Crockery Lake Evaluation Study and Restoration Plan
Ottawa County, Michigan

Provided for: Crockery Lake Association

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September, 2024

1.0 EXECUTIVE SUMMARY

Crockery Lake is located in Chester Township (T.9N, R.13W; Figure 1) Ottawa County, Michigan, and is a natural lake with an outlet. The lake surface area is comprised of 111 acres (RLS, 2022; Figure 1). The lake outlet is located at the southwest end of the lake and drains into Crockery Creek. The maximum depth of the lake is approximately 54 feet. The lake shoreline is approximately 2.54 miles. The fetch (longest distance across the lake) is approximately 1.0 mile. The lake has an immediate watershed of approximately 2,533 acres which is 22.8 times the lake surface area and means that Crockery Lake has a large immediate watershed. A larger watershed allows for more pollutant and nutrient inputs over time. Crockery Lake has elevated nutrient concentrations with very high total phosphorus (TP) measured near the bottom which indicates internal loading that leads to increased weed and algae growth due to the anoxic (very low dissolved oxygen) concentrations also measured at the lake bottom.

The small lake size makes it vulnerable to nutrient loading, resulting in algal blooms and/or excessive submersed aquatic vegetation growth. The lake association has levied an assessment through a Special Assessment District (SAD) under P.A. 188 of 1954, which can fund improvements solely for aquatic vegetation management for a period of up to 20 years. The current assessment for this SAD is at $126.66 per property for a total of 105 assessed parcels. In consideration of this cost, it is clear that substantial restoration of the lake will add to this cost and thus cost-effective strategies are needed for a sustainable lake restoration program. A reduction in lake nutrients through the recommended methods cited in the sections below would be expected to reduce algal abundance and associated treatment costs over time.

The largest issue regarding the health of Crockery Lake is external loading of nutrients from drains that are resulting in an internal loading of phosphorus in the lake basin. Additionally, non-point source nutrients from septic drain fields are also likely contributors to nutrient loading in the lake. Both of these source types have resulted in accelerated eutrophication of the lake in the form of increased and widespread algal blooms and nuisance submersed aquatic vegetation.

While reduction of nutrients from the drains (immediate watershed) is critical, highly selective management of only invasive aquatic vegetation is also important. Current aquatic vegetation treatment should include the use of systemic herbicides for invasive milfoil to reduce treatment costs in future years. Removal of too much submersed aquatic vegetation relative to the lake surface area can result in increased nutrient uptake by algae which can worsen the lake condition.

RLS recommends continued sampling all of the drains and the two deepest lake basins in future years as required by a future EGLE permit. Such data collection is critical for the generation of data trends to determine the efficacy of nutrient reduction BMP's such as filters and other methods in reducing nutrient loads. The major BMPs should include the following:

1. Collaboration with all farms that abut the tributaries for reducing farm runoff and using innovative vegetative and soil retention technologies.
2. Implementation of a lake-wide septic system maintenance program with proof of good function. Possible implementation of site-specific aerobic digesters may also be used to reduce nutrients from drain fields to the water table and lake water.
3. Implementation of Biochar or other vegetative filters in the lake drains to reduce nutrient loads to the lake.
4. Installation of hypolimnetic oxygenation units in the two deepest basins to increase dissolved oxygen at depth and prevent the continual current release of phosphorus.
5. Continued riparian involvement in local decision-making relative to lake health with educational workshops on the aforementioned BMP's.

The major goals and objectives for the lake include reduction of incoming nutrient loads, a septic maintenance program, and sustained reduction of harmful algal blooms and invasive aquatic plant growth. The estimated costs for these improvements per assessed property in the current SAD are shown in Section 9.0. Note that only aquatic vegetation treatment is allowed for the current SAD program, and thus no restoration funds are currently available.

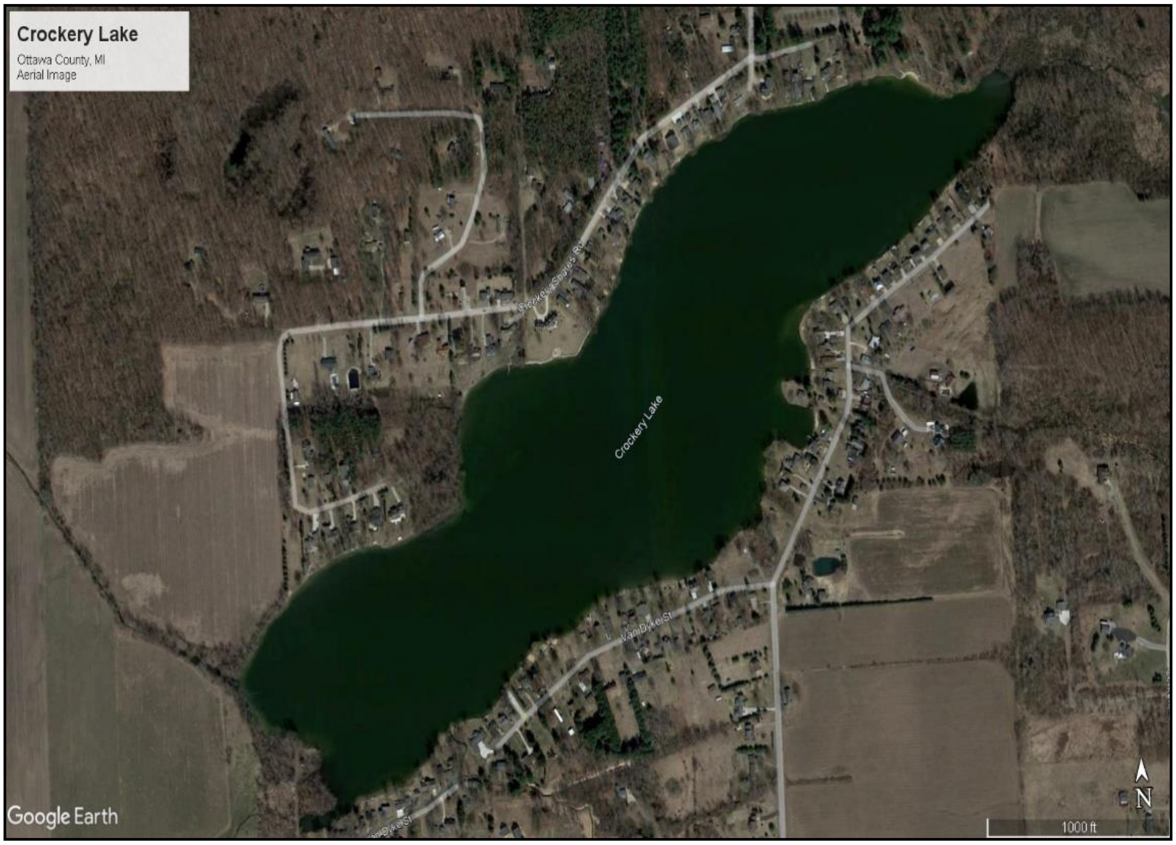


Figure 1. Aerial base map of Crockery Lake, Ottawa County, MI.

2.0 LAKE ECOLOGY BACKGROUND INFORMATION

2.1 Introductory Concepts

Limnology is a multi-disciplinary field which involves the study of the biological, chemical, and physical properties of freshwater ecosystems. A basic knowledge of these processes is necessary to understand the complexities involved and how management techniques are applicable to current lake issues. The following terms will provide the reader with a more thorough understanding of the forthcoming lake management recommendations for Crockery Lake.

2.1.1 Lake Hydrology

Aquatic ecosystems include rivers, streams, ponds, lakes, and the Laurentian Great Lakes. There are thousands of lakes in the state of Michigan, and each possesses unique ecological functions and socio-economic contributions. In general, lakes are divided into four categories:

- Seepage Lakes,
- Drainage Lakes,
- Spring-Fed Lakes, and
- Drained Lakes.

Some lakes (seepage lakes) contain closed basins and lack inlets and outlets, relying solely on precipitation or groundwater for a water source. Seepage lakes generally have small watersheds with long hydraulic retention times which render them sensitive to pollutants. Drainage lakes receive significant water quantities from tributaries and rivers. Drainage lakes contain at least one inlet and an outlet and generally are confined within larger watersheds with shorter hydraulic retention times. As a result, they are less susceptible to pollution. Spring-fed lakes rarely contain an inlet but always have an outlet with considerable flow. The majority of water in this lake type originates from groundwater and is associated with a short hydraulic retention time. Drained lakes are similar to seepage lakes, yet rarely contain an inlet and have a low-flow outlet. The groundwater and seepage from surrounding wetlands supply the majority of water to this lake type and the hydraulic retention times are rather high, making these lakes relatively more vulnerable to pollutants. The water quality of a lake may thus be influenced by the quality of both groundwater and precipitation, along with other internal and external physical, chemical, and biological processes. Crockery Lake may be categorized as a drainage lake since it has four prominent inlets as well as an outlet at the southwest section of the lake which enters Crockery Creek and eventually empties into the Grand River and into Lake Michigan.

2.1.2 Biodiversity and Habitat Health

A healthy aquatic ecosystem possesses a variety and abundance of niches (environmental habitats) available for all of its inhabitants. The distribution and abundance of preferable habitat depends on limiting influence from development, while preserving sensitive or rare habitats. As a result of this, undisturbed or protected areas generally contain a greater number of biological species and are considered more diverse. A highly diverse aquatic ecosystem is preferred over one with less diversity because it allows a particular ecosystem to possess a greater number of functions and contribute to both the intrinsic and socio-economic values of the lake. Healthy lakes have a greater biodiversity of aquatic macroinvertebrates, aquatic macrophytes (plants), fishes, phytoplankton, and may possess a plentiful yet beneficial benthic microbial community (Wetzel, 2001).

2.1.3 Watersheds and Land Use

A watershed is defined as an area of land that drains to a common point and is influenced by both surface water and groundwater resources that are often impacted by land use activities. In general, larger watersheds possess more opportunities for pollutants to enter the ecosystem, altering the water quality and ecological communities. In addition, watersheds that contain abundant development and industrial sites are more vulnerable to water quality degradation from pollution which may negatively affect both surface and ground water. Since many inland lakes in Michigan are relatively small in size (i.e. less than 300 acres), they are inherently vulnerable to nutrient and pollutant inputs, due to the reduced water volumes and small surface areas. As a result, the living (biotic) components of the smaller lakes (i.e. fishery, aquatic plants, macro-invertebrates, benthic organisms, etc.) are highly sensitive to changes in water quality from watershed influences. Land use activities have a dramatic impact on the quality of surface waters and groundwater.

In addition, the topography of the land surrounding a lake may make it vulnerable to nutrient inputs and consequential loading over time. Topography and the morphometry of a lake dictate the ultimate fate and transport of pollutants and nutrients entering the lake. Surface runoff from the steep slopes surrounding a lake will enter a lake more readily than runoff from land surfaces at or near the same grade as the lake. In addition, lakes with steep drop-offs may act as collection basins for the substances that are transported to the lake from the land. Land use activities, such as residential land use, industrial land use, agricultural land use, water supply land use, wastewater treatment land use, and storm water management, can influence the watershed of a particular lake. All land uses contribute to the water quality of the lake through the influx of pollutants from non-point sources (NPS) or from point sources. Non-point sources are often diffuse and arise when climatic events carry pollutants from the land into the lake. Point-source pollutants are discharged from a pipe or input device and empty directly into a lake or watercourse.

Residential land use activities involve the use of lawn fertilizers on lakefront lawns, the utilization of septic tank systems for treatment of residential sewage, the construction of impervious (impermeable, hard-surfaced) surfaces on lands within the watershed, the burning of leaves near the lakeshore, the dumping of leaves or other pollutants into storm drains, and removal of vegetation from the land and near the water. In addition to residential land use activities, agricultural practices by vegetable crop and cattle farmers may contribute nutrient loads to lakes and streams. Industrial land use activities may include possible contamination of groundwater through discharges of chemical pollutants.

3.0 CROCKERY LAKE PHYSICAL CHARACTERISTICS

3.1 The Crockery Lake Basin

The lake surface area of Crockery Lake is comprised of 111 acres (RLS, 2024). The lake outlet is located at the southwest end of the lake and drains into Crockery Creek and eventually into the Grand River and Lake Michigan. The maximum depth of the lake is approximately 54 feet. The lake shoreline is approximately 2.54 miles. The fetch (longest distance across the lake) is approximately 1.0 mile. The lake has an immediate watershed of approximately 2,533 acres which is 22.8 times the lake surface area and means that Crockery Lake has a large immediate watershed. There are four key areas of drainage that enter the lake and contribute nutrients (Figure 2).

A bathymetric (depth contour) map was created in 2024 (Figure 3) by scanning the lake basin with a specialized transducer and Lowrance HDS 9® GPS unit. Additionally, a bottom sediment hardness scan was conducted of the entire lake bottom on May 29, 2024 (Figure 4). The bottom hardness map shows that most of the lake bottom consists of fairly consolidated sediment throughout the lake with a few areas with soft bottom. This is not surprising given the amount of sandy loams in the region which contribute to lake geology. Table 1 shows the categories of relative bottom hardness with 0.0-0.1 referring to the softest and least consolidated bottom and >0.4 referring to the most consolidated bottom for the lake basin. This scale does not mean that any of the lake contains a truly “hard” bottom but rather a bottom that is more cohesive and not flocculent.

Table 1. Crockery Lake basin relative hardness of the lake bottom by category or hardness and percent cover of each category (relative cover).

Lake Bottom Relative Hardness Category	# GPS Points in Each Category (Total =3,487)	% Relative Cover of Bottom by Category
0.0-0.1	0	0.0
0.1-0.2	111	3.2
0.2-0.3	1976	56.7
0.3-0.4	1399	40.1
>0.4	1	0.0

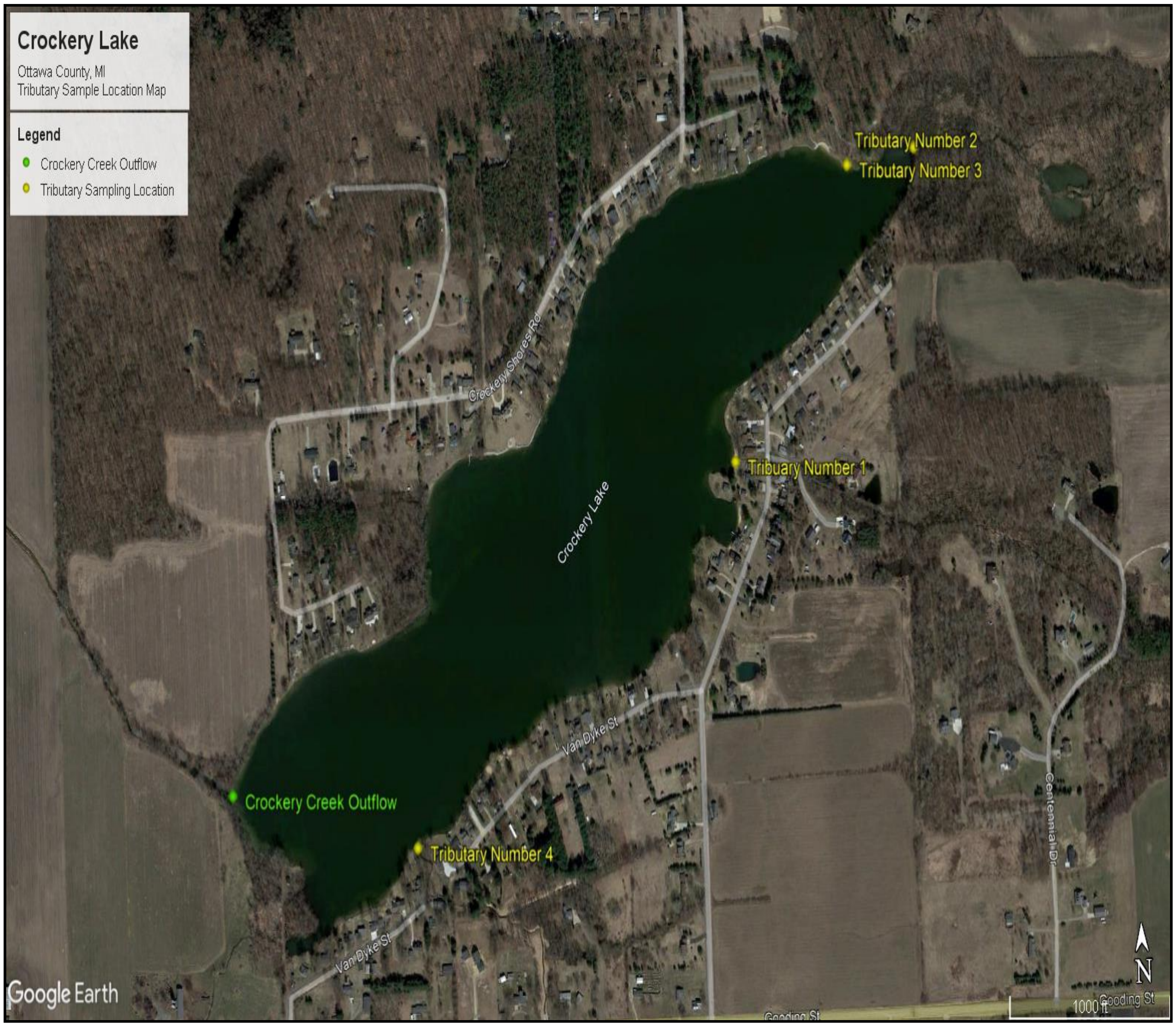


Figure 2. Crockery Lake Tributary and Outlet Map, Ottawa County, Michigan (RLS, 2024).

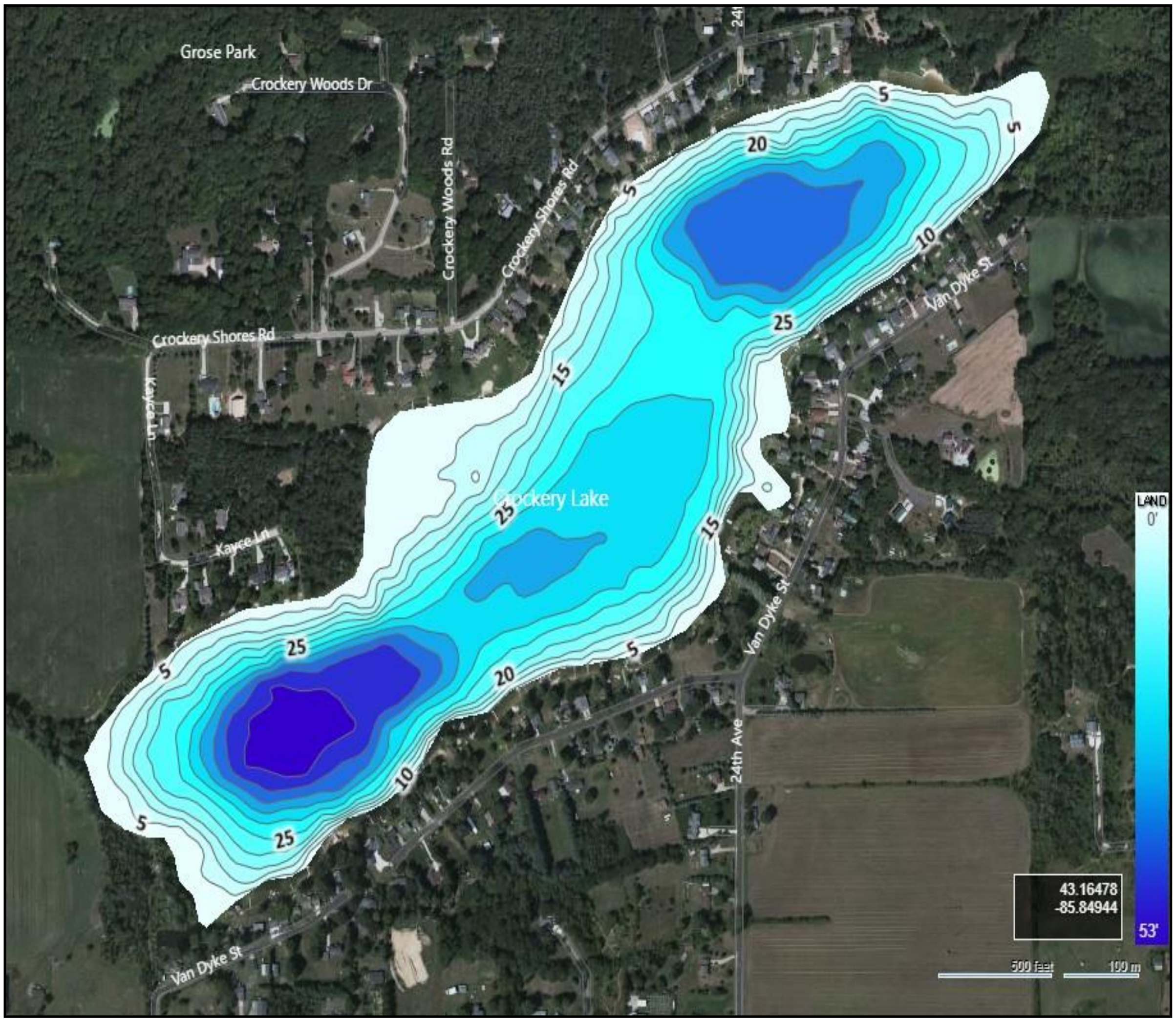


Figure 3. Crockery Lake basin depth contour map (RLS, 2024).

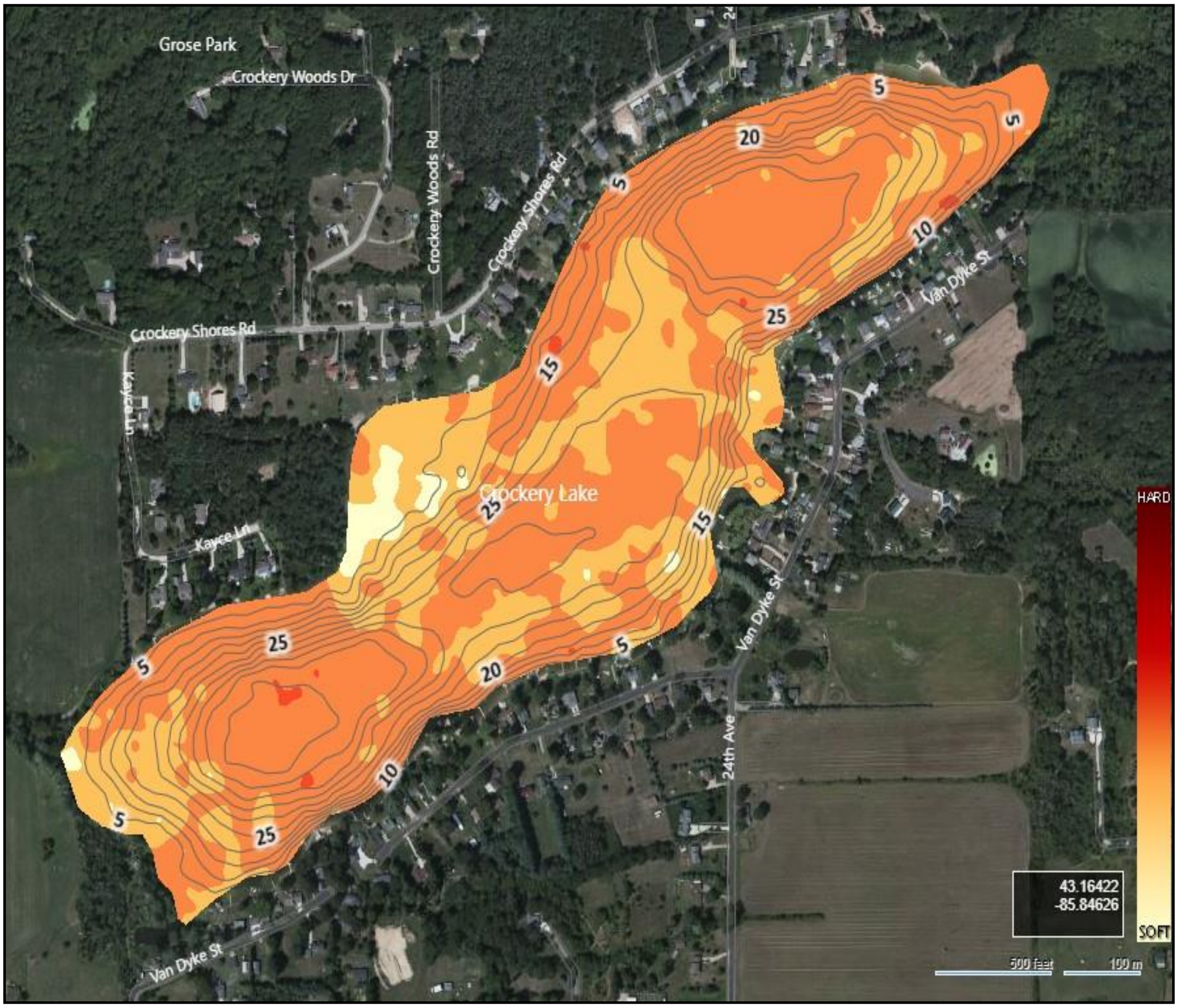


Figure 4. Crockery Lake basin sediment relative hardness map (RLS, 2024).

4.0 CROCKERY LAKE IMMEDIATE WATERSHED AND NUTRIENT POLLUTION

The term nonpoint source pollution refers to pollutants that are diffuse and usually have more than one source. The immediate watershed surrounding Crockery Lake contributes nonpoint source (NPS) pollutants to the lake through the drains, septic systems, and runoff. It is nearly impossible to control the inputs from such as large area and in the absence of requested legal easements for upstream drain improvements. Thus, improvements at the junction of the lake and drain are the most likely to reduce inputs. Upstream efforts should include working with all farms abutting the tributaries to reduce runoff and associated nutrients. This can be accomplished with focus groups that include the farm owners, Association members, and other relevant stakeholders.

An immediate watershed is defined as a region surrounding a lake that contributes water and nutrients to a waterbody through drainage sources. Watershed size differs greatly among lakes and also significantly impacts lake water quality. Large watersheds with much development, numerous impervious or paved surfaces, abundant storm water drain inputs, and surrounding agricultural lands, have the potential to contribute significant nutrient and pollution loads to aquatic ecosystems.

Crockery Lake is located within the Grand River extended watershed. The Grand River is Michigan's longest river at 270 miles in length beginning in Hillsdale and Jackson counties and ending in Ottawa County where it empties into Lake Michigan near Grand Haven. The Grand River watershed is so large that it is often divided into an upper and lower section with the Lower Grand River watershed including counties such as Allegan, Barry, Eaton, Ionia, Kent, Mecosta, Montcalm, Muskegon, Newaygo, and Ottawa counties. The watershed encompasses an area of approximately 3,020 mi^2. Additionally, there is a drop in elevation within the watershed from 1,260 feet above mean sea level to an elevation of 577 feet. This information is valuable on a regional scale; however, it is at the immediate watershed scale that significant improvements can be made by the local lake community.

The immediate watershed of Crockery Lake consists of the area around the lake that directly drains to the lake and measures approximately 2,533 acres in size (Figure 5; RLS, 2022). The immediate watershed is about 22.8 times the size of the lake, which is considered a large immediate watershed. The lakefront itself has a diverse application of land uses such as beachfront for swimming, wetlands, and forested lands. Thus, management options should also consider all of these land uses and preserve their unique functions. Drain influxes of nutrients are the largest threat to the water quality of Crockery Lake next to septic systems. There are four key areas of drainage that enter the lake (Figure 6).

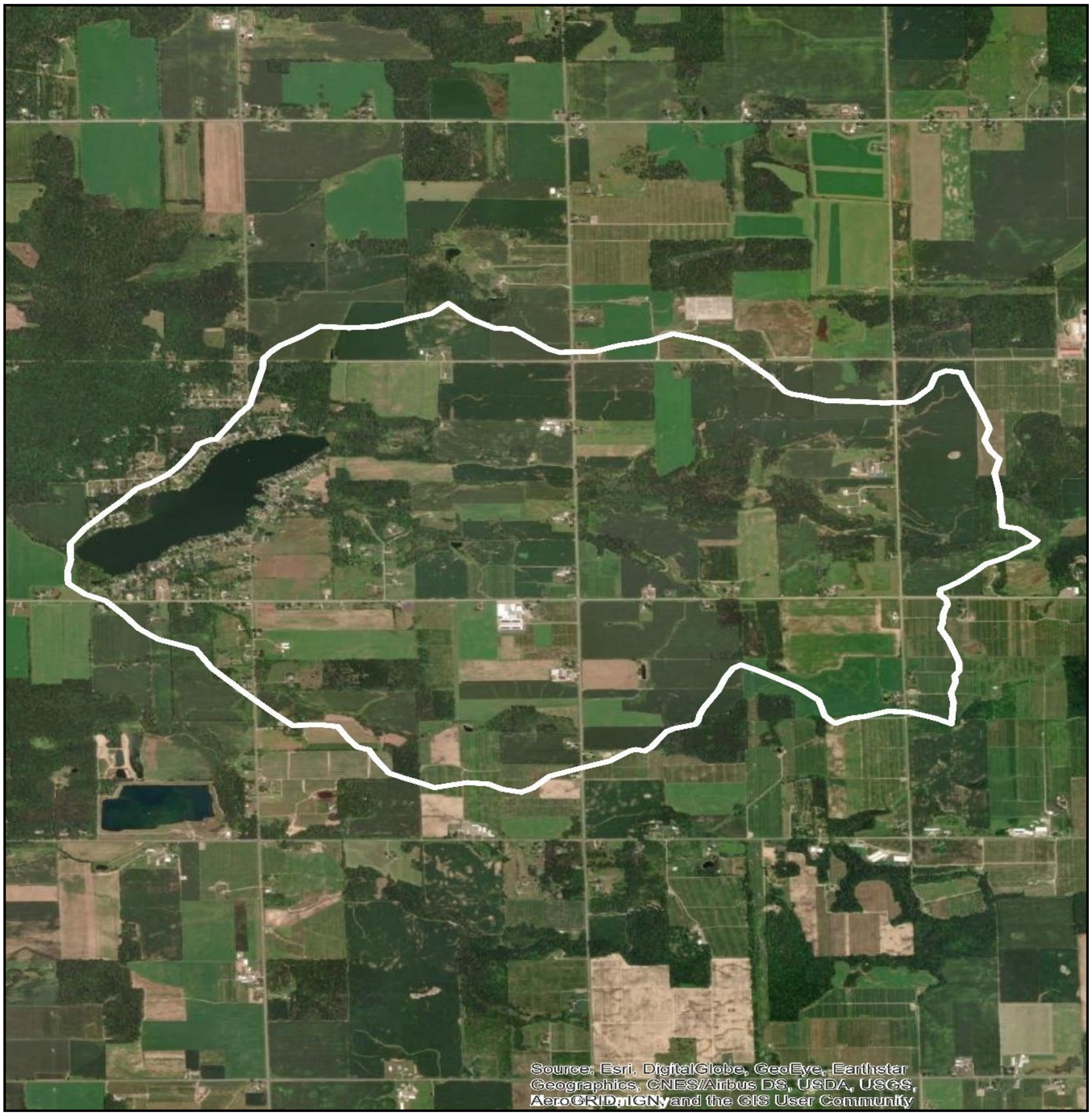


Figure 5. Crockery Lake immediate watershed boundary (RLS, 2022.)

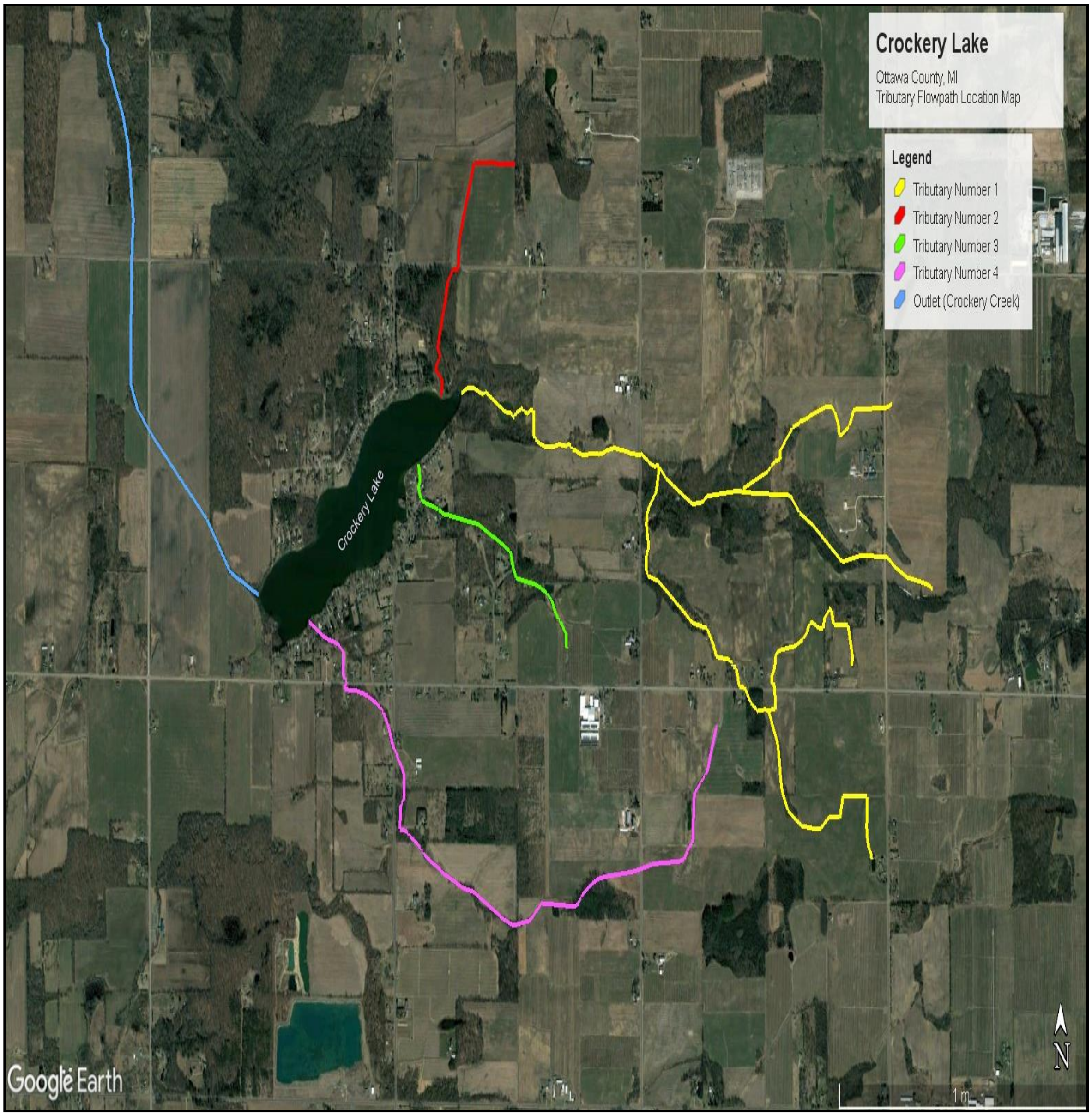


Figure 6. A map showing the drainage courses into Crockery Lake (RLS, 2024).

There are 7 major soil types immediately surrounding Crockery Lake which may impact the water quality of the lake and may dictate the particular land use activities within the area (Table 2). The denotes a lake with fairly complex geology (Figure 7; created with data from the United States Department of Agriculture and Natural Resources Conservation Service, 1999) demonstrates the precise soil types and locations around Crockery Lake. Major characteristics of the dominant soil types directly surrounding the Crockery Lake shoreline are discussed below.

Table 2. Crockery Lake Shoreline Soil Types (USDA-NRCS data).

USDA-NRCS Soil Series	***Location***	***Primary Characteristics***
Adrian Muck (0-1% slopes)	south-central	Poorly drained
Granby loamy sand (0-2% slopes)	s, sw, se	Very deep, poorly drained
Newaygo sandy loam (0-6% slopes)	south	Very deep, well drained
Richter sandy loam (2-6% slopes)	northwest	Very deep, somewhat poorly drained
Shoals loam	east	Very deep, somewhat poorly drained
Tekenink-Spinks loamy sands (6-12 % slopes)	n, ne	Very deep, well drained
Warners muck	northwest	Poorly drained

Where n = north, s = south, w = west, and e = east.

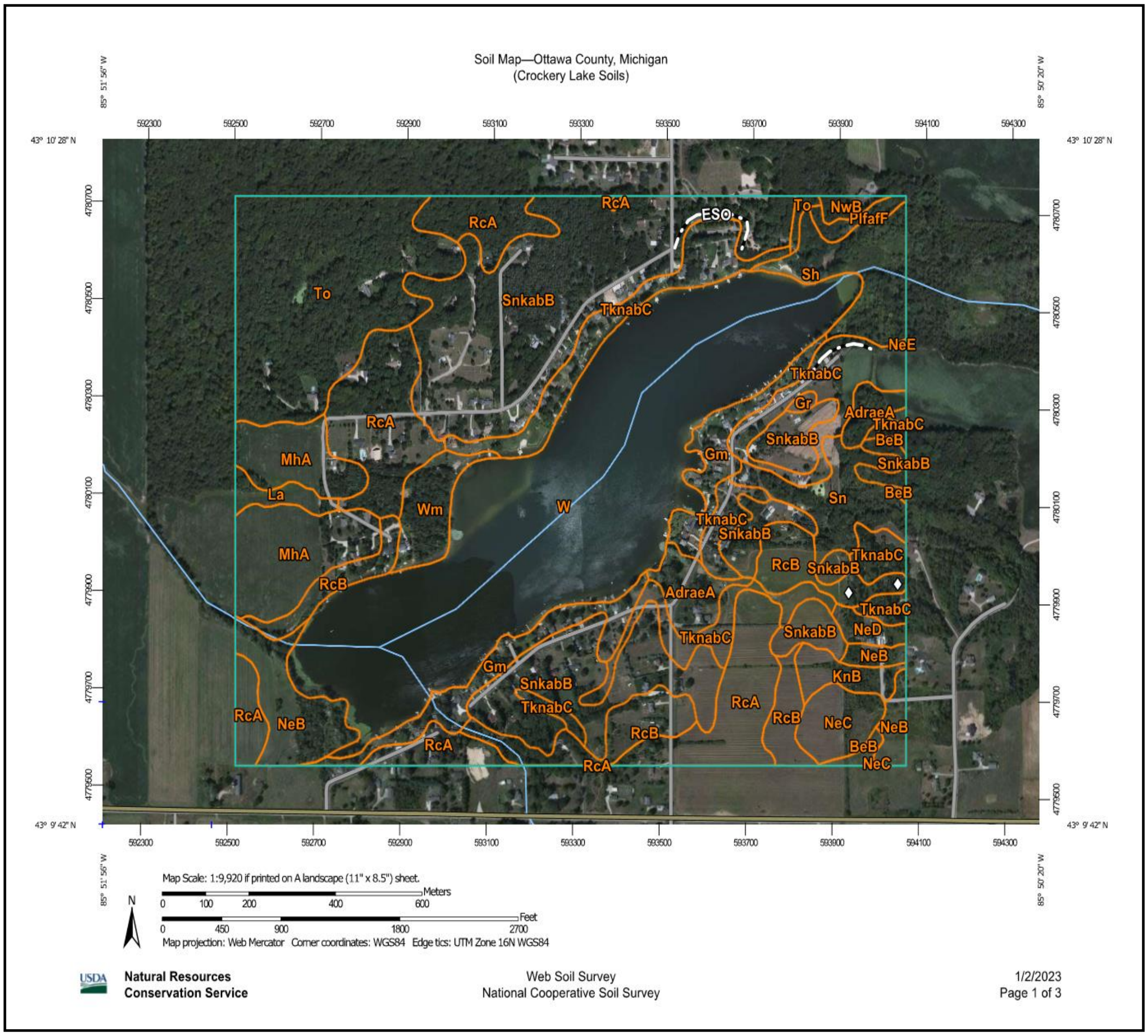


Figure 7. Crockery Lake shoreline soils map (NRCS-USDA data).

The majority of the soils around Crockery Lake are sandy loams which are very deep and somewhat well drained to well drained soils. These soils are located along the north shore and are in an area of higher slopes (6-12%). Improper land stabilization may result in erosion of properties without proper erosion control management and also during periods of high water.

There are also organic saturated soils such as the Adrian and Warners mucks, present near the central lake shorelines that are very deep, very poorly drained soils with the potential for ponding. Ponding occurs when water cannot permeate the soil and accumulates on the ground surface which then many runoff into nearby waterways such as the lake and carry nutrients and sediments into the water.

Excessive ponding of such soils may lead to flooding of some low-lying shoreline areas, resulting in nutrients entering the lake via surface runoff since these soils do not promote adequate drainage or filtration of nutrients. The mucks located in the wetlands may become ponded during extended rainfall and the wetlands can serve as a source of nutrients to the lake. When the soils of the wetland are not saturated, the wetland can serve as a sink for nutrients and the nutrients are filtered by wetland plants. The following sections discuss the sources and impacts of nutrients from non-point sources (NPS) which includes drains and septic systems.

4.1 Nutrient Shifts and Reduction

The control of nutrients from a surrounding watershed or catchment to any lake is a proven necessity for long-term nutrient reduction. Although nutrients are a necessity for the primary production of algae and aquatic plants in a lake ecosystem, an overabundance of nutrients causes substantial problems as noted above. Lakes that lie within an agricultural watershed may experience acute and chronic influx of sediments, nutrients, and bacteria, among other pollutants. Those within urbanized watersheds face other stressors that include nutrient pollution but also influx of metals, dissolved solids, among other pollutants. In many areas, however, the watershed reduction approach is limited, and restorative measures must begin within the lake basin. Annadotter et *al*., (1999) noted that even years after a sewage treatment plant was built along the shores of Lake Finjasjön (Sweden), the lake trophic status continued to decline. This was due to the existence of sediments that continuously leaked phosphorus into the overlying waters. A combination of intensive lake restoration methods was needed to significantly improve the water quality and consisted of sediment removal, constructed wetlands for watershed nutrient removal, and food web manipulation to improve the fishery. Their study proved that in cases of extreme water quality degradation, multiple techniques are often needed to bring a marked balance back to the lake ecosystem. In other words, one solution may not be enough to accomplish restoration.

4.2 Impacts of NPS Pollution on Inland Waters:

Beginning in 2007 and continuing to the present day, the USEPA Office of Water and Office of Research and Development has partnered with multiple stakeholders at both the state and federal levels to derive comparisons among the nation's aquatic resources which include lakes, wadable streams, large rivers, coastal estuaries, and wetlands. During the assessment, 1,028 lakes have been sampled along with 124 reference lakes and 100 lakes which were re-sampled. Lakes were selected from the National Hydrography Data Set (NHD) using a set of criteria that addressed trophic status, locale, and physical characteristics. Water quality indicators such as biological integrity, habitat quality, trophic status, chemical stressors, pathogens, and paleolimnological changes were measured.

Although 56% of the nation's lakes possessed healthy biological communities, approximately 30% of lakes had the toxin microcystin, which is produced by the blue-green algae *Microcystis*. Approximately 49% of the lakes had mercury concentrations in fish tissues that exceeded healthy limits. The key stressors of the lakes were determined to be poor shoreline habitat and excessive nutrients. A favorable outcome of the inventory revealed that half of the lakes exhibited declines in phosphorus levels compared to levels noted in the early 1970's. Despite this observed decline, many of our inland lakes continue to experience degradations in water quality. One reason for this problem is that many lakes have properties that utilize septic systems. Since riparians have little control over local pollutant loading from agriculture to inland lakes, the maintenance of septic systems is critical for water quality protection.

4.3 Crockery Lake Critical Source Areas (CSA's):

Non-point source (NPS) pollutants are diffuse and have many potential sources to inland lakes such as large agricultural land use activities that abut waterways and drain into Crockery Lake. Once identified, these are referred to as critical source areas (CSA's) which are areas that contribute directly to the detriment of receiving waters. CSA's often generate substantially more nutrient, and sediment loads than most of the immediate watershed area (White et *al*., 2009) and thus are a critical component for the discovery of target areas with highest impact on water quality. CSA's can contribute high loads of nutrients and sediments to inland waterways and often escape detection during lake management programs. In vulnerable areas, these pollutants enter lakes after a climatic event such as heavy rainfall or snowmelt. The surrounding landscape is critical for the determination of CSA's as some areas contain high slopes which increase the probability of erosion, while others contain soils that pond and contribute pollutants to the lake via runoff from the land. This information is critical to include in a watershed management program since Best Management Practices (BMP's) should be site-specific and address the pollutant loads at the site-level. Many BMP's will follow recommendations from Low Impact Development (LID) which aims to reduce the amount of imperviousness in developed areas. Since so many lake shorelines are already developed or are being further developed, the use of LID practices will help reduce runoff and protect water quality.

Critical Source Areas (CSA's) for Crockery Lake were determined based on characteristics that would likely contribute nutrient or sediment loads to Crockery Lake which includes major drains. A total of 4 CSA's were found in the immediate watershed entering Crockery Lake and are shown in Figures 8-11. In addition, it is important to remember that during high rainfall periods, wetlands around the lake may act as a source, rather than a sink, for nutrients that may enter the lake. This is a natural process that does not have a man-made solution.

Elder (1985) discusses the sink-source interactions between wetlands and rivers or other waterways. He cites timing and duration of flooding events as being the key predictors of nutrient and material transport from the wetland to the waterway.

It is important to retain many of the wetland features, as any entry portals cut through the wetland (i.e., via cutting emergent cattails or other vegetation), may cause overland flow which could carry nutrients and sediments directly from wetlands into Crockery Lake. Wetlands have been traditional for the treatment of storm water in that they filter out nutrients and sediments. However, during very intense rainfall events, the hydric (saturated) soils in the wetland may actually contribute nutrients to Crockery Lake.

Based on the data below in Section 7.0, the tributaries entering Crockery Lake are significant sources of nutrients such as phosphorus and nitrogen to the lake, especially during intense rainfall events. Upstream BMP's with farmers are critical for reducing these inputs in the future and a collaborative approach is recommended.

Figure 8. CSA #1 draining into Crockery Lake (east side). This drain is approximately 5-6' feet in width

Figure 9. CSA #2 draining into Crockery lake (northeast) near the swamp. This drain is approximately 8-10’ in width.

Figure 10. CSA #3 draining into Crockery Lake (north) near Grosse Park. This drain is approximately 4-6’ in width near the lake.

Figure 11. CSA #4 draining into Crockery Lake (by foot bridge). This drain is approximately 10-12' in width.

5.0 CROCKERY LAKE WATER QUALITY

Water quality is highly variable among Michigan's inland lakes, although some characteristics are common among particular lake classification types. The water quality of each lake is affected by both land use practices and climatic events. Climatic factors (i.e. spring runoff, heavy rainfall) may alter water quality in the short term; whereas, anthropogenic (man-induced) factors (i.e. shoreline development, lawn fertilizer use) alter water quality over longer time periods. Since many lakes have a fairly long hydraulic residence time, the water may remain in the lake for years and is therefore sensitive to nutrient loading and pollutants. Furthermore, lake water quality helps to determine the classification of particular lakes (Table 3). Lakes that are high in nutrients (such as phosphorus and nitrogen) and chlorophyll-*a*, and low in transparency are classified as eutrophic; whereas those that are low in nutrients and chlorophyll-*a*, and high in transparency are classified as oligotrophic. Lakes that fall in between these two categories are classified as mesotrophic. Crockery Lake is classified as hyper-eutrophic (very nutrient-enriched) due to the very high nutrients and low Secchi transparency, elevated chlorophyll-a, and marked dissolved oxygen depletion with depth (Figure 12).

Table 3. General Lake Trophic Status Classification Table.

Lake Trophic Status	*Total Phosphorus (mg L^{-1})*	*Chlorophyll-a (µg L^{-1})*	*Secchi Transparency (feet)*
Oligotrophic	< 0.010	< 2.2	> 15.0
Mesotrophic	0.010-0.025	2.2 – 6.0	7.5 – 15.0
Eutrophic	> 0.025	> 6.0	< 7.5

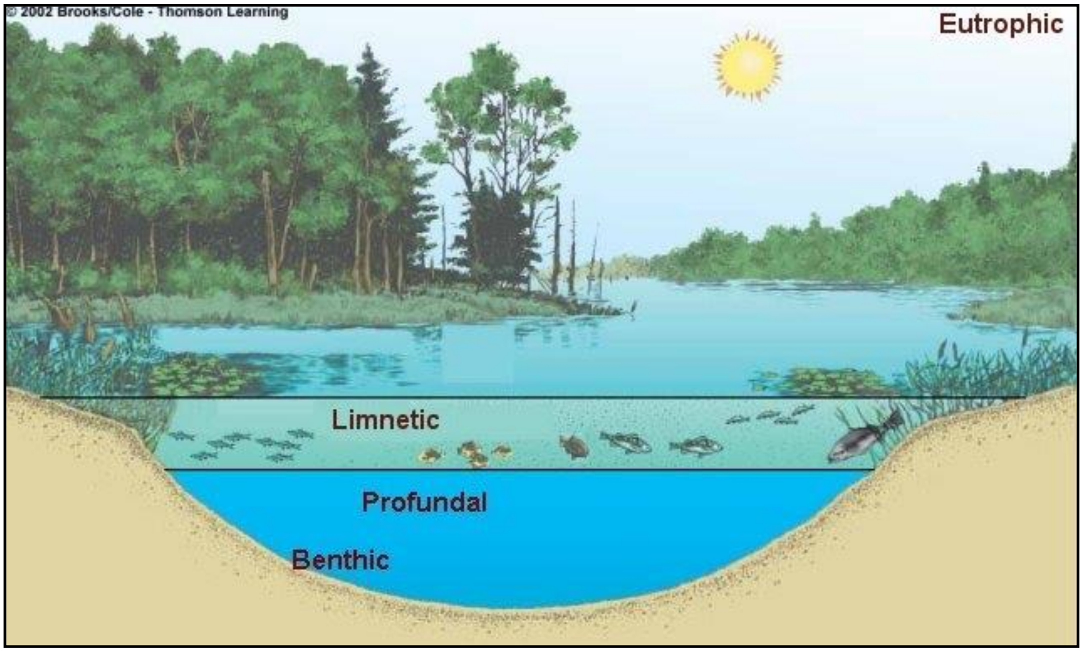


Figure 12. Diagram showing a eutrophic or nutrient-enriched lake ecosystem (photo adapted from Brooks/Cole Thomson learning online).

5.1 Water Quality Parameters

Parameters such as dissolved oxygen (in mg/L), water temperature (in °C), specific conductivity (mS/cm), total dissolved solids (mg/L), total suspended solids (mg/L), pH (S.U.), total phosphorus and ortho-phosphorus (also known as soluble reactive phosphorus or SRP measured in mg/L), total Kjeldahl nitrogen and total inorganic nitrogen (in mg/L), chlorophyll-a (in µg/L), and Secchi transparency (in feet) are parameters that respond to changes in water quality and consequently serve as indicators of change over time. The deep basin results for all abiotic and biotic water quality parameters are discussed below and are presented in Tables 6-18. A statistical summary of all water quality data collected to date is shown in Table 19. A map showing the sampling locations for all water quality samples is shown below in Figure 13. All water samples and readings were collected at the 2 deepest basins on May 29, 2024, July 22, 2024, and September 3, 2024 with the use of a 3.2-Liter Van Dorn horizontal water sampler and calibrated Eureka Manta II® multi-meter probe with parameter electrodes, respectively. All samples were taken to a NELAC-certified laboratory for analysis. In addition, 5 sediment samples (Figure 14) were collected throughout the lake basin using an Ekman hand dredge on September 3, 2024. Sediment samples were analyzed for sediment organic matter percentage in mg/kg and particle size. Specific sampling methods for each parameter are discussed in each parameter section below.

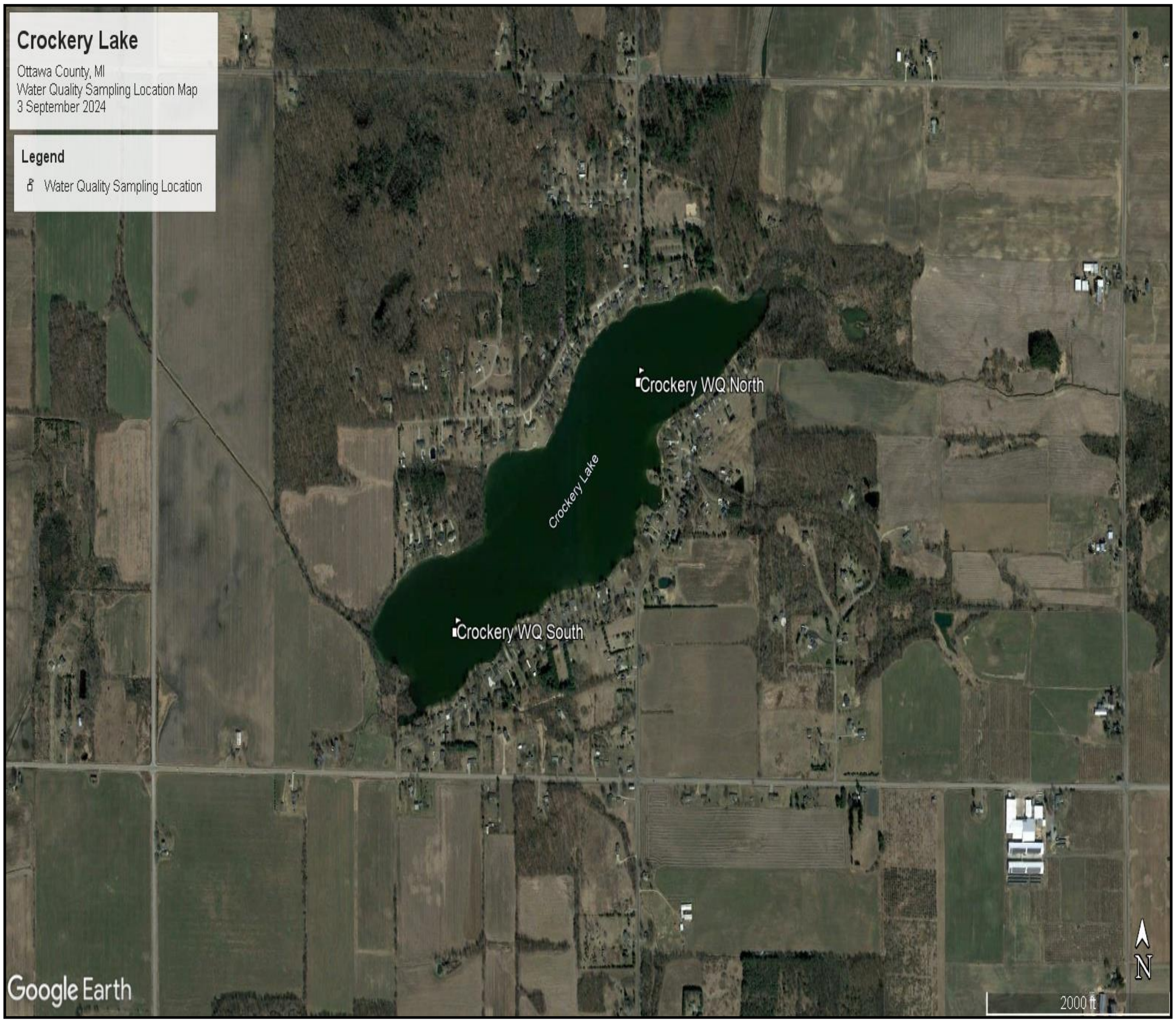


Figure 13. Locations for water quality sampling of the deep basins in Crockery Lake (2024).

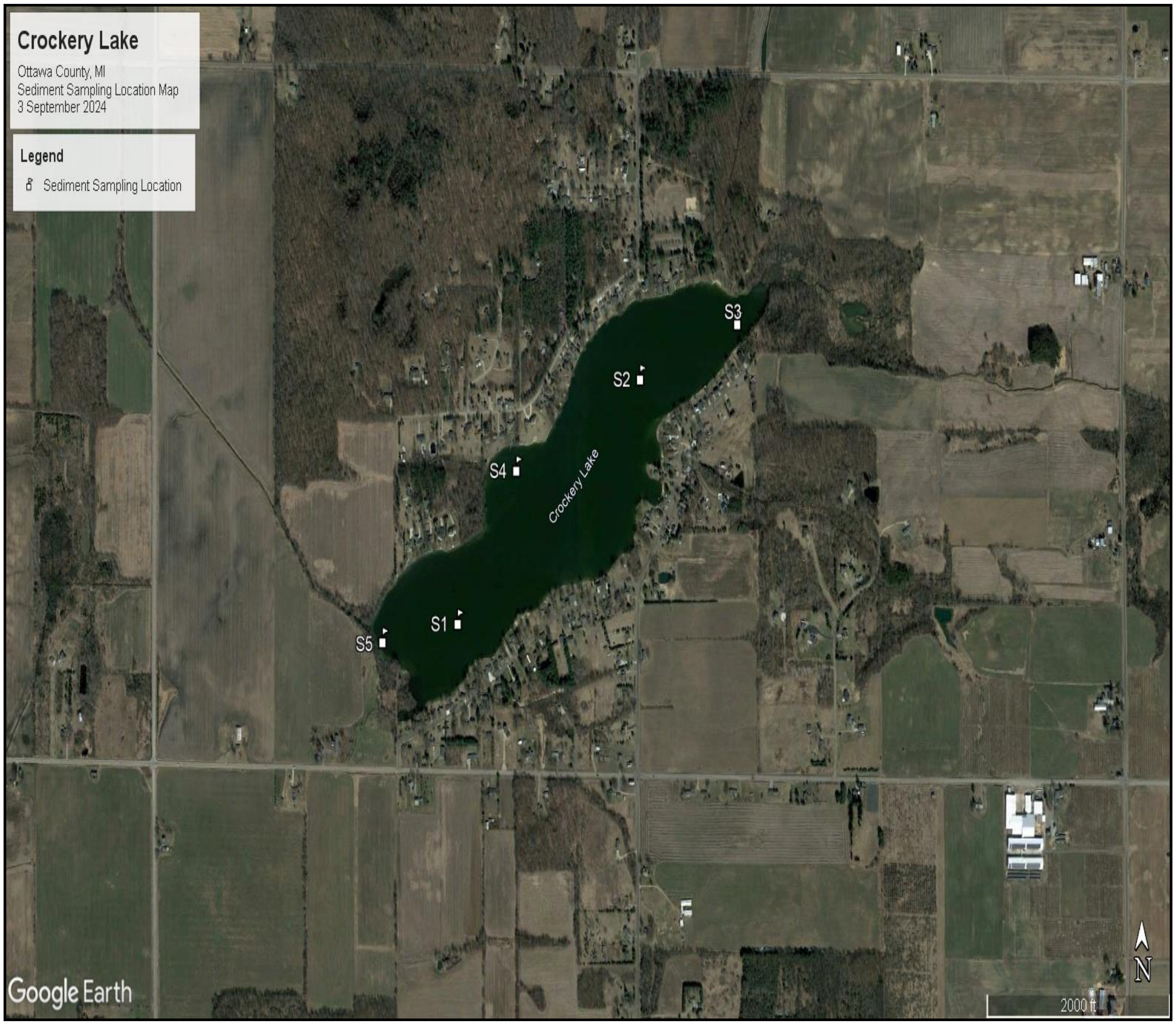
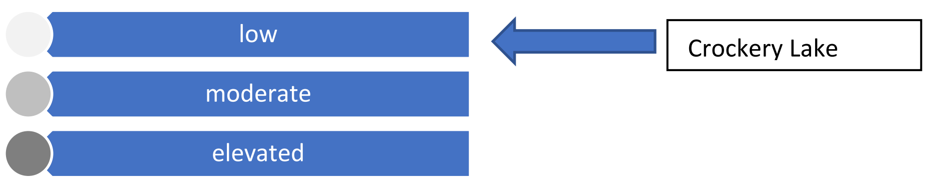


Figure 14. Sediment sampling locations in Crockery Lake (September 3, 2024).

5.1.1 Dissolved Oxygen

Dissolved oxygen is a measure of the amount of oxygen that exists in the water column. In general, dissolved oxygen levels should be greater than 5 mg/L to sustain a healthy warm-water fishery. Dissolved oxygen concentrations may decline if there is a high biochemical oxygen demand (BOD) where organismal consumption of oxygen is high due to respiration. Dissolved oxygen is generally higher in colder waters. Dissolved oxygen was measured in milligrams per liter (mg/L) with the use of a calibrated Eureka Manta II® dissolved oxygen meter. The mean dissolved oxygen concentrations in the basin of Crockery Lake ranged from 2.9-3.3 mg/L which is very low. Substantial DO depletion was evident beyond depths of 4-5 meters by late May which is not favorable.

The bottom of the lake produces a biochemical oxygen demand (BOD) due to microbial activity attempting to break down high quantities of organic plant matter, which reduces dissolved oxygen in the water column at depth. Furthermore, the lake bottom is distant from the atmosphere where the exchange of oxygen occurs. A decline in the dissolved oxygen concentrations to near zero may result in an increase in the release rates of phosphorus (P) from lake bottom sediments. This means that Crockery Lake has a large area of low oxygen throughout the summer months.



5.1.2 Water Temperature

A lake's water temperature varies within and among seasons, and is nearly uniform with depth under the winter ice cover because lake mixing is reduced when waters are not exposed to the wind. When the upper layers of water begin to warm in the spring after ice-off, the colder, dense layers remain at the bottom. This process results in a "thermocline" that acts as a transition layer between warmer and colder water layers. During the fall season, the upper layers begin to cool and become denser than the warmer layers, causing an inversion known as "fall turnover" (Figure 15). In general, shallow lakes will not stratify and deeper lakes may experience single or multiple turnover cycles. Water temperature was measured in degrees Celsius (ºC) with the use of a calibrated Eureka Manta II® submersible thermometer. The mean water temperature measurements in the basin of Crockery Lake ranged from 13.3-16.6°C.

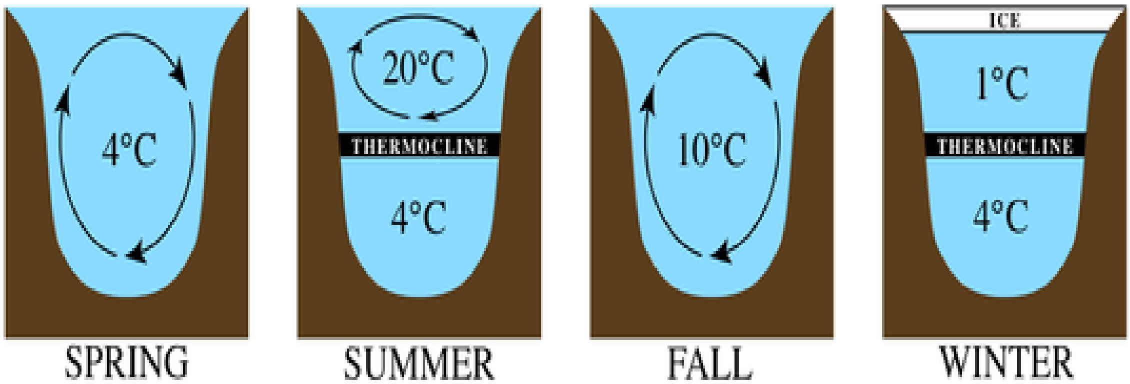
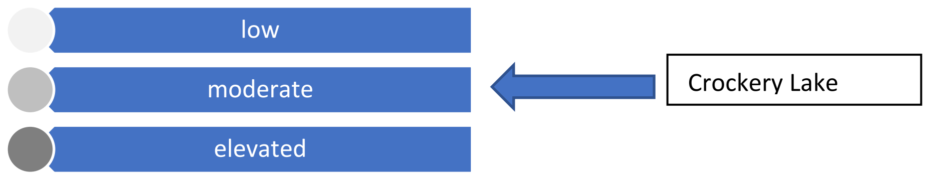


Figure 15. The lake thermal stratification process.

5.1.3 Specific Conductivity

Specific conductivity is a measure of the number of mineral ions present in the water, especially those of salts and other dissolved inorganic substances. Conductivity generally increases with water temperature and the amount of dissolved minerals and salts in a lake. Specific conductivity was measured in micro Siemens per centimeter (µS/cm) with the use of a calibrated Eureka Manta II® conductivity probe and meter. The mean conductivity values in the basins of Crockery Lake ranged from 482-496 mS/cm which are moderate.

Since these values are moderate for an inland lake, the lake water contains some dissolved metals and ions such as calcium, potassium, sodium, chlorides, sulfates, and carbonates. Baseline parameter data such as conductivity are important to measure the possible influences of land use activities (i.e. road salt influences) on Crockery Lake over a long period of time, or to trace the origin of a substance to the lake in an effort to reduce pollutant loading. Elevated conductivity values over 800 mS/cm can negatively impact aquatic life.

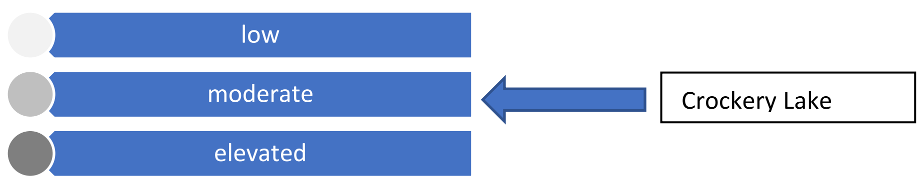


5.1.4 Total Dissolved Solids and Total Suspended Solids

Total Dissolved Solids

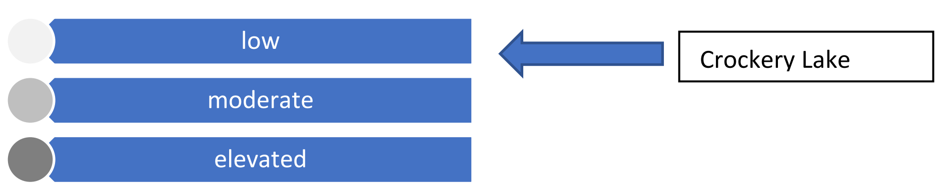
Total dissolved solids (TDS) are a measure of the amount of dissolved organic and inorganic particles in the water column. Particles dissolved in the water column absorb heat from the sun and raise the water temperature and increase conductivity.

Total dissolved solids were measured with the use of a calibrated Eureka Manta II® meter in mg/L. Spring values are usually higher due to increased watershed inputs from spring runoff and/or increased planktonic algal communities. The mean TDS concentrations in the basin of Crockery Lake ranged from 309-317 mg/L. These values are moderate for an inland lake and correlates with the measured moderate conductivity.



Total Suspended Solids (TSS)

Total suspended solids are the measure of the number of suspended particles in the water column. Particles suspended in the water column absorb heat from the sun and raise the water temperature. Total suspended solids were measured in mg/L and analyzed in the laboratory with Method SM 2540 D-11. The lake bottom contains some fine sediment particles that are easily perturbed from winds and wave turbulence. Spring values would likely be higher due to increased watershed inputs from spring runoff and/or increased planktonic algal communities. The mean TSS concentrations in the basins of Crockery Lake were all <10 mg/L, which is optimal.



5.1.5 pH

pH is the measure of acidity or basicity of water. pH was measured with a calibrated Eureka Manta II® pH electrode and pH-meter in Standard Units (S.U). The standard pH scale ranges from 0 (acidic) to 14 (alkaline), with neutral values around 7. Most Michigan lakes have pH values that range from 7.0 to 9.5 S.U. Acidic lakes (pH < 7) are rare in Michigan and are most sensitive to inputs of acidic substances due to a low acid neutralizing capacity (ANC).

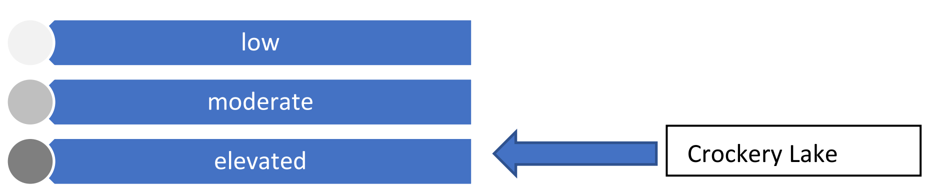
The mean pH values in the basins of Crockery Lake ranged from 7.9-8.0 S.U. This range of pH is neutral to alkaline on the pH scale and is ideal for an inland lake. pH tends to rise when abundant aquatic plants are actively growing through photosynthesis or when abundant marl deposits are present.

5.1.6 Total Phosphorus and Ortho-Phosphorus (SRP)

Total Phosphorus

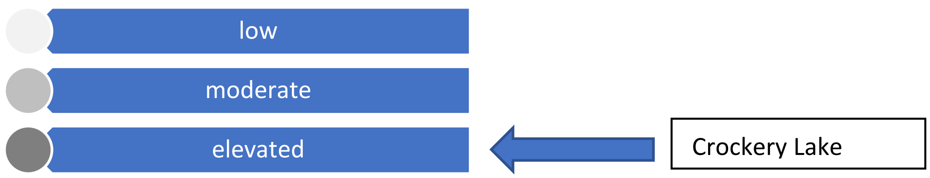
Total phosphorus (TP) is a measure of the amount of phosphorus (P) present in the water column. Phosphorus is the primary nutrient necessary for abundant algae and aquatic plant growth. Lakes which contain greater than 0.020 mg/L of TP are defined as eutrophic or nutrient-enriched. TP concentrations are usually higher at increased depths due to the higher release rates of P from lake sediments under low oxygen (anoxic) conditions. Phosphorus may also be released from sediments as pH increases. Total phosphorus was measured in milligrams per liter (mg/L) with the use of Method EPA 200.7 (Rev. 4.4). The mean TP concentrations in the basins of Crockery Lake ranged from 0.137-0.311 mg/L which are very high values and well above the eutrophic threshold. The highest concentration was 0.860 mg/L which is extremely high.

These concentrations tend to be higher at the bottom depths and are indicative of internal loading of TP which means that the TP is accumulating in the lake bottom and is released when the dissolved oxygen level is low. This in turn re-circulates the TP throughout the lake and makes it constantly available for algae and aquatic plants to use for growth.



Ortho-Phosphorus

Ortho-Phosphorus (also known as soluble reactive phosphorus or SRP) was measured with Method SM 4500-P (E-11). SRP refers to the most bioavailable from of P used by all aquatic life. The mean SRP concentrations in the basins of Crockery Lake ranged from 0.088-0.214 mg/L. These values are also well above the eutrophic threshold like total phosphorus and are a major threat for increasing the density of blue-green algal blooms.

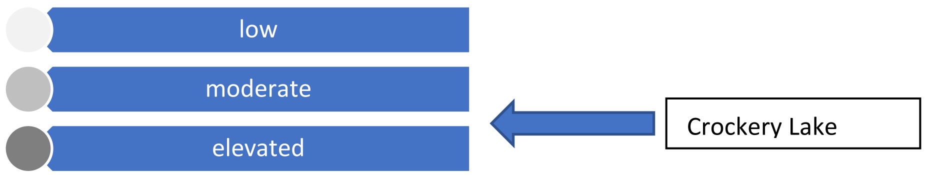


5.1.7 Total Kjeldahl Nitrogen and Total Inorganic Nitrogen

Total Kjeldahl Nitrogen (TKN) is the sum of nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_4^+), and organic nitrogen forms in freshwater systems. TKN was measured with Method EPA 351.2 (Rev. 2.0) and Total Inorganic Nitrogen (TIN) was calculated based on the aforementioned three different forms of nitrogen at Trace Analytical Laboratories, Inc. (a NELAC-certified laboratory). Much nitrogen (amino acids and proteins) also comprises the bulk of living organisms in an aquatic ecosystem. Nitrogen originates from atmospheric inputs (i.e. burning of fossil fuels), wastewater sources from developed areas (i.e. runoff from fertilized lawns), agricultural lands, septic systems, and from waterfowl droppings. It also enters lakes through groundwater or surface drainage, drainage from marshes and wetlands, or from precipitation (Wetzel, 2001). In lakes with an abundance of nitrogen (N: P > 15), phosphorus may be the limiting nutrient for phytoplankton and aquatic macrophyte growth. Alternatively, in lakes with low nitrogen concentrations (and relatively high phosphorus), the blue-green algae populations may increase due to the ability to fix nitrogen gas from atmospheric inputs. Lakes with a mean TKN value of 0.66 mg/L may be classified as oligotrophic, those with a mean TKN value of 0.75 mg /L may be classified as mesotrophic, and those with a mean TKN value greater than 1.88 mg/L may be classified as eutrophic. The mean TKN concentrations in the basins of Crockery Lake ranged from 1.6-2.6 mg/L. These values are slightly elevated for an inland lake of similar size. In the absence of dissolved oxygen, nitrogen is usually in the ammonia form and will contribute to rigorous submersed aquatic plant growth if adequate water transparency is present, which is the case in Crockery Lake for the first part of the growing season.

The total inorganic nitrogen (TIN) consists of nitrate (NO_3), nitrite (NO_2), and ammonia (NH_3) forms of nitrogen without the organic forms of nitrogen. The mean TIN concentrations in the basin of Crockery Lake ranged from 1.4-2.1 mg/L which is quite high.

Two major reasons why submersed rooted aquatic plant growth is not more prevalent given these concentrations are due to depth limitations and the lack of water clarity which is critical for higher aquatic plant growth. The mean nitrate concentrations in the basins ranged from 0.100-0.410 mg/L which are moderate. The mean nitrite values for the lake ranged from 0.100-0.205 mg/L which is concerning given above detectable limits of nitrite. Overall, there is an abundance of nitrogen in Crockery Lake which is mostly in the ammonia form with a mean concentration range from 0.815-2.1 mg/L which is quite high.



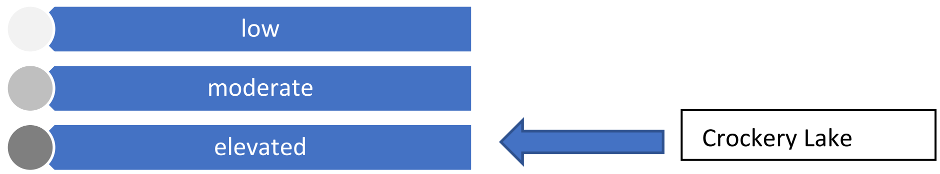
5.1.8 Chlorophyll-a and Algal Community Composition

Chlorophyll-*a* is a measure of the amount of green plant pigment present in the water, often in the form of planktonic algae. Chlorophyll-a water samples were measured in situ with a calibrated *in situ* Turner Designs® fluorimeter. High chlorophyll-a concentrations are indicative of nutrient-enriched lakes. Chlorophyll-*a* concentrations greater than 6 µg/L are found in eutrophic or nutrient-enriched aquatic systems, whereas chlorophyll-*a* concentrations less than 2.2 µg/L are found in nutrient-poor or oligotrophic lakes. The chlorophyll-a concentrations varied depending upon laboratory method or in situ testing. The lab method resulted in a mean range of 0.0-2.3 µg/L, whereas the in situ method showed values that ranged from 6-16 µg/L. These are well above eutrophic water readings and indicative of a major issue with algae in Crockery Lake. The in situ methods likely show higher values because those measurements are collected at the surface where buoyant blue-green algae aggregate on the water surface.

The dominant algae in the lake (blue green) tends to be buoyant and float on the surface which reduces light to other favorable algae below. Cyanobacteria (blue-green algae) have the distinct advantage of using nitrate and ammonia in the water (along with N_2 gas from the atmosphere) as food and can out-compete the green algae due to their faster growth rates and ability to be buoyant at the lake surface which reduces light to underlying algae.

To determine the presence of algal genera from the composite water samples collected from the deep basins of Crockery Lake, 500 ml of preserved sample were collected, and a 1-mL subsample was placed to settle onto a Sedgewick-Rafter counting chamber. The ocular micrometer scale was calibrated. The samples were observed under a
Zeiss® compound microscope at 400X magnification and scanned at 100X magnification to allow for the detection of a broad range of taxa present.

All taxa were identified to Genus level. Phytoplankton samples were enumerated for the July and September sampling events and are shown below in Tables 4 and 5. The blue-green algae were more dominant than both green algae and diatoms. Diatoms and green algae are the more favorable algal genera.



RLS is aware of some recent reports of harmful algal blooms (HAB's) noted on the lake. EGLE has a protocol for reporting HAB's via email at: algaebloom@michigan.gov. All riparians should avoid all surface scums and immediately wash after exiting the lake.

Table 4. Counts (# cells per 1 mL sub-sample) for each genera of algae found at each sampling location (n=2) in the lake basins of Crockery Lake (July 22, 2024).

Taxa Present	Type	DB1	DB2
Cladophora sp.	G	56	31
Rhizoclonium sp.	G	1	6
Pediastrum sp.	G	11	13
Ulothrix sp.	G	7	3
Haematococcus sp.	G	9	2
Microcystis sp.	BG	~10,500	~15,000
Navicula sp.	D	8	1
Synedra sp.	D	19	5
Fragillaria sp.	D	11	4
Rhoicosphenia sp.	R	6	14

Note: G = green algae (Chlorophyta); BG = blue-green algae (Cyanophyta); D = diatoms (Bacillariophyta); R = rotifers (Rotifera)

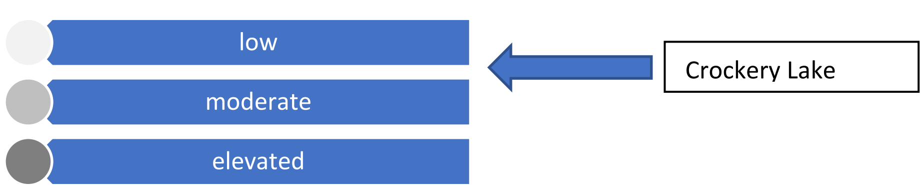
Table 5. Counts (# cells per 1 mL sub-sample) for each genera of algae found at each sampling location (n=2) in the lake basins of Crockery Lake (September 3, 2024).

Taxa Present	Type	DB1	DB2
Cladophora sp.	G	26	7
Pediastrum sp.	G	16	4
Ulothrix sp.	G	10	7
Haematococcus sp.	G	12	5
Scenedesmus sp.	G	1	0
Microcystis sp.	BG	~15,500	~18,000
Navicula sp.	D	3	6
Synedra sp.	D	5	2
Fragillaria sp.	D	7	0

Note: G = green algae (Chlorophyta); BG = blue-green algae (Cyanophyta); D = diatoms (Bacillariophyta); R = rotifers (Rotifera)

5.1.9 Secchi Transparency

Secchi transparency is a measure of the clarity or transparency of lake water, and is measured with the use of an 8-inch diameter standardized Secchi disk during calm to light wind conditions. Secchi disk transparency was measured in feet (ft.) by lowering the disk over the shaded side of a boat around noon and taking the mean of the measurements of disappearance and reappearance of the disk (Figure 16). Elevated Secchi transparency readings allow for more aquatic plant and algae growth. Eutrophic systems generally have Secchi disk transparency measurements less than 7.5 feet due to turbidity caused by excessive planktonic algae growth. The mean Secchi transparency in Crockery Lake ranged from 2.6-4.6 feet which is low. It is clear that the Secchi transparency declined throughout the season which was largely due to the growth of blue-green algal blooms. This transparency indicates that an abundance of algae are present throughout the water column which reduces water clarity. Secchi transparency is variable and depends on the amount of suspended particles in the water (often due to windy conditions of lake water mixing) and the amount of sunlight present at the time of measurement.



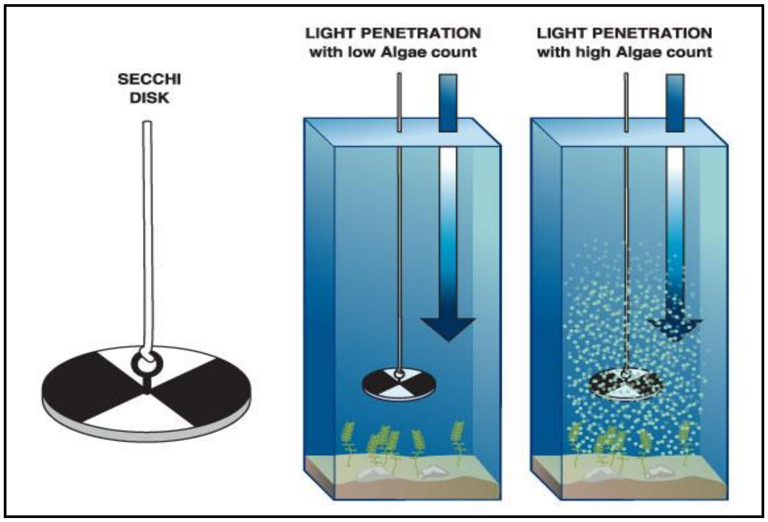


Figure 16. Measurement of water transparency with a Secchi disk.

5.1.10 Sediment Organic Carbon and Particle Size

Organic matter (OM) contains a high amount of carbon which is derived from biota such as decayed plant and animal matter. Detritus is the term for all dead organic matter which is different than living organic and inorganic matter. OM may be autochthonous or allochthonous in nature where it originates from within the system or external to the system, respectively. Sediment samples were collected during the September 3, 2024 sampling event using an Ekman hand dredge at each of the 5 sampling locations (Table 6). Sediment OM is measured with the ASTM D2974 Method and is usually expressed in a percentage (%) of total bulk volume. Many factors affect the degradation of organic matter including basin size, water temperature, thermal stratification, dissolved oxygen concentrations, particle size, and quantity and type of organic matter present. There are two major biochemical pathways for the reduction of organic matter to forms which may be purged as waste. First, the conversion of carbohydrates and lipids via hydrolysis are converted to simple sugars or fatty acids and then fermented to alcohol, CO_2, or CH_4. Second, proteins may be proteolyzed to amino acids, deaminated to NH_3+, nitrified to NO_2- or NO_3-, and denitrified to N_2 gas. Bacteria are the major factor in the degradation of organic matter in sediments (Fenchel and Blackburn, 1979). The organic matter content ranged from 7.3-13.0% which is fairly low in organic carbon. There were no gravel particles present with the samples containing only sand and fine particles.

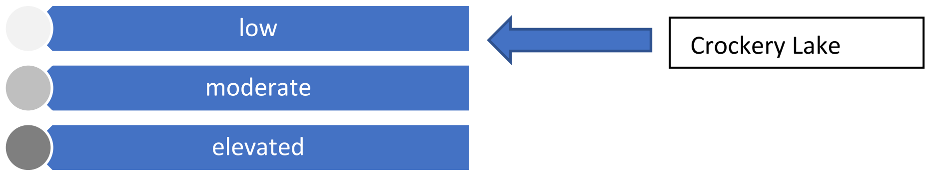


Table 6. Crockery Lake sediment parameter data collected throughout the lake basin (September 3, 2024).

Sample Site #	% Organic Carbon	% Gravel	% Sand	% Fines
S1	7.3	0	65.7	34.3
S2	11.0	0	64.6	35.4
S3	12.0	0	51.6	48.4
S4	9.0	0	62.7	37.3
S5	13.0	0	62.4	37.6

Table 7. Crockery Lake physical water quality parameter data collected at deep basin #1 (May 29, 2024).

Depth (m)	Water Temp (°C)	DO (mg/L)	pH (S.U.)	Conduc. (mS/cm)	TDS (mg/L)	Secchi Depth (ft)
0	21.0	8.9	8.8	425	272	4.0
0.5	20.7	9.1	8.8	426	273	
1.0	20.6	9.0	8.8	426	272	
1.5	20.1	8.9	8.8	426	272	
2.0	20.1	8.7	8.8	426	273	
2.5	20.1	8.6	8.8	426	273	
3.0	20.0	8.4	8.8	426	273	
3.5	19.9	8.4	8.8	425	273	
4.0	19.3	7.4	8.4	435	277	
4.5	18.6	6.9	8.1	448	287	
5.0	17.8	4.8	7.9	462	296	
5.5	14.4	2.5	7.8	488	310	
6.0	13.1	1.8	7.8	504	323	
6.5	12.0	1.0	7.8	506	324	
7.0	11.5	0.7	7.8	508	325	
7.5	11.2	0.5	7.8	508	325	
8.0	10.9	0.4	7.8	509	325	
8.5	10.7	0.3	7.8	509	326	
9.0	10.6	0.2	7.8	509	326	
9.5	10.3	0.2	7.8	510	327	
10.0	10.2	0.1	7.8	511	327	
10.5	10.0	0.1	7.8	512	328	
11.0	9.9	0.1	7.8	512	328	
11.5	9.6	0.1	7.8	512	328	
12.0	9.2	0.1	7.8	514	329	
12.5	9.0	0.04	7.7	514	329	
13.0	8.6	0.04	7.7	516	330	
13.5	7.9	0.04	7.7	521	333	
14.0	7.8	0.04	7.6	522	334	
14.5	7.7	0.04	7.5	525	336	
15.0	7.7	0.04	7.5	525	336	
15.5	7.6	0.04	7.4	525	336	
16.0	7.5	0.04	7.4	530	339	
16.5	7.3	0.04	7.3	642	411	
17.0	7.3	0.04	7.2	643	411	
17.5	7.3	0.04	7.1	643	411	

18.0	7.3	0.04	6.8	646	413	
18.5	7.3	0.04	6.7	645	413	

Table 8. Crockery Lake chemical water quality parameter data collected at deep basin #1 (May 29, 2024).

Depth (m)	TKN (mg/L)	TIN (mg/L)	NH_3 (mg/L)	NO_3- (mg/L)	NO_2- (mg/L)	TSS (mg/L)	TP (mg/L)	Ortho-P (mg/L)	Chl-a (µg/L)
0	1.0	0.610	0.160	0.450	<0.20	<10	0.058	<0.010	1.03
9.5	1.6	1.3	0.640	0.460	0.230	<10	0.038	<0.010	--
18.5	1.9	3.0	1.9	<0.20	<0.20	<10	0.290	0.220	--

Table 9. Crockery Lake physical water quality parameter data collected at deep basin #2 (May 29, 2024).

Depth (m)	Water Temp (°C)	DO (mg/L)	pH (S.U.)	Conduc. (mS/cm)	TDS (mg/L)	Secchi Depth (ft)
0	20.8	10.1	9.0	423	271	4.2
0.5	20.7	10.0	9.0	423	271	
1.0	20.2	9.9	9.0	425	272	
1.5	19.9	9.7	8.8	426	273	
2.0	19.7	9.2	8.6	429	274	
2.5	19.6	8.4	8.6	432	276	
3.0	19.5	7.7	8.4	434	278	
3.5	19.2	6.8	8.3	439	281	
4.0	18.9	6.2	8.2	445	284	
4.5	18.4	5.3	8.0	453	289	
5.0	17.7	4.8	7.9	464	297	
5.5	16.8	3.4	7.8	470	307	
6.0	15.0	2.5	7.8	494	317	
6.5	13.4	1.7	7.8	500	320	
7.0	12.4	1.1	7.8	505	322	
7.5	11.7	0.7	7.8	506	324	
8.0	11.0	0.5	7.8	509	326	
8.5	10.7	0.4	7.8	510	326	
9.0	10.5	0.3	7.8	510	326	
9.5	10.4	0.2	7.7	510	327	
10.0	10.2	0.2	7.7	511	327	
10.5	10.2	0.1	7.7	512	327	
11.0	10.1	0.1	7.7	512	328	
11.5	10.0	0.1	7.7	513	329	
12.0	9.8	0.1	7.6	516	330	
12.5	9.7	0.1	7.6	520	333	
13.0	9.5	0.1	7.6	524	336	
13.5	9.4	0.04	7.4	528	338	

Table 10. Crockery Lake chemical water quality parameter data collected at deep basin #2 (May 29, 2024).

Depth (m)	TKN (mg/L)	TIN (mg/L)	NH_3 (mg/L)	NO_3- (mg/L)	NO_2- (mg/L)	TSS (mg/L)	TP (mg/L)	Ortho-P (mg/L)	Chl-a (µg/L)
0	1.2	0.590	0.130	0.560	<0.20	<10	0.070	<0.010	0.710
6.5	1.2	0.890	0.260	0.590	<0.20	<10	0.038	<0.010	
13.5	2.6	1.8	1.8	<0.20	<0.20	<10	0.330	0.270	

Table 11. Crockery Lake physical water quality parameter data collected at deep basin #1 (July 22, 2024).

Depth (m)	Water Temp (°C)	DO (mg/L)	pH (S.U.)	Conduc. (mS/cm)	TDS (mg/L)	Secchi Depth (ft)
0	26.7	9.9	9.3	411	263	2.3
0.5	26.6	10.5	9.3	410	263	
1.0	26.1	10.8	9.3	410	262	
1.5	25.8	11.0	9.2	409	262	
2.0	25.6	11.1	9.2	410	262	
2.5	25.5	11.0	9.2	411	263	
3.0	25.4	10.5	9.1	412	263	
3.5	24.9	10.2	8.7	420	269	
4.0	24.5	8.2	8.3	427	273	
4.5	23.7	1.6	7.9	436	278	
5.0	22.5	1.1	7.8	443	285	
5.5	20.8	0.6	7.7	458	293	
6.0	18.3	0.3	7.7	481	308	
6.5	18.3	0.2	7.7	494	316	
7.0	14.6	0.1	7.7	506	324	
7.5	13.4	0.1	7.7	512	328	
8.0	11.8	0.1	7.7	516	331	
8.5	11.3	0.1	7.6	519	332	
9.0	10.8	0.04	7.6	520	333	
9.5	10.3	0.04	7.6	522	333	
10.0	10.2	0.04	7.6	524	335	
10.5	10.1	0.04	7.6	524	335	
11.0	10.0	0.04	7.6	526	336	
11.5	9.9	0.04	7.6	526	336	
12.0	9.6	0.04	7.6	527	337	
12.5	9.5	0.04	7.6	530	339	
13.0	9.2	0.04	7.5	531	340	
13.5	9.0	0.04	7.5	536	343	
14.0	8.8	0.04	7.4	541	346	
14.5	8.7	0.04	7.4	545	349	
15.0	8.5	0.04	7.4	550	352	
15.5	8.5	0.04	7.3	554	355	
16.0	8.4	0.04	7.3	561	359	

Table 12. Crockery Lake chemical water quality parameter data collected at deep basin #1 (July 22, 2024).

Depth (m)	TKN (mg/L)	TIN (mg/L)	NH_3 (mg/L)	NO_3- (mg/L)	NO_2- (mg/L)	TSS (mg/L)	TP (mg/L)	Ortho-P (mg/L)	Chl-a (µg/L)
0	0.8	<0.200	0.022	<0.20	<0.20	<10	0.028	<0.010	3.56
8.0	1.8	1.1	1.1	<0.20	0.230	<10	0.094	0.063	--
16.0	4.5	3.5	3.5	<0.20	<0.20	<10	0.540	0.490	

Table 13. Crockery Lake physical water quality parameter data collected at deep basin #2 (July 22, 2024).

Depth (m)	Water Temp (°C)	DO (mg/L)	pH (S.U.)	Conduc. (mS/cm)	TDS (mg/L)	Secchi Depth (ft)
0	27.1	9.0	9.3	410	262	2.8
0.5	27.0	10.3	9.3	409	262	
1.0	26.7	11.2	9.3	411	263	
1.5	26.0	11.3	9.3	412	264	
2.0	25.8	11.2	9.3	410	263	
2.5	25.6	11.0	9.2	412	264	
3.0	25.6	10.2	9.0	415	265	
3.5	25.2	9.1	8.8	418	268	
4.0	25.0	7.6	8.5	422	271	
4.5	24.5	6.1	8.1	430	275	
5.0	22.8	1.5	7.9	444	283	
5.5	21.1	0.8	7.8	454	292	
6.0	19.2	0.3	7.8	467	299	
6.5	16.1	0.2	7.7	497	318	
7.0	13.8	0.1	7.7	510	326	
7.5	12.2	0.1	7.7	514	330	
8.0	11.4	0.1	7.7	517	331	
8.5	10.9	0.1	7.6	520	333	
9.0	10.6	0.1	7.6	522	334	
9.5	10.4	0.1	7.6	524	335	
10.0	10.2	0.04	7.5	525	337	
10.5	10.1	0.04	7.5	527	337	
11.0	10.0	0.04	7.5	529	338	
11.5	9.9	0.04	7.4	535	342	
12.0	9.7	0.04	7.4	544	348	
12.5	9.6	0.04	7.3	551	352	
13.0	9.5	0.04	7.3	557	357	
13.5	9.4	0.04	7.2	565	363	

Table 14. Crockery Lake chemical water quality parameter data collected at deep basin #2 (July 22, 2024).

Depth (m)	TKN (mg/L)	TIN (mg/L)	NH_3 (mg/L)	NO_3^- (mg/L)	NO_2^- (mg/L)	TSS (mg/L)	TP (mg/L)	Ortho-P (mg/L)	Chl-a (µg/L)
0	0.8	<0.200	0.014	<0.20	<0.20	<10	0.026	<0.010	1.06
6.5	1.5	0.740	0.740	<0.20	<0.20	<10	0.034	<0.010	--
13.5	4.8	4.0	4.0	<0.20	<0.20	<10	0.710	0.700	--

Table 15. Crockery Lake physical water quality parameter data collected at deep basin #1 (September 3, 2024).

Depth (m)	Water Temp (°C)	DO (mg/L)	pH (S.U.)	Conduc. (mS/cm)	TDS (mg/L)	Secchi Depth (ft)
0	24.0	8.1	9.0	409	262	4.8
0.5	24.0	8.0	9.0	409	262	
1.0	24.0	8.0	9.0	409	262	
1.5	24.0	8.0	9.0	409	262	
2.0	24.0	8.0	9.0	409	262	
2.5	24.0	7.9	9.0	409	262	
3.0	24.0	7.9	9.0	409	262	
3.5	24.0	7.9	9.0	409	262	
4.0	24.0	7.8	8.8	413	264	
4.5	23.5	7.3	8.7	412	264	
5.0	23.4	6.4	8.4	418	268	
5.5	23.4	3.4	7.9	427	273	
6.0	20.9	1.8	7.8	435	278	
6.5	19.6	1.0	7.6	452	289	
7.0	18.1	0.5	7.6	477	306	
7.5	14.1	0.2	7.5	506	323	
8.0	12.4	0.2	7.5	511	327	
8.5	11.6	0.1	7.5	514	329	
9.0	11.0	0.1	7.5	517	331	
9.5	10.7	0.1	7.5	520	333	
10.0	10.5	0.1	7.5	522	334	
10.5	10.3	0.04	7.5	524	335	
11.0	10.1	0.04	7.5	523	336	
11.5	10.0	0.04	7.5	523	335	
12.0	9.9	0.04	7.5	524	335	
12.5	9.7	0.04	7.5	525	336	

13.0	9.5	0.04	7.5	527	337	
13.5	9.4	0.04	7.4	534	345	
14.0	8.9	0.04	7.3	554	355	
14.5	8.7	0.04	7.2	561	358	
15.0	8.6	0.04	7.2	565	362	
15.5	8.6	0.04	7.2	572	366	
16.0	8.5	0.05	7.2	578	370	
16.5	8.5	0.05	7.1	585	376	

Table 16. Crockery Lake chemical water quality parameter data collected at deep basin #1 (September 3, 2024).

Depth (m)	TKN (mg/L)	TIN (mg/L)	NH_3 (mg/L)	NO_3^- (mg/L)	NO_2^- (mg/L)	TSS (mg/L)	TP (mg/L)	Ortho-P (mg/L)	Chl-a (µg/L)
0	0.7	<0.100	<0.010	<0.100	<0.10	<10	0.020	<0.010	0.0
8.5	1.7	1.1	1.1	<0.100	0.10	<10	0.086	0.028	
16.5	6.0	5.7	5.7	<0.100	<0.10	<10	0.860	0.083	

Table 17. Crockery Lake physical water quality parameter data collected at deep basin #2 (September 3, 2024).

Depth (m)	Water Temp (°C)	DO (mg/L)	pH (S.U.)	Conduc. (mS/cm)	TDS (mg/L)	Secchi Depth (ft)
0	24.0	8.2	9.0	410	262	4.3
0.5	24.0	8.0	9.0	410	262	
1.0	24.0	7.8	9.0	410	262	
1.5	24.0	7.8	9.0	410	262	
2.0	24.0	7.8	9.0	410	262	
2.5	24.0	7.8	9.0	410	262	
3.0	24.0	7.8	9.0	410	262	
3.5	23.9	7.8	9.0	410	263	
4.0	23.9	7.5	8.5	413	264	
4.5	23.7	7.1	8.4	419	268	
5.0	23.3	5.0	8.0	423	271	
5.5	22.9	3.5	7.9	425	272	
6.0	21.1	1.7	7.8	435	278	
6.5	18.9	0.7	7.6	463	294	
7.0	16.9	0.5	7.5	494	315	
7.5	16.9	0.2	7.6	490	313	
8.0	14.5	0.1	7.6	504	323	
8.5	13.0	0.1	7.5	508	326	
9.0	12.3	0.1	7.5	513	328	
9.5	11.5	0.04	7.5	517	330	
10.0	10.9	0.04	7.5	520	333	
10.5	10.6	0.04	7.5	522	334	
11.0	10.4	0.04	7.5	524	335	
11.5	10.2	0.04	7.5	528	338	
12.0	10.0	0.04	7.4	535	342	
12.5	9.8	0.04	7.3	545	349	
13.0	9.6	0.04	7.2	562	358	
13.5	9.5	0.04	7.2	572	366	
14.0	9.4	0.04	7.1	580	372	
14.5	9.4	0.04	7.1	596	383	

Table 18. Crockery Lake chemical water quality parameter data collected at deep basin #2 (September 3, 2024).

Depth (m)	TKN (mg/L)	TIN (mg/L)	NH_3 (mg/L)	NO_3- (mg/L)	NO_2- (mg/L)	TSS (mg/L)	TP (mg/L)	Ortho-P (mg/L)	Chl-a (µg/L)
0	0.6	<0.100	0.010	<0.10	<0.10	<10	0.020	<0.010	0.0
7.5	1.4	0.670	0.670	<0.10	<0.10	<10	0.028	<0.010	--
14.5	5.2	4.9	4.9	<0.10	<0.10	<10	0.850	0.750	--

Table 19. Descriptive statistics of all water quality parameters in the basins of Crockery Lake collected on May 29, 2024, July 22, 2024, and September 3, 2024.

Water Quality Parameter Measured	May 29, 2024 Means ± SD	July 22, 2024 Means ± SD	Sept 3, 2024 Means ± SD
Water temp (°C)	13.3±4.9	16.6±7.3	16.4±6.5
pH (S.U.)	7.9±0.5	8.0±0.7	7.9±0.7
Dissolved oxygen (mg/L)	3.0±3.8	3.3±4.7	2.9±3.6
Conductivity (mS/cm)	496±57	484±55	482±62
Total dissolved solids (mg/L)	317±36	310±35	309±40
Secchi transparency (ft.)	4.1±0.1	2.6±0.4	4.6±0.4
Chlorophyll-a (µg/L)	0.9±0.2	2.3±1.8	0.0±0.0
Total Kjeldahl nitrogen (mg/L)	1.6±0.6	2.4±1.8	2.6±2.0
Total inorganic nitrogen (mg/L)	1.4±0.9	1.6±1.7	2.1±2.5
Ammonia nitrogen (mg/L)	0.815±0.8	1.6±1.8	2.1±2.5
Nitrate nitrogen (mg/L)	0.410±0.2	0.200±0.0	0.100±0.0
Nitrite nitrogen (mg/L)	0.205±0.0	0.205±0.0	0.100±0.0
Total phosphorus (mg/L)	0.137±0.1	0.239±0.3	0.311±0.4
Ortho-phosphorus (mg/L)	0.088±0.1	0.214±0.3	0.149±0.3
Total suspended solids (mg/L)	<10±0.0	<10±0.0	<10±0.0

6.0 CROCKERY LAKE AQUATIC VEGETATION COMMUNITIES

Aquatic plants (macrophytes) are an essential component in the littoral zones of most lakes in that they serve as suitable habitat and food for macroinvertebrates, contribute oxygen to the surrounding waters through photosynthesis, stabilize bottom sediments (if in the rooted growth form), and contribute to the cycling of nutrients such as phosphorus and nitrogen upon decay. In addition, decaying aquatic plants contribute organic matter to lake sediments which further supports healthy growth of successive aquatic plant communities that are necessary for a balanced aquatic ecosystem. An overabundance of aquatic vegetation may cause organic matter to accumulate on the lake bottom faster than it can break down. Aquatic plants generally consist of rooted submersed, free-floating submersed, floating-leaved, and emergent growth forms. The emergent growth form (i.e. Cattails, Native Loosestrife) is critical for the diversity of insects onshore and for the health of nearby wetlands. Submersed aquatic plants can be rooted in the lake sediment (i.e. Milfoils, Pondweeds), or free-floating in the water column (i.e. Coontail). Nonetheless, there is evidence that the diversity of submersed aquatic macrophytes can greatly influence the diversity of macroinvertebrates associated with aquatic plants of different structural morphologies (Parsons and Matthews, 1995). Therefore, it is possible that declines in the biodiversity and abundance of submersed aquatic plant species and associated macroinvertebrates, could negatively impact the fisheries of inland lakes. Alternatively, the overabundance of aquatic vegetation can compromise recreational activities, aesthetics, and property values. Crockery Lake currently has a moderate quantity of submersed aquatic vegetation for the lake surface area, and it is recommended to maintain a minimum of 33% cover for optimal lake health. Over-management of the native aquatic vegetation is not advised as it will only encourage excess growth by algae since the latter competes with the vegetation for vital water column nutrients.

The Point-Intercept Survey method is used to assess the presence and percent cumulative cover of submersed, floating-leaved, and emergent aquatic vegetation within and around the littoral zones of inland lakes. With this survey method, sampling locations are geo-referenced (via GPS waypoints) and assessed throughout the entire lake to determine the species of aquatic macrophytes present and density of each macrophyte which are recorded onto a data sheet. Each separate plant species found in each sampling location with the use of multiple rake tosses and visual surveying is recorded along with an estimate of each plant density. Each macrophyte species corresponds to an assigned number. There are designated density codes for the aquatic vegetation surveys, where a = found (occupying < 2% of the surface area of the lake), b = sparse (occupying 2-20% of the surface area of the lake), c = common, (occupying 21-60% of the surface area of the lake), and d = dense (occupying > 60% of the surface area of the lake).

The survey of the basins of Crockery Lake consisted of 105 sampling locations around the littoral zone (Figure 17). Data were placed in a table showing the relative abundance of each aquatic plant species found and a resultant calculation showing the frequency of each plant, and cumulative cover.

A whole-lake scan of the aquatic vegetation biovolume in Crockery Lake was conducted on May 29, 2024 with a WAAS-enabled Lowrance HDS 9® GPS with variable frequency transducer. This data included 3,487 data sounding points. Points were then uploaded into a cloud software program to reveal maps that displayed depth contours, sediment hardness, and aquatic vegetation biovolume (Figure 18). On this map, the color blue refers to areas that lack vegetation. The color green refers to low-lying vegetation. The colors red/orange refer to tall-growing vegetation. There are many areas around the littoral (shallow) zone of the lake that contain low-growing plants like Chara or Coontail. In addition, any emergent canopies or lily pads will present as red color on the map. For this reason, the scans are conducted in conjunction with a whole lake GPS survey to account for individual species identification of all aquatic plants in the lake. Table 20 shows the biovolume categories by plant cover during the May 29, 2024 scan and survey. The majority of the biovolume (91.4%) is in the low-growing category.

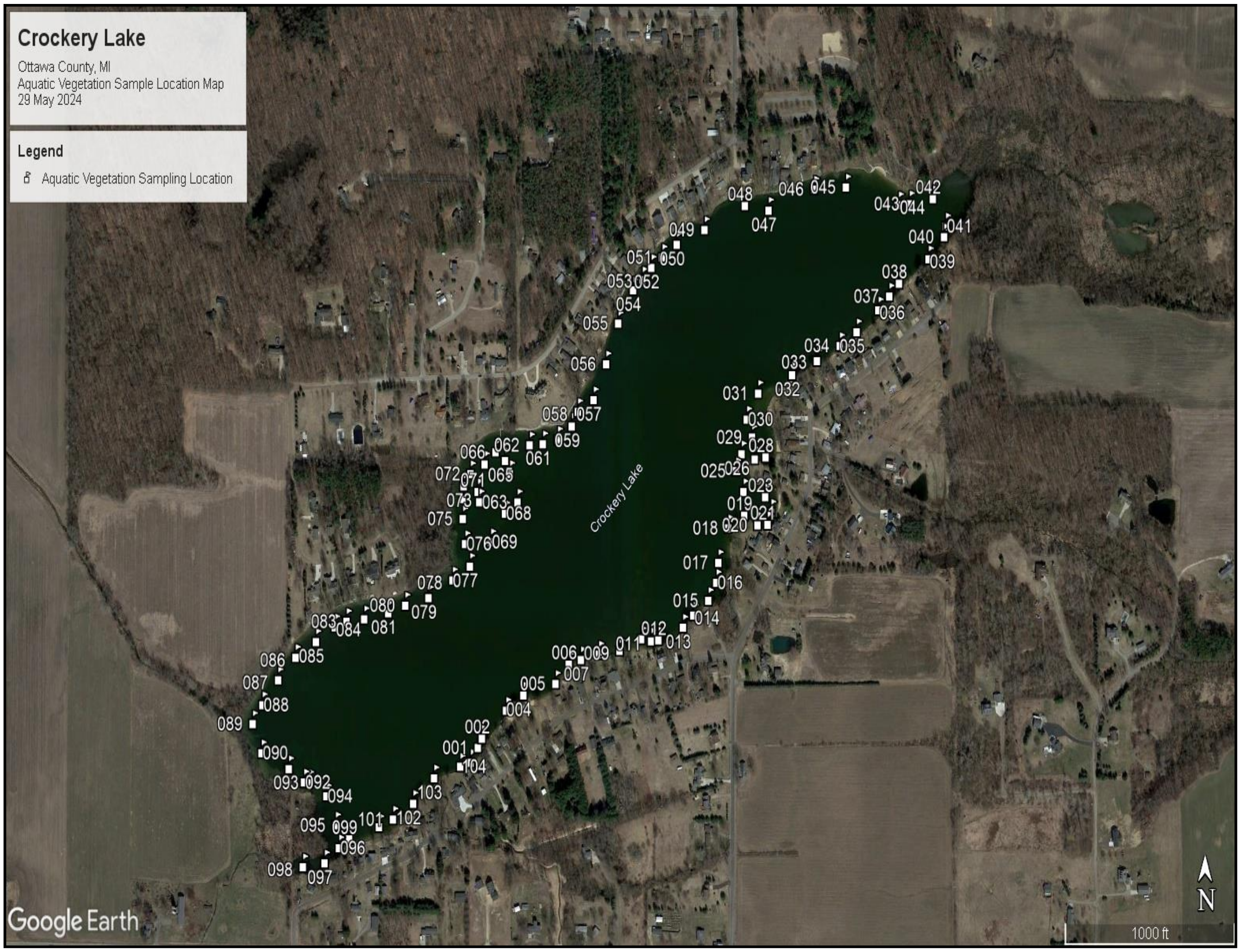


Figure 17. Crockery Lake aquatic vegetation sampling location map (May 29, 2024).

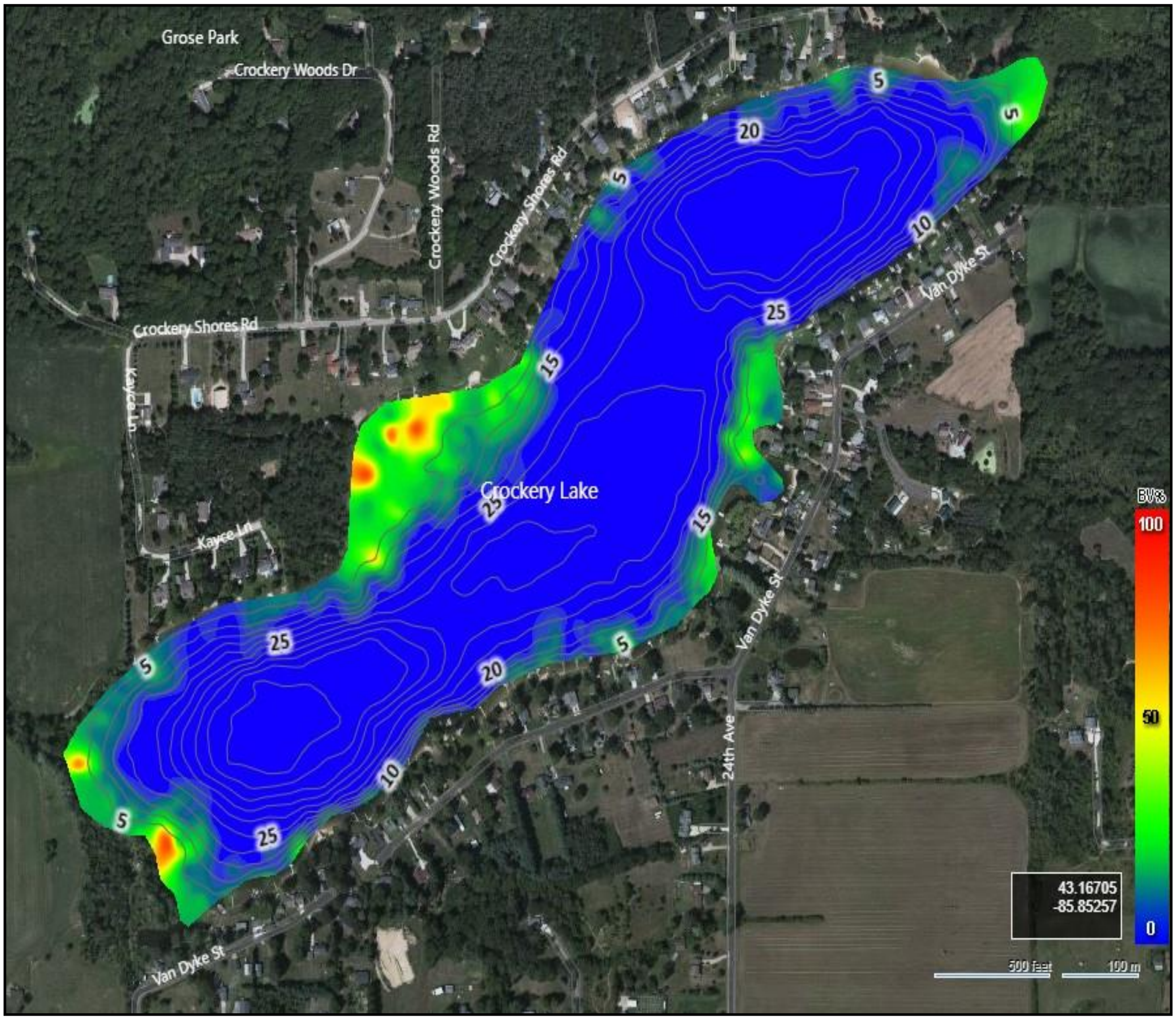


Figure 18. Aquatic plant biovolume of all aquatic plants in Crockery Lake, Ottawa County, Michigan (May 29, 2024). Note: Red color denotes high-growing aquatic plants, green color denotes low-growing aquatic plants, and blue color represents a lack of aquatic vegetation.

Table 20. Crockery Lake aquatic vegetation biovolume by category (relative cover on May 29, 2024).

Biovolume Cover Category	% Relative Cover of Bottom by Category
0-20%	91.4
20-40%	4.9
40-60%	2.0
60-80%	0.2
>80%	1.6

6.1.1 Crockery Lake Native Aquatic Macrophytes

There are hundreds of native aquatic plant species in the waters of the United States. The most diverse native genera include the Potamogetonaceae (Pondweeds) and the Haloragaceae (Milfoils). Native aquatic plants may grow to nuisance levels in lakes with abundant nutrients (both water column and sediment) such as phosphorus, and in sites with high water transparency. The diversity of native aquatic plants is essential for the balance of aquatic ecosystems, because each plant harbors different macroinvertebrate communities and varies in fish habitat structure.

The basin of Crockery Lake contained 6 native submersed, 2 floating-leaved, and 5 emergent aquatic plant species, for a total of 13 native aquatic macrophyte species (Table 21). Photos of all native aquatic plants are shown below in Figures 19-31. The majority of the emergent macrophytes may be found along the shoreline of the lake. Protection of these native emergents is very important for shoreline stabilization and wildlife habitat. The majority of the floating-leaved macrophyte species can be found near the shoreline and wetland areas and serve as excellent habitat for macroinvertebrates and amphibians.

The dominant native aquatic plants in the basin of the lake included the rootless submersed Coontail (70.5% of the sampling sites) and the floating-leaved White Waterlily (62.9% of the sampling sites), and Sago Pondweed, which is a thin-leaf pondweed (51.4% of the sampling sites). The lake contained some favorable native species of pondweeds, but they were sparse. The pondweeds grow tall in the water column and serve as excellent fish cover. In dense quantities, however, they can be a nuisance for swimming and boating and can be controlled with selective herbicide management or with mechanical harvesting.

Because both rooted and non-rooted species (Coontail) were prevalent in the lake, the most likely nutrient sources are equally the sediments and water column. This indicates a highly productive lake ecosystem with high nutrients and phytoplankton as previously measured.

Table 21. Crockery Lake native aquatic plants (May 29, 2024).

Aquatic Plant Common Name	Aquatic Plant Latin Name	A level	B level	C level	D level	# Sites Found (% of total)
Muskgrass	*Chara vulgaris*	1	0	0	0	1.0
Sago Pondweed	*Stuckenia pectinata*	13	29	12	0	51.4
Wild Celery	*Vallisneria americana*	1	0	0	0	1.0
Illinois Pondweed	*Potamogeton illinoensis*	1	0	0	0	1.0
Small-leaf Pondweed	*Potamogeton pusillus*	2	0	0	0	1.9
Coontail	*Ceratophyllum demersum*	32	35	7	0	70.5
White Waterlily	*Nymphaea odorata*	34	21	11	0	62.9
Yellow Waterlily	*Nuphar variegata*	1	5	6	4	15.2
Cattails	*Typha latifolia*	1	4	0	0	4.8
Swamp Loosestrife	*Decodon verticillata*	4	6	5	0	14.3
Bulrushes	*Schoenoplectus* sp.	6	1	0	0	6.7
Iris	*Iris* sp.	5	1	0	0	5.7
Arrowhead	*Arrow arum*	5	2	0	0	6.7

Figure 19. Chara (Muskgrass) ©RLS

Figure 20. Sago Pondweed ©RLS

Figure 21. Wild Celery ©RLS

Figure 22. Illinois Pondweed ©RLS

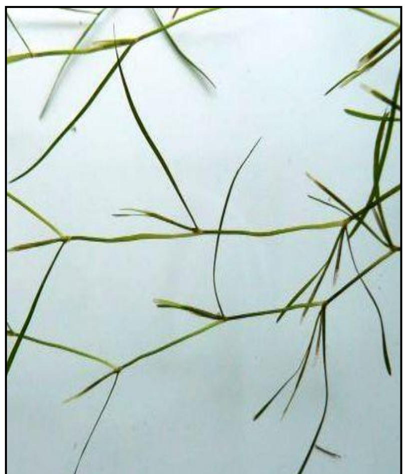


Figure 23. Small-leaf Pondweed ©RLS

Figure 24. Coontail ©RLS

Figure 25. White Waterlily ©RLS

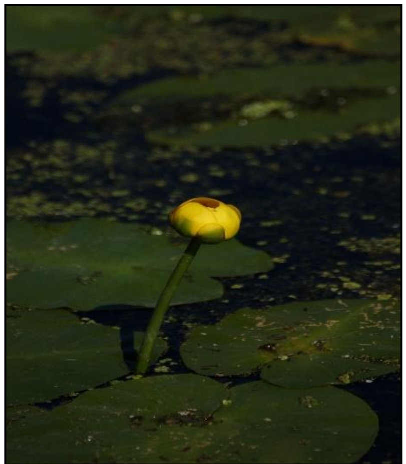


Figure 26. Yellow Waterlily ©RLS

Figure 27. Cattails ©RLS

Figure 28. Swamp Loosestrife ©RLS

Figure 29. Bulrushes ©RLS

Figure 30. Iris ©RLS

Figure 31. Arrowhead ©RLS

6.1.2 Crockery Lake Exotic Aquatic Macrophytes

Exotic aquatic plants (macrophytes) are not native to a particular site, but are introduced by some biotic (living) or abiotic (non-living) vector. Such vectors include the transfer of aquatic plant seeds and fragments by boats and trailers (especially if the lake has public access sites), waterfowl, or by wind dispersal. In addition, exotic species may be introduced into aquatic systems through the release of aquarium or water garden plants into a water body. An aquatic exotic species may have profound impacts on the aquatic ecosystem. Eurasian Watermilfoil (*Myriophyllum spicatum*; Figure 32) is an exotic aquatic macrophyte first documented in the United States in the 1880's (Reed 1997), although other reports (Couch and Nelson 1985) suggest it was first found in the 1940's. In recent years, this species has hybridized with native milfoil species to form hybrid species. Eurasian Watermilfoil has since spread to thousands of inland lakes in various states through the use of boats and trailers, waterfowl, seed dispersal, and intentional introduction for fish habitat. Eurasian Watermilfoil is a major threat to the ecological balance of an aquatic ecosystem through causation of significant declines in favorable native vegetation within lakes (Madsen et *al*. 1991), in that it forms dense canopies and may limit light from reaching native aquatic plant species (Newroth 1985; Aiken et *al*. 1979; Figure 33). Additionally, Eurasian Watermilfoil can alter the macroinvertebrate populations associated with particular native plants of certain structural architecture (Newroth 1985). Eurasian Watermilfoil has been shown to hybridize with other native strains of milfoil which results in significant issues with herbicide tolerance.

Eurasian Watermilfoil was found to occupy 2.5 acres of surface area in Crockery Lake during the May 29, 2024 survey. Eurasian Watermilfoil growth in Crockery Lake is capable of producing dense surface canopies and may increase significantly if not managed. Figure 34 shows the distribution of milfoil throughout the lake. Table 22 shows all of the various invasives found and their relative abundance in the lake.

Figure 32. Hybrid Eurasian Watermilfoil plant with seed head and fragments (©RLS).

Figure 33. Hybrid Eurasian Watermilfoil Canopy on an inland lake (©RLS).

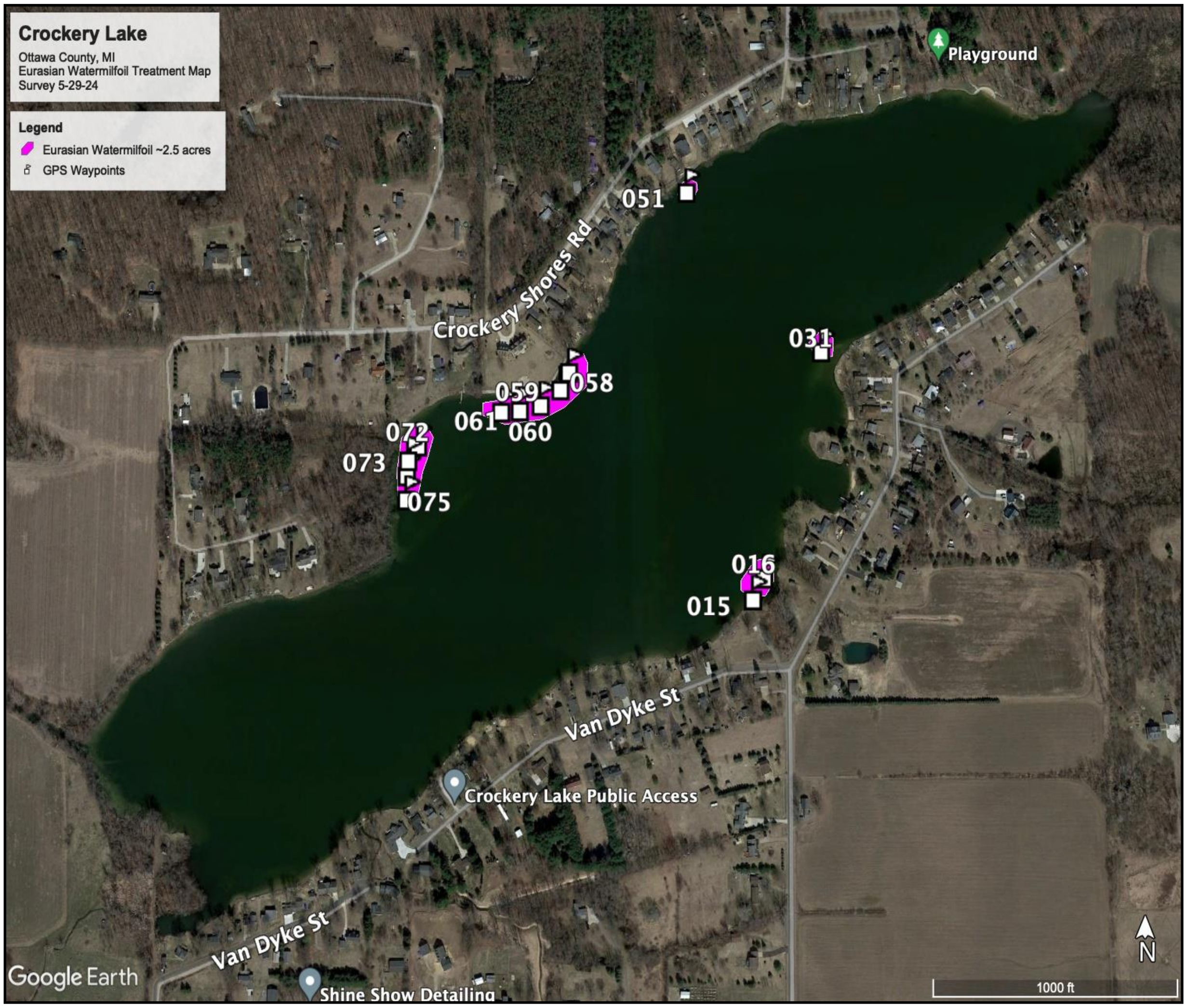


Figure 34. Distribution of EWM in Crockery Lake (May 29, 2024).

Curly-leaf Pondweed (*Potamogeton crispus*; Figure 35) is an exotic, submersed, rooted aquatic plant that was introduced into the United States in 1807 but was abundant by the early 1900's. It is easily distinguished from other native pondweeds by its wavy leaf margins. It grows early in the spring and as a result may prevent other favorable native aquatic species from germinating. The plant reproduces by the formation of fruiting structures called turions. It does not reproduce by fragmentation as invasive watermilfoil does; however, the turions may be deposited in the lake sediment and germinate in following seasons. Curly-leaf Pondweed is a pioneering aquatic plant species and specializes in colonizing disturbed habitats. It is highly invasive in aquatic ecosystems with low biodiversity and unique sediment characteristics. Approximately 5.1 acres of Curly-leaf pondweed were present during the May 29, 2024 survey (Figure 36). It is unlikely that this plant will be problematic later in the summer given its natural tendency to die back in mid-summer.

Figure 35. Curly-leaf Pondweed (©RLS).

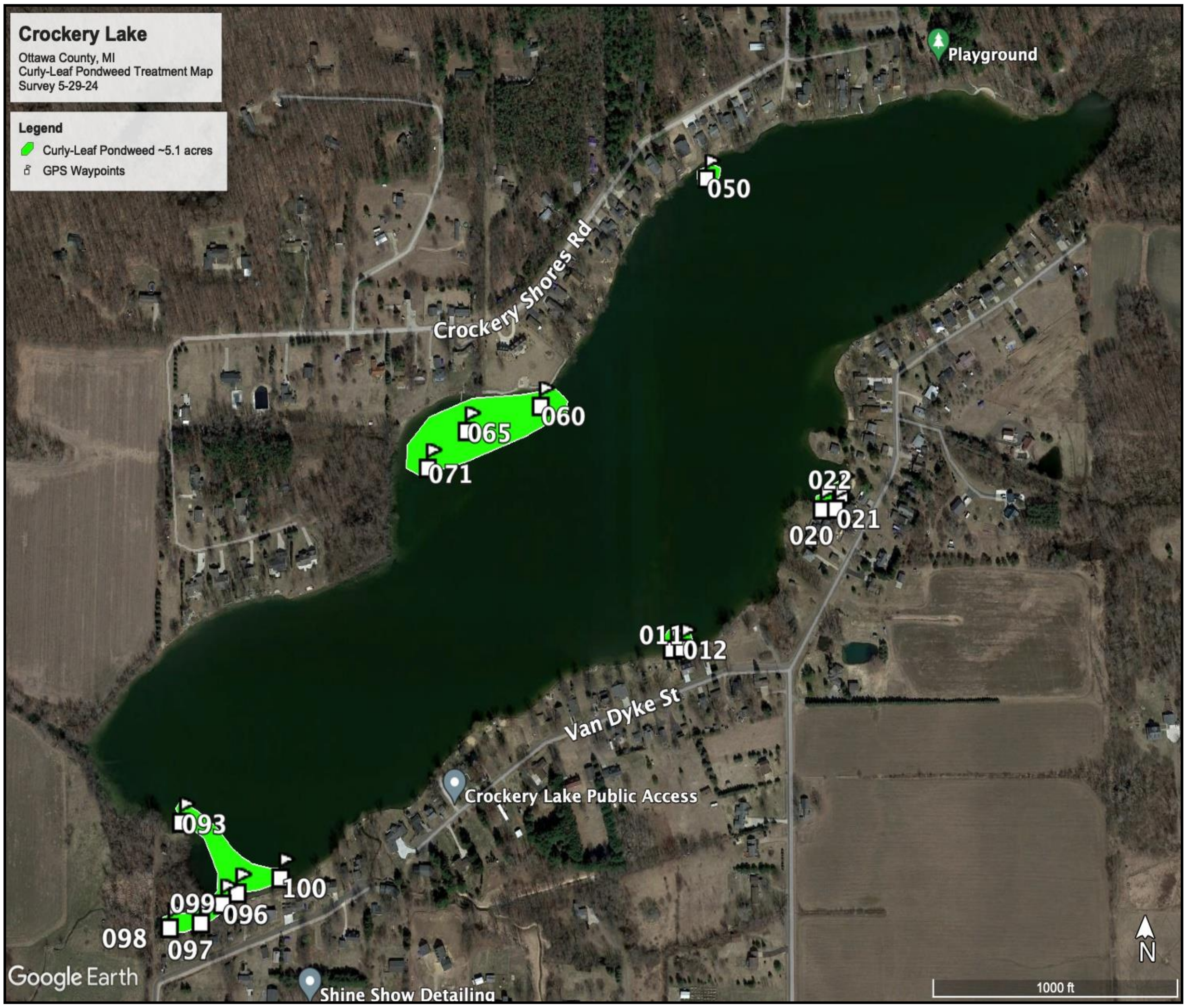


Figure 36. Distribution of CLP in Crockery Lake (May 29, 2024).

Table 22. Crockery Lake invasive aquatic plants (May 29, 2024).

Aquatic Plant Common Name	Aquatic Plant Latin Name	A level	B level	C level	D level	# Sites Found (% of total)
Hybrid Eurasian Watermilfoil	*Myriophyllum spicatum* var. *sibiricum*	2	2	5	4	12.4
Curly-leaf Pondweed	*Potamogeton crispus*	9	5	4	0	17.1

7.0 CROCKERY LAKE ZOOPLANKTON AND FOOD CHAIN BASE

The zooplankton and macroinvertebrates make up the food chain base in an aquatic ecosystem and thus are integral components. Zooplankton are usually microscopic, but some can be seen with the unaided eye. Macroinvertebrates can be readily seen and are also known as aquatic insects or bugs. The zooplankton migrate throughout the water column of the lake according to daylight/evening cycles and are prime food for the lake fishery. Macroinvertebrates can be found in a variety of locations including on aquatic vegetation, near the shoreline, and in the lake bottom sediments. The biodiversity and relative abundance of both food chain groups are indicative of water quality status and productivity.

A zooplankton tow using a Wildco® pelagic plankton net (63 micrometer) with collection jar (Figure 37) was conducted by RLS scientists on July 22, 2024 over the 2 deep basins of Crockery Lake. The plankton net was left at depth for 30 seconds and then raised slowly to the surface at an approximate rate of 4 feet/second. The net was then raised above the lake surface and water was splashed on the outside of the net to dislodge any zooplankton from the net into the jar. The jar was then drained into a 125-mL bottle with a CO2 tablet to anesthetize the zooplankton. The sample was then preserved with a 70% ethyl alcohol solution.

Plankton sub-samples (in 1 ml aliquots) were analyzed under a Zeiss® dissection scope with the use of a Bogorov counting chamber. Taxa were keyed to species when possible and are shown in Table 23 below. A taxa present is shown below in Figure 38. The rotifers were the most dominant taxa along with the cladoceran *Daphnia*.

Table 23. Zooplankton taxa and count data from Crockery Lake (July 22, 2024).

Zooplankton Taxa	DB1	DB2
Cladocerans		
Daphnia spp.	15	26
Bosmina spp.	2	8
Chydorus sp.	1	0
Copepods/Cyclopods		
Mesocyclops	7	1
Rotifers		
Keratella	11	2
Kellicotia	5	6

Figure 37. A zooplankton collection tow net (©RLS).

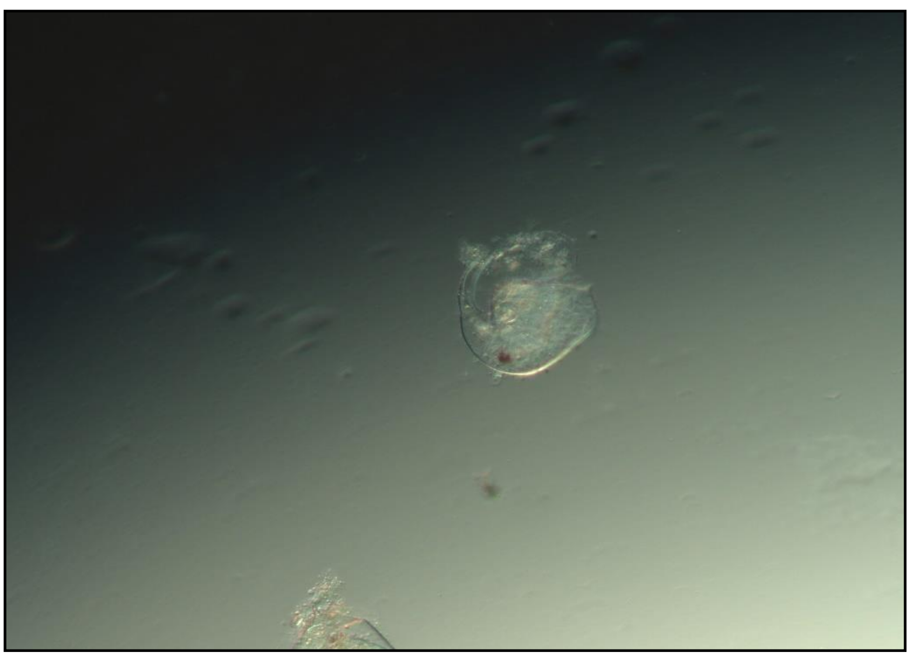


Figure 38. Microscopic image of zooplankton from Crockery Lake (©RLS).

8.0 CROCKERY LAKE MANAGEMENT AND RESTORATION METHODS

Lake restoration methods consist of strategies to reduce invasive aquatic plants, reduce the transport of invasive species, reduce nuisance algae, improve water quality, reduce nutrient transport, and facilitate proper immediate watershed management. The following sections offer useful and effective methods for improving the overall condition of Crockery Lake. Watershed improvements are discussed in the second section of this report for immediate watershed management. The goals of a lake restoration plan such as this are to increase water quality, increase favorable wildlife habitat and aquatic plant and animal biodiversity, optimize recreational use, and protect property values. Regardless of the restoration goals, all decisions must be site-specific and should consider the socio-economic, scientific, and environmental components of the plan.

8.1 Crockery Lake Aquatic Plant Management

The management of submersed invasive aquatic plants is necessary in Crockery Lake due to accelerated growth and distribution. Management options should be environmentally and ecologically-sound and financially feasible. Options for control of aquatic plants are limited yet are capable of achieving strong results when used properly. Implementation of more growth of favorable native aquatic plants (especially the low growing native plants) in Crockery Lake to provide for a healthier lake is recommended though this may require significant increases in water clarity along with reductions in invasive plant cover. All aquatic vegetation should be managed with solutions that will yield the longest-term results.

8.1.1 Aquatic Invasive Species Prevention

An exotic species is a non-native species that does not originate from a particular location. When international commerce and travel became prevalent, many of these species were transported to areas of the world where they did not originate. Due to their small size, insects, plants, animals, and aquatic organisms may escape detection and be unknowingly transferred to unintended habitats.

The first ingredient to successful prevention of unwanted transfers of exotic species to Crockery Lake is awareness and education (Figures 39 and 40). The majority of the exotic species of concern have been listed in this report. Other exotic species on the move could be introduced to the riparians around Crockery Lake through the use of a professionally developed educational newsletter distributed to all lake residents.

Public boat launches are a primary area of vector transport for all invasive species and thus boat washing stations have become more common. With over 13 million registered boaters in the U.S. alone, the need for reducing transfer of aquatic invasive species (AIS) has never been greater. The Minnesota Sea Grant program identifies five major boat wash scenarios which include: 1) Permanent washing stations at launch sites, 2) Portable drive-thru or transient systems, 3) Commercial car washes, 4) Home washing, and 5) Mandatory vs. volunteer washing. Boat washing stations promote the Clean Waters Clean Boats volunteer education program by educating boaters to wash boating equipment (including trailers and bait buckets) before entry into every lake. Critical elements of this education include: 1) How to approach boaters, 2) Demonstration of effective boat and trailer inspections and cleaning techniques, 3) The recording of important information, 4) Identification of high-priority invasive species, and 5) Sharing findings with others. If a boat washing station is placed on Crockery Lake, the residents should work together to educate the public and lake users on proper cleaning techniques and other invasive species information. A "Landing Blitz" can be held once the station is in place and the public can be invited to a field demonstration of how to use the washing station. A typical boat washing station typically costs around $20,000-$40,000 (Figure 41)

Additional educational information regarding these stations and education can be found on the following websites:

1) USDA: https://www.invasivespeciesinfo.gov/us/Michigan
2) Michigan Wildlife Federation Invasive animals, plants list, and native plants/animals list: https://www.Michiganwildlife.org/wildlife
3) Stop Aquatic Hitchhikers!: www.protectyourwaters.net

Figure 39. An aquatic invasive prevention sign for public access sites.

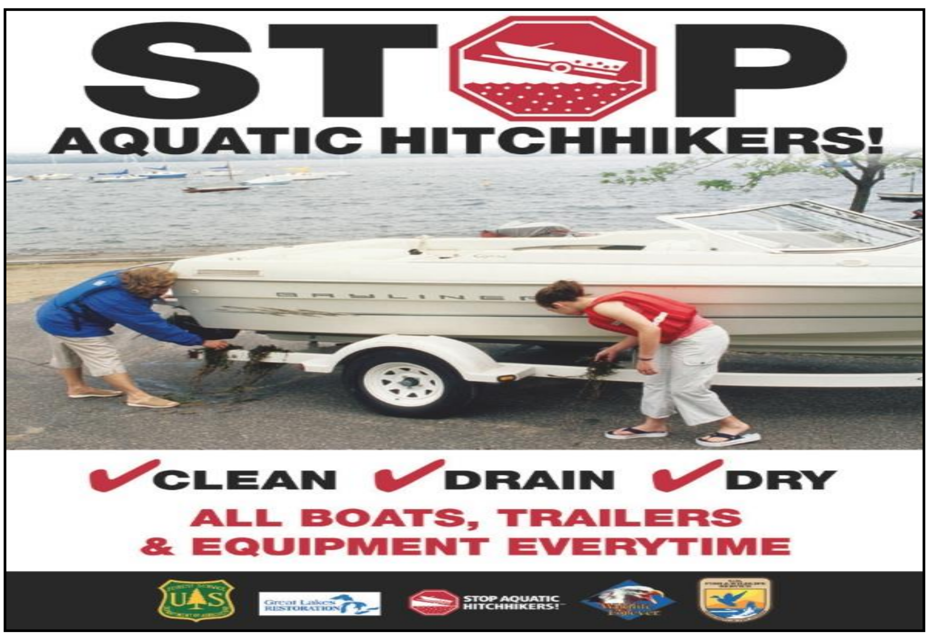


Figure 40. An aquatic invasive prevention sign for public access sites.

Figure 41. A public boat washing station for boat access sites.

Zebra Mussels

Zebra Mussels (*Dreissena polymorpha*; Figure 42) were first discovered in Lake St. Clair in 1988 and likely arrived in ballast water or on shipping vessels from Europe (McMahon 1996). They are easily transferred to other lakes because they inherit a larval (nearly microscopic) stage where they can easily avoid detection. The mussels then grow into the adult (shelled) form and attach to substrates (i.e. boats, rafts, docks, pipes, aquatic plants, and lake bottom sediments) with the use of byssal threads. The fecundity (reproductive rate) of female Zebra Mussels is high, with as many as 40,000 eggs laid per reproductive cycle and up to 1,000,000 in a single spawning season (Mackie and Schlosser 1996). Although the mussels only live 2-3 years, they are capable of great harm to aquatic environments. In particular, they have shown selective grazing capabilities by feeding on the preferred zooplankton food source (green algae) and expulsion of the non-preferred blue green algae (cyanobacteria). Additionally, they may decrease the abundance of beneficial diatoms in aquatic ecosystems (Holland 1993). Such declines in favorable algae, can decrease zooplankton populations and ultimately the biomass of planktivorous fish populations. Zebra Mussels are viewed by some as beneficial to lakes due to their filtration capabilities and subsequent contributions to increased water clarity. However, such water clarity may allow other photosynthetic aquatic plants to grow to nuisance levels (Skubinna et *al*. 1995). Some specimens were found in Crockery Lake by RLS scientists during the lake study.

The recommended prevention protocols for introduction of zebra mussels includes steam-washing all boats, boat trailers, jet-skis, and floaters prior to placing them into Crockery Lake. Fishing poles, lures, and other equipment used in other lakes (and especially the Great Lakes) should also be thoroughly steam-washed before use in Crockery Lake. Additionally, all solid construction materials (if recycled from other lakes) must also be steam-washed. Boat transom wells must always be steam-washed and emptied prior to entry into the lake.
Excessive waterfowl should also be discouraged from the lake since they are a natural transportation vector of the microscopic zebra mussel larvae or mature adults.

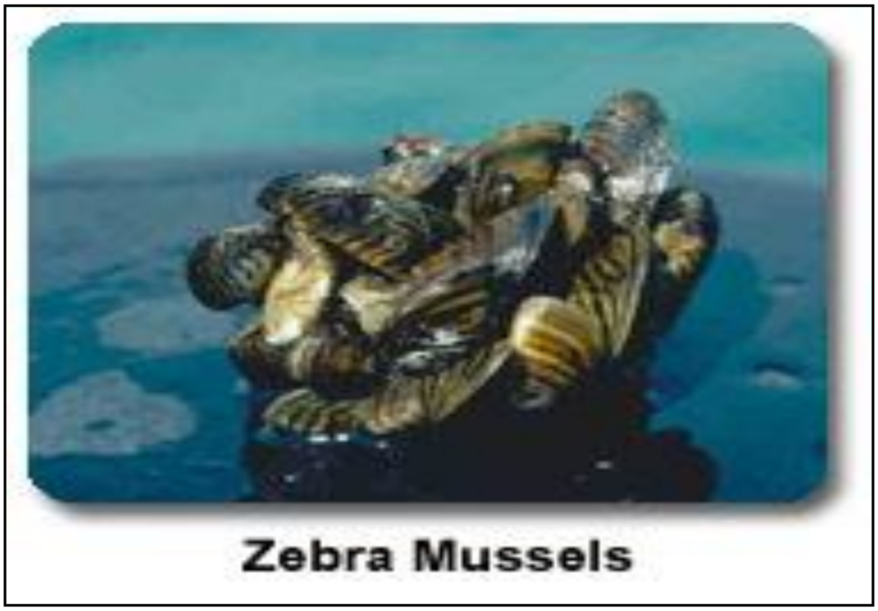


Figure 42. Zebra Mussels (Photo courtesy of USGS).

8.1.2 Aquatic Herbicides and Applications

The use of aquatic chemical herbicides is regulated by the Michigan Department of Environment, Great Lakes, and Energy (EGLE) and requires a permit. Aquatic herbicides are generally applied via an airboat or skiff equipped with mixing tanks and drop hoses (Figure 43). The permit contains a list of approved herbicides for a particular body of water, as well as dosage rates, treatment areas, and water use restrictions. Contact and systemic aquatic herbicides are the two primary categories used in aquatic systems.

Figure 43. A boat used to apply aquatic herbicides in inland lakes (©RLS).

Contact herbicides such as diquat, flumioxazin, and hydrothol cause damage to leaf and stem structures; whereas systemic herbicides are assimilated by the plant roots and are lethal to the entire plant. Wherever possible, it is preferred to use a systemic herbicide for longer-lasting aquatic plant control of invasives. In Crockery Lake, the use of contact herbicides (such as diquat and flumioxazin) is not currently needed or recommended since invasive milfoil is the only problematic aquatic plant and is best treated with targeted systemic herbicides.

Algaecides should only be used on green algal blooms since many treatments can exacerbate blue-green algae blooms. The blue-green algae, *Microcystis* sp. was the most prevalent algae in the lake, which is an indicator of poor water quality (Figure 44). *Microcystis* colonies are a few micrometers in diameter and are evenly distributed throughout a gelatinous matrix. Younger colonies are spherical and older ones are more irregularly shaped. There are numerous gas vesicles, and the algae can thrive at the surface with minimal photo-degradation (breaking down) by the sun. When the sunlight is excessive, the algae can break down and release toxins and lower the dissolved oxygen in the water column. The algae are the only type known to fix nitrogen gas into ammonia for growth. *Microcystis* has also been shown to overwinter in lake sediments (Fallon et *al.*, 1981). In addition, it may thrive in a mucilage layer with sediment bacteria that can release phosphorus under anaerobic conditions (Brunberg, 1995). They assume a high volume in the water column (Reynolds, 1984) compared to diatoms and other single-celled green algae.

The blue-green algae have been on the planet nearly 2.15 billion years and have assumed strong adaptation mechanisms for survival. In general, calm surface conditions will facilitate enhanced growth of this type of algae since downward transport is reduced. *Microcystis* may also be toxic to zooplankton such as *Daphnia* which was a zooplankton present in Crockery Lake and in most lakes (Nizan et *al.*, 1986). Without adequate grazers to reduce algae, especially blue greens, the blue-green population will continue to increase and create negative impacts to water bodies.

Figure 44. A surface scum of blue-green algae on Crockery Lake (July, 2024).

Systemic herbicides such as 2, 4-D, triclopyr, and ProcellaCOR® are the three primary systemic herbicides used to treat milfoil that occurs in a scattered distribution. Fluridone (trade name, SONAR®) is a systemic whole-lake herbicide treatment that is applied to the entire lake volume in the spring and is used for extensive infestations. Whenever possible, it is best to use granular systemics as they stay in place for optimal root uptake and reduce the presence of invasive milfoil over time by killing the roots.

8.1.3 Mechanical Harvesting

Mechanical harvesting involves the physical removal of nuisance aquatic vegetation with the use of a mechanical harvesting machine (Figure 45). The mechanical harvester collects numerous loads of aquatic plants as they are cut near the lake bottom. The plants are off-loaded onto a conveyor and then into a dump truck. Harvested plants are then taken to an offsite landfill or farm where they can be used as fertilizer. Mechanical harvesting is preferred over chemical herbicides when primarily native aquatic plants exist, or when excessive amounts of plant biomass need to be removed. Mechanical harvesting is usually not recommended for the removal of Eurasian Watermilfoil since the plant may fragment when cut and re-grow on the lake bottom. It may be considered in future years for Crockery Lake if the milfoil is not present and the submersed aquatic vegetation grows to nuisance levels and the residents desire a biomass removal technique that does not consist of the use of contact herbicides.

Figure 45. A mechanical harvester used to remove aquatic plants (©RLS).

8.1.4 Benthic Barriers and Nearshore Management Methods

The use of benthic barrier mats (Figure 46) or Weed Rollers (Figure 47) have been used to reduce weed growth in small areas such as in beach areas and around docks. The benthic mats are placed on the lake bottom in early spring prior to the germination of aquatic vegetation. They act to reduce germination of all aquatic plants and lead to a local area free of most aquatic vegetation. Benthic barriers may come in various sizes between 100-400 feet in length.

They are anchored to the lake bottom to avoid becoming a navigation hazard. The cost of the barriers varies among vendors but can range from $100-$1,000 per mat. Benthic barrier mats can be purchased online at: www.lakemat.com or www.lakebottomblanket.com.

The efficacy of benthic barrier mats has been studied by Laitala et *al.* (2012) who report a minimum of 75% reduction in invasive milfoil in the treatment areas. Lastly, benthic barrier mats should not be placed in areas where fishery spawning habitat is present and/or spawning activity is occurring.

Weed Rollers are electrical devices which utilize a rolling arm that rolls along the lake bottom in small areas (usually not more than 50 feet) and pulverizes the lake bottom to reduce germination of any aquatic vegetation in that area. They can be purchased online at: www.crary.com/marine or at: www.lakegroomer.net.

Both methods are useful in recreational lakes such as Crockery Lake and work best in beach areas and near docks to reduce nuisance aquatic vegetation growth if it becomes prevalent in future years.

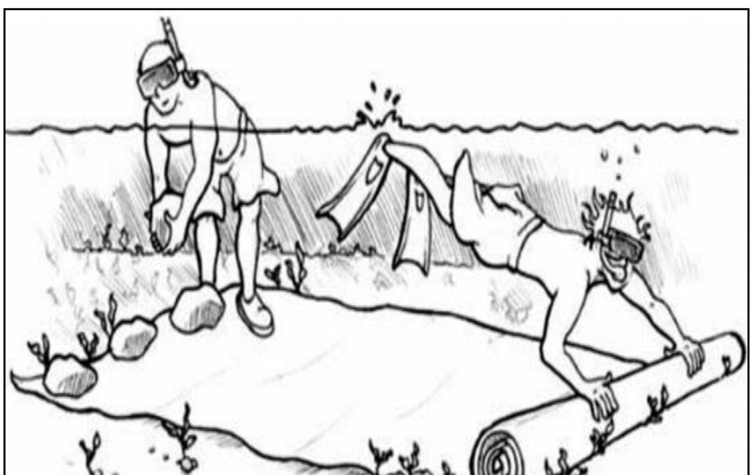


Figure 46. A Benthic Barrier. Photo courtesy of Cornell Cooperative Extension.

Figure 47. A Weed Roller.

8.1.5 Diver Assisted Suction Harvesting (DASH)

Suction harvesting via a Diver Assisted Suction Harvesting (DASH) boat (Figure 48) involves hand removal of individual plants by a SCUBA diver in selected areas of lake bottom with the use of a hand-operated suction hose. Samples are dewatered on land or removed via fabric bags to an offsite location. This method is generally recommended for small (less than 1 acre) spot removal of vegetation since it is costly on a large scale. It may be used in the future to remove small areas of dense growth in shallow areas but is not recommended at this time.

Furthermore, this activity may cause re-suspension of sediments (Nayar et *al*., 2007) which may lead to increased turbidity and reduced clarity of the water. This method is a sustainable option for removal of plant beds in beach areas and areas where herbicide treatments may be restricted. It is also optimal for areas of dense lily pads that are impeding navigation and recreational activities.

Figure 48. A DASH boat used for aquatic plant removal (©RLS).

8.2 Crockery Lake Water Quality Improvement

In addition to lake improvement methods that reduce invasive aquatic plant communities, there are methods to improve the water quality within the lake basin. These methods are often large in scale and costly but are highly effective at increasing water clarity, reducing algae, increasing dissolved oxygen, and allowing for enhanced recreational activities.

8.2.1 Hypolimnetic Oxygenation for P Inactivation

Hypolimnetic oxygenation via a PrO2 unit (Figure 49) made by Greener Planet Systems® (Iowa, USA), is a technology that has been previously used in wastewater treatment. The treatment of wastewater to reduce nutrients and pollutants is required for state-issued discharge permits. This technology is a patented technology that utilizes pure oxygen that is pumped into the bottom of a lake through direct hoses that deliver the oxygen to the hypolimnion to avoid destratification of the water column. This reduces the release of phosphorus from lake sediments which reduces the nutrients in the upper water layers and thus reduces the presence of blue-green algae blooms.

Dissolved oxygen from the PrO2 Series is not limited by ambient saturation levels because the delivered oxygen is already dissolved and will experience no effects of buoyancy because it is not a bubble.

The PrO2 Series efficiently delivers extremely large amounts of dissolved oxygen into waste matter with up to 96% oxygen transfer efficiency. As a result, the oxygen rich environment will accelerate the natural breakdown of organic matter while creating and preserving an odor free environment. The major deliverables offered by the PrO2 unit are as follows:

- Empowers Microbes to Consume 95% of Organic Waste
- 96% Oxygen Transfer Efficiency
- 75% Reduction in Conventional Aeration Costs
- Targeted Application Control (oxygenates the deep basin only if desired)
- Remote and Onsite Control Options (can maintain constant stable dissolved oxygen concentrations)
- Scalable to every lake size (includes a secure shed or trailer for large units)

Figure 49. Diagram of PrO2 Hypolimnetic Oxygenation System.

8.2.2 Other P Inactivation Methods

There are a few products on the lake improvement market that aim to reduce phosphorus in the water column and the release of phosphorus from a lake bottom. Such products are usually applied as a slurry by a special dose-metered vessel to the water column or just above the lake bottom. Most of these formulas can be applied in aerobic (oxygenated) or anaerobic (oxygen-deficient) conditions. Agricultural watersheds create substantial challenges for lakes (Detenbeck et *al.*, 1993).

In lakes that lack ample dissolved oxygen at depth, this product may help prevent phosphorus release from the sediments. A few disadvantages include cost, inability to bind high concentrations of phosphorus especially in lakes that receive high external loads of phosphorus (i.e. lakes such as Crockery Lake with a large catchment or watershed), and the addition of an aluminum floc to the lake sediments which may impact benthic macroinvertebrate diversity and relative abundance (Pilgrim and Brezonik, 2005). Some formulas utilize a clay base with the P-inactivating lanthanum (Phoslock®) which may reduce sediment toxicity of alum.

If this method is implemented, it is highly recommended that sampling the lake sediments for sediment pore water phosphorus concentrations be conducted to determine internal releases of phosphorus pre-alum and then monitoring post-alum implementation. Additionally, external phosphorus loads must be significantly reduced since these inputs would compromise phosphorus-inactivation formulas (Nürnberg, 2017).

A study by Onterra LLC of Little Green Lake in Wisconsin (March, 2022), determined that the hypoxic area of the lake occupied approximately 127 acres. They estimated that even if 90% of the P released from sediments in 2021 was reduced with an alum treatment, the ambient mean P in the water column would have only been reduced from 70 µg/L to 56 µg/L. Sondergaard et *al*., (2001) cite the importance of external P reduction in order for within-basin methods such as alum to be effective.

At this time, a hypolimnetic oxygenation technology would be preferred over application of alum since a higher dissolved oxygen concentration is desired throughout the water column and on the lake bottom to reduce internal release of phosphorus and also decrease blue-green algal blooms and increase water clarity while improving the zooplankton and benthic macroinvertebrate biodiversity to support a strong fishery.

8.2.3 Nutrient Filtration Methods

There is a great need for reduction of the nutrients and pollutants previously discussed that negatively impact the water quality of Crockery Lake. An innovative and natural product called Biochar (Figure 50) has been used with measurable reductions in nutrients and solids in stormwater and water body improvement programs.

A natural charcoal technology called TimberChar Biochar® is available for filtration of nutrients and pollutants that may enter inland waters such as Crockery Lake. The Biochar is comprised of 87.4% organic carbon based on percentage of total dry mass. Particles range in size from 8-25 mm so there is inherent variability in particle size. This variability allows for the adsorption of nutrients and pollutants due to increased adsorptive surface area. Biochar may be placed in a multi-filament polypropylene sock (such as Silt Sock®) which has a life expectancy of up to 3 years. It is considered an inert product with no chemical effect on the environment. This product allows for the Biochar to be contained in an area and serves to consolidate the particles for optimum filtration efficiency. Previous data collected by RLS on an inland lake inlet that utilized the Biochar showed significant reductions in nutrients such as phosphorus and nitrogen as well as total suspended solids (Jermalowicz-Jones, 2012-2016). Additionally, another pilot project on Silver Lake in Oceana County, MI in 2023 demonstrated substantial reductions in total phosphorus, ammonia, nitrate nitrogen, and total suspended solids. The filters were applied to significant incoming drains as well as to numerous docks and boats in the lake basin. Minimal algal blooms occurred in 2023.

Figure 50. Biochar filters in front of a lake drain.

8.3 Crockery Lake Immediate Watershed Improvements

Inland waters such as lakes provide multiple benefits to riparian communities and local municipalities through a variety of ecosystem services. Stynes (2002) estimated that Michigan's 11,000 inland lakes support a recreational industry that is valued at approximately 15 billion dollars per year. Inland lakes also provide economic and aesthetic values to riparian waterfront property owners with increased residential lot property values and scenic views. A survey of approximately 485 riparians that represented five lakes in Kalamazoo County, Michigan, USA, was conducted in 2002 by Lemberg et *al*. (2002) and revealed that the most important benefit of lakefront ownership was the vista. Thus, lakes clearly provide aesthetic as well as recreational benefits to riparians and those that use them.

For some time, lakes have been under continuous stress from surrounding development and land use activities. A major source of this stress includes the anthropogenic contributions of nutrients, sediments, and pathogens to the lake water from the surrounding landscape (Carpenter et *al*., 1998). Nutrients have caused critical water quality issues such as the inundation of lakes with dense, filamentous green algae, or worse, toxic blue-green algae. Submersed aquatic vegetation also increases with high levels of phosphorus and leads to impedance of navigation and recreational activities, as well as decreases in water clarity and dissolved oxygen that lead to widespread fish kills.

The existence of excess phosphorus in inland waterways has been well established by many scholars (Carpenter et *al*., 1998; Millennium Ecosystem Assessment, 2005, among numerous others). Major sources of phosphorus for inland waterways include fertilizers from riparian lawns, septic drain fields, and non-point source transport from agricultural activities in the vicinity of a water body. Non-point source effluents such as phosphorus are difficult to intercept due to the diffuse geographical dispersion across a large area of land. Additionally, watersheds generally export more non-point source loads relative to point source loads as a result of the reductions of point source pollution required by the Clean Water Act of 1972 (Nizeyimana et *al*., 1997; Morgan and Owens, 2001).

Impacts of NPS Pollution on Inland Waters:

Beginning in 2007 and continuing to the present day, the USEPA Office of Water and Office of Research and Development has partnered with multiple stakeholders at both the state and federal levels to derive comparisons among the nation's aquatic resources which include lakes, wadable streams, large rivers, coastal estuaries, and wetlands. During the assessment, 1,028 lakes have been sampled along with 124 reference lakes and 100 lakes which were re-sampled. Lakes were selected from the National Hydrography Data Set (NHD) using a set of criteria that addressed trophic status, locale, and physical characteristics. Water quality indicators such as biological integrity, habitat quality, trophic status, chemical stressors, pathogens, and paleolimnological changes were measured.

Although 56% of the nation's lakes possessed healthy biological communities, approximately 30% of lakes had the toxin microcystin, which is produced by the blue-green algae *Microcystis*. This was also the case for Crockery Lake.

Approximately 49% of the lakes had mercury concentrations in fish tissues that exceeded healthy limits. The key stressors of the lakes were determined to be poor shoreline habitat and excessive nutrients. A favorable outcome of the inventory revealed that half of the lakes exhibited declines in phosphorus levels compared to levels noted in the early 1970's. Despite this observed decline, many of our inland lakes continue to experience degradations in water quality. One reason for this problem is that many lakes have properties that utilize septic systems. Since riparians have little control over local pollutant loading from agriculture to inland lakes, the maintenance of septic systems is critical for water quality protection.

Regulation of Nutrient Pollution in Inland Lakes

EGLE regulates some activities through the Inland Lakes and Streams Program, pursuant to Part 301 of the Natural Resources Environmental Protection Act, P.A. 451 of 1994, as amended. Currently regulated activities include permits for shoreline improvements and beach alterations, wetland mitigation, and dredging.

Non-point source pollutants from adjacent lands are loosely regulated, generally through the derivation of Total Maximum Daily Loads (TMDL's) pursuant to the federal Clean Water Act of 1972 (CWA) for water bodies that do not meet state Water Quality Standards (WQS). An initial goal of the CWA was to reduce the discharge of all pollutants into navigable waters by 1985. This goal was clearly not achieved and thus the policy was not as effective as previously assumed. A TMDL is the maximum amount of a specific pollutant a water body can absorb and still maintain good water quality. In Michigan, waters that do not meet WQS must be studied to determine the TMDL's for specific pollutants. Once the TMDL's are established for the water body by the EGLE, they are submitted to the United States Environmental Protection Agency (EPA) for approval. Once approved, the TMDL's are implemented through the regulation of National Pollutant Discharge Elimination System (NPDES) permits for point source pollutants or through improvement programs for non-point source pollution. The WQS strive to maintain waters with acceptable dissolved oxygen concentrations for the fishery, suitable conditions for recreation, and the protection of high-quality waters. A primary problem with the current TMDL system is that sites need to be monitored frequently to determine what the TMDL should be and once determined, if the system is showing signs of improvement. Although the MDEQ maintains a current list of waters with TMDL's throughout the state, the impairments still exist on many water bodies (Jermalowicz-Jones, *unpublished data*). The monitoring frequency needed to obtain accurate information is often not executed and the runoff of phosphorus from farmland is often unmeasured and unknown. Furthermore, intense monitoring of agricultural non-point pollutant loads would be expensive and transaction costs associated with regulation policies would likely be high (Dosi and Zeitouni, 2001).

8.3.1 Crockery Lake Inlet Water Quality Data

Non-point source (NPS) pollutants are diffuse and have many potential sources to inland lakes such as large agricultural land use activities that abut waterways and drain into Crockery Lake. Once identified, these are referred to as critical source areas (CSA's) which are areas that contribute directly to the detriment of receiving waters. CSA's often generate substantially more nutrient and sediment loads than most of the immediate watershed area (White et *al*., 2009) and thus are a critical component for the discovery of target areas with highest impact on water quality. CSA's can contribute high loads of nutrients and sediments to inland waterways and often escape detection during lake management programs. In vulnerable areas, these pollutants enter lakes after a climatic event such as heavy rainfall or snowmelt. The surrounding landscape is critical for the determination of CSA's as some areas contain high slopes which increase the probability of erosion, while others contain soils that pond and contribute pollutants to the lake via runoff from the land. This information is critical to include in a watershed management program since Best Management Practices (BMP's) should be site-specific and address the pollutant loads at the site scale. The Ottawa County Conservation District is developing a watershed improvement program. Many BMP's will follow recommendations from Low Impact Development (LID) which aim to reduce the amount of imperviousness in developed areas. Since so many lake shorelines are already developed or are being further developed, the use of LID practices will help reduce runoff and protect water quality.

Elder (1985) discusses the sink-source interactions between wetlands and rivers or other waterways. He cites timing and duration of flooding events as being the key predictors of nutrient and material transport from the wetland to the waterway. It is important to retain many of the wetland features, as any entry portals cut through the wetland (i.e., via cutting emergent cattails or other vegetation), may cause overland flow which could carry nutrients and sediments directly from wetlands into Crockery Lake. Wetlands have been traditional for the treatment of storm water in that they filter out nutrients and sediments. However, during very intense rainfall events, the hydric (saturated) soils in the wetland may actually contribute nutrients to Crockery Lake.

Water quality parameters such as dissolved oxygen, water temperature, pH, conductivity, total dissolved solids, total suspended solids, total phosphorus, ortho-phosphorus, total inorganic nitrogen (specifically ammonia, nitrate, and nitrite), and total Kjeldahl nitrogen were measured at each of the inlet areas under flowing conditions. Samples consisted of preserved grab bottles which were placed on ice and transported to the NELAC-certified laboratory for analysis. The data for the inlets are discussed below and are presented in Tables 24-25.

Samples and water quality measurements were collected on September 8, 2022. Measurements were taken with a calibrated Eureka Manta II® multi-parameter probe. Flow rates were measured with a calibrated Swoffer® digital flow meter. All tributaries except #1 had high TP and TIN with very high TSS in tributary #2.

Table 24. Crockery Lake physical water quality parameter data collected in the tributaries (September 28, 2022). NOTE: Tributary #1 was not flowing at the time of sampling and thus could not be sampled.

Tributary Site	Water Temp (°C)	pH (S.U.)	DO (mg/L)	Conduc. (mS/cm)	TDS (mg/L)	Flow (cfs)
Trib #1	NA	NA	NA	NA	NA	NA
Trib #2	10.7	8.0	9.9	656	420	0.01
Trib #3	11.0	8.3	10.8	528	338	0.1
Trib #4	11.3	8.1	11.0	539	345	6.6

Table 25. Crockery Lake chemical water quality parameter data collected in the tributaries (September 28, 2022). NOTE: Tributary #1 was not flowing at the time of sampling and thus could not be sampled.

Tributary Site	TKN (mg/L)	TIN (mg/L)	TP (mg/L)	Ortho-P (mg/L)	NH_3 (mg/L)	NO_2- (mg/L)	NO_3- (mg/L)	TSS (mg/L)
Trib #1	NA	NA	NA	NA	NA	NA	NA	NA
Trib #2	0.5	0.770	0.180	0.029	0.080	0.130	0.570	36
Trib #3	0.5	1.3	0.100	0.014	0.031	<0.10	1.3	150
Trib #4	<0.5	1.7	0.042	0.028	0.037	<0.10	1.6	<10

These values likely change quickly during intense rain events. Table 26 displays additional 2023 means for the inlets with values reflective of reduced nutrient loads due to lower rainfall.

Table 26. Descriptive statistics of all water quality parameters in the inlets of Crockery Lake for parameters collected on November 8, 2023 and July 1, 2023.

Water Quality Parameter	Inlets November 8, 2023	Inlets July 1, 2023
Water temp (°C)	8.4±0.4	18.5±0.6
pH (S.U.)	8.1±0.0	7.8±0.4
Dissolved oxygen (mg/L)	10.1±0.4	9.3±1.1
Conductivity (mS/cm)	415±4.9	346±14
Total dissolved solids (mg/L)	265±2.8	222±8.5
Total Kjeldahl nitrogen (mg/L)	0.7±0.1	1.5±0.6
Total inorganic nitrogen (mg/L)	0.210±0.1	0.520±0.1
Ammonia nitrogen (mg/L)	0.027±0.0	0.081±0.0
Nitrate nitrogen (mg/L)	0.180±0.1	0.440±0.1
Nitrite nitrogen (mg/L)	0.100±0.0	0.100±0.0
Total phosphorus (mg/L)	0.030±0.0	0.043±0.0
Ortho-phosphorus (mg/L)	0.013±0.0	0.029±0.0
Total suspended solids (mg/L)	10±0.0	10±0.0
Total Alkalinity (mg/L)	165±7.1	130±14

8.3.2 Nutrient Source Reduction

The control of nutrients from a surrounding watershed or catchment to any lake is a proven necessity for long-term nutrient reduction. Although nutrients are a necessity for the primary production of algae and aquatic plants in a lake ecosystem, an overabundance of nutrients causes substantial problems as noted above. Lakes that lie within an agricultural watershed may experience acute and chronic influx of sediments, nutrients, and bacteria, among other pollutants. Those within urbanized watersheds face other stressors that include nutrient pollution but also influx of metals, dissolved solids, among other pollutants. In many areas, however, the watershed reduction approach is limited, and restorative measures must begin within the lake basin. Annadotter et *al*., (1999) noted that even years after a sewage treatment plant was built along the shores of Lake Finjasjön (Sweden), the lake trophic status continued to decline. This was due to the existence of sediments that continuously leaked phosphorus into the overlying waters.

A combination of intensive lake restoration methods was needed to significantly improve the water quality and consisted of sediment removal, constructed wetlands for watershed nutrient removal, and food web manipulation to improve the fishery. Their study proved that in cases of extreme water quality degradation, multiple techniques are often needed to bring a marked balance back to the lake ecosystem. In other words, one solution may not be enough to accomplish restoration.

Nutrient pollution of inland lakes from septic systems and other land use activities is not a modern realization and has been known for multiple decades. The problem is also not unique to Michigan Lakes and was first described in Montreal Canada by Lesauteur (1968) who noticed that summer cottages were having negative impacts on many water bodies. He further noted that a broader policy was needed to garner control of these systems because they were becoming more common over time. Many of our inland lakes such as Crockery Lake are in rural areas and thus sewer systems or other centralized wastewater collection methods are not practical. Thus, septic systems have been common in those areas since development on inland lakes began. Septic systems have four main components consisting of a pipe from the residence, a septic tank or reservoir, a drainage field, and the surrounding soils (Figure 51).

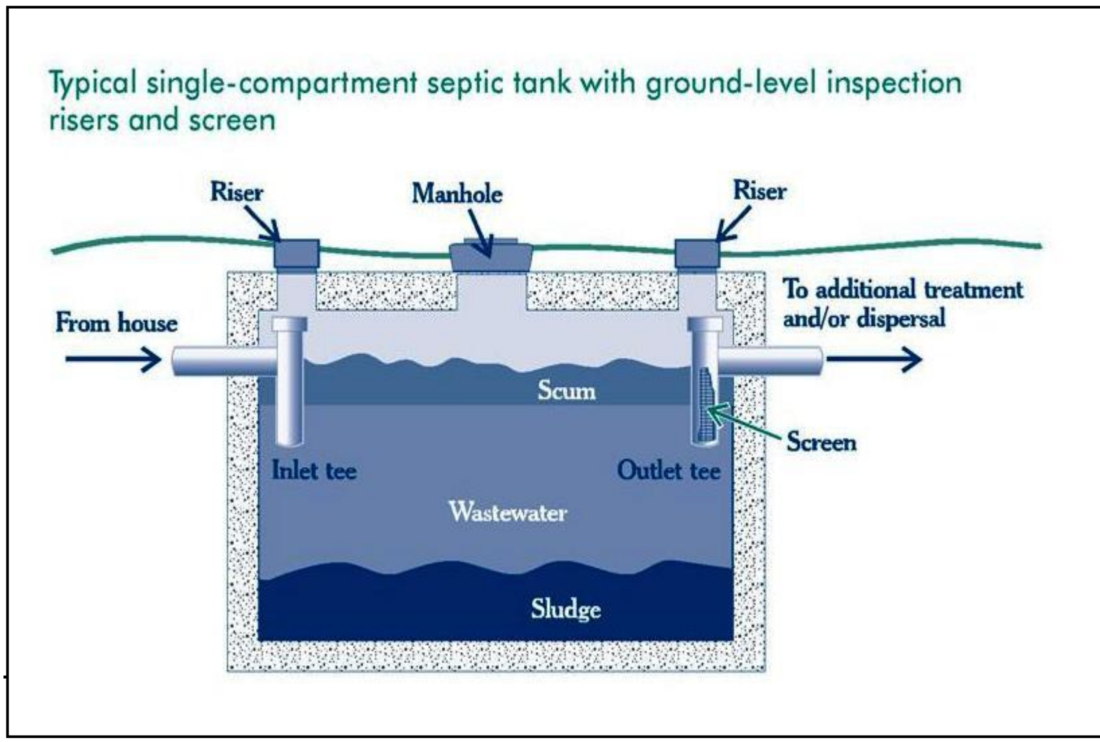


Figure 51. Diagram of a septic tank system (USEPA).

On ideal soil types, microbes in the soil are able to decompose nutrients and reduce the probability of groundwater contamination. However, many lakes in Michigan contain soils that are not suitable for septic systems. Soils that are not very permeable, prone to saturation or ponding, and have mucks exist around many lakes and currently have properties with septic systems.

In fact, soils that are saturated may be associated with a marked reduction in phosphorus assimilation and adsorption (Gilliom and Patmont, 1983; Shawney and Starr, 1977) which leads to the discharge of phosphorus into the groundwater, especially in areas with a high water table. In the study by Gilliom and Patmont (1983) on Pine Lake in the Puget Sound of the western U.S., they found that it may take 20-30 years for the phosphorus to make its way to the lake and cause negative impacts on water quality.

Typical septic tank effluents are rich in nutrients such as phosphorus and nitrogen, chlorides, fecal coliform, sulfates, and carbon (Cantor and Knox, 1985). Phosphorus and nitrogen have long been identified as the key causes of nuisance aquatic plant and algae growth in inland lakes. Although phosphorus is often the limiting growth factor for aquatic plant growth, nitrogen is often more mobile in the groundwater and thus is found in abundance in groundwater contributions to lakes. A groundwater seepage study on submersed aquatic plant growth in White Lake, Muskegon County, Michigan, was conducted in 2005 by Jermalowicz-Jones (MS thesis, Grand Valley State University) and found that both phosphorus and nitrogen concentrations were higher in developed areas than in undeveloped areas. This helped to explain why the relatively undeveloped northern shore of White Lake contained significantly less submersed aquatic plant growth than the developed southern shoreline. The research also showed that more nutrients were entering the lake from groundwater than in some of the major tributaries.

Cheruvelil-Spence and Soranno (2008) studied 54 inland lakes in Michigan and found that total aquatic plant cover (including submersed plants) was most related to secchi depth and mean depth. However, they also determined that man-made land use activities are also predictors of aquatic plant cover since such variables can also influence these patterns of growth. Prior to changes in offshore aquatic plant communities, an additional indicator of land use impacts on lake water quality in oligotrophic lakes (lakes that are low in nutrients) includes changes in periphytic algae associated with development nearshore. Such algae can determine impacts of septic leachate before other more noticeable changes offshore are found (Rosenberger et *al*., 2008). Development in the watershed also may influence the relative species abundance of individual aquatic plant species. Sass et *al*. (2010) found that lakes associated with rigorous development in surrounding watersheds had more invasive species and less native aquatic plant diversity than less developed lakes. Thus, land use activities such as failing septic systems may not only affect aquatic plant biomass and algal biomass, but also the composition and species richness of aquatic plant communities.

A groundwater investigation of nutrient contributions to Narrow Lake in Central Alberta, Canada by Shaw et *al*., 1990, utilized mini-piezometers and seepage meters to measure contributions of groundwater flow to the lake. They estimated that groundwater was a significant source of water to the lake by contributing approximately 30% of the annual load to the lake. Additionally, phosphorus concentrations in the sediment pore water were up to eight times higher than groundwater from nearby lake wells.

It is estimated that Michigan has over 1.2 million septic systems currently installed with many of them occurring in rural areas around inland lakes. Currently only seven counties in Michigan (Benzie, Grand Traverse, Macomb, Ottawa, Shiawassee, Washtenaw, and Wayne) require a septic system inspection prior to a property being sold. The number of septic systems that are a risk to the aquatic environment is unknown which makes riparian awareness of these systems critical for protection of lake water. Construction of new septic tanks require notification and application by the homeowner to the county Department of Public Health and also that soils must be tested to determine suitability of the system for human health and the environment. It is recommended that each septic tank be inspected every 2-3 years and pumped every 3-5 years depending upon usage. The drain field should be inspected as well and only grasses should be planted in the vicinity of the system since tree roots can cause the drain field to malfunction. Additionally, toxins should not be added to the tank since this would kill beneficial microbes needed to digest septic waste. Areas that contain large amounts of peat or muck soils may not be conducive to septic tank placement due to the ability of these soils to retain septic material and cause ponding in the drain field. Other soils that contain excessive sands or gravels may also not be favorable due to excessive transfer of septage into underlying groundwater. Many sandy soils do not have a strong adsorption capacity for phosphorus and thus the nutrient is easily transported to groundwater. Nitrates, however, are even more mobile and travel quickly with the groundwater and thus are also a threat to water quality.

The utilization of septic systems by riparians is still quite common around inland lake shorelines. A basic septic system typically consists of a pipe leading from the home to the septic tank, the septic tank itself, the drain field, and the soil. The tank is usually an impermeable substance such as concrete or polyethylene and delivers the waste from the home to the drain field. The sludge settles out at the tank bottom and the oils and buoyant materials float to the surface. Ultimately the drain field receives the contents of the septic tank and disperses the materials into the surrounding soils. The problem arises when this material enters the zone of water near the water table and gradually seeps into the lake bottom. This phenomenon has been noted by many scholars on inland waterways as it contributes sizeable loads of nutrients and pathogens to lake water. Lakebed seepage is highly dependent upon water table characteristics such as slope (Winter 1981). The higher the rainfall, the more likely seepage will occur and allow groundwater nutrients to enter waterways. Seepage velocities will differ greatly among sites and thus failing septic systems will have varying impacts on the water quality of specific lakes.

Lee (1977) studied seepage in lake systems and found that seepage occurs as far as 80 meters from the shore. This finding may help explain the observed increases in submersed aquatic plant growth near areas with abundant septic tank systems that may not be adequately maintained. Loeb and Goldman (1978) found that groundwater contributes approximately 44% of the total soluble reactive phosphorus (SRP) and 49% of total nitrates to Lake Tahoe from the Ward Valley watershed. Additionally, Canter (1981) determined that man-made (anthropogenic) activities such as the use of septic systems can greatly contribute nutrients to groundwater.

Poorly maintained septic systems may also lead to increases in toxin-producing blue-green algae such as *Microcystis.* This alga is indicative of highly nutrient-rich waters and forms an unsightly green scum on the surface of a water body. Toxins are released from the algal cells and may be dangerous to animals and humans in elevated concentrations. Furthermore, the alga may shade light from underlying native aquatic plants and create a sharp decline in biomass which leads to lower dissolved oxygen levels in the water column. Repeated algae treatments are often not enough to compensate for this algal growth and the problem persists.

9.0 CROCKERY LAKE RESTORATION PROJECT CONCLUSIONS & RECOMMENDATIONS

Crockery Lake is facing significant issues that degrade water quality over time, including inputs of nutrients and sediments from surrounding drains, and leaking septic tanks and drain fields which lead to a decline in lake health. The lake fishery is becoming impaired by harmful algal blooms and the increased BOD is resulting in a decline in dissolved oxygen with depth throughout the lake. There are also natural wetlands around the lake that are high in organic carbon and nutrients that can serve as a source of nutrients, tannins, and organic matter to the lake during periods of extended saturation. The high nutrients have also led to increased blue-green algal blooms that secrete toxins such as microcystins that are a public and pet health hazard and result in lake advisories. These algae also reduce light to aquatic plants and favor an algal-dominated state. The result of the overabundance of algae is higher turbidity, lower water clarity, and fewer aquatic plants (especially the native submersed types that cannot tolerate low light conditions). The lake basin will continue to deteriorate unless drain/inlet improvements are made, and efforts are made to oxygenate the hypolimnion to reduce the continuous release of phosphorus. Hypolimnetic oxygenation (with a PrO2 unit) is recommended for the lake basin to oxygenate the lake bottom and reduce the release of phosphorus while maintaining stratified conditions in the epilimnion and metalimnion. This will result in increased clarity, dissolved oxygen, and reduced algal blooms. It may also help to improve the lake fishery and provide better algal food choices for the zooplankton, which are at the base of the lake food chain.

Also critical is the development of a lake wide septic system maintenance program in the absence of a municipal sewer system. With this approach, lakefront lots are surveyed with permissions and tested for evidence of E. coli leakage which might arise from failing septic systems. The owners of these lots are then notified with the suggestion that they have their septic systems and fields inspected, as this is the only way to verify or rule out a septic-related problem on their property. Regardless of how many are found, there is a critical need for a lake-wide septic management program. In addition to the use of this method, residents should have a lake-wide annual septic pump-out day where all participate. Evaluations of the drain field should also be conducted every few years. Lastly, when lots are determined to have septic leachate issues, the implementation of SludgeHammer® units to reduce nutrients exiting the drain field are recommended to reduce inputs to the lake over time. These units would have to be individually paid for and usually cost between $3,000-$5,000 per unit.

There are several different methods available to reduce the threat of NPS pollution to inland lakes and each are able to be site-specific. The following sections offer many of these methods with specific applications to the individual areas (CSA's) that are contributing significant nutrient loads to Crockery Lake.

Best Management Practices (BMPs)

The increased developmental pressures and usage of aquatic ecosystems necessitate inland lake management practices as well as watershed Best Management Practices (BMP's) to restore balance within Crockery Lake. For optimum results, BMP's should be site-specific and tailored directly to the impaired area (Maguire et *al.*, 2009). Best Management Practices (BMP's) can be implemented to improve a lake's water quality. The guidebook, Lakescaping for Wildlife and Water Quality (Henderson et *al*. 1998) provides the following guidelines:

1) Maintenance of brush cover on lands with steep slopes (>6% slope)
2) Development of a vegetation buffer zone 25-30 feet from the land-water interface with approximately 60-80% of the shoreline bordered with vegetation (Figure 52 is an example of a lack of riparian buffer)

Figure 52. A photo of a lakefront without an adequate vegetation buffer.

3) Limiting boat traffic and boat size to reduce wave energy and thus erosion potential
4) Encouraging the growth of dense shrubs or emergent shoreline vegetation to control erosion
5) Using only <u>native</u> genotype plants (those native to a particular lake and region) around the lake since they are most likely to establish and thrive than those not acclimated to growing in the area soils

6) Avoid the use of lawn fertilizers that contain phosphorus (P) and nitrogen (N). P is the main nutrient required for aquatic plant and algae growth, and plants grow in excess when P and N, especially ammonia and nitrate, are abundant. There are other natural products that serve as soil conditioners that reduce the transfer of nutrients into the lake. They can be found at: www.bloomfieldroots.com and www.milorganite.com.
7) Preserve riparian vegetation buffers around a lake (such as those that consist of Cattails, Bulrushes, and Swamp Loosestrife), since they act as a filter to catch nutrients and pollutants that occur on land and may run off into a lake.
8) Do not burn leaves near the lake shoreline since the ash is a high source of P. The ash is lightweight and may become airborne and land in the water eventually dissolved and utilized by aquatic vegetation and algae.
9) Ensure that all areas that drain to a lake from the surrounding land are vegetated and that no fertilizers are used in areas with saturated soils.
10) The construction of impervious surfaces (i.e. paved roads and walkways, houses) should be minimized and kept at least 100 feet from the lakefront shoreline to reduce surface runoff potential. In addition, any wetland areas around a lake should be preserved to act as a filter of nutrients from the land and to provide valuable wildlife habitat. Construction practices near the lakeshore should minimize the chances for erosion and sedimentation by keeping land areas adjacent to the water stabilized with rock, vegetation, or wood retaining walls. This is especially critical in areas that contain land slopes greater than 6%.
11) In areas where the shoreline contains metal or concrete seawalls, placement of natural vegetation or tall emergent plants around the shoreline is encouraged. Erosion of soils into the water may lead to increased turbidity and nutrient loading to a lake. Seawalls should consist of riprap (stone, rock), rather than metal, due to the fact that riprap offers a more favorable habitat for lakeshore organisms, which are critical to the ecological balance of the lake ecosystem. Riprap should be installed in front of areas where metal seawalls are currently in use. The riprap should extend into the water to create a presence of microhabitats for enhanced biodiversity of the aquatic organisms within a lake. The emergent aquatic plants, *Schoenoplectus* sp. (Bulrushes) or Cattails present around a lake may offer satisfactory stabilization of shoreline sediments and assist in the minimization of sediment release into a lake. There are also natural shorelines that can be constructed on lakefronts. More information on those can be found at: www.shorelinepartnership.org. Canada geese (*Branta canadensis*) usually do not prefer lakefront lawns with dense riparian vegetation because they are concerned about the potential of hidden predators within the vegetation.

12) The U.S. Environmental Protection Agency (USEPA) offers excellent educational resources and reference materials that riparians can use to care for their septic systems. To learn more about septic systems and how to care for them, visit the website: http://water.epa.gov/infrastructure/septic/. Some lake associations have created "annual septic pump out" days where septic tank contractors visit individual properties and clean out the septic tanks as well as inspect the drain fields for any issues that may negatively affect water quality. Annual pump out days are a great way to interact with riparian neighbors and learn about the many different types and locations of individual septic systems. Additionally, riparians should always maintain an awareness of the aquatic vegetation and algae in their lake so they can report any significant deviations from the normal observations. An awareness of the ambient lake water quality is also useful since degradations in water quality often occur over a long period of time and can be subtle.
13) Furthermore, a professional limnologist/aquatic botanist should perform regular GPS-guided whole-lake surveys each spring and late summer/early fall to monitor the growth and distribution of all invasives and nuisance aquatic vegetation growth prior to and after treatments to determine treatment efficacy if treatments are conducted. Continuous monitoring of the lake for potential influxes of other exotic aquatic plant genera (i.e. *Hydrilla*) that could also significantly disrupt the ecological stability of Crockery Lake is critical. The lake manager should oversee all management activities and would be responsible for the creation of aquatic plant management survey maps, direction of the licensed herbicide applicator to target-specific areas of aquatic vegetation for removal, recommendations for implementation of watershed best management practices, administrative duties such as the review of contractor invoices, and lake management education.

A complete list of recommended lake restoration options for this proposed lake restoration plan can be found in Table 27 below. It is important to coordinate these methods with objectives so that baseline conditions can be compared to post-implementation conditions once the methods have been implemented to justify continued expenses and ensure a favorable cost to benefit ratio.

Successful Strategies Used by Stakeholders for a Sustainable NPS Pollution Management Program

Goldston (2009) discusses the challenges involved with the influence of science on the adoption of environmental policy. Emphasis is placed on the necessity to separate scientific inquiry from questions regarding policy. In Minnesota, the formation of Watershed Management Organizations (WMOs) which interact with Local Government Units (LGUs), has provided the state with a powerful group of resources for surface water management that allows for a transfer of scientific knowledge from the WMOs to the LGUs which have taxation authority. The Minnesota Legislature passed the Metropolitan Area Surface Water Management Act in 1982 which mandates local governments in the seven-county metro area to prepare and implement surface water management plans in coordination with WMOs. In Michigan, the two governing Acts which involve protection of surface waters include Public Act (PA) 188 and allows townships and municipalities to levy taxes for surface water and other environmental improvements, and PA 451 which allows statutorily formed boards to levy taxes for water quality improvements. Both Acts were designed more for solution implementation than for prevention programs that are urgently needed to address the NPS pollution effects on surface waters.

If communication regarding a sustainable program was strictly between riparians and the local municipality, a voice for the necessary lifestyle adjustment would be absent with counterproductive consequences. With this realization, the outside can objectively assess the existing surface water conditions and offer unbiased solutions to be considered by the riparians and the LGUs. Kimmerer (2002) discusses the positive role that Traditional Ecological Knowledge (TEK) can have on issues regarding environmental sustainability. TEK is distinguished from Scientific Ecological Knowledge (SEK) in that social and spiritual attributes of the culture cannot be separated from the knowledge in the former. Riparian communities may be a significant source of TEK since many riparians have resided on particular lakes for decades and have likely experienced interactions with the lake system that may be shielded from the objective views of an expert scientist. Additionally, bias that may be unknowingly present in the sampling methods or by the researcher can be reduced through having multiple investigators work on a common water quality issue (Rutherford and Ahlgren 1991). This would support restoration firms such as RLS working collaboratively with the Association and the Township.

Objective assistance on the issues pertaining to NPS pollution may be provided to municipalities by the private sector, which may assist in the determination of initial goals and implementation of objective solutions (Plummer 2002). In order to ascertain that decisions made by the private sector are effectively targeted, riparians may contribute a wealth of knowledge regarding their collective needs which reduces uncertainty in the eyes of the municipality officials and garners needed support for successful immediate watershed management. A list of goals and objectives can be found in Table 27.

Table 27. List of Crockery Lake proposed restoration methods with primary and secondary goals and locations for implementation.

Proposed Improvement Method	Primary Goal	Secondary Goal	Where to Implement
Systemic herbicide spot-treatments for invasives	Reduce invasives in lake	Reduce long-term use of herbicides in lake	Entire lake where invasives present
Hypolimnetic Oxygenation	Increase DO, reduce blue-green algae, increase water clarity	Reduce nutrients in the water column and sediments	Deepest Basin(s) N=2
Timberchar® Biochar Drain Filters	To reduce incoming nutrient loads	To reduce algal blooms associated with incoming nutrients	All 4 drains
Septic System Maintenance Program	To reduce nutrient loads to the water table and lake	To reduce associated algal blooms	Each property for annual inspections and consideration of SludgeHammer® units (individually funded)
Farm BMP's; use of innovative products to reduce runoff and maximize yields	To reduce nutrient loads into tributaries/drains	To reduce runoff from farms and maximize crop yields	All farms along tributary water courses
Bi-annual water quality monitoring of lake and drains (CSA's)	Monitor efficacy of BMP's implemented, including any oxygenation, drain filters, etc.	Compare baseline water quality and drain data to modern data to view trends for data-driven management	Both the lake and all major drains (CSA's)
Annual lake surveys pre and post-treatment	To determine efficacy of herbicide treatments on invasives	To determine ability of native aquatic vegetation biodiversity to recover post-management implementation	Entire lake
Riparian/Community Education	To raise awareness of lake/drain issues and empower all to participate in lake protection	Long-term sustainability requires ongoing awareness and action	Entire lake community and those who frequent the lake; may also include relevant stakeholders

9.1 Cost Estimates for Crockery Lake Improvements

The proposed lake restoration program for Crockery Lake is recommended to begin as soon as possible. Since hypolimnetic oxygenation and Biochar are likely to be the costliest improvements, it may be conducted over a period of five years or more to reduce annual cost. A breakdown of estimated costs associated with the various proposed treatments in Crockery Lake is presented in Table 28. It should be noted that proposed costs are estimates and may change in response to changes in environmental conditions (i.e. increases in aquatic plant growth or distribution, or changes in herbicide costs). Note that this table is adaptive and is likely to change over time. Thus, this entire restoration plan is an adaptive plan.

Due to the very high cost to effectively restore Crockery Lake, it is recommended that the filters be implemented in the first year, along with development of the septic maintenance program. The PrO2 system should be implemented in the second or third year. Note that the fees proposed by RLS for professional services includes the data needed to be in compliance with the oxygenation system with permitting requirements.

Table 28. Crockery Lake proposed lake restoration program costs. NOTE: Items with asterisks are estimates only and are likely to change based on acquisition of formal quotes from qualified vendors.

Proposed Crockery Lake Improvement Item	Year 1 Costs	Years 2-5 (Annual) Costs[4]
Systemic herbicides [1] for EWM treatment	$11,520	$10,580
PrO2 System[2] (includes annual lease cost and electrical for each year as well as maintenance)	$70,000	$70,000
Drain filters[3] for drains Note: maintenance for future years	$5,000	$3,000
Framework for septic system maintenance program; implementation[4]	$7,000	$1,500
Professional services (limnologist management of lake, oversight, EGLE compliance, implementation of restoration program, education)[5]	$25,000	$25,500
Contingency[6]	$11,852	$11,058
Total Annual Estimated Cost	$130,372	$121,638

[1] Herbicide treatment scope may change annually due to changes in the distribution and/or abundance of aquatic plants.

[2] Oxygenation system is an estimate and will likely change with vendor proposals/costs. This is a rough number based on experiences with similar lakes.

[3]Drain filters include individual, retrofitted biologically activated filters for nutrient and solid reductions. In future years, maintenance of the filters will be required.

[4]Septic system framework cost based on record gathering needed and time allocated for development. Future years, maintenance of records is expected.

[5] Professional services includes comprehensive management of the lake with two annual GPS-guided, aquatic vegetation surveys, pre and post-treatment surveys for aquatic plant control methods, oversight and management of the aquatic plant control program and all management activities, all water quality monitoring and evaluation of all restoration methods, review of all invoices from contractors and others billing for services related to the improvement program, education of local riparians through attendance at up to three regularly scheduled annual board meetings, meetings with farmers on BMP's and collaboration with the local Conservation District or other partners.

[6] Contingency is 10% of the total project cost, to assure that extra funds are available for unexpected expenses. Note: Contingency may be advised and/or needed for future treatment years. Contingency funds may also be used for other water quality improvements and watershed management.

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