27
Chlorophyll mean (µg/L)	6.5	8.5	4.3	4 - 10
Chlorophyll max (µg/L)	14.3	12.5		<15
Secchi disk (feet)	8.8	10.8	11.0	8 – 15
(meters)	(2.7)	(3.3)	(3.3)	2.4 – 4.6
Total Kjeldahl Nitrogen (mg/L)	0.46	0.49	0.65	<0.4 – 0.75
Alkalinity (mg/L)	15	16	15	40 - 140
Color (Pt-Co Units)	30	18	20	10 - 35
pH (SU)	6.8	6.7	7.7	7.2 – 8.3
Chloride (mg/L)	<1.0	<1.0	<1.0	0.6 – 1.2
Total suspended solids (mg/L)	1.6	2.1	1.6	<1 - 2
Total suspended inorganic solids (mg/L)	1.6	1.6	<1.0	<1 - 2
Conductivity (umhos/cm)	38	34	39	50 - 250
Total nitrogen: Total phosphorus ratio	33 : 1	35 : 1	43 : 1	25:1 - 35:1

Table 8. Bear Head Lake cation, anion, and total organic carbon measurements. Typical (IQ) range derived from 64 NLA lakes sampled in 2007 is provided as a basis for comparison. A value of half the detection limit was substituted for those values reported as less than the detection limit.

Date	Ca mg/L	Mg mg/L	K mg/L	Na mg/L	SO_4 mg/L	Cl mg/L	TOC mg/L
2008 Average	5.4	0.6	0.5	0.9	1.6	0.5	7.2
2009 Average	5.1	1.1	0.45	0.9	1.2	0.5	7.4
2010 Average	5.4	1.1	0.5	0.9	1.2	0.5	6.7
NLA IQ range	19.1-33.7	6.7-26.9	0.9-4.8	2.2-9.0	2.2-14.1	1.5-18.4	7.3-14.2
	µeq/L						
2008 Average	269	49	14	39	33	14	
2009 Average	254	90	12	39	25	14	
2010 Average	269	90	13	39	25	14	

Dissolved oxygen and temperature profiles

In 2008 MDNR installed a temperature logger in Bear Head that recorded data at 30 minute intervals. Data were collected six feet below the surface at the lake's maximum depth, and are summarized in Table 9 and Figure 16.

MPCA and MDNR data were combined to produce DO and temperature profiles for 2008, the year with the most profile data collected (approximately bi-weekly; Figure 17). Spring, late summer, and fall temperature profiles for 2008-2010 are shown in Figure 18. Bear Head tended to be stratified by late May each year, and stratification remained until October (the May 2008 sample was collected a few days after ice-out, before the lake began to stratify). Maximum surface temperatures peaked in mid-August in 2008 (Figure 17). The fall of 2009 was much cooler than normal, (http://climate.umn.edu/cawap/monsum/0910.txt) and this was the main factor for cooler water temperatures that October (Figure 18). Annual mean water temperatures were nearly identical among years 2008-2010 (Table 9); however, spring and early summer water temperatures were cooler in 2008, because ice out occurred five weeks later that year (May 6 in 2008, versus March 31 in 2010; Figure 16).

Epilimnetic DO concentrations exceeded 5 milligrams per liter (mg/L) throughout the 2008 field season, at concentrations needed to sustain a productive cool and warm water fishery. The hypolimnion started becoming anoxic in early July, and low DO concentrations reached their peak in the water column, a depth of 6 m (20 feet), in mid-August (Figure 17). Hypoxic conditions started to decline by early September, coinciding with cooling water temperatures and the change in seasons.

Table 9. Summary of 2008-2010 Bear Head Lake temperature data (Celsius) (MDNR data)

2008 mean	2008 spring mean	2008 summer mean	2009 mean	2009 spring mean	2009 summer mean	2010 mean	2010 spring mean	2010 summer mean
15.8	9.7	19.2	15.9	10.5	19.4	15.9	11.9	20.2

Figure 16. 2008 and 2010 Bear Head Lake average daily water temperatures (C)

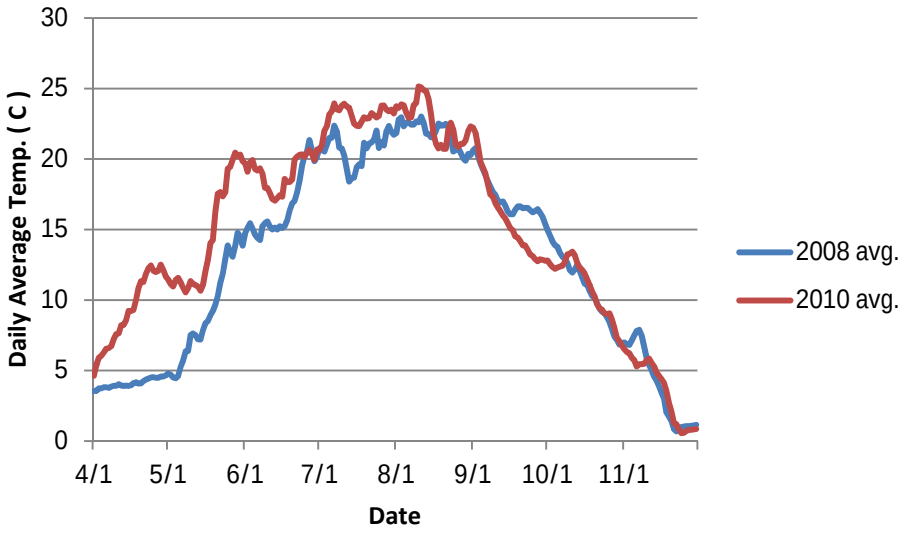
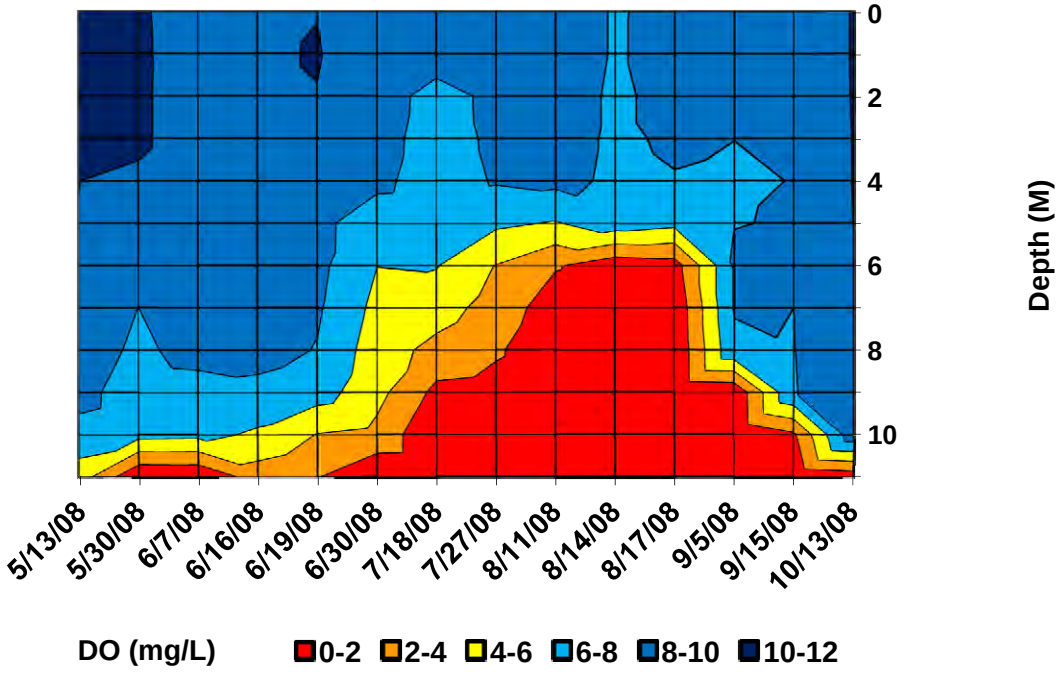


Figure 17. 2008 Bear Head Lake dissolved oxygen and temperature profiles (MPCA and MDNR data)



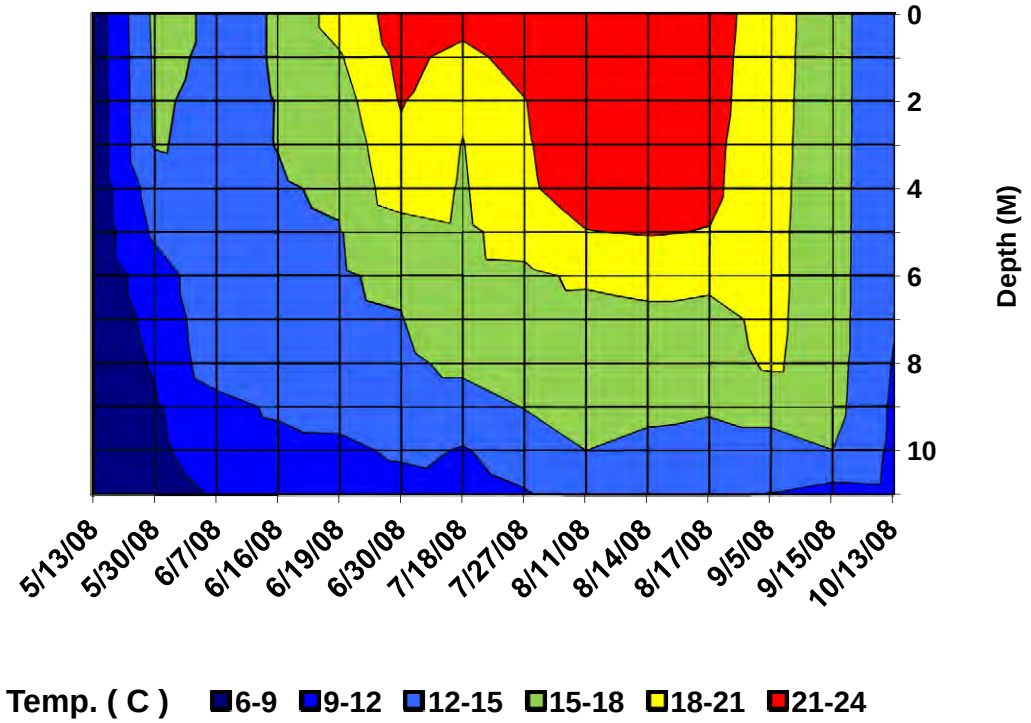
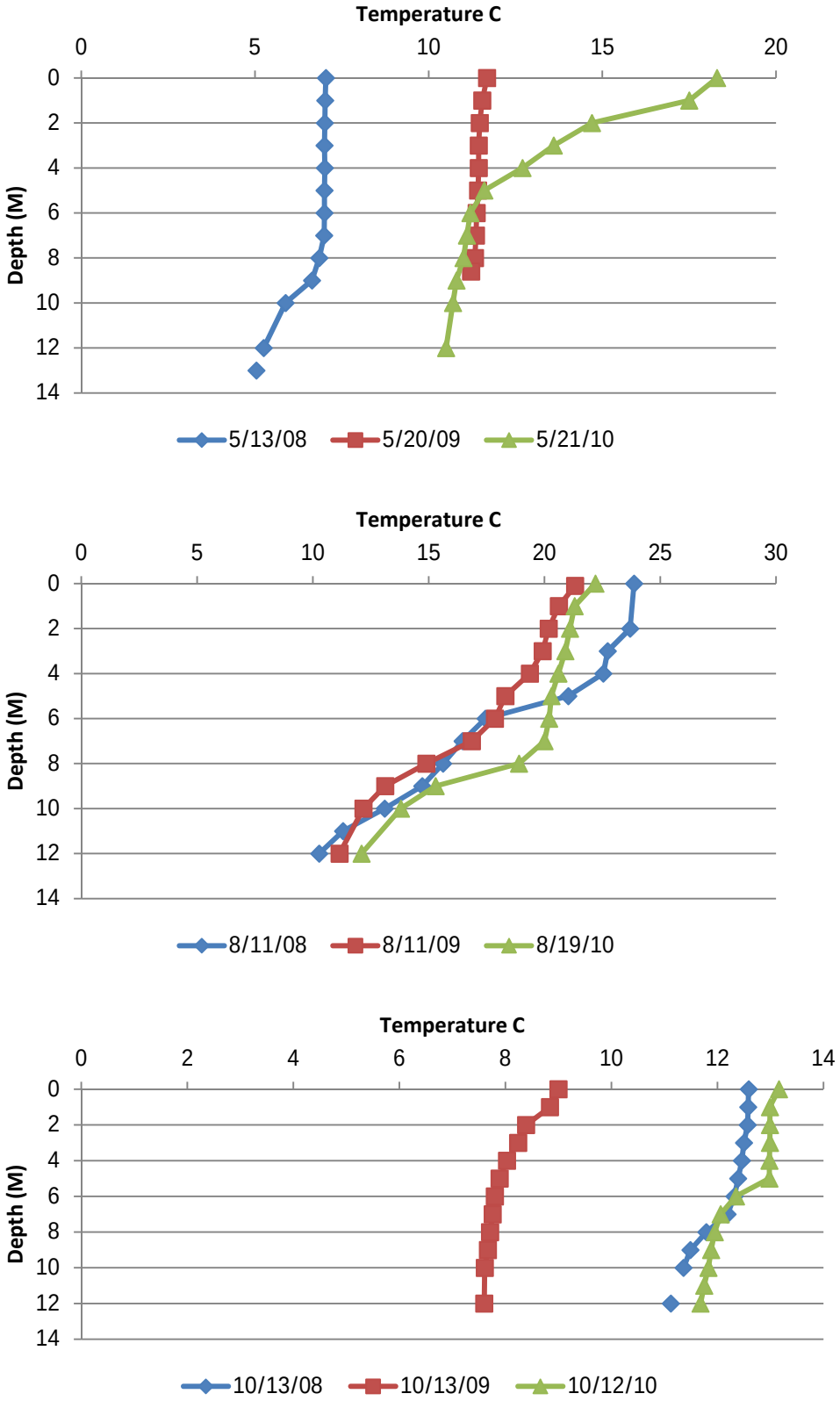


Figure 18. Bear Head Lake 2008-10 spring, summer, and fall temperature profiles



Total phosphorus (TP) concentrations did not change significantly between years, averaging 13µg/L in 2008, 14 µg/L in 2009, and 15 µg/L in 2010. Similarly, there was minimal monthly variation in TP from spring through summer (Figure 19). Spring 2009 concentrations were slightly elevated compared to spring 2008 and 2010. Bear Head's stable TP concentrations are likely due to several factors - the lake's undeveloped forested watershed, small watershed area, and seepage hydrology, which minimizes surface runoff and TP loading into the lake. For most deep, oligotrophic to mesotrophic (low to moderate nutrient) lakes it is common to observe stable to slightly declining TP from May through September, accompanied by slight increases in chl-*a* and slight decreases in Secchi transparency. This is primarily the result of sedimentation of sediment-attached TP early in the summer along with algal uptake of phosphorus and sedimentation as algae grow and die over the summer. Annual average near-bottom (hypolimnion) TP concentrations were higher and more variable than the surface values in Bear Head, which is normal for deep stratified lakes (Figure 20). Hypolimnetic TP was typically highest in late summer during peak stratification (Figure 21). Overall, TP values in Bear Head Lake indicate mesotrophic conditions.

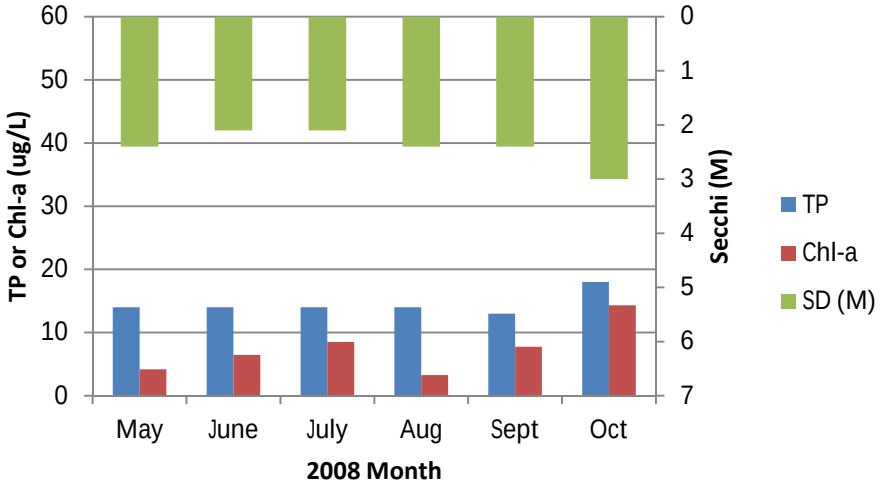
Chlorophyll-*a* (chl-*a*) concentrations provide an estimate of the amount of algal production in a lake. During 2008-10, chl-*a* levels were moderate in Bear Head and indicated mesotrophic conditions. Summer average concentrations ranged from 4.3 µg/L to 8.5 µg/L, yearly maximum values occasionally exceeded 10 µg/L. (Figure 19). Concentrations greater than 20 µg/L will typically be perceived as a nuisance bloom in northern Minnesota lakes (Heiskary and Walker, 1988). Nuisance blooms were not observed on Bear Head from 2008-2010, and during most sampling events algae levels in the epilimnion were sparse.

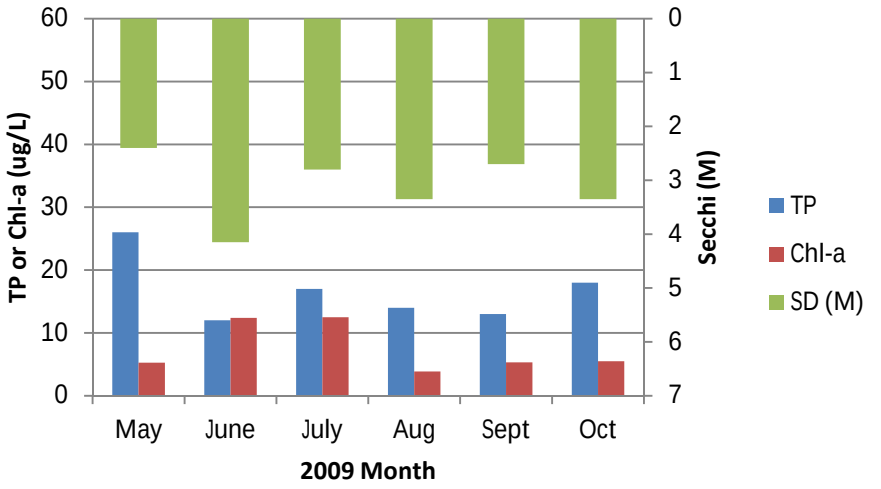
Secchi disk transparency averaged 3.0 m from 2008-10, and summer-mean transparency increased during the three years (Table 7). Transparency readings are within the NLF ecoregion range. Transparency was highest in the spring or fall, coinciding with low levels of algae, and was lowest in mid-summer, which is normal for mesotrophic lakes in the NLF. Bear Head has a slight bog stain (20 Platinum-Cobalt units) originating from forest and wetlands within the watershed, which (when elevated) can influence transparency; however, color was low to moderate during most sampling events and transparency was highly correlated with algal productivity.

Additional water quality parameters were measured, as part of the long-term monitoring of Bear Head and other Sentinel lakes. This includes some of the standard MPCA lake monitoring measures of total suspended solids (TSS), alkalinity, conductivity and color (Table 7), as well as major cations, anions, and total organic carbon (Table 8). While several of these parameters have "typical" ecoregion-based concentrations, some do not. For parameters without ecoregion–based comparisons, data from the 2007 NLA study were used to provide perspective on reported concentrations. Since the NLA lakes were selected randomly, they provide a reasonable basis for describing typical ranges and distributions at the statewide level.

For the conventional lake monitoring parameters listed in Table 7, most on Bear Head were outside (commonly lower than) the typical NLF range because few of the NLF ecoregion reference lakes were headwater seepage lakes. The low alkalinity, cation, and anion concentrations indicate very soft water. Chloride is an excellent tracer of human impacts to water resources, and is typically found in low concentrations in northeast Minnesota lakes, absent man-induced inputs from road salting or wastewater discharges. Examination of chloride data indicated that nearly all values were below 1 mg/L, with most below detection limits (0.5 – 1.0 mg/L). This was expected given the lake's park setting. Collectively, these data further indicate that Bear Head has excellent water quality.

Figure 19. Bear Head Lake 2008-10 total phosphorus, chlorophyll-a and Secchi depth





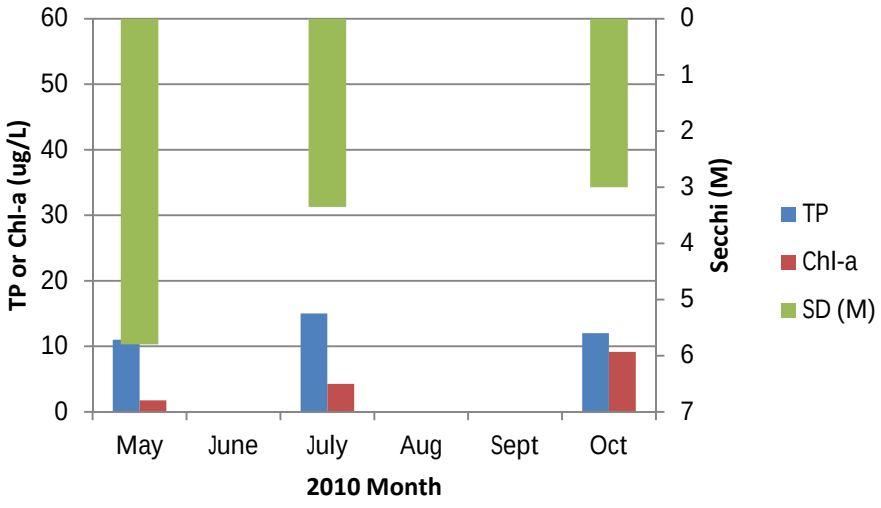


Figure 20. 2008-10 average Bear Head Lake total phosphorus concentrations in the epilimnion and hypolimnion. Starndard errors noted in red.

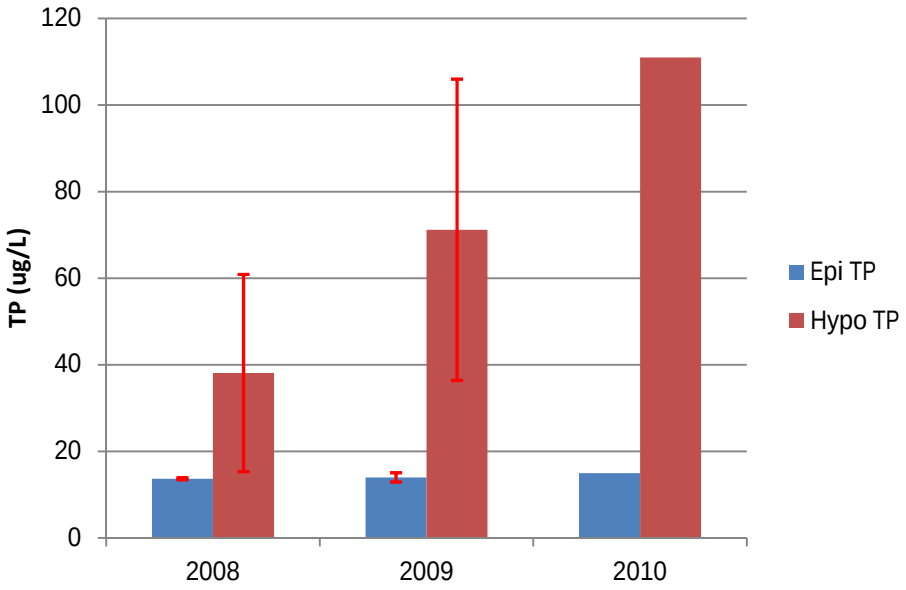
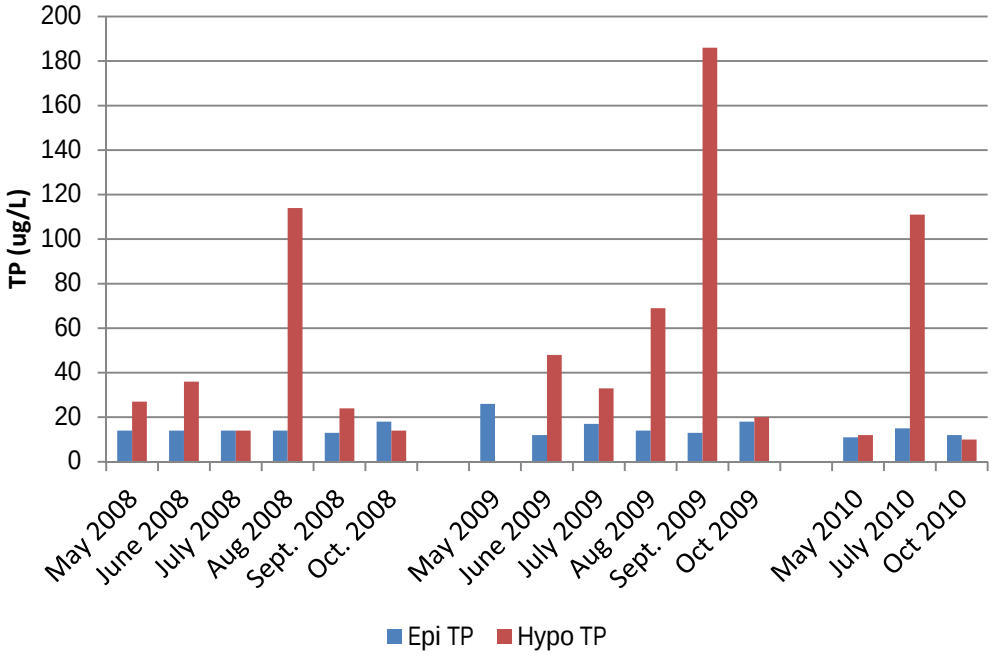


Figure 21. 2008-2010 monthly comparisons of total phosphorus concentrations in the epilimnion and hypolimnion.



Phytoplankton (algae) for Bear Head Lake in 2008 and 2009 are presented in terms of algal type (Figures 22 and 23). The samples from July 2008 were lost or damaged, so direct comparisons among years are limited. Blue greens and diatoms were the dominant forms, respectively, while dinoflagellates, yellow-browns, and green algae were sparse. Seasonal algal dynamics did vary between years. Green algae were more common in the summer of 2009. Blue greens dominated the community in late summer both years, which is normal for mesotrophic lakes. A total of 18 taxa were identified in 2008 versus 27 taxa in 2009. This may be a function of climate, or natural variability in algae species or sample collection. A seasonal transition in algal types from diatoms to green to blue-green algae is rather typical for mesotrophic and eutrophic lakes in Minnesota. In practice, greens are seldom abundant in Minnesota lakes and there is often a transition from diatom to blue-green dominance.

Figure 22. Algal composition for Bear Head Lake in 2008

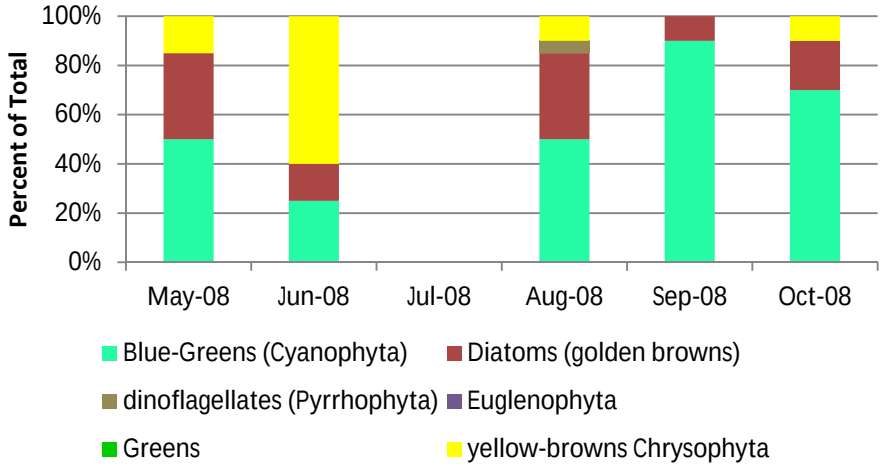
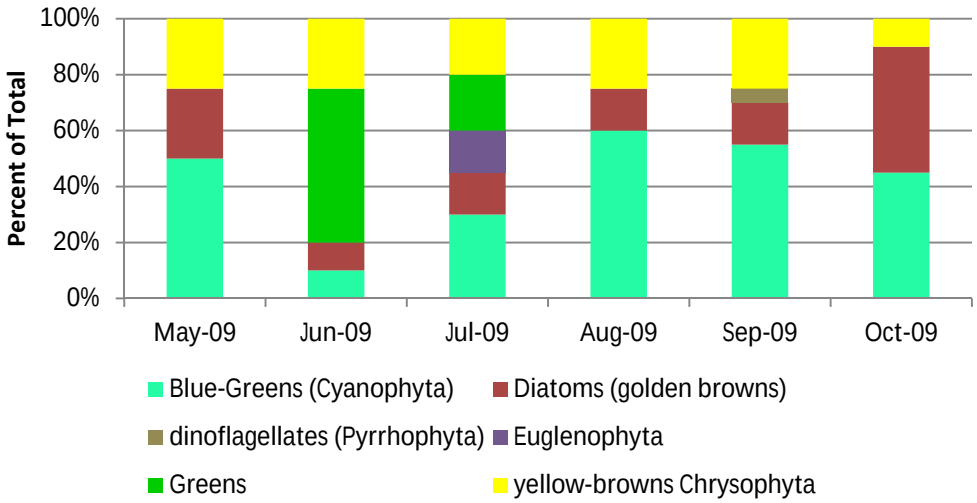


Figure 23. Algal composition for Bear Head Lake in 2009



Zooplankton

Zooplankton samples were analyzed by Jodie Hirsch at the MDNR. A summary report was prepared that included information for all the Sentinel lakes and that report is the basis for the following comments on Bear Head Lake (Hirsch 2009). Mean 2008 zooplankton densities in Bear Head were below average when compared to the five other Border region Sentinel lakes (Table 10). Hirsch (2009) found that, in general, as lake productivity increased (e.g. TP or chl-*a*) the relative abundance (biomass) of zooplankton increased as well. This appears to be the case for Bear Head, although its abundance is similar to the oligotrophic Trout Lake (Figure 24). Northern Light Lake had the lowest density and biomass, and has since been replaced by Tait Lake. Densities and biomass in Bear Head tended to be highest in spring and lower later in the season, perhaps because of predation by fish (Figure 24). Other observations on Bear Head's zooplankton community were provided by Hirsch (personal communication, November 2011):

1. Compared to all 24 Sentinel lakes, Bear Head would be expected to be one of the lakes with the lowest densities and biomass because of its location in the Shield Ecoregion.
2. Compared to the other five lakes in the Shield Ecoregion, it is one of the lakes with the lowest densities and biomass. Trout Lake has similar densities and biomass, but Trout Lake has lower TP and chl-*a* levels than Bear Head.
3. Possible explanations for the low densities and biomass in Bear Head could be fish predation. During the last decade, bluegill - which are efficient grazers of cladoceran zooplankton - have been very abundant in the lake. Crappie, another zooplanktivore, may also be more prominent now than in the past (Figure 11). Early in the year there are larger cladocerans (*Daphnia*) present but numbers drop as the season progresses, presumably as fish predation ramps up. Cladocerans present later in the season tend to be the smaller *Bosmina* and *Chydorus*.
4. The morphology of Bear Head Lake may also contribute to the higher fish predation. A good portion of the lake is fairly shallow, less than 9 m (30 feet), especially the northern half of the lake, which would be good for fish like bluegill, but not for *Daphnia*, as the *Daphnia* do not have a lot of volume in the hypolimion to vertically migrate down to avoid predation during the day.

Zooplankton biomass and density from 2008-2010 in Bear Head Lake are shown in Figure 25. Figure 26 shows the relative composition of cladocerans and copepods. *Daphnia* were often low in number and biomass (Figure 25). The zooplankton community over the three year period of record tended to be dominated by copepods (Figure 26). Zooplankton density tended to be highest in the spring, and slowly declined throughout the season.

Figure 24. Mean monthly zooplankton densities and biomass for border Sentinel lakes

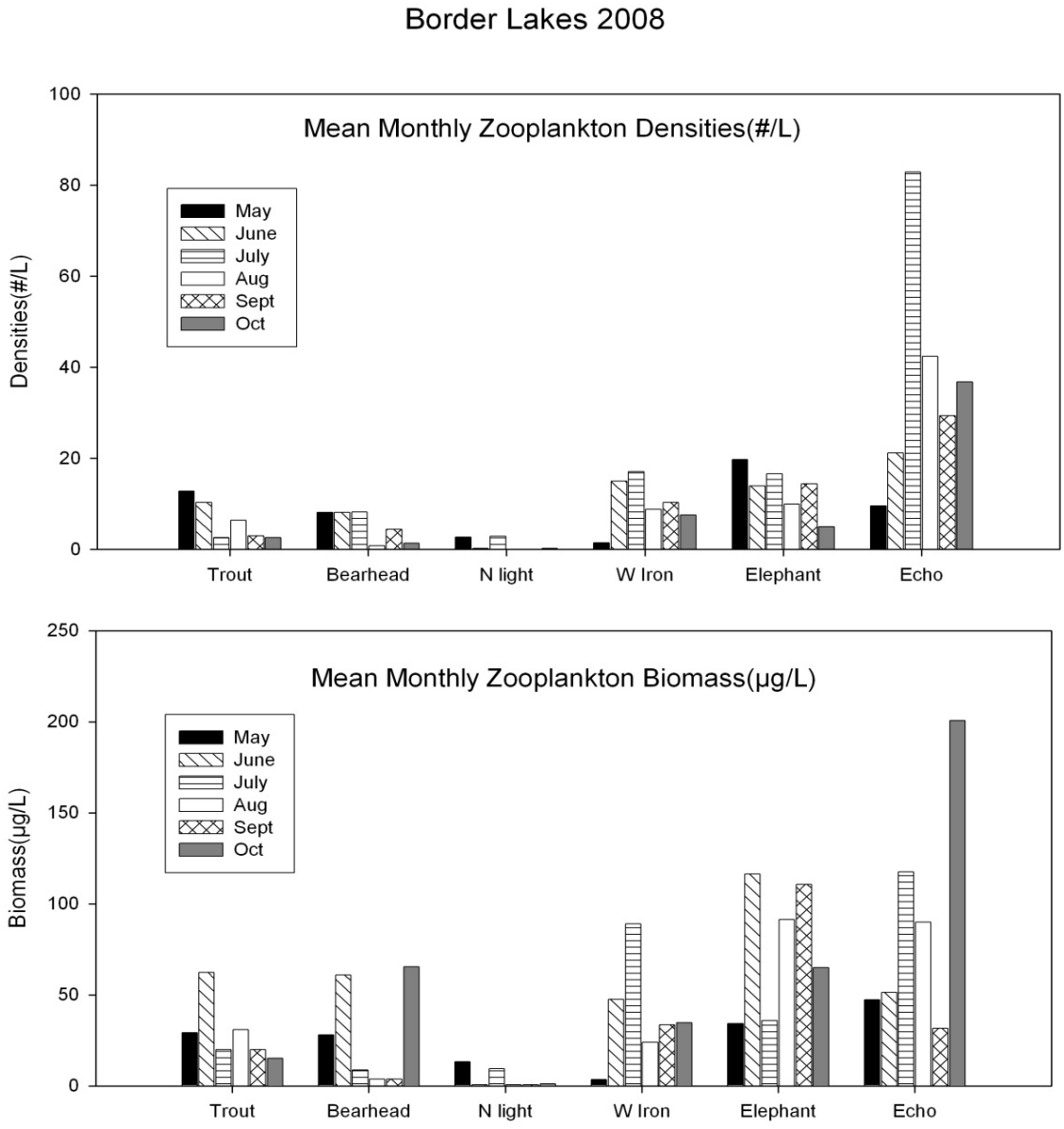
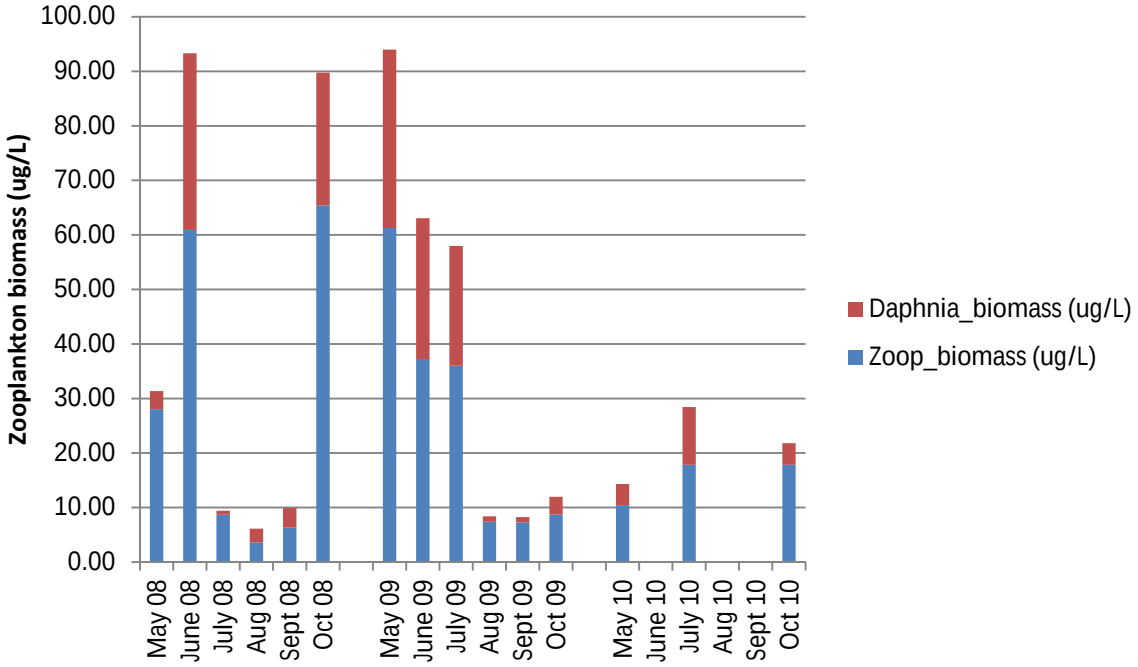


Table 10. 2008 zooplankton data from all Sentinel lakes

Sentinel lakes zooplankton 2008	Mean annual densities (#/L)	Mean annual biomass (µg/L)	Total# taxa
Western Cornbelt Plains (WCBP & NGP)			
Artichoke	139.64	724.05	12
Shaokotan	107.55	1070.97	11
St. James	62.73	108.56	10
St.Olaf	60.23	336.20	15
Carrie	56.41	254.21	13
Madison	52.78	310.93	14
North Central Hardwood Forest (NCHF)			
Peltier	78.75	1098.39	12
Pearl	59.68	221.13	14
Belle	57.67	340.06	12
South Center	24.72	123.71	18
Carlos	19.66	73.49	16
Cedar	11.31	41.85	11
Northern Lakes and Forests (NLF)			
Portage	100.10	277.38	10
Red Sand	79.31	127.96	18
South Twin	25.83	54.93	12
Hill	17.73	147.29	11
Elk	16.95	47.10	12
Ten Mile	14.94	44.89	14
Border Lakes (NLF)			
Echo	37.03	89.68	12
Elephant	13.26	75.50	12
White Iron	10.00	38.64	14
Trout	6.28	29.52	13
Bear Head	5.15	38.37	14
Northern Light	1.03	4.16	13

Figure 25. Zooplankton biomass and density in Bear Head Lake, 2008-2010



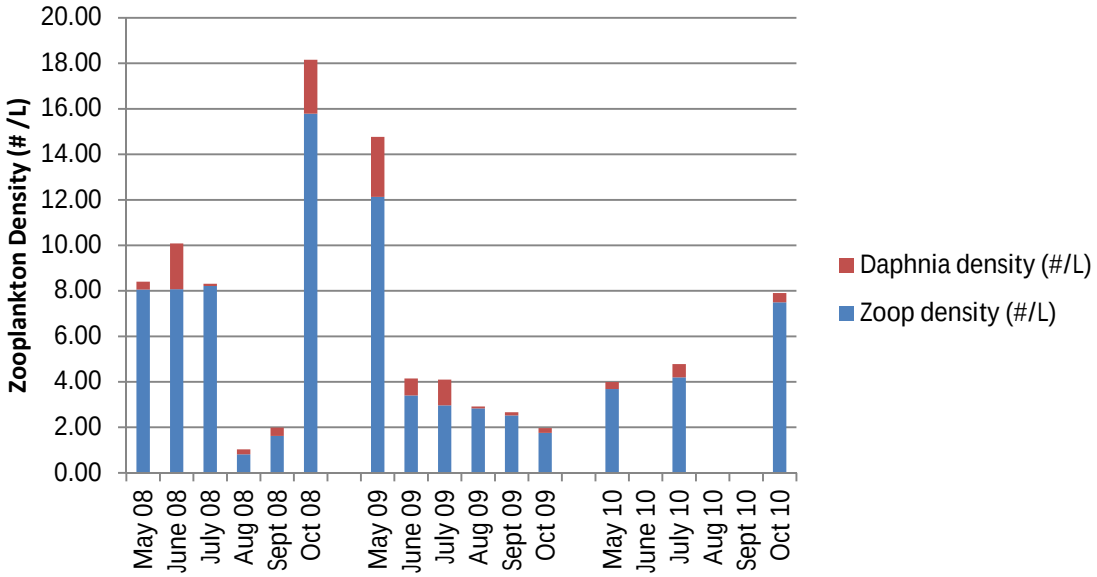
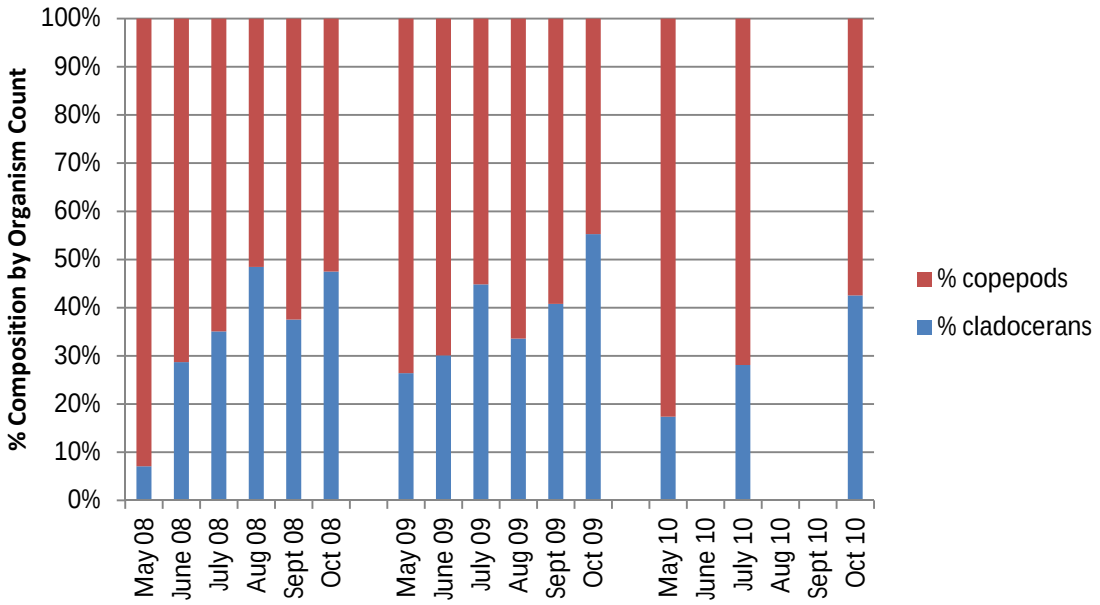


Figure 26. Cladoceran and copepod counts in Bear Head Lake, 2008-2010



Trophic state index

One way to evaluate the trophic status of a lake and to interpret the relationship between TP, chl-*a*, and Secchi disk transparency is Carlson's Trophic State Index (TSI) (Carlson 1977). TSI values are calculated as follows:

Total Phosphorus TSI (TSIP) = 14.42 ln (TP) + 4.15

Chlorophyll-*a* TSI (TSIC) = 9.81 ln (chl-*a*) + 30.6

Secchi disk TSI (TSIS) = 60 – 14.41 ln (SD)

TP and chl-*a* are in µg/L and Secchi disk is in meters. TSI values range from 0 (ultra-oligotrophic) to 100 (hypereutrophic). In this index, each increase of ten units represents a doubling of algal biomass. Comparisons of the individual TSI measures provide a basis for assessing the relationship among TP, chl-*a,* and Secchi (Figure 27). In general, the phosphorus, chlorophyll, and Secchi TSI values for Bear Head Lake are in fairly close correspondence with each other (though chl-*a* is slightly high relative to TP). The TSI values are shown based on MPCA data for 2008-2010 (Figure 27). Based on an average TSI score of 46 Bear Head Lake would be characterized as mesotrophic.

Figure 27. Bear Head Lake TSI values from 2008-2010 MPCA Sentinel lake monitoring data

TSI < 30 Classical Oligotrophy: Clear water, oxygen throughout the year in the hypolimnion, salmonid fisheries in deep lakes.

TSI 30 - 40 Deeper lakes still exhibit classical oligotrophy, but some shallower lakes will become anoxic in the hypolimnion during the summer.

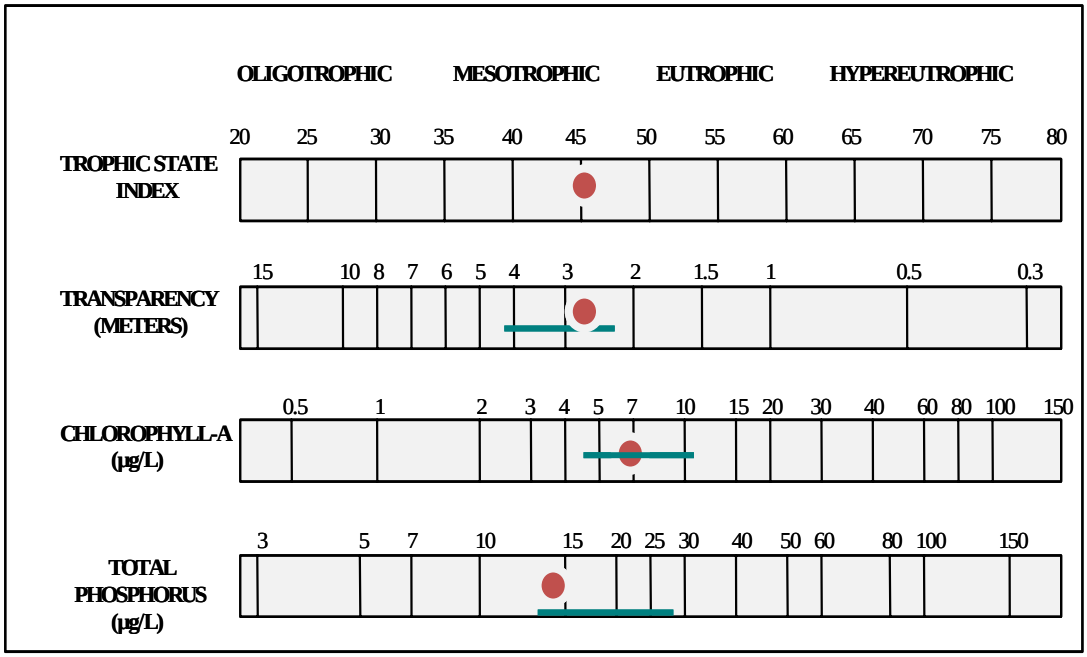
TSI 40 - 50 Water moderately clear, but increasing probability of anoxia in hypolimnion during summer.

TSI 50 - 60 Lower boundary of classical eutrophy: Decreased transparency, anoxic hypolimnia during the summer, macrophyte problems evident, warm-water fisheries only.

TSI 60 - 70 Dominance of blue-green algae, algal scums probable, extensive macrophyte problems.

TSI 70 - 80 Heavy algal blooms possible throughout the summer, dense macrophyte beds, but extent limited by light penetration. Often would be classified as hypereutrophic.

TSI > 80 Algal scums, summer fish kills, few macrophytes, dominance of rough fish.



After Moore, l. and K. Thornton, [Ed.]1988. Lake and Reservoir Restoration Guidance Manual. USEPA>EPA 440/5-88-002.

NLF Ecoregion Range ——— Bear Head Lake 2008-2010 ●

Trophic Status Trends

One aspect of lake monitoring is to assess trends in the condition of the lake, where possible, based on data gathered through the MPCA's Citizen Lake Monitoring Program or other available data in STORET. A review of STORET data indicates that historical data are very sparse on Bear Head, limited to one phosphorus sample from the 1970s (14 µg/L in 1977), one Secchi measurement in June 1961 (5.5 m), and several snapshots from LANDSAT satellite imagery (http://lakes.gis.umn.edu/#69025400). Therefore, water quality trends cannot be determined, since consistent sampling began in 2008 with the start of Sentinel lakes monitoring. For most of our trend assessments, we seek a minimum of seven-eight years of data before we start to examine data for significant trends.

Even though historical data are lacking on Bear Head, the data were explored for seasonal patterns. An examination of the seasonal (i.e. May, July, and October) sampling events indicate that there is little variability among years (Figure 19). The spring 2009 TP concentrations were slightly higher than 2008 and 2010; the May 2009 sample may have been influenced by windy conditions during sample collection. Very high winds that day prevented sampling at the established site. The sample was collected in shallower water near shore. Given Bear Head's relatively stable lake levels, seepage hydrology, and small forested watershed, we expect seasonal concentrations to exhibit minimal variation and be fairly similar among years.

Modeling

Numerous complex mathematical models are available for estimating nutrient and water budgets for lakes. These models can be used to relate the flow of water and nutrients from a lake's watershed to observed conditions in the lake. Alternatively, they may be used for estimating changes in the quality of the lake as a result of altering nutrient inputs to the lake (e.g., changing land uses in the watershed) or altering the flow or amount of water that enters the lake. To analyze the 2008-10 water quality of Bear Head Lake, the Minnesota Lake Eutrophication Analysis Procedures (MINLEAP) model (Wilson and Walker, 1989) was used. A comparison of MINLEAP predicted vs. observed values is presented in Table 11.

MINLEAP was developed by MPCA staff based on an analysis of data collected from the ecoregion reference lakes. It is intended to be used as a screening tool for estimating lake conditions with minimal input data and is described in greater detail in Wilson and Walker (1989). The model predicts in-lake TP from these inputs. Chl-*a* and Secchi predictions are derived from Minnesota-based regression equations. For analysis of Bear Head Lake, MINLEAP was applied as a basis for comparing the observed (2008-10 average) TP, chl-*a,* and Secchi values with those predicted by the model based on the lake size and depth and the area of the watershed.

The BATHTUB model (Walker, 2004) provides a further basis for estimating water and nutrient budgets for Bear Head Lake using a combination of runoff and P export coefficients based on land use in the watershed and data from similar systems in this ecoregion. Because groundwater cannot be modeled with BATHTUB, and no streams enter the lake, modeled sources of TP to the lake were minimal and

included precipitation, dry atmospheric deposition, and direct runoff to the lake from the surrounding forests and wetlands. Human-caused sources of TP to the lake, such as wastewater, were estimated only for the park's two restroom / shower buildings, since the waste is treated with an on-site septic system. Potential wastewater impacts from the park's remaining outhouses and RV pump stations were excluded because that wastewater is routinely pumped and hauled away to a wastewater treatment plant.

Bear Head Lake is located in the NLF ecoregion and the MINLEAP model was run using NLF-based inputs. To improve model predictions, inflow TP concentration were calibrated at 30 µg/L (less than the 52 µg/L default) to reflect the lake's relatively pristine forested watershed and limited overland runoff. The observed and predicted TP values for Bear Head Lake were identical. Observed ch-*a* is higher than predicted and that results in lower than predicted Secchi; however the differences among observed and predicted values are not statistically significant. Still, this difference will be important to monitor since elevated chlorophyll beyond what is predicted from total phosphorous is an indicator of over-predation by fish or other predators on *Daphnia* zooplankton.

MINLEAP predicts a phosphorus loading rate of about 116 kilograms per year entering Bear Head Lake from its small forested watershed and atmospheric deposition on the lake surface. The model predicts approximately 65 percent of the TP will be retained in the lake, a reasonable estimate given the lake's small watershed, volume, and relatively long residence time (estimated at ~ 4 years). An additional subroutine in the MINLEAP model estimates the "background" TP for the lake based on its alkalinity and mean depth and a regression equation developed by Vighi and Chiaudani (1985). For Bear Head Lake, this value is estimated to be 12 µg/L, close to the observed concentration (Table 11).

BATHTUB predicted slightly higher concentrations of chl-a, and lower Secchi values than MINLEAP; however, the concentrations were also not statistically different than the observed values. BATHTUB's estimates of water load, volume, and residence time were also comparable to results from the MINLEAP model (Table 12). BATHTUB estimated an annual TP load to Bear Head Lake of 135 kg, very similar to the MINLEAP estimate of 116 kg (Table 11 and 12). Overall, predictions for Bear Head from both models indicate the relative proportion of phosphorus loading to the lake, and observed TP concentrations in the lake are very close to what we would expect for a lake of this size, in this region of the state, and with this type of landuse. Given that Bear Head is a seepage lake and likely has significant interaction with groundwater (both inflow and outflow) the nutrient and water budgets and water residence time should be considered best estimates given the available information.

The TP load from the park's shower buildings was estimated at 9.4 kg per year, based on the park's water usage rate of 500,000 gallons per season (personal communication, Jody Popesh, Bear Head Lake State Park, November 2011), and a septic effluent TP concentration of 5 mg/L (US EPA, 2002); however, we assume that a well maintained and up to code septic system will retain about 80 percent of the phosphorus in the soil, which reduces the relative contribution to approximately 1.8 kg (or <2 percent of the lake's total TP load based on BATHTUB's estimate). Although water quality remains excellent (and variability remains low; Figure 19), and the majority of TP entering the lake comes from natural sources (such as precipitation and runoff from the surrounding forests and wetlands), it is important that all anthropogenic sources of TP and runoff to the lake be minimized. Park staff should continue their good practices in maintaining the water and wastewater systems, and staff and visitors should be encouraged to reduce water usage and minimize soil erosion near the lake shore.

Table 11. MINLEAP model results for Bear Head Lake

Parameter	2008- 2010 Bear Head Lake Observed	MINLEAP Predicted NLF Ecoregion
TP (µg/L)	14	14
Chl-*a* (µg /L)	7.1	3.0
Secchi (m)	3.0	3.9
P loading rate (kg/yr)	-	116
P retention (%)	-	65
P inflow conc. (µg/L)	-	30
Water Load (m/yr)	-	1.1
Outflow volume (hm^3/yr)	-	2.9
Residence time (yrs)		3.9
Vighi & Chiaudani P (ug/L)		12

Table 12. BATHTUB model results for Bear Head Lake

Parameter	2008- 2010 Bear Head Lake Observed	BATHTUB Predicted
TP (µg/L)	14	15.7
Chl-*a* (µg /L)	7.1	7.2
Secchi (m)	3.0	3.1
P loading rate (kg/yr)	-	135
P retention (%)	-	65
P inflow conc. (µg/L)	-	30
Water Load (m/yr)	-	1.1
Outflow volume (hm^3/yr)	-	3.0
Residence time (yrs)		3.7

303(d) Assessment and Goal Setting

The federal Clean Water Act requires states to adopt water quality standards to protect waters from pollution. These standards define how much of a pollutant can be in the water and still allow it to meet designated uses, such as drinking water, fishing, and swimming. The standards are set on a wide range of pollutants, including bacteria, nutrients, turbidity, and mercury. A water body is "impaired" if it fails to meet one or more water quality standards.

Under Section 303(d) of the Clean Water Act, Minnesota is required to asses all waters of the state to determine if they meet water quality standards. Waters that do not meet standards (i.e., impaired waters) are added to the 303(d) list and updated every even-numbered year. In order for a lake to be considered impaired for aquatic recreation use, the average TP concentration must exceed the water quality standard for its ecoregion. In addition, either the chl-*a* concentration for the lake must exceed the standard or the Secchi data for the lake must be below the standard. A minimum of eight samples collected over two or more years are needed to conduct the assessment. There are numerous other water quality standards for which we assess Minnesota's water resources. An example is mercury found in fish tissue. If a water body is listed, an investigative Total Maximum Daily Load (TMDL) study must be conducted to determine the sources and extent of pollution, and to establish pollutant reduction goals needed to restore the resource to meet the determined water quality standards for its ecoregion. The MPCA is responsible for performing assessment activities, listing impaired waters, and conducting TMDL studies in Minnesota.

Bear Head Lake was assessed relative to the NLF Class 2B ecoregion standards (Table 13). The 2008, 2009, 2010, and long-term summer-mean TP, chl-*a* and Secchi for Bear Head Lake fully meet the water quality standards (Table 13). Based on these results, Bear Head Lake is meeting eutrophication standards for NLF ecoregion 2B waters (i.e. those waters that support a cool and warm water fishery).

Table 13. Eutrophication standards by ecoregion and lake type (Heiskary and Wilson, 2005). Bear Head Lake 2008-2010 summer means; long-term means provided for comparison.

Ecoregion	TP µg/L	Chl-*a* µg/L	Secchi meters
NLF – Lake trout (Class 2A)	< 12	< 3	> 4.8
NLF – Stream trout (Class 2A)	< 20	< 6	> 2.5
NLF – Aquatic Rec. Use (Class 2B)	**< 30**	**< 9**	**> 2.0**
NCHF – Stream trout (Class 2a)	< 20	< 6	> 2.5
NCHF – Aquatic Rec. Use (Class 2b)	< 40	< 14	> 1.4
NCHF – Aquatic Rec. Use (Class 2b) Shallow lakes	< 60	< 20	> 1.0
WCBP & NGP – Aquatic Rec. Use (Class 2B)	< 65	< 22	> 0.9
WCBP & NGP – Aquatic Rec. Use (Class 2b) Shallow lakes	< 90	< 30	> 0.7
Bear Head Lake 2008	**13.7**	**6.5**	**2.7**
Bear Head Lake 2009	**14.0**	**8.5**	**3.3**
Bear Head Lake 2010	**15.0**	**4.3**	**3.3**
Bear Head Lake long-term mean	**14.2**	**6.4**	**3.0**

References

Beck, M. W., L. Hatch, B. Vondracek, and R. D. Valley. 2010. Development of a macrophyte-based index of biotic integrity for Minnesota lakes. Ecological Indicators 5:968-979.

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

Charpentier, F. and B.H. Jamnick. 1994. ZCOUNT-A zoological counting program. Version 2.4 Voila Data Inc., Gloucester, Ontario.

Drake, M. T., and D. L. Pereira. 2002. Development of a fish-based index of biotic integrity for small inland lakes in central Minnesota. North American Journal of Fisheries Management 22:1105-1123.

Fayram, A. H., M. J. Hansen, and T. J. Ehlinger. 2005. Interactions between walleyes and four fish species with implications for walleye stocking. North American Journal of Fisheries Management 25:1321-1330.

Heiskary, S.A. and W.W. Walker Jr. 1988. Developing Phosphorus Criteria for Minnesota Lakes. Lake and Reservoir Management 4(1): 1-9.

Heiskary, S.A. and C.B. Wilson, 2005. Minnesota lake water quality assessment report: Developing nutrient criteria, 3rd edition. Minnesota Pollution Control Agency, 176 p.

Heiskary, S.A. and C.B. Wilson. 2008. Minnesota's approach to lake nutrient criteria development. Lake and Reserv. Manage. 24:282-297.

Hirsch, J. 2009. Sentinel Lakes Study Progress Report- Zooplankton 2008

Jacobson, P.C., H.G. Stefan, and D.L. Pereira.2010. Coldwater fish oxythermal habitat in Minnesota lakes: influence of lake productivity, morphometry, and climate. Canadian Journal of Fisheries and Aquatic Sciences 67:2002-2013.

Li, J., Y. Cohen, D. H. Schupp, and I. R. Adelman. 1996a. Effects of walleye stocking on population abundance and fish size. North American Journal of Fisheries Management 16:830-839.

Li, J., Y. Cohen, D. H. Schupp, and I. R. Adelman. 1996b. Effects of walleye stocking on year-class strength. North American Journal of Fisheries Management 16:840-850.

Lyons, J., T. Zorn, J. Stewart, P. Seelbach, K. Wehrly, and L. Wang. 2009. Defining and characterizing coolwater streams and their fish assemblages in Michigan and Wisconsin, USA. North American Journal of Fisheries Management 29:1130-1151.

Madsen, J. D. 1999. Point intercept and line intercept methods for aquatic plant management. Army Corps of Engineers Waterways Experiment Station, MI-02, Vicksburg, MS.

McCollor, S. and S. Heiskary. Selected water quality characteristics of minimally impacted streams from Minnesota's seven ecoregions. Addendum to Descriptive characteristics of the seven ecoregions of Minnesota. MPCA. St. Paul MN

McInerny, M. C., and T. K. Cross. 2008. Length at age estimates of black crappie and white crappie among lake classes, reservoirs, impoundments, and rivers in Minnesota. Minnesota Department of Natural Resources, 551, St. Paul.

MN DNR. 2008. Long range plan for muskellunge and large northern pike management through 2020. Available at: http://files.dnr.state.mn.us/fish_wildlife/fisheries/plans/muskiepike_2020.pdf

Omernik, J.M. 1987. Ecoregions of the conterminous United States. Annals of the Asso. Amer. Geogr. 77(1):118-125.

Schupp, D. and B. Wilson. 1993. Developing lake goals for water quality and fisheries. Lakeline 13: 18-21.

US Environmental Protection Agency, 2002. Onsite wastewater treatment systems manual, EPA/625/R-00/008**,** Office of Water, Office of Research and Development, U.S. Environmental Protection Agency February 2002. http://www.epa.gov/nrmrl/pubs/625r00008/html/625R00008.htm

Valley, R. D. 2009 Sustaining Lakes in a Changing Environment: operational research and management plan. Division of Fish and Wildlife, unpublished draft report.

Walker, W., 2004. BATHTUB version 6.1. Simplified Techniques for Eutrophication Assessment and Prediction. USAE Waterways Experiment Station, Vicksburg, Mississippi; April 2004.

Wilson, C.B. and W.W. Walker 1989. Development of lake assessment methods based upon the aquatic ecoregion concept. Lake and Reserv. Manage. 5(2):11-22.

Appendix A

Lake surface water quality data for Bear Head Lake for 2008-2010

All water quality data can be accessed at: http://www.pca.state.mn.us/data/eda; blank cells = no data

Lake name	Lake ID	Sample date	Site ID	Secchi	TP	Chl-*a*	Alkalinity	Chloride	TKN	Color, apparent	TSS
				Meters	µg/L	µg/L	mg/L	mg/L	mg/L	PCU	mg/L
Bear Head	69-0254	5/13/2008	101	2.4	14	4.17	13	<1	0.4	40	2.4
Bear Head	69-0254	6/16/2008	101	2.1	14	6.45	15	<1	0.46	40	<1
Bear Head	69-0254	7/10/2008	101	2.1	14	8.52	15	<1	0.44	30	1.2
Bear Head	69-0254	8/11/2008	101	2.4	14	3.26	15	<!	0.48	20	2
Bear Head	69-0254	9/15/2008	101	2.4	13	7.76		<1	0.46		
Bear Head	69-0254	10/13/2008	101	3	18	14.3	15	<1	0.5	20	2.4
Bear Head	69-0254	5/20/2009	101	2.4	26	5.27	14	<1	0.66	30	1.6
Bear Head	69-0254	6/9/2009	101	4.15	12	12.4			0.38		
Bear Head	69-0254	7/15/2009	101	2.8	17	12.5	16	<1	0.66	5	2.4
Bear Head	69-0254	8/11/2009	101	3.35	14	3.86			0.48		
Bear Head	69-0254	9/22/2009	101	2.7	13	5.3			0.47		
Bear Head	69-0254	10/13/2009	101	3.35	18	5.49	15	<1	0.63	20	2.4
Bear Head	69-0254	5/25/2010	101	5.8	11	1.75	15	0.504	0.39	10	2
Bear Head	69-0254	7/20/2010	101	3.35	15	4.26	15	<1	0.65	20	1.6
Bear Head	69-0254	10/12/2010	101	3	12	9.16	18	<0.5	0.62	20	5.2