Arrowhead and Indianhead Lakes Water Quality Study

Prepared for
Nine Mile Creek Watershed District

August 2022

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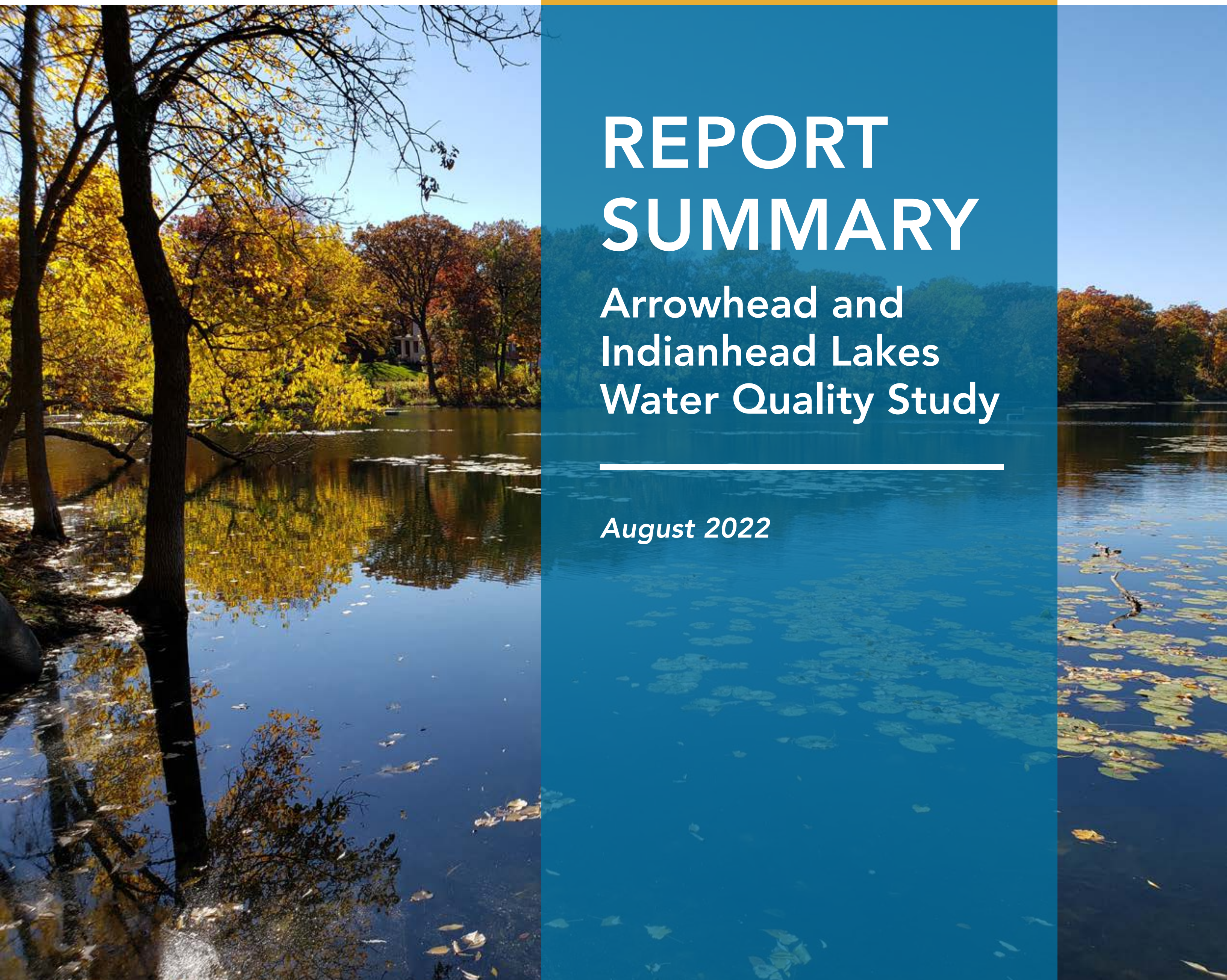

REPORT SUMMARY

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Watershed District

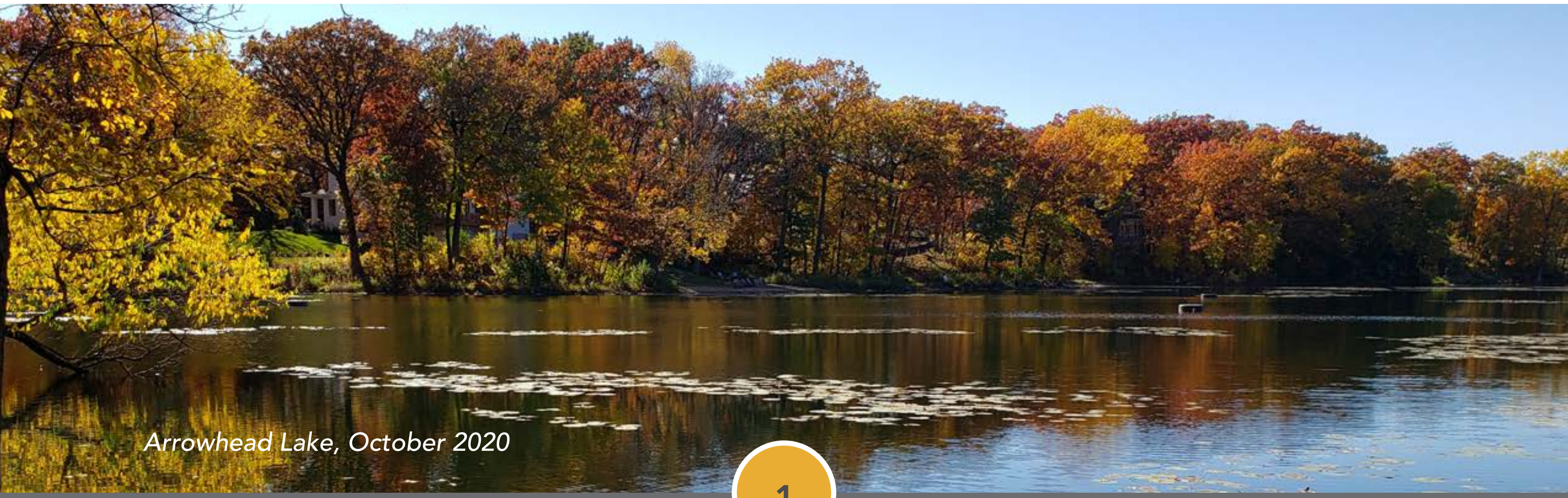
IMPROVING LAKE WATER QUALITY

REPORT SUMMARY CONTENTS

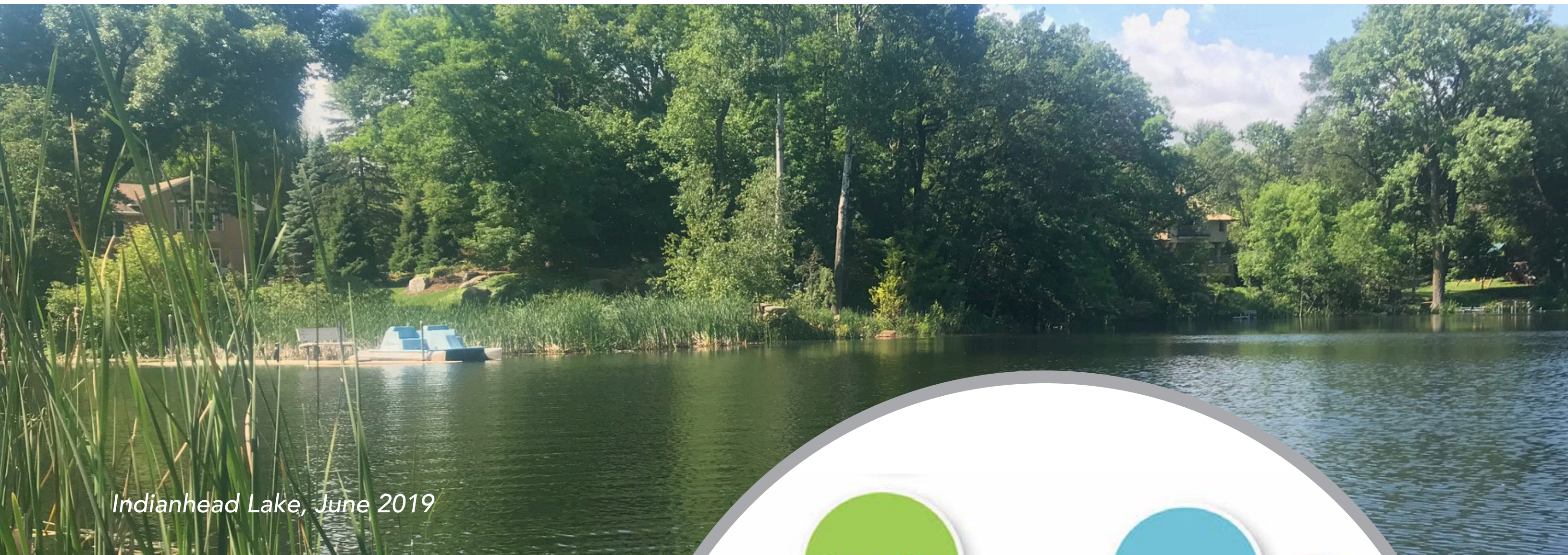
Protecting and Enhancing Water Quality

Arrowhead Lake and Indianhead Lake are shallow lakes located in the southwestern portion of the city of Edina, south of Highway 62 and east of Highway 169. The shallow, urban lakes suffer from moderate to poor water quality. The Nine Mile Creek Watershed District (NMCWD), a local unit of government that works to address water-related problems, conducted a study of Arrowhead and Indianhead lakes in 2021 to evaluate current water quality and identify protection and improvement strategies. Additional information on the current lake conditions, water quality challenges, and recommended management strategies are summarized in this project overview, including proposed implementation timelines.

Protecting and enhancing the water quality of the lakes within the Nine Mile Creek watershed is one of the primary goals of the Nine Mile Creek Watershed District. The NMCWD's lake management program includes data collection (monitoring), assessment (e.g., studies), and implementation of projects and programs to protect and improve water quality and aquatic habitat. Using monitoring data collected by NMCWD in recent years (2019 and 2020), the objectives of this study were to assess or "diagnose" the lakes' water quality problems, understand the cause or sources of the problems, and recommend management strategies to improve the water quality and overall health of the lakes.



Arrowhead Lake, October 2020



Indianhead Lake, June 2019

Lake Management Goals

When assessing the ecological health of a lake, it is important to take a holistic approach, considering factors such as in-lake water quality (e.g., phosphorus and nitrogen concentrations), the health and quality of the aquatic communities, and water quantity (see Figure 1). How recreation and wildlife habitat affect and are affected by overall lake health are also considered. Numerical goals exist for some of these factors, such as state water quality standards. However, other factors are assessed relative to narrative criteria that describe the desired condition and do not have strict numerical goals. For this study, the primary goals are to achieve the water quality standards for shallow lakes; attain a diverse, native macrophyte (aquatic plant) population; and support a healthy, balanced aquatic ecosystem.

Figure 1

For this study, the primary goals are to achieve the water quality standards for shallow lakes, attain a diverse, native macrophyte (aquatic plant) population, and support a healthy, balanced fishery.

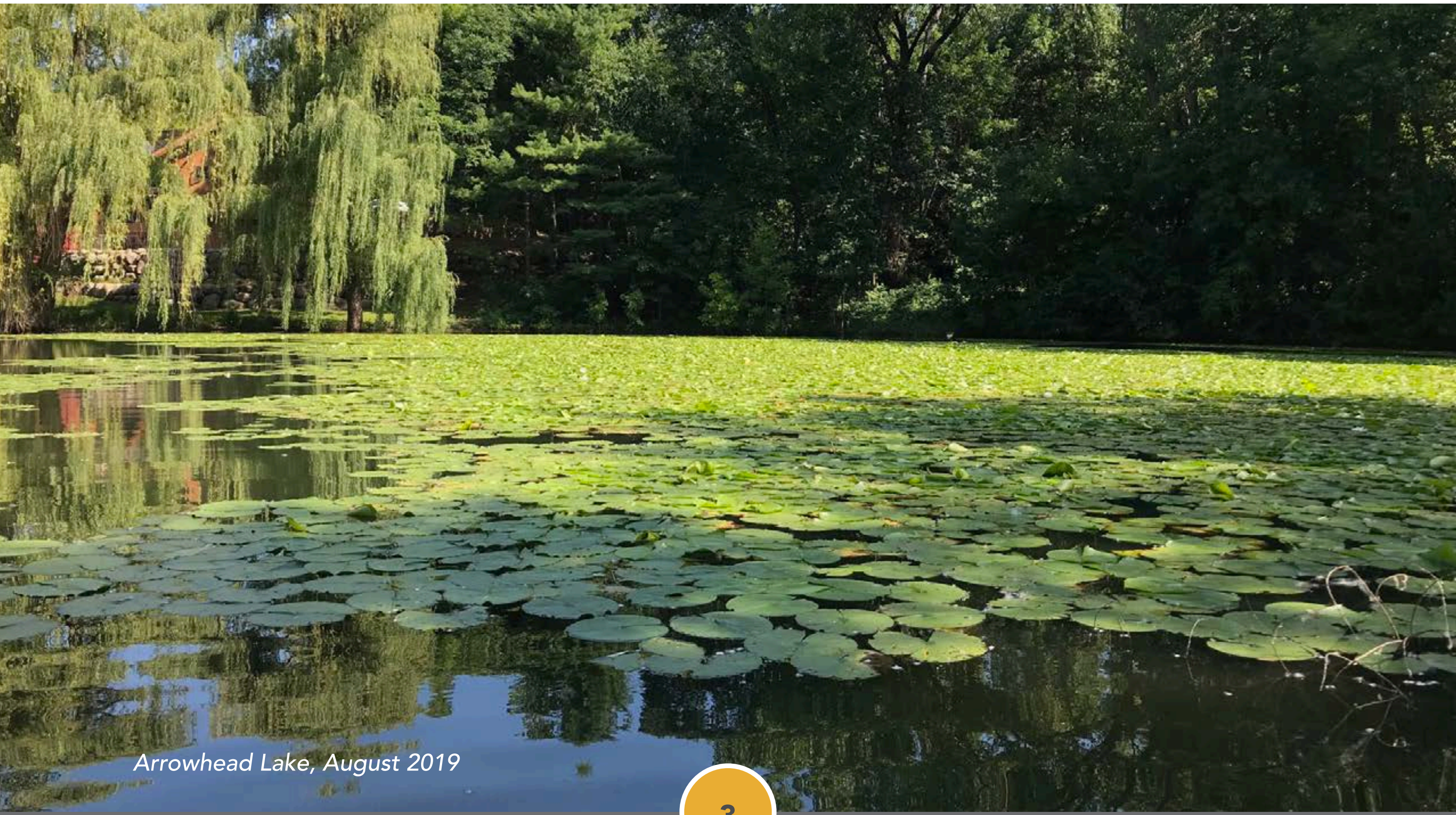
9 MILE CREEK WATERSHED DISTRICT

Looking at Current Lake Conditions

Healthy Shallow Lakes

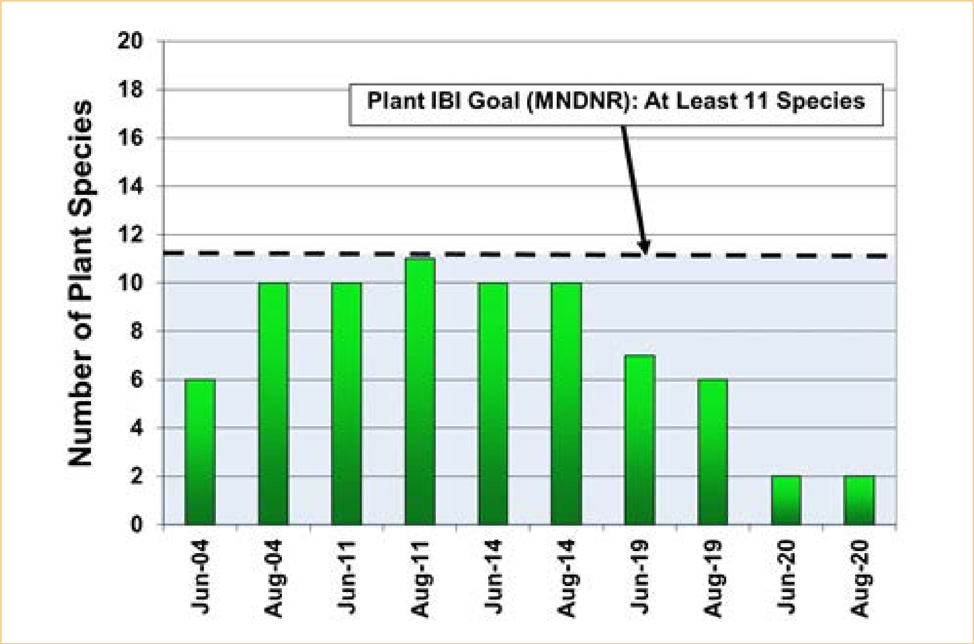
Shallow lakes are unique ecosystems that differ from deeper lakes. Shallow lakes have depths that allow for light to reach the lake bottom throughout most or all of the lake (often less than 10 feet deep). These lakes also tend to be more nutrient-rich than other deeper lakes, especially in an urban setting where they receive nutrients (e.g., phosphorus and nitrogen) from stormwater. A healthy shallow lake will have abundant aquatic plant growth due to the shallowness and nutrients. However, excess nutrients can lead to algal growth that creates turbid (murky-looking, low clarity) water and limits or prevents aquatic plant growth. Aquatic plants are good for shallow lake ecosystems. Healthy shallow lakes have plants growing throughout the entire lake, with a variety of species such as coontail, native pondweed, and water lily. The plants can take phosphorus and nitrogen from the lake water, reducing the amount of nutrients available for algae. Aquatic plants also provide excellent habitat for insects, zooplankton, fish, waterfowl and other wildlife.

One measure of a lake's health is the community of plants, fish and aquatic life it sustains. For aquatic plants, the Minnesota Department of Natural Resources (MNDNR) has developed an index of biological integrity (IBI), which is a score that compares the types and numbers of plants observed in a lake to what is expected for a healthy lake. As shown on page 4, the number of plant species in Arrowhead and Indianhead lakes in recent years are well below the DNR's threshold of at least 11 species for a healthy lake. In 2020, only 2–3 species were found in the lakes.

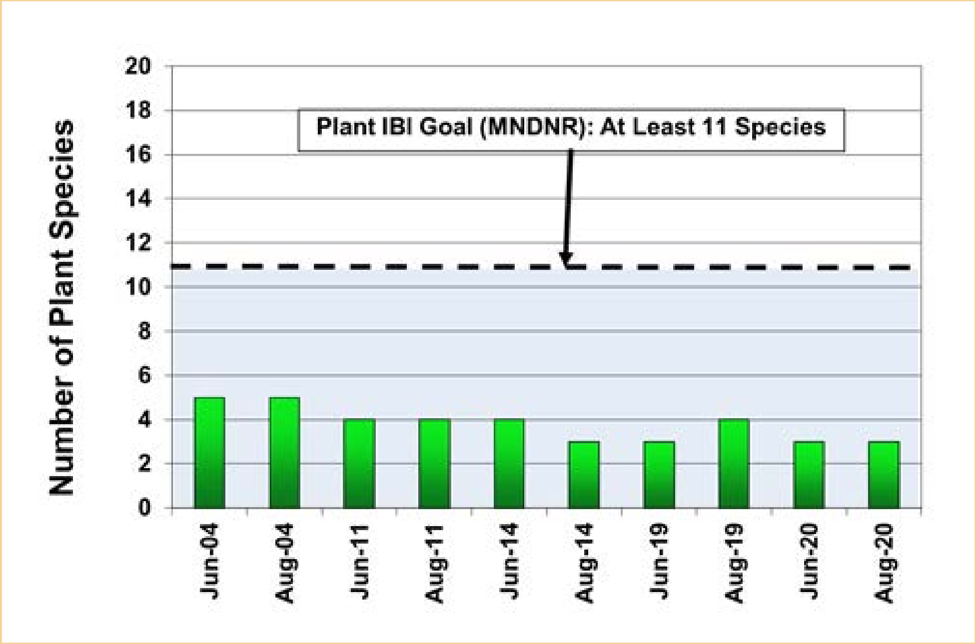


Arrowhead Lake, August 2019

Arrowhead and Indianhead Lakes are below the MNDNR threshold for healthy number of plant species in the lakes, indicating a degraded plant community.



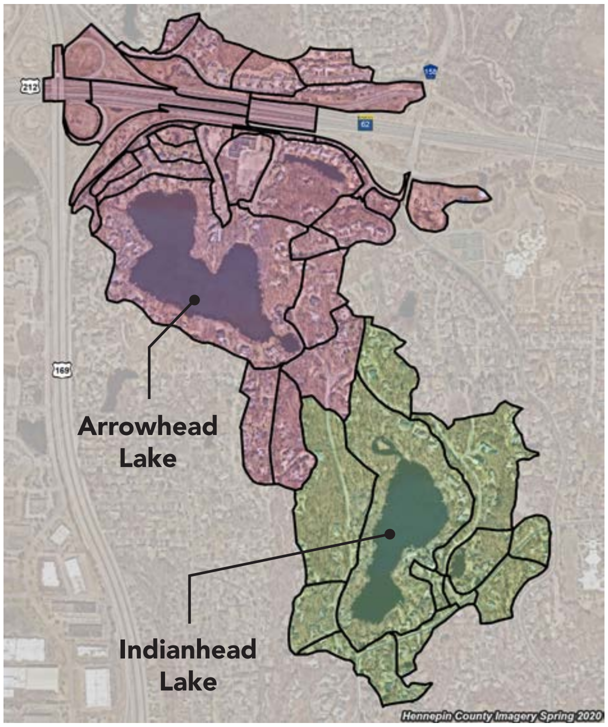
Arrowhead Lake Macrophyte Species Richness Compared with Plant IBI Threshold for Species Richness



Indianhead Lake Macrophyte Species Richness Compared with Plant IBI Threshold for Species Richness

Urban Watersheds

A lake watershed is all the land area that drains to the lake through overland flow, channels, and storm pipes. Land use practices within a lake's watershed impact the lake and its water quality by altering the amount of stormwater runoff, sediment, and nutrients (namely phosphorus and nitrogen) that reaches the lake. Each type of land use contributes a different amount of runoff and pollutants to the lake, thereby impacting the lake's water quality differently. Land use within the highly developed Arrowhead and Indianhead watersheds is primarily single family residential, highway, open water, and public open space, with smaller areas of multi-family residential and churches. Arrowhead and Indianhead lakes can be particularly sensitive to land use impacts on stormwater quantity and quality because both are land-locked with no surface outlets.



Map showing watersheds for Arrowhead Lake (shaded purple) and Indianhead Lake (shaded green).

Arrowhead Lake, June 2019

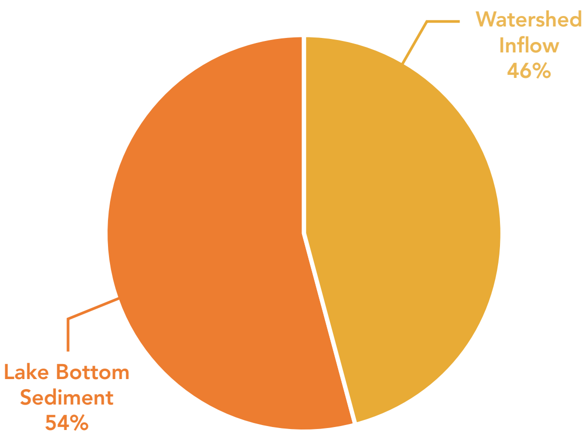
Sources of Nutrients

Nutrients (phosphorus and nitrogen) are a food source for algae. An overabundance of these nutrients in a lake can result in nuisance algal blooms and threaten the health of the aquatic plant community. In Minnesota, phosphorus is most commonly the "limiting nutrient," although nitrogen can also be limiting for portions of the growing season. Whether phosphorus or nitrogen is the "limiting nutrient" this means the available quantity of this nutrient tends to control the amount of algae and aquatic plants produced. The two primary sources are summarized below:

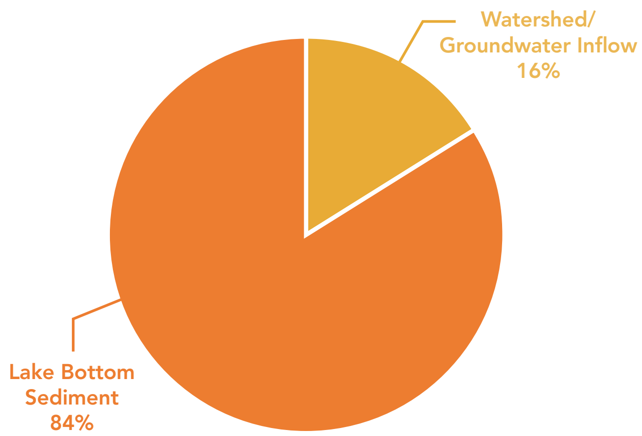
- **Phosphorus and nitrogen in stormwater runoff from the direct watershed—** Stormwater runoff conveys phosphorus and nitrogen from streets, lawns, and parking lots within the direct watersheds to Arrowhead and Indianhead lakes via a series of drainage channels and storm drain pipes. This study confirmed that stormwater runoff is a major contributor of phosphorus and nitrogen to Arrowhead and Indianhead lakes.

- **Nutrient-rich sediment—**Phosphorus builds up over time in lake bottom sediments as a result of sedimentation and die-off of vegetation and algae. In general, two forms of sediment phosphorus can release back into the water column when certain environmental conditions are met. When oxygen levels are low at the lake bottom (typically periodically throughout the summer), the form of phosphorus called "mobile-P" is released from the sediment into the water column. "Organic-P" can also release from bottom sediments, where the release rate is controlled by lake water temperature. This study confirmed that phosphorus release from lake bottom sediments, typically termed "internal loading," is a major contributor of phosphorus to Arrowhead and Indianhead Lakes.

Arrowhead Lake 2020
Total Phosphorus Sources



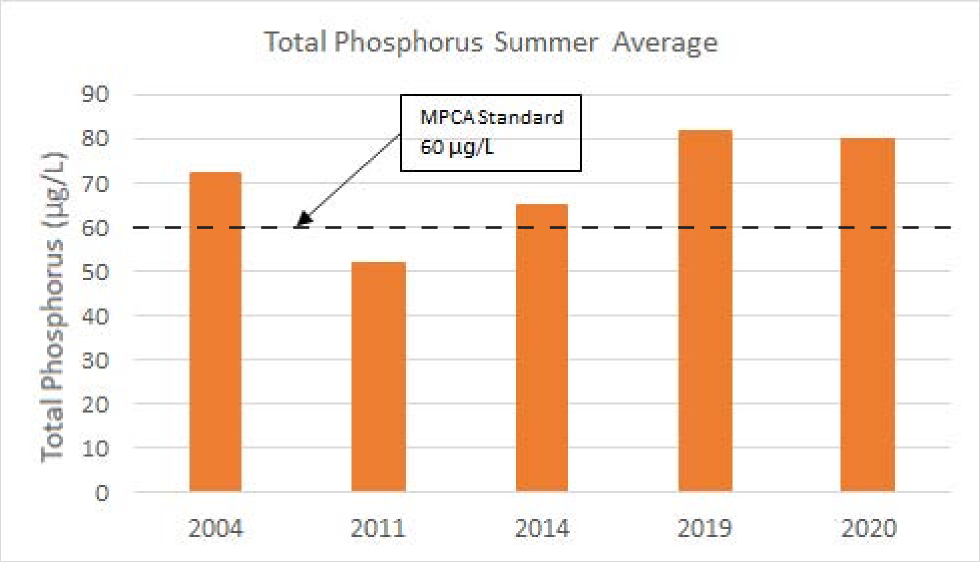
Indianhead Lake 2020
Total Phosphorus Sources



Arrowhead Lake, September 2020

Arrowhead Lake Water Quality Challenges

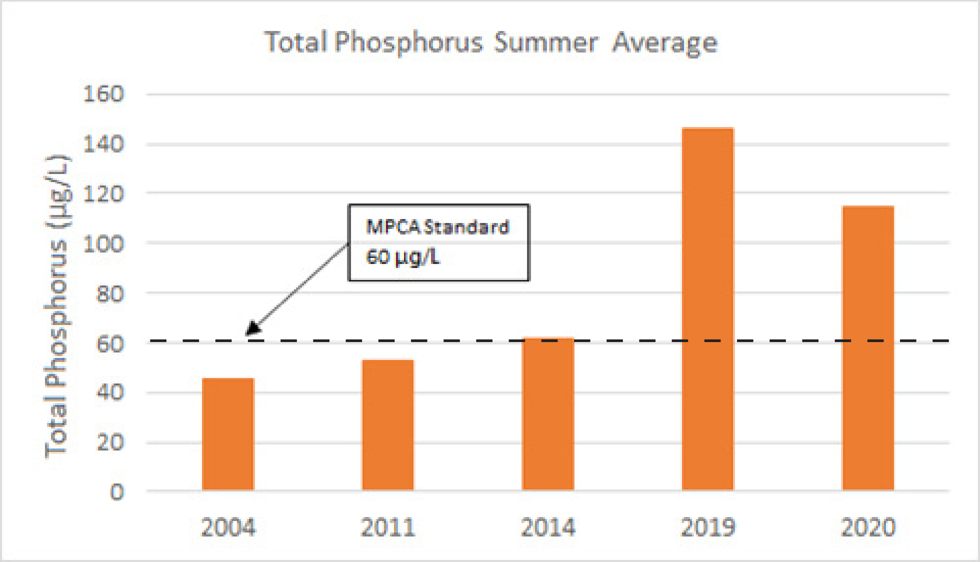
Review of historic data indicates that water quality in Arrowhead Lake is poor, with summer average total phosphorus and chlorophyll-*a* concentrations generally above the state standard for shallow lakes. The poor water quality is primarily due to excess nutrients in the lake, which fuels algal growth and decreases water clarity. The phosphorus in Arrowhead Lake comes from several sources, including stormwater runoff from the watershed and internal sources such as nutrient-rich sediments. Additionally, the decrease in the number of plant species as well as the quantity of plants in the lake since 2014 is likely contributing to the decrease in water quality.



Summer average total phosphorus concentrations measured in Arrowhead Lake between 2004 and 2020

Indianhead Lake Water Quality Challenges

Review of historic data indicates that water quality in Indianhead Lake has been declining since 2004, with summer average total phosphorus above the state standards for shallow lakes in 2019 and 2020 and chlorophyll-*a* concentrations generally above the state standard for shallow lakes since 2011. The degradation in water quality is primarily due to excess nutrients in the lake, which fuels algal growth and decreases water clarity. The phosphorus in Indianhead Lake comes from several sources, including stormwater runoff from the watershed and internal sources such as nutrient-rich sediments. Additionally, vegetation management reducing the number of plant species as well as the quantity of plants in the lake is likely contributing to the decrease in water quality.



Summer average total phosphorus concentrations measured in Indianhead Lake between 2004 and 2020

Too Much Salt

Observed chloride concentrations in Arrowhead Lake in April 2019 were moderately high (185 mg/L). The MPCA chloride standard is 230 mg/L. While chloride occurs naturally in lakes and streams, too much chloride can be harmful to fish and other aquatic life. The primary source of chlorides in our lakes and streams is road salt, which is commonly used in the winter to minimize the amount of ice on our roadways, parking lots, and sidewalks. With Arrowhead Lake receiving stormwater runoff from several highways, local roadways, private parking lots, and an area of developed residential properties, the lake is especially vulnerable to chloride pollution. NMCWD works to provide training and other resources to reduce the harmful impacts of chloride on our local waterbodies. For more information about chloride, visit: www.pca.state.mn.us/water/chloride-salts


Indianhead Lake, August 2019

Managing to Protect and Improve Our Lakes

Water quality in Arrowhead and Indianhead Lakes has declined in the past decade. The lakes currently do not meet water quality and ecological health goals and given this, future management efforts should focus on improving lake water quality and ecosystem health, monitoring for changes, and continuing water quality and ecosystem health protection measures as improvements are obtained. The recommended management and protection strategies for Arrowhead and Indianhead Lakes are summarized on the next page.

Planning-level opinions of probable cost were developed for several new management alternatives evaluated as part of this study. These opinions of cost are intended to provide assistance in evaluating and comparing alternatives and should not be considered as absolute values. All estimated costs are presented in 2021 dollars and include costs for engineering and project administration.

- Arrowhead Lake Bottom Sediment Treatment: $125,000
- Indianhead Lake Bottom Sediment Treatment: $120,000
- Arrowhead and Indianhead Lakes Street Sweeping Program: $250,000
- Arrowhead and Indianhead Lakes Fertilization Optimization Program: $20,000

Management/Protection Action		Basis	Estimated Timeline
Address Internal Bottom Sediment Loading	Continuous dissolved oxygen monitoring	Determine aeration capacity of existing system	2022 - 2024
	Alum and iron treatment	Reduce bottom sediment phosphorus load	2023/2024
	Modify aeration system, as needed		2024
	Sediment release monitoring	Assess management effectiveness	2024 - 2025+
Address External Nutrient Loading	Enhanced street sweeping program	Reduce pollutant loading from stormwater	2022 - 2023 (Planning begins)
	Fertilizer management program	Reduce nitrogen sources from excess fertilizer use	2022 - 2023 (Planning begins)
	Chloride monitoring	Continue to identify/track chloride levels from winter salt use	As part of continued lake monitoring program
	Promote NMCWD cost-share grants to watershed residents	In a fully developed watershed, opportunities for largescale BMPs are limited	2022+
Aquatic Invasive Species	Curly-leaf pondweed management	Continue to monitor and treat curly-leaf pondweed growth	2022+
Promote Sustainable Management	Discontinue copper sulfate treatments	Evaluate timeline to discontinue copper sulfate treatments after internal loading management	2025
	Promote native aquatic plant growth	Encourage native plants to promote clear water conditions and competition with algae	2022
	Discontinue blue dye applications	Unnecessary addition of chemicals	2022

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Acronyms

Acronym	Description
AIS	Aquatic Invasive Species
AACE	Association for the Advancement of Cost Engineering
BMP	Best Management Practice
FQI	Floristic Quality Index
IBI	Index of Biological Integrity
MCES	Metropolitan Council of Environmental Services
MNDNR	Minnesota Department of Natural Resources
MPCA	Minnesota Pollution Control Agency
NGVD29	National Geodetic Vertical Datum of 1929
NMCWD	Nine Mile Creek Watershed District
NOAA	National Oceanic and Atmospheric Administration
N-P-K	Nitrogen-Phosphorus-Potassium
P8	Program for Predicting Polluting Particle Passage through Pits, Puddles and Ponds
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphorus
WHO	World Health Organization
UAA	Use Attainability Analysis

1.0 Introduction

This report describes the results of the water quality study for Arrowhead and Indianhead Lakes in Edina, Minnesota. The study represents a scientific assessment of the physical, chemical, and biological conditions of these lakes, and includes both a water quality assessment and a prescription of protective and/or remedial measures for Arrowhead and Indianhead Lakes and the lakes' tributary watersheds. The work presented in this report provides an update of analyses that were previously completed for a water quality study developed by Nine Mile Creek Watershed District (NMCWD) for Arrowhead and Indianhead Lakes in 2006 (Barr Engineering Co., 2006).

The conclusions and recommendations presented in this report are based on historical water quality data, a fisheries survey conducted in 2021, several years of aquatic plant surveys, and the results of intensive lake water quality monitoring in 2020. Lake water quality and ecological models were developed and calibrated to the 2020 dataset to gain a better understanding of the relative and absolute effect of various nutrient (e.g., nitrogen and phosphorus) sources on lake water quality.

1.1 Water Quality Study Approach

The Nine Mile Creek Watershed District (NMCWD) has historically used a process referred to as a Use Attainability Analysis (UAA) to assess the water quality condition of its lakes relative to the desired beneficial uses that can be reasonably achieved and maintained with implementation of management recommendations. The objective of a UAA is to provide a scientific foundation for a lake-specific management plan that will permit maintenance of, or attainment of, the intended beneficial uses of a waterbody. The UAA process addresses a wide range of goals (e.g., water quantity, aquatic communities, recreational use, and wildlife), with the primary focus being achievement of water quality goals.

As part of the *Nine Mile Creek Watershed District Water Management Plan* (Plan) adopted in 2017 and amended in 2018 and 2019 (NMCWD, 2017, amended 2019), the NMCWD adopted the Minnesota eutrophication standards. In addition, the NMCWD expanded its emphasis on the role of ecological indicators (aquatic plants, phytoplankton, fish, etc.) in overall lake health, as well as the feedback mechanisms between these indicators. A properly functioning ecosystem supports the attainment of good water quality.

While the UAA terminology is not included in the title of this water quality study, a similar analysis process was employed, utilizing observed data, watershed modeling and in-lake modeling to understand and diagnose lake health issues and evaluate protective or remedial management activities. The water quality study utilized a watershed runoff model and an in-lake water quality and ecological model to quantify pollutants from various sources and to quantify the benefits of management efforts. The in-lake water quality model predicts changes in lake water quality based on the results of the watershed runoff model (external inputs) as well as internal processes such as sediment phosphorus release due to anoxia, submerged vegetation death and decay, phytoplankton growth and decay, and nutrient settling to lake sediments. Using these models, various watershed and lake management strategies can be evaluated to determine their likely effects on lake water quality. The resulting lake water quality can then be compared with the water quality goals to see if the management strategies are able to produce the desired changes in the lake. Using the modeling tools, the cost-effectiveness of the management strategies can also be evaluated.

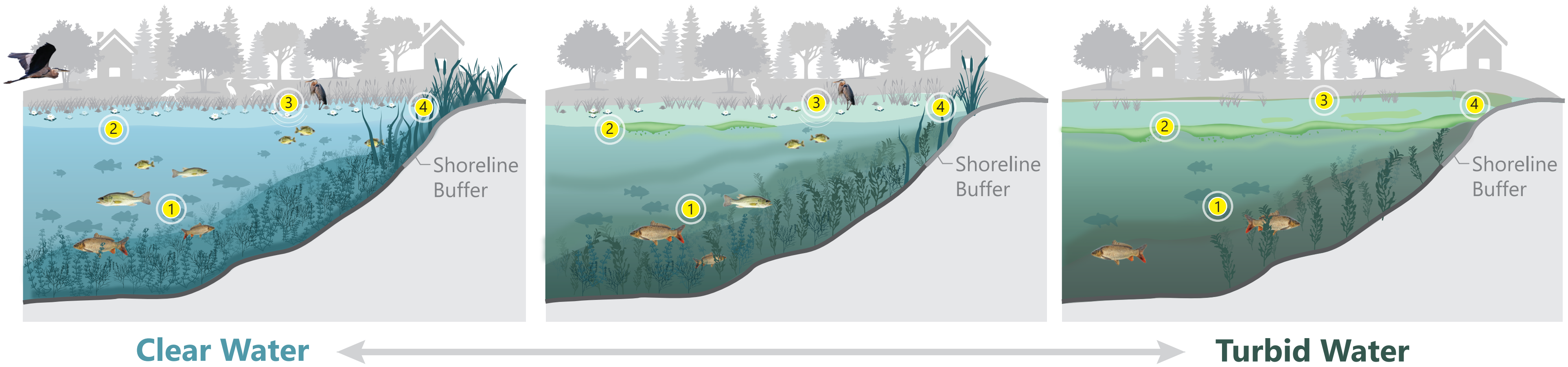
2.0 Shallow Lake Characteristics and Water Quality

Shallow lakes are unique ecosystems that differ from deeper lakes. Shallow lakes are lakes that generally have well mixed water columns throughout most of the year and have depths that potentially allow for light penetration to reach most of the lake bottom. Shallow lakes can support macrophyte growth across the entire lake surface when lake clarity is reasonably high. Shallow lakes classically exist in two states: (1) clear water with extensive coverage of submerged and emergent macrophytes and low phytoplankton (algae) abundance; and (2) turbid water where phytoplankton dominate and macrophyte coverage is limited due to phytoplankton shading. The concentration of nutrients entering the shallow water system (from stormwater or from lake bottom sediments), fishery balance and composition, the presence or absence of invasive species (such as curly-leaf pondweed, carp, and goldfish), and dissolved oxygen concentrations are primary drivers that determine the state of shallow lakes (Figure 2-1).

There are a number of concepts and terminology that are necessary to describe and evaluate a lake's water quality. This section is a brief discussion of those concepts.

2.1 Eutrophication

Eutrophication, or lake degradation, is the accumulation of sediments and nutrients in lakes. As a lake naturally becomes more fertile, biological production enhances and sediment inflow accumulates filling the lake's basin. Over a period of hundreds to thousands of years, a lake can successively become a pond, a marsh and, ultimately, a terrestrial site. This process of eutrophication is natural and results from the normal environmental forces that influence a lake. Cultural eutrophication, however, is an acceleration of the natural processes and is caused by human activities. Nutrient and sediment inputs from stormwater runoff can far exceed the natural inputs to a lake. Nutrient enrichment in lakes often intensifies algal blooms. Enhanced sediment loadings can attenuate light and reduce lake transparency, which can limit macrophyte growth. Since macrophytes assist in creating a stable water state (e.g., improved clarity, reduced sediment resuspension, improved habitat for aquatic organisms), especially in shallow lakes, high suspended sediment and enhanced nutrients can often lead to impaired water quality.



Clear Water

1. Good fishery balance
2. Algae blooms rare
3. Diverse prey options and healthy habitat for birds
4. Numerous and diverse native plants in the lake and within shoreline buffers; low invasive species present

Intermediate

1. Less balanced fishery, more rough fish (e.g., carp)
2. Algae blooms moderate
3. Less prey options and habitat for birds
4. Less diverse native plants in the lake and within shoreline buffers; invasive species present

Turbid Water

1. Fishery not balanced, mostly rough fish, winter fish kills
2. Algae blooms dominant, blue-green algae possible
3. Limited prey options and habitat for birds
4. Low diversity and quantity of native plants in the lake and within shoreline buffers; invasive species present

Figure 2-1 Depiction of shallow lake states

2.2 Nutrients

Biological production in an aquatic ecosystem is limited by the concentrations of essential nutrients. The "limiting nutrient" concept is a widely applied principle in ecology and in the study of eutrophication. It is based on the idea that phytoplankton and plants require many nutrients to grow, but the nutrient with the lowest availability, relative to the amount needed by the phytoplankton or plant, will limit growth. It follows then, that identifying the limiting nutrient will point the way to controlling aquatic plant and algal growth. Nitrogen (N) and phosphorus (P) are generally the two growth-limiting macronutrients in most natural waters. Thus, efforts to improve water quality typically focus on reducing the growth-limiting nutrient concentration in the waterbody; however, it is often difficult to identify and control all the nutrient loadings to a specific waterbody.

Two primary sources, external and internal loads, are responsible for elevated nutrient concentrations in lakes. Nutrients that enter lakes through watershed runoff, groundwater inputs, or atmospheric deposition are considered external loads. As urbanization has occurred, more areas of impermeable surfaces have been developed causing increased stormwater runoff and pollutant transport during storm and spring thaw events. In urbanized areas, stormwater runoff typically flows through storm sewer systems to the downstream waterbody, which generally results in faster velocities than natural channel flow and can result in higher suspended loadings. Implementation of the NMCWD's stormwater management rules for new development and redevelopment and efforts to install retrofit best management practices (BMPs) are helping to reduce external loads to nearby waterbodies. However, for many shallow lakes, internal load reduction measures (e.g., alum treatment, aquatic plant management, fish management) are also required to meet water quality goals.

Once external nutrient loads enter a lake, over time, the nutrients accumulate in the sediment through the settling of particulates and through organism decay. Natural lake processes such as sediment resuspension, chemical dissolution, or microbial reduction can reintroduce these nutrients to the overlying water body resulting in internal loading. This is specifically common for phosphorus, which can be found bound to the sediment under oxidized conditions. The binding of phosphorus to iron in sediments allows the sediment to act as a sink or source depending on the lake's physical and chemical conditions. Therefore, understanding the chemical and physical conditions and the timing of these conditions will be important considerations when developing an internal loading management plan.

2.2.1 Stratification Impacts on Internal Phosphorus Loading

Lake stratification, the separating of an upper, well mixed warm layer (epilimnion) from a cool, bottom layer (hypolimnion) (Figure 2-2), can lead to low oxygen concentrations in lake bottom waters and trigger internal phosphorus loading. For shallow lakes like Arrowhead and Indianhead Lakes, stratification is typically irregular and can happen on a daily, weekly, or longer timescale. Mixing likely occurs regularly in Arrowhead and Indianhead Lakes and phosphorus released from sediments is then made available to phytoplankton during these frequent mixing events.

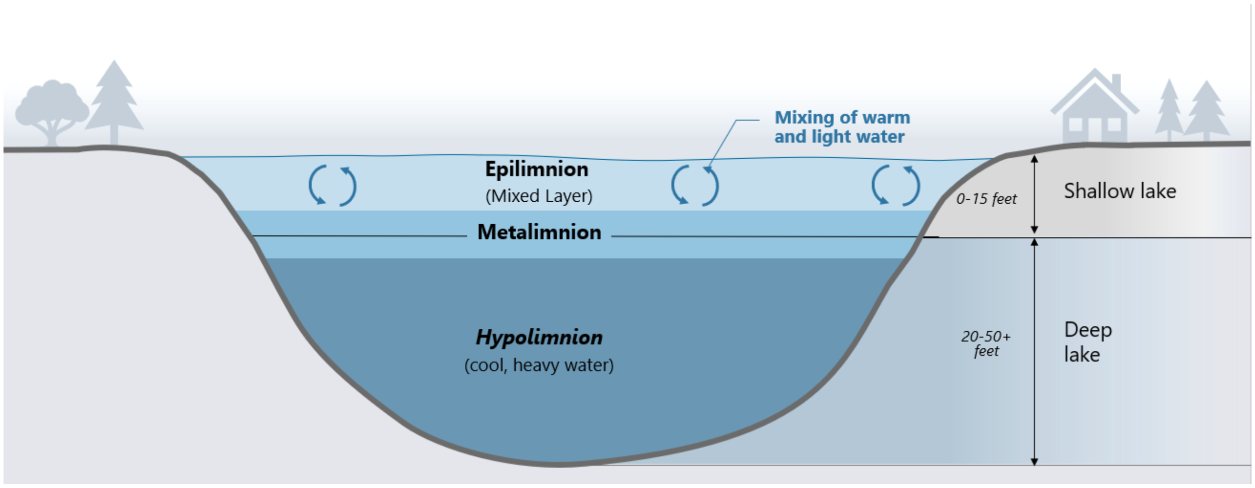


Figure 2-2 Generalized thermal lake stratification diagram

2.2.2 pH Impacts on Internal Phosphorus Loading

The pH of the water column can also play a vital role in affecting the phosphorus release rate under conditions when oxygen is present in the water column (oxic conditions). Photosynthesis by macrophytes (aquatic plants) and algae during the day tend to raise the pH in the water column, which can enhance the phosphorus release rate from the oxic sediment. Enhancement of phosphorus release at elevated pH (pH > 8.2) is thought to occur through replacement of the phosphate ion (PO_4^{-3}) with the excess hydroxyl ion (OH^-) on the oxidized iron compound (James, Barko, & Eakin, 2001). Large increases in pH are often the consequence of phytoplankton blooms (e.g., cyanobacteria harmful algal blooms).

2.2.3 Organism Impacts on Internal Phosphorus Loading

Benthivorous, rough fish, such as carp and bullhead, can have a direct influence on the phosphorus concentration in a lake (LaMarra, 1975). These fish typically feed on decaying plant and animal matter and other organic particulates found at the sediment surface. The fish digest the organic matter, and excrete soluble nutrients, thereby transforming sediment phosphorus into soluble phosphorus available for uptake by algae at the lake surface. Benthivorous (bottom-feeding) fish can also cause resuspension of sediments in shallow ponds and lakes, transporting phosphorus from sediment into the water column, causing reduced water clarity and poor aquatic plant growth, as well as high phosphorus concentrations (Cooke, Welch, Peterson, & Newroth, 1993). In some cases, the water quality impairment caused by benthivorous fish can negate the positive effects of BMPs and lake restoration.

The critical difference between biological (e.g., benthivorous fish feeding) and physical (e.g., wind and waves) sediment resuspension is the area and the frequency to which these components can induce impacts. The volume of sediment impacted by physical resuspension is largely influenced by the geometry of the lake (e.g., size, fetch, bathymetry) and wind events (e.g., direction, velocity). For example, a wind event may develop wave induced sediment resuspension along a portion of the shoreline. However, biological resuspension from feeding or mating activities of fish can occur over a much larger area and is impacted by the number of organisms in the aquatic ecosystem. Additionally, while physical resuspension occurs in a periodic, episodic-based fashion, benthivorous fish resuspension can be more continuous.

2.2.4 Curly-leaf Pondweed Impacts on Internal Phosphorus Loading

Another potential source of internal phosphorus loading is the growth and die-off of curly-leaf pondweed. Curly-leaf pondweed is an invasive (i.e., non-native) aquatic plant that is common in many Twin Cities metropolitan area lakes. Curly-leaf pondweed grows under the ice during the winter and gets an early start in the spring, crowding out native species. It releases a small reproductive pod that resembles a small pinecone in late-June, and then begins its die-back in late-June and early-July. The biomass sinks to the bottom of the lake and begins to decay, releasing nutrients into the water column and causing oxygen depletion, exacerbating the internal sediment release of phosphorus. This cycle can result in an increase in nutrient concentrations in the lake in late-June or early-July in lakes with a higher percentage of invasive growth.

2.2.5 Nitrogen Inputs and Limitations

Nitrogen is a nutrient required for phytoplankton growth and hence nitrogen management also needs to be considered as an important component of lake management. Increases in nitrogen concentrations in lakes can be attributed to a combination of factors in the watershed, including increased fertilizer application rates and frequency, increased impervious surface areas, expansion of storm sewer systems, and loss of riparian wetlands. Land use changes and increased nitrogen loading can result in a decreased natural capacity for nitrogen uptake and assimilation by plants and decreased cycling back to the atmosphere as nitrogen gas (N_2) through natural nitrification and denitrification processes. Thus, this can result in high nitrogen concentrations in open water systems.

For the last couple of decades, phosphorus reduction has generally been the primary focus for lake management in Minnesota based on the premise that phosphorus limitation is dominant in freshwater lakes (e.g., reducing phosphorus inputs alone will limit primary productivity and algal bloom growth). While phosphorus management has been successful or partially successful in a number of lake management projects, recent research is showing that nitrogen limitation or dual nitrogen-phosphorus limitation may be more significant than initially anticipated (Paerl et. al, 2016). This is particularly true for shallow lakes. The nutrient that limits phytoplankton/algal growth can vary geographically, but limitation can also vary seasonally in a single lake. Some lakes have been shown to display phosphorus limitation in the spring but switch to nitrogen limitation in the summer and fall. Furthermore, an additional benefit of managing nitrogen in upstream ecosystems is that this reduces some of the burden in vulnerable ecosystems further downstream that are nitrogen limited (e.g., Gulf of Mexico). Given that recent research is showing higher evidence of dual nitrogen-phosphorus limitation in freshwater lakes, there is a benefit for determining whether source control programs that target both phosphorus and nitrogen will provide greater ecosystem benefits.

2.3 Climate Change Considerations

Considerable studies have been devoted to predicting the impacts of a warming climate on the hydrologic cycle. Of particular concern are the changes to atmospheric moisture content, evaporation, precipitation intensity, and the possibility of increased risk for drought and flooding extremes (Trenberth, 1999; Trenberth, Smith, Qian, Dai, & Fasullo, 2003; Giorgi, et al., 2011; Trenberth, 2011).

Alterations to the hydrologic cycle will consequently impact freshwater ecosystems. Observational records and climate model projections show evidence of freshwater vulnerability to a warming climate (Dokulil & Teubner, Eutrophication and climate change: Present situation and future scenarios, 2011). Freshwater characteristics such as lake stratification and mixing, ice coverage, and river flow could see discernable changes by the end of the 21st century (Dokulil & Teubner, 2011; Dokulil, 2013). Increases in nutrient loadings and water temperatures, changes to water levels, and amplified eutrophication could impact aquatic organisms and influence biodiversity.

2.3.1 Projected Changes to the Hydrologic Cycle

Larger concentrations of greenhouse gases in the atmosphere, such as carbon dioxide and methane, create an increased downwelling of longwave radiation to the earth's surface (Trenberth, 1999). This enhanced downwelling not only escalates surface temperature warming, but also induces changes to the atmospheric moisture content and evaporation. Higher atmospheric temperatures allow for an expanded water holding-capacity of the atmosphere and enhanced radiation causes elevated rates of evaporation. This results in increases to the atmospheric moisture content, which, consequently, will impact precipitation (Trenberth, 1999; Trenberth, Smith, Qian, Dai, & Fasullo, 2003; Kharin, Zwiers, Zhang, & Wehner, 2013).

While changes to precipitation amounts and intensity are expected on a global scale, the changes will be geographically disproportionate. According to the National Oceanic and Atmospheric Administration's (NOAA's) 2013 assessment of climate trends for the Midwest (NOAA, 2013), upward trends in annual and summer precipitation amounts have been observed. The frequency of higher intensity storms has also been noted. Specifically in Minnesota, climatologists have identified four significant climate trends (MNDNR, 2017):

- Increasing annual precipitation
- Increasing frequency and size of extreme rainfall events
- Increasing temperatures, with winter temperatures warming the fastest
- Decline in severity and frequency of extreme cold weather

Overall, the changes to precipitation induced by atmospheric warming pose difficult challenges. The shift to more frequent, high intensity precipitation events in Minnesota indicates a risk for extreme flood events. Higher intensity precipitation events typically produce more runoff than lower intensity events with similar amounts of precipitation because higher intensity rainfall can overwhelm the capacity of the land surface to infiltrate and attenuate runoff.

Not only do these hydrologic changes pose challenges for agriculture, infrastructure, and human safety; but also has the potential to induce changes to aquatic environments. The subsequent section describes the anticipated impacts to aquatic ecosystems if atmospheric warming trends continue.

2.3.2 Projected Changes to Waterbodies (Physical and Chemical)

In freshwater lakes, one of the most important atmospheric variables influencing the lake's physical and chemical parameters is temperature. Due to enhanced air temperatures and the projected increasing trends, lake water temperature and the number of ice-free days are projected to change in most inland waters globally. Increases in lake temperature will affect mixing regimes, the length and depth of summer stratification in deep lakes, and the oxygen concentration in the hypolimnion (Dokulil, 2013; Dokulil, 2014; Dokulil, 2016), as well as phytoplankton growth rates, and phosphorus cycling (e.g., release of phosphorus from bottom sediments). As water temperature rises, lake stability enhances, which results in longer thermal stratification and shorter mixing periods (Dokulil, 2013). Resistance to mixing, particularly in deep lakes, between the nutrient rich hypolimnion and nutrient poor epilimnion across the thermocline increases considerably at temperature gradients of only a few degrees Fahrenheit (Sahoo, et al., 2016).

Prolonged lake stability and a lower thermocline may enhance the risk of oxygen depletion in the hypolimnion (Jeppesen, et al., 2009; Sahoo, et al., 2016). Anoxic conditions in the hypolimnion can cause nutrient release from the sediments, which raises the potential for algal blooms. Additionally, overall oxygen concentrations in the lake can be reduced as solubility decreases when the water temperature warms, which can impact fishery balance (Dokulil & Teubner, 2011).

In mid-latitudes where precipitation is likely to increase, with the heighted chance for extreme events, other concerns are warranted. Intense rainfalls resulting in flooding could raise the loading of suspended sediments associated with larger areas experiencing soil erosion (Dokulil & Teubner, 2011; Dokulil, 2016). The combination of longer dry periods and extreme precipitation events could create episodic and intense pulse flows affecting aquatic habitats, bank stability, and species (Dokulil, 2016). Additionally, the increase in the number of extreme, high intensity rain events is likely to increase the runoff driven phosphorus transfers from the land to the water (Jeppesen, et al., 2009).

2.3.3 Projected Changes to Waterbodies (Biological)

The potential for increased erosion and nutrient inputs from large runoff rates combined with higher water temperatures and prolonged lake stratification in summer could lead to widespread, climate-related eutrophication based on the results of existing studies (Dokulil & Teubner, 2011; Dokulil, 2013). Nutrient enrichment, whether through external or internal loading, stimulates the development of phytoplankton biomass. This resulting surface biomass absorbs light, can shade out benthic algae or macrophytes, and can produce negative lake aesthetics (Dokulil & Teubner, 2011). Unfortunately, not only has previous research projected larger biomasses of phytoplankton in a warmer climate, but research also predicts that a higher proportion of these phytoplankton biomasses will consist of potentially toxic cyanobacteria assemblages (Jeppesen, et al., 2009; Dokulil & Teubner, 2011; Jeppesen, et al., 2014; Dokulil, 2016). Multiple regression analyses on data from 250 Danish lakes sampled during the month of August indicated higher dominance of cyanobacteria with a warming climate. Studies during heat waves in the northern hemisphere also showed that higher percentages of cyanobacteria correlated with rises in temperature (Huisman, Matthijs, & Visser, 2005).

Changes in the seasonal pattern and dynamics of freshwater productivity could also be a consequence of a changing climate. With the earlier onset of warmer air temperatures in the spring, the timing of the phytoplankton peak is likely to shift forward. If the phytoplankton blooms contain a larger percentage of cyanobacteria species or if the timing of algal production falls out of synchrony with the food demands of zooplankton and fish, then upper levels of the food chain could be negatively impacted (Dokulil, 2016). Enhanced phytoplankton biomasses can also induce thermal feedback mechanisms for lakes. A large area of phytoplankton biomass can result in greater surface temperatures and stronger stratification (Dokulil, 2013). Additionally, increased light attenuation at the surface will reduce light availability at the lake bottom influencing macrophyte growth (Jeppesen, et al., 2014).

This water quality study did not directly assess potential impacts to lake responses due to a changing climate. However, any current and/or future management efforts for waterbodies will be affected by changing climate conditions. Continued monitoring of lake conditions will be important as management efforts are implemented and as changing climate conditions progress. Long-term studies of waterbodies will be essential to create the most effective plans to overcome climate-induced impacts.

3.0 Identification of Goals and Expectations

3.1 NMCWD Goals for Lake Management

The NMCWD's approach to evaluating and improving lake health includes numerous health assessment factors, as illustrated in Figure 3-1. The primary factors identified as affecting lake ecological health include chemical water quality (e.g., nutrient concentrations), aquatic communities, and water quantity (groundwater and surface water). The effects of recreation and wildlife habitat on overall lake health are also considered.

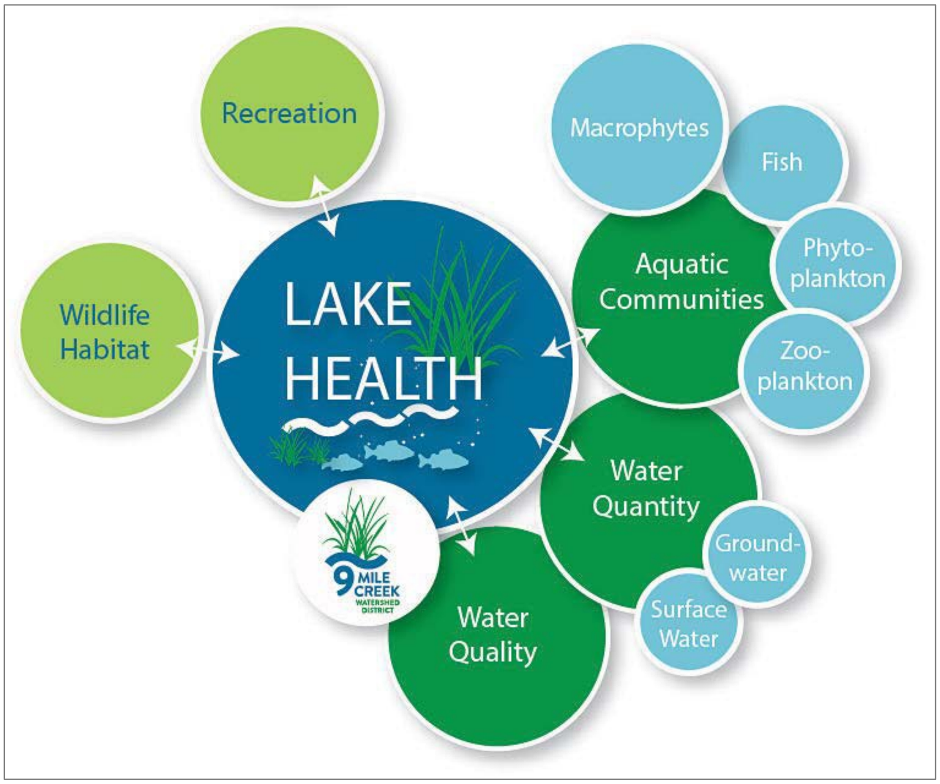


Figure 3-1 NMCWD Holistic Lake Health Assessment Factors (NMCWD, 2017, amended 2019)

3.1.1 Water Quality Goals

One of the primary goals of the NMCWD is to "ensure the water quality of the lakes and streams of the NMCWD is protected and enhanced." In 1996, the NMCWD established lake water quality management goals based on designated uses for a waterbody (i.e., full-contact recreational activities such as swimming; non-full body contact recreational activities such as boating, canoeing, or water skiing; fishing and aesthetic viewing; runoff management). In 2008, the Minnesota Pollution Control Agency (MPCA) adopted eutrophication water quality standards for Minnesota lakes, which vary by ecoregion and include criteria for both shallow and deep lakes. The MPCA defines "shallow" lakes as having a maximum depth of 15 feet or less or having at least 80% of the lake area shallow enough to support aquatic plants (referred to as "littoral area").

In their 2017 Plan, the NMCWD adopted the state's lake eutrophication standards as their lake water quality goals, as well as the state water quality standards for Escherichia coli and chloride. The water quality goals for shallow lakes (including Arrowhead and Indianhead Lake) are presented in Table 3-1.

Table 3-1 NMCWD water quality goals for shallow lakes

Water Quality Parameter	Water Quality Standard for Shallow Lakes[1, 2]
Total Phosphorus (summer average, µg/L)	60
Chlorophyll-*a* (summer average, µg/L)	20
Secchi Disk Transparency (summer average, m)	1.0
Total Suspended Solids (mg/L)	NA
Daily Dissolved Oxygen Flux (mg/L)	NA
Biological Oxygen Demand (5 day) (mg/L)	NA
Escherichia coli (# per 100 mL)	126 [3]
Chloride (mg/L)	230[4]

[1] NMCWD goals are based on MPCA standards included in MN Rules 7050. Revisions to MN Rules 7050 will supersede NMCWD standards. Note that MN Rule 7050.0220 includes standards for additional parameters that are enforced by the MPCA.
[2] Shallow lakes have a maximum depth less than 15 feet or littoral area greater than 80% of the total lake surface area.
[3] 126 organisms per 100 mL as a geometric mean of not less than five samples within any month, nor shall more than 10% of all samples within a month exceed 1,260 organisms per 100 mL.
[4] The MPCA has established a chronic exposure chloride standard of 230 mg/L or less and considers two or more exceedances of the chronic standard in three years to be an impairment.

3.1.2 Other Lake Health Goals

In addition to the water quality goals presented in Table 3-1, the NMCWD's 2017 Plan expresses the desire to establish holistic lake health targets for NMCWD-managed lakes. The holistic lake health targets consider a wide range of factors, with an increased emphasis on the role of ecological factors in overall lake health and the interrelated nature of these factors.

Table 3-2 lists the evaluation factors used by the NMCWD to holistically assess lake health. Numerical goals exist for some of the factors presented in this table (e.g., MPCA water quality standards), while other holistic health factors are assessed qualitatively by comparing to narrative criteria. The NMCWD collaborates with stakeholders and regulatory agencies (e.g., MPCA, Minnesota Department of Natural Resources (MNDNR)) to develop lake-specific numerical goals for ecological indicators where appropriate.

Table 3-2 NMCWD holistic lake health assessment evaluation factors

Lake Health Assessment Factors	Evaluation Factors
Chemical Water Quality	• Nutrients • Sediment • Clarity • Chlorophyll-*a* • Chloride
Aquatic Communities	• Aquatic Plant IBI[1]- species richness and floristic quality • Invasive Species Presence • Phytoplankton Populations • Cyanobacteria/Blue-green Algae Presence • Zooplankton Populations
Water Quantity	• Water Levels • Water Level Bounce • Groundwater Levels
Recreation	• Shore Access • Navigation Potential • Aesthetics • Use Metrics
Wildlife	• Upland biodiversity • Buffer extent/width

[1] Lake plant eutrophication Index of Biotic Integrity (IBI) methodology developed by the MNDNR and MPCA

3.2 NMCWD Adaptive Management Approach

The NMCWD implements an adaptive management approach to improve lake health based on water quality and assessment of the other holistic lake health factors. While striving to achieve the state standards for shallow lakes, the NMCWD recognizes that achieving the water quality goals may not be feasible for some lakes or may require a timeframe that extends several decades. For these situations, the NMCWD's objective is to make reasonable and measurable progress towards meeting the water quality goals and other holistic lake health targets.

The NMCWD reviews lake monitoring data annually to assess progress toward lake management goals. For lakes that are meeting the goals, the NMCWD continues periodic monitoring to track variations in water quality and potential trends. If water quality declines or if water quality does not meet NMCWD goals, a lake-specific water quality study is conducted (or updated) to identify additional protection and improvement measures, as is being completed in this report for Arrowhead and Indianhead Lakes.

4.0 Lake Basin and Watershed Characteristics

The following sections describe the unique characteristics of the Arrowhead and Indianhead Lakes and watersheds. Both lakes are located in the southwestern portion of the City of Edina, south of Highway 62 and east of Highway 169.

4.1 Arrowhead Lake Basin Characteristics

Arrowhead Lake has a water surface area of approximately 22 acres, a maximum depth of approximately 8 feet, and a mean depth of 3.2 feet at a 10-year average water surface elevation of 874.8 (NGVD29). At this elevation the lake volume is approximately 83 acre-feet (Figure 4-1). Arrowhead Lake is land-locked with no surface outlets. Thus, the water level in the lake depends on weather conditions (snowmelt, rainfall, evaporation) and groundwater flow. The stage-storage relationship that was used in this study for Arrowhead Lake is shown in Table 4-1 and was based on bathymetric measurements completed by the City of Edina in 2017 and LiDAR collected in 2011 by the MNDNR. The approximate natural overflow elevation from Arrowhead Lake is 882.5 feet.

Since Arrowhead Lake is shallow, the lake may be prone to frequent wind-driven mixing of the lake's shallow waters during the summer. Additionally, lake mixing may be influenced by the existing aeration system as well as nighttime cooling. Therefore, one would expect Arrowhead Lake to be *polymictic* (mixing many times per year) as opposed to lakes with deep, steep-sided basins that are usually *dimictic* (mixing only twice per year). Daily monitoring of the lake would be necessary to precisely characterize the mixing dynamics of a lake, but the current data gathered from Arrowhead Lake strongly suggests that the lake is polymictic.

Table 4-1 Stage-storage-discharge relationships for Arrowhead Lake

Elevation	Area (acres)	Cumulative Storage (ac-ft)	Comment
867.0	0.08	0.0	Wet Detention Storage Volume
868.0	0.55	0.3	
869.0	1.40	1.3	
870.0	3.68	3.8	
871.0	9.58	10.5	
872.0	16.65	23.6	
873.0	21.58	42.7	
874.8	22.33	82.6	Average 10-year WSE
875.8	22.99	105.3	Available Live Storage to Natural Overflow
876.8	23.74	128.7	
877.8	24.55	152.8	
878.8	25.35	177.8	
879.8	26.09	203.5	
880.8	26.78	229.9	
881.8	27.50	257.0	
882.5	27.96	276.0	

City of Edina Bathymetry (2017)

Elevation, NGVD29

867
868
869
870
871
872
873
874
875

0 250
Feet

ARROWHEAD LAKE BATHYMETRY

FIGURE 4-1

4.2 Arrowhead Lake Watershed Characteristics

Arrowhead Lake's direct watershed is approximately 178 acres, including the surface area of the lake (22 acres). The watershed area compared to the lake surface area is relatively small (approximately 8:1 acres). Runoff from the watershed enters Arrowhead Lake through overland flow and from several storm sewer outfalls at various points along the lakeshore. Subwatersheds and locations of the major stormwater conveyance features are shown on Figure 4-2.

4.2.1 Land Use

Land use practices within a lake's watershed impact the lake and its water quality by altering the volume of stormwater runoff, sediment load, and nutrient load (namely phosphorus and nitrogen) that reach the lake from the lake's watershed. Each land use contributes a different amount of runoff and nutrients to the lake, thereby impacting the lake's water quality differently. As land use changes over time, changes can be expected in downstream water bodies as a result.

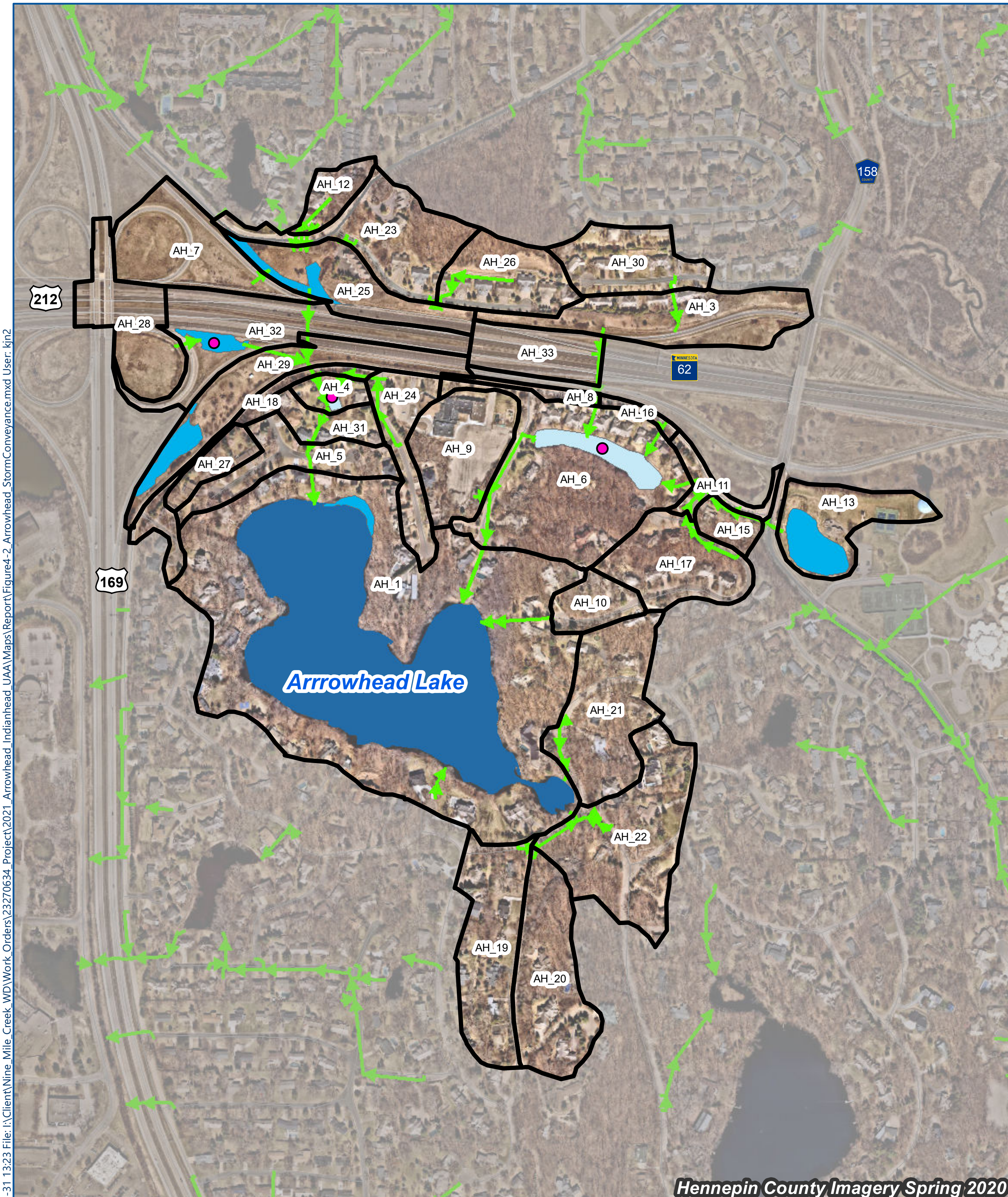
Historically, the Arrowhead Lake watershed was primarily comprised of basswood, sugar maple, and oak forests. There were also numerous wetlands located throughout the watershed. The terrain varies from relatively flat to rolling.

Based on the 2016 Met Council Land Use Dataset, the watershed of Arrowhead Lake is near fully developed (Metropolitan Council, 2016). Table 4-2 provides a summary of the land use classifications within the watershed. The major land use classification in the Arrowhead Lake watershed is single family detached residential. The watershed also includes major highway, and to a lesser extent open water, single family attached residential, undeveloped/open space, parks and recreational, and institutional land uses. Figure 4-3 shows a map of the land use classifications within the Arrowhead Lake watershed.

Table 4-2 Land use classifications in the Arrowhead Lake watershed

Land Use Classification	Percent of Watershed
Single Family Detached[1]	45%
Major Highway	21%
Open Water	12%
Single Family Attached[1]	11%
Undeveloped/Open Space	4%
Park and Recreational	3%
Institutional	3%
Multi-Family	0.1%
Total Watershed Area (ac)	178

[1] Single family residential homes sharing no exterior walls with another home or building are considered "detached." Attached housing shares walls on one or more sides with other homes.



P8 Model Treatment Devices
Subwatersheds
Storm Sewer

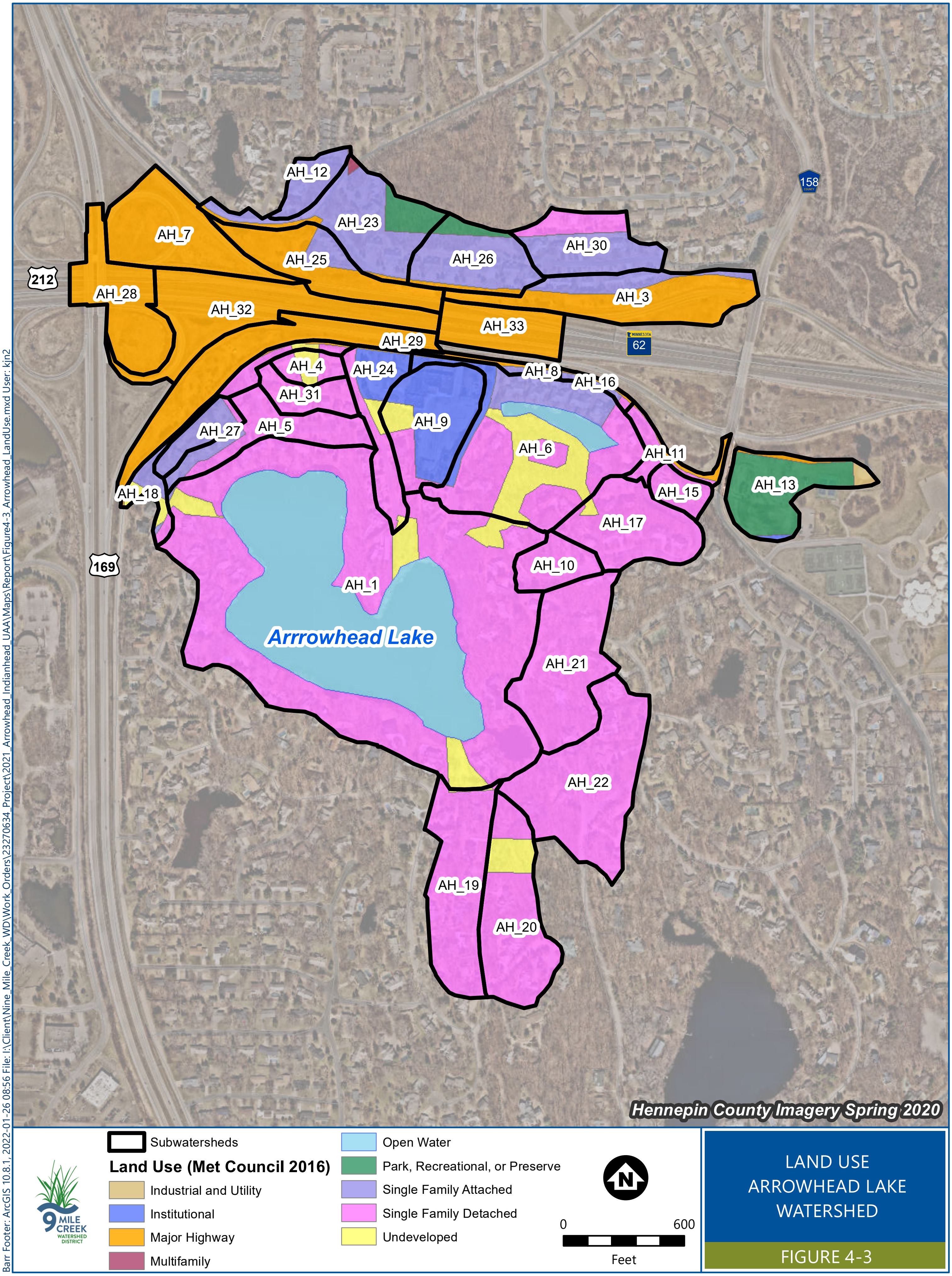
National Wetland Inventory (NWI) Wetlands

Freshwater Emergent Wetland
Freshwater Pond
Lake

0 600
Feet

ARROWHEAD LAKE SUBWATERSHEDS & STORMWATER CONVEYANCE

FIGURE 4-2



LAND USE
ARROWHEAD LAKE
WATERSHED

FIGURE 4-3

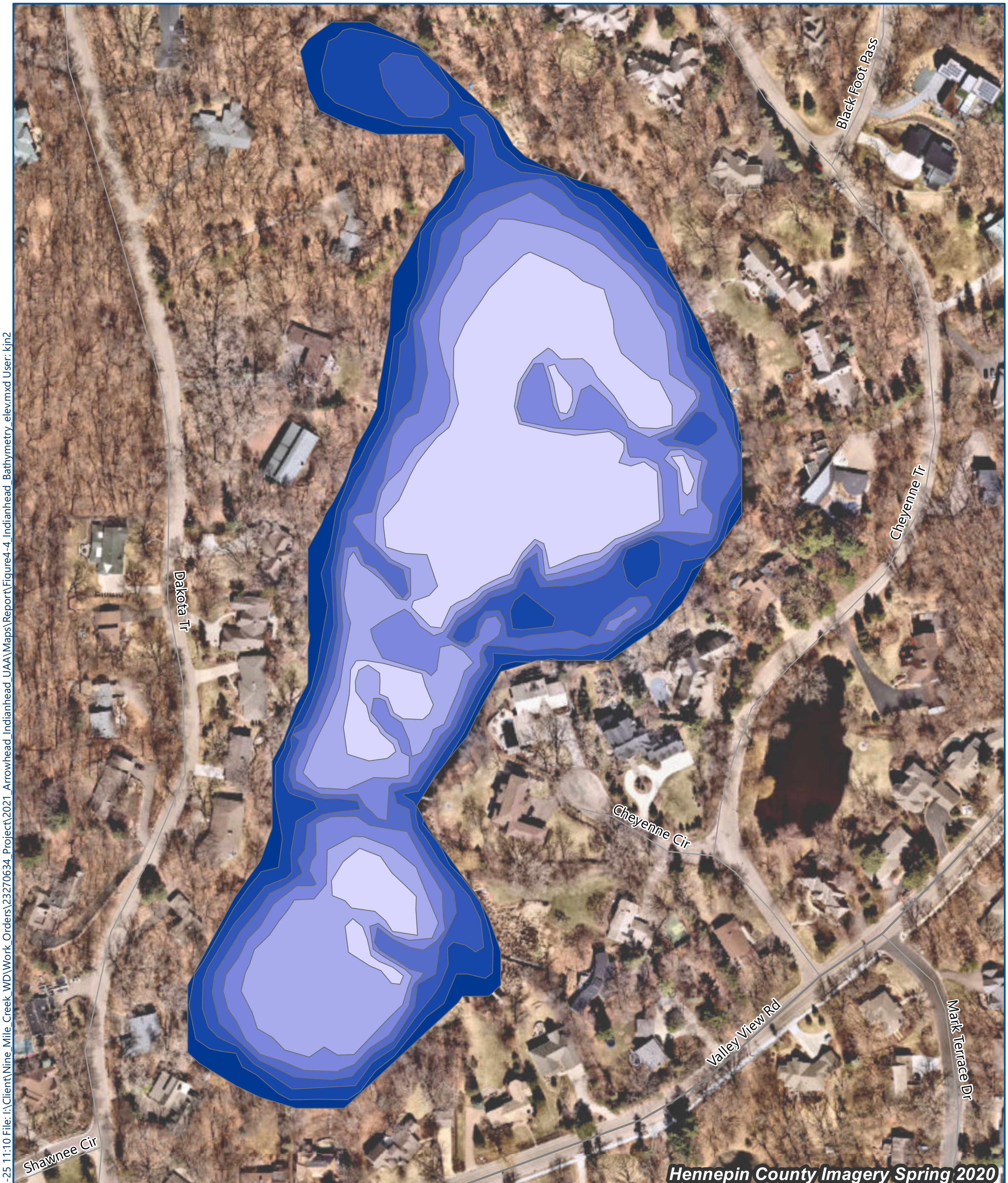
4.3 Indianhead Lake Basin Characteristics

Indianhead Lake has a water surface area of approximately 14.3 acres, a maximum depth of approximately 5.1 feet, and a mean depth of 3.1 feet at a 10-year average water surface elevation of 863.1 (NGVD29). At this elevation the lake volume is approximately 49.4 acre-feet (Figure 4-4). Indianhead Lake is land-locked with no surface outlets. Thus, the water level in the lake depends on weather conditions (snowmelt, rainfall, evaporation) and groundwater flow. The stage-storage relationship that was used in this study for Indianhead Lake is shown in Table 4-3 and was based on bathymetric measurements completed by the City of Edina in 2017 and MNDNR LiDAR collected in 2011. The approximate natural overflow elevation is 881.4 feet.

Since Indianhead Lake is shallow, the lake may be prone to frequent wind-driven mixing of the lake's shallow waters during the summer. Additionally, lake mixing may be influenced by the existing aeration system as well as nighttime cooling. Therefore, one would expect Indianhead Lake to be *polymictic* (mixing many times per year) as opposed to lakes with deep, steep-sided basins that are usually *dimictic* (mixing only twice per year). Daily monitoring of the lake would be necessary to precisely characterize the mixing dynamics of a lake, but the current data gathered from Indianhead Lake strongly suggests that the lake is polymictic.

Table 4-3 Stage-storage-discharge relationships for Indianhead Lake

Elevation	Area (acres)	Cumulative Storage (ac-ft)	Comment
858	3.59	0	Wet Detention Storage Volume
859	6.74	5.2	
860	9.08	13.1	
861	10.50	22.9	
862	12.47	34.3	
863	14.16	47.7	
863.1	14.29	49.4	Average 10-year WSE
864	15.21	62.4	Available Live Storage to Natural Overflow
866.8	17.15	108.1	
868.8	18.42	143.6	
870.8	19.56	181.6	
872.8	20.74	221.9	
874.8	22.11	264.7	
876.8	23.73	310.6	
878.8	25.22	359.5	
881.4	26.90	426.8	



City of Edina Bathymetry (2017)

Elevation, NGVD29

858
859
860
861
862
863
864

0 200 Feet

INDIANHEAD LAKE BATHYMETRY

FIGURE 4-4

4.4 Indianhead Lake Watershed Characteristics

Indianhead Lake's direct watershed is approximately 107 acres, including the surface area of the lake (14.3 acres). The watershed area compared to the lake surface area is relatively small (approximately 8:1 acres). Runoff from the watershed enters Indianhead Lake through overland flow and from several storm sewer outfalls at various points along the lakeshore. Subwatersheds and locations of the major stormwater conveyance features are shown on Figure 4-5.

4.4.1 Land Use

Land use within a lake's watershed impact the lake and its water quality by altering the volume of stormwater runoff, sediment load, and nutrient load (namely phosphorus and nitrogen) that reaches the lake from the lake's watershed. Each land use contributes a different amount of runoff and nutrients to the lake, thereby impacting the lake's water quality differently. As land use changes over time, changes can be expected in downstream water bodies as a result.

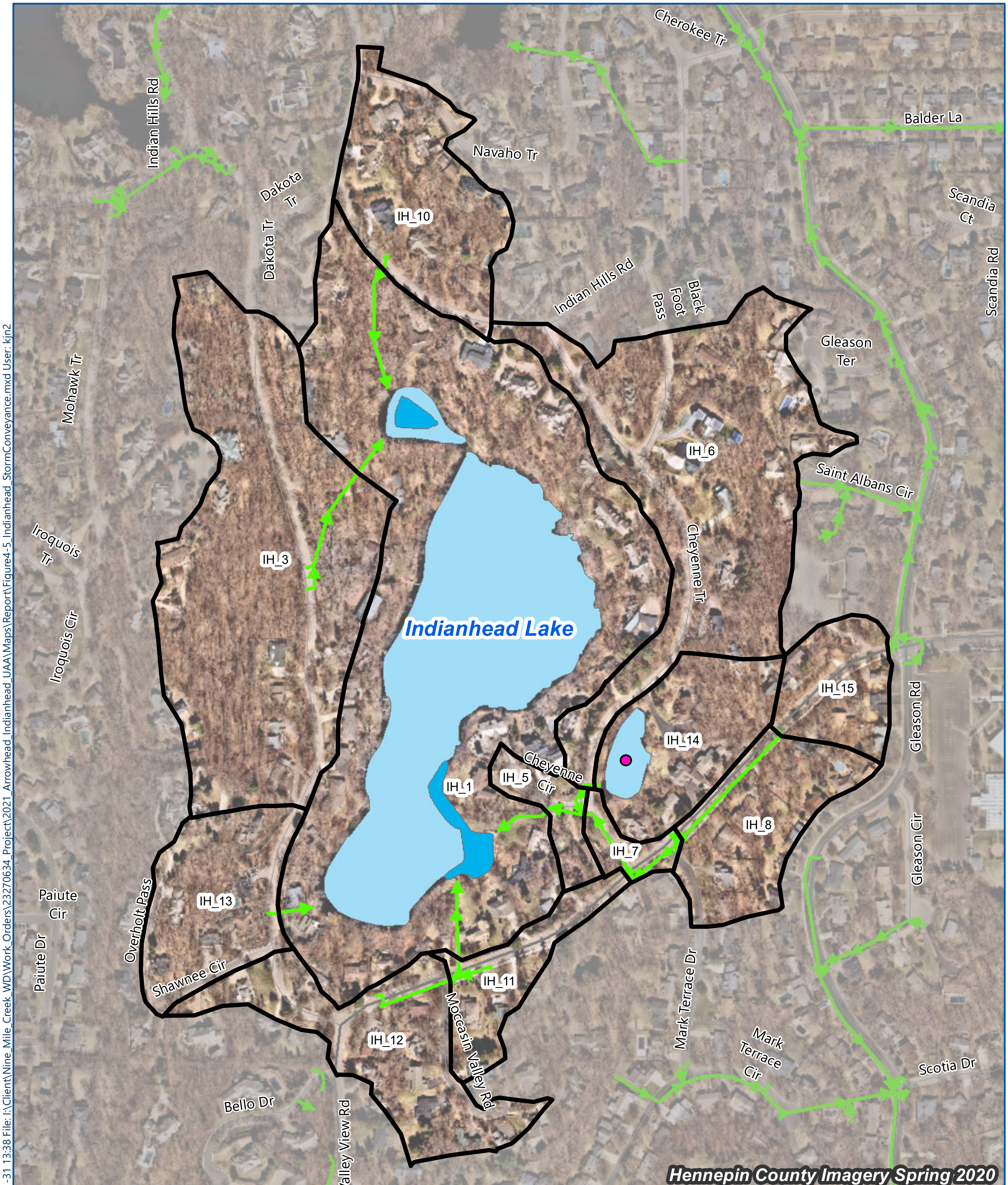
Similar to Arrowhead Lake, historically, the Indianhead Lake watershed was primarily comprised of basswood, sugar maple, and oak forests. There were also numerous wetlands located throughout the watershed. The terrain varies from relatively flat to rolling.

Based on the 2016 Metropolitan Council of Environmental Services (MCES) Land Use Dataset, the watershed of Indianhead Lake is near fully-developed (Metropolitan Council, 2016). Table 4-4 provides a summary of the land use classifications within the watershed. The major land use classification in the Indianhead Lake watershed is single family detached residential. To a lesser extent, the land use also includes open water, undeveloped/open space, and institutional. Figure 4-6 shows a map of the land use classifications within the Indianhead Lake watershed.

Table 4-4 Land use classifications in the Indianhead Lake watershed

Land Use Classification	Percent of Watershed
Single Family Detached[1]	82%
Open Water	13%
Undeveloped/Open Space	6%
Institutional	1%
Total Watershed Area (ac)	107

[1] Single family residential homes sharing no exterior walls with another home or building are considered "detached." Attached housing shares walls on one or more sides with other homes.



- P8 Model Treatment Devices
- Subwatersheds
- Storm Sewer

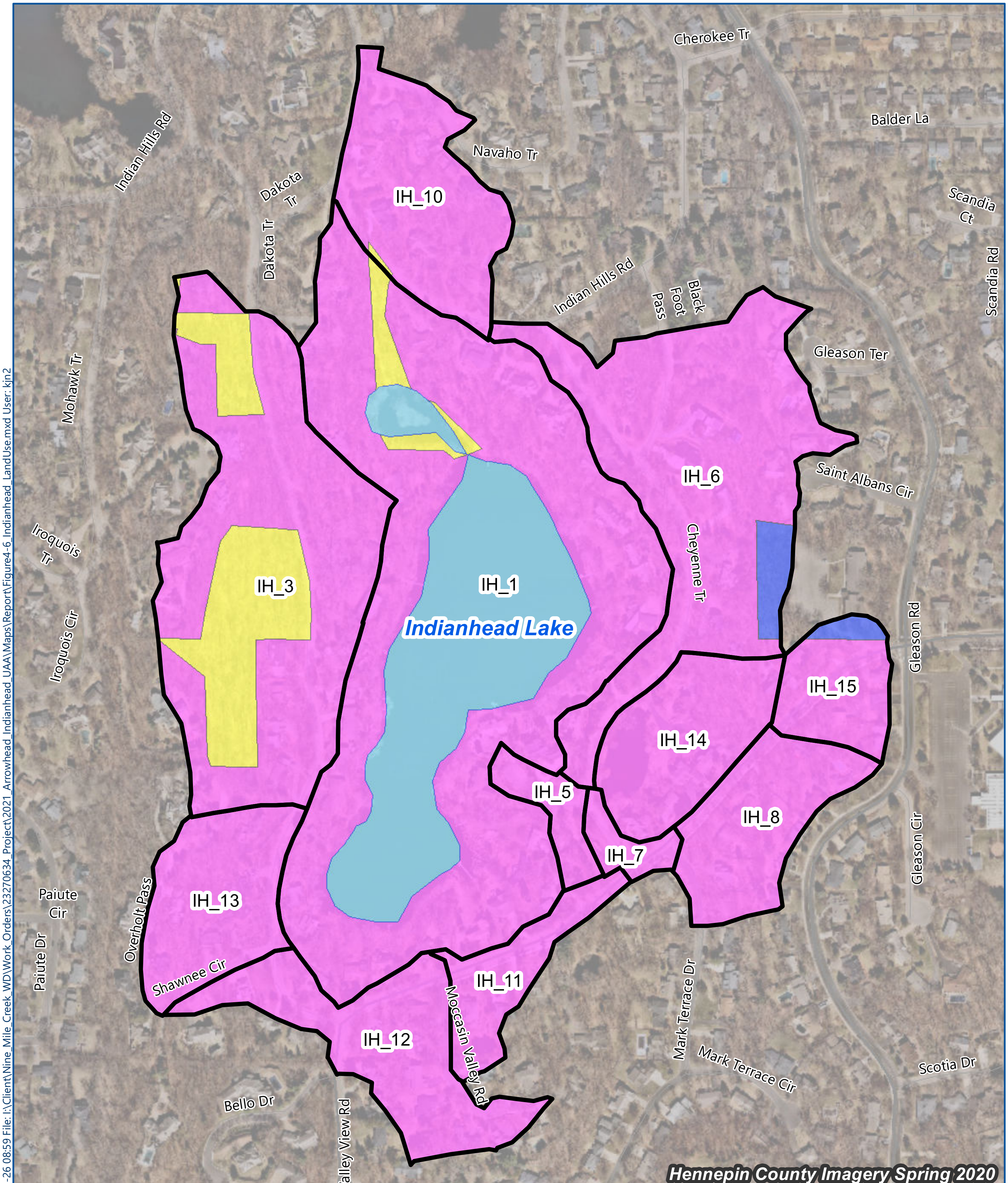
National Wetland Inventory (NWI) Wetland

- Freshwater Emergent Wetland
- Freshwater Pond

0 400
Feet

INDIANHEAD LAKE SUBWATERSHEDS & STORMWATER CONVEYANCE

FIGURE 4-5



Subwatersheds

Land Use (Met Council 2016)

- Institutional
- Open Water
- Single Family Detached
- Undeveloped

0 400

Feet

9 MILE CREEK WATERSHED DISTRICT

LAND USE
INDIANHEAD LAKE
WATERSHED

FIGURE 4-6

5.0 Existing Water Quality and Ecological Health

5.1 Water Quality

The NMCWD conducted intensive water quality monitoring in Arrowhead and Indianhead Lakes in 2019 and 2020 in support of this water quality study. The NMCWD also collected data in 2004, 2011, and 2014.

5.1.1 Eutrophication Parameters - Phosphorus, Chlorophyll-*a*, and Clarity

The NMCWD intensive monitoring included the lake eutrophication parameters of total phosphorus (TP), chlorophyll-*a*, and Secchi disk transparency depth to assess water clarity. Data are presented using box plots. The box plots show averages (black 'x'), median values (straight horizontal line), minimum and maximum values (whiskers), as well as the region where 50 percent of the data lie (the area within the boxes). Box plots shown on Figure 5-1 display the observed summer-average TP and chlorophyll-*a* concentrations and the Secchi disk transparency depths from 2004 through 2020 for Arrowhead Lake. Figure 5-2 shows the observed summer-average TP and chlorophyll-*a* concentrations and the Secchi disk transparency depths from 2004 through 2020 for Indianhead Lake.

There is variability in TP and chlorophyll-*a* concentrations and the Secchi disk transparency depths in Arrowhead and Indianhead Lakes from year to year, as well as within a given year. The variability can be a reflection of numerous factors, including climatic variability, changing aquatic plant and other aquatic community populations, management efforts, and changes in external pollutant loadings from the direct watershed.

For Arrowhead Lake, summer average TP and chlorophyll-*a* concentrations have remained fairly consistent between 2004 and 2020. Monitoring year 2011 was the only observed year where the summer average TP concentration met the MPCA water quality standard of 60 µg/L at a concentration of 52 µg/L. For the other years monitored, summer average TP concentrations ranged from 65 – 82 µg/L. Monitoring of chlorophyll-*a* concentrations showed that summer average concentrations met the MPCA water quality standard (20 µg/L) in 2004 and 2019 at concentrations of 19 and 18 µg/L, respectively. For the other years monitored, summer average chlorophyll-*a* concentrations exceeded the standard, ranging from 23 – 38 µg/L. Secchi disk transparency measurements have shown a decrease in transparency since 2011, with summer average Secchi disk transparency depths decreasing from 1.2 meters in 2011 to 0.5 meters in 2020.

For Indianhead Lake, water quality has generally declined between 2004 and 2020. Summer average TP and chlorophyll-*a* concentrations have generally increased between 2004 and 2020. In 2004 and 2011, the summer average TP concentrations met the MPCA water quality standard of 60 µg/L at concentrations of 46 and 53 µg/L, respectively. In 2014, the summer average TP concentration was only slightly above the MPCA standard at 61 µg/L. In 2019 and 2020, the monitoring data showed a significant increase in TP concentrations, with summer average concentrations of 146 and 115 µg/L, respectively. Summer average chlorophyll-*a* concentrations met the MPCA water quality standard (20 µg/L) in 2004 and 2019 at concentrations of 9 and 19 µg/L, respectively. For the other years monitored, summer average chlorophyll-*a* concentrations exceed the standard, ranging from 25 – 35 µg/L. Monitoring of Secchi disk transparency depths has shown a decrease in transparency since 2011, with observed summer average Secchi disk transparency depths decreasing from 1.3 meters in 2011 to 0.5 meters in 2020.

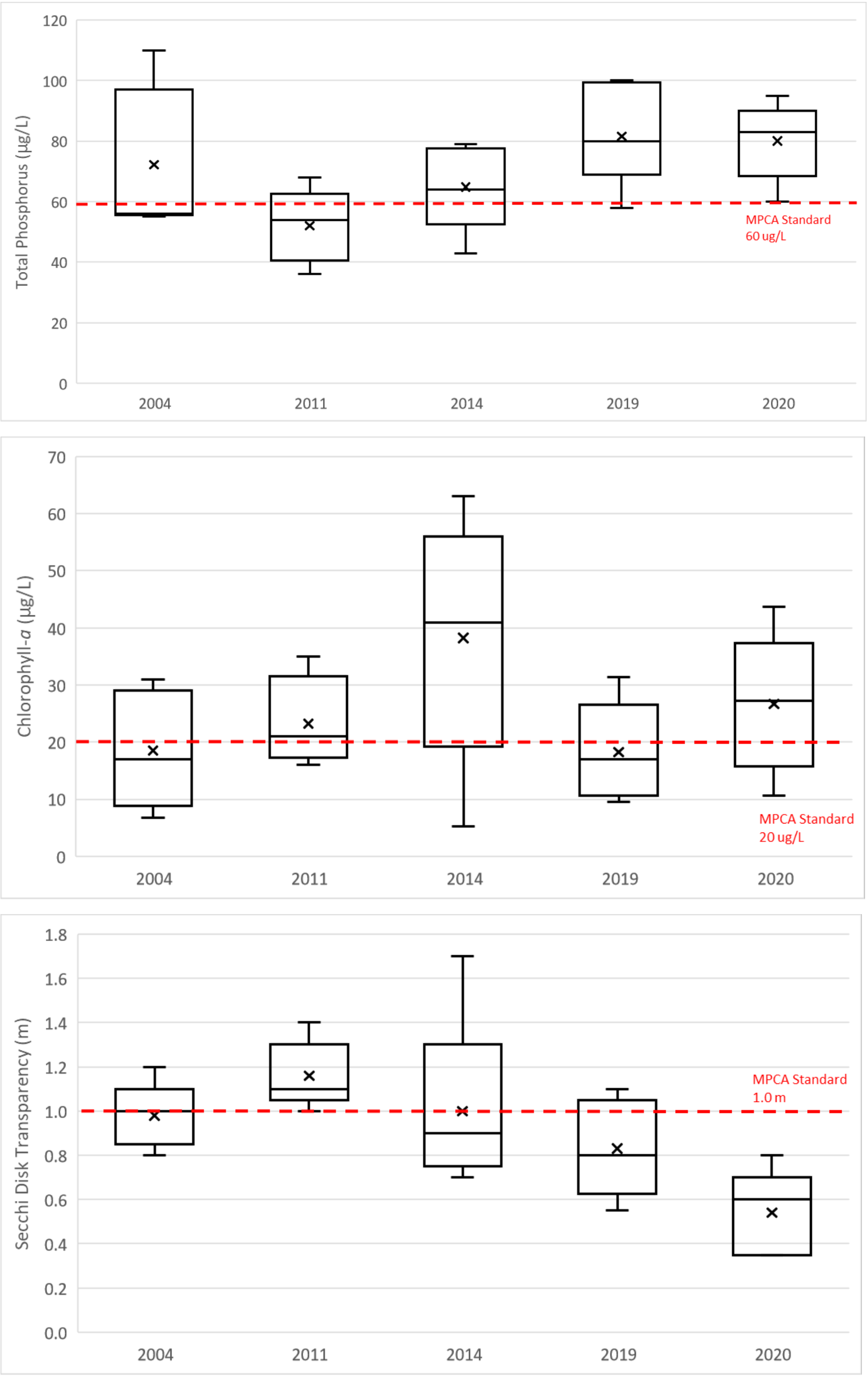


Figure 5-1 Total phosphorus, chlorophyll-*a*, and Secchi disk transparency from 2004 through 2020 in Arrowhead Lake. The black "x" indicates the summer average (June through September).

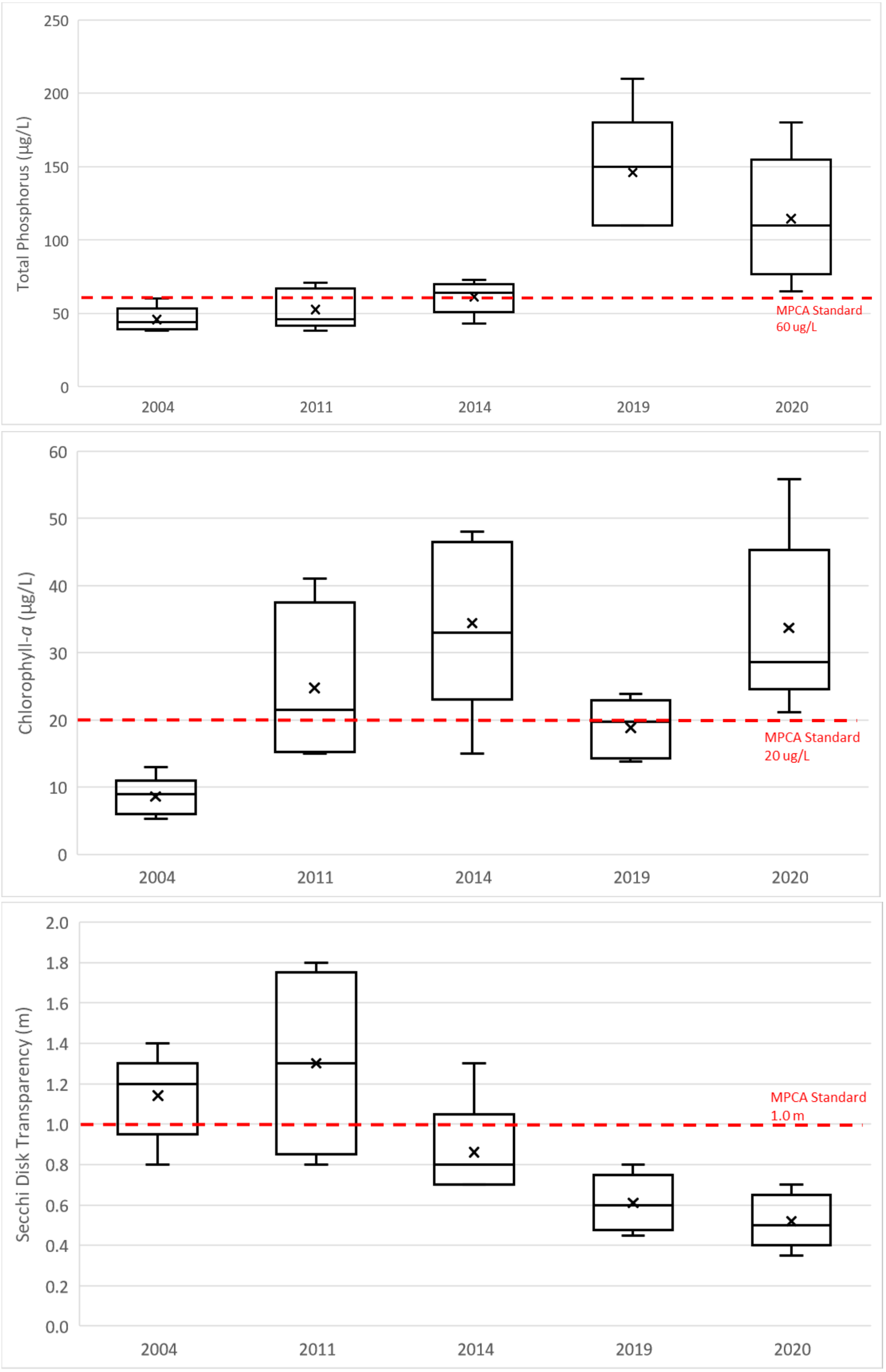


Figure 5-2 Total phosphorus, chlorophyll-*a*, and Secchi disk transparency from 2004 through 2020 in Indianhead Lake. The black "x" indicates the summer-average (June through September).

5.1.2 Nitrogen

The NMCWD intensive monitoring in 2019 and 2020 included Total Kjehdahl Nitrogen (TKN) and nitrate/nitrite concentrations. TKN data are presented using box plots. The box plots show averages (black 'x'), median values (straight horizontal line), minimum and maximum values (whiskers), as well as the region where 50 percent of the data lie (the area within the boxes). Box plots shown on Figure 5-3 and Figure 5-4 display the observed summer-average TKN concentrations in 2019 and 2020 for Arrowhead Lake and Indianhead Lake, respectively. Most observed nitrate/nitrite concentrations in Arrowhead and Indianhead Lakes were below the detection limit (~5 µg/L). The highest observed nitrate/nitrite concentrations in Arrowhead (16 µg/L) and Indianhead (13 µg/L) Lakes occurred in mid-August 2020. These nitrate/nitrite concentrations represent 0.9% and 0.8% of the TKN concentrations, respectively.

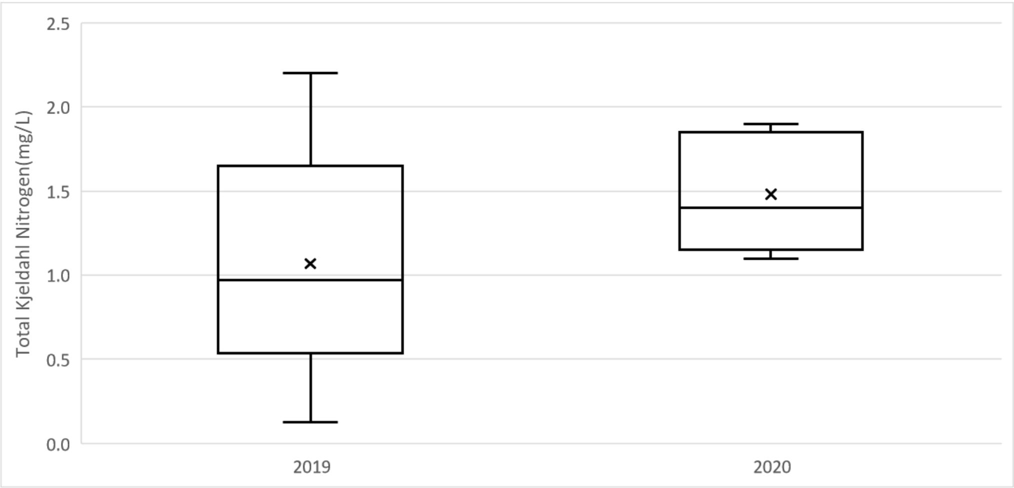


Figure 5-3 Total Kjehdahl Nitrogen 2019 through 2020 in Arrowhead Lake. The black "x" indicates the summer-average (June through September).

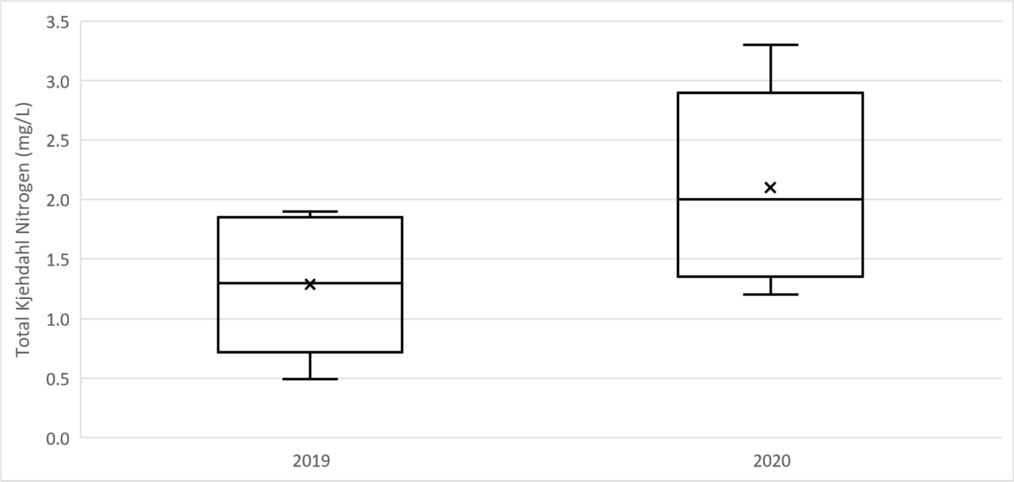


Figure 5-4 Total Kjehdahl Nitrogen 2019 through 2020 in Indianhead Lake. The black "x" indicates the summer-average (June through September).

5.1.3 Chlorides

Chloride concentrations in area lakes have increased since the early 1990s when many government agencies switched from sand or sand/salt mixtures to salt for winter road maintenance. When snow and ice melts, the salt goes with it, washing into lakes, streams, wetlands, and groundwater. Once chlorides reach downstream waterbodies, they are considered permanent pollutants since there is no way to remove chloride without extensive financial implications.

To protect fish and plant life, the MPCA has established a chronic exposure chloride standard of 230 mg/L or less and considers two or more exceedances of the chronic standard in 3 years to be an impairment. Based on the Arrowhead Lake monitoring data collected in 2011, 2014, 2019, and 2020, chloride concentrations have not been observed to exceed 230 mg/L. The highest concentration recorded was 185 mg/L in April 2019. Average chloride concentrations from 2011 – 2020 remained fairly consistent (average yearly concentrations (April – October) ranged from 120 – 150 mg/L). Based on the Indianhead Lake monitoring data collected in 2011, 2014, 2019, and 2020, chloride concentrations have not been observed to exceed 230 mg/L. The highest concentration recorded was 66 mg/L in April 2019. Average chloride concentrations from 2011 – 2020 remained fairly consistent (average yearly concentrations (April – October) ranged from 34 – 57 mg/L). Arrowhead Lake chloride concentrations are significantly higher than Indianhead Lake, which may be due to highway land use within the Arrowhead Lake watershed.

5.1.4 Dissolved Oxygen & Aeration

5.1.4.1 Arrowhead Lake

Dissolved oxygen measured in Arrowhead Lake in 2020 at the routine monitoring location ranged from 9.3 to 5.3 mg/L in the surface waters. For the most part, oxygen was fairly uniform from the surface to the bottom. This is likely due to the operation of three aerators in Arrowhead Lake. The minimum bottom oxygen concentration was 3.8 mg/L. These dissolved oxygen concentrations are high enough to prevent phosphorus release from lake bottom sediments that are dominated by iron-bound phosphorus (see Section 5.2 for a more complete discussion of phosphorus release from lake bottom sediments).

To confirm the conclusion that dissolved oxygen is high enough in Arrowhead Lake to control internal loading from iron-bound phosphorus release, two dissolved oxygen probes were placed mid-depth in the lake in August 2021 and operated through the third week of September. The purpose of placing these probes in the lake was to determine if oxygen was high enough during the night when phytoplankton consume oxygen and dissolved oxygen can become quite low. Dissolved oxygen measurements for the probe placed on the west end of the lake away from the aerators indicate that there were significant changes in dissolved oxygen from day to night (change as high as 8 mg/L), but that dissolved oxygen did not drop below a key level of 2 mg/L (Figure 5-5). For the probe placed near the aerators on the east end of the lake, dissolved oxygen did not change as notably from day to night and the concentrations were above 2 mg/L for all the measurements (Figure 5-6). Dissolved oxygen measurements taken across the lake for one event during August 2021 also demonstrated that dissolved oxygen concentrations were similar across the entire lake surface.

Given these monitoring results, internal load management strategies can be crafted assuming that oxygen concentrations are high enough to prevent iron-phosphate release under most conditions.

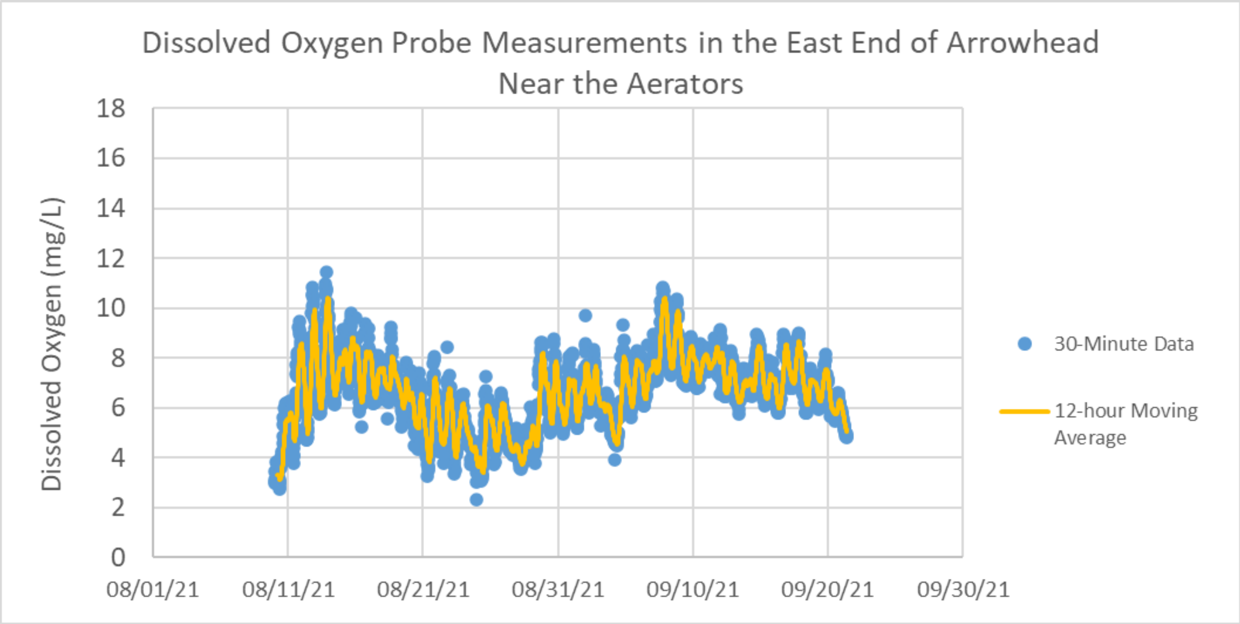


Figure 5-5 Arrowhead Lake dissolved oxygen concentrations near the aerators (east end)

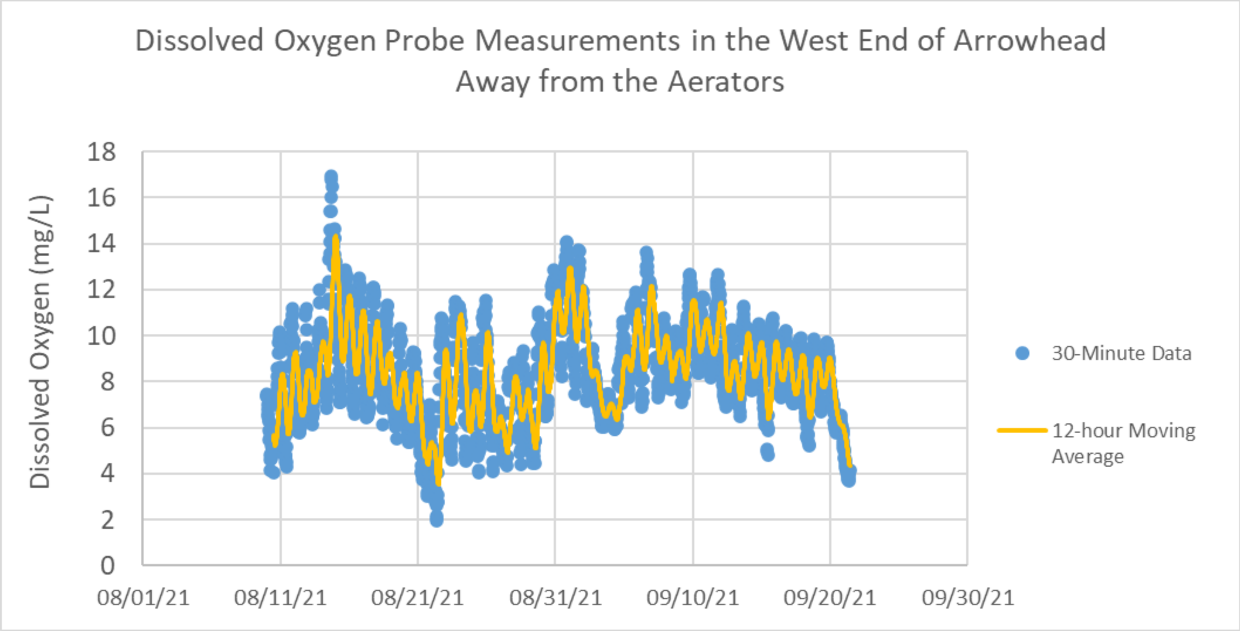


Figure 5-6 Arrowhead Lake dissolved oxygen concentrations away from aerators (west end)

5.1.4.2 Indianhead Lake

Dissolved oxygen measured in Indianhead Lake in 2020 at the routine monitoring location ranged from 19 to 4.3 mg/L in the surface waters. For the most part, oxygen was fairly uniform from the surface to the bottom except for the measurement on August 4, 2020 where the bottom dissolved oxygen was 2.7 mg/L. This may have been a result of a copper sulfate treatment completed on July 26, 2020 to treat for high concentrations of algae (permit applied for by the Indianhead Lake Association). For additional discussion on copper sulfate treatments, see Sections 5.3.2 and 6.3.3.1. Outside of observed low dissolved oxygen concentrations on August 4, 2020, higher dissolved oxygen concentrations in Indianhead Lake are likely due to the operation of four aerators.

Additional dissolved oxygen measurements taken across Indianhead Lake on August 24, 2021 were consistently high in the surface samples (approximately 10 mg/L) with bottom measurements ranging from 7 to 9 mg/L. These concentrations are high enough to prevent phosphorus release from lake bottom sediments that are dominated by iron-bound phosphorus (see Section 5.2 for a more complete discussion of phosphorus release from lake bottom sediments).

5.2 Sediment Quality

Phosphorus in lake bottom sediments is often bound to a range of different elements such as iron and manganese (often referred to as mobile phosphorus), aluminum, or calcium. It is the mobile phosphorus fraction that releases from sediment during low oxygen conditions. Phosphorus can also be found incorporated into organic matter in the sediment (organically bound phosphorus). Organically bound phosphorus can also release phosphorus from lake sediment but typically at a slower rate than mobile phosphorus; release is controlled by lake water temperature. Phosphorus release from sediment is typically termed as "internal phosphorus loading".

Sediment cores from Arrowhead and Indianhead Lakes were collected in 2021 and used to inform the potential internal phosphorus loading potential of the mobile and organically bound phosphorus fractions. In both Arrowhead and Indianhead Lake the amount of mobile phosphorus was low; however, the amount of organically bound phosphorus in the sediments was high, indicating potential for internal phosphorus loading. In both lakes, the amount of organically bound phosphorus was significantly higher than the mobile phosphorus fraction. The average concentration of organically bound phosphorus and mobile phosphorus in the top 4 centimeters of three cores taken from Arrowhead Lake was 36.1 and 4.1 µg P/cm^3 wet sediment, respectively. The average concentration of organically bound phosphorus and mobile phosphorus in the top 4 centimeters of two cores taken from Indianhead Lake was 39.6 and 5.6 µg P/cm^3 wet sediment, respectively. These observed concentrations indicate that a significantly larger percentage of internal phosphorus loading in both lakes is due to organically bound phosphorus (organic-P) rather than mobile phosphorus (mobile-P).

5.3 Aquatic Communities

The fish, zooplankton, phytoplankton, and aquatic plants residing in lakes are all linked, and the composition and abundance of biota observed in the lakes provide indication of lake health and if biological management should be considered to improve water quality.

5.3.1 Aquatic Plants

Macrophytes, also called aquatic plants, grow in aquatic systems such as streams and lakes. There is a wide range of macrophytes including species attached to the lake bottom, species unattached and floating, submerged species, and emergent species (e.g., cattails). Macrophytes are an important part of a shallow lake ecosystem and provide critical habitat for aquatic insects and fish. A healthy native plant community contributes to the overall health of the lake. However, a dense non-native plant community can create problems, including recreational use impairment, fluctuating water quality, and a less than ideal fisheries habitat, which has adverse impacts on the fish community. The dense growth can make it difficult for invertebrates and other organisms that fish eat to survive. So, with less to eat and less open water, fish populations decrease (MPCA, Eurasian Water Milfoil, 2019). The dense growth can also make it difficult for fish to catch food. When fish are less effective at controlling prey species, an unbalanced fishery results (Indiana Department of Natural Resources, 2019).

The NMCWD conducted qualitative macrophyte monitoring as part of its routine monitoring of Arrowhead and Indianhead Lakes in 2004, 2011, 2014, 2019, and 2020. The macrophyte monitoring consisted of conducting qualitative plant surveys in June and August of each of the monitored years, with qualitative notation of plants observed and their density throughout the lakes.

The Minnesota Department of Natural Resources (MNDNR) developed the Lake Plant Eutrophication Index of Biological Integrity (IBI) to develop thresholds to indicate plant degradation (communities likely stressed from anthropogenic eutrophication). The Lake Plant Eutrophication IBI includes two metrics to measure the response of a lake plant community to eutrophication. The first metric is species richness—the estimated number of species in a lake. The second metric is floristic quality index (FQI), which distinguishes the quality of the plant community and can be a reflection of the quantity of nutrients in the lake.

The MNDNR's Lake Plant Eutrophication IBI was used to assess the health of the Arrowhead and Indianhead Lake plant communities, based on results of the macrophyte surveys. Aquatic plant data collected by NMCWD from 2004 through 2020 was used to determine species richness and Floristic Quality Index (FQI) scores. The scores were then compared with MNDNR Lake Plant Eutrophication IBI thresholds for shallow lakes (a minimum of 11 species and an FQI score of at least 17.8) to assess the health of the Arrowhead and Indianhead Lake plant communities.

The Arrowhead Lake plant community failed to meet the MNDNR Lake Plant Eutrophication IBI criteria for measurements taken in 2004, June 2011, 2014, 2019, and 2020 (Figure 5-7). The Arrowhead Lake plant community met the MNDNR Lake Plant Eutrophication IBI criteria in August 2011 (i.e., at least 11 plant species). The number of species observed in Arrowhead Lake generally increased from 2004 to 2014. In June 2004, six plant species were found during survey. From August 2004 to August 2014, 10 – 11 plant species were observed in Arrowhead Lake. However, the number of plant species found in 2019 and 2020 showed a significant decrease, which reflects the lake's poor water quality during that time period (i.e., total phosphorus and chlorophyll-*a* concentrations above Minnesota State shallow lake water quality standards). The number of species observed in Arrowhead Lake in 2019 ranged from 6 – 7 species and the number of species observed in 2020 was 2 species. The decrease in observed species can be reflective of degrading water quality, but may also be a reflection of plant management conducted by lake residents.

The FQI values follow a similar trend to the number of plant species observed in Arrowhead Lake over time. FQI values were near or above the MDNR plant IBI threshold of 17.8 from August 2004 through August 2014 and ranged from 17.1 to 19.9 (Figure 5-8). FQI values from 2019 to 2020 decreased, ranging from 9.2 to 12.9, which is lower than the plant IBI threshold for FQI of at least 17.8 (Figure 5-8).

The Indianhead Lake plant community failed to meet the MNDNR Lake Plant Eutrophication IBI criteria for measurements taken in 2004, 2011, 2014, 2019, and 2020, with all observed data falling below the desired threshold of 11 plant species (Figure 5-9). The number of species observed in Indianhead Lake generally remained consistent from 2004 to 2020, likely due to plant management efforts conducted by residents. From 2004 to 2020 the number of plant species observed in Indianhead Lake ranged from 3 – 5 species. The decrease in observed species may be reflective of degrading water quality conditions, but this correlation is difficult to quantify due to yearly plant management efforts.

The FQI values in Indianhead Lake show a decreasing trend over time. FQI values were below the MNDNR plant IBI threshold of 17.8 for all years monitored (2004 – 2020). FQI values were the highest in 2004 at 15.2 and have been decreasing over time where FQI values monitored in 2020 were approximately 11.5 (Figure 5-10).

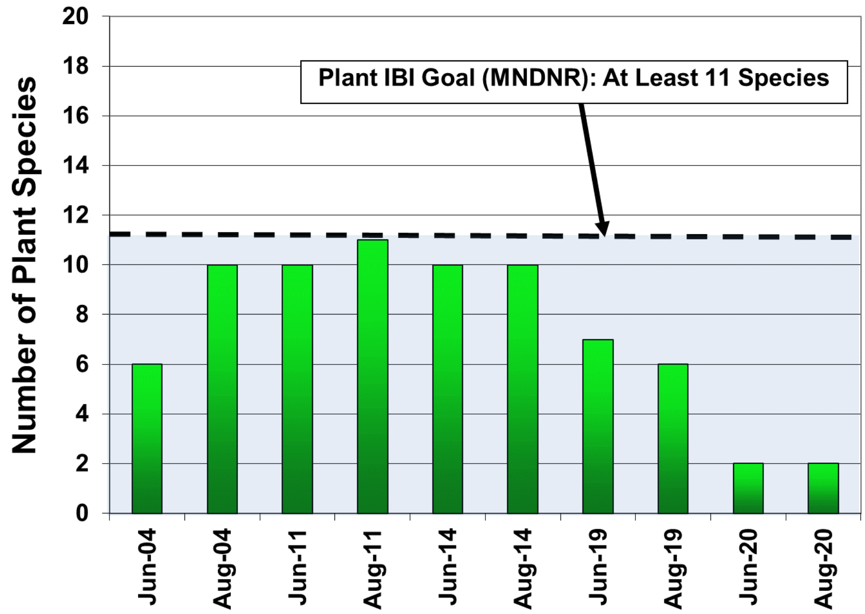


Figure 5-7 **Arrowhead Lake Macrophyte Species Richness Compared with Plant IBI Threshold for Species Richness**

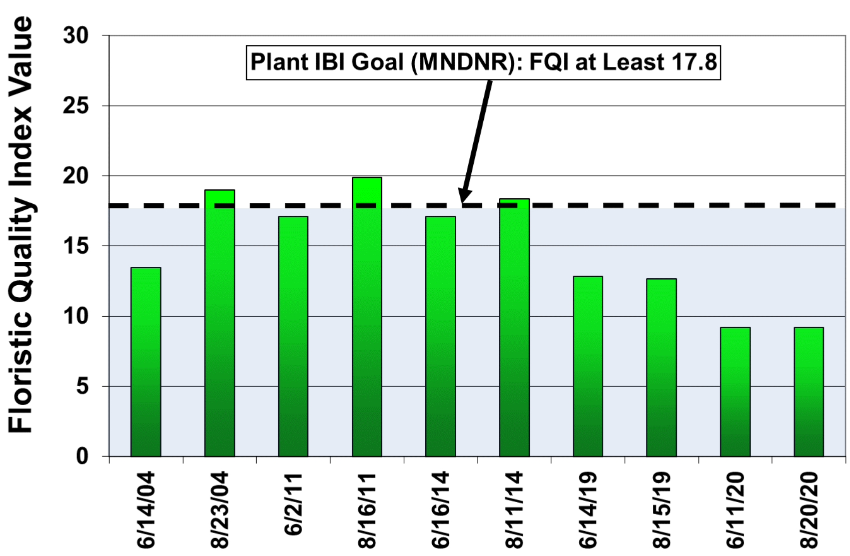


Figure 5-8 **Arrowhead Lake Macrophyte Species Richness Compared with Plant IBI Threshold for Floristic Quality Index (FQI)**

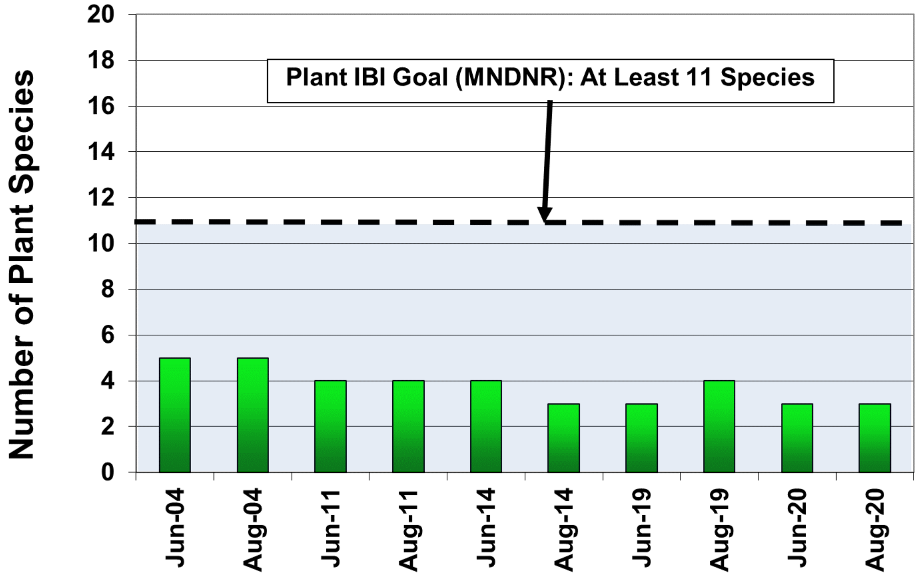


Figure 5-9 **Indianhead Lake Macrophyte Species Richness Compared with Plant IBI Threshold for Species Richness**

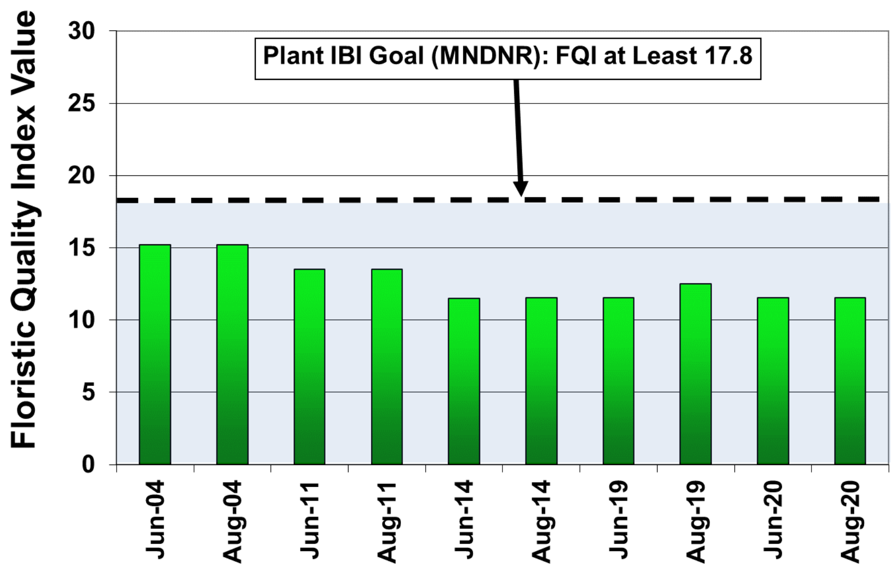


Figure 5-10 **Indianhead Lake Macrophyte Species Richness Compared with Plant IBI Threshold for Floristic Quality Index (FQI)**

Two non-native aquatic invasive species (AIS) are currently present in Arrowhead Lake: Purple loosestrife and curly-leaf pondweed. Eurasian watermilfoil has been observed in the past but was not present in the most recent survey completed in 2020.

Purple loosestrife has been observed in Arrowhead Lake since 2011. Purple loosestrife has been observed along the south and southwest shorelines. Curly-leaf pondweed has been observed in Arrowhead Lake since 2004. Although curly-leaf pondweed is not depicted in the June 2004 macrophyte survey map completed by NMCWD, herbicide treatment documentation indicates curly-leaf pondweed was present in early spring. In 2011, curly-leaf pondweed was found in northern, eastern, and western portions of the lake. In 2014, curly-leaf pondweed was more widespread with observations not only in the northern, eastern, and western portions of the lake, but also in the southern portions. In June 2019 and 2020, less curly-leaf pondweed was observed during the June macrophyte surveys due to management efforts completed by the City of Edina in spring 2019 and 2020. The City of Edina has been managing for curly-leaf pondweed in Arrowhead Lake since spring 2017. Eurasian watermilfoil was found in Arrowhead Lake in the first recorded survey in 2004 in the eastern, western, and southern portions of the lake. By 2011, Eurasian watermilfoil was more widespread with observations not only in the eastern, western, and southern portions, but also in the north. Similar extents of Eurasian watermilfoil were also observed in 2014. The extent of Eurasian watermilfoil decreased in 2019, with observations noted in northern portions of the lake. No observations of Eurasian watermilfoil were noted in the June and August 2020 surveys. The NMCWD will continue to track invasive species' growth in Arrowhead Lake.

Three non-native AIS are currently present in Indianhead Lake: Purple loosestrife, curly-leaf pondweed, and yellow iris.

Purple loosestrife has been observed in Indianhead Lake since a macrophyte survey was completed in 2019. Purple loosestrife has been observed along the southwestern and southeastern shorelines. A macrophyte survey in 2014 identified a widespread curly-leaf pondweed population in Indianhead Lake. In June 2019 and 2020, less curly-leaf pondweed was observed during the June macrophyte surveys due to management efforts completed by the City of Edina in spring 2019 and 2020. Yellow iris was observed along the northern, eastern, and southern portions of the Indianhead Lake shoreline in the first recorded survey in 2004. By 2011, yellow iris was more widespread with observations not only in the northern, eastern, and southern portions, but also in the west. Similar extents of yellow iris were also observed in 2019 and 2020. The NMCWD will continue to track invasive species' growth in Indianhead Lake.

Aquatic plant maps from 2004 through 2020 are provided in Appendix A.

5.3.2 Phytoplankton

Samples of phytoplankton, microscopic aquatic algae, were collected from Arrowhead and Indianhead Lakes in 2004, 2011, 2014, 2019, and 2020 as part of NMCWD's routine monitoring to evaluate water quality and the quality of food available to zooplankton (microscopic animals).

Phytoplankton numbers in Arrowhead Lake generally increased during the monitoring period of 2004 through 2020. In 2004, the summer average phytoplankton number was 13,350 per milliliter. In 2020, the summer average phytoplankton number increased to 48,845 per mL. Blue-green algae numbers have also increased from 2004 to 2020. In 2004, the summer average blue-green algae numbers were approximately 240 per mL. In 2020, the blue-green algae summer average numbers increased to approximately 38,880 per mL (Figure 5-11). The highest observed concentration of blue-green algae from the routine monitoring location was 76,960 per mL in July 2020.

Blue-green algae are associated with water quality problems and can be a source of health concerns. The World Health Organization (WHO) has established the following thresholds for assessing the probability of adverse health effects to lake users from exposure to blue-green algae (World Health Organization, 2003):

- ***Low Probability of Adverse Health Effects:*** Exposure to lakes with blue-green algae density levels between 20,000 and 100,000 cells per milliliter poses a low probability of adverse health effects (i.e., skin irritation or allergenic effects such as watery eyes).
- ***Moderate Probability of Adverse Health Effects:*** Exposure to lakes with blue-green algae densities greater than 100,000 cells per milliliter poses a moderate probability of adverse health effects (i.e., long-term illness from algal toxins is possible).
- ***High Probability of Adverse Health Effects:*** Exposure to lakes with blue-green scum in areas where whole body contact or ingestion/aspiration occur poses a high probability of adverse health effects (i.e., acute poisoning from algal toxins is possible).

Figure 5-12 shows the observed blue-green algae counts in Arrowhead Lake in comparison with the WHO thresholds for probability of adverse health effects. From July through August 2020, observed blue-green algae counts were above the threshold for low probability of adverse health effects level. Observed blue-green algae counts in Arrowhead Lake in August 2014 and August 2019 were also above the threshold for low probability of adverse health effects from exposure to blue green algae.

Phytoplankton numbers in Indianhead Lake during the monitoring period of 2004 through 2020 followed a pattern similar to that of the water quality parameters (e.g., total phosphorus, chlorophyll-*a*, Secchi disk depth), both reflecting degrading water quality over time. In 2004, the summer average phytoplankton number was 16,550 per milliliter. In 2020, the summer average phytoplankton number increased to 76,430 per mL. Blue-green algae numbers have also increased from 2004 to 2020. In 2004, the summer average blue-green algae numbers were approximately 190 per mL, whereas in 2020, the blue-green algae summer average count increased to approximately 56,500 per mL (Figure 5-13). The highest observed concentration of blue-green algae from the routine monitoring location was 144,740 per mL in July 2020.

Figure 5-14 shows the observed blue-green algae counts in Indianhead Lake in comparison with the WHO thresholds for probability of adverse health effects. In July and August 2020, blue-green algae counts were above the thresholds for moderate and low probability of adverse health effects levels, respectively. Prior to 2020, blue-green algae cell counts were consistently below the WHO threshold for low probability of adverse health effects.

5.3.2.1 Copper Sulfate Treatments

Copper sulfate treatments have been applied to Arrowhead and Indianhead Lakes in the past to control algal blooms. The Arrowhead Lake Association and Indianhead Lake Association have worked with the City of Edina to coordinate these treatments with licensed contractors and apply for the appropriate permits from the MnDNR. The approximate dates of the most recent algal treatments based on records available from the City of Edina are as follows:

- Arrowhead Lake: 9/19/2019, 6/11/2020, 8/6/2020
- Indianhead Lake: 7/26/2019, 7/8/2020

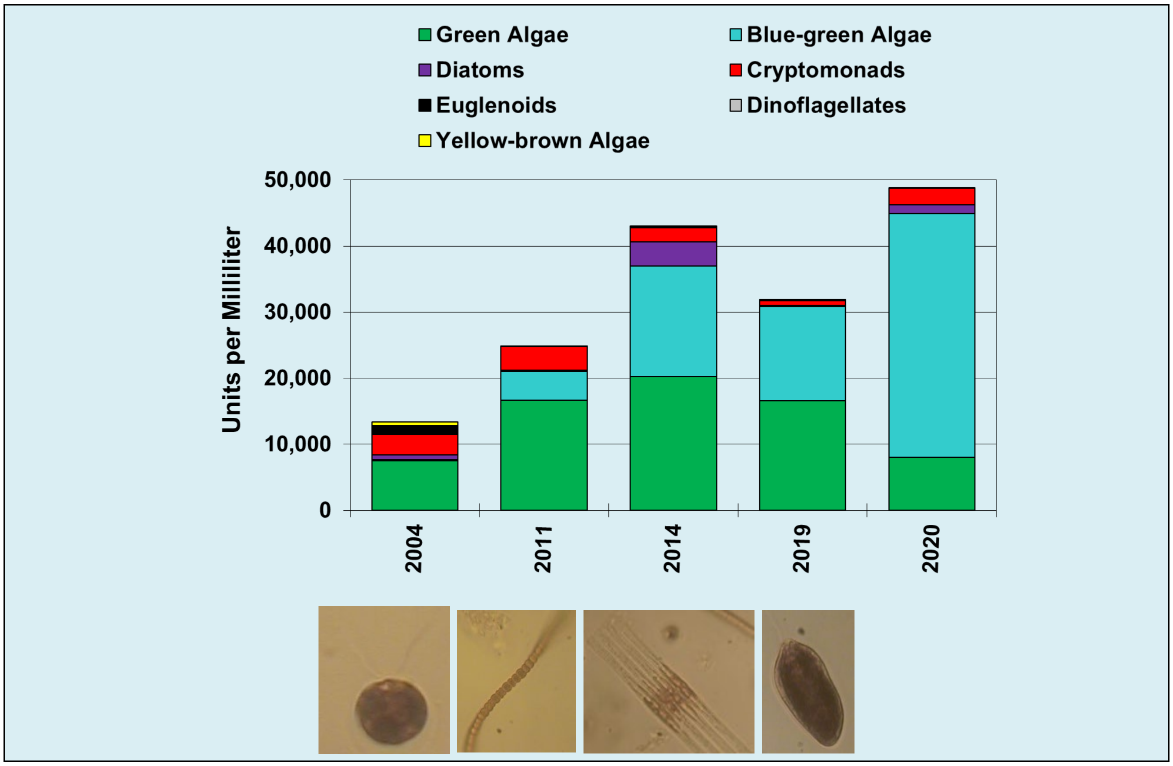


Figure 5-11 **Top, Arrowhead Lake 2004-2020 summer average phytoplankton numbers and bottom, microscopic pictures of phytoplankton species, from left to right, Chlamydomonas globosa (green algae) Dolichospermum affine (blue-green algae), Fragilaria crotonensis (diatom), and Cryptomonas erosa (cryptomonad).**

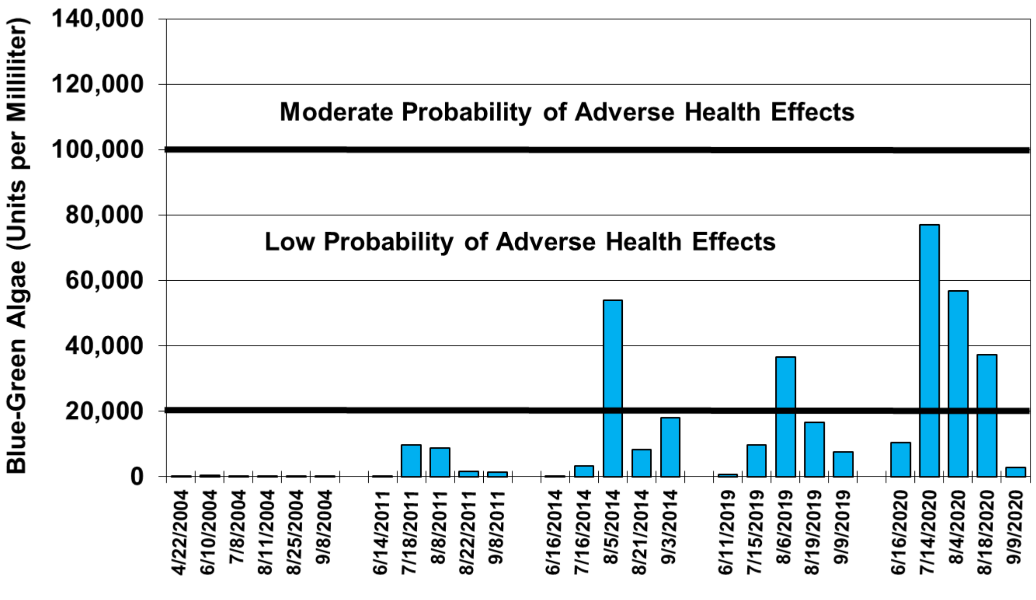


Figure 5-12 **Arrowhead Lake blue-green algae data compared with the World Health Organization's Thresholds for Adverse Health Effects Guidelines**

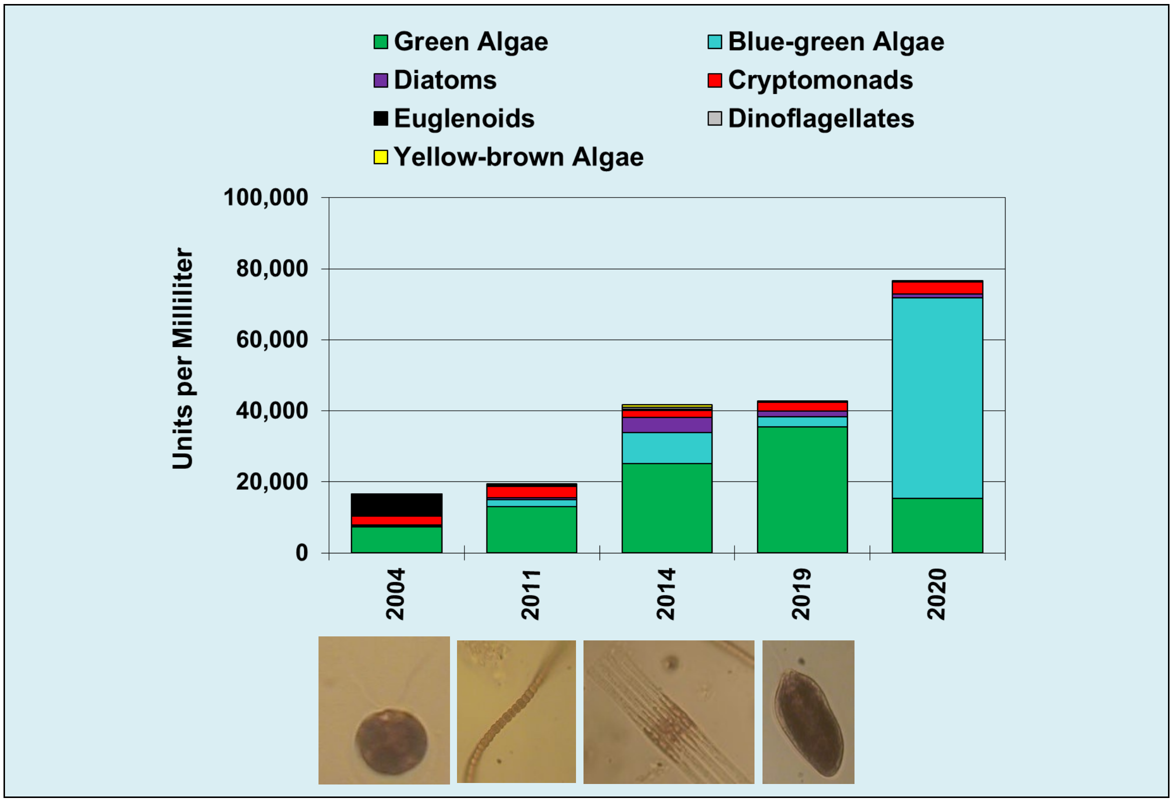


Figure 5-13 Top, Indianhead Lake 2004-2020 summer average phytoplankton numbers and bottom, microscopic pictures of phytoplankton species, from left to right, Chlamydomonas globosa (green algae) Dolichospermum affine (blue-green algae), Fragilaria crotonensis (diatom), and Cryptomonas erosa (cryptomonad).

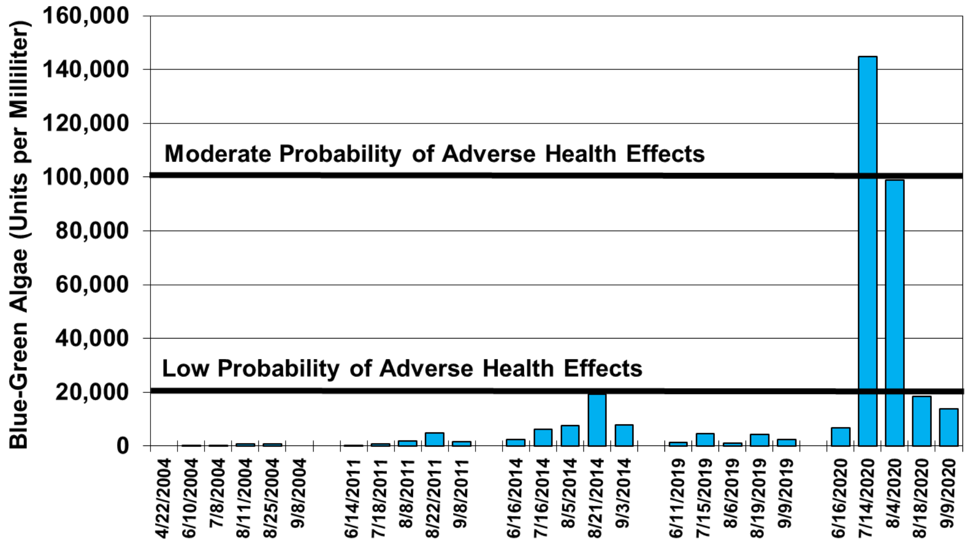


Figure 5-14 Indianhead Lake blue-green algae data compared with the World Health Organization's Risk of Adverse Health Effects Guidelines

5.3.3 Zooplankton

Zooplankton are microscopic animals that feed on phytoplankton (algae) and organic matter that are a source of food for fish (e.g., bluegills, crappies). Samples of zooplankton were collected from Arrowhead and Indianhead Lakes in 2004, 2011, 2014, 2019, and 2020 as part of NMCWD's routing monitoring program.

In general, the average quantity of zooplankton has increased since 2004 in Arrowhead Lake. In 2004, the yearly average total number of zooplankton per square meter was less than 1 million. In 2020, the yearly average total number of zooplankton increased to over 3 million per square meter. Since 2004, the percentage of rotifers observed in Arrowhead Lake has decreased while the percentage of cladocerans and copepods has increased (Figure 5-15). The data indicate the zooplankton community provided an abundant supply of food for planktivorous fish in the lake.

In Indianhead Lake, the average quantity of zooplankton per square meter increased from 2004 (2.2 million) to 2011 (4.7 million). From 2011 – 2014, the average zooplankton quantity and community composition stayed fairly consistent with the dominant zooplankton group being rotifers. From 2014 to 2019, the average zooplankton quantity per square meter decreased. Numbers of cladocerans and copepods were, on average, higher in 2019 and 2020 than previous years resulting in a more even distribution between the 3 groups of zooplankton. The total number of zooplankton in 2020 was, on average, higher than 2019, but lower than numbers observed in 2011 and 2014. Nonetheless, the 2020 data indicate the zooplankton community provided an abundant supply of food for planktivorous fish in the lake.

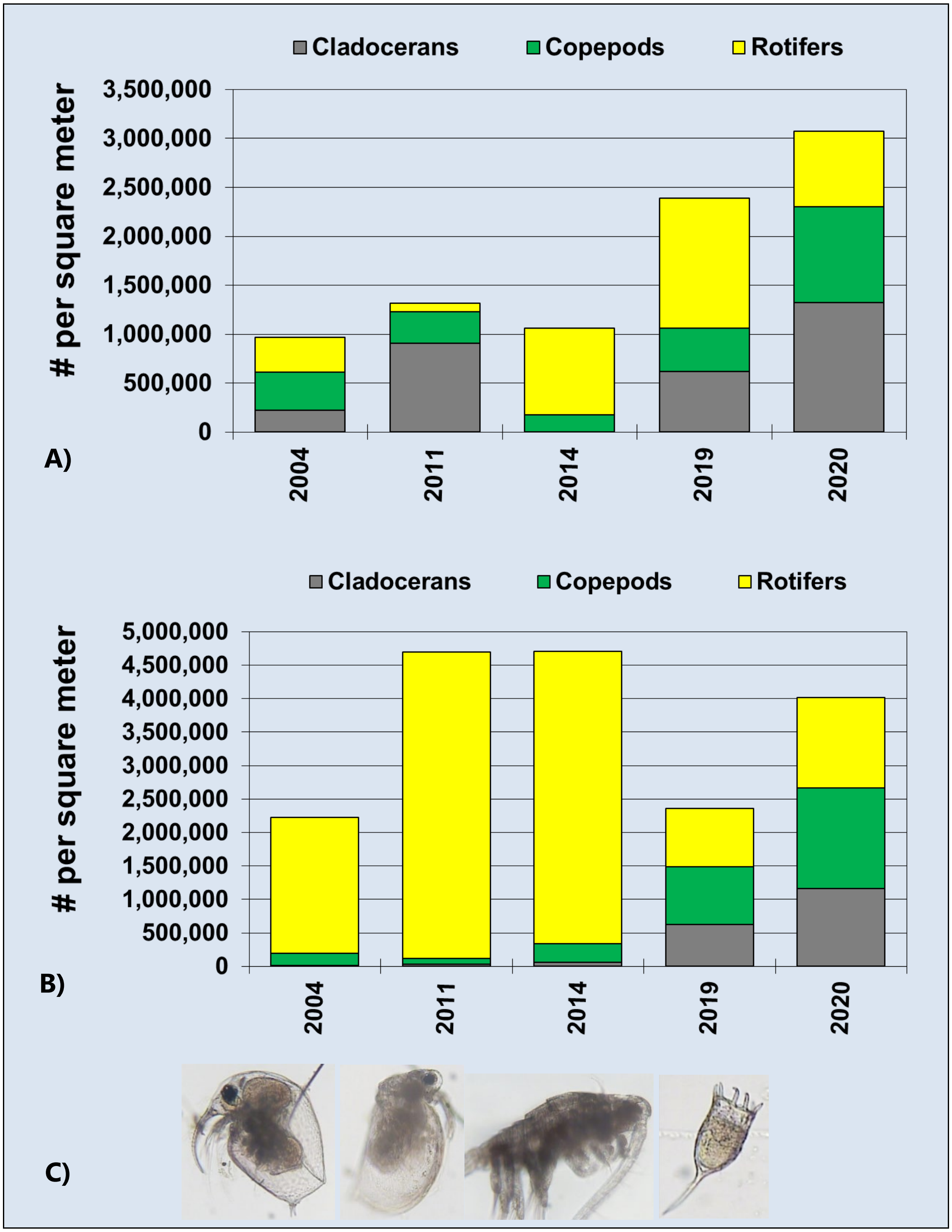


Figure 5-15 A) Arrowhead Lake 2004-2020 zooplankton numbers, B) Indianhead Lake 2004 – 2020 zooplankton numbers, and C) microscopic pictures of zooplankton species, from left to right, Bosmina longirostris. (cladoceran), Ceriodaphnia sp. (cladoceran), Diaptomus sp. (copepod), and Keratella cochlearis (rotifer).

5.3.3.1 Impact of Copper Sulfate on Zooplankton

Research has shown that copper sulfate treatments do not only reduce algal abundance, but treatments can deplete food availability for zooplankton and copper toxicity can affect zooplankton health and survival. Results of zooplankton monitoring in Indianhead Lake in 2020 indicates a probable impact of a copper sulfate treatment on the zooplankton community. All three zooplankton groups showed a decrease in abundance between mid-July and early-August; however, rotifers showed the largest decrease in abundance (Figure 5-16). Rotifer abundance was approximately 4.2 million per square meter on July 14, 2020 and decreased to 95,500 per square meter by August 4, 2020. A copper sulfate treatment was applied on July 8, 2020. Future monitoring should be completed to confirm direct cause and effect of copper sulfate on zooplankton communities and rule out other factors impacting growth (e.g., fish predation changes).

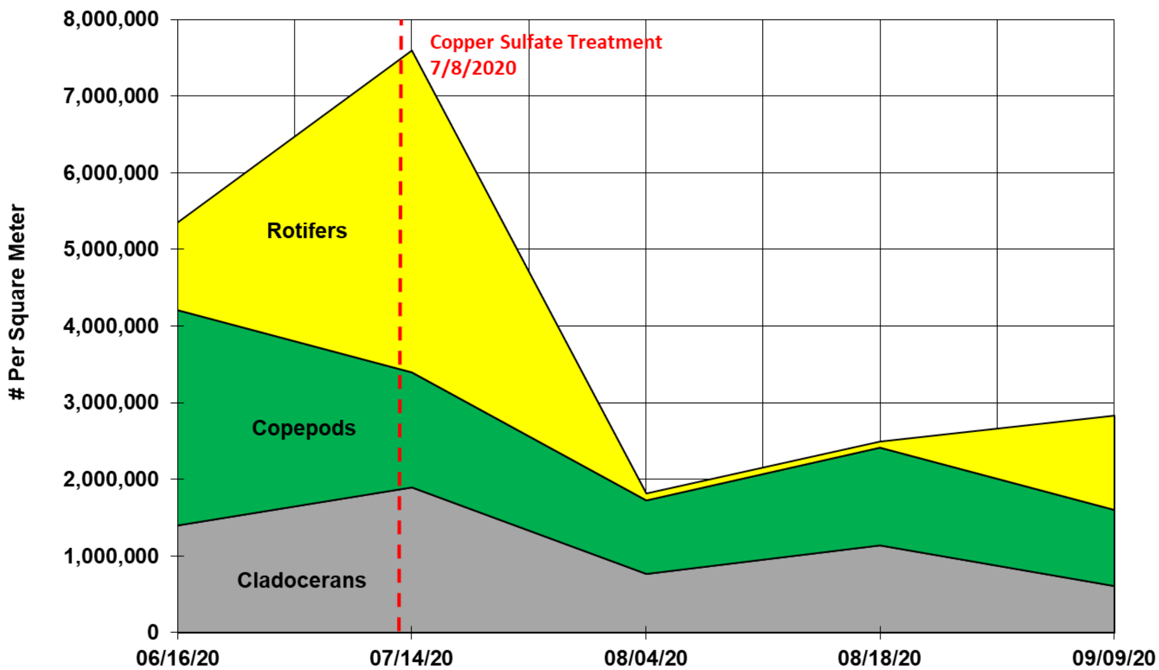


Figure 5-16 Zooplankton abundance and community changes in Indianhead Lake compared to timing of algal copper sulfate treatment in 2020

5.3.4 Fish

The environmental consulting firm WSB completed a fisheries assessment of Arrowhead and Indianhead Lakes in fall 2021. Between September 19 through 21, 2021 WSB completed a standard lake survey of Arrowhead and Indianhead Lakes using three standard double frame fyke trap nets and three mini fyke trap nets.

During the standard lake survey in early September 2021, a variety of species were sampled in Arrowhead Lake, including bluegill, black bullhead, green sunfish, hybrid sunfish, and largemouth bass. Bluegill were found to be the most prominent fish in the lake with an average size of 5.8 inches. Largemouth bass was found to be the most prominent predator fish in the lake with an average size of 13.1 inches. Prior to the

2021 fisheries assessment, the MNDNR completed a standard fisheries assessment of Arrowhead Lake in 1995. In 1995, black bullhead and green sunfish were the most prominent fish species in Arrowhead Lake, which is a stark contrast to the observed species in 2021. The increase in blue gill and large mouth bass species is likely due to a recorded fish stocking event in 2016. Recorded fish stocking reports are available from the MNDNR. Within the last 10 years, Arrowhead Lake was stocked in 2016 (Bluegills – 1,000 fingerlings, 1,000 yearlings; Largemouth Bass – 430 fingerlings, 90 yearlings).

During the standard lake survey in early September 2021, a variety of species were sampled in Indianhead Lake, including bluegill, hybrid sunfish, black crappie, golden shiner, and largemouth bass. Bluegill were found to be the most prominent fish in the lake with an average size of 6.7 inches. Largemouth bass was found to be the most prominent predator fish in the lake with an average size of 10.6 inches. Prior to the 2021 fisheries assessment, no standard MNDNR fisheries assessments have been completed on Indianhead Lake. Recorded fish stocking reports are available from the MNDNR. Within the last 10 years, Indianhead Lake was stocked in 2013 (Black Crappie – 50 adults; Bluegill Sunfish – 200 adults; Largemouth Bass – 200 yearlings) and 2016 (Black Crappie – 2,000 yearlings; Bluegill Sunfish – 5,000 yearlings; Hybrid Sunfish – 1,000 yearlings; Largemouth Bass – 900 fingerlings, 1,000 yearlings). The 2021 fisheries assessment indicates high survival of the stocked fish, although the lack of abundant small fish (< 3 inches) may suggest low recruitment (low survival of fish spawned within the lake).

In spring 2022, WSB plans to conduct follow-up fish surveys of Arrowhead and Indianhead Lakes using electrofishing. Electrofishing data should expand upon the data collected in fall 2021 using the fyke trap nets. A final report will be developed following this survey with results of the fall 2021 and spring 2022 surveys.

The official 2021 fisheries assessment reports can be found in Appendix B.

5.4 Water Levels

Arrowhead and Indianhead lakes are land-locked with no surface outlets. Thus, the water levels in the lakes depend on weather conditions (snowmelt, rainfall, evaporation) and groundwater flow. The observed water surface elevations in Arrowhead and Indianhead lakes monitored since 2010 by the NMCWD are shown in Figure 5-17 and Figure 5-18, respectively. Both lakes experienced significantly higher water levels in 2014, 2017, and 2019 due to above average precipitation and high groundwater levels. Since mid-2020 water surface elevations have been falling in both lakes due to below average precipitation in 2020 and 2021 and changes in groundwater levels.

Predicting how water quality conditions will change in land-locked lakes due to water level variations can be difficult. While watershed models, such as P8, can be used to predict changes in stormwater inflow concentrations due to above or below average precipitation, estimating the changes to in-lake processes can be more challenging. For example, in some lakes, high water levels may result in improved water quality because high water levels correspond to more water volume and lower nutrient concentrations (i.e., nutrients are diluted by more water volume). However, in other lakes, high water levels may result in degrading water quality because high water levels may increase erosion in upland areas or water may extend into upland areas that are heavily fertilized. How water quality responds to changing water levels may also vary from year to year.

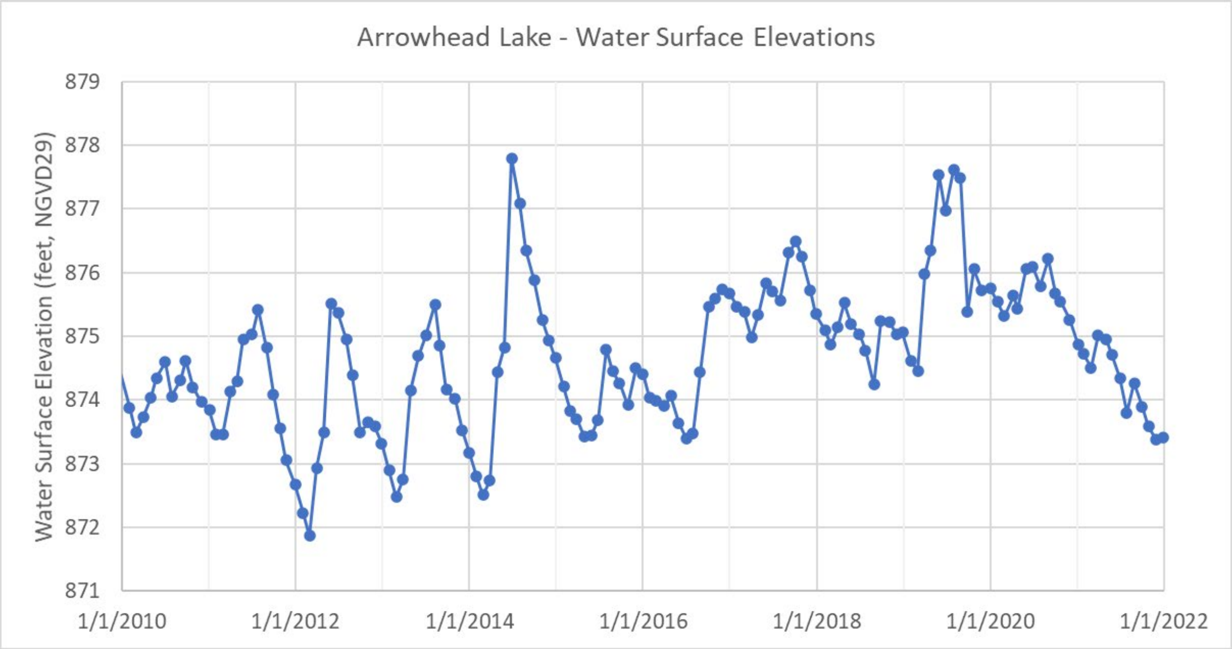


Figure 5-17 Observed Water Surface Elevations on Arrowhead Lake

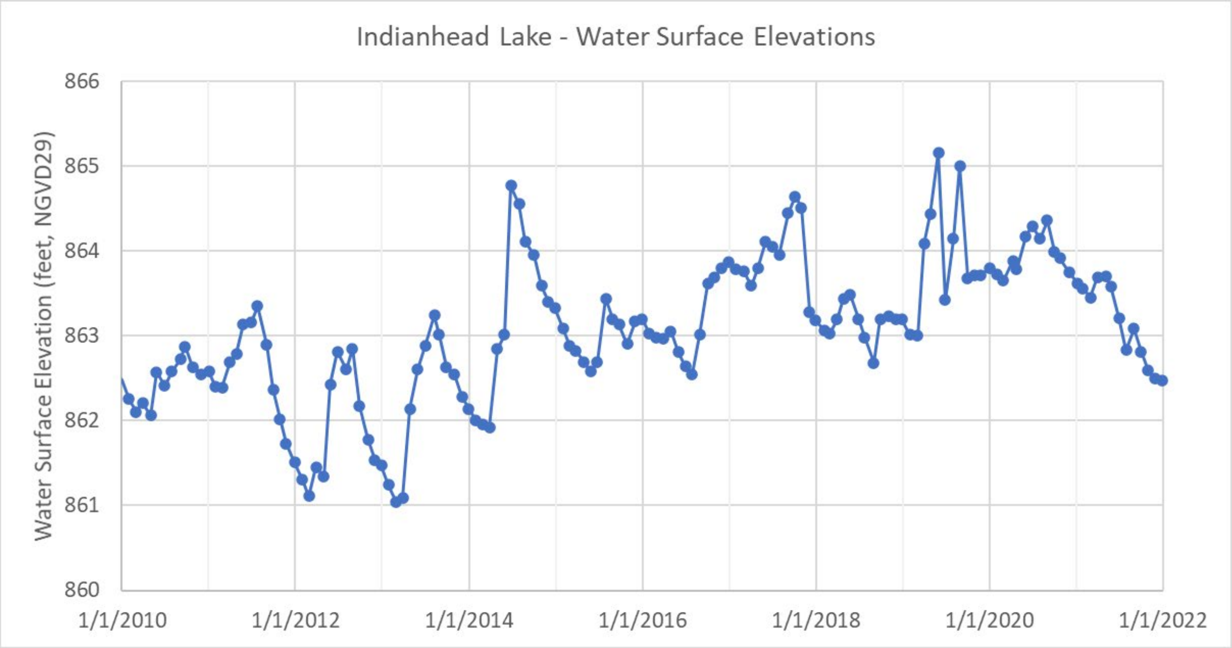


Figure 5-18 Observed Water Surface Elevations on Indianhead Lake

6.0 Water Quality Modeling

Computer modeling was used in this study to estimate stormwater runoff and pollutant contributions from the watershed and link water and nutrient loading to observed nutrient concentrations in the water column of the lake (e.g., total phosphorus, orthophosphate, Total Kjeldahl Nitrogen (TKN), nitrate/nitrite). In-lake modeling included simulation of dynamic internal lake processes such as phosphorus release from lake sediments (internal sediment loads), phytoplankton/macrophyte nutrient uptake, and phytoplankton/macrophyte death and decay. The in-lake model was also updated to include algorithms to calculate effects of in-lake management efforts such as copper sulfate treatments to reduced algal abundance. The watershed and in-lake models were used to simulate conditions in 2020. Model year 2020 was typical of the variability that Arrowhead or Indianhead Lake may experience from a watershed loading, in-lake loading, and biological variability perspective.

6.1 P8 Model Runoff and Phosphorus Loading

Central to a lake water quality analysis is the use of a water quality model that has the capacity to predict the amount of runoff and pollutants that reach a lake via stormwater runoff (external loading). The P8 (Program for Predicting Polluting Particle Passage through Pits, Puddles and Ponds) modeling software was used to estimate watershed loads to the lake (I.E.P, Inc., 1990). The P8 model incorporates hourly precipitation and daily temperature data. The P8 model was used to calculate the daily water volume and nutrient loads introduced from each tributary subwatershed in the Arrowhead and Indianhead Lake watersheds.

P8 model inputs included:

- **Climate Data:** hourly precipitation (source: Bryant Lake precipitation gages) and daily temperature (source: National Weather Service gage at Minneapolis-St. Paul International Airport, MSP)
- **Watershed:** tributary land areas (both pervious and impervious), soil conditions
- **Conveyance:** storm sewer system
- **Best management practices:** ponds, including the water storage and solids and phosphorus settling functionalities

The P8 model was run for the Arrowhead and Indianhead Lake watersheds for water year 2020.

Since inflow water quantity or quality data were not collected for Arrowhead or Indianhead Lakes on a subwatershed-scale, detailed calibration of the P8 models was not conducted. Therefore, the accuracy of P8 model outputs, used as inputs for the in-lake model (described below) were critically evaluated through the in-lake modeling process. In-lake model calibrations confirmed that total phosphorus concentrations predicted by the P8 model were best-suited for considering relative changes in loading under varying watershed conditions. However, the total nitrogen and orthophosphate concentrations predicted by the P8 model needed to be modified during the in-lake calibration process. The inflow orthophosphate concentrations were reduced by 90% for the entire modeling period (April – October). P8 nitrogen inflow concentrations were increased by applying a multiplier on a month-by-month basis to match in-lake concentrations (e.g., Arrowhead Lake P8 nitrogen inflow concentrations increased by 1 – 5 times, Indianhead Lake P8 nitrogen inflow concentrations increased by 10 times).

6.1.1 P8 Model Updates

A P8 watershed model was developed for the previous Arrowhead and Indianhead Lake UAA that was based on City of Edina land use information from 2003. Since then, a limited number of permit applications have been submitted to NMCWD for projects within the Arrowhead and Indianhead Lake watersheds. This is not surprising since the watersheds were nearly fully developed in 2003. The permit applications submitted since 2003 were reviewed and no changes were made to the existing P8 model.

6.2 Water Balance Calibration

6.2.1 Precipitation and Runoff

The annual water and watershed nutrient loads to Arrowhead and Indianhead Lake under existing land use conditions were estimated for model year 2020. Precipitation totals during model year 2020 are summarized in Table 6-1 (source: Bryant Lake precipitation gages).

Table 6-1 Modeled total precipitation for the 2020 Growing Season (May 1 through Sept. 30)

Model Year	Growing Season (May 1 through Sept 30) Precipitation (inches)
2020	21.2

6.2.2 Stormwater Volume Calibration (Water Balance)

Water balance models were developed for Arrowhead and Indianhead Lake. The changes in water volumes of the lake over time were calibrated by matching the modeled surface elevations to monitored data. To translate the water loadings into water surface elevations, a water balance model was utilized. The model uses estimated daily watershed runoff inflows (predicted by P8 models), daily precipitation, daily evaporation, estimated groundwater inflow or outflow, and observed lake levels to estimate changes in the water level of the lake. Since both lakes are land locked, no discharge rating curves were used.

Figure 6-1 shows the water balance calibration that was completed for Arrowhead Lake for model year 2020. The predicted water levels, shown by the orange line on the plot, were calibrated to match as closely as possible to the observed monthly water levels, indicated by the blue circles. Model calibration showed groundwater outflow in model year 2020 for Arrowhead Lake.

Figure 6-2 shows the water balance calibration that was completed for Indianhead Lake for model year 2020. The predicted water levels, shown by the orange line on the plot, were calibrated to match as closely as possible to the observed monthly water levels, indicated by the blue circles. Model calibration showed groundwater inflow from April through June in model year 2020 for Indianhead Lake.

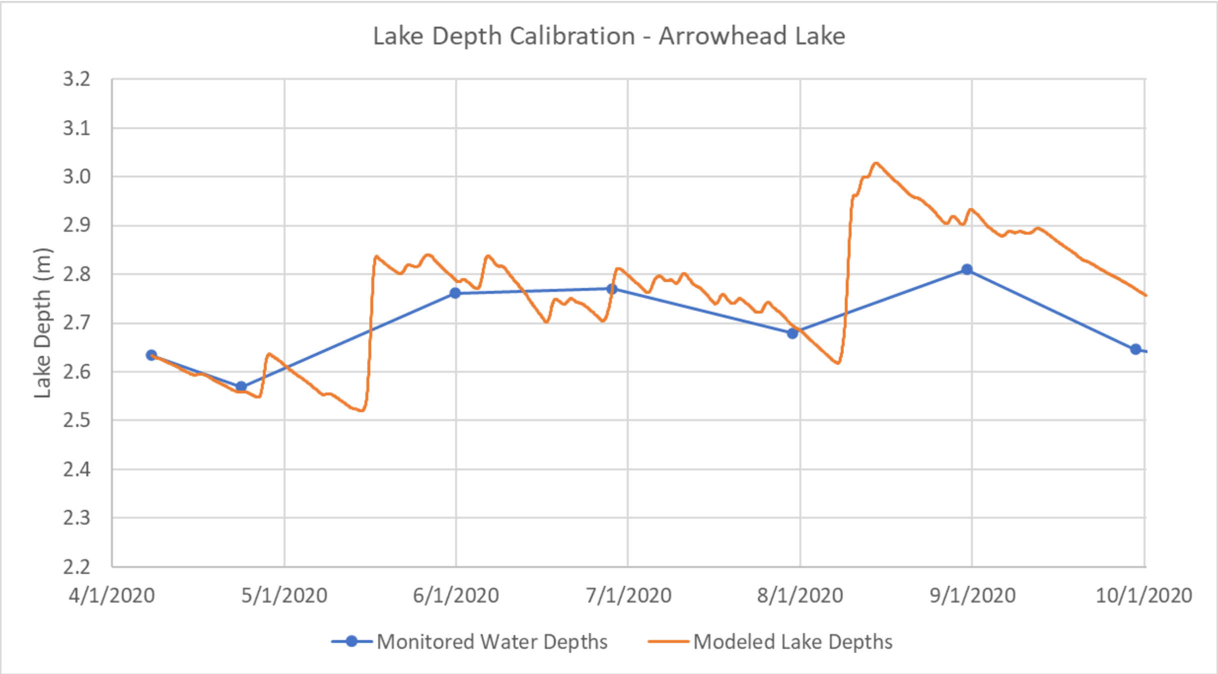


Figure 6-1 Arrowhead Lake (2020) Water Balance

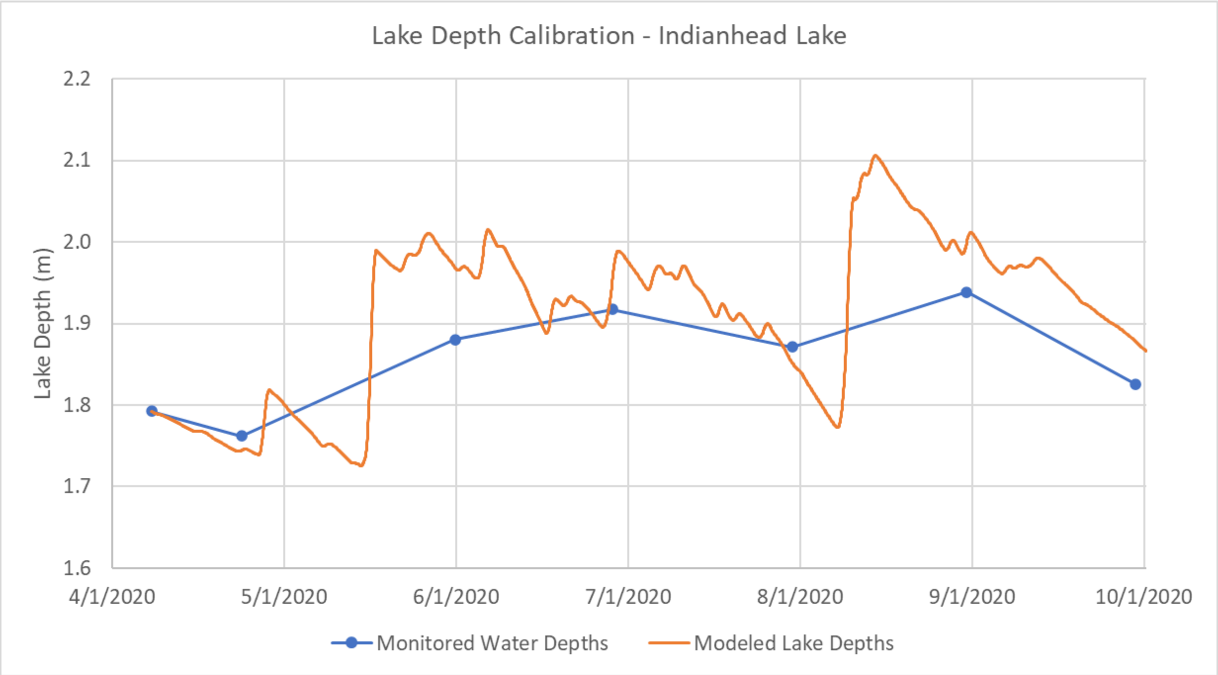


Figure 6-2 Indianhead Lake (2020) Water Balance

Overall, the water balance calibrations for both Arrowhead Lake and Indianhead Lake correlate well with the observed monitored data. Figure 6-3 provides a water balance volume comparison for Arrowhead and Indianhead lakes for 2020. Since both lakes are landlocked, in-lake nutrient processes as well as the quality and quantity of watershed inflows, will have an impact on the lakes' overall water quality.

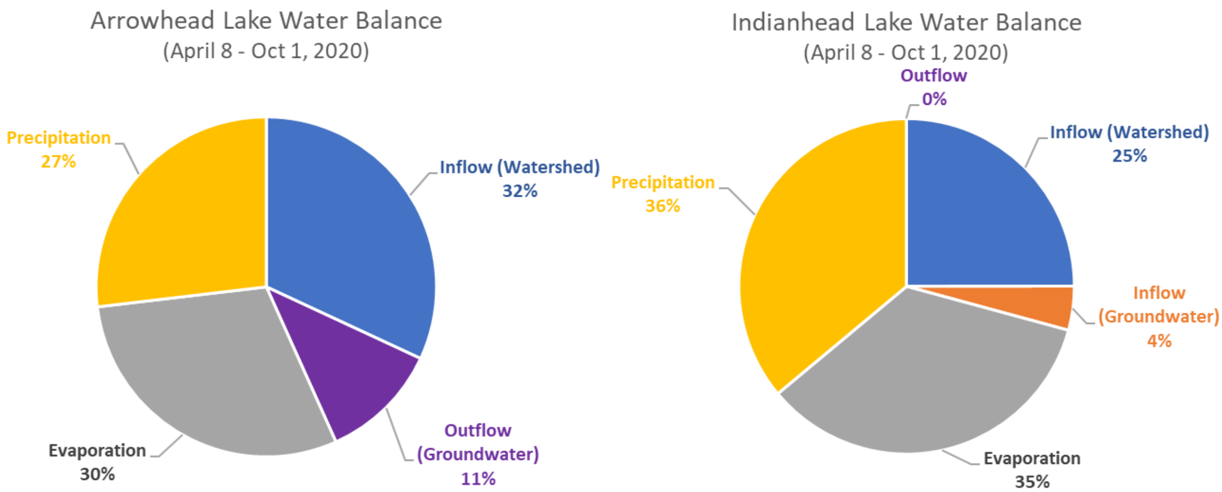


Figure 6-3 Arrowhead Lake and Indianhead Lake water balance summaries

6.3 In-Lake Modeling

The purpose of in-lake modeling is to establish a relationship between the amount of nutrients that enter a lake and the concentration of these nutrients that remain in a lake. Generally, for freshwater lakes, phosphorus is the main nutrient of concern and is discussed in greater detail in this report. However, nitrogen also plays a role in limiting growth in lakes and is also discussed.

There are several processes that dynamically increase or decrease the concentration of phosphorus in the lake water column, including (the "-" or "+" indicates that the mechanism generally either reduces or increases phosphorus):

- **Watershed Runoff (+):** Phosphorus enters the lake through natural channels, sheet flow from turfed backyards, and discharge from storm sewer pipes following precipitation or snow melt events.
- **Atmospheric Deposition (+):** Phosphorus deposits into the water body from the atmosphere
- **Settling (-)**: Phosphorus in phytoplankton and attached to particles settles out of the lake water column to the sediments.
- **Flushing (-)**: Typically represents the phosphorus that is discharged through an outlet structure. Since Arrowhead and Indianhead Lakes are land-locked, this includes phosphorus that is discharged to groundwater.
- **Lake Bottom Sediment Loading (+)**: Mobile phosphorus from lake bottom sediments may release into the water column during low oxygen conditions. Organic phosphorus will release as

bacteria breakdown debris in the lake sediment that contains phosphorus (e.g., decaying leaves, plants, and algae). This is typically referred to as internal loading.

- **Phytoplankton and macrophyte growth (-):** Phosphorus will be removed from the water column and the sediment through uptake by phytoplankton and macrophytes during the growth phase.
- **Phytoplankton and macrophyte die-off and decay (+):** Phosphorus in the phytoplankton and plant tissues is released into the water column when the species die and decay.
- **Curly-leaf pondweed die-off and decay (+)**: Phosphorus in the plant tissue is released into the water column when curly-leaf pondweed dies and decays. Curly-leaf pondweed die-off and decay occurs much earlier than other native plant species (typically in late June and July), so this species is modeled separately.
- **Copper sulfate treatment (-):** Copper sulfate is applied as an algal management technique. Monitoring data indicates that the type of copper sulfate application used in Arrowhead and Indianhead not only removed algae from the water column, but also coagulated and flocculated out total phosphorus from the water column.

The in-lake model used for this study is a finite difference lake model developed by Barr Engineering Co. The model integrates the phosphorus inputs and losses described above on an hourly time-step. The lake model is considered to be zero-dimensional, meaning, it is assumed that every input to the model is completely mixed both vertically and horizontally in the lake water column. Biological components, as discussed above, include phytoplankton and macrophytes (aquatic plants and attached filamentous algae) and growth is dependent upon phosphorus, nitrogen, light, and temperature. Macrophytes can derive nutrients from the sediment and the water column. Each of these processes occur at different levels during different periods and hence they are quantified (e.g., calibrated) by matching the in-lake phosphorus and nitrogen concentrations with the field-measured phosphorus and nitrogen concentrations.

6.3.1 In-Lake Water Quality Model Calibration

Calibration is a process in which model parameters and coefficients are reasonably adjusted such that the model predictions are similar to in-lake measurements. The Arrowhead and Indianhead Lake models were calibrated to the following water quality parameters:

- Total Phosphorus (TP)
- Orthophosphate (Ortho-P)
- Chlorophyll-*a*
- Total Kjeldahl Nitrogen (TKN)
- Nitrate + Nitrite

Example in-lake model calibrations for Arrowhead Lake and Indianhead Lake are provided below. Figure 6-4 and Figure 6-5 show the 2020 calibrations for TP and TKN concentrations in Arrowhead Lake, respectively. The orange line represents the modeled in-lake concentrations, and the blue circles represent the monitored concentrations. Figure 6-6 and Figure 6-7 show the TP and TKN in-lake model calibrations for Indianhead Lake in 2020. Plots showing all parameters used for calibration can be found in Appendix C.

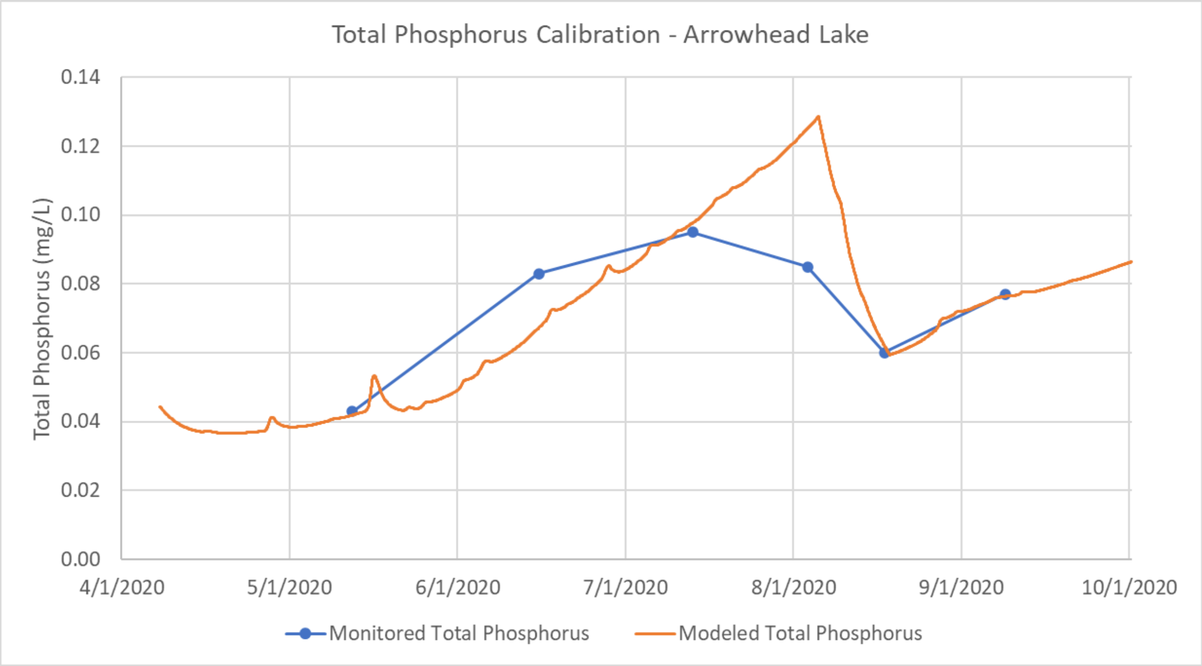


Figure 6-4 Arrowhead Lake In-Lake Total Phosphorus Calibration

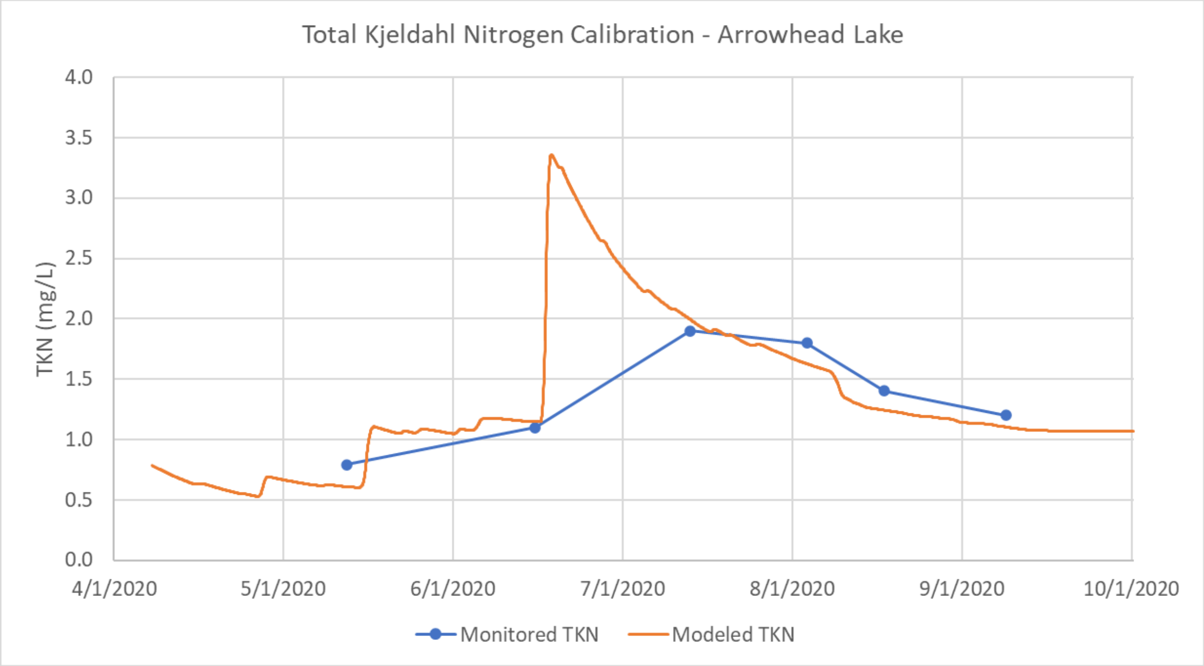


Figure 6-5 Arrowhead Lake In-Lake Total Kjeldahl Nitrogen Calibration

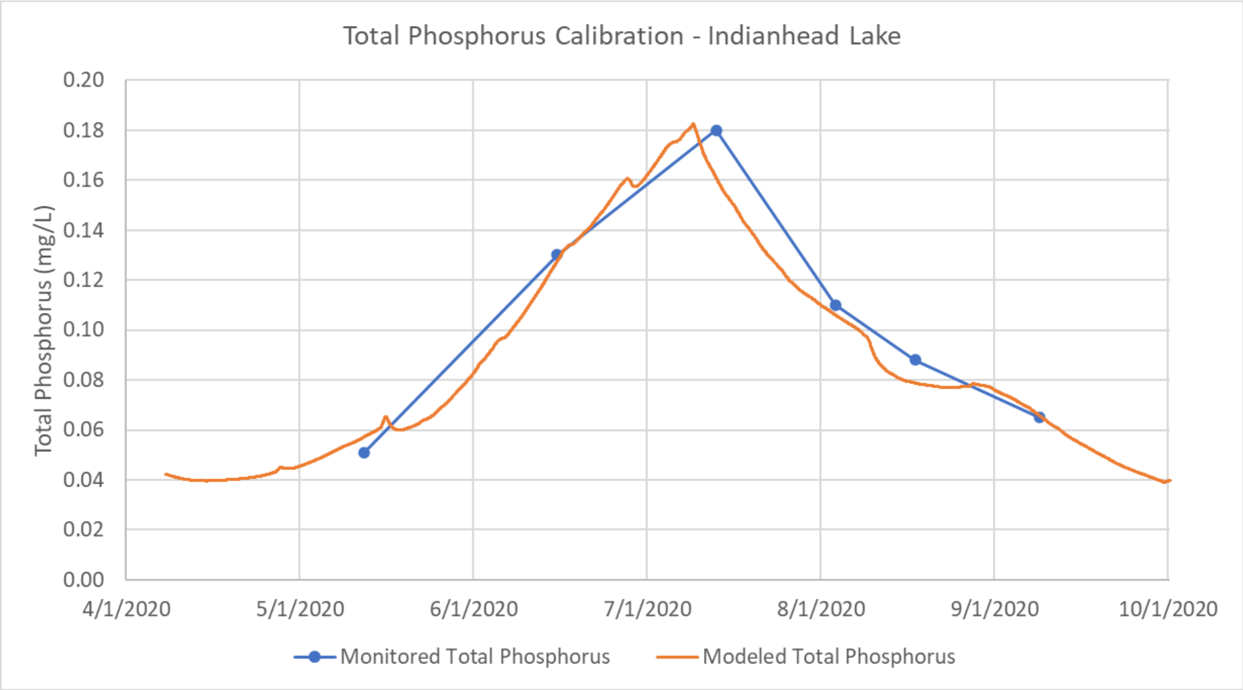


Figure 6-6 Indianhead Lake In-Lake Total Phosphorus Calibration

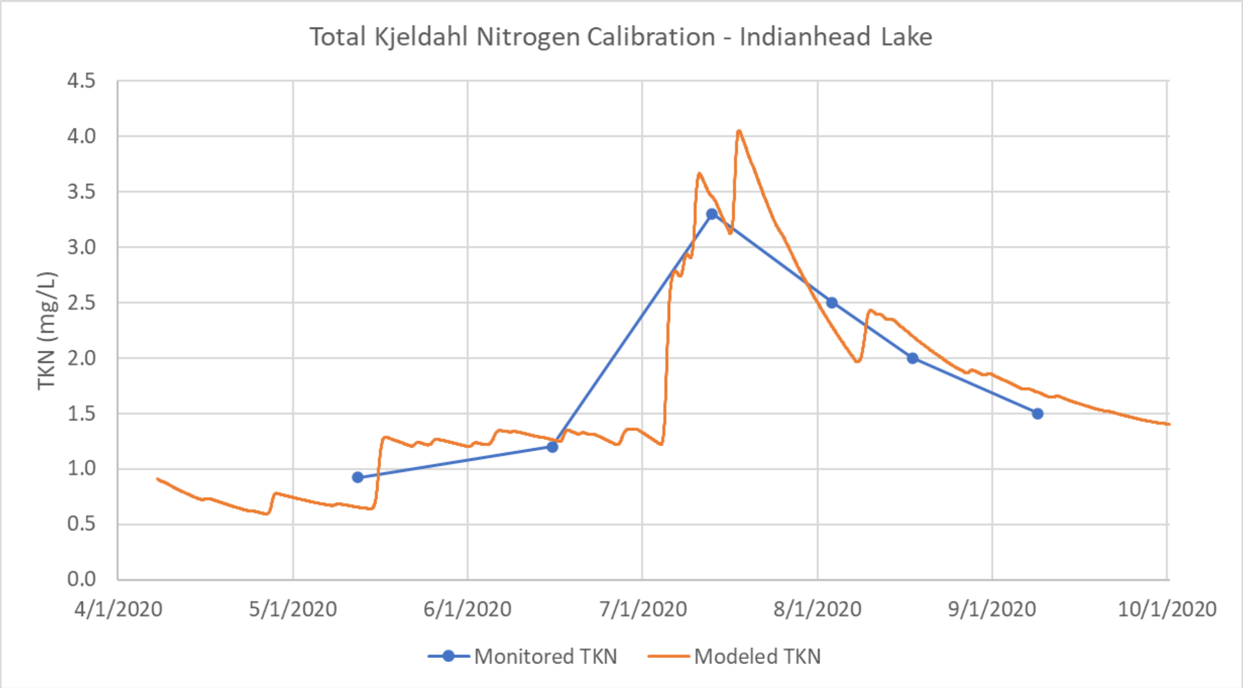


Figure 6-7 Indianhead Lake In-Lake Total Kjeldahl Nitrogen Calibration

6.3.2 In-Lake Water Quality (Phosphorus) Model Calibration Loading Summaries

After the in-lake water quality model calibrations were finalized, loading summaries were developed. Figure 6-8 shows the total phosphorus loading summaries for Arrowhead and Indianhead Lakes during the 2020 growing season (June – Sept). The percentage of total phosphorus loading from the watershed and the sediment were similar for Arrowhead Lake. The in-lake calibration shows that approximately 54% of the total phosphorus load to Arrowhead Lake during the modeled period of 2020 was from the sediment (internal loading). The remaining 46% of the total phosphorus load entered from watershed runoff. For Indianhead Lake, a much larger percentage of the total phosphorus load came from the sediment (84%) and a smaller portion entered from watershed runoff and groundwater inflow (16%).

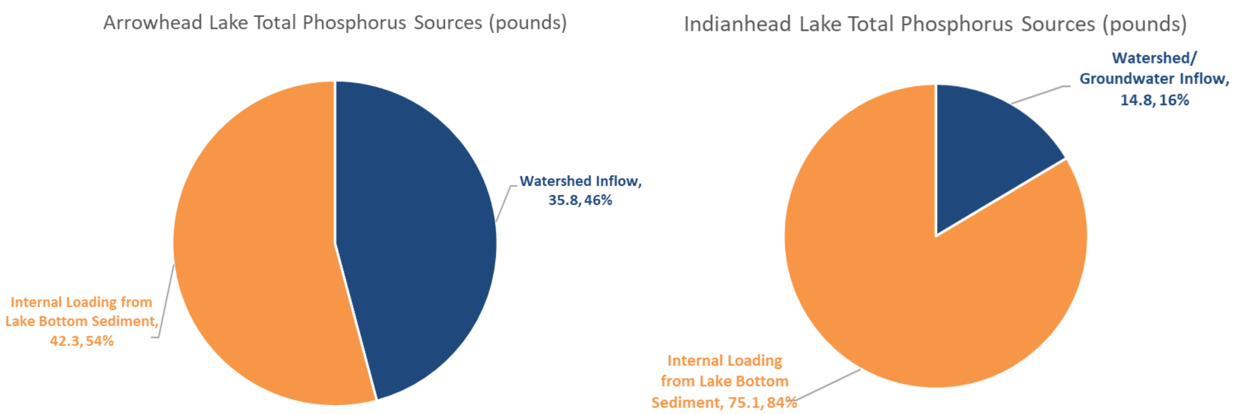


Figure 6-8 2020 Total Phosphorus Loading Summaries (Watershed and Internal Loading from Lake Bottom Sediment) from Arrowhead and Indianhead Lakes In-Lake Calibration Models

6.3.3 In-Lake Water Quality Additional Observations

6.3.3.1 Copper Sulfate Impacts to In-Lake Water Quality

Water quality monitoring data collected approximately monthly from Arrowhead and Indianhead Lakes in 2020 indicates that the copper sulfate treatments applied to both lakes not only impacted phytoplankton (i.e., chlorophyll-*a* concentrations), but also impacted the total nitrogen and total phosphorus concentrations. The in-lake model calibrations from Indianhead Lake are shown below as an example.

A contractor was hired to apply a copper sulfate treatment to Indianhead Lake on July 8, 2020. Figure 6-9 shows the impact to chlorophyll-*a* concentrations due to the copper sulfate treatment. The orange line represents the modeled in-lake concentrations, and the blue circles represent the monitored concentrations. As expected, chlorophyll-*a* concentrations decreased after the copper sulfate treatment because of the toxic effect on algal species.

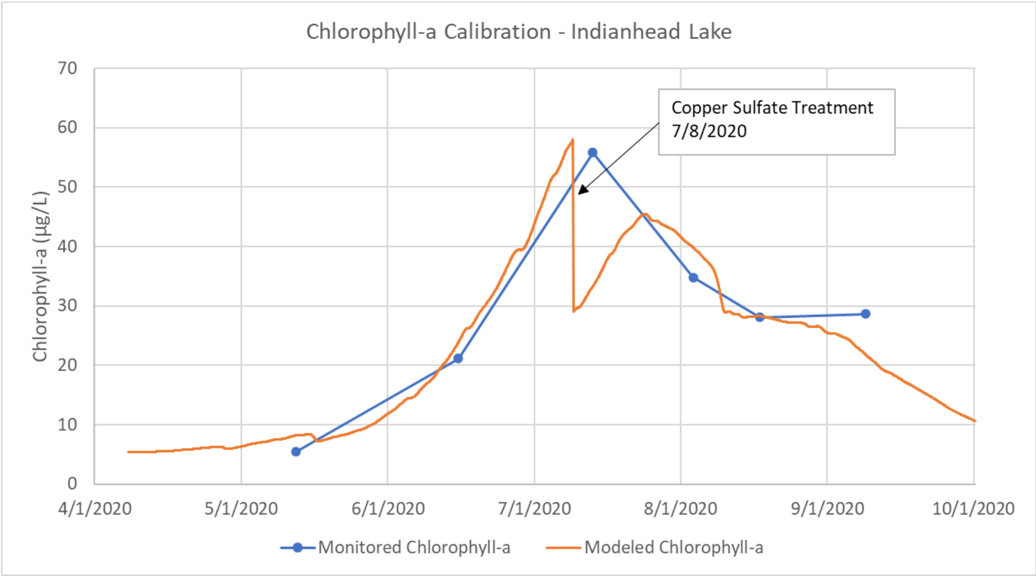


Figure 6-9 Indianhead Lake Chlorophyll-*a* calibration impacted by copper sulfate

Unexpectedly, the copper sulfate treatment also decreased the total phosphorus concentrations in Indianhead Lake following the application. The orange line in Figure 6-10 shows the calibrated total phosphorus concentrations compared to the monitored data represented with the blue circles. The purple line shows the expected total phosphorus concentrations if a copper sulfate treatment was not applied to the lake. From this purple line, we can see that the total phosphorus concentrations in late-summer and early-fall would have been significantly higher without the copper sulfate treatment. Therefore, it is hypothesized that the type of copper sulfate treatment applied to Indianhead Lake in early-July 2020 coagulated and flocculated phosphorus suspended in the water column.

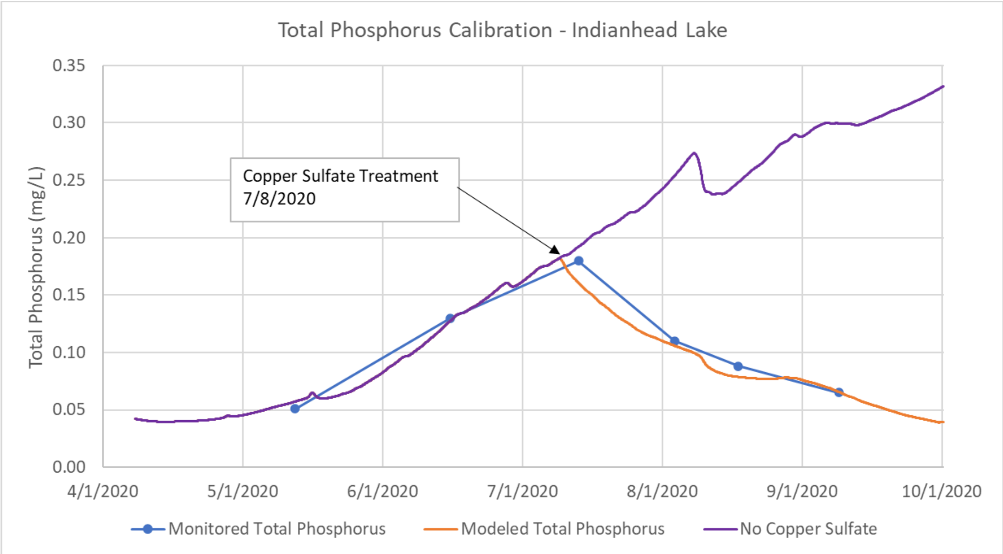


Figure 6-10 Impact of copper sulfate on Indianhead Lake total phosphorus calibration

Investigation of the monitoring data also indicated that a copper sulfate treatment has the potential to increase TKN concentration in Indianhead Lake. The orange line in Figure 6-11 shows the calibrated TKN concentrations compared to the monitored data represented with the blue circles. The purple line shows the expected TKN concentrations if a copper sulfate treatment was not applied to the lake. The purple line indicates that TKN concentrations in late-summer and early-fall would likely have been significantly lower without a copper sulfate treatment. Therefore, it is hypothesized that the type of copper sulfate treatment applied to Indianhead Lake was likely chelated. Chelation allows copper sulfate, which is normally in a solid form, to remain in a liquid state for spray applications. Chelated copper can also remain in the water column for longer periods, which can increase the toxicity to algae and extends the target application area. Several chelating agents can have high concentrations of nitrogen, and this is likely why we are seeing a large increase in nitrogen concentrations around the timing of the copper sulfate application. This was not confirmed as information on the application procedure and products was not available.

The impacts of copper sulfate treatment on chlorophyll-*a*, total phosphorus, and TKN were very similar in Arrowhead Lake.

To better understand and quantify the impacts of copper sulfate on water quality parameters (e.g., chlorophyll-*a*, TKN, total phosphorus), more rigorous monitoring could be employed before, during, and after future copper sulfate applications.

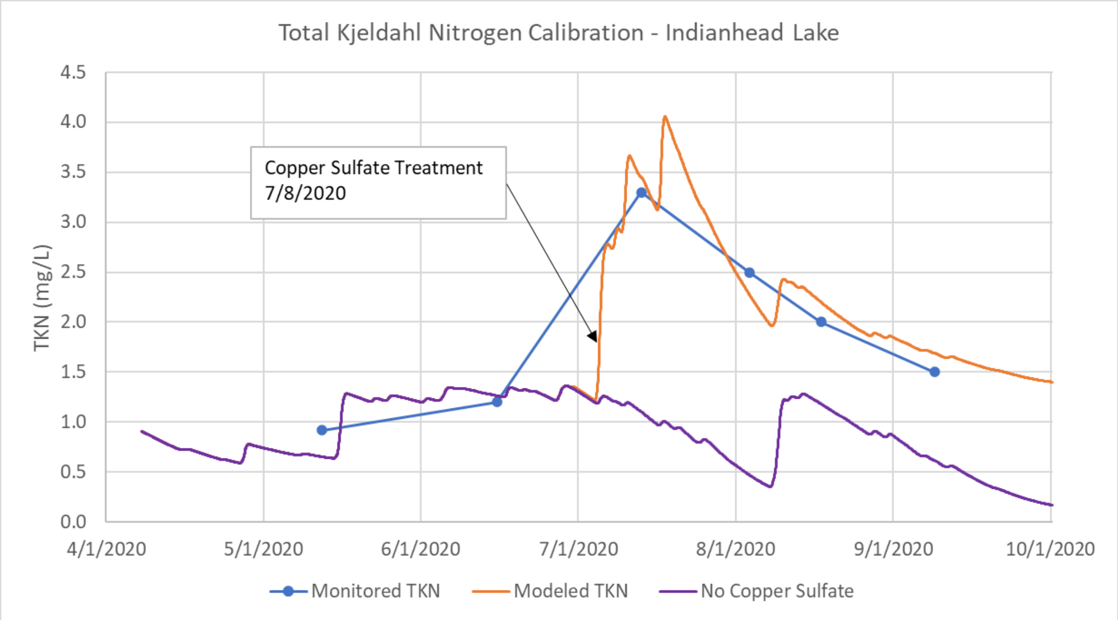


Figure 6-11 Impact of copper sulfate on Indianhead Lake total nitrogen concentrations

6.3.3.2 Macrophyte Nutrient Uptake

Macrophytes provide many benefits to lake ecosystems, including the uptake of nutrients. Model results indicate that phosphorus uptake by aquatic plants in Arrowhead Lake in 2020 likely created competition for phytoplankton and kept phytoplankton concentrations lower than they would be with fewer aquatic plants.

Macrophyte management through herbicide treatments or mechanical removal has been completed in Indianhead Lake for a number of years. Although, lake-wide submerged macrophyte removal was stopped in spring 2019, macrophyte surveys in 2019 and 2020 indicate limited submerged macrophytes throughout the lake. As such, macrophytes are not available to utilize nutrients in the lake providing minimal competition with phytoplankton (algae).

6.3.3.3 Phytoplankton Limitation

Throughout the growing season, various factors can influence the rate and volume of phytoplankton growth, such as phosphorus, nitrogen, light, and temperature. The model uses Michaelis Menten kinetics to determine which factor or combination of factors limit growth throughout the modeled time period.

As part of the calibration process, plots were developed that show which factors limited phytoplankton growth over the model period. Figure 6-12 and Figure 6-13 show the phytoplankton limitation plots for Arrowhead Lake and Indianhead Lake, respectively. A phytoplankton limitation value of 0 indicates complete limitation and a value of 1 indicates no limitation. Therefore, the closer a line approaches the x-axis, the more limiting the factor. The limitation factors summarized include light, phosphorus (orthophosphate, organic phosphorus), and nitrogen (nitrates).

In Arrowhead Lake, nitrogen, phosphorus, and light showed similar phytoplankton limitation during the spring of 2020. From May through mid-June, nitrogen was the most limiting factor, although not significantly more than phosphorus. For the remainder of the summer, phosphorus was the most limiting factor for phytoplankton growth in Arrowhead Lake.

For Indianhead Lake, nitrogen and light were limiting phytoplankton growth from April through early June 2020 due to excess orthophosphate in the water column in spring and early summer. From early-June through late-July, nitrogen was the most limiting factor. From late-July through early-fall, the most limiting factor changed from nitrogen to phosphorus. Review of the data suggests that the stronger nitrogen limitation in Indianhead Lake is likely because the growth rate of phytoplankton is greater than the degradation rate of nitrogen (slow decomposition from organic nitrogen forms to ammonia and/or slow nitrification rate changing ammonia to nitrite and nitrate). In other words, the phytoplankton continue to grow until they have used up nitrate in the water column, which limits how much phytoplankton biomass is produced. Monitoring data in 2020 also show high concentrations of total Kjeldahl nitrogen in Indianhead Lake (summer average 2.1 mg/L), which further suggests that the nitrogen limitation in the lake is influenced more by the rate of degradation of nitrogen into different forms rather than the total mass of nitrogen in the lake.

The phytoplankton growth limitations developed during model calibration reflect which parameters are currently limiting growth. As management is implemented, the phytoplankton growth limitations will change. For example, if phosphorus loading from lake bottom sediment is reduced, phosphorus limitation may become more dominant throughout the growing season. However, since the calibrated models indicate that the lakes are partially limited by nitrogen for portions of the growing season under current conditions, this indicates that nitrogen management can be a complementary management approach with phosphorus reduction.

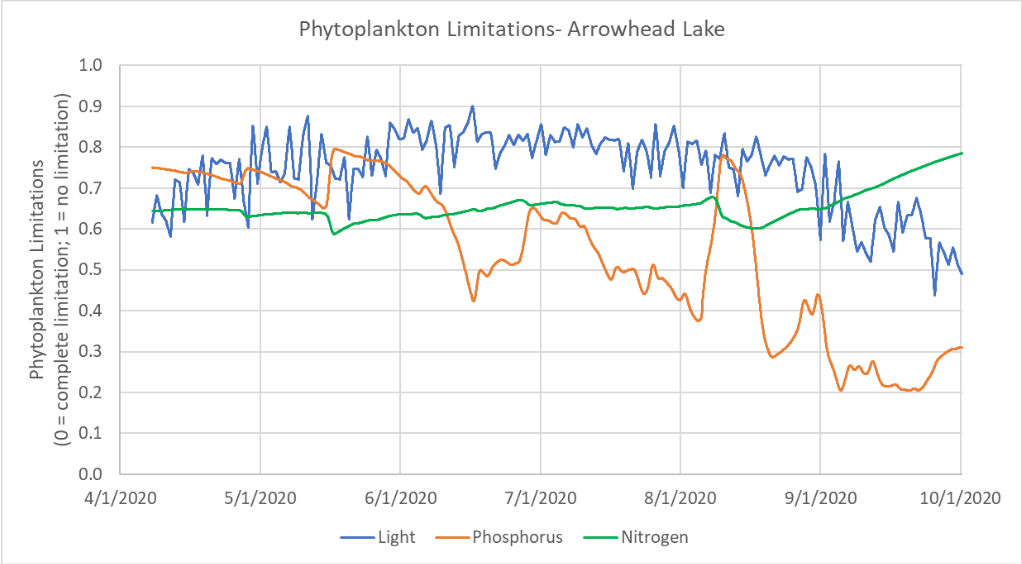


Figure 6-12 Phytoplankton Growth Limitation in Arrowhead Lake in 2020

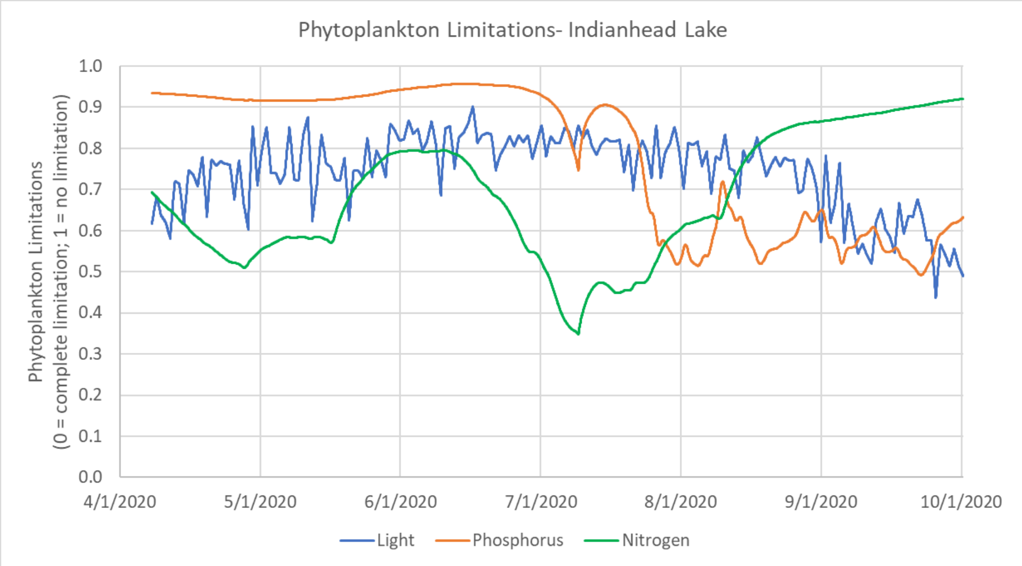


Figure 6-13 Phytoplankton Growth Limitation in Indianhead Lake in 2020

6.3.3.4 Curly-leaf Pondweed as a Phosphorus Source

The presence of curly-leaf pondweed and its mid-summer die-off can negatively impact the water quality of a shallow lake. When lakes start to accumulate a prolific growth of curly-leaf pondweed, a spike in in-lake total phosphorus concentration is generally observed during the same period of curly-leaf pondweed die-off and decay. The City of Edina has been monitoring and treating for curly-leaf pondweed in Arrowhead Lake since 2017 and Indianhead Lake since 2019. Therefore, curly-leaf pondweed did not influence water quality in Arrowhead and Indianhead Lakes in 2020.

7.0 Public Engagement

Public engagement is an important part of completing and implementing water quality studies for lakes in the Nine Mile Creek watershed. For this study, public engagement included two public meetings and a survey of residents living adjacent to the lakes, both discussed further below.

7.1 Public Stakeholder Meetings

Because the recommendations that stem from this study will impact residents adjacent to Arrowhead and Indianhead Lakes, input from residents was sought at two public engagement meetings. The meetings allowed NMCWD to gain further insight on lake use and historic management through comments, photos, and data provided by residents. The meetings also presented an opportunity to get feedback from the public on lake management options and willingness to participate in various activities to improve lake water quality.

7.1.1 Public Engagement Meeting #1- May 25, 2021

The first public stakeholder engagement meeting was held virtually due to the ongoing Covid-19 pandemic and public safety concerns. In early May 2021, a postcard was mailed to Arrowhead Lake and Indianhead Lake residents informing them of a planned virtual community meeting held via Zoom on May 25, 2021. At this meeting, the NMCWD staff and engineers, as well as City of Edina staff provided an overview of the upcoming study and goals for future management of the lakes. Following the background presentation on the study, the remainder of the meeting involved open discussion with residents regarding their observations and concerns regarding lake health. During the meeting, residents were informed that a formal survey would be mailed to all residents living on the lakes and made available online so that the NMCWD could gather additional feedback from residents. Comments provided during the virtual community meeting in May 2021 were considered during the development of management recommendations and will continue to be considered during implementation of recommended lake management activities.

7.1.2 Public Engagement Meeting #2 – April 19, 2022

In early April 2021, a postcard was mailed to Arrowhead Lake and Indianhead Lake residents informing them of a planned community meeting held at Edina Public Works on April 19, 2022. At this meeting, the NMCWD staff and engineers, as well as City of Edina staff provided an overview of the study conclusions and anticipated timeline of the proposed lake management activities. Following the background presentation on the study, the remainder of the meeting involved open discussion with residents to answer questions and address concerns. Comments provided during the community meeting in April 2022 were considered during development of the final water quality report and will continue to be considered during implementation of recommended lake management activities.

7.2 Resident Survey

NMCWD developed a survey for residents living adjacent to Arrowhead and Indianhead Lakes to better understand residents' lake use, values and perceptions related to the lakes, concerns and issues, current management activities, and willingness to participate in lake improvement efforts. Residents were able to participate in the survey via a paper survey received in the mail or online. The online survey was active from July 9 through August 16, 2021, and paper surveys were mailed to residents before July 9, 2021. Thirty-five (35) surveys were mailed to Arrowhead Lake residents and 33 surveys were mailed to Indianhead Lake residents. Of the 68 surveys mailed to residents, 31 responses were received (either mailed back or answers provided online). Of the 31 responses, 14 responses were received from Arrowhead Lake, and 17 responses were received from Indianhead Lake.

The survey was intended to provide additional community feedback to assist in the evaluation of management strategies and to provide additional observations, photos, and data to help define lake health. A summary of the survey questions and provided responses can be found in Appendix D. Comments provided in the survey were considered during the development of management recommendations and will continue to be considered during implementation of recommended lake management activities.

8.0 Conclusions and Recommendations

8.1 Conclusions

Recent monitoring data indicates that Arrowhead Lake and Indianhead Lake are not meeting Minnesota's water quality standards for shallow lakes.

The summer average (June 1-Sept 30) total phosphorus concentrations measured in 2004, 2014, 2019, and 2020 in Arrowhead Lake were above the shallow lake standard of 60 µg/L. The Arrowhead Lake summer average chlorophyll-*a* concentrations measured in 2011, 2014, and 2020 were also above the shallow lake standard of 20 µg/L and the summer average Secchi disk transparency depths in 2019 and 2020 were less than the 1.0 meter Secchi depth standard (Figure 8-1).

The plant surveys completed from 2014 through 2020 in Arrowhead Lake indicate declining health of the macrophyte plant community. In August 2014, 10 plant species were observed in Arrowhead Lake. The number of species observed in Arrowhead Lake in 2019 ranged from 6 – 7 species, while 2 species were observed in 2020. The decrease in observed species may be the result of degrading water quality (e.g., reduced lake clarity) and plant management activities.

Phytoplankton (microscopic aquatic algae) populations in Arrowhead Lake generally increased from 2004 through 2020. In 2004, the summer average phytoplankton abundance was 13,350 per milliliter. In 2020, the summer average phytoplankton abundance increased to 48,845 per milliliter. Blue-green algae abundance increased from 2004 to 2020. The highest concentration of blue-green algae was sampled in July 2020 at 76,960 per milliliter, which is above the low probability of adverse health effects level set by the World Health Organization (WHO).

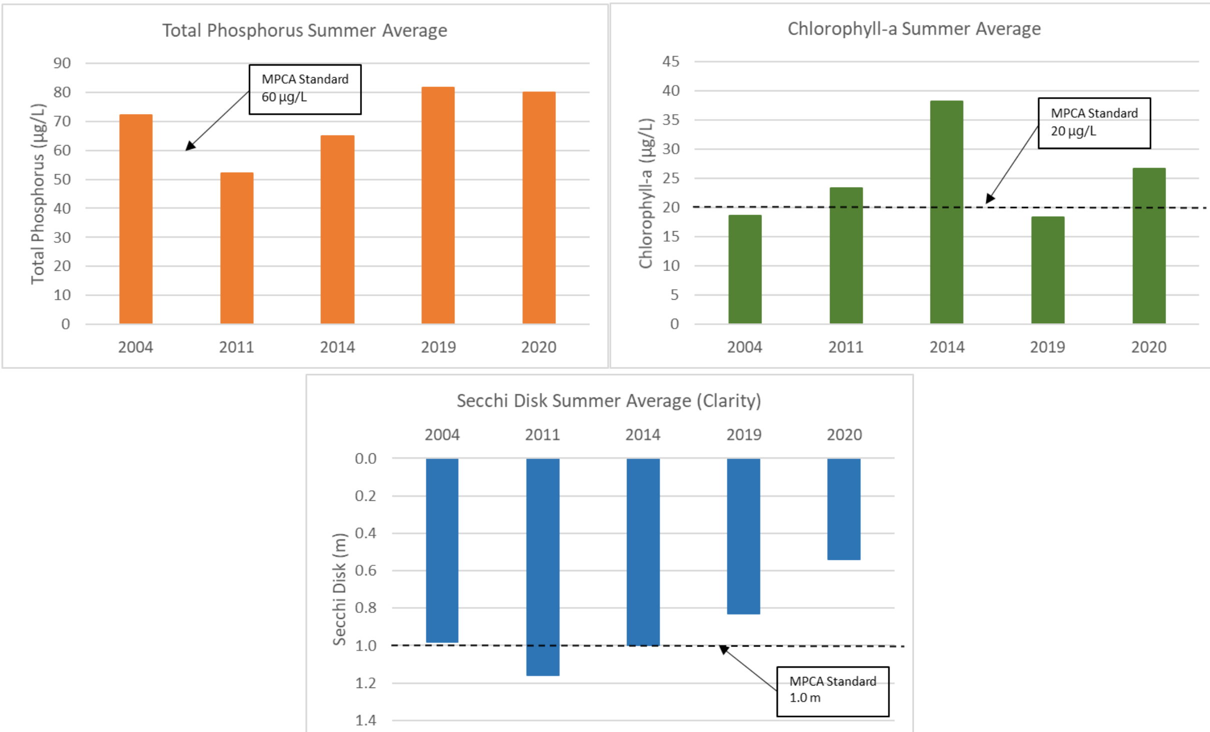


Figure 8-1 Summer average total phosphorus and chlorophyll-*a* concentrations and Secchi disk depth measured in Arrowhead Lake between 2004 and 2020

For Indianhead Lake, water quality has generally declined between 2004 and 2020. The summer average (June 1-Sept 30) total phosphorus concentrations measured in 2019 and 2020 in Indianhead Lake were above the shallow lake standard of 60 µg/L. The Indianhead Lake summer average chlorophyll-*a* concentrations measured in 2011, 2014, and 2020 were also above the shallow lake standard of 20 µg/L and the summer average Secchi disk depths in 2014, 2019, and 2020 were less than the 1.0 meter Secchi depth standard (Figure 8-2).

The plant surveys completed from 2004 through 2020 in Indianhead Lake indicate poor health of the macrophyte plant community. The number of plant species observed in Indianhead Lake from 2004 to 2020 was consistently low, ranging from 3 – 5 species. The observed lower species count may be caused by degraded water quality (e.g., reduced lake clarity); however, this correlation is difficult to ascertain due to yearly plant management efforts.

Changes in phytoplankton populations monitored from 2004 through 2020 corresponded with water quality (e.g., total phosphorus, chlorophyll-*a*, Secchi disk depth) changes, both reflecting degrading water quality in Indianhead Lake over time. In 2004, the summer average phytoplankton abundance was 16,550 per milliliter. In 2020, the summer average phytoplankton abundance increased to 76,430 per milliliter. Blue-green algae abundance increased from 2004 to 2020. The highest concentration of blue-green algae was sampled in July 2020 at 144,740 per milliliter, which is above the WHO threshold for moderate probability of adverse health effects.

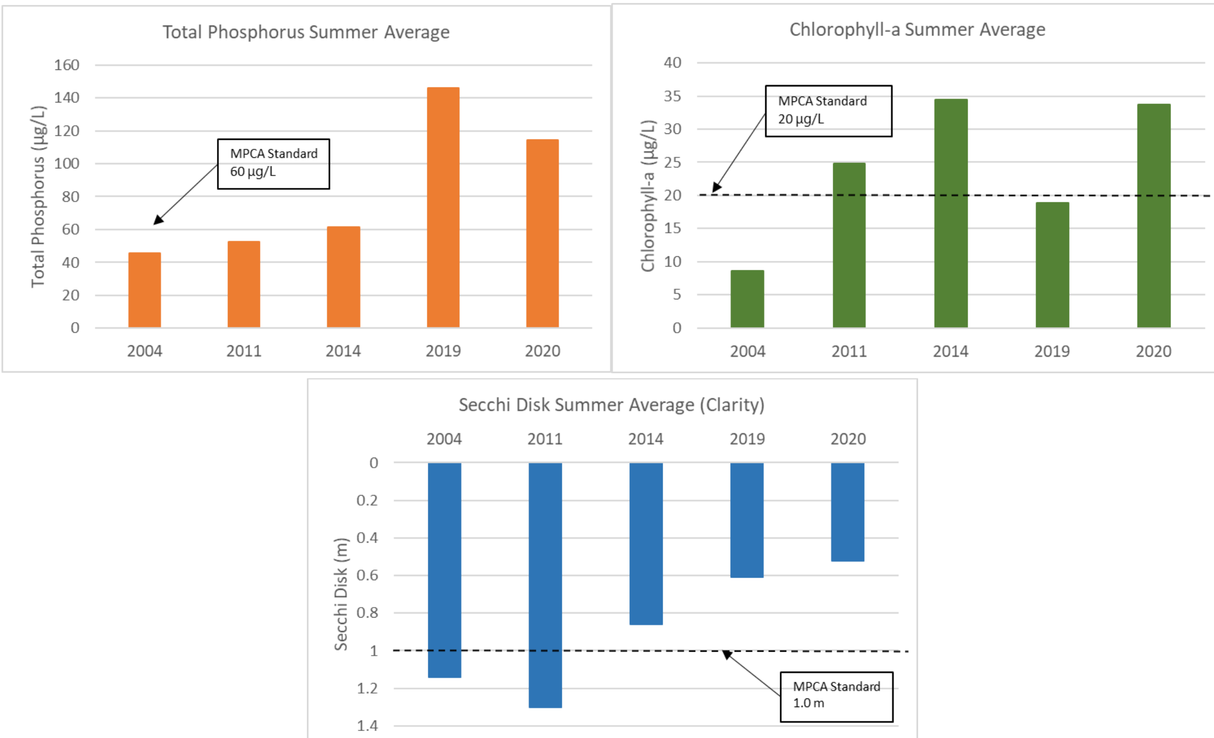


Figure 8-2 Summer average total phosphorus and chlorophyll-*a* concentrations and Secchi disk depth measured in Indianhead Lake between 2004 and 2020

8.2 Recommendations

Water quality in Arrowhead and Indianhead Lakes has declined in the past decade and the lakes currently do not meet water quality standards and ecological health goals. Given this, future management efforts should be focused on improving lake water quality and ecosystem health with monitoring to assess progress toward goals and overall changes. The following sections summarize the recommended monitoring and management strategies for Arrowhead and Indianhead Lakes. These recommended management efforts are based on a review of available monitoring data and in-lake modeling to predict improvements resulting from management activities. The modeled water quality improvements can be viewed in Appendix E (i.e., changes to in-lake phosphorus, nitrogen, and chlorophyll-*a* concentrations).

8.2.1 Reduce Phosphorus Loading from Lake Bottom Sediment (Internal Loading)

In-lake modeling for this water quality study demonstrated that phosphorus release from bottom sediments (typically termed internal phosphorus loading) significantly affects lake water quality in both Arrowhead Lake and Indianhead Lake. Internal phosphorus loading represented 54% and 84% of the total phosphorus load to Arrowhead Lake and Indianhead Lake, respectively, for the summer growing period of June through September 2020.

For both lakes, most of the internal sediment loading was due to the release of organically bound phosphorus rather than the mobile phosphorus fraction. Phosphorus in lake bottom sediments is often bound to a range of different elements such as iron and manganese (often referred to as mobile phosphorus), aluminum, or calcium. It is the mobile phosphorus fraction that releases from sediment during low oxygen conditions. Phosphorus can also be found incorporated into organic matter (organically bound phosphorus). Organically bound phosphorus also releases phosphorus from lake sediment but typically at a slower rate than mobile phosphorus and the release rate is controlled by lake water temperature.

Sediment cores collected from Arrowhead and Indianhead Lakes in 2021 showed that the average concentration of organically bound phosphorus in the top 4 centimeters of sediment was significantly higher than mobile phosphorus. In Arrowhead Lake the average concentration of organically bound phosphorus was 36.1 mg P/cm^3 wet sediment, while the mobile fraction was 4.1 mg/cm^3 wet sediment. Similarly, for Indianhead Lake the average concentration of organically bound phosphorus was 39.6 mg P/cm^3 wet sediment, while the mobile fraction was 5.6 mg/cm^3 wet sediment. These observed concentrations indicate that a significantly larger percentage of internal phosphorus loading in both lakes is due to organically bound phosphorus (organic-P) rather than mobile phosphorus (mobile-P). Also, because Arrowhead and Indianhead Lakes are shallow, have small water volumes, and have no existing outlets, even a low internal loading rate can significantly increase phosphorus concentrations in the lake water column.

Because a higher proportion of the internal sediment loading is due to organic-P instead of mobile-P, internal phosphorus loading will need to be controlled with the addition of iron as well as alum. The iron addition is designed to capture phosphorus as it is released from the organic-P fraction. Iron is only effective when oxygen is high enough to keep the iron activated (i.e., in chemistry terminology the iron is oxidized). Hence, adequate oxygen levels in the lake are important for a successful iron treatment.

In summary, the following sediment management approach is recommended:

- Year 1 (May – September) - Monitor the effectiveness of the existing aerators in Arrowhead and Indianhead Lakes to determine the extent of bottom sediment aeration and decide if additional aeration is needed to cover a larger percentage of the bottom sediments. By enhancing the existing aeration systems, sediment treatments that require adequate dissolved oxygen concentrations can be applied to the lakes (e.g., iron).
- Year 2 or 3 (Spring) – Apply ferric chloride and alum (as sodium aluminate) to the lake to prevent internal load from organic phosphorus in lake bottom sediments. Install additional aerator in the north-west lobe of Arrowhead Lake and the south lobe of Indianhead if needed.

The in-lake models for Arrowhead and Indianhead Lakes were used to predict improvements in lake water quality by implementing the recommended sediment management approach. Since a sediment management approach that specifically targets organically bound phosphorus has not been widely applied in Twin Cities lakes, two assumptions for effectiveness of the internal load reduction from lake bottom sediment were applied (50% and 70% reduction in internal phosphorus loading from lake bottom sediments). Table 8-1 summarizes the estimated pounds of phosphorus removed from each lake during the growing season assuming the application of a sediment treatment. Table 8-2 summarizes the estimated reduction in 2020 summer-average total phosphorus and chlorophyll-*a* concentrations assuming a sediment treatment was applied to the lakes. The results presented in these tables assume copper sulfate treatments are no longer applied to manage algae.

In Arrowhead Lake, assuming a 50% - 70% reduction in internal loading from sediments, modeling indicates a reduction of 21 – 30 pounds of total phosphorus. This reduction in phosphorus load translates to a reduction in the summer average total phosphorus and chlorophyll-*a* concentrations. Modeling indicates that the 2020 summer average total phosphorus concentration of 80 µg/L in Arrowhead Lake would be reduced to 51 – 67 µg/L. The MPCA shallow lake total phosphorus water quality standard is 60 µg/L. A reduction in total phosphorus concentrations also leads to a reduction in chlorophyll-*a* concentrations. Modeling indicates that the 2020 summer average chlorophyll-*a* concentration of 27 µg/L would be reduced to 16 – 20 µg/L. The MPCA shallow lake chlorophyll-*a* water quality standard is 20 µg/L.

In Indianhead Lake, assuming a 50% - 70% reduction in internal loading from sediments, modeling indicates a reduction of 37 – 52 pounds of total phosphorus. This reduction in phosphorus load translates to a reduction in the summer average total phosphorus and chlorophyll-*a* concentrations. Modeling indicates that the 2020 summer average total phosphorus concentration of 115 µg/L in Indianhead Lake would reduce to 71 – 108 µg/L. The MPCA shallow lake total phosphorus water quality standard is 60 µg/L. A reduction in total phosphorus concentrations also lead to a reduction in chlorophyll-*a* concentrations. Modeling indicates that the 2020 summer average chlorophyll-*a* concentration of 34 µg/L would reduce to 20 – 30 µg/L. The MPCA shallow lake chlorophyll-*a* water quality standard is 20 µg/L.

Table 8-1 Growing season estimated pounds of phosphorus removed through management of internal loading from lake bottom sediments

Lake	Pounds of Phosphorus Removed (Growing Season)	
	Reduced Internal Loading from Lake Bottom Sediments by 50%	Reduced Internal Loading from Lake Bottom Sediments by 70%
Arrowhead Lake	21	30
Indianhead Lake	37	52

Table 8-2 Summer average total phosphorus and chlorophyll-*a* concentrations with management of internal loading from bottom sediments

Lake	Summer Average Concentrations					
	Total Phosphorus (µg/L)			Chlorophyll-*a* (µg/L)		
	Existing Conditions[1]	Reduced Internal Loading from Lake Bottom Sediments by 50%[2]	Reduced Internal Loading from Lake Bottom Sediments by 70%[2]	Existing Conditions[1]	Reduced Internal Loading from Lake Bottom Sediments by 50%[2]	Reduced Internal Loading from Lake Bottom Sediments by 70%[2]
Arrowhead Lake	80	67	51	27	20	16
Indianhead Lake	115	108	71	34	30	20

[1] Existing conditions summer average concentrations from observed 2020 monitoring data
[2] Summer average concentrations reported assuming copper sulfate treatments no longer applied to manage algae.

8.2.2 Reduce Pollutant Loading from Stormwater Runoff

Watershed and in-lake modeling demonstrated that pollutant loading from the watershed contributes to water quality concerns in Arrowhead and Indianhead Lakes. Increased impervious areas and storm sewer systems in the highly residential watersheds allow plant debris, sediment, and fertilizer residuals to flow towards Arrowhead and Indianhead Lakes at higher volumes.

8.2.2.1 Reduce External Phosphorus Load

Watershed loading represented approximately 46% and 16% of the total phosphorus load to Arrowhead Lake and Indianhead Lake, respectively, during the summer growing season period of June – September 2020. This suggests that phosphorus management strategies should also focus on reducing external loading within the direct watershed, when feasible. Since the watershed is mostly fully developed, there may be limited opportunities for external loading management. NMCWD has stormwater management rules in place for land development activities. As additional development or re-development occurs in the watershed, it is recommended that NMCWD consider partnering with landowners to add additional and/or enhanced BMPs, where feasible and cost effective. Additionally, close monitoring of construction projects within the watershed is recommended to ensure adequate erosion control practices are in place and maintained. The NMCWD should also consider seeking out and/or prioritizing project opportunities through their cost share program (Section 8.2.7).

Cross View Lutheran Church was originally investigated as a potential location to install external BMPs in the Arrowhead Lake watershed as a part of this water quality study. However, in 2018/2019 Cross View Lutheran Church applied for a NMCWD permit to install a building addition and complete parking lot modifications. As part of this construction project, subsurface storage and rain gardens were installed to retain and treat stormwater runoff from portions of the site. A geotechnical investigation was completed as part of the permit application and indicated that the underlying soils are clay. Given the poor, underlaying soils, the site qualified as restricted. Because Cross View Lutheran Church has already installed

BMPs as part of the NMCWD redevelopment rules and given the underlying soils are not conducive to infiltration, no further BMPs were assessed for this parcel as a part of this water quality study. If in the future, Cross View Lutheran Church reaches out to the NMCWD or the City of Edina with interest in providing additional water quality treatment, considerations can be made for partnership opportunities at that time.

As an alternative to largescale BMPs, a more rigorous street sweeping program within the Arrowhead and Indianhead watersheds is an external management practice that could reduce external phosphorus loading. An advantage of such a program, especially in a fully developed watershed, is that the management practice can be implemented rapidly and is not dependent upon uncontrollable factors such as redevelopment timelines or land ownership practices. Street sweeping is a source control practice that directly reduces the potential for plant debris and sediment discharges to downstream lakes. The City of Edina has expressed interest in a targeted public street sweeping program as follows: Sweeping two times a month in spring and fall (May, October, November) and sweeping one time per month in summer (June, July, August, September). While implementation of this enhanced sweeping frequency would capture more debris and sediment than the City's existing program (twice a year), a disadvantage of street sweeping is that pollutants can still build-up and wash off between sweepings depending on climate conditions. It is recommended that NMCWD continue to work with the City of Edina to evaluate public street sweeping options and the most appropriate way to track success of an enhanced street sweeping program.

Published research on street sweeping effectiveness has largely focused on the mass of solids removed from impervious surfaces rather than impacts to stormwater runoff concentrations and downstream waterbodies. Due to limited quantification of street sweeping's impacts to stormwater runoff concentrations, the effectiveness of street sweeping as a BMP could not be applied to the models used in this study. Therefore, no specific estimates of phosphorus removal or impacts to summer average concentrations are reported for street sweeping.

8.2.2.2 Reduce External Nitrogen Loads

External nitrogen loading, in the form of plant debris and fertilizer residues, can also affect lake water quality by supporting algal growth. A targeted street sweeping program that reduces phosphorus will also reduce nitrogen. It is recommended that the NMCWD continue to work with the City of Edina to evaluate public street sweeping options and the most appropriate way to track nitrogen and phosphorus source control outcomes in the watersheds.

Fertilizer application to residential lawns is a source of nitrogen to Arrowhead and Indianhead Lakes and reduced fertilizer application can improve the water quality of these lakes. It is recommended that the NMCWD continue to educate citizens on fertilization best practices for downstream water quality protection. One program that the NMCWD could consider is to promote/coordinate testing of residential soils. Testing of residential soils could help residents to better understand the need for nitrogen fertilization on their lawns and help avoid over-fertilization practices.

The University of Minnesota Soil Testing Laboratory offers lawn analysis testing (Regular test $17). Soil samples collected from existing lawns and tested by the laboratory are intended to aid in evaluating the fertility and chemical condition of the soils. Based on the test results, fertilization recommendations are calculated to assist residents to provide adequate levels of nutrients for healthy plant growth without adversely affecting the environment. Fertilization recommendations include:

- Fertilization Ratio (N-P-K)
- Total amount of each nutrient to apply each year
- Recommendations on when to fertilize and how much to apply each application
- Amount of lime to apply each year

If residents increase their knowledge on existing lawn health, fertilization practices can be reduced and/or optimized in the watershed. The University recommends performing a soil test approximately every 3 years to reassess if lawn management practices should change.

While reducing external nitrogen inputs to downstream waterbodies is always a best practice, decreasing the nitrogen load from the Arrowhead and Indianhead watersheds will likely not result in short-term water quality benefits. Review of the monitoring and modeling data indicates that when phytoplankton experienced growth limitation due to nitrogen, this correlated with phytoplankton growth rates exceeding nitrogen degradation rates to bioavailable forms rather than the total mass of nitrogen in the lake. In both Arrowhead and Indianhead Lakes the total Kjeldahl nitrogen (TKN) concentrations were high compared to nitrate concentrations (bioavailable form). Since there already are high existing concentrations of TKN in Arrowhead and Indianhead Lakes, reductions in external nitrogen loading will have limited impact on phytoplankton growth in the short-term. However, enacting management efforts to control nitrogen can have long-term water quality benefits, especially when tied with external phosphorus control, such as street sweeping.

8.2.2.3 Reduce External Chloride Loads

Observed chloride concentrations in Arrowhead Lake are higher than chloride concentrations in Indianhead Lake. This is likely due to the larger proportion of highway land use in the Arrowhead Lake watershed. Because high concentrations of chloride can harm fish and plant life, the MPCA has established a chronic exposure chloride standard of 230 mg/L or less and considers two or more exceedances of the chronic standard in 3 years to be an impairment. Of the Arrowhead Lake monitoring data collected in 2011, 2014, 2019, and 2020, chloride concentrations have not been observed to exceed 230 mg/L. The highest concentration recorded was 185 mg/L in April 2019. Average chloride concentrations in Arrowhead Lake from 2011 – 2020 remained fairly consistent (average yearly concentrations (April – October) ranged from 120 – 150 mg/L). Comparatively, the highest concentration recorded in Indianhead Lake was 66 mg/L in April 2019. Average chloride concentrations in Indianhead Lake from 2011 – 2020 remained fairly consistent (average yearly concentrations (April – October) ranged from 34 – 57 mg/L). Continued periodic water quality monitoring of chloride concentrations is recommended. NMCWD should also consider seeking opportunities to work with MnDOT and other property owners and/or management companies, especially within the Arrowhead Lake watershed, to reduce winter salt usage.

8.2.3 Continue to Monitor Growth and Impacts from Curly-leaf Pondweed

The presence of curly-leaf pondweed and its mid-summer die-off can negatively impact lake water quality. The City of Edina has been managing curly-leaf pondweed in Arrowhead Lake since 2017 and Indianhead Lake since 2019 to reduce species growth and proliferation. The invasive species growth should continue to be tracked with periodic surveys to assess if conditions are changing and management should continue as needed.

8.2.4 Determine Timeline to Discontinue Copper Sulfate Treatments

Copper sulfate treatments have been used in Arrowhead and Indianhead Lakes to manage algal growth. Review of the Arrowhead Lake and Indianhead Lake monitoring data collected before and after copper treatments provides the following observations and conclusions regarding the effects of copper treatment on lake water quality:

- Chlorophyll-*a* concentrations decreased following treatment due to toxicity of copper to phytoplankton species
- Total phosphorus concentrations decreased based on monitoring data and modeling results. The hypothesis regarding this observation is that the type of copper treatment applied to the lakes coagulated and flocculated phosphorus suspended in the water column, resulting in reduced total phosphorus concentrations.
- Total nitrogen concentrations significantly increased at the time of application based on monitoring data and modeling results. The hypothesis regarding this observation is that the type of copper sulfate treatment applied to the lakes was chelated. Chelation allows copper sulfate, which is normally in a solid form, to remain in a liquid state for spray applications. Chelated copper sulfate can also remain buoyant in the water column for longer periods, which can increase the toxicity to algae and extends the target application area. Several chelating agents can have high concentrations of nitrogen, and this is likely why there was a large increase in nitrogen concentrations around the timing of the copper sulfate application. This has not been confirmed, as the application procedure and products used were not disclosed.

The NMCWD does not typically recommend conducting copper treatments to manage algae, preferring to focus on long-term strategies to reduce nutrients (algal food source) versus short-term removal of excessive algae. However, the observed decreases in total phosphorus following treatments were unanticipated. Due to the unexpected impacts of copper sulfate treatments on phosphorus and nitrogen, the following are recommended for consideration:

- To better quantify the impacts of copper sulfate on water quality parameters (e.g., chlorophyll-*a*, total nitrogen, total phosphorus), more rigorous monitoring is recommended before, during, and after a copper sulfate application. Monitoring observations could then be used to inform future in-lake water quality modeling and develop prescriptive management recommendations for copper sulfate treatments.

- In-lake modeling shows that copper sulfate treatments (following best practices) reduced phosphorus concentrations in Arrowhead and Indianhead Lakes in 2020. While ultimately it is recommended that the copper treatments be discontinued, it may be beneficial to wait to discontinue until internal loading has been controlled (by alum and iron treatments).
- A quantitative and qualitative assessment will be conducted by NMCWD after one year of lake monitoring data has been collected following the final internal load treatment. If observations indicate that summer average chlorophyll-*a* concentrations have fallen below 20 µg/L, NMCWD will recommend that copper treatments be discontinued.

8.2.5 Encourage Residents to Promote Healthy Aquatic and Shoreline Plant Growth

The Arrowhead and Indianhead Lake Associations have participated in submerged macrophyte removal programs in the past by making requests to the City of Edina. Although the City has recommended that these macrophyte removal practices stop, the City has accommodated these requests in the past and has coordinated contractors to apply for appropriate permits from the MNDNR and conduct the treatments. Due to numerous benefits of healthy aquatic macrophyte communities (e.g., phytoplankton competition, invasive macrophyte competition, fisheries habitat, increased water clarity), it is recommended that NMCWD and the City continue to educate residents regarding the benefits of macrophytes in lakes and discourage removal practices.

Residents have expressed concerns about lily pads impeding lake recreation to the City of Edina and during public open house events attended by NMCWD and the City. The MNDNR allows lakeshore residents to maintain a channel a maximum of 15 feet wide to open water by cutting or pulling floating-leaf plants by hand. Any other destruction of floating-leaf vegetation requires a permit with the MNDNR. Lakeshore residents can work with the City of Edina to discuss City policies regarding lily pad removal. Due to the high value of aquatic plants to lake ecosystems, NMCWD does not encourage the removal of native submerged or floating-leaf vegetation beyond the extent allowed by MNDNR.

Promoting healthy shoreline vegetation and increasing buffer widths can help to improve wildlife habitat and decrease overland stormwater inflow into lakes. The invasive species, purple loosestrife, was found in shoreline buffers surrounding Arrowhead Lake. The invasive species, purple loosestrife and yellow iris, were found in shoreline buffers surrounding Indianhead Lake. It is recommended to encourage residents to apply for NMCWD cost-share grants to assist with the invasive species removal and native species restoration of their shorelines. Please see Section 8.2.7 for additional information.

8.2.6 Encourage Residents to Discontinue Lake Dye Applications

The Arrowhead and Indianhead Lake Associations have participated in dye applications (Aquashade, Sky Blue) in the past. Pond dyes are sold as products that block light and restrict algal photosynthesis and submerged macrophyte growth. Typically, the dyes are used in smaller applications, such as ornamental ponds, fountains, and golf course ponds. The effectiveness of using pond dyes on larger lake scales is not well documented and the impacts of these dyes on aquatic organisms (e.g., reproduction, toxicity, food web changes) are not well understood. It is recommended that the dye applications be discontinued.

8.2.7 Encourage Residents to Apply for NMCWD Cost-Share Grants

Because the Arrowhead and Indianhead Lake watersheds are almost fully developed, opportunities for large-scale external BMPs will be limited. It is recommended that NMCWD continue to promote their cost share grant programs to residents, associations, nonprofits, schools, and businesses for smaller-scale projects. NMCWD Stewardship Grants can help individuals install projects that prevent stormwater pollution to downstream lakes, such as rain gardens, shoreline buffer improvements, and permeable pavers. Native Habitat Restoration Grants are also available to assist with project costs associated with restoring native plant and wildlife habitat, such as prairie and woodland restorations.

Additional information on NMCWD Cost-Share Grants can be found at
https://www.ninemilecreek.org/get-involved/grants/

9.0 Cost – Benefit Analysis

9.1 Opinion of Probable Cost

Planning-level opinions of probable cost were developed for the evaluated management alternatives that have the greatest potential for water quality improvement in Arrowhead and Indianhead Lakes, as discussed in Section 8.2. These opinions of cost are intended to provide assistance in evaluating and comparing alternatives and should not be assumed as absolute values. The estimated costs are summarized in Table 9-1. Detailed opinions of probable cost are included in Appendix F.

The opinions of probable cost summarized in Table 9-1 generally correspond to standards established by the Association for the Advancement of Cost Engineering (AACE). Class 5 planning-level opinions of costs were used based on the limited project definition, wide-scale use of parametric models to calculate estimated costs (i.e., making extensive use of order-of-magnitude costs from similar projects), and uncertainty, with an acceptable range of between -30% and +50% of the estimated project cost.

Table 9-1 Planning-level cost estimates for evaluated management alternatives

Description	Planning-Level Cost Estimate[1]	Planning-Level Cost Range	Estimated Life of Project
Arrowhead Lake Bottom Sediment Treatment (alum, iron, aerator optimization, monitoring)	$125,000	$87,000 - $186,000	10 years
Indianhead Lake Bottom Sediment Treatment (alum, iron, aerator optimization, monitoring)	$120,000	$85,000 -$182,000	10 years
Arrowhead and Indianhead Lake Watershed Targeted Street Sweeping Program	$250,000[2]	$176,000 - $377,000	10 years
Soil Sampling Program for Resident Fertilization Assessment	$20,000	$14,000 – $30,000	3 years

[1] Rounded to the nearest $5,000.
[2]The planning-level cost estimate for a targeted street sweeping program includes capital costs for purchasing a regenerative air sweeper and includes operations and maintenance costs for a one-year trial run of enhanced sweeping in the Arrowhead and Indianhead lakes watersheds.

9.1.1 Cost Details

9.1.1.1 Lake Bottom Sediment Treatments

The opinions of probable cost for the lake bottom sediment treatments of Arrowhead and Indianhead Lakes are based on correspondence with alum application contractors, ferric chloride application contractors, and aeration installation and management contractors. The primary assumptions for the sediment treatment opinions of cost are:

- Mobilization/Demobilization approximately $15,000
- Arrowhead Lake aluminum treatment:
    - 3954 gallons alum
    - 1977 gallons sodium aluminate
- Indianhead Lake aluminum treatment:
    - 4273 gallons alum
    - 2136 gallons sodium aluminate
- Dissolved oxygen monitoring to assess aeration needs
- Addition of 1 aerator to Arrowhead Lake and 1 aerator to Indianhead Lake
- Arrowhead Lake iron treatment
    - 4,300 gallons ferric chloride
- Indianhead Lake iron treatment
    - 5,580 gallons ferric chloride
- 150 hours per lake for project planning, design, data review, field observation, and monitoring

It should be noted that some laboratory experimental work will need to be conducted as part of the feasibility study to determine the gallons of sodium aluminate (a base / buffer) needed to balance the acidity of ferric chloride (an acid).

9.1.1.2 Targeted Street Sweeping

Unit costs for targeted street sweeping in the Arrowhead and Indianhead Lake watersheds were based, in part, on the values summarized in the *City of Edina MN Street Sweeping Management Plan* (Emmons & Olivier Resources, Inc. (EOR), 2015). The assumptions used to develop the opinion of cost are:

- The cost of a new Crosswind 4-Wheel Regenerative Air Sweeper is approximately $210,000 and the buy-back cost after 10 years of use is approximately $20,000. It was assumed a new Sweeper is needed to account for the additional area.
- Within the Arrowhead and Indianhead Lake watersheds there is approximately 9.6 miles of sweepable public street curb.
- Sweeper operation speed is estimated at 4.5 miles per hour and average fuel consumption is 5 miles per gallon.
- The sweeping path width of a high efficiency, two-sided broom sweeper with a pick-up head is approximately 12 feet.
- 1.5 hours of labor is needed for every 4 hours of sweeping time.
- Total transit (brush off) is about 3 times the total amount of swept miles.
- The maximum number of hours worked in one week by a single worker is 40 hours.
- Sweeping frequency is as follows:
    - Twice a month in May, October, and November
    - Once a month from June - September
- Labor cost = $75/hour

- Fuel cost = $3.50/gallon
- Sweeper Maintenance cost = $4,800/year
- The City of Edina is responsible for the operations and maintenance of the street sweeping program.

Using the outlined assumptions, to sweep the public streets in the Arrowhead and Indianhead Lake watersheds 10 times per year, one high efficiency regenerative air sweeper would be needed. Since the City of Edina currently owns one high-efficiency regenerative air sweeper that is used all over the city, the opinion of cost assumes one additional high-efficiency regenerative sweeper would be purchased. Vehicle maintenance, labor, and fuel costs are summarized as annual costs.

9.1.1.3 Soil Sampling for Resident Fertilization Assessment

The primary opinion of cost assumptions for the soil sampling program to assess resident fertilization practices and target nitrogen reductions are:

- University of Minnesota Standard Soil Testing per sample = $17/sample
- 50% participation of residents adjacent to Arrowhead and Indianhead Lakes (68 total residential properties adjacent to Arrowhead and Indianhead Lakes) = 34 residential properties
    - NMCWD can consider expanding sampling efforts to non-lakeshore residents living within the watersheds.
- 3 hours of labor per residential property needed to provide project background, schedule soil sampling field work, and discuss results summary
- 1 hour of labor per residential property needed to complete field soil sample collection
- 8 hours of project-wide data review by project engineer
- 16 hours of initial team project planning

9.2 Cost Benefit Analysis

The management strategies considered to help improve water quality in Arrowhead and Indianhead Lakes range in type, scale, cost, and effectiveness. Some strategies have larger, upfront capital costs, whereas others are more programmatic or may require periodic or annual recurrence. To account for these variations, a comparison of cost-benefit of the potential management strategies was conducted, where reasonably feasible. Results of the cost-benefit analysis can help to understand the value derived and associated costs, for each management practice and combinations thereof.

Estimated costs for the evaluated management activities were annualized to help compare the cost-benefit ratio. The annualized cost for each management alternative is based on anticipated maintenance, replacement costs, and anticipated useful life span of the projects/treatments. A 3% inflation rate was assumed. The annualized cost for each alternative is calculated as the value of 'n' equal, annual payments, where 'n' is the anticipated useful life span of the project or treatment. The annualized cost estimates for each management alternative are summarized in

Table 9-2. For the cost-benefit analysis, the benefit is in terms of phosphorus removed (in pounds) during the time period of June through September (i.e., phosphorus that did not enter the lake system as a result of the management practice).

Table 9-2 Cost-benefit summaries for Arrowhead and Indianhead evaluated management alternatives

Description	Management Type	Estimated Annualized Cost	Average Pounds of TP Load Removed (June - Sept)	Annualized Cost per Pound of TP Removed (June - Sept)
Arrowhead Lake Bottom Sediment Treatment	Internal	$14,000 - $15,000	21 - 30	$500 - $700
Indianhead Lake Bottom Sediment Treatment	Internal	$14,000 - $15,000	37 - 52	$300 - $400
Arrowhead and Indianhead Lake Watershed Targeted Street Sweeping Program	External	$42,000	Not Modeled	-
Soil Sampling Program for Resident Fertilization Assessment	External	$7,000	Targets Nitrogen Reduction	-

10.0 References

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Appendices

Appendix A

Aquatic Plant Surveys

Appendix B

Fisheries Assessment (2021)

Appendix C

In-lake Water Quality Calibration Plots

Appendix D

Arrowhead Lake and Indianhead Lake Public Survey

Appendix E

In-lake Water Quality Proposed Best Management Plots

Appendix F

Opinions of Probable Cost