Emmons & Olivier Resources, Inc.
for the Comfort Lake-Forest Lake Watershed District

Moody Lake Internal Load Treatment Options

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PROJECT BACKGROUND

Moody Lake, located in the Comfort Lake – Forest Lake Watershed District (CLFLWD), was included in MPCA's 2008 draft of its 303d list of impaired waters for excess nutrients based on a study of water quality in Moody Lake and ten other lakes in the CLFLWD in 2006. The District's Water Quality Study identified high sediment release rates under anoxic conditions, a persistent population of curly-leaf pondweed, a lack of macrophyte diversity, and a rough fish problem in Moody Lake (Wenck 2007). To reduce the phosphorus loading to Moody Lake and improve its water quality, the study proposed four phosphorus load reduction methods: a livestock exclusion and wetland restoration along a major tributary, rough fish removal, herbicide treatment of curly-leaf pondweed, and an in-lake alum treatment of sediment phosphorus. Many of the recommended actions are underway. The District completed a livestock exclusion project and wetland restoration in Subwatershed NBL12 near 250th Street and Lofton Avenue identified by the Water Quality Study (Wenck 2007) and has completed a feedlot project in a drainage area just west of Moody Lake in Subwatershed NBL18 near 245th Street and Lofton Avenue. The livestock exclusion project in Subwatershed NBL12 is expected to reduce 23 pounds of its model-predicted livestock phosphorus contribution to Moody Lake (99 pounds of total phosphorus per year; Wenck 2007). Rough fish removal from Moody Lake was conducted in 2009 and resulted in the removal of a large number of bullheads from Moody Lake. The District is also planning the installation of a fish barrier that would block passage of fish between Moody Lake and the downstream Bone Lake. A fish barrier is also being considered for the north inlet to Moody Lake.

With the completion of a number of management activities in the watershed and in Moody Lake, the goal of the current project is to collect new data and re-evaluate options for internal phosphorus load management of Moody Lake. The options evaluated in this study include methods to address phosphorus loads from macrophytes, rough fish, and sediments.

The report is organized into four main sections. The first section, In-Lake Data Summary, is a summary of existing in-lake data from the CLFLWD Water Quality Study (Wenck 2007) and in-lake data collected in 2009 for the current study. The second section, Macrophyte Management, reviews and analyzes historical macrophyte surveys in Moody Lake for curly-leaf pondweed invasion threat. The third section, In-Lake Phosphorus Loading Treatment Options, reviews lake management options to reduce phosphorus loading reported in the CLFLWD Water Quality Study and other options that are applicable to Moody Lake including evaluation of curly-leaf pondweed treatment options. The final section of the report, Summary of Management Recommendations, presents our recommendations for the most suitable in-lake phosphorus loading treatment options for Moody Lake and a recommended monitoring and treatment schedule for the next five years.

IN-LAKE WATER QUALITY DATA SUMMARY

The following is a summary of existing in-lake water quality data for Moody Lake. This section provides a summary analysis of the background data used to evaluate treatment options based on in-lake conditions. The physical setting, hydrology, fish community, and watershed loading and lake response model data were summarized from the District's Water Quality Report (Wenck 2007). Recent sediment, water quality, and lake stratification data were collected and/or analyzed for this report by EOR. These parameters were studied because of their importance to in-lake phosphorus loading and water quality. A detailed description of each parameter is included below. Note that the macrophyte community is described in the Macrophyte Management section.

Physical Setting

Moody Lake is located in the Comfort Lake-Forest Lake Watershed District, within Chisago Lake Township and just north of the City of Scandia. The physical setting of a lake determines the level of interaction between lake waters and the watershed and sediments. A large watershed area to lake surface area ratio results in greater phosphorus loads from the watershed and a smaller lake surface area in which to assimilate the phosphorus. The water quality of shallow lakes tends to be strongly influenced by the macrophyte community and sediments. The water quality of deep lakes tends to be influenced more strongly by lake stratification and dissolved oxygen levels in bottom waters.. While Moody Lake is not classified as a shallow lake, it has large areas of shallow waters and deep waters. Therefore, an assessment of in-lake water quality in Moody Lake should address the macrophyte community, sediments, and lake mixing.

The surface area of Moody Lake is fairly small at 34 acres with a volume of 465 ac-ft. Other physical parameters of Moody Lake are summarized in Table 1. The majority of the lake is shallow with a small proportion of deep (>15 feet) waters. The relationship between lake volume and depth is illustrated by Figure 1 and Table 2. The main tributaries of Moody Lake drain the northeast and northwest sections of the watershed through culverts on the north edge. The watershed area draining into Moody Lake is 2435 acres, or 72 times the size of the surface of the lake. This is a fairly high watershed to lake area ratio suggesting that watershed loading is a large contributor to phosphorus loading. The land use in the watershed is composed of 31% cropland, 25% wetland, 17% grassland, and 14% forest. Additional evaluation of watershed loading sources is provided in the Watershed Loading and Lake Response Model section below.

Table 1. Moody Lake physical parameters (adapted from Wenck 2007)

Parameter	Value	Unit
Lake area	34	ac
Lake volume	465	ac-ft
Watershed area	2435	ac
Watershed: lake area	72	
Average depth	13.8	ft
Maximum depth	48	ft
Littoral area (< 15 feet)	21	ac
	61	%

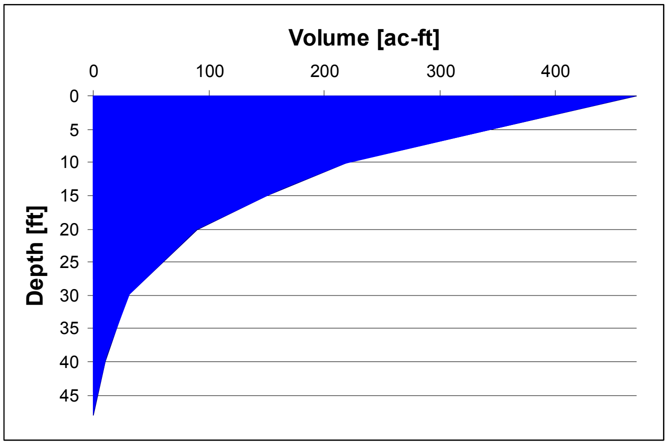


Figure 1. Moody Lake water volume to lake depth

Table 2. Moody Lake water volume to lake depth data

Depth (ft)	Area (ac)	Volume (ac-ft)
0	34	470
10	17	220
15	13	150
20	9	90
30	3	30
40	2	10
48	-	-

Hydrology

The dominant inflow of water to Moody Lake is watershed runoff, accounting for 81%, 86%, and 69% of total inflow under benchmark, wet, and dry conditions, respectively (Wenck 2007). Other sources of water are precipitation directly on the lake surface and flow from upstream water bodies via surface and groundwater. The dominant outflow of water from Moody Lake is discharge through an outlet under benchmark (77%) and wet (90%) conditions. Under dry conditions, outflow is composed fairly evenly of evaporation, discharge from the outlet, and discharge via regional groundwater flow. Residence time within a lake corresponds to the length of time for the volume of the lake to be replaced. The residence time of water in Moody Lake is short, 0.3 to 2.0 years, with the shortest residence time occurring under wet conditions. Therefore, changes made in the watershed that reduce phosphorus loading may affect in-lake TP within 1-2 years after implementation. The inflow and outflow volumes for Moody Lake are summarized in Table 3.

Table 3. Moody Lake water budget under benchmark, wet, and dry conditions (adapted from Wenck 2007)

Moody Lake Water Budget Outflow and Inflow Volumes		Benchmark Conditions (2004)	Wet Conditions (2003)	Dry Conditions (2006)
Inflow [ac-ft]	Watershed Runoff	498 (81%)	1,288 (86%)	160 (69%)
	Precipitation (direct)	61 (10%)	66 (4%)	64 (27%)
	Flow from upstream lakes via surface	38 (6%)	110 (7%)	7 (3%)
	Flow from upstream lakes via groundwater	16 (3%)	41 (3%)	2 (1%)
TOTAL INFLOW [ac-ft]		**614 (100%)**	**1,505 (100%)**	**233 (100%)**
Outflow [ac-ft]	Evaporation from lake	(81)	(87)	(87)
	Discharge through outlet	(470)	(1,355)	(82)
	Regional groundwater outflow	(64)	(64)	(64)
TOTAL OUTFLOW [ac-ft]		**(614)**	**(1,505)**	**(233)**
Moody Lake Residence Time [yr]		0.8	0.3	2.0

Lake Stratification

The stratification of lake waters influences in-lake water quality because of differences in dissolved oxygen concentrations between bottom and surface waters. When surface waters warm up faster than bottom waters during the summer, a strong temperature differential can develop in deep areas of lakes which prevent surface and bottom waters from mixing. During stratification, dissolved oxygen levels in bottoms water can become very low and result in chemical release of phosphorus from the sediments. When phosphorus rich bottom waters mix with surface waters in spring and fall, noxious algal blooms can occur.

Moody Lake was strongly thermally stratified every year between 2005 and 2007 (Figure 2, Figure 3, and Figure 4). The cold, bottom waters typically comprised the lowest 8 feet of lake depth and the warm, surface waters typically comprised the upper 4 feet of lake depth. The waters between 4 and 8 feet in lake depth were characterized by rapidly declining temperature and dissolved oxygen. There was no dissolved oxygen present in the bottom waters of Moody Lake during the growing season in 2005 through 2007. Phosphorus release from deep sediments is expected in Moody Lake. Dissolved oxygen level and depth time series for 2005 to 2007 are illustrated in Figure 5, Figure 6, and Figure 7.

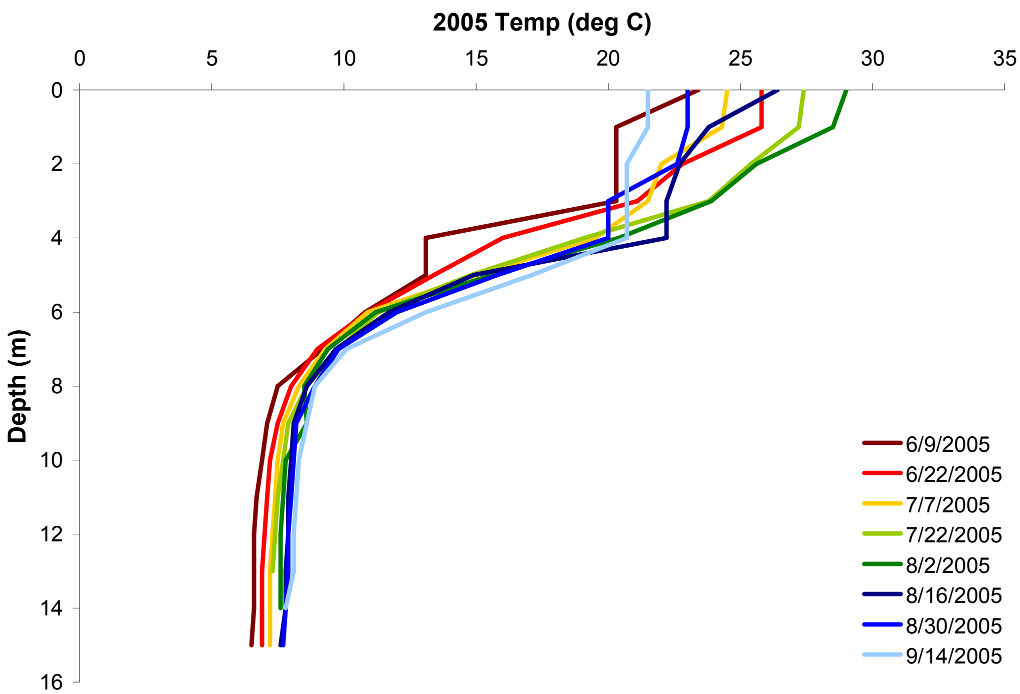


Figure 2. Temperature and depth time series for Moody Lake, 2005

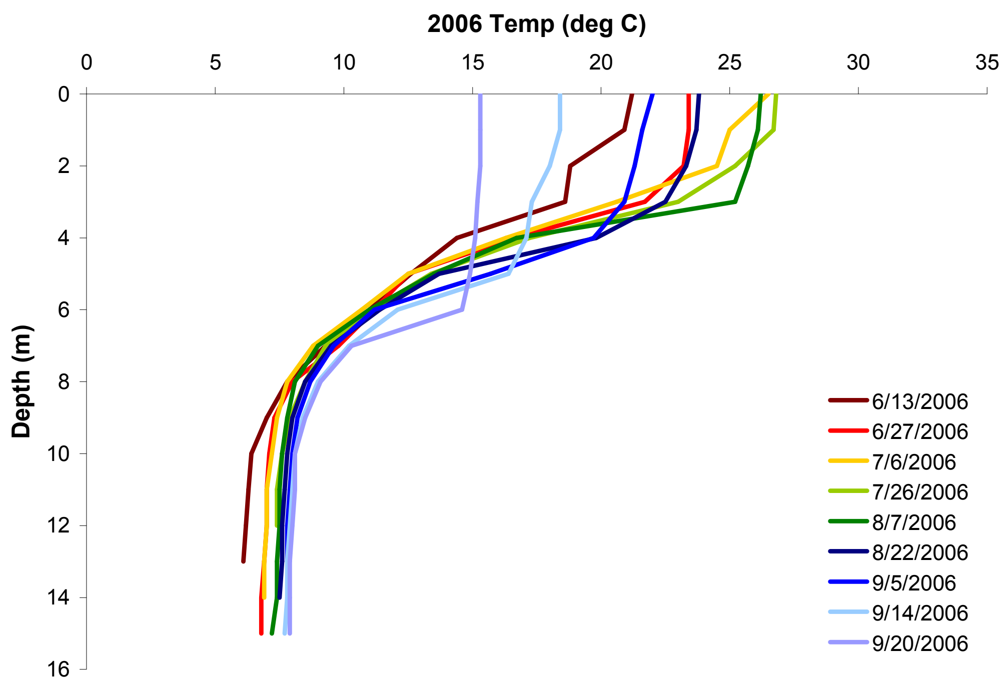


Figure 3. Temperature and depth time series for Moody Lake, 2006

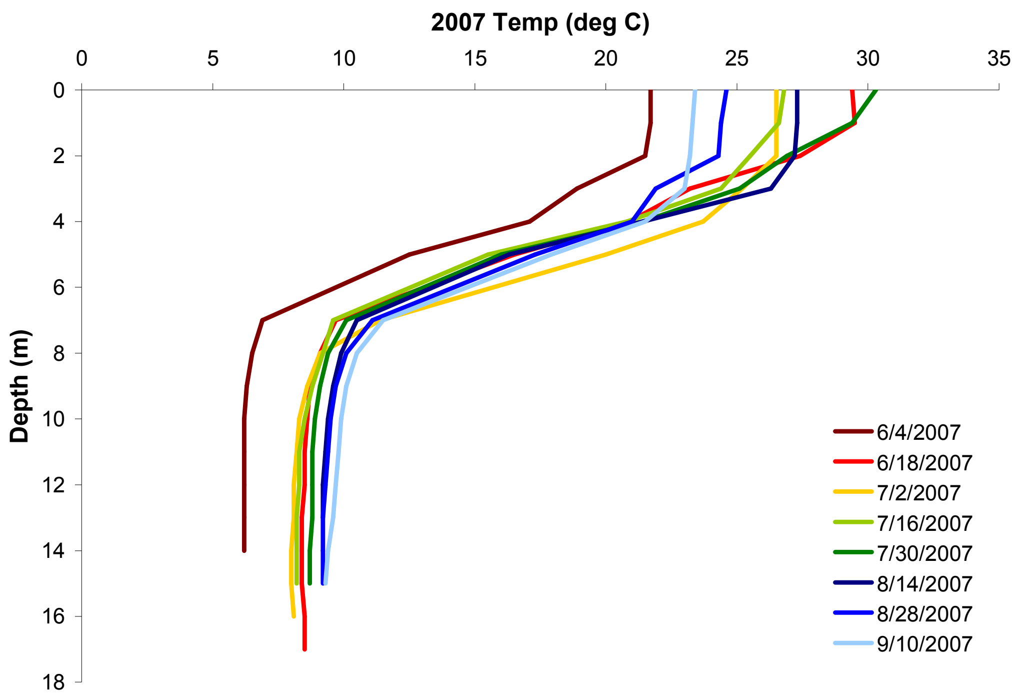


Figure 4. Temperature and depth time series for Moody Lake, 2007.

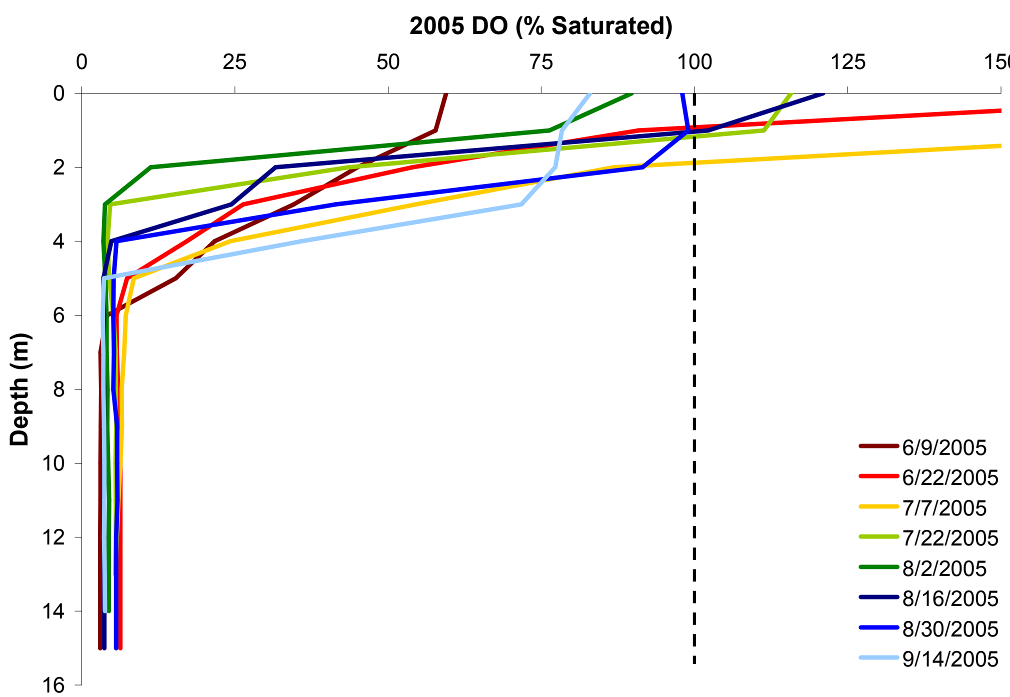


Figure 5. Dissolved oxygen and depth time series for Moody Lake, 2005

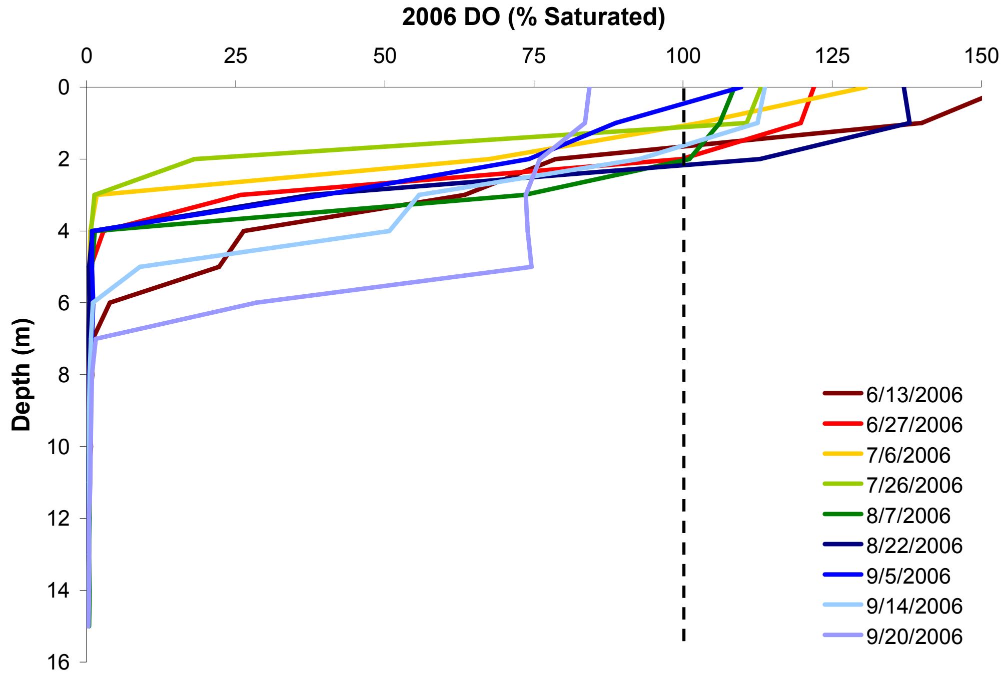


Figure 6. Dissolved oxygen an depth time series for Moody Lake, 2006

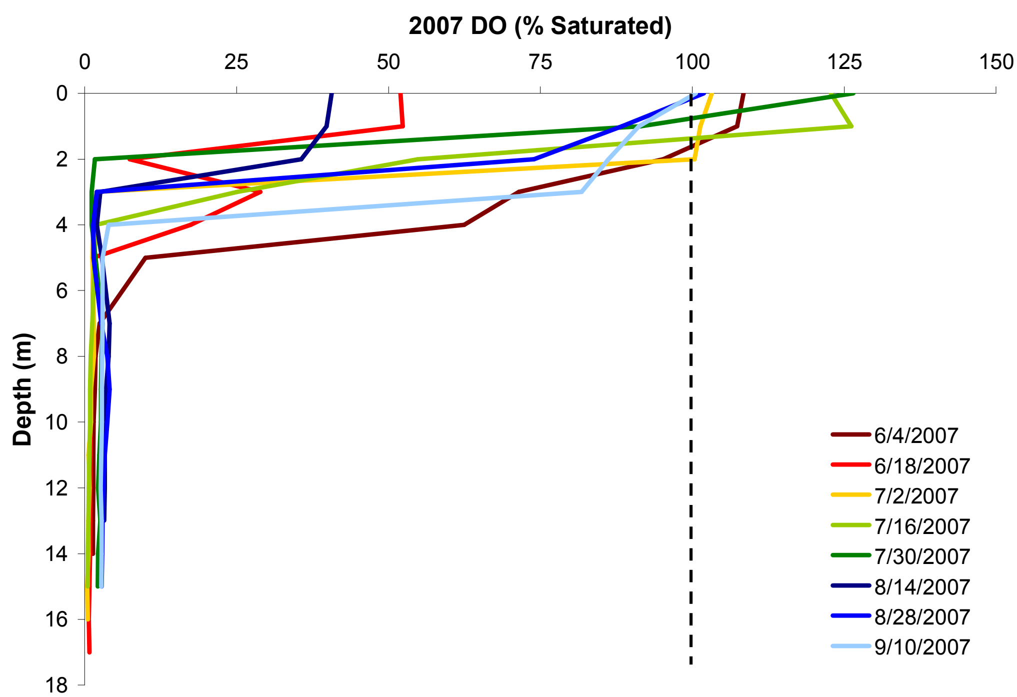


Figure 7. Dissolved oxygen and depth time series for Moody Lake, 2007

Fish Community

A lake's fish community can impact water quality and clarity. In a typical lake food web, zooplankton abundance is controlled by young panfish feeding, and phytoplankton (e.g. algae) abundance is controlled by zooplankton feeding. Fish communities dominated by panfish can result in low zooplankton abundance, increased algae growth, and decreased water clarity. Fish communities can also impact water quality and clarity if they are dominated by rough fish species. The feeding habits of rough fish species disturb lake sediments which releases sediment phosphorus to lake waters and increases algal growth.

Fish surveys were conducted in Moody Lake by the MN DNR in 1959, 1989, and 2012 (Figure 8). The fish community in Moody Lake is summarized in Table 4 and includes Black bullheads (bottom feeders); Yellow perch, Bluegill, Pumpkinseed, and Black crappie (panfish); and Northern pike and Bowfin (top predators). The fish community was dominated by panfish in 1959. A mixed community of rough fish, panfish, and top predators was observed in 1989 and 2012. An additional survey conducted in 1999 revealed a fish community that was composed almost entirely of rough fish; however, it is unknown whether this survey was representative of the entire fish community or targeted to rough fish. As a result, the 1999 fish survey data are not shown in Figure 8. Winterkill has not been documented in Moody Lake, but future presence of winterkill species (black bullhead and golden shiner) in conjunction with a dramatic decrease in panfish populations may indicate that the lake suffered some degree of past winterkill. There is currently no direct evidence of winter fish kills in Moody Lake. The DNR fish survey results are summarized in Figure 8.

The impact of bullhead versus carp on water quality

In 2009, a black bullhead harvest was conducted to remove rough fish from Moody Lake. While the impact of carp feeding behavior on sediment resuspension is well documented (Lougheed et al. 1998; Zambrano et al. 2001), we could not find scientific evidence in peer-reviewed journals that support the hypothesis that black bullheads increase lake turbidity. Braig and Johnson (2003) experimentally tested the effects of black bullhead abundance on shallow aquatic ecosystem turbidity in Ohio using mesocosm enclosures with and without black bullhead. The turbidity of enclosures with black bullhead was greater than enclosures without black bullhead, but the turbidity of the open water was greater than in either enclosure. They concluded that fetch (wind) has greater influence on turbidity than black bullhead abundance. In addition, Mork and others (2009) conducted a survey of black bullhead abundance in three Iowa lakes with different water quality. They found that black bullhead abundance was highest in the most eutrophic lake. However, they attributed this pattern to the high tolerance of black bullheads to high turbidity and low oxygen conditions, not to feeding behaviors. Based on these studies, high abundance of black bullheads is more likely a consequence, not a cause, of turbid water quality.

Table 4. Fish community of Moody Lake

Trophic group	Species	Ecological Significance
Bottom feeders	Black bullheads	Tolerant of turbid, low oxygen waters.
Panfish	Yellow perch Bluegill Pumpkinseed Black crappie	As young, they feed on zooplankton. At high abundance, they can significantly reduce zooplankton populations.
Top predators	Northern pike and Bowfin	Feed on panfish

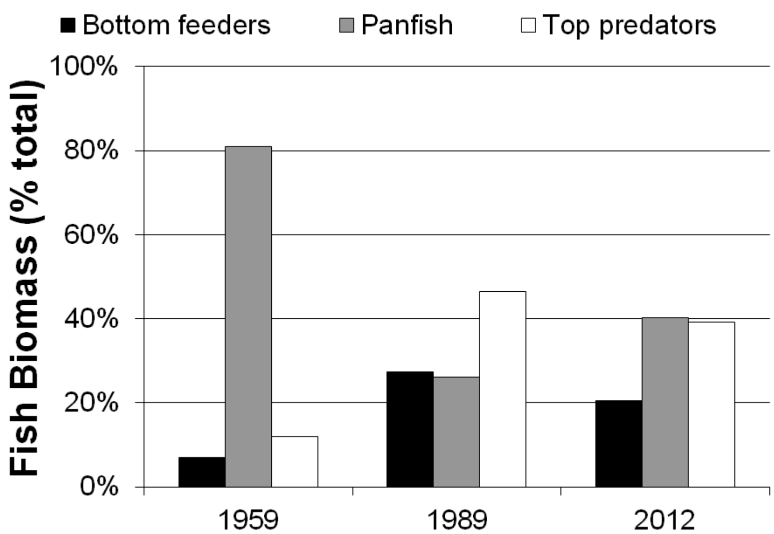


Figure 8. Moody Lake DNR fish survey data (1959, 1989, and 2012)

Water Quality

The primary water quality parameters measured in lakes are total phosphorus, chlororphyll-a, and secchi transparency. Phosphorus is typically the nutrient in lakes that control algal and in-lake vegetation growth - as total phosphorus increases, algal and plant growth tends to increase as well. Chlorophyll-a is a compound found in algae and other plants. High chlorophyll-a levels tend to correspond to high algal growth. Lakes with high algal growth appear green and have reduced clarity. Secchi transparency is the depth at which a black and white disk can no longer be seen in lake water and is used as a measure of lake water clarity. Low secchi transparency can be caused by high algae concentrations or by sediment suspended in the water. These three measures are used together to evaluate lake water quality.

The water quality of Moody Lake exceeded the lake water quality standards for total phosphorus, chlorophyll-a, and Secchi transparency depth during 2005 through 2007 (Table 5). The 3-yr growing season means were 142 µg/L TP, 46 µg/L Chl-a, and 1.0 m Secchi depth. TP and Chl-a showed dramatic violations of water quality standards. The Secchi transparency depth in Moody Lake appears to be closer to the standard, however, there is a limit to how low secchi depth can be. Exceptionally clear lakes can have very high secchi depths. Square Lake in Washington County, for example, often records secchi depths of over 8 meters (over 26 feet). Moody Lake's average secchi depth of 1 meter reflects the poor water quality of the lake. Secchi transparency is influenced by the particle size of algae suspended in water in addition to total algal abundance. Small algae, such as blue-greens, decrease transparency more than an equivalent biomass of large algae or clumps of small algae. Therefore, the correlation between transparency and TP or Chl-a is often weaker than the correlation between TP and Chl-a. The growing season means for all water quality parameters were fairly stable from year to year, indicating no significant change in water quality in Moody Lake during that time (Figure 9, Figure 10, and Figure 11). The seasonal trends of water quality were characterized by maximum TP and Chl-a levels and minimum transparency at the beginning of July (Figure 12).

Bottom water TP was measured in 2006 and is summarized in Figure 13. Bottom water total phosphorus is one way to evaluate the release of phosphorus from lake sediments under low oxygen conditions. Phosphorus that accumulates in bottom waters typically does not contribute to algal growth until the lake mixes in the spring and fall. The bottom waters in Moody Lake did have low oxygen levels during the summer so phosphorus was expected to accumulate (see Lake Stratification section). Bottom water TP increased throughout the growing season then dropped sharply during mixing with surface waters in October. Mean bottom water TP concentration was 844 µg/L at the beginning of the growing season, increased to a maximum of 2050 µg/L at the beginning of October, and decreased to 220 µg/L during lake mixing in mid-October. Seasonal trends of TP in Moody Lake support this observation with high surface water TP following ice-out and increasing surface water TP in October (Figure 12).

Table 5. Growing season mean total phosphorus, chlorophyll-a, and Secchi depth, 2005-2007.

Water Quality Parameter	Growing Season Mean 2005-2007	Eutrophication Standard (Deep Lakes)
Total Phosphorus (µg/L)	142	< 40
Chlorophyll-*a* (µg/L)	46	< 14
Secchi Transparency (m)	1.0	> 1.4

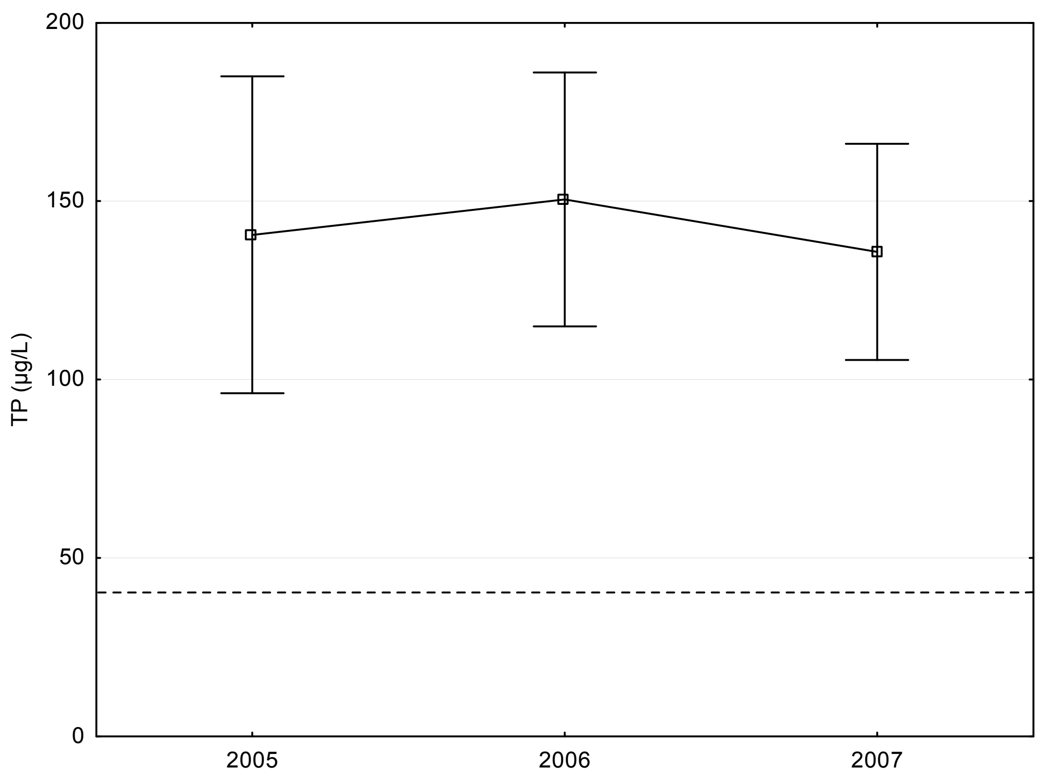


Figure 9. Annual growing season mean (± SE) TP, 2005-2007.
The dashed line represents the lake water quality standard for TP (40 µg/L).

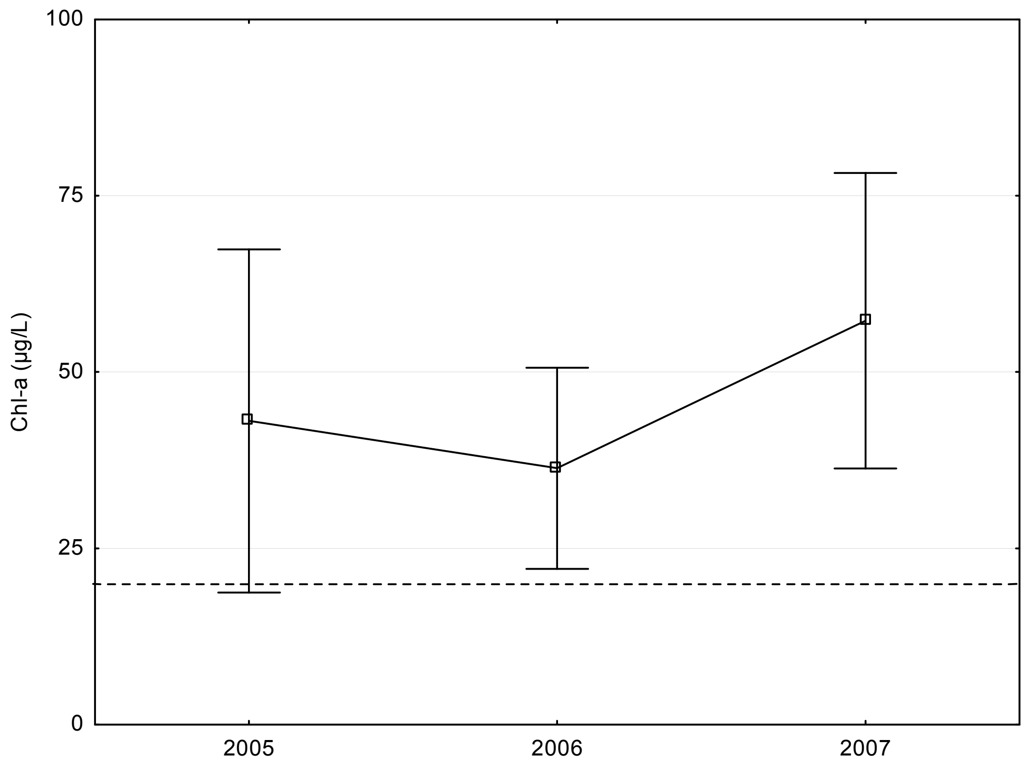


Figure 10. Annual growing season mean (± SE) Chl-*a*, 2005-2007.
The dashed line represents the lake water quality standard for Chl-*a* (14 µg/L).

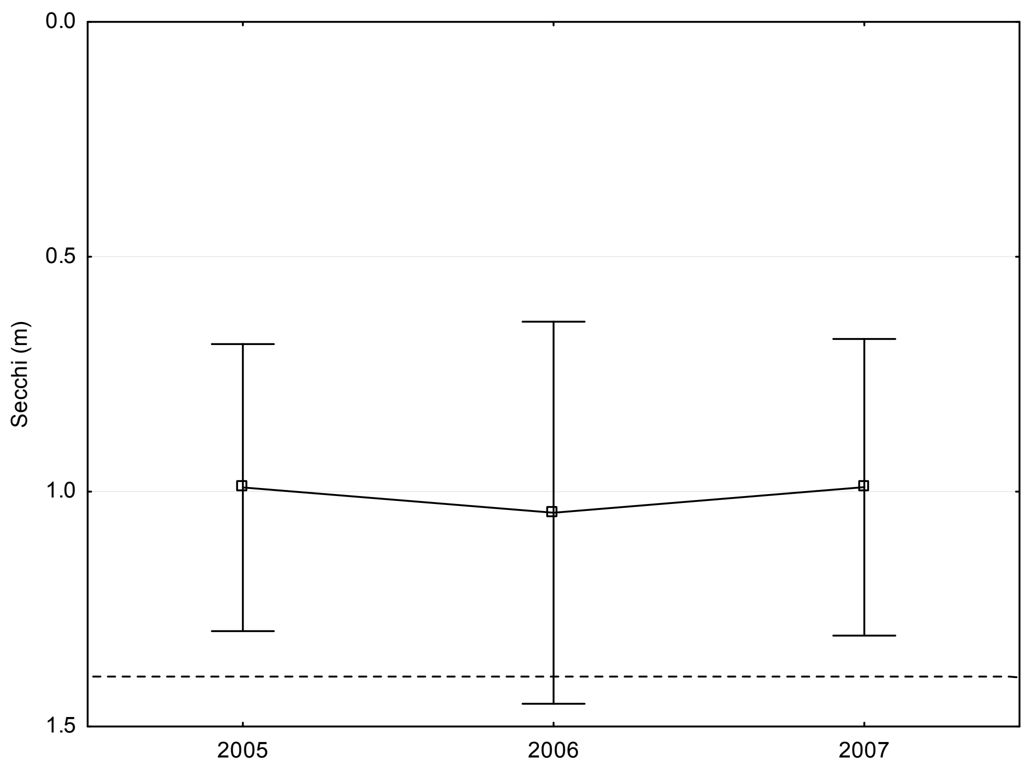


Figure 11. Annual growing season mean (± SE) Secchi transparency, 2005-2007.
The dashed line represents the lake water quality standard for transparency (1.4 m).

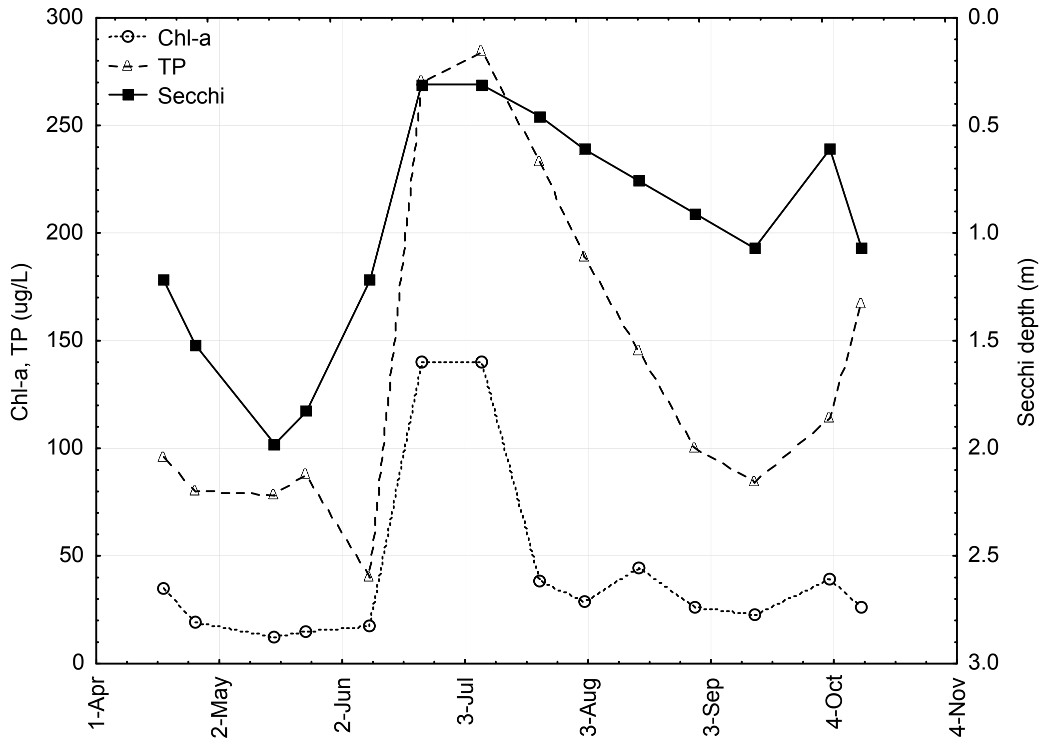


Figure 12. Seasonal trend of Chl-a, TP, and Secchi depth, 2005

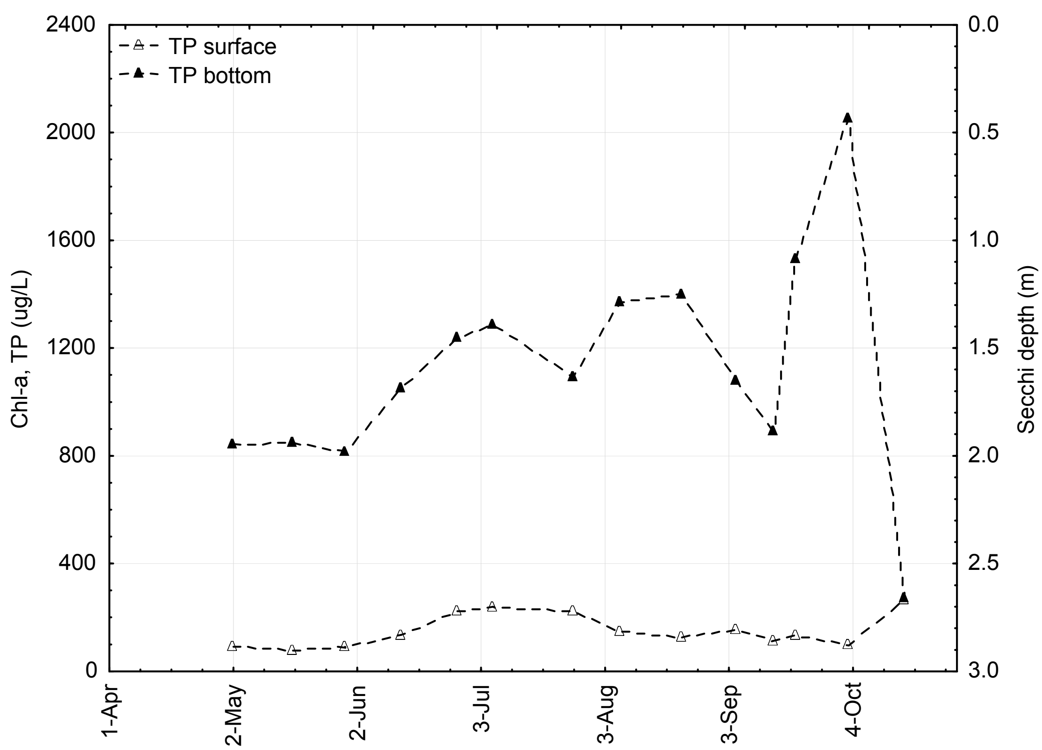


Figure 13. Seasonal trend of surface and bottom TP, 2006

Watershed Loading and Lake Response Model

Watershed loading and lake response models help determine the relative contribution of watershed sources and internal sources of phosphorus to a lake and predict the response of lake water quality parameters (TP, Chl-a, and transparency) to changes in phosphorus loads to the lake.

A detailed description for the development of the watershed loading and lake response model for Moody Lake can be found in Sections 2.1 and 2.2 and Appendices E through G of the CLFLWD Water Quality Study (Wenck 2007). Briefly, watershed phosphorus loads were calculated based on the land use within the Moody Lake watershed and available literature values of total phosphorus loading rates for Minnesota land uses based on the Detailed Assessment of Phosphorus Sources to Minnesota Watersheds (MPCA, 2004). Internal phosphorus loading rates from the sediments were estimated from the rate of phosphorus accumulation in the bottom waters during the growing season in 2006.

According to the model, the majority of phosphorus loading to Moody Lake originated from the watershed. Between 40 and 50 percent of the total phosphorus load was due to watershed runoff, excluding additional phosphorus loads from animal husbandry. The next largest load of phosphorus was internal loading from the sediments, accounting for 26% to 41% of total phosphorus loads, depending on the hydrologic conditions. Livestock in the watershed accounted for 20% of the total phosphorus loads. Other loads from upstream water bodies, groundwater, lakeshore septic system, and the atmosphere accounted for just 3% of the total phosphorus loads. The modeled phosphorus inflows and outflows for Moody Lake are summarized in Table 6 and Figure 14.

According to the lake response model, an annual load reduction of 879 lbs of total phosphorus from the watershed and internal sources is required to meet the 144 lb/yr load that would allow the lake to meet the water quality standard in-lake phosphorus goal of 40 µg/L.

Table 6. Moody Lake watershed loading and lake response model summary table (adapted from Wenck 2007)

Phosphorus Source lb TP/yr (% of total)	Benchmark (2004)	Wet (2003)	Dry (2006)
Inflow P	**1,023**	**1,398**	**891**
Runoff	431 (42%)	688 (49%)	345 (39%)
Livestock	194 (19%)	310 (22%)	155 (17%)
Upstream	15	12	12
Groundwater	2	6	0
Atmospheric	4	5	4
Lakeshore septic	9	9	9
Internal load	368 (36%)	368 (26%)	368 (41%)
Outflow P	**1,035**	**1,378**	**891**
Lake outlet flow	186 (18%)	436 (32%)	56 (6%)
Regional GW	22		
Sedimentation	837 (81%)	942 (68%)	835 (94%)
Watershed: Internal Load	**1.8**	**2.8**	**1.4**

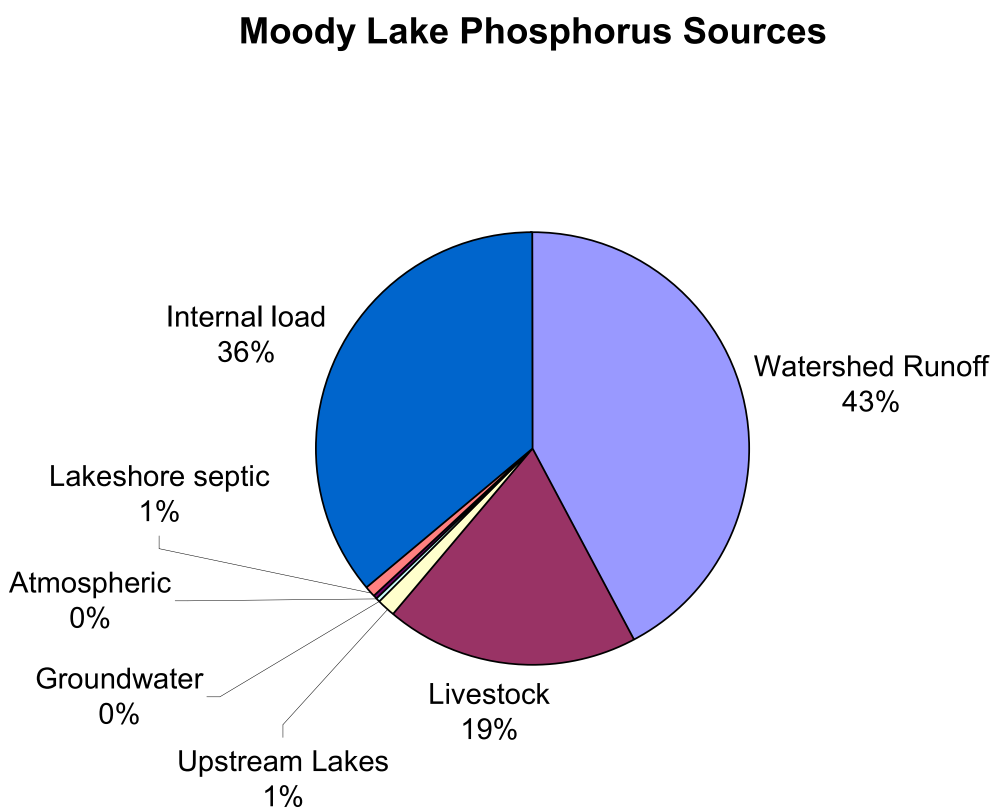


Figure 14. Moody Lake Phosphorus Sources under Benchmark Conditions

Watershed Best Management Practices

A field reconnaissance was conducted of the Moody Lake Watershed in an effort to assess the potential to reduce phosphorus loading through construction of stormwater Best Management Practices (BMPs). The following observations were made.

- In general the agricultural land within the watershed is well buffered and does not likely provide an overly high level of phosphorus loading to Moody Lake.
- There is an opportunity to provide a stormwater BMP (likely a detention basin) in the southwestern quadrant of Lofton Avenue and 250th Street N.
- The most significant inflow of stormwater comes at the north end of Moody Lake through a large, mostly submerged culvert beneath 245th Street N. There is an opportunity to provide greater TSS and phosphorus removal (in terms of a longer retention time) upstream of 245th Street N through a modification of the outlet structure.
- There is an opportunity to restore the wetland along 245th Street N. immediately north of Lendt Lake.
- Ditched wetlands north of Fourth Lake may provide other wetland restoration opportunities.

MACROPHYTE MANAGEMENT

Macrophytes, such as submerged and floating aquatic plants, are an important component of a lake ecosystem because they provide refuge for small prey organisms and protect the sediments from physical disturbance. Macrophytes are particularly important because they dominate phosphorus uptake from lake sediments and keep algal growth low and water clarity high. If macrophytes were to be suddenly removed from a lake, large loads of phosphorus from the sediments would be available for algal growth resulting in reduced water clarity. Such alternate trophic states are common to small or shallow lakes: macrophyte-dominated clear waters and algal-dominated turbid waters.

One macrophyte of concern in Minnesota lakes is curly-leaf pondweed. The unique life cycle of curly leaf pondweed – early growth in spring and mid-summer senescence – allows it to outcompete other macrophyte species and dominate a lake. When high density growths of curly leaf pondweed die off in mid-summer, they release large amounts of phosphorus into lake waters which result in noxious algal blooms and reduced water clarity.

Macrophyte Surveys

Aquatic macrophyte surveys have been conducted on Moody Lake by the Minnesota DNR (Spring 1989), the Washington Conservation District (Spring and Fall 2006), The Watershed District Administrator (Spring and Fall 2009) and Emmons & Olivier Resources, Inc. (Spring 2011). The data was collected using a similar transect method by each entity. The DNR survey included a relative abundance rating for the lake for each observed species. The Washington Conservation District, Watershed District Administrator methodology was to note the presence/absence of each species along the sample transect. The EOR survey methodology was to note the relative density of plants at each transect point as described below.

The DNR relative abundance rating includes the following categories: abundant; common; occasional; rare; and present. In order to compare the Washington Conservation District, Watershed District Administrator and EOR survey data and display all surveys graphically, percent occurrence value was assigned to each DNR category in the following manner:

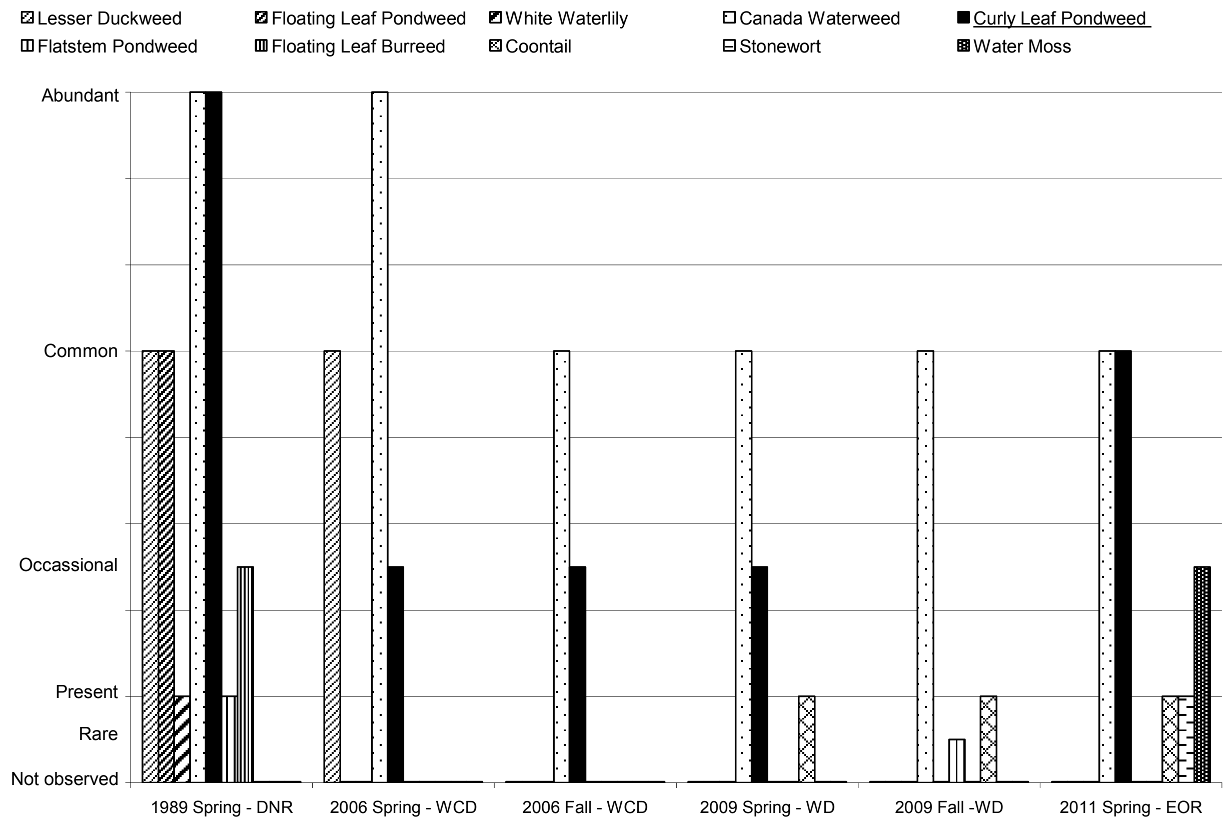
- Abundant = 80%
- Common = 50%
- Occasional = 25%
- Rare = 10%
- Present = 5%
- Not Observed = 0%

The Washington Conservation District, Watershed District Administrator, and EOR presence/absence data for each lake was summarized as the percent of transects where the species was observed and one of the above relative abundance ratings was assigned so that data across all surveys could be displayed graphically and compared.

Curly-leaf pondweed was first documented in Moody Lake during a spring 1989 survey conducted by the Minnesota DNR. It has since been observed at varying levels of abundance in subsequent surveys. In the 1989 survey the curly-leaf pondweed population was rated abundant, which relates approximately to 80% coverage. The abundance was rated as occasional (approximately 25% coverage) in the spring 2006, fall 2006, and spring 2009 surveys. It was not observed in the fall 2009 survey but was found in the spring 2011 spring survey when it was rated common. A comparison of the aquatic macrophyte composition of

Moody Lake in the vegetation surveys conducted since 1989 is shown in Figure 15. The figure shows that the number and abundance of species decreased from the 1989 survey to the surveys of 2006 and 2009.

Figure 15. Moody Lake historical vegetation surveys



In the most recent survey conducted in spring of 2011, curly-leaf pondweed was observed at 18 of 31 sampling locations (Figure 16). The density of plants is measured by the quantity of plant material on the sampling rake and is rated as follows:

1. A few plants on rake head
2. Rake head is about ½ full. Can easily see the top of the rake head
3. Overflowing. Cannot see the top of the rake head

The density for 15 of the 18 sampling sites in spring 2011 was rated as a 1 and for only 3 of the sites was rated as a 2. At no sites was the density rated a 3.

Curly-leaf pondweed was observed in the fall 2006 survey which, at the time, was alarming since the plant typically senesces by fall and only turions are expected to be seen. During the fall 2009 survey curly-leaf pondweed was not observed.

The variability in abundance over time and the relatively low density of curly-leaf pondweed in the most recent survey raises a question as to whether treatment of the plant population in Moody Lake is warranted at this time.

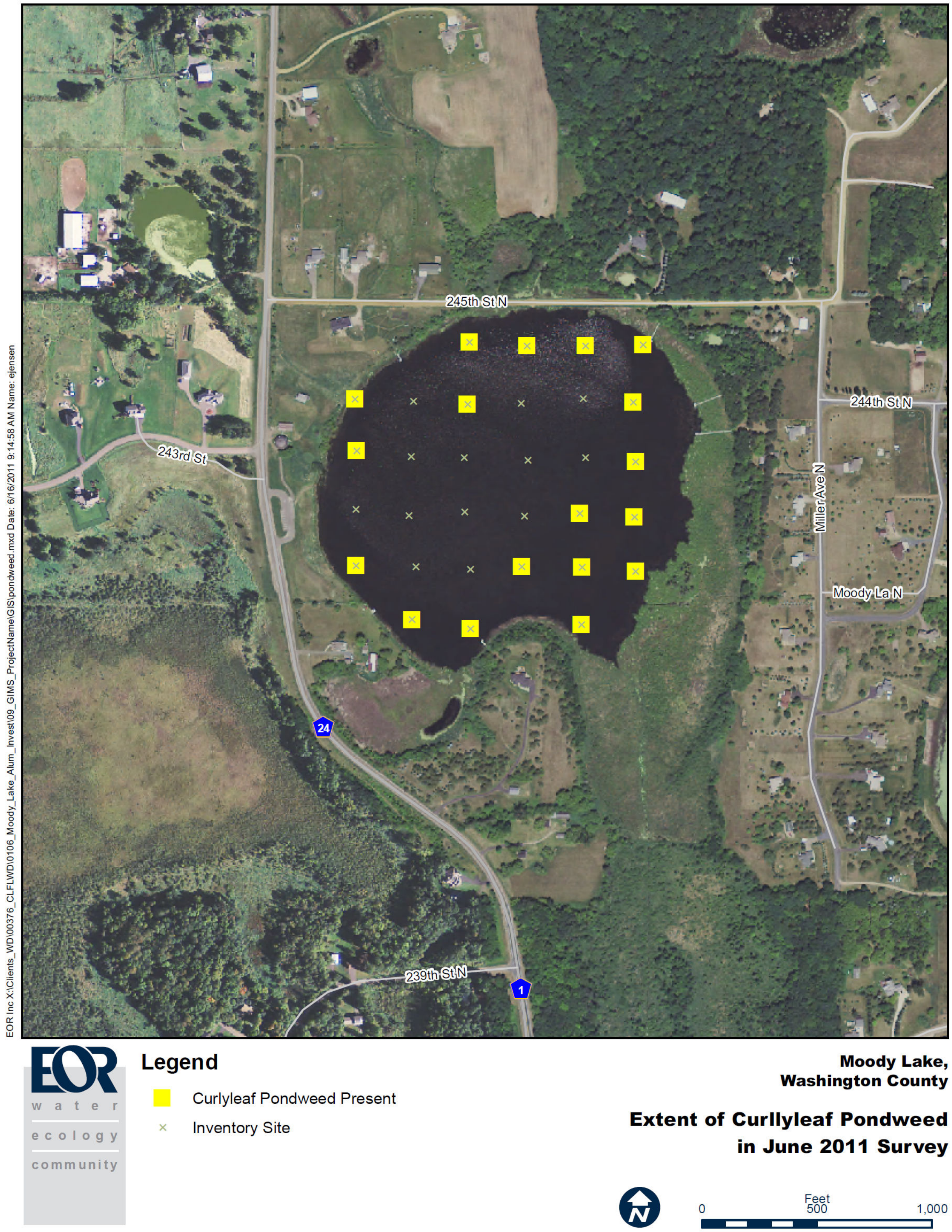


Figure 16. Sites with Curly-leaf Pondweed Present in Spring 2011 Macrophyte Survey

Curly-leaf Pondweed Threat Evaluation

To evaluate the potential threat, impacts, and potential for treatment of a curly-leaf pondweed infestation on Moody Lake the extent and speed of possible infestation, nature of possible impacts, and ability to spread was evaluated. The evaluation is designed to answer the following questions pertaining to curly-leaf pondweed in Moody Lake:

Extent and Speed of Possible Infestation
- What portion of Moody Lake could be colonized?
  - estimated as the area with water depth <20 ft
- What is the potential for dense bed formation?
  - estimated as the area with softer sediments in water <10 ft deep
- What is the potential for rapid (<3 years) spread of curly-leaf pondweed?
  - estimated as the common area from the two questions above that is not densely covered by native plants

Nature of Possible Impacts
- What resources and uses are potentially threatened?
  - water supply
  - swimming
  - boating
  - fishing
  - aesthetics
  - sensitive or protected populations

Ability to Spread
- What is the potential strength of vectors of curly-leaf pondweed spread?
  - water flow
  - boat traffic
  - daily or seasonally mobile bird populations
  - other human activities

The results of the curly-leaf pondweed threat evaluation are summarized in Table 7. The finding of this evaluation is that there is a low to medium threat of curly-leaf pondweed becoming a significant problem in Moody Lake.

Table 7. Curly-leaf pondweed threat evaluation

Extent and speed of possible infestation		
A large area could be affected	Y	82% of Moody Lake is less than 20' depth
Plant density could be high	Y	65% of Moody Lake is less than 10' depth. Additionally, historically Moody Lake has had periods of high density Curlyleaf pondweed. If water quality improves, greater water transparencies could lead to an increase in all macrophytes due to greater sunlight penetration to lake substrate
Spread could be rapid	N	While there is a large area that could rapidly become covered with Curlyleaf pondweed, the aquatic macrophyte survey indicates that native plants are in similar abundance throughout the Lake
Threat Evaluation	**Medium**	
Nature of possible impacts		
Water supply may be impacted	N	Moody Lake is not used for water supply
Swimming may be impacted	Y	Moody Lake is used for swimming. There is a swimming platform out from the north end of the lake
Boating may be impacted	Y	A large portion of Moody Lake could become difficult for boating
Fishing may be impacted	Y	Fishing on Moody Lake could become impacted by large mats of Curlyleaf pondweed
Aesthetics may be impacted	Y	Large mats of Curlyleaf pondweed would impact the aesthetics of the lake
Sensitive species may be impacted	N	No sensitive species have been observed in Moody Lake
Protected species may be impacted	N	No protected species have been observed in Moody Lake
Threat Evaluation	**Medium**	
Ability to spread		
Spread by water flow likely	N	Water flow through Moody Lake is not a significant vector for spread.
Spread by birds likely	N	Bird populations have not been identified as significant on Moody Lake
Spread by boating likely	N	Minimal boating occurs on Moody Lake
Spread by other human activities likely	N	No additional human activities which would hasten the spread of Curlyleaf pondweed have been identified on Moody Lake
Threat Evaluation	**Low**	

Sediment Properties and Curly-leaf Pondweed Growth

Some experimental work suggests that lake-bottom chemistry can affect the ability of curly-leaf pondweed to thrive in a lake (McComas 2005). In a survey of 50 lakes, the primary lake sediment parameter correlated with nuisance curly-leaf pondweed growth was a pH above 7.7. Other important parameters included a bulk density less than 0.50 g/cm^3-dry, organic matter greater than 30%, and high iron concentration (>150 ug/cm^3); originally reported as an important parameter was an iron to manganese ratio of less than 1.6. In a later publication by the same author, manganese concentration showed no significant correlation to heavy curly-leaf pondweed growth (Blue Water Science 2010; Table 8). The iron to manganese ratio remained significant because of the high significance of the iron parameter.

One potential reason for the correlation between pH / percent organic matter and curly-leaf pondweed growth could be that they are all related to overall lake productivity. Highly productive lakes tend to have high pH and high sediment organic matter. In addition, highly productive lakes tend to have higher nutrient levels which would enhance curly-leaf pondweed growth. Iron is thought to control curly-leaf pondweed growth by binding with phosphorus in the sediments so that curly-leaf pondweed growth is limited by phosphorus. These correlations should be used with caution as there may be many confounding variables that could alter the relationship between sediment characteristics and potential curly-leaf pondweed growth. For example, iron bound phosphorus is released under low oxygen conditions and microbial activity in sediments with high organic matter greatly depletes oxygen levels just below the sediment-water interface.

Sediment core samples were collected from water depths ranging between 4.3 and 5.9 feet at seven locations in Moody Lake in June of 2011 by EOR. Sediment samples were analyzed by Pace Analytical Services, Inc. for pH, iron, manganese, organic matter, and bulk density according to the protocols listed in Table 9. Mean sediment pH was 6.9 standard units, iron concentration was 493 µg/cm^3, organic matter was 26.0%, and bulk density was 1.00 g/mL (Table 9). According to the sediment characteristics reported by Steve McComas (Table 8), heavy curly-leaf pondweed growth is not expected in Moody Lake. Individual sediment core characteristics are reported in Table 10.

Table 8. Sediment characteristics and curly-leaf pondweed growth of untreated lakes (Blue Water Science)

Parameter	Lake Sediments Supporting Light Growth (n=45)	Lake Sediments Supporting Heavy Growth (n=20)	t-Test (p-value)
pH	< 6.8	> 7.7	8×10^{-11}
Iron, Fe (µg/cm^3)	150	48.8	9×10^{-12}
Manganese, Mn (µg/cm^3)	24.7	20.5	0.16
Fe: Mn	5.3	1.6	4×10^{-8}
Organic matter (%)	7.27	20.2	0.001
Bulk density (g/cm^3-dry)	1.0	0.51	2×10^{-5}

Table 9. Mean sediment characteristics and potential curly-leaf pondweed growth in Moody Lake, 2011

Sediment Parameter	Mean	SE	Unit	Protocol	Potential CLP growth
pH	6.9	1.1	S.U.	EPA 9045	Light
Iron	493	83	µg/cm^3	EPA 6010	Light
Organic Matter	26.0	1.6	% w/w	ASA 29-3.5.2	Heavy
Bulk Density	1.00	0.01	g/mL	ASTM D5057	Light
Overall					**LIGHT**

Table 10. Individual sediment core characteristics and potential curly-leaf pondweed growth, 2011

Core	Water depth (feet)	pH (S.U.)	Iron ($\mu g/cm^3$)	Organic Matter (%)	Bulk Density (g/mL)	Potential CLP growth
1	5.1	7	521	32.3	1.03	Light
2	5.2	7	986	21.1	1.03	Light
3	5.9	6.9	482	26.1	1.01	Light
4	5.2	7	361	22.2	1.04	Light
5	5.5	6.9	415	23.1	1.03	Light
6	5.1	6.8	299	27.7	0.999	Light
7	4.3	6.8	460	29.7	1.02	Light

CONCLUSIONS OF IN-LAKE WATER QUALITY DATA EVALUATION

Moody Lake has a large watershed area to lake surface area ratio with more than two-thirds of the hydrological inputs to the lake originating from watershed runoff. The watershed loading and lake response model results support this conclusion with total watershed phosphorus loads 1.4 to 2.8 times larger than total internal phosphorus loads, depending on hydrological conditions. However, the actual inputs to the lake have not been monitored or measured.

Possible sources of internal phosphorus loads to Moody Lake are anoxic bottom waters, rough fish, and curly-leaf pondweed. The bottom waters of Moody Lake have low oxygen levels during the summer which contribute to phosphorus release from the sediments. The presence of rough fish in Moody Lake may also contribute to phosphorus release from the sediments.

While curly-leaf pondweed was observed in Moody Lake, it is currently not abundant and not expected to contribute significantly to internal phosphorus loads.

A summary of phosphorus sources and water quality in Moody Lake is found in Table 11.

Table 11. Summary of phosphorus sources and water quality in Moody Lake

<table>
<tr><th colspan="2">Parameter</th><th>Result</th><th>Importance</th></tr>
<tr><td rowspan="2">Watershed Loads</td><td>Watershed area: Lake surface area</td><td>High (72:1)</td><td>High phosphorus loads are expected from the watershed</td></tr>
<tr><td>Hydrology</td><td>Watershed inputs 69-86% of total</td><td>In-lake water quality is expected to be heavily influenced by the watershed</td></tr>
<tr><td rowspan="3">Internal Loads</td><td>Fish community</td><td>Dominated by black bullheads and panfish</td><td>Imbalanced fish community reduces zooplankton grazing of algae</td></tr>
<tr><td>Lake stratification</td><td>Bottom waters anoxic during the growing season</td><td>Anoxic release of phosphorus from sediments in deep waters is expected to contribute to lake phosphorus loads</td></tr>
<tr><td>Macrophyte community</td><td>Curly-leaf pondweed present but not abundant</td><td>Curly-leaf pondweed is not currently expected to contribute to lake phosphorus loads, but may become a large internal P source if abundance increases</td></tr>
<tr><td rowspan="2">P Loading Model</td><td>Watershed: Internal phosphorus load</td><td>1.4 (Dry conditions)
1.8 (Benchmark conditions)
2.8 (Wet conditions)</td><td>The majority of phosphorus loading to Moody Lake originates from the watershed</td></tr>
<tr><td>Water quality</td><td>TP, Chl-a and Secchi transparency violate lake water quality standards</td><td>An in-lake total phosphorus goal of 40 μg/L requires an annual load reduction of 879 lbs TP/year (~85%) from watershed and internal P sources</td></tr>
</table>

PHOSPHORUS LOADING TREATMENT OPTIONS

A number of options exist for the management of internal phosphorus loads in Moody Lake. Over 15 different options were analyzed to determine if the option is applicable to the conditions in Moody Lake. Each of these options is explained briefly in Table 12; those options that were not ruled out because of inapplicability to the conditions in Moody Lake are check marked in the right-most column. The options which were identified as potentially applicable to Moody Lake as well as a few other options identified as areas of particular interest for this study are discussed in more detail in this section.

Vegetation Management

Herbicide Treatment of Curly-leaf Pondweed

Approximately 20 acres (61% of total area) of Moody Lake are littoral and capable of supporting macrophyte growth (see In-Lake Data Summary: Physical Setting). Curly-leaf pondweed has been present in Moody Lake since at least 1989, and the predominance of curly-leaf pondweed has increased over time. In 1989, the macrophyte vegetation was a balanced, abundant community of native species with curly leaf pondweed comprising a small proportion of the total community. According to recent surveys, macrophyte vegetation cover is sparse, but dominated by curly leaf pondweed. The abundance of curly-leaf pondweed in Moody Lake has been quite variable throughout the past 12 years and current densities of plants are not alarming. In addition, the threat of curly-leaf pondweed becoming a significant problem in Moody Lake is fairly low at current water clarity levels (mean Secchi transparency depth of 1.0 m). The 2007 Water Quality Study proposed an herbicide treatment to manage curly-leaf pondweed in Moody Lake. Herbicide treatment is not recommended at this time because of the low abundance of curly-leaf pondweed. However herbicide treatment could be used in the future if curly-leaf pondweed increases in abundance as water clarity improves due to phosphorus load reductions to Moody Lake. Treatment of curly-leaf pondweed may reduce internal loading in the lake, however results are not always consistent.

Completion of macrophyte surveys for Moody Lake will help the District determine if or when curly-leaf pondweed becomes abundant enough to require herbicide treatment. If it is determined that the population of curly-leaf pondweed should be treated in the future because it has become consistently abundant throughout the lake, an herbicide treatment may be justified. A broad application of Diquat or Endothall could be used to treat curly-leaf pondweed in Moody Lake if treatment becomes justified.

We recommend that the District monitor curly-leaf pondweed abundance in May or June (i.e., before senescence) annually during phosphorus reduction treatments and consider future herbicide treatment if curly-leaf pondweed abundance increases with improving water clarity.

<u>Costs</u>
The estimated cost for an annual macrophyte survey is $2,000.

<u>Considerations</u>

- Senescence of curly-leaf pondweed in mid-summer has been associated with large mid-summer phosphorus loads. However, the effects of herbicide treatment on curly-leaf pondweed on in-lake phosphorus loading in Moody Lake will depend on the amount of total phosphorus load contributed by its senescence, which is unknown at this time.
- A permit for aquatic plant management is required from the DNR for the use of herbicides to manage curly-leaf pondweed.

Fisheries Management

In 2009, rough fish (bullheads) were removed by netting in Moody Lake. The commercial fisherman who conducted the bullhead removal indicated that in addition to the bullheads, the lake appeared to have a good number of panfish but few predator fish. However, a DNR fish survey conducted in 2012 indicated that the current fish population structure in the lake was well-balanced and not dominated by rough fish or panfish (see Figure 8 in the above section titled “Fish Community”). Also mentioned in the above section titled “Fish Community,” there is no strong scientific evidence that black bullheads significantly decrease lake water quality in the same manner as carp. In addition, fish barriers are planned to prevent potential movement of carp into Moody Lake.

Fish Surveys
We recommend that the District continue to periodically (every other year) conduct a fish survey of Moody Lake to determine when fisheries management strategies might be needed in the future.

Costs
Fish surveys can be conducted by the DNR; however, priority tends to go to lakes with public access. The estimated cost for the District to conduct a survey of the lake’s fish population is $2,800.

Fish Stocking
If the results of a future fish survey indicate that black bullhead and panfish become dominant in the lake, we recommend stocking Moody Lake with a large predator fish such as walleye or bass to control the panfish population and aid in food web control of algae growth. Fish stocking should be implemented in conjunction with the installation of a winter aeration system to eliminate partial winterkills (see “Winter Aeration” below).

Costs
Stocking can be conducted by the DNR on lakes with public access; however, Moody Lake does not have a public access at this time. The District can also conduct fish stocking and may purchase fish from the DNR to use in stocking Moody Lake. A cost for stocking has not been estimated at this time.

Considerations
- The effectiveness of top predator fish stocking on food web control of algae is strongest when the dominant planktivorous fish species (e.g., bluegill) are large components of the top predator’s diet.
- Fish stocking should be implemented in conjunction with installation of a winter aeration unit to prevent winter fish kills (see Winter Aeration section below).

Rough Fish Harvest
A bullhead harvest was conducted in 2009 to reduce the proportion of bullheads in the lake’s fish population. Future harvesting of bullheads may be needed to maintain a balanced fish population composition. However, an additional harvest is not recommended at this time because the population is not expected to have re-established to dominant levels.

Costs
A cost for a bullhead harvest has not been estimated at this time.

Considerations

- Past harvests along with proposed stocking with predator fish and winterkill prevention are expected to maintain the bullhead population at a low level.

Winter Aeration
Few predator fish and overabundance of black bullheads are evidence of periodic winter fish kills caused by low oxygen conditions. To eliminate the occurrence of fish kills and to encourage the reestablishment of predator fish, we recommend a winter aeration system be installed on Moody Lake. Winter aeration systems create a small plume of high oxygen water near the shore where fish can survive under extremely low oxygen conditions during the winter. Alternatively, winter aeration systems can be run in the deeper portions of the lake in the same manner as a summer aeration system. Bullheads are more tolerant of low oxygen conditions than top predators, therefore winter aeration will help to maintain the bullhead population at lower levels in Moody Lake because predators will have a refuge and other species will be given the opportunity to prosper and provide competition to the bullheads.

Costs
Shoreline winter aeration systems to provide a "safe harbor" for fish is have not been estimated at this time, but are expected to be similar in cost to a summer diffusion aeration system or about $15,000.

Considerations
- A winter aeration system results in an area of open water, limiting ice coverage of the lake in that area. However, the open water area could be in shallower waters, reducing the safety risk.
- Aeration by the shoreline does not provide the same refuge as aeration in deeper waters and fish tend to move to deeper waters in the winter.
- A permit from the DNR is required to install a winter aeration unit and the area of open water must be properly posted with signage for safety. In addition, public notices in the local newspaper must be posted prior to starting the winter aeration system and general liability coverage of $500,000 is required.

Phosphorus Cycling Management

Internal phosphorus loading in lakes is a result of long-term accumulation of past phosphorus inputs from the watershed. Therefore, long-term improvements in lake water quality in Moody Lake will only be achieved with proper management of watershed sources to reduce future input of phosphorus to Moody Lake. The goal of in-lake phosphorus treatment options is to ameliorate the effects of historic watershed phosphorus loads on in-lake water quality.

Chemical Treatment with Alum
Moody Lake strongly stratifies every summer with anoxic bottom waters below 20 feet in depth and subsequent phosphorus release from the sediments. Moreover, total phosphorus in the bottom waters increases to approximately 2000 µg/L during the summer, which is then transported to and mixed with the surface waters during fall mixing. The aluminum sulfate used in alum treatments permanently binds with phosphorus through a chemical reaction, prohibiting phosphorus release during anoxic conditions. The alum strips phosphorus from the water column during application and also forms a layer on the surface of lake bottom sediments This sediment alum layer also binds with phosphorus in surface sediments and with phosphorus slowly released from underlying sediments. Alum treatments are typically effective for 5 to 10 years. Alum treatment is a viable option in Moody Lake.

<u>Costs</u>
The estimated 2012 cost is $190,000 for alum treatment of 423 lb of internal phosphorus load in Moody Lake.

<u>Considerations</u>

- Alum treatments are typically effective for 5 to 10 years.
- Reliability of alum treatments depends on alum dosing. Too little alum will result only in a short-term improvement in water quality resulting primarily from the stripping of phosphorus in the water column as alum settles to the bottom. A sufficient dose of alum will also bind with phosphorus in the upper layers of the sediments. Phosphorus slowly diffuses from deeper sediments into upper sediments which can then be released into the water column. This diffusion results in the perceived ineffectiveness of an under dosed alum treatment over time.
- Watershed input of nutrients can add new phosphorus to the bottom sediments when high loads of nutrients continue to enter the lake after alum treatment. The phosphorus in these new bottom sediments may not be absorbed by the alum layer. Therefore, significant reduction of watershed phosphorus loads to Moody Lake should be achieved prior to an alum treatment.
- Alum treatments do not require a permit, but do require a letter of approval from the MPCA. The MPCA requires an alum application plan outlining dosing and the project schedule prior to writing a letter of approval. They also ask that the application be noticed to public agencies and that follow-up monitoring be sent to the MPCA.

Lake Aeration
Oxygenation of lake bottom waters (hypolimnion) temporarily limits the release of phosphorus from lake-bottom sediments by keeping bottom waters oxygenated. The effectiveness of hypolimnetic oxygenation depends on the phosphorus binding capacity of the sediments. Even under oxic conditions, if phosphorus is not bound to sediment particles, the high concentration of phosphorus in sediments will result in phosphorus diffusion into the water column. In Lake Vadnais, hypolimnetic oxygenation was implemented in conjunction with addition of ferric chloride as a phosphorus binding agent (Engstrom 2005). Based on sediment samples collected in 2010, the amount of iron adsorbed P was 1380 mg/kg and the total amount of sediment iron was 8176 ± 725. This is equivalent to an Fe-adsorbed P to sediment Fe ratio of 0.17, which is near the theoretical capacity of adsorption of phosphorus to sediment iron (0 – 0.2; Lijklema 1980). Therefore, iron may need to be added to Moody Lake sediments if an hypolimnetic oxygenation system is installed.

Large external phosphorus loads can mask the effects of hypolimnetic oxygenation on water quality, so direct correlations between hypolimnetic oxygenation with improved surface water quality are not always observed. Reduction of watershed phosphorus loading is still essential to improve lake water quality.

Summer oxygen profiles indicate that low oxygen conditions persist throughout the summer in deeper waters in Moody Lake. Aeration could be used to limit these low oxygen conditions and the resulting phosphorus release from the sediment. Aeration can be completed through the addition of air at the bottom of the lake or through circulation units that pull lake bottom water to the surface to artificially mix the water column.

An alternative system is to mix only the epilimnion (the warmer top layer) in an effort to limit the growth of blue-green algae. This system limits the growth of algae which could settle to the bottom sediments but maintains a stratified system with continued internal load from the bottom sediments. Blue-green algae blooms are not a primary concern in Moody Lake, but blooms have been observed along the north shore of the lake.

Costs

The estimated cost of a summer aeration system is $17,000 for installation of a diffusion system with annual maintenance costs expected to be about $1,500. This system would also require coordination and costs to gain electric service for the system.

The estimated cost of a solar powered circulation system to mix the entire depth of the lake is $38,600 with annual remote access costs at about $600 per year.

The “SolarBee” circulation system was primarily designed to horizontally mix the epilimnion (warmer top layer) to reduce noxious blue-green algae blooms. It is estimated to cost $50,000 with annual operation costs of $3,000.

Considerations

- Aeration systems are effective only when they are in operation, therefore to have a continued effect on the lake, the system would have to be operated each summer every year into the future.
- Aeration systems are also only as effective as the phosphorus binding capacity of the sediment. Therefore, iron may also need to be added in conjunction with an aeration system.
- Aeration systems are permitted by the DNR. The permit requires signage, liability coverage, and newspaper notices for winter aeration, but simply requires an issued permit for summer aeration.

Treatment with Iron Filings or Ferric Chloride

The addition of iron filings or ferric chloride has been suggested as a way to limit the movement of phosphorus out of lake-bottom sediments. Phosphorus and iron bind together under oxygenated conditions making the phosphorus unavailable for use by algae and macrophytes in the lake. Under anoxic conditions, however, the phosphorus is released from the iron and is available for uptake by algae and macrophytes. With anoxic conditions present in the deeper portions of Moody Lake throughout the summer, the addition of iron would only be effective in conjunction with hypolimnetic oxygenation.

Costs

Treatment with iron filings or ferric chloride is not a recommended in-lake treatment option for Moody Lake without hypolimnetic oxygenation.

Considerations

- Iron is effective at binding phosphorus only under oxic conditions. Moody Lake bottom sediments are anoxic in the deeper portions of the lake where phosphorus release is occurring.

Watershed Phosphorus Load Reduction

Internal phosphorus loading in lakes is a result of long-term accumulation of past phosphorus inputs from the watershed. Therefore, long-term improvements in lake water quality in Moody Lake will only be achieved with proper management of watershed sources to reduce future input of phosphorus to Moody Lake. Described below are several phosphorus load reduction projects that have already been completed in the Moody Lake watershed and recommendations for future projects.

Completed Load Reduction Projects

The watershed, including general land use and livestock operations, was identified through modeling as the dominant source of phosphorus to Moody Lake with an estimated 62% of the total load to the lake. The District has completed two livestock management and wetland restoration projects which are expected to assist in reducing watershed and livestock loads to the lake. Two wetlands upstream of Moody Lake are currently undergoing livestock exclusion and restoration to limit livestock access to wetlands, catch phosphorus runoff from livestock operations, and restore wetlands in the watershed to limit phosphorus transport to Moody Lake.

Potential Load Reduction Projects

The two livestock management projects mentioned above appear to address the major livestock sources in the contributing watershed. In addition, three other potential watershed improvement projects were identified during a field visit throughout the contributing watershed in 2011:

- Stormwater BMP (likely a detention basin) in the southwestern quadrant of Lofton Avenue and 250th Street N.
- Modification of the culvert upstream of 245th Street N to provide greater TSS and phosphorus removal (by increasing stormwater retention time upstream).
- Wetland restoration along 245th Street N. immediately north of Lendt Lake.
- Wetland restoration of wetland north of Fourth Lake. Past ditching may have impacted wetlands north of Fourth Lake that could result in higher transport of nutrients out of the wetlands and into Moody Lake.

The District's cost-share and grant programs could also be used to target the Moody Lake watershed to encourage implementation of residential and agricultural BMPs. In-line chemical treatment with ferric chloride could be implemented in watershed tributaries and outlets to reduce phosphorus loads to Moody Lake. However, this is often a cost prohibitive and maintenance intensive option.

We recommend that the District monitor flows and phosphorus concentrations in the tributary inlets to Moody Lake to confirm that current watershed load reduction efforts (livestock exclusion and restoration) have resulted in a reduction in average watershed phosphorus loading to less than the 144 lb/yr total watershed and internal load needed to attain goal water quality. Extending monitoring upstream to wetland and contributing lake outlets would allow the District to pinpoint any remaining areas of excess load.

The watershed flow and phosphorus concentration at the tributary inlet to Moody Lake were monitored in 2012 to determine whether the tributary inlet was a significant source of TP to Moody Lake. The monitored event mean TP concentration in 2012 (0.60 mg/L) was higher than the average watershed TP concentration (0.27 mg/L) modeled in the 2007 Water Quality Study. However, it is difficult to make accurate comparisons between monitored and modeled data. Water quality models are based on long-term data from multiple years while the 2012 monitoring data was based on four individual precipitation events in one year with many large rainfall events. Multiple years of event mean TP concentration would need to be collected at the main inlet to Moody Lake to identify any significant, long-term reductions in watershed TP loading resulting from the current watershed load reduction efforts (livestock exclusion and restoration).

To identify long-term reductions in watershed TP loading, we recommend one of the following two options:

1. The estimation of watershed TP load reductions based on changes in land use and/or BMP phosphorus removal efficiencies resulting from current watershed load reduction efforts.
2. The collection of at least two additional years of tributary phosphorus concentrations following major rainfall events at the main inlet to Moody Lake. Extending monitoring upstream to the west and east main tributary streams contributing to the outlet would allow the District to more specifically identify remaining areas of excess load in the watershed.

If long-term watershed load reductions are not achieved, we recommend a renewed focus on the implementation of other watershed loading reduction projects as identified above.

RECOMMENDATIONS

Watershed Phosphorus Load Reduction

- We recommend estimating the watershed TP load reductions based on changes in land use and/or BMP phosphorus removal efficiencies resulting from the current watershed load reduction efforts, or collecting at least two additional years of tributary phosphorus concentrations following major rainfall events at the main inlet to Moody Lake.
- If long-term reductions in watershed TP loading are not achieved, we recommend a renewed focus on the implementation of other watershed loading reduction projects such as wetland restoration, agricultural BMPs, ponding, and flow and storage modifications in the contributing watershed.

Fisheries Management

- We recommend that the District periodically conduct a fish survey of Moody Lake to allow the District to evaluate the effectiveness of the fisheries management strategies.
- We recommend that the District install a winter aeration system on Moody Lake to eliminate the occurrence of fish kills and to encourage the establishment of predator fish.
- Fish stocking and a bullhead harvest are not recommended at this time.

Phosphorus Cycling Management

- Once long-term reductions in watershed TP loading are achieved, we recommend an alum treatment to the stratified portion of Moody Lake to reduce phosphorus loading from the sediments. Chemical treatment with alum is a comparable treatment option to lake aeration; however, lake aeration systems are only effective when in operation and may need to be installed in conjunction with the addition of iron to increase the phosphorus binding capacity of the sediment in Moody Lake.
- A lake aeration system to oxygenate bottom waters is not recommended at this time.
- Iron filings and ferric chloride are not recommended without oxygenation of bottom waters.

Vegetation Management

- We recommend that the District monitor curly-leaf pondweed abundance in May or June (i.e., before senescence) annually during phosphorus reduction treatments and consider future herbicide treatment if curly-leaf pondweed abundance increases with improving water clarity.

Table 12. In-Lake Phosphorus Loading Treatment Options for Moody Lake.

Category	In-Lake Treatment Method	Description & Typical Goals of Method	Applicability	Pros	Cons	Applicability to Moody Lake ✓ treatment option not ruled out with available data $ treatment option tends to be more costly	
Vegetation Management	Drawdown	A lowering of water level to expose sediments to the air and to freezing conditions. Goal is typically to allow consolidation of sediments, encouragement of native plants, and exposure to freezing and drying to limit growth of certain nuisance macrophytes such as curly-leaf pondweed.	- Lakes with an adjustable outlet are more feasible for drawdown, otherwise pumping is needed.	- Can limit growth of a number of macrophytes (milfoil, curly-leaf pondweed) and encourage natives - A side benefit for infested waters is that it may also reduce zebra mussel populations	- Landowners must approve the drawdown, which is often difficult - May negatively impact wildlife (beavers, frogs, turtles) and macroinvertebrates (mussels, snails, insects) - May negatively impact desired vegetation - May cause in-lake oxygen problems and algal blooms after water levels increase	Lake too deep	
	Herbicide	Application of chemical herbicides to the littoral area of the lake. Goal is to kill aquatic vegetation to eliminate it as a source of nutrients.	- Fluridone is often used for Eurasian watermilfoil control - Endothall is often used for curly-leaf pondweed control - Treatment of both milfoil and curly-leaf pondweed typically use a combination of herbicides (endothall and 2-4, D or triclopyr)	- Properly applied herbicides generally have little effect on overall native macrophytes, though can change species abundance	- Multiple years of treatment needed - If used for milfoil control, won't eliminate milfoil, just slows its spread and reduces nuisance conditions - May eliminate some desired native species - 2-4, D is a likely endocrine disruptor	Curly-leaf pondweed currently present but not dense May need to consider later application of Endothall or enhance native vegetation if increased water clarity increases CLP growth	✓
	Mechanical harvesting	Cutting and removal of aquatic vegetation. Goal is to remove vegetation from the water to eliminate it as a source of nutrients as the vegetation degrades.	- Lakes with vegetation at or near the surface (for boat-type mechanical harvester) - For milfoil, would only be applicable for lakes with widespread coverage of milfoil	- No addition of chemicals needed and no change to lake chemistry - Allow immediate recreational access to harvested areas	- Mechanical harvesting can spread milfoil and curly-leaf pondweed - Ongoing harvesting needed	May increase curly leaf pondweed density	
Fisheries Management	Fish stocking/ Biomanipulation of trophic status	Alteration of fish population structure. Goal is to alter fish population structure so that fewer planktivorous fish are present, leaving the zooplankton present to reduce the algae population.	- Lakes with unbalanced fish populations that don't respond to contributing watershed load reductions - Rotenone, fish harvest, and fish stocking can be used to support biomanipulation - May be more effective in shallow lakes	- Side benefit can be a transition to a fish population and size structure that is more attractive to anglers (if piscivorous fish are desired over planktivorous fish)	- May not be effective if high internal load from sediment still present - May take a long time to see full effect of biomanipulation efforts	Fish community dominated by rough fish with few panfish No evidence of excess planktivory by panfish	✓
	Fish kill – rotenone	Kill fish population using pesticide. Goal is to eliminate an unbalanced fish population in order to re-establish a healthy fish population.	All lakes; however, larger lakes are more costly to treat and re-stock. May also want to consider interaction of treated water with downstream water bodies.	- Allows lake to be "restarted" with fully defined new fish population - Treatment has been able to shift shallow systems to clear water state for a period of time (many years)	- Kills all fish, but not usually black bullheads or carp - May also kill zooplankton - May limit use of lake as habitat for wildlife because of lack of available food (fish) - Need to rotenone entire watershed to be most effective	Fish community dominated by black bullheads which are less susceptible to rotenone	
	Fish kill – reverse aeration	Kill fish population by lowering oxygen levels in the water column by moving anoxic water from the lake bottom through the full water column under ice cover. Goal is to eliminate an unbalanced fish population in order to re-establish a healthy fish population.	Shallow, hyper-eutrophic systems are most likely to produce effective results	- Chemical free fish kill method - If aeration system present, can use existing system	- May not kill fish that are more tolerant of low dissolved oxygen (e.g black bullheads, carp) - Can exacerbate carp problem, if present, by allowing a new carp cohort to survive due to lack of predators - May not work if mixing doesn't cause low enough oxygen, or if mixing is not complete	Current fish community is composed of black bullheads which are tolerant to low oxygen	
	Rough fish harvest	Selective removal of rough fish (carp, bullheads) by commercial fishermen. Goal is to remove benthivorous fish that stir up bottom sediments and decrease water quality.	Easier to harvest more of the target fish population in smaller lakes	- Removes unwanted fish - No anticipated negative impacts on other fish species	- May only remove a small proportion of the rough fish community. - May need to repeat harvest often, or install barriers to keep fish from re-populating. Fish barriers may not be successful.	Fish community dominated by black bullheads which do not aid food web control of algae	

Category	In-Lake Treatment Method	Description & Typical Goals of Method	Applicability	Pros	Cons	Applicability to Moody Lake ✓ treatment option not ruled out with available data $ treatment option tends to be more costly	
	Rough fish exclusion	Restrict movement of fish, particularly carp, into the water body. Goal is to maintain the desired fish population particularly after harvest or other fish management activities.	Lakes with defined fish access or fish movement points	- Minimizes movement of fish into or out of the lake (depending on barrier type and design) - Assists in isolating fish population for management	- Most barrier designs limit movement of all types of fish, including desired species	No evidence of resident rough fish populations by migration into Moody Lake through a surface inlet. Bullheads are not known to migrate like carp.	
	Winter aeration	Maintain a small plume of high oxygen water in lake. Goal is to eliminate winter fish kills.	Lakes with frequent winter fish kills	- Increases oxygen to maintain game fish species with minimal energy consumption - Takes away competitive advantage of bullheads and carp under low oxygen conditions	- Requires electricity and ongoing maintenance - Must obtain a permit to install and fence off aerated lake area	Winter fish kills have been observed in Moody Lake	✓
Phosphorus Cycling Management	Alum – in-lake	Injection of aluminum sulfate into the water column. Goal is to bind phosphorus so that it is no longer biologically active or available to support algae or macrophyte growth.	Lakes where the external load has been adequately controlled. Best used in deeper lakes that stratify (not as effective in shallow lakes). Not effective in lakes with high alkalinity.	- Improvement seen shortly after treatment - Treatment typically lasts over 10 years	- Ineffective if external load not adequately controlled. - Can negatively impact benthic organisms.	Watershed load 1.5 – 2 times internal load Good option if combined with watershed management to reduce watershed P loads Application recommended after CLP senesces in June to allow for subsequent growth of native macrophytes	✓
	Phoslock	Lanthanum embedded in bentonite (a type of clay), removes phosphate from water column or sediment pore water, producing lanthanum phosphate.			- Relatively new approach, not much information available.		
	Iron Filings	Addition of iron to the bottom sediments. Goal is to bind phosphorus in the sediment and reduce the amount of biologically available phosphorus.	Lakes with iron-poor sediments in oxygenated zones	- Iron should bind phosphorus unless low-oxygen conditions occur - May also change sediment properties to limit the growth of curly-leaf pondweed; however this is considered experimental and outcomes are not fully known. Use of iron to specifically impact vegetation is not an approved herbicide for lakes.	- Unsuccessful if bottom waters have low oxygen.	Bottom waters have extremely low oxygen levels	
	Barley straw	Placement of barley straw into the water body. Goal is to reduce the growth of algae through uptake of nutrients into the microbial community instead of in algae.	Primarily used on ponds but has shown mixed results on lakes.	- No chemical inputs	- Not shown to be consistently effective - Not approved by EPA as an algaecide	Lake too deep	
	Lake Aeration	Add air to bottom waters (hypolimnion). Goal is to ensure that bottom waters are oxygenated so that phosphorus is not released from sediment.	Lakes with high sediment internal load that would benefit from oxic bottom waters	- Limits phosphorus transport from sediments - For lakes with undesired winter fish kill, can also be used in winter to prevent fish kill.	- - Requires ongoing maintenance - Ongoing energy needs - Warms deeper waters in deep lakes	Bottom waters have extremely low oxygen levels	✓
	Hypolimnetic withdrawal & in-line ferric chloride treatment	Removal, treatment, and replacement of hypolimnetic lake water by pumping or siphoning. Goal is to reduce hypolimnetic P concentration or, if water is not replaced, to reduce the residence time of the hypolimnion to speed up downward oxygen transport from surface waters.	Stratified lakes with high hypolimnion P concentration	- No chemical inputs to lake sediments - Direct removal of phosphorus loads from lake	- Could destabilize lake stratification during replacement - Hypolimnetic P may be replaced quickly thorugh diffusion of P from deeper sediments	Lake strongly stratifies and has high hypolimnetic P concentration	$
Misc	Removal of bottom sediments by dredging	Excavation and disposal of bottom sediments. Goal is to remove phosphorus-laden sediment from the water body.	Shallow lakes with no other viable treatment options.	- Direct removal of phosphorus loads from lake	- Disturbs lake ecosystem (seed bank, existing vegetation and animals) - Often prohibitively expensive	No refuge for zooplankton and no aquatic plant uptake of watershed P may result in a noxious algae bloom	$
	Reduce or eliminate motorboat activity in shallow areas	Through ordinances, control the extent of motorboat activity that disturbs lake sediments and harms native plant communities.	Shallow lakes			Excessive motorboat activity not an issue	

Category	In-Lake Treatment Method	Description & Typical Goals of Method	Applicability	Pros	Cons	Applicability to Moody Lake ✓ treatment option not ruled out with available data $ treatment option tends to be more costly	
Proprietary Devices	Floating treatment wetlands	Floating constructed wetland system. Goal is to filter lake water and take up nutrients by vegetation and microbial action.	Smaller lakes and ponds	- May work well as supplement to existing aeration system to provide additional filtration	- Experimental - Most studies in rivers and small wastewater treatment ponds	Not sufficient evidence of feasibility in natural lake systems	
	Solar Bee	Solar powered lake circulation system. Goal is to horizontally circulate lake water to reduce the volume of stagnant waters where blue-green algae outcompete other algae for nutrients and light.	Lakes with persistent noxious blue-green algae blooms	- Solar powered option, no extra energy needs - Conversion of the blue-green algae community to algae species that are more edible by zooplankton, aiding food web control of water quality	- See aeration, although no extra energy needs since solar powered - Often prohibitively expensive - Nutrient loads are not reduced	Bottom waters have extremely low oxygen levels	

SUMMARY OF MANAGEMENT RECOMMENDATIONS

Management Plan Flow Chart

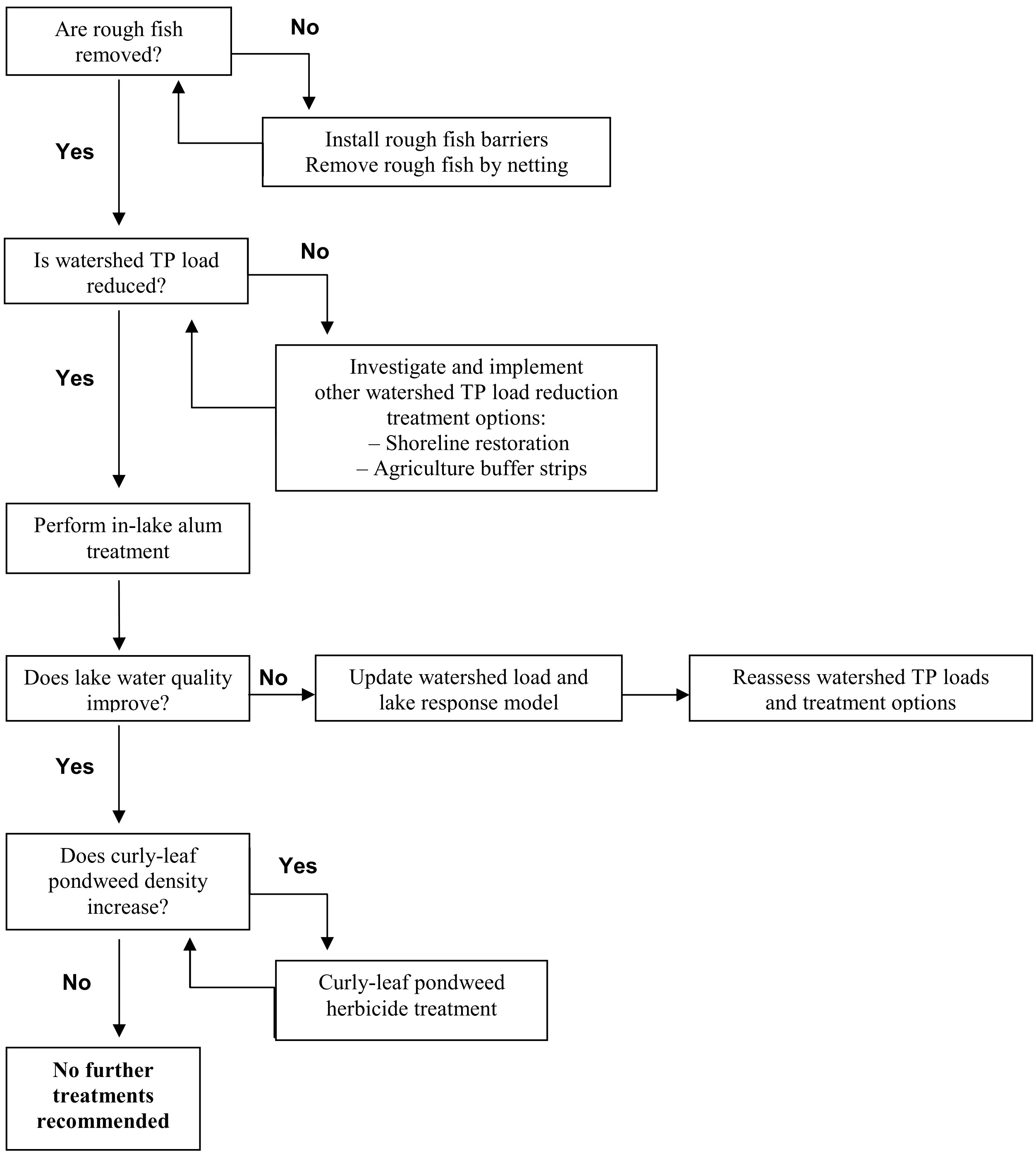


Figure 17. In-lake phosphorus management plan for Moody Lake

Table 13. Example in-lake phosphorus reduction treatment 5-year schedule for Moody Lake

	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
	2012		**2013**		**2014**		**2015**		**2016**	
Rough fish survey	■		■							
Rough fish barrier installation		■								
Watershed outlet TP monitoring	■	■								
Tributary inlet TP monitoring	■	■	■	■	■	■	■	■		
In-lake alum treatment			■							
In-lake water quality monitoring			■	■	■	■	■	■		
Curly-leaf pondweed survey	■		■		■		■		■	
CLP herbicide treatment, if needed							■			

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