Lake Noquebay Nutrient Study

Marinette County, Wisconsin

Final Report to the

Lake Noquebay Rehabilitation District

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Marinette County Land & Water Conservation

EXECUTIVE SUMMARY

Lake Noquebay is a 2,411 acre drainage lake located in Marinette County Wisconsin. For management purposes Lake Noquebay is considered a "shallow lake". The maximum depth is 52 feet but more than 80% of the lake less than 15 feet deep. The water level is controlled by a dam that maintains a maximum head of approximately three feet during the summer months. The Lake Noquebay watershed encompasses 84,160-acres and is located entirely within Marinette County.

Lake Noquebay is a regionally important resource and is economically significant to Marinette County. The lake is known for its panfish, bass, northern pike, and musky fishing. The lake is also popular with water skiers, personal watercraft users, waterfowl hunters, and other motorboat operators.

The Lake Noquebay Nutrient Study Project was undertaken in 2018 in response to a documented increase in phosphorus concentrations between 1979 and 2016. Field work was conducted throughout the project to obtain the data needed to better understand the hydrology and water quality in Lake Noquebay and its watershed. These data included water quality and water loading data from three major tributaries draining to Lake Noquebay and groundwater inflow. Data were used to estimate an annual phosphorus budget for Lake Noquebay and to make predictions about future water quality.

Lake Noquebay and its watershed make up a complex system. Water quality is driven by external inputs from the lakes watershed and internal processes that determine how nutrients are used, stored, recycled, and exported. The watershed, as a whole, contributes 88% of the annual phosphorus load to Lake Noquebay. This includes direct runoff from shoreland areas and tributary loads. Direct deposition, groundwater inputs, and internal loading account for the remaining 12% of phosphorus load to the lake.

As part of the project, lake water quality was monitored in 2018 and 2020. While surface phosphorus levels during this period remained higher than pre-2000 levels, they were significantly lower than the 2007 - 2016 average surface TP concentration. This may be the result of changes in agricultural loading due to the successful implementation of the Lake Noquebay Priority Watershed Program, which ended in 2006, and general trends in agricultural land use and management.

Currently Lake Noquebay has good water quality for a large, shallow drainage lake. The lake has nutrient rich sediments and good water clarity which results in excellent growing conditions for rooted aquatic plant growth in nearly 80% of the lake basin.

Lake modeling clearly demonstrates that phosphorus load reductions can result in measurable water quality improvements. Reducing external phosphorus loads will help assure that the recent water quality improvements will continue. These improvements will not impact aquatic plant growth in the lake, but they will further reduce the chances for nuisance algae blooms. More importantly, lake models predict that increased phosphorus loading will lead to higher total phosphorus levels in Lake Noquebay and an increase in the frequency and severity of algae blooms.

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INTRODUCTION AND BACKGROUND

Lake Noquebay is a 2,411 acre drainage lake located in Marinette County Wisconsin. While the lake has a maximum depth of 52 feet, it is relatively shallow overall, and nearly 80% of the lake is less than 15 feet deep (Figure 1). The lake level is controlled by a dam that maintains a maximum head of approximately three feet during the summer months.

The Lake Noquebay watershed encompasses 84,160-acres and is located entirely within Marinette County (Figure 2). Approximately 46% of the watershed area is woodland and 30% is wetland. Agricultural land use makes up approximately 20,000 acres, or 25% of the watershed area. The Lake Noquebay shoreline is heavily developed with more than 275 permanent and seasonal dwellings. The lake also hosts significant lengths of undeveloped shoreline including a state wildlife area.

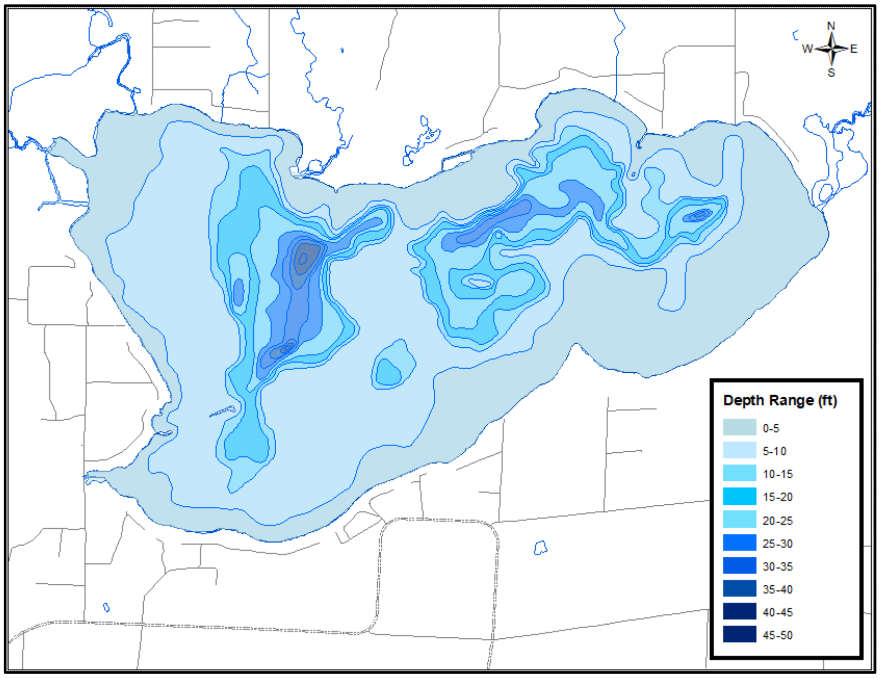

Figure 1. Hydrographic map of Lake Noquebay.

Known throughout Northeast Wisconsin for its panfish, bass, northern pike, and musky fishing, Lake Noquebay is one of the most important recreational resources in Marinette County. In addition to its draw as a fishing destination, Lake Noquebay is popular with water skiers, personal watercraft users, waterfowl hunters, and other motorboat operators. The lake is home to the Crivitz Ski Cats, an amateur water ski club that practices and performs on the lake.

Lake Noquebay offers a wide variety of public and private recreational opportunities. There are three active resorts on the lake offering cabins, boat rentals, and swimming areas. Lake Noquebay County Park on the south shore offers a swimming beach, bathroom & changing house, boat launch, picnic & play areas, and an indoor pavilion. Public access is adequate with two improved public landings, each with space for more than 30 vehicles and trailers and abundant overflow parking at Lake Noquebay Park. Three smaller landings offer boat launching with limited roadside parking. In addition to the boat landings, walk in access is available at two road right-of-way sites and at the Lake Noquebay dam.

The Lake Noquebay Rehabilitation District (LNRD) was formed in 1975 in response to excessive aquatic plant growth, which had been severely restricting navigation on several hundred acres of

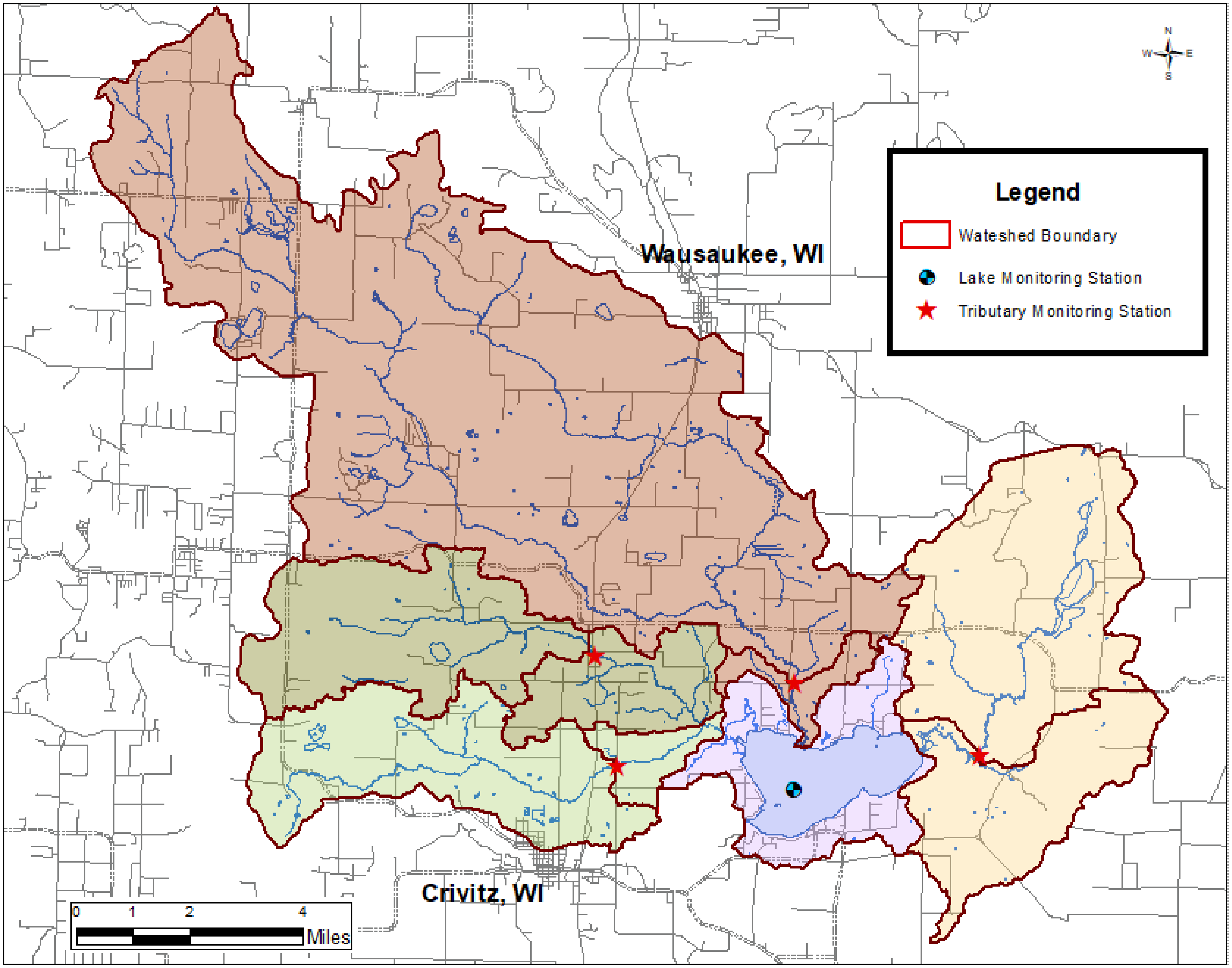

Figure 2. Lake Noquebay watershed and sub-watersheds with lake and tributary monitoring sites

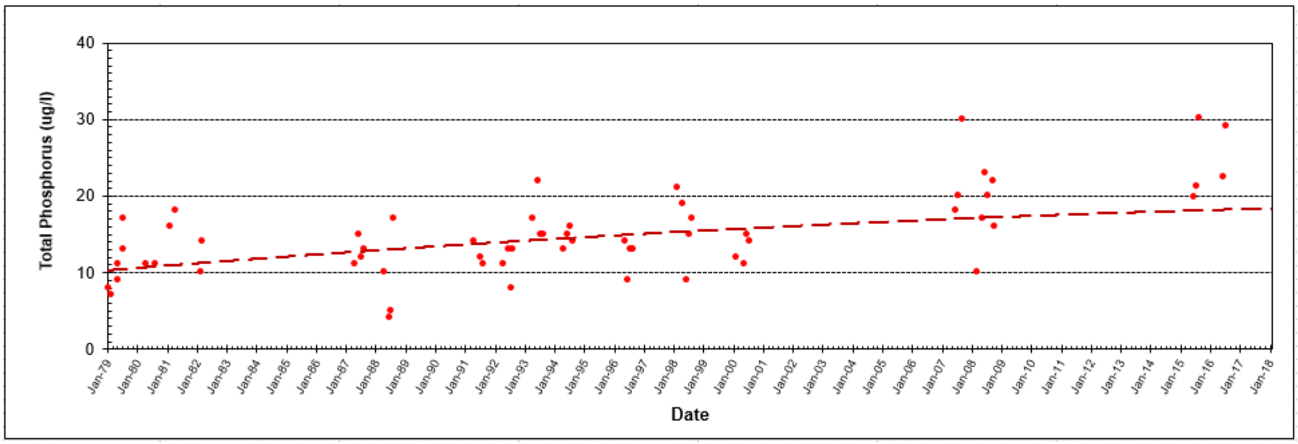

Figure 3. Surface total phosphorus concentrations and trend from 1979 through 2017

the lake. Since 1978 the LNRD has operated an aquatic plant harvesting operation to maintain navigability and remove floating plants that accumulate on the lakeshore. The District also works cooperatively with Marinette County to operate and maintain the dam. Since 1993 the LNRD has participated in several WDNR grant funded projects to conduct lake and watershed studies.

In 1995 Lake Noquebay was designated a priority watershed by the Wisconsin DNR for the control of runoff pollution in the lakes watershed. An extensive inventory of farms in the watershed was conducted and cost-share funds were made available for a wide variety of agricultural best management practices to reduce nutrient runoff. When the watershed project ended in 2006, most of the active farms in the watershed had participated in the effort leading to an estimated reduction in phosphorus runoff of 1,052 lbs. annually, primarily through the construction of manure storage facilities and the subsequent reduction in winter-spread manure.

PURPOSE

The Lake Noquebay Nutrient Study Project was undertaken in response to a long history of increasing phosphorus concentrations in the lake (Figure 3). Between 1979 and 2015, the mean annual total phosphorus (TP) concentration increased by 35%. During the same period the mean spring turnover TP increased by 21%, and the mean summer TP increased by 47%. Despite increasing phosphorus levels, water clarity and algae concentrations have remained relatively stable during the last 30 years. However, lake residents have reported an increase in the frequency and severity of algae blooms during the last several years. While these blooms have been relatively mild and short lived, there is concern that increasing phosphorus concentrations may lead to more severe algae blooms.

Like many shallow lakes, Lake Noquebay supports abundant aquatic plant growth. Excellent water clarity allows for a maximum rooting depth of approximately 15 feet. At this depth more than 80% of the lake can support the growth of rooted aquatic macrophytes (Figure 4). Scientific literature is replete with studies supporting the theory of alternate stable states for shallow lakes. This theory postulates that nutrient rich lakes can exist in a clear-water state where aquatic plants dominate the ecosystem, or a turbid-water state where algae dominate the ecosystem, and the difficulty of moving a lake from the turbid-water phase to a clear-water phase.

The purpose of the study was to evaluate nutrient loading sources to Lake Noquebay, identify major nutrient sources, develop nutrient loading models, and model the effect of nutrient reductions and/or increases on lake water quality. Ultimately, lake managers want to ensure that Lake Noquebay remains in the clear-water state.

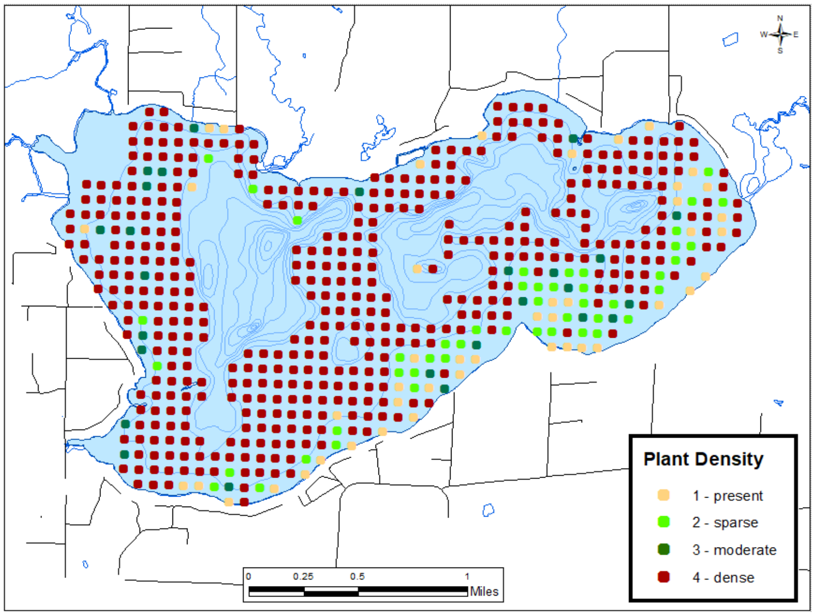

Figure 4. Aquatic plant density in Lake Noquebay.

GOALS AND OBJECTIVES

This project took place in two phases. In phase I, in-lake water quality conditions were investigated along with an evaluation of groundwater and watershed nutrient loading. In Phase II, continued lake and stream monitoring was conducted along with data analysis, phosphorus load modeling, lake response modeling and alternatives analysis.

Goal 1: Evaluate current water quality conditions in Lake Noquebay.

- The proposal includes two additional years of comprehensive water quality monitoring to provide a much-needed update to the existing water quality record and allow for further refinement of water quality trends analysis.

Goal 2: Evaluate external nutrient loading to Lake Noquebay.

- Conduct continuous flow monitoring on Smith Creek, Middle Inlet, Upper Inlet and The Outlet for use in watershed nutrient loading estimates and lake nutrient budgeting.
- Monitor nutrient concentrations in Smith Creek, Middle Inlet, Upper Inlet, and ungauged tributaries for use in watershed loading estimates, water quality modeling, and evaluation of land use effects on nutrient loading.
- Identify zones of groundwater inflow and outflow and quantify groundwater loading to Lake Noquebay.
- Monitor nutrient concentrations in groundwater for use in groundwater loading estimates and lake nutrient budgeting.

Goal 3: Model external loading, create a nutrient budget for Lake Noquebay and evaluate alternative load reduction strategies to protect the lake for future generations.

- Estimate nutrient loading using the Flux^{32} Mass Transport Program developed by the US Army Corps of Engineers.
- Create a nutrient budget for Lake Noquebay and analyze the effect of different nutrient increase/reduction scenarios on lake water quality using the Wisconsin Lake Modeling Suite (WiLMS).

METHODS

Lake Noquebay receives runoff and nutrients from multiple sources. The study was designed to evaluate runoff from overland flow, groundwater inputs, direct deposition, and internal loading.

Lake Monitoring

In 2018 and 2020, lake water quality data was collected at the deep hole on Lake Noquebay, a small 52-foot deep area located on the west end of the lake (Figure 2). Samples for analysis were collected at the surface using a 1-meter integrated sampler and analyzed for total phosphorus (TP), soluble reactive phosphorus (SRP), total Kjeldahl nitrogen (TKN), nitrate and nitrite (NO_2^-- NO_3^-), and ammonia nitrogen (NH_4^+). Samples were collected one meter from the bottom using a VanDorn water sampler and analyzed for the same chemical constituents as the surface samples. All samples were collected according to WDNR monitoring protocols and analyzed at the Wisconsin State Laboratory of Hygiene (SLOH).

During each monitoring event, a HydroLab Datasonde 4a was used to measure temperature and dissolved oxygen (DO) at one-meter intervals to develop temperature and DO profiles of the lake and evaluate the degree of stratification.

Samples for algae were collected from Lake Noquebay during the growing season (May through September) in 2018 and 2020. Samples were collected with a 1-meter integrated sampler and field filtered prior to delivery to the lab. Samples were analyzed for chlorophyll-a by the Wisconsin SLOH. A Secchi disk was used to measure water clarity during the open-water season.

Tributary Monitoring

Lake Noquebay receives drainage from an 84,160 acre watershed through five major tributaries; Smith Creek, Lower Middle Inlet, Middle Inlet, Upper Middle Inlet, and Upper Inlet. The naming of the tributaries to Lake Noquebay is somewhat humorous, but unfortunate as it can be confusing. Lower Middle Inlet empties into Smith Creek then into Lake Noquebay from the west. Upper Inlet empties into Lake Noquebay on the east end, but Upper Middle inlet flows into Middle Inlet before flowing into the lake from the north. The outlet of Lake Noquebay is officially named “The Outlet”. It is not known how the stream naming came to be, perhaps it was the work of a lazy surveyor or cartographer trying to finish a map at the end of a long week!

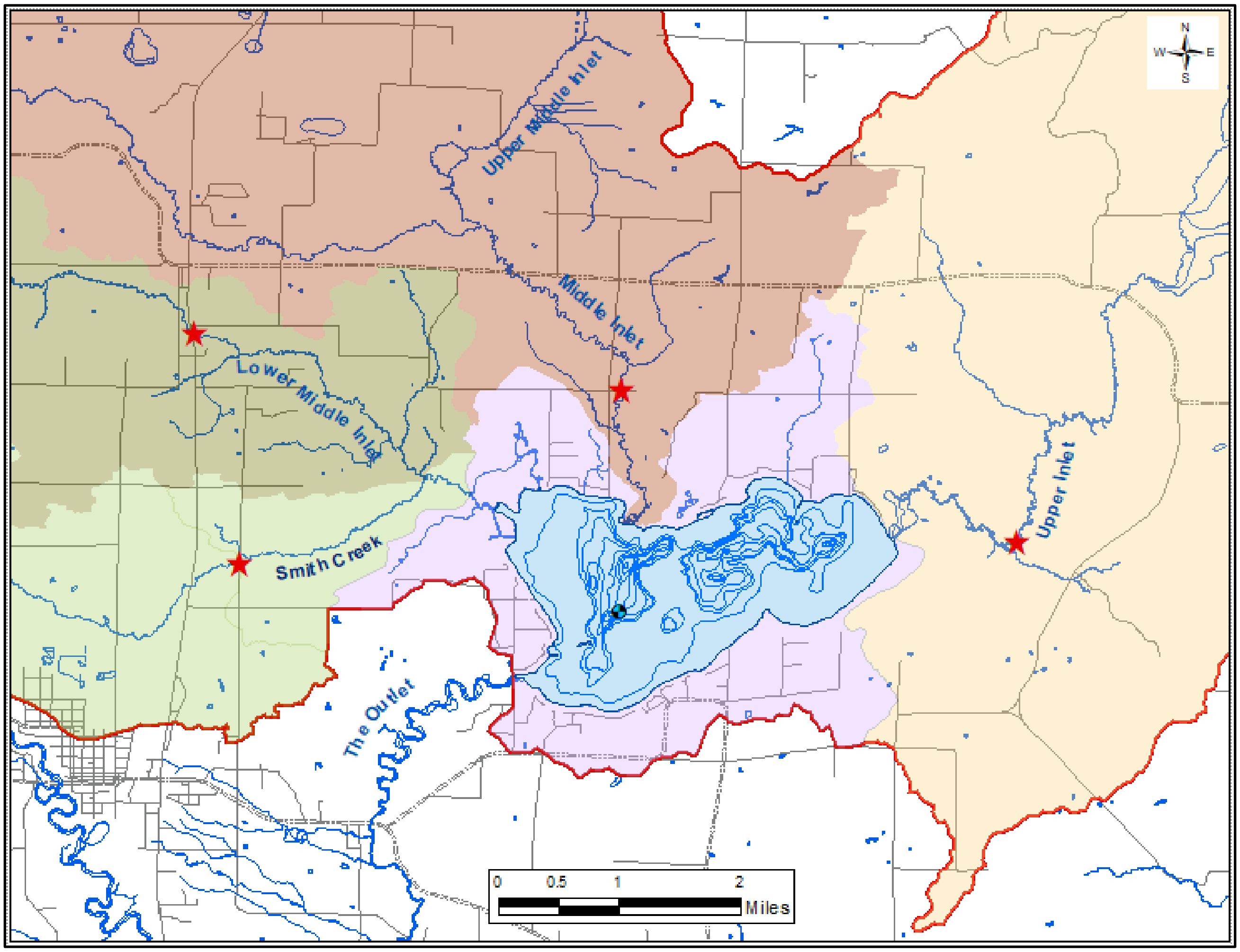

Figure 5. Location of tributary gauging stations for flow monitoring and sample collection.

Stream stage was monitored in each of the tributaries using a Solinst Levelogger pressure transducer installed in a 2” diameter “stilling well” driven into the streambed. The Leveloggers were programmed to take a reading every 15 minutes. At least twice each year Levelogger data was downloaded and corrected using barometric pressure readings collected with a Solinst Barrologger. Stream flow was measured several times during the project period at each location during various flow regimes using a Marsh McBurney FlowMate meter utilizing the cross-sectional method on Lower Middle Inlet, and the culvert flow method on Smith Creek, Middle Inlet, and Upper Inlet. Stream stage data and measured flows were used to develop a stage discharge curve for each stream. Figure 5 shows the location of each gauging station. Each station was established as close to the lake as practicable to maximize the drainage area that was monitored. Loading data for each of the sub-watersheds was adjusted to cover the ungauged watershed area.

Water samples were collected for lab analysis from 2018 through 2020 during a variety of flow conditions and analyzed for TP and SRP. A subset of the samples were also analyzed for total suspended solids (TSS), chloride, TKN, NO_2^-- NO_3^-, and NH_4^+. Sample collection was completed according to WDNR monitoring protocols and analyzed at the Wisconsin SLOH.

Tributary Load Modeling

Annual phosphorus loading was modeled using FLUX32 Load Estimating Software which calculates constituent loads through a flow-concentration relationship (Walker 1996). Each of the monitoring stations was modeled individually using a continuous record of mean daily flow and nutrient concentration data from sampling during the 2018 through 2020 field seasons. Stream data was stratified by flow to produce the best load/flow correlations. Phosphorus loading was calculated using several regression methods; the method which most closely estimated the observed concentrations was selected for each stream. The best fit regression was used to generate daily cumulative flows and phosphorus loads.

Groundwater Monitoring

Groundwater flow conditions were assessed approximately every 300 feet around the Lake Noquebay shore using mini-piezometers and seepage meters (Figure 6). Piezometer wells and seepage meter locations were recorded using a Trimble handheld GPS tablet with sub-meter accuracy and mapped using GIS. Chemical analyses was completed by the Wisconsin SLOH on 37 groundwater water samples for TP, SRP, TKN, NO_2^-- NO_3^- and NH_4^+.

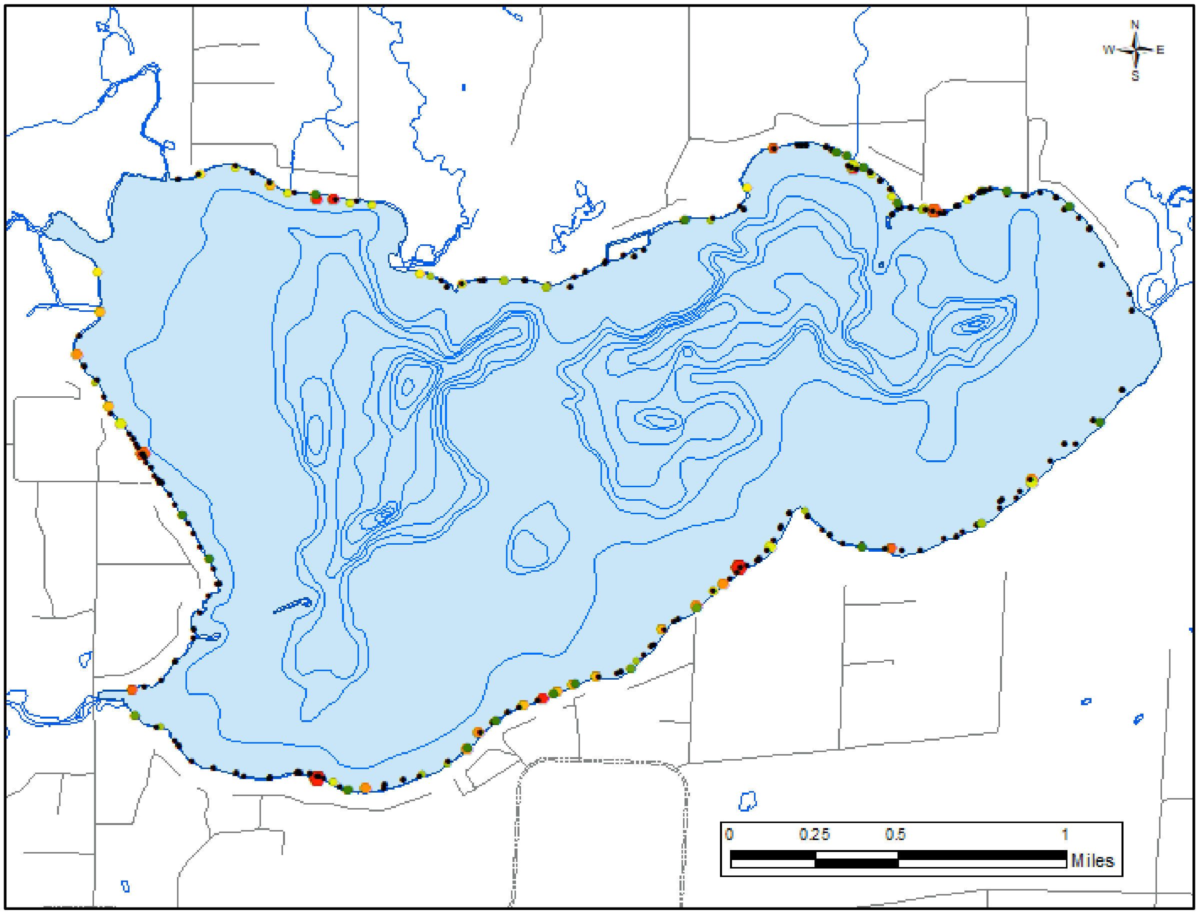

Figure 6. Groundwater monitoring locations were spaced approximately every 300 feet along the shoreline.

The mini-piezometer wells were constructed from 4-foot lengths of ¼" I.D. polypropylene tubing which was sealed on the bottom end. A 3/64-inch drill bit was used to perforate the bottom 3-inches of the tubing.

The mini piezometers were inserted 18 to 22 inches in the lake bed in an average water depth of 16 inches. Piezometers were installed by driving a ½ inch piece of water pipe into the lake bed with a 3/8-inch by 1.5-inch carriage bolt inserted into the end. A metal rod was then inserted into the pipe to tap the carriage bolt until it was loose. The piezometer tubing was then inserted into the pipe and held in place while the pipe was withdrawn. Sediment around the well was tamped to seal the well tubing.

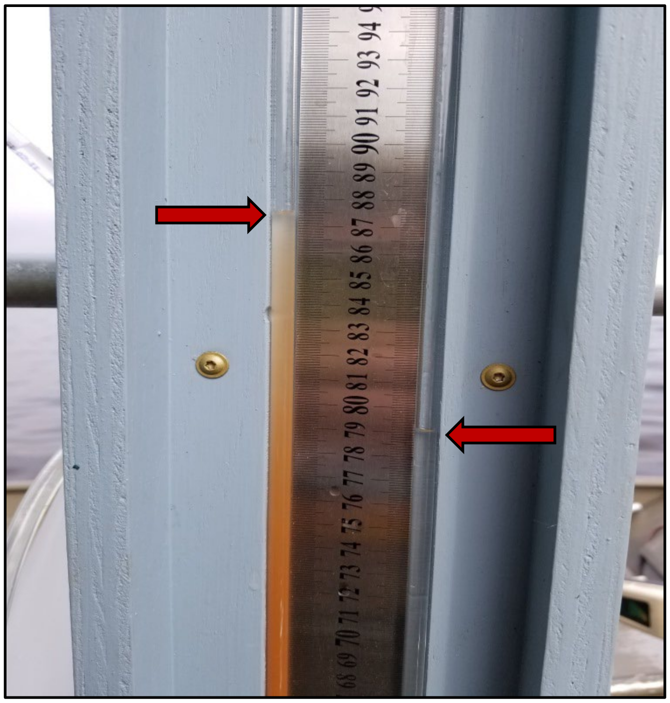

Figure 7. **The difference in height between the well (silty water) and the lake (clear water) indicates the groundwater head is greater than the lake surface.**

At each sample site, measurements of water depth, installation depth, and distance from shore were recorded. With the surface water tube clamped, a hand pump was used to draw water up inside the manometer from the groundwater well then the surface-water tube was opened to fill the instrument with water. After a few minutes air was slowly reintroduced from the top of the instrument until the water level in the well tube and surface-water tube were within the measuring range. The pressure was left to equilibrate for 15 minutes and the difference in height between the well tubing and the surface-water tube was measured. The difference is the head between the groundwater well and the stage of the lake (Figure 7).

Figure 8. Seepage meters were constructed from 50-gallon plastic barrels.

Seepage meters were installed at sites where the mini-piezometers indicated groundwater inflow. Seepage meters were constructed from the ends, and the first eight to twelve inches of sidewall, of 55-gallon high-density polyethylene drums (Rosenberry, 2008). The meters isolated an area of 0.24 m^2 of lake bed.

Seepage meters were inserted into the sediment until only two to three inches remained above the lakebed (Figure 8). A port in the top of the seepage meter allowed air to be purged during installation and was then plugged. A short length of tubing was inserted into a second port, located on the side of the seepage meter and a thin, flexible 2-quart plastic bag was fastened to the end of the hose. The collection bag was pre-filled with 180 ml of lake water and carefully connected to the outflow tube and placed in a small plastic tote to help shield it from lake waves and disturbance. The tote was set next to the seepage meter and held underwater with a brick.

After a known period of time (typically 20 to 24 hours) the bag was carefully removed and the ending volume of the bag was measured. The difference in volume within the collection bag represented the cumulative water exchange from the lakebed enclosed within the seepage meter over the recorded time period. Bags that were nearly full when checked were emptied and reinstalled for a shorter period of time.

Groundwater samples were collected from areas of groundwater seepage using the mini-piezometer to draw a sample from 18 to 22 inches below the sediment surface.

Lake Water Quality Modeling

The Wisconsin Lake Modeling Suite (WiLMS) was used to predict phosphorus loading from the un-monitored direct drainage sub-watershed and internal phosphorus loads. WiLMS can be used as both a descriptive and predictive tool. By calibrating the model to observed data, predictions of how changes in the watershed may impact water quality conditions in the lake were obtained.

The WiLMS model uses watershed characteristics and lake response to predict total phosphorus (TP) concentrations in lakes. The WiLMS model structure is organized into four principal parts including the front-end, phosphorus prediction, internal load prediction, and trophic response. The front-end portion or model setup includes the lake characteristics, watershed loading calculation inputs, and the observed in-lake TP. Both the phosphorus prediction and internal load estimator use the front-end portion of the model for lake and watershed inputs. The phosphorus prediction portion contains 13 phosphorus prediction regressions and uncertainty analysis routines. The internal load estimation platform provides four methods to estimate a lake’s internal loading. The trophic response segment of the program develops a trophic evaluation and comparison. The models used in WiLMS are empirical methods developed via statistical analysis of lake and reservoir systems.

RESULTS AND DISCUSSION

Lake Hydrology

Hydrology is the branch of science concerned with the properties of water, and its movement in relation to land. Factors such as the area of a lake, average depth, maximum depth and the volume and quality of water draining to a lake are critical in determining water quality within the lake and will affect the entire aquatic ecosystem.

Lake Noquebay covers 2,411 acres and has a maximum depth of 52 feet. However, most of the lake is less than 15 feet deep and supports the growth of aquatic plants. As such, Lake Noquebay is considered a "shallow lake". Shallow lakes typically remain mixed throughout the year due to wind driven circulation of the water. The frequency and completeness of mixing is important in the fate of nutrients and nutrient cycling in lakes.

Lake Noquebay receives water from direct precipitation on the lake, surface runoff from the watershed, and groundwater inflow. The majority of water entering the lake flows through three major streams. Smith Creek/Lower Middle Inlet from the west, Middle Inlet from the north, and Upper Inlet from the east. Together, these streams drain more than 84,000 acres. Water exits the lake through The Outlet, which flows to the Peshtigo River.

As runoff from rain moves across the land it picks up soluble and particulate matter that is carried to streams and transported downstream to the receiving water. The slope of the land, vegetative cover, soil type, and land use determine how much runoff flows from the land and the amount of associated nutrients that are delivered to a stream. Natural, undisturbed landscapes typically deliver the least amount of runoff, have the capacity to hold water for longer periods of time, and filter particulates from the runoff. Human disturbance typically short circuits natural flow paths through the building of agricultural ditches, road ditches, and shaping land to remove runoff from the landscape faster. These changes increase the volume of runoff and the amount of associated nutrients delivered to lakes and streams.

Precipitation

Precipitation feeds lakes and their tributaries directly via surface runoff and groundwater inflow. Typically, about one third of the precipitation that falls infiltrates into the ground to recharge groundwater. The rest of this precipitation is incorporated into plant growth, lost through evapotranspiration, or makes its way to wetlands, streams and lakes as surface runoff. Interactions between soil type, topography, land use, and changes to drainage patterns influence the volume and chemistry of runoff water. Historic precipitation records show that precipitation near Lake Noquebay averages approximately 32 inches per year, resulting in about 10 inches of annual groundwater recharge and 12 inches of runoff.

Surface Watersheds

A surface watershed is the land area where runoff from precipitation drains to water bodies before it can infiltrate into the ground. Surface watersheds with large amounts of steeply sloped land, higher percentage of agricultural land use, or a higher percentage of impervious surface (buildings, roads, compacted soil) deliver more runoff volume and increased nutrient loads to local streams, and ultimately Lake Noquebay.

The surface watershed for Lake Noquebay was taken from WDNR watershed layers and refined using GIS software (ArcView) and a digital elevation map. The surface watershed has an area of 84,160 acres.

Lake Water Quality

The body of water quality data for Lake Noquebay spans more than 40 years. While there are years-long gaps in the record, few lakes in Wisconsin have such a wealth of water quality data. For this study, in-lake water quality was monitored in 2018 and 2020. Water samples were collected at the surface using a one-meter integrated sampler and one-meter from the bottom using a VanDorn sampler. All samples were collected at the deepest part of the lake. The lake was monitored through the ice in February, soon after ice-breakup, May, June, July, August, September, and after fall turnover. All samples were analyzed for TP, SRP, TKN, NO_2^-- NO_3^-, and NH_4^+. During the growing season (May through September) samples were also collected and analyzed for Chlorophyll-a. All analysis was conducted by the Wisconsin SLOH. Results of the most recent water quality monitoring effort and water quality trends are discussed below according to the constituent being monitored.

During each monitoring event physical properties were measured at one meter intervals from the surface to the bottom of the lake using a Hydrolab Datasonde 4. These include temperature, dissolved oxygen, oxygen saturation, pH, and conductivity. Secchi depth was also measured.

Temperature and Dissolved Oxygen

Dissolved oxygen is critical to biological life in the lake. Oxygen dissolves in lake water primarily through diffusion of oxygen from the atmosphere at the surface of the lake. This process is enhanced by wind driven waves which aerate the water and produce currents that help mix the oxygen deeper into the lake. Oxygen is also produced by plants through the process of photosynthesis during daylight hours.

Oxygen is removed from the lake by biological activity including decaying organic material plant material, and through plant respiration, which occurs at night. Dissolved oxygen concentrations are also affected by water temperature. Water at 75 degrees F can hold 8.4 mg of oxygen per liter of water. The same water at 33 degrees F can hold 14.2 mg/l.

Temperature variations throughout the year can affect how water mixes within the lake because the density of water changes with temperature. Warm water is less dense than cold water and rises to the surface of the lake. Swimmers are familiar with this effect when they swim down and experience ever colder water as they descend. As water cools it becomes denser until it reaches the temperature of 39°F (4°C). As it cools further, the water actually becomes less dense again until it forms ice. This phenomenon is unique to water and allows ice to float at the surface of the lake.

Temperature and mixing are important since the frequency of mixing plays a role in dissolved oxygen concentration and internal nutrient cycling. Shallow lakes typically remain mixed throughout the year while deep lakes often stratify during the summer months. Stratification is a separation of the water into two distinct layers, a warmer top layer (epilimnion) and a much cooler bottom layer (hypolimnion). These two layers are separated by a transition zone (metalimnion), which anglers know as the thermocline. In deep lakes the difference in density is very strong and

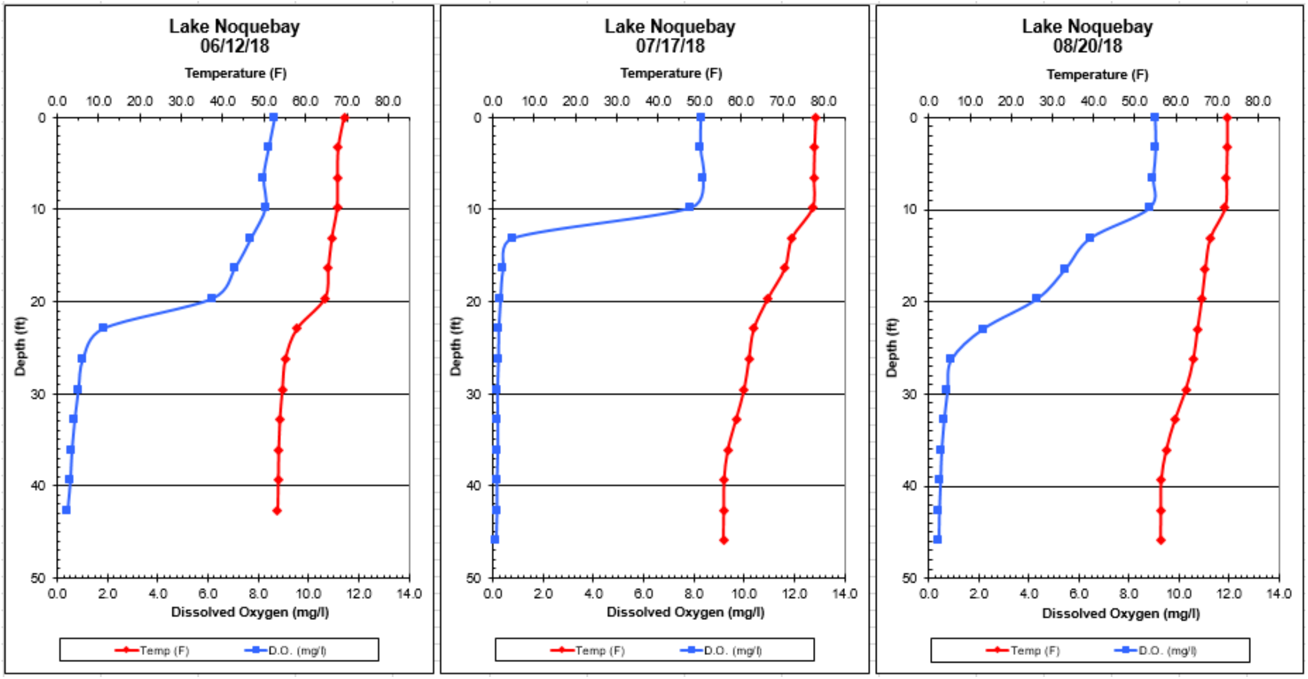

Figure 9. Typical temperature and dissolved oxygen profiles from the deep hole of Lake Noquebay in the summer of 2018. Temperature stratification is weak but calm weather can allow for oxygen depletion of the hypolimnion. The August profile shows oxygen mixing into the hypolimnion, likely due to increased wind induced circulation.

prevents the two layers from mixing until fall when the surface temperature falls and equals the temperature of the hypolimnion. Winter stratification in lakes is also common as ice cover prevents all wind-induced mixing.

In Lake Noquebay, when the ice melts in early spring the temperature of the lake water is similar from top to bottom and wind will cause the lake to uniformly mix because all the water is the same density. This mixing redistributes dissolved oxygen and other dissolved constituents evenly from top to bottom within the lake. This mixing phenomenon is called overturn. Overturn also occurs in the fall as the surface of the lake cools.

Due to its relatively shallow depth and large surface area exposed to the wind, Lake Noquebay remains fairly well mixed throughout the summer months. However, in deeper areas of the lake stratification is common, resulting in oxygen depletion below the 20-foot depth. Monitoring data shows that thermal stratification in these areas is inconsistent and fairly weak (Figure 9). The area affected by stratification represents only 12% of the lake area and 7.6% of the lakes volume.

Phosphorus

Phosphorus is the limiting nutrient in Lake Noquebay, meaning it is the nutrient that is in “short supply” and thus limits the amount of algae growth. Since it is the limiting nutrient, even small additions of phosphorus will lead to increased productivity in a lake, often expressed as an increase in the frequency and severity of algae blooms (Wetzel 2002). Most lakes in Wisconsin are phosphorus limited.

Phosphorus is present throughout the lakes watershed where it is bound to soil particles, and is an abundant element in all living things. Phosphorus is transferred to the lake through the erosion of soil and organic matter, runoff of animal waste and fertilizers, effluent from septic systems, through groundwater inputs, and through atmospheric deposition. Within the lake, phosphorus can be released from sediments and decaying plant matter.

The most common mechanism for the transport of phosphorus from the land to the water is via surface runoff. Some forms of phosphorus adhere tightly to soil/sediment particles. During rain events those particles (soil, organic material, etc.) can be disturbed and carried by the runoff. Phosphorus can also travel to Lake Noquebay in a dissolved form when decaying vegetation, animal waste, and fertilizer are conveyed by water to receiving streams and water bodies. Phosphorus is transported out of the lake through outflow, but the majority remains in the lake where it becomes part of the aquatic system in the form of plant and animal tissue, sediments, and in solution in the water. Phosphorus continues to cycle within the lake ecosystem and is very difficult to remove once it enters the lake.

Once in the lake phosphorus can form an insoluble precipitate with calcium (marl), iron, and aluminum. This helps to reduce phosphorus concentrations in the water column that would be available for algal growth (Shaw et al. 2000). In the sediment, phosphorus reacts very differently under aerobic (oxygenated) versus anaerobic (no oxygen) conditions, as well as under changes to temperatures and pH. These reactions can either contribute to further phosphorus enrichment (internal loading) or make phosphorus unavailable for use by algae and plants.

Zebra mussels (*Dreissena polymorpha*) were discovered in Lake Noquebay in 2008. They have been documented as removing particulate nutrients (primarily in algae and zooplankton) through filtration but, may in fact, be recycling and excreting soluble phosphorus (SRP) back into the water (James et al. 1997; Arnott and Vanni 1996).

Phosphorus in its dissolved form can also travel to the lake in groundwater. This is typically caused by organic sources of phosphorus (manure or human waste) that seep into the water table. Contamination of the groundwater occurs when the capacity of the soil to hold the phosphorus becomes overwhelmed by concentrated sources such as barnyards, excessive field spread manure, or septic drain fields. The highest risk areas are those with course sandy soils and where groundwater is near the surface.

In this study, two forms of phosphorus were measured: soluble reactive phosphorus (SRP) and total phosphorus (TP). SRP is dissolved phosphorus. It is typically found in low concentrations within the lake because free SRP is rapidly taken up by aquatic plants and algae (Wetzel 2002). TP is a measure of the dissolved phosphorus plus organic and inorganic particulate phosphorus in the water. Examples of organic phosphorus would be plant or animal matter. Inorganic particulate phosphorus is typically bound to soil particles. TP is commonly used as a measure of lake phosphorus because its concentrations are more stable than SRP. Phosphorus availability can vary within a lake seasonally, annually, and spatially.

Deep lakes that experience strong thermal stratification typically experience high surface TP concentrations in the spring and fall, just after turnover. In the summer months, algae and nutrients sink below the thermocline where they are no longer available for plant and algae growth. This buildup of nutrients occurs during the summer and winter, whenever the hypolimnion is anoxic. During these periods of anoxia additional phosphorus is released from the sediment as SRP. When the lake turns over in the fall and spring these nutrients are mixed throughout the water column, leading to higher seasonal TP readings

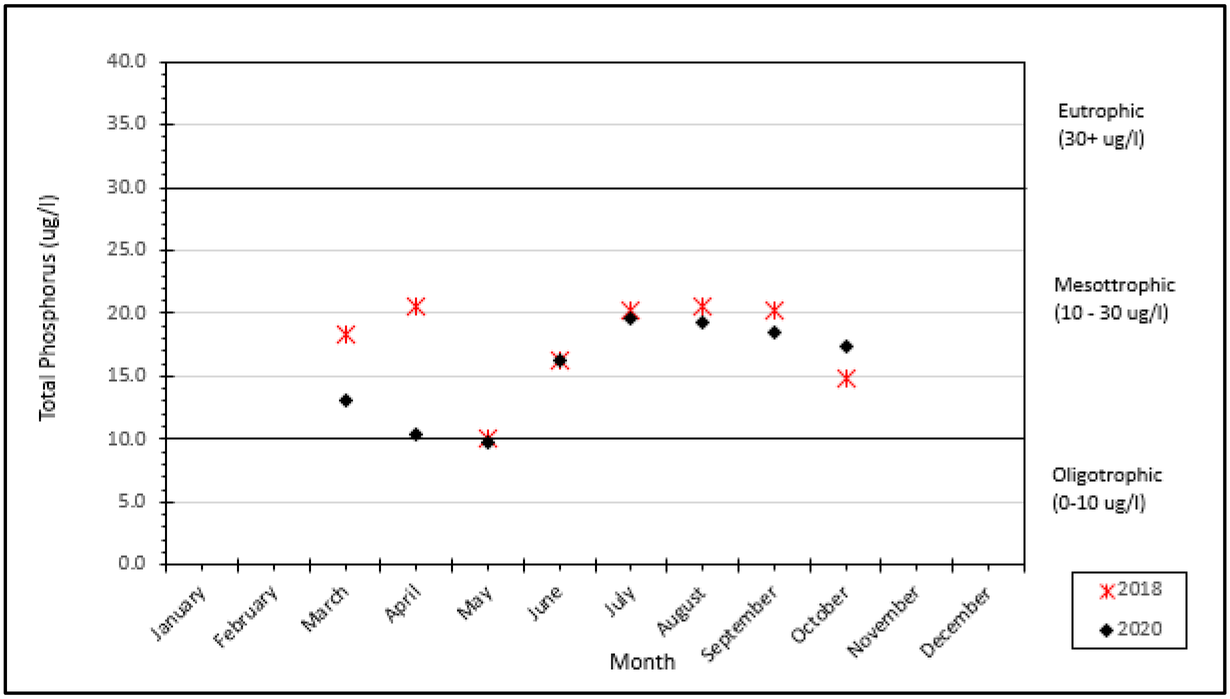

Figure 10. Lake Noquebay surface TP concentrations during the 2018 and 2020 monitoring periods.

In shallow lakes this pattern is often reversed. Surface TP is generally lowest at spring turnover and increases during the summer months. The summer increase is often due to a form of daily internal loading that occurs in dense plant beds when respiration by plants consumes oxygen at night. This can lead to short periods where dissolved oxygen at the sediment surface falls to zero, resulting in SRP release from the sediment into the overlying water.

Figure 10 shows surface TP concentration in Lake Noquebay in 2018 and 2020. During the monitoring period TP ranged from a low of 9.78 micrograms/liter (ug/l) to 20.6 ug/l. In 2020 surface TP followed the typical pattern for shallow lakes, with the lowest TP concentration in the spring and the maximum TP during the summer months. In 2018 however, phosphorus levels were highest in the spring after ice-out, likely due to internal loading and runoff. Figure 11 shows the 40-year average surface TP concentration by month. While there is considerable variability, the average spring TP concentration (14.1 ug/l) is not much lower than the summer average TP concentration (15.8 ug/l). There are several factors that could be responsible for the pattern in monthly TP levels in Lake Noquebay. Winter growing conditions under the ice can vary considerably from year-to-year. When the ice is more transparent and snow cover is lower, more aquatic plants can survive under the ice. Conversely, when the ice is more opaque or there is

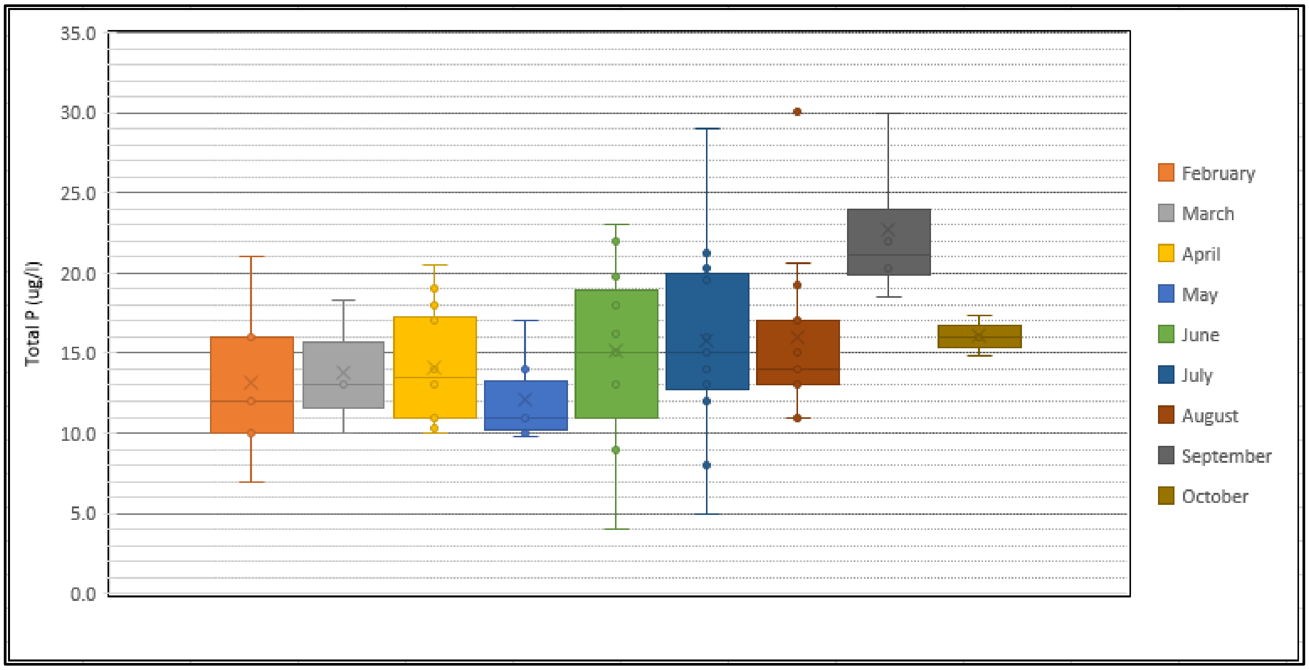

Figure 11. Average monthly TP concentration for Lake Noquebay from 1997 through 2020.

heavy snow cover light transmission is drastically reduced, leading to more plant die-back and decomposition. This would result in more SRP available at spring turnover compared to a winter with more transparent ice cover.

The annual maximum TP concentration is typically recorded in September (Figure 11). This is likely due to phosphorus release from the sediment after periods of summer stratification. While temperature stratification is weak, oxygen depletion often results in a notable increase in hypolimnetic phosphorus, which is typically mixed throughout the lake in September. Hypolimnetic TP concentrations have only been measured since 1993. Since 1993 the average hypolimnetic phosphorus concentration in Lake Noquebay is 31.2 ug/l (Figure 12). In 2018 a period of especially strong stratification resulted in hypolimnetic TP maximum of concentration of 310 ug/l.

A review of temperature and dissolved oxygen profiles and late-winter hypolimnetic phosphorus levels indicates that winter stratification that results in significant internal phosphorus loading is uncommon in Lake Noquebay.

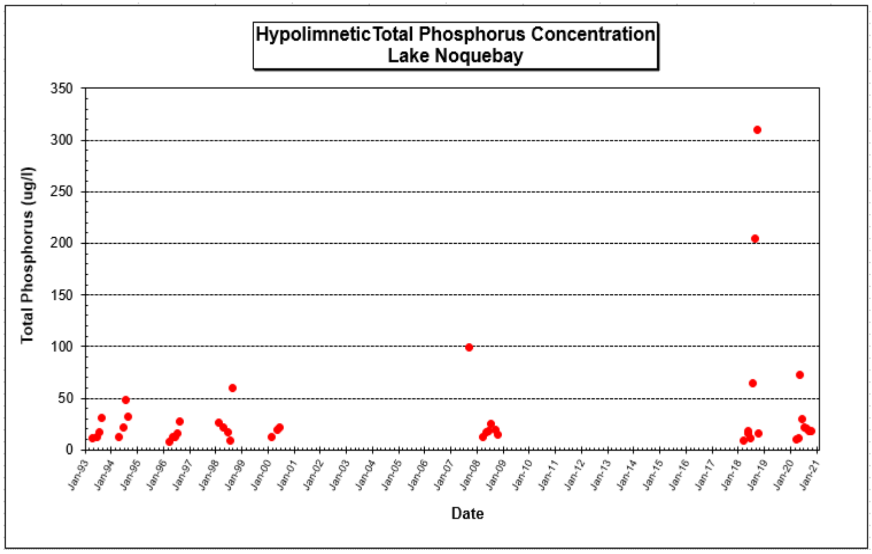

Figure 12. Hypolimnetic phosphorus concentrations in Lake Noquebay.

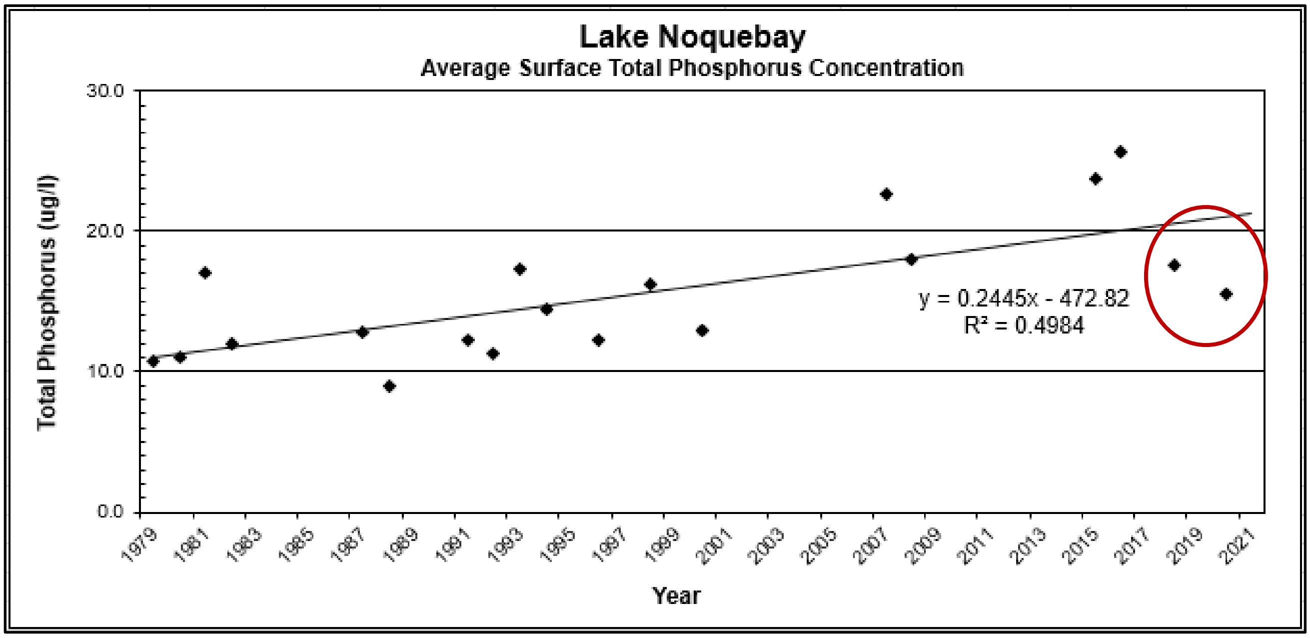

Figure 13. Average annual surface TP concentration for Lake Noquebay (n=80). The most recent monitoring effort (red oval) shows a clear departure from the long-term trend.

Long Term Phosphorus Trend

One of the driving forces for investigating nutrient inputs to Lake Noquebay is an unmistakable upward trend in surface TP concentrations that was seen between 1979 and 2016. However, monitoring conducted during 2018 and 2020 show a notable departure from the long-term trend (Figure 13). A review of historical water quality data clearly shows that Lake Noquebay has experienced measurable changes in phosphorus levels over the last 40 years. Between 1979 and 2000 the growing season mean (GSM) surface TP level was 12.8 ug/l. Between 2007 and 2016 the GSM surface TP concentration averaged 22.7 ug/l, a 44% increase. The most recent monitoring effort (2018 – 2020) revealed an average GSM surface TP concentration of 17.1 ug/l, a 25% decrease from the previous high.

The reduction in TP seen during the current monitoring period may be due to annual variability, or it could be due to decreased nutrient loading from the lakes watershed. In 1992 Lake Noquebay was chosen as one of the state’s first Priority Watershed Projects. A voluntary project which used cost-share funding to incentivize the installation of agricultural best management practices to reduce nutrient runoff from agricultural sources. Best management practices including barnyard runoff controls, installation of manure storage facilities to reduce winter spread manure, soil conservation practices, and nutrient management planning were adopted by most of the active farms in the watershed. By 2006 it was estimated that best management practices resulted in a 1,052 lb. annual reduction in phosphorus runoff, primarily from the installation of manure storage facilities and the subsequent reduction in winter-spread manure. Long-term trends in agricultural management practices and a reduction in animal units in the Lake Noquebay watershed likely play a role in declining agricultural inputs, particularly from land-spread animal waste.

Soluble Reactive Phosphorus

Soluble reactive phosphorus (SRP) is readily available for use by algae and aquatic plants. In 2018 SRP averaged 0.85 ug/l with a high of 4.7 ug/l in June. In 2020 SRP averaged 11.1 ug/l with a high of 17.8 ug/l in August. The high SRP readings seen in 2020 were unusual when compared to historical SRP concentrations. Prior to 2020 SRP was measured 39 times and only one of those exceeded 10 ug/l. In shallow lakes, high SRP readings during the summer are often the result of decaying vegetation and the associated release of phosphorus from shallow sediments.

2019 and 2020 were exceptionally wet seasons characterized by historically high water levels on many local lakes. In Lake Noquebay, increased runoff from wetlands within the lakes watershed delivers a lot of dissolved tannins to the lake, leading to a seasonal decrease in water clarity. In 2018 the average Secchi disk depth in Lake Noquebay was 10.7 feet. In 2020 the average Secchi disk depth was 7.2 feet. If the reduction in water clarity is sudden, as it often is after heavy spring runoff, aquatic plant communities become stressed and die back in deeper areas of the lake.

Lake Noquebay also has invasive zebra mussels (Dreissena polymorpha). The zebra mussels are commonly found growing in great numbers on the stems of aquatic plants in the lake. This often results in plants sinking under the weight of the accumulating zebra mussels, further stressing plants growing in deeper areas. While zebra mussels have been documented as removing particulate nutrients through filtration, they also excrete SRP back into the water (James et al. 1997; Arnott and Vanni 1996).

Increased SRP release in 2020 is likely due to decaying vegetation brought on by a sharp decrease in water clarity. More than 20% of Lake Noquebay is between 10 and 15 feet deep. With a maximum rooting depth of 15 feet, a 3.5 foot reduction in water clarity can result in a large dieback of aquatic plants and the subsequent release of SRP. This would be compounded by the effect of zebra mussels on vegetation and nutrient cycling within the lake.

Shaw, et al. (2000) suggests that the SRP concentrations following spring overturn should be 10 µg/l or less to prevent summer algae blooms. A review of surface SRP data for Lake Noquebay shows this threshold was exceeded in only one instance (April 30, 1981) when SRP was 16 ug/l.

Nitrogen

Nitrogen is second only to phosphorus as a key nutrient that influences aquatic plant and algal growth in lakes. Nitrogen is a major component of soil, all plant and animal tissue, and therefore organic matter. It is also found in precipitation, which can be the primary nitrogen source in some seepage and drainage lakes. Sources of nitrogen include agricultural and home-use fertilizers, animal waste, and septic system effluent.

Nitrogen enters and exits lakes in a variety of forms. The most common include ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), and organic nitrogen associated with living or dead biological matter. These forms summed yield total nitrogen. Aquatic plants and algae can use all inorganic forms of nitrogen (NH_4^+ , NO_3^-, and NO_2^-). If inorganic forms of nitrogen exceed 0.3 mg/l in spring, there is sufficient nitrogen to support summer algae blooms (Shaw et al., 2000). Organic forms of nitrogen can also become available after biological conversion to ammonium.

In the samples collected from Lake Noquebay inorganic nitrogen concentrations were low. The inorganic forms of nitrogen exceeded 0.3 mg/l only once during the monitoring period, in February of 2018 when inorganic nitrogen was 0.39 mg/l. The average inorganic nitrogen concentration during the period was 0.09 mg/l. Throughout the course of the year, much of the nitrogen in the lake was in the organic form.

Nitrogen Phosphorus Ratio

The amount of aquatic plants and algae that can grow in a lake depends on the amount of nutrients that are available. The major nutrients of concern for surface waters in Wisconsin are phosphorus and nitrogen. In a given body of water, a plant community's requirement for phosphorus is usually different than for nitrogen. The total nitrogen (TN) to total phosphorus (TP) ratio indicates whether nitrogen or phosphorus is the limiting nutrient for plant growth. When the TN:TP ratio is greater than 15:1, plant growth is generally restricted by the amount of phosphorus available. The average TN:TP ratio in Lake Noquebay during the monitoring period was 37:1, which indicates that plant and algae growth in Lake Noquebay is limited by phosphorus, and that efforts to control phosphorus inputs to the lake will have the most direct impact on algae and aquatic plant growth.

Water Clarity and Chlorophyll a

Water clarity is a measure of how far light can penetrate into the lake. Light penetration can be affected by algal growth, turbidity from suspended solids, and color from dissolved components in the water. Water clarity is measured with a Secchi disk, an 8 inch black and white disk that is lowered into the water until it disappears. This distance is the Secchi disk depth.

Lake Noquebay has clear, slightly stained water. The slight brown staining is due to tannins, dissolved organic compounds released by leaves and needles as they decompose in wetlands

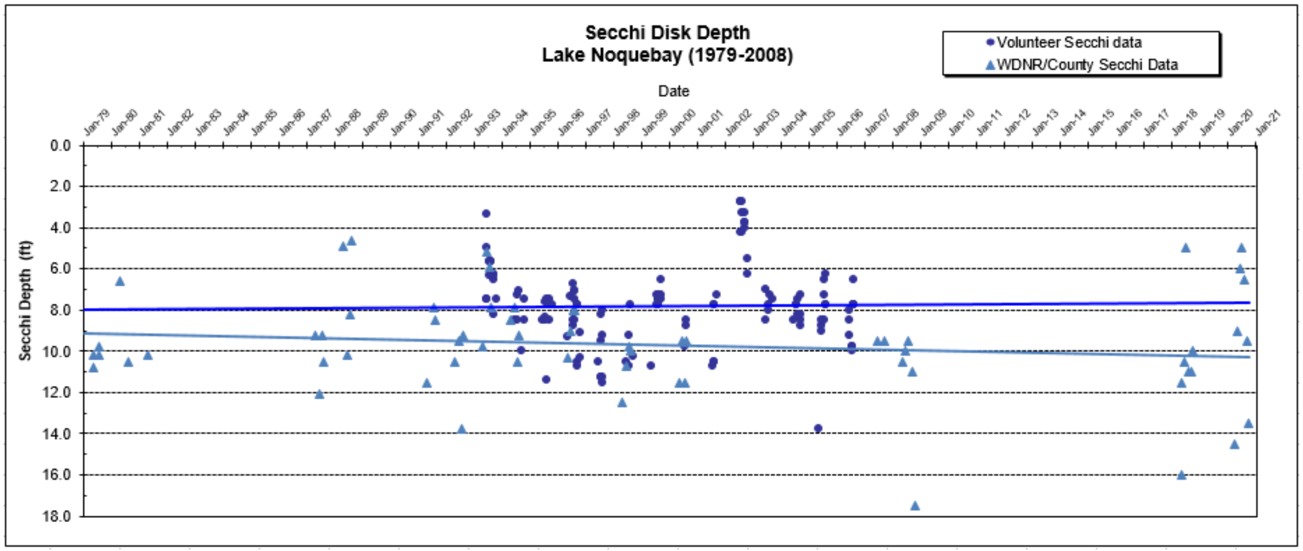

Figure 14. Average Secchi disk depth of Lake Noquebay as measured by WDNR, Marinette County staff, and volunteer monitors.

within the lake's watershed. The average Secchi disk depth during the study period was 9.9 feet. Overall, the Secchi disk depth for Lake Noquebay is better than the statewide average for similar lakes.

Water clarity measurements have been taken in Lake Noquebay since 1979 by volunteer water quality monitors, WDNR staff, and Marinette County staff (Figure 14). Secchi disk readings show considerable seasonal and year-to-year variability. There is also a notable difference between the volunteer monitor and WDNR and County staff. Some of the variability may be due to the measurer and technique used. The average Secchi disk depth for the monitoring period was 9.9 feet, with a range of 5 to 14.5 feet. The average Secchi disk depth since 1979 was 7.8 feet as measured by the volunteer monitor, and 9.7 feet as measured by the WDNR and County staff.

Chlorophyll a is a green pigment and the primary form of chlorophyll found in green plants and algae. In water samples it is used as a measure of algal abundance. Chlorophyll a is typically only measured during the growing season and varies seasonally and annually according to algae abundance. During the monitoring period chlorophyll a averaged 5.84 ug/l with a high of 7.01 ug/l in July of 2018. Since 1979 the average chlorophyll a concentration is 4.7 ug/l with a maximum of 12.6 ug/l in late April of 1980. Chlorophyll a concentrations greater than 30 µg/l is considered a potentially nuisance level of algae, and severe algae blooms may result in chlorophyll-a concentrations in excess of 100 ug/l.

Trophic State Indices

Secchi disk depth, phosphorus concentration and chlorophyll-a concentration are commonly used to calculate a Trophic State Index (TSI) for lakes. The TSI is a number that describes the nutrient enrichment level of a lake. Oligotrophic lakes (<**40**) are nutrient poor, these lakes are unproductive and have very clear water. Eutrophic lakes (>**50**) have excessive nutrients. These lakes are very productive (able to grow lots of plants, fish and insects) and usually weedy, or support large algae blooms, or both. Mesotrophic lakes (**TSI of 40-50**) have moderate nutrient levels and fall

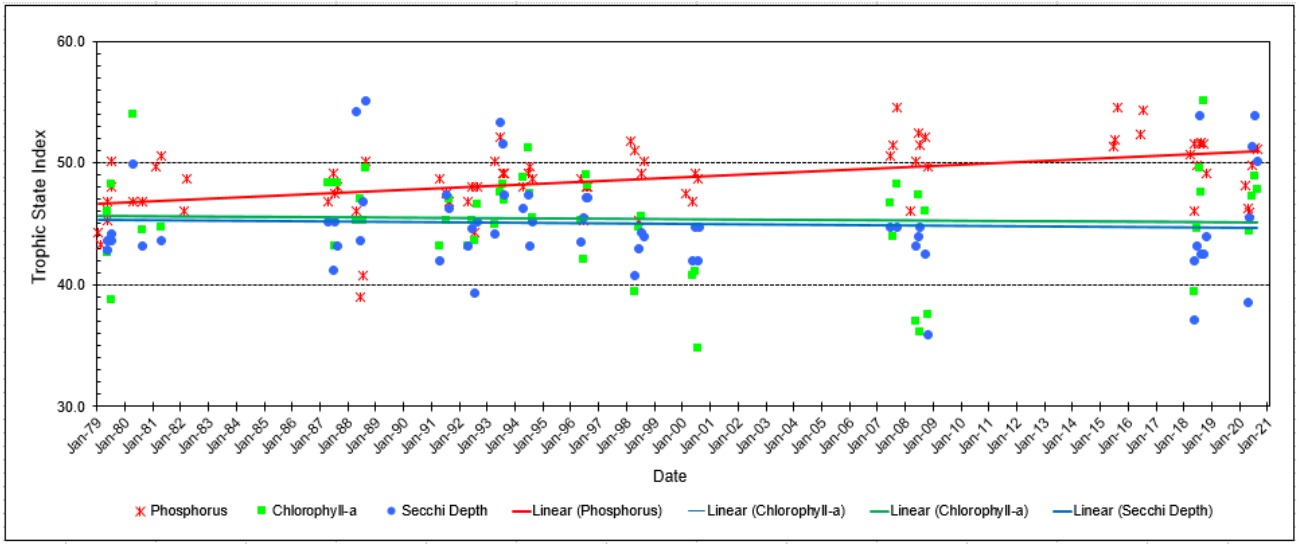

Figure 15. Lake Noquebay trophic state index values from 1979 through 2020.

somewhere between the two extremes in aquatic plant and fish productivity. Using phosphorus as an indicator, the growing season trophic state for Lake Noquebay during the study period was 49.9 which is right at the cutoff of Eutrophic, or nutrient rich, lakes. The Secchi TSI (47.1) and chlorophyll-a TSI (47.2) were slightly lower.

Figure 15 shows growing season TSI values for Lake Noquebay from 1979 through 2020. The phosphorus TSI shows a clear increase, which is to be expected as the TSI measure mirrors TP concentrations in the lake. During the same 40-year period the Secchi TSI and chlorophyll-a TSI are basically unchanged and squarely within the mesotrophic range. The discrepancy in trophic state indices calculated using phosphorus versus Secchi depth and chlorophyll a is not uncommon in shallow lakes that are dominated by aquatic plants. It indicates that rooted plants take up most of the nutrients in the lake.

Land Use and Watershed Nutrient Loading

The land area draining to Lake Noquebay (the watershed) covers approximately 84,160 acres. Runoff from this area is the primary source of water and nutrients to Lake Noquebay. Other sources include direct precipitation on the lake surface and groundwater inflow. The amount of water and nutrients that are exported from a landscape over a period of time is known as the nutrient export rate, and it varies considerably across different land covers and land use practices. The amount of nutrient exported to the lake over the course of a year is known as the annual nutrient load.

Land Use Effects

Generally, nutrient export is lowest from undeveloped and undisturbed lands such as forests and wetlands, and higher from human altered landscapes such as agricultural and urban areas. In forested lands the canopy cover intercepts rainfall, which reduces runoff, and well-structured soils (not compacted) allows for adequate infiltration. Dense and diverse vegetation also takes up water and nutrients to fuel vegetative growth.

Wetlands are a critical component in healthy watersheds. Wetlands act as pollutant filters for surface water and groundwater. Runoff flowing across the landscape in shallow concentrated flow is slowed upon entering a wetland, allowing sediment and nutrients to settle out. This effectively filters runoff before it reaches the stream. Wetlands adjacent to a stream, also known as floodplains, also temporarily store runoff during high flow events, allowing for increased infiltration and reducing flood flows to the lake.

Agriculture lands can contribute significant amounts of nutrients and sediment to runoff. The nutrient load can vary considerably depending upon the specific type of agriculture (row crops versus perennial forage crops), soil type, management practices being used on a farm (conventional versus conservation tillage), and the distance to the water body. Animal waste management practices are especially important in determining nutrient loading rates. Uncontrolled runoff from barnyards, feed lots, or manure stacks, and surface-spread manure on frozen or snow-covered fields can deliver relatively large amounts of nutrients to the lake.

Nutrient loads from urban and developed residential areas can also be elevated far above those see in an undisturbed landscape. Residential areas typically have a high percentage of impervious surface and compacted soils. Impervious surfaces include roof tops, sidewalks, and paved and unpaved roads and driveways. Urban and rural developed areas are also designed with interconnected drainage systems (ditches and storm sewers) to rapidly move water off the landscape and deliver it to a nearby stream or wetland. Runoff from these areas is often rich in nitrogen, phosphorus, chloride (from road salt) and other pollutants.

Sub-watershed Land Use

An analysis of land use patterns was performed in sub-watersheds to help interpret nutrient loads in associated tributaries. The lakes watershed was divided into four sub-watersheds. The Smith Creek/LMI, Middle Inlet, and Upper Inlet sub-watersheds correspond with the three main tributaries feeding Lake Noquebay (Figure 16). The direct drainage sub-watershed consists of lands

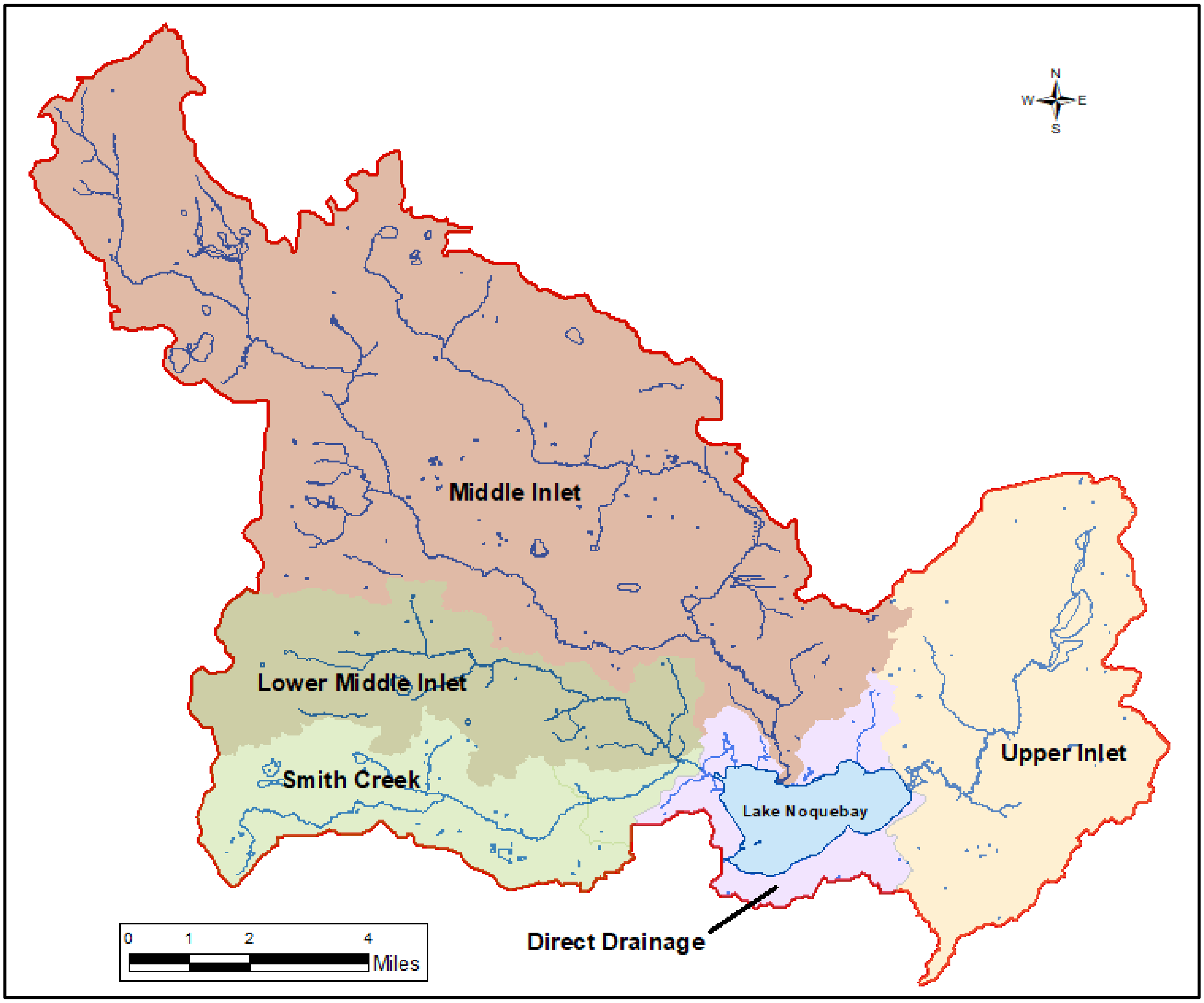

Figure 16. Lake Noquebay watershed and sub-watershed divisions used in flow monitoring and load calculations.

that drain directly to the lake through diffuse overland flow and several small perennial and intermittent drainages. Runoff from the direct drainage sub-watershed was not gauged.

Smith Creek & Lower Middle Inlet Sub-watersheds

The Smith Creek/LMI watershed contains two similar sized streams (Smith Creek and Lower Middle Inlet) that combine just before emptying into Lake Noquebay. The watersheds are roughly the same size and watershed land use is similar. Due to the difficulty of finding a gauging station below the confluence of Smith Creek and Lower Middle Inlet, two gauging stations were established for nutrient and flow monitoring, one on each stream.

The riverine portion of Smith Creek begins in S14, T32N, R19E and empties into Lake Noquebay on the northwest end of the lake. Lower Middle Inlet originates as the outlet of Chrizel Lake in S35, T33N, R19E. The SC/LMI sub-watershed drains 19,951 acres, or 23.7% of the total watershed area. Forested land and wetland accounts for 67% of the area, followed by agricultural lands at 26%. There are five lakes in the SC/LMI sub-watershed; Campbell, Charles, Rush, Chrizel, and Retcof Lakes.

Smith Creek and Lower Middle Inlet have a cold water Class I sport fish community consisting of brook trout and forage species. Prior to implementation of the Lake Noquebay Priority Watershed Project, nutrient loads calculated from monitoring data showed that phosphorus and nitrogen levels were elevated in Smith Creek. Water resource reports estimated that nitrogen loading from Smith Creek was 252% higher than the non-agricultural Upper Inlet sub-watershed, while phosphorus loading was 168% higher.

Middle Inlet Sub-watershed

The Middle Inlet sub-watershed is the largest sub-watershed, covering more than 43,756 acres or 52.0% of the Lake Noquebay watershed. 77% of the sub-watershed consists of forest land and wetlands. Agricultural lands cover 21.1% of the land area. There two major tributaries and fifteen lakes within the Middle Inlet sub-watershed. Middle Inlet originates in S8, T34N, R19E and flows into Lake Noquebay on the north side of the lake. Upper Middle Inlet originates as the outlet to Spies Lake in S30, T34N, R20E and flows into Middle Inlet approximately 3.3 miles from Lake Noquebay.

Below the junction of Middle Inlet and Upper Middle Inlet, the stream has a cold water Class II sport fish community consisting of brook trout, brown trout, and forage species. The 23.6 miles of stream located upstream of the junction are classified as cold water Class I. Fish species consist of brook trout and forage species in the upper reaches, with brown trout in the lower reaches closer to Lake Noquebay.

The largest concentration of farms is located in the Middle Inlet sub-watershed. Prior to implementation of the Lake Noquebay Priority Watershed Project, areal loads of nitrogen were listed as 26% higher than the largely forested Upper Inlet sub-watershed.

Upper Inlet Sub-watershed

Upper Inlet begins as the outlet to Stephenson Lake in S19, T33N, R22E then flows through Mud Lake, Lake Mary and Lake Julia before emptying into Lake Noquebay. Upper Inlet drains 16,577 acres, 19.7% of the total watershed area. Forest and wetland account for 14,750 aces, or nearly 97% of the watershed area. Agricultural uses cover just over 480 acres, or 3% of the area.

Upper Inlet is classified as a warm water sport fish community. Historical water quality monitoring showed very low phosphorus and nitrogen loading from the Upper Inlet.

Direct Drainage Sub-watershed

The direct drainage sub-watershed consists of land around Lake Noquebay that drains directly to the lake through overland flow or minor, often intermittent, tributaries. The direct drainage sub-watershed covers 3,876 acres, or 4.6% of the total watershed area. Woodlands and wetlands accounts for 287 acres, or 74% of the sub-watershed area. Urban riparian land use accounts for 806 acres (21%) and agricultural land use covers 192 ac, or 4.9% of the sub-watershed area.

Sub-watershed Nutrient Loading

Nitrogen and Phosphorus were monitored at each of the sub-watershed gauging stations between the summer of 2018 and the fall of 2020. Nutrient loading from each of the sub-watersheds was evaluated individually, as well as the stream and watershed characteristics that influence export. A subset of samples were also analyzed for total suspended solids (TSS) and Chloride.

Nitrogen

Nitrogen is transported to streams via runoff bound to particulates and in solution. Since many forms of nitrogen are water soluble, groundwater can also transport dissolved nitrogen within the watershed. The range of total, inorganic (nitrogen in solution), and organic (particulate nitrogen) nitrogen loads were explored for all tributaries.

Total Nitrogen (TN)

The Environmental Protection Agency (EPA) has developed nutrient criteria for Wisconsin based on ecoregions. The Lake Noquebay watershed is located in the North Central Hardwood Forests Ecoregion (Ecoregion VIII, sub-region 50). The reference condition is defined as the 25th percentile of the data for the region and would represent a minimally disturbed watershed. For this area the

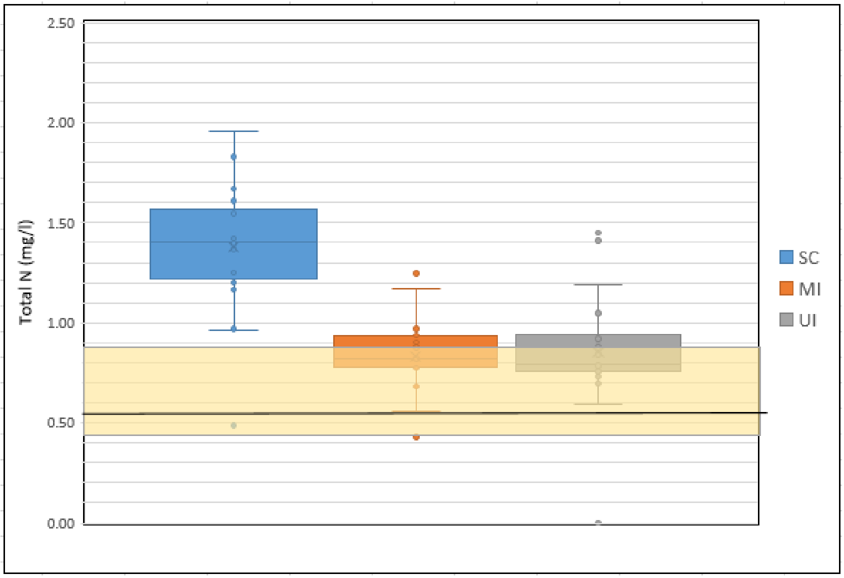

Figure 17. Total Nitrogen concentrations in Lake Noquebay Tributaries and comparison to EPA reference conditions.

reference condition for Total N is 0.44 mg/l. The median for the region is 0.53 mg/l. The 75th percentile is 0.87 mg/l. Figure 17 shows the TN data for Lake Noquebay Tributaries. The average TN concentration from Smith Creek was 1.44 mg/l and most samples exceeded the reference conditions, which are represented by the yellow box. TN concentrations in Middle Inlet and Upper Inlet were considerably lower, but most readings exceeded the median for the ecoregion and many exceeded the 75th percentile.

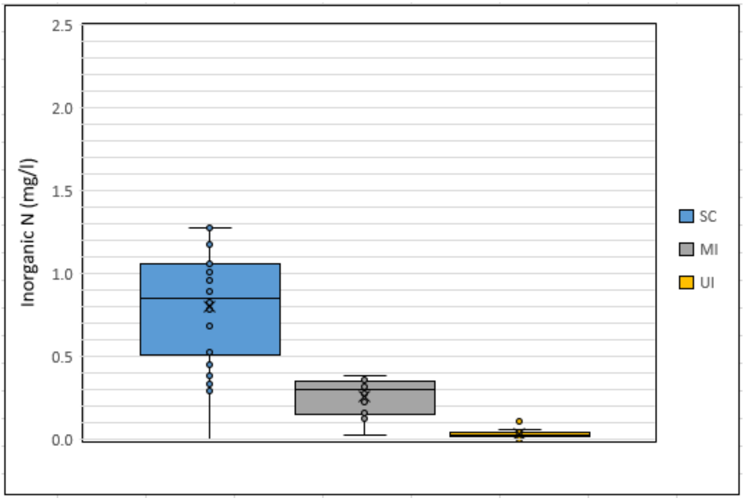

Figure 18. Measured inorganic nitrogen concentrations in Lake Noquebay tributaries.

Inorganic Nitrogen

Inorganic nitrogen is nitrogen that is in solution in the water. It consists of NO_2^- - NO_3^- (nitrate) plus NH_4^+ (ammonia). Inorganic nitrogen is of greatest concern because it is immediately available for use by aquatic plants and algae. Figure 18 shows the inorganic nitrogen concentration data for the Lake Noquebay tributaries. The concentration of inorganic nitrogen was considerably higher in Smith Creek (avg. = 0.85 mg/l) than Middle Inlet (avg. = 0.31 mg/l) or Upper Inlet (avg. = 0.04 mg/l). Elevated inorganic nitrogen is common in streams that are impacted by agriculture.

Organic Nitrogen

Organic nitrogen is nitrogen that is tied up in organic material in the water, including live or partially decomposed plants and animals. Organic nitrogen is closely tied to total suspended solids (particulate matter) in runoff and can be indicative of increased erosion and direct runoff of land-spread manure. Organic nitrogen concentrations were similar between all streams (Figure 19) with the highest concentrations from Upper Inlet (avg. = 0.87 mg/l). The water samples for Upper Inlet were collected at the outfall of the Lake Noquebay Wildlife Area marsh, and likely represents algae and decomposing organic matter flowing out of the marsh. This stream also had very low inorganic nitrogen, supporting the theory that most nitrogen in the marsh is tied up in plants and animals.

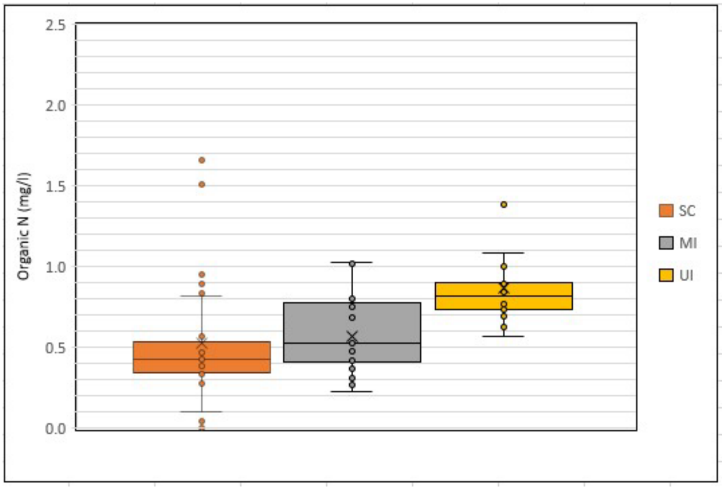

Figure 19. Measured organic nitrogen concentrations in Lake Noquebay tributaries.

Nitrogen Loading

The nitrogen loading rate is the amount of total nitrogen (TN) that is delivered to the lake per hectare (2.3 acres) of watershed area. The TN loading rate for

Smith Creek (2.80 mg/ha/yr) during the monitoring period is more than double the rate for Middle Inlet (0.870 mg/ha/yr) or Upper Inlet (1.160 mg/ha/yr). The higher concentration of TN in likely due to agricultural inputs. Upper inlet, despite having very little agriculture also has a higher loading rate than Middle Inlet. Since most of the nitrogen load coming from Upper Inlet is in the form of organic nitrogen, it is likely due to nitrogen mobilization from upstream lakes and the extensive marshlands in the Upper Inlet watershed.

On an annual loading basis, the largest load of total nitrogen comes from Middle Inlet (15,395 kg/yr) followed by Smith Creek (11,189 kg/yr) and Upper Inlet (7,782 kg/yr). Despite having a lower TN loading "rate", the total load from Middle Inlet is higher due to the larger watershed size. The Middle Inlet sub-watershed is more than twice as large as the Smith Creek or Upper Inlet sub-watersheds, and delivers proportionally more water to Lake Noquebay.

Phosphorus

Watershed streams were monitored for total phosphorus (TP) and soluble reactive phosphorus (SRP). TP loads were calculated for each sub-watershed. TP consists of phosphorus that is dissolved in the water (SRP) and particulate phosphorus which is bound up in organic matter or attached to soil particles.

Total Phosphorus

The EPA reference conditions for total P in the Lake Noquebay Watershed (Ecoregion VIII, sub-region 50) is 13.5 ug/l to 52.5 ug/l. A concentration of 13.5 ug/l is the lower quartile of the dataset and is representative of an undisturbed watershed. 52.5 ug/l is the upper quartile, and is representative of watersheds that are more disturbed. The average TP concentration for all streams in the ecoregion (n = 677) across all seasons was 26.2 ug/l.

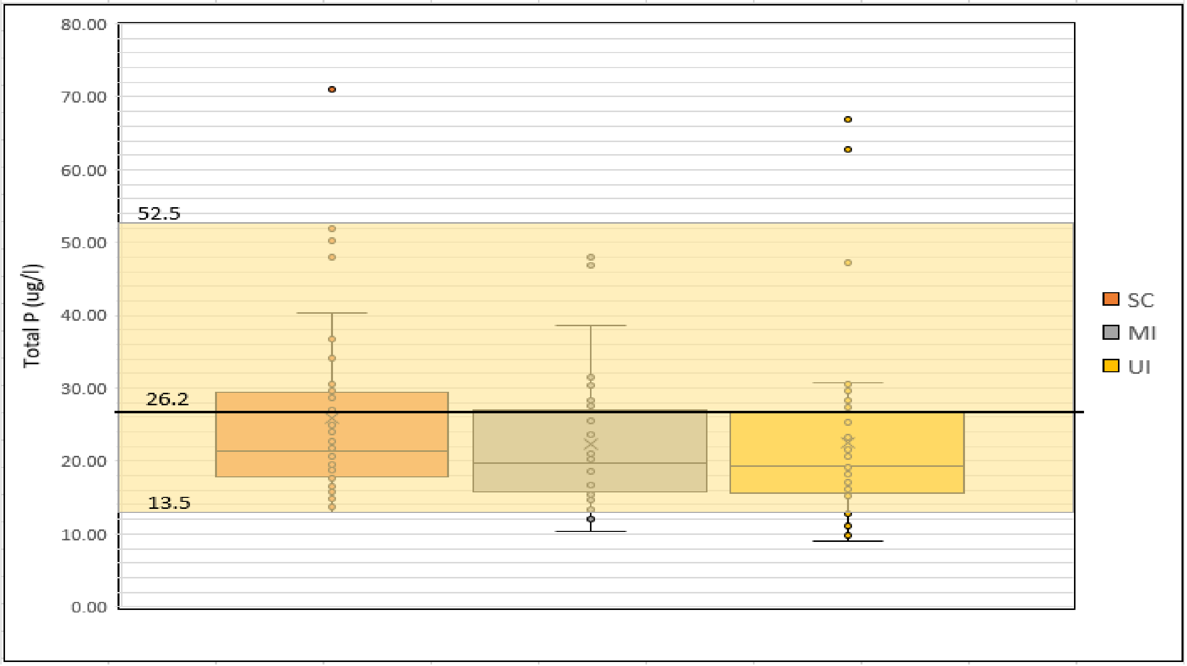

Figure 20. Total phosphorus concentration data for Lake Noquebay tributaries and comparison to EPA reference conditions.

Total P concentrations measured in streams draining to Lake Noquebay were fairly consistent. While some samples exceeded the upper bound of 52.5 ug/l, the average total P and the upper and lower quartile for all tributaries were below the upper bound, and most were below the ecoregion average of 26.2 ug/l (Figure 20). The average Total P concentration from Smith Creek (25.9 ug/l) was only slightly higher than Middle Inlet (22.3 ug/l) or Upper Inlet (22.6 ug/l).

Soluble Reactive Phosphorus

The average annual SRP concentration within the ecoregion for all seasons is 6.85 ug/l with a reference concentration of 5.00 ug/l to 12.18 ug/l. The average SRP concentration for the Smith Creek sub-watershed was 19.4 ug/l and most samples exceeded reference condition (Figure 21). The average SRP concentration for Middle Inlet (11.9 ug/l) and Upper Inlet (10.3 ug/l) were within the reference concentration but exceeded the ecoregion average. The higher SRP concentrations in Smith Creek may be due to proportionally greater impacts from agricultural sources within the Smith Creek and Lower Middle Inlet watersheds.

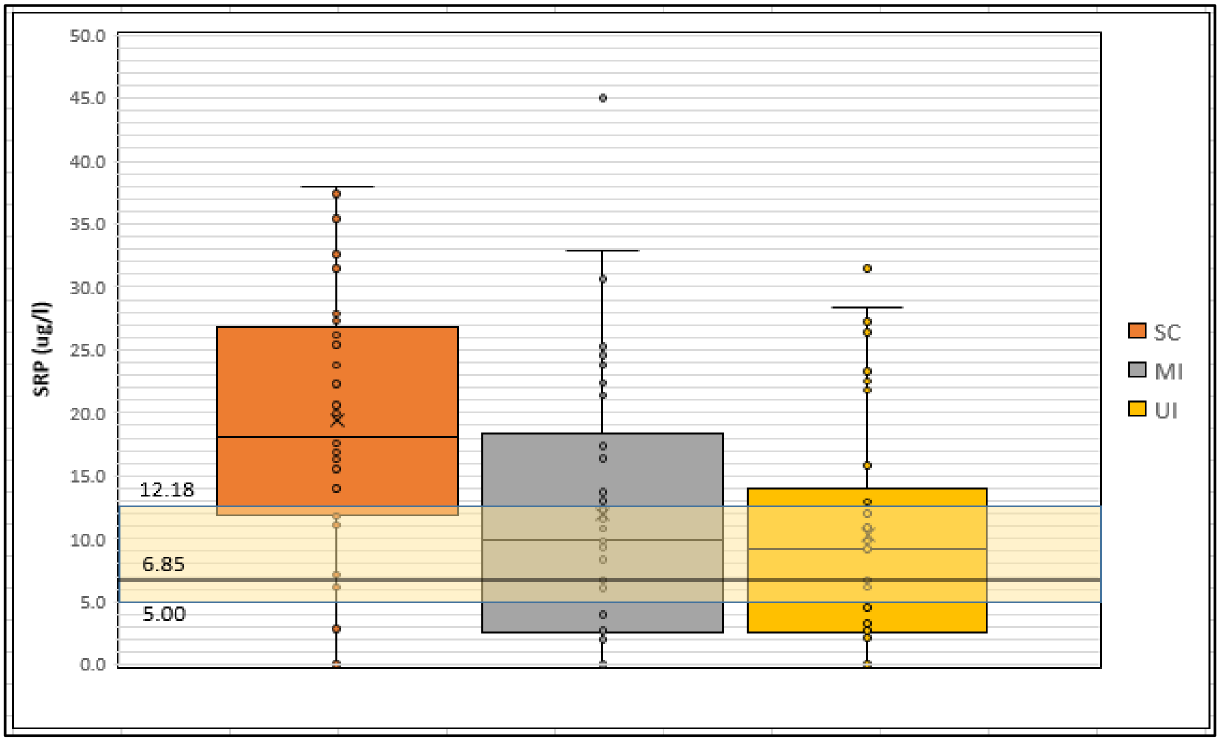

Figure 21. Soluble reactive phosphorus concentration data for Lake Noquebay tributaries and comparison to EPA reference conditions.

Tributary Phosphorus Loading

While the phosphorus concentration in runoff is important, concentration alone is only part of the equation. Water quality in Lake Noquebay is driven by the phosphorus load, which is defined as the amount of phosphorus delivered to a lake during a year. Phosphorus load is typically expressed in kilograms (kg), and the loading rate from each sub-watershed in kilograms per hectare per year (kg/ha/yr). In standard units, 1 kg/ha/yr is equal to 0.92 lbs/ac/yr.

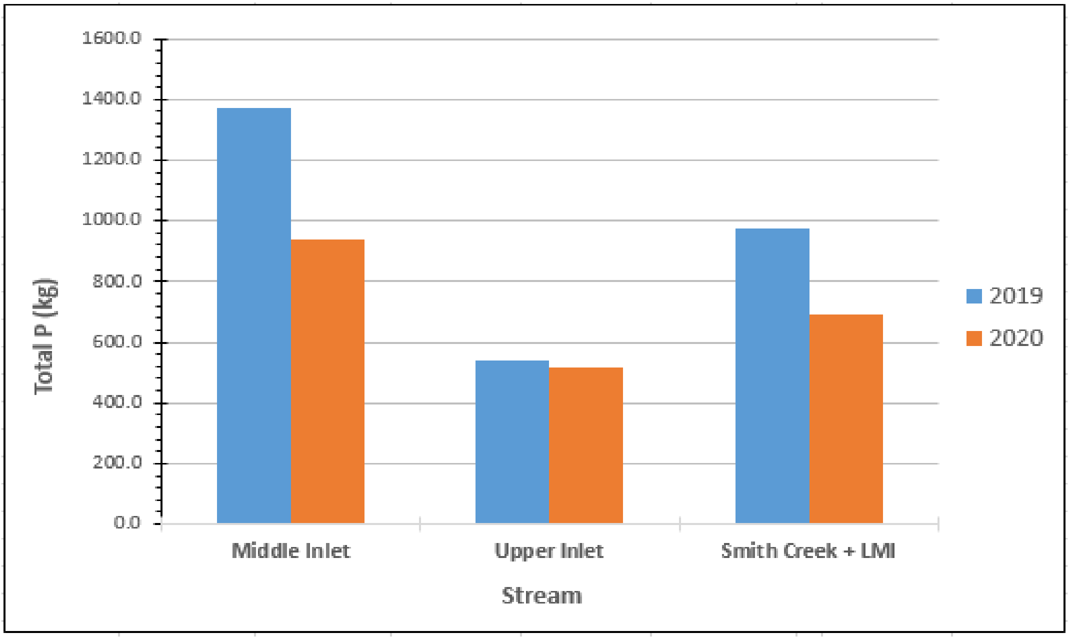

Figure 22. Comparison of tributary TP loads for 2019 and 2020.

Phosphorus loading was modeled using FLUX^{32} Load Estimating Software which calculates constituent loads through a flow-concentration relationship (Walker 1996). Figure 22 shows the modeled TP loads for the three major streams feeding Lake Noquebay. During the two monitored years (2018-2019), Middle inlet delivered the highest phosphorus load to Lake Noquebay with an average load of 1155.1 kg, followed by Smith Creek/Lower Middle Inlet (821.4 kg) and Upper Inlet (546.0 kg). Although Middle Inlet delivers the highest TP load, the sub-watershed is more than twice the size of Smith Creek/Lower Middle Inlet and Upper Inlet sub-watersheds. On an aerial loading basis (Figure 23), Smith Creek/Lower Middle Inlet delivers nearly twice as much phosphorus (0.102 kg/ha/yr) than Middle Inlet (0.065 kg/ha/yr). An analysis of land use shows that the Smith Creek sub-watershed is 26% agricultural land uses compared to 20.1% in the Middle Inlet sub-watershed. Since Smith Creek and Lower Middle Inlet were monitored individually, the loading rate for each was calculated. The loading rate for Smith Creek was calculated at 0.078 kg/ha/yr. while the rate for Lower Middle Inlet was 0.121 kg/ha/yr. The higher TP loading rate for Lower Middle Inlet may be due to differences in soil type, slope, or location of the agricultural land in relation to the

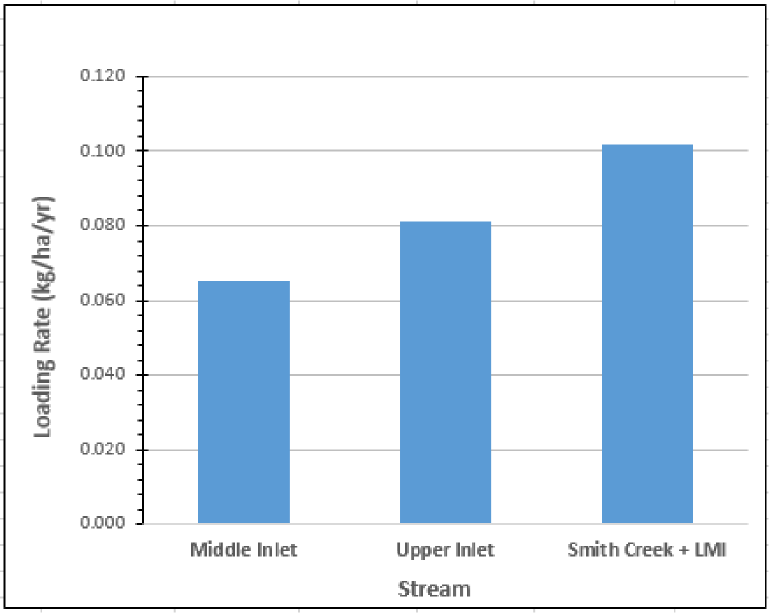

Figure 23. Average TP loading rate for Lake Noquebay tributaries.

stream, leading to differences in connectivity and TP delivery. The TP loading rate for Upper Inlet was (0.081 kg/ha/yr).

Shoreland Phosphorus Loading

The land area surrounding Lake Noquebay that drains directly to the lake or through small intermittent drainages covers 3,876 acres. Runoff from the direct drainage sub-watershed was not monitored due to its diffuse nature. Likewise, runoff volume from the land area was not monitored. Phosphorus loading from the direct drainage sub-watershed was calculated using land use data and phosphorus export coefficients developed by Panuska and Lillie (1995). Total phosphorus loading from the direct drainage sub watershed was calculated to be 408 kg annually. The calculated loading rate is 0.103 kg/ha/yr.

Developed lands cover 20.8% of the direct drainage sub-watershed. These areas can be divided into two land use categories. The first and second tier of shoreline development consists of those homes located on the shoreline and directly across the road from the lake. These are primarily small lots with a high percentage of impervious surface (roof tops, concrete, asphalt etc.) and direct connectivity to the lake. This high-density development delivers an estimated 252 kg of TP to the lake annually. Development located farther from the lake generally consists of larger lots, less impervious surface, and is more disconnected from the lake. This low-density development delivers an estimated 39.4 kg of TP to the lake annually. Agricultural land within the direct drainage sub-watershed accounts for only 4.9% of the sub-watershed area and contributes and estimated 58.6 kg of TP. Forests, wetlands, and fallow farmlands make up nearly 75% of the sub-watershed area and deliver 58.2 kg of TP annually.

Groundwater Evaluation

Groundwater was evaluated using mini-piezometers and seepage meters to determine areas of groundwater inflow to the lake and measure flow rates. Mini-piezometers were installed at 130 locations around Lake Noquebay. Groundwater inflow, indicated by a groundwater head of at least 1.0 cm, was detected at 53 of the monitoring locations (41%). Seepage meters were then installed at sites identified as having significant groundwater inflow. However, it soon became apparent that there was little to no correlation between mini-piezometer readings and measured seepage rates. As a result, mini-piezometer data was not used as a screening step. Instead, seepage meters were installed around the perimeter of the lake at 164 locations, approximately every 300 feet, to determine areas of groundwater inflow.

Groundwater inflow, defined as at least 1.0 L/m^2/day was detected at 64 of the 164 seepage monitoring locations (39%). Figure 24 shows the areas where groundwater seepage was detected and the relative level of groundwater input. The inflow zones were estimated to cover an area of 23.8 acres (9.6 ha). The volume of groundwater inflow was estimated at 637,575 m3/yr (517 ac/ft) based on the average measured seepage rate in the contributing area.

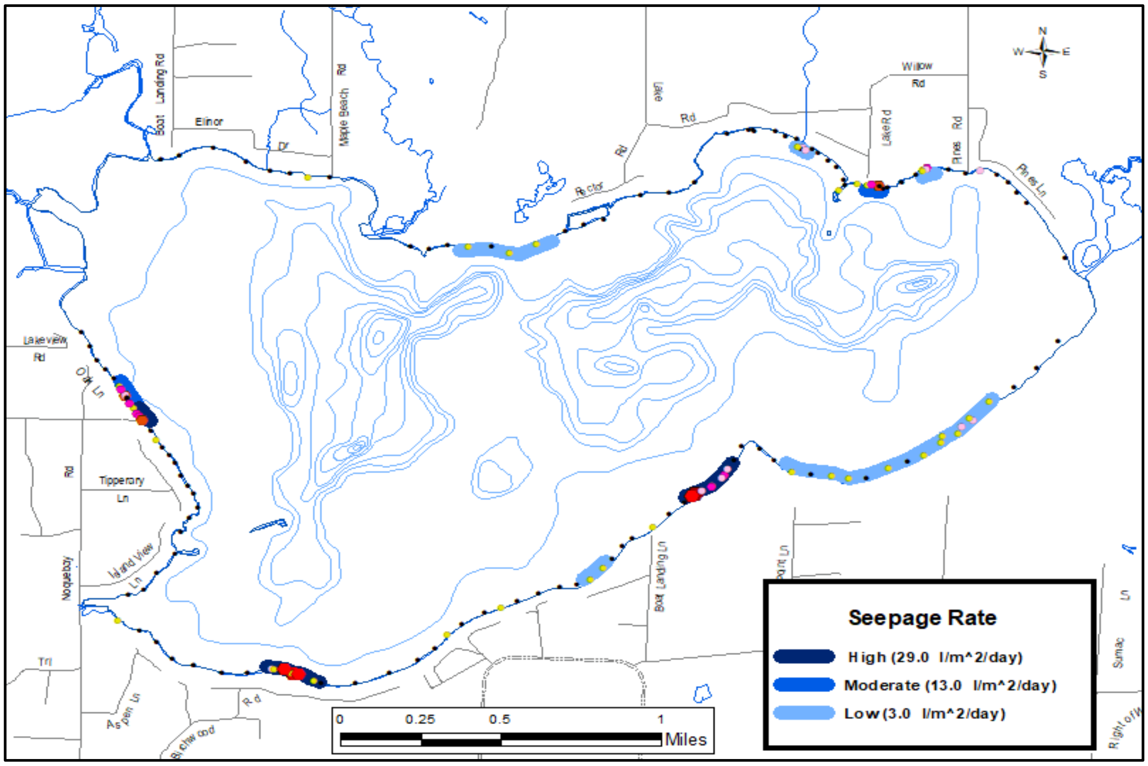

Figure 24. Location and calculated flow rate for areas of significant groundwater inflow. Colored dots represent individual seepage rates measured with seepage meters.

Water samples were collected from at 36 sites using the mini-piezometers, drawing water from approximately 20” below the sediment surface. Samples were analyzed for soluble reactive phosphorus (SRP), inorganic nitrogen (NO_2^- - NO_3^- plus NH_4^+), and chloride (Cl). Overall SRP concentrations were low with an average SRP concentration of 41.17 ug/l (figure 25). The minimum SRP concentration was 19.1 ug/l with a maximum of 88 ug/l.

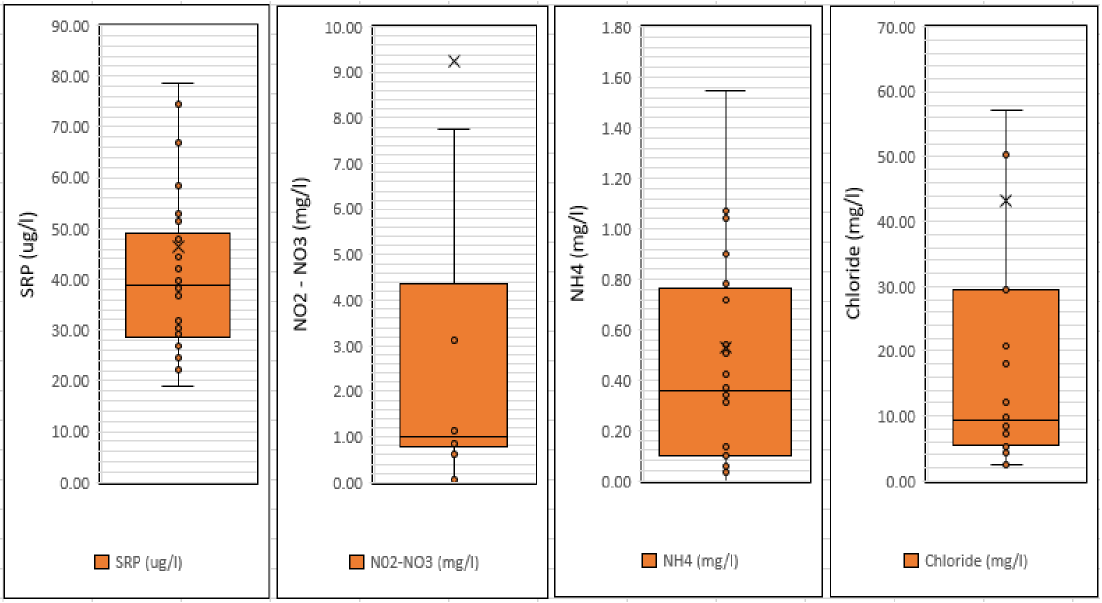

Figure 25. Groundwater sampling results for Lake Noquebay.

A phosphorus load of 43 kg/yr was calculated by multiplying the calculated inflow volume by the average concentration in the contributing area. This was within the range estimated by the WI Lake Model Spreadsheet (23.45 to 75.04 kg/yr) based on capita years of occupancy in residences within one-half mile of the lake.

Lake Phosphorus Budget

A phosphorus budget for Lake Noquebay was created using monitored water and phosphorus loading data for major tributaries and groundwater inputs. Estimated water loads and total phosphorus loads were calculated for the direct drainage, dry deposition, internal loading, and aquatic plants. Figure 26 shows the annual estimated water and total phosphorus loads for Lake Noquebay. Runoff from the lakes watershed is estimated at 156,418 ac/ft/yr., or 13.8 inches of runoff. Water loading from the watershed represents more than 95% of the water delivered to Lake Noquebay every year. The average annual total phosphorus load to Lake Noquebay is 3,312.6 kg/year. Runoff from the lake's watershed accounts for 89.8% of the annual TP load.

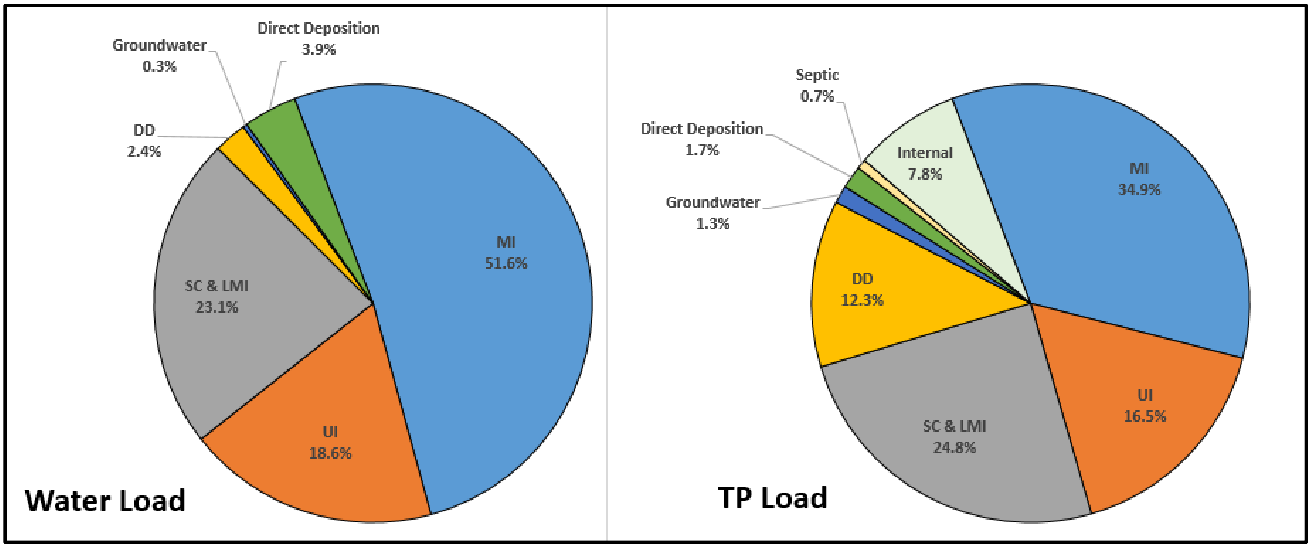

Figure 26. Average annual water and nutrient loads to Lake Noquebay.

Watershed Inputs

Phosphorus loads from the major tributaries were monitored and modeled using the FLUX^{32} Load Estimating Software as described earlier and scaled to include the ungauged portions of each sub watershed. Loading from the direct drainage (DD) sub-watershed was estimated using land use export coefficients and modeled using the Wisconsin Lake Management (WiLMS) spreadsheet. Together, runoff from the lakes watershed accounts for 2,930 kg of TP annually, or 89.8% of the total load.

Groundwater Inputs

Groundwater phosphorus inputs were calculated using seepage data and groundwater monitoring results. The annual groundwater TP load was estimated at 43 kg of TP, or 1.3% of the total load.

Precipitation & Dry Deposition

Precipitation and dry deposition of phosphorus onto the lake surface occurs throughout the year with rain, snow, or as dry fall from particulate matter in the air. A phosphorus concentration of 7 µg/L of precipitation was estimated using data collected by the National Atmospheric Deposition Program and the average annual rainfall of 32.1 inches for Crivitz, WI. Atmospheric deposition is estimated at 55.7 kg of TP annually, or approximately 3.9% of the total load.

Internal Loading

Phosphorus in lakes can be found as part of plant tissue, dissolved in the water, and in the sediment where it can be loosely or tightly bound to sediment particles and organic matter where it forms complexes with other chemicals. At different times the lake sediment can act as both a sink and a source for phosphorus. In shallow, unstratified lakes there are several mechanisms by which P can be recycled from the sediment to overlying waters (Welch and Cook 1995). These mechanisms can interact at the same time and vary in importance over time. Because of the changing nature of these mechanisms it can be very difficult to determine annual internal loading rates on shallow lakes.

Resuspension of flocculent sediment by wind, boat wakes, or bottom-feeding fish can lead to increased internal P loading. In Lake Noquebay most shallow sediments are coarse sands that are not easily suspended. In deeper water, nearly complete aquatic plant cover stabilizes the sediment and protects it from wind and boat driven turbulence. As a result, sediment resuspension of P is likely very low.

The senescence (die-back) and decomposition of aquatic plants can also result in internal P release. Typically this happens outside of the growing season in the fall and winter. Senescence during the growing season can occur with some aquatic invasive species, particularly curly-leaf pondweed (*Potamogeton crispus*) which begins growth under the ice and typically dies back in late July or August, releasing the stored nutrients to the overlying water. Curly-leaf pondweed is not found in Lake Noquebay, nor is Eurasian watermilfoil (*Myriophyllum spicatum*), which has also been linked with summer senescence and increase internal P loading.

In deep lakes, water below the thermocline (the hypolimnion) often experience prolonged periods of anoxia (no oxygen) that results in P release from the sediment that is mixed throughout the lake during spring and fall turnover. In shallow lakes, respiration of aquatic plants at night, and prolonged windless periods can also result in anoxic waters above the sediment surface, resulting in P release from the sediment. Periodic mixing can release the resulting P to overlying waters, resulting in high internal P loading throughout the summer months. In Lake Noquebay, the deep areas that might experience long-term stratification make up less than 8% of the lake. Dissolved oxygen monitoring shows that thermal stratification in the deep hole is weak and sporadic, often occurring only in late July through August. Monitoring shows that hypolimnetic P release due to anoxia is not a common occurrence. Since 1993 the average hypolimnetic phosphorus concentration was 34 ug/l, with a median of 17.8 ug/l. Since 1993, hypolimnetic P levels only exceeded 100 ug/l in August and September 2018.

According to Welch and Cook (1995) internal P loading from shallow lake sediments is more common in lakes with very low iron to phosphorus ratios (Fe:P ratio). In 2020 Fe:P ratio in Lake Noquebay just above the sediment surface was 4.6, which is moderate and would tend to reduce sediment P release from periods of short-term anoxia.

Hypolimnetic TP concentrations and monitored dissolved oxygen values were used to calculate an internal phosphorus load for Lake Noquebay using the Wisconsin Lake Model Suite which uses four methods to estimate internal P loading. Predicted sediment P release rates ranged from 6.9 to 12.7 mg/m^2/day with a total estimated annual load of 160 to 481 kg per year. The chosen method using actual P concentrations predicted 260 kg/year, or 7.8% of the total P budget.

Internal loading would be most notable after turnover in years with relatively strong and prolonged thermal stratification. A review of monthly TP data shows that the highest average monthly TP concentration (22.7 ug/l) occurs in September when lake temperatures cool and turnover would take place (Figure 11).

Aquatic Plant Removal

The Lake Noquebay Rehabilitation District has been harvesting aquatic plants since 1978 with a focus on harvesting variable-leaf watermilfoil (*Myriophyllum heterophyllum*) to maintain navigability through dense plant beds. Since 2000 harvesting and shoreline cleanup has removed an average of 1,300 tons (1,179,340 kg) of aquatic plants from the lake annually. The removal of plant material also removes phosphorus contained within the plants. A sample of aquatic plants collected from the harvester contained 0.0021 kg P/kg or dry plants. Assuming 90% moisture content, the average total P removed from Lake Noquebay through harvesting is 247 kg annually. The P removal is not included in the total P budget but it would show up in reduced internal loading through a reduction in dead plant material.

Wisconsin Lake Model Suite (WiLMS) - Model Structure and Results

Average TP loading data from the 2019-2020, along with internal loading estimates was used to calibrate the WiLMS model and simulate in-lake phosphorus concentrations. Calculated stream flows and TP loads were input as point sources. Loading from the direct drainage sub-watershed was calculated within the model based on land use data. Septic loading was estimated based on annual capita years of occupancy that was self-reported by lake residents.

Overall model fit was excellent, with predicted TP in a range from 13 ug/l to 24 ug/l and an average estimated growing season mean (GSM) TP level of 18.2 ug/l. The measured GSM TP concentration in Lake Noquebay from 2000 to 2020 is 18.7 ug/l. Individual models with the best fit include Vollenweider (18 ug/l), Reckhow (19 ug/l), Walker (20 ug/l) and Canfield-Bachman Artificial Lake (20 ug/l).

One phosphorus load reduction scenario (20% reduction) and two phosphorus increase scenarios (20% and 40% increase) were run to predict GSM TP concentrations under various changes in watershed loading rates. The change in predicted surface total phosphorus during the growing season are shown in Table 1.

Parameter	Current	20% reduction	20% increase	40% increase
Total P Load	3298	2018	3895	4491
Lake Model				
Vollenweider, 1982 (combined)	18	15	20	23
Reckhow, 1977	19	15	22	26
Walker, 1977 (general lakes)	20	17	24	28
Canfield-Bachmann, 1981 (artificial lake)	20	17	23	26
Average of models	19.2	16.0	22.5	25.7
Predicted change in GSM phosphorus	0	- 16%	+ 17%	+ 34%

Table 1. Estimated total phosphorus concentrations in Lake Noquebay and loading change scenarios calculated using the WiLMS.

A 20% reduction in P load is predicted to decrease the growing season mean TP concentration by 16% to an average of 16ug/l. For comparison, the actual GSM total phosphorus concentration from 1979 to 1999 was 12.9 ug/l. A 20% increase in P load is predicted to increase the GSM TP concentration by 17% to 22.5 ug/l, a concentration that is sufficient for periodic nuisance algae blooms. A 40% increase in phosphorus load is predicted to increase GSM TP levels by more than 34%, to an average of 25.7 ug/l. As phosphorus loads increase, the resulting TP levels seen in the lake are likely to increase at a similar rate until the point where algae blooms begin to reduce rooted aquatic plant growth.

SUMMARY AND CONCLUSIONS

Long-term water quality monitoring in Lake Noquebay reveals a steady upward trend in surface phosphorus levels between 1979 and 2016. Despite this, Lake Noquebay has maintained very low algal concentrations and excellent water clarity, especially for a large, shallow drainage lake. Like most shallow lakes, aquatic plants are abundant, with nearly 80% of the lake supporting some aquatic plant growth.

Lake Noquebay and its watershed make up a complex system. Water quality is driven by external inputs from the lakes watershed and internal processes that determine how nutrients are used, stored, recycled, and exported. The goal of the Lake Noquebay Nutrient Study was to investigate these factors and attempt to explain recent changes in water quality and recommend changes to protect and improve the lake for future generations.

As part of the project, lake water quality was monitored in 2018 and 2020. While surface phosphorus levels remained higher than pre-2000 levels, they were significantly lower than the average surface TP concentrations from 2007 to 2016. While there is always considerable year-to-year variability in phosphorus loading, the recent decrease does track with external loading and agrees with lake model results. The reason for the recent decrease in TP is most likely changes in agricultural loading due to the successful implementation of the Lake Noquebay Priority Watershed

Program, and general trends in agricultural land use and management. Additional water quality monitoring should be conducted to determine if the most recent data is part of a new downward trend in TP levels.

Water quality in Lake Noquebay is primarily dependent on external phosphorus loading. The watershed, as a whole, contributes 88% of the annual phosphorus load. This includes direct runoff from shoreland areas and tributary loads. Addressing land use practices near shore and within the watershed are probably the most manageable in terms of phosphorus reduction. Reductions in near-shore phosphorus loading would have the swiftest effect on nutrient reduction to Lake Noquebay. Within the larger watershed, the area with the highest per/acre loading rate was the Smith Creek/Lower Middle Inlet sub-watershed.

Internal factors that affect Lake Noquebay phosphorus levels include sediment release and plant community changes caused by invasive species and plant harvesting. Zebra mussels have been established in the lake for more than 15 years and contribute to internal loading by consuming algae and increasing soluble reactive phosphorus levels. The LNRD plant harvesting program also has an impact on internal loading by removing biomass and phosphorus that would otherwise be released to the water during the winter months. Efforts to prevent future invasive species introductions should be increased, especially since other shallow lakes in Wisconsin have seen large increases in internal loading with the introduction of curly leaf pondweed (*Potamogeton crispus*).

Lake Noquebay is also seeing the effects of climate change. Regional warming has already resulted in a longer ice-free period on Northern Wisconsin Lakes. This trend is predicted to continue, resulting in longer growing seasons. The greatest degree of warming is predicted to occur during the winter months, resulting in decreased snow cover and an increase in the frequency and intensity of winter rain events. Rain events on frozen ground result in increased runoff volume, higher soil erosion rates, and increased phosphorus loading.

Lake modeling clearly demonstrates that phosphorus load reductions can result in measurable water quality improvements. Reducing external loading will help assure that the recent water quality improvements will continue. These improvements will not impact aquatic plant growth in the lake, but they will further reduce the chances for nuisance algae blooms. More importantly, lake models predict that an increased phosphorus loading will lead to higher total phosphorus levels in Lake Noquebay and an increase in the frequency and severity of algae blooms, threatening a shift to a more algae dominated state within the lake.

Multiple studies have demonstrated that shallow lakes can exist in one of two stable states, a clear-water state where aquatic plants dominate the ecosystem, or a turbid-water state where algae dominate the ecosystem (Scheffer et al. 1993). Figure 27 illustrates the phenomenon where a lake (the ball) can exist in one of two stable states (the cup) over a range of nutrient concentrations (Hobbs Et Al). In this model a shallow lake with low nutrient concentrations will have good water clarity, allowing sunlight to penetrate deep into the water column. In this condition the lake supports abundant aquatic plant growth and nutrient levels are seldom high enough to sustain algae blooms. Lake Noquebay is in this clear-water state.

As nutrient levels rise and the lake becomes even more nutrient rich, the lake tends to remain in the clear-water phase past the level where phosphorus is sufficient to cause increased algal production. This is due to a number of internal buffering systems that help maintain the clear-water state (Blindow 1993).

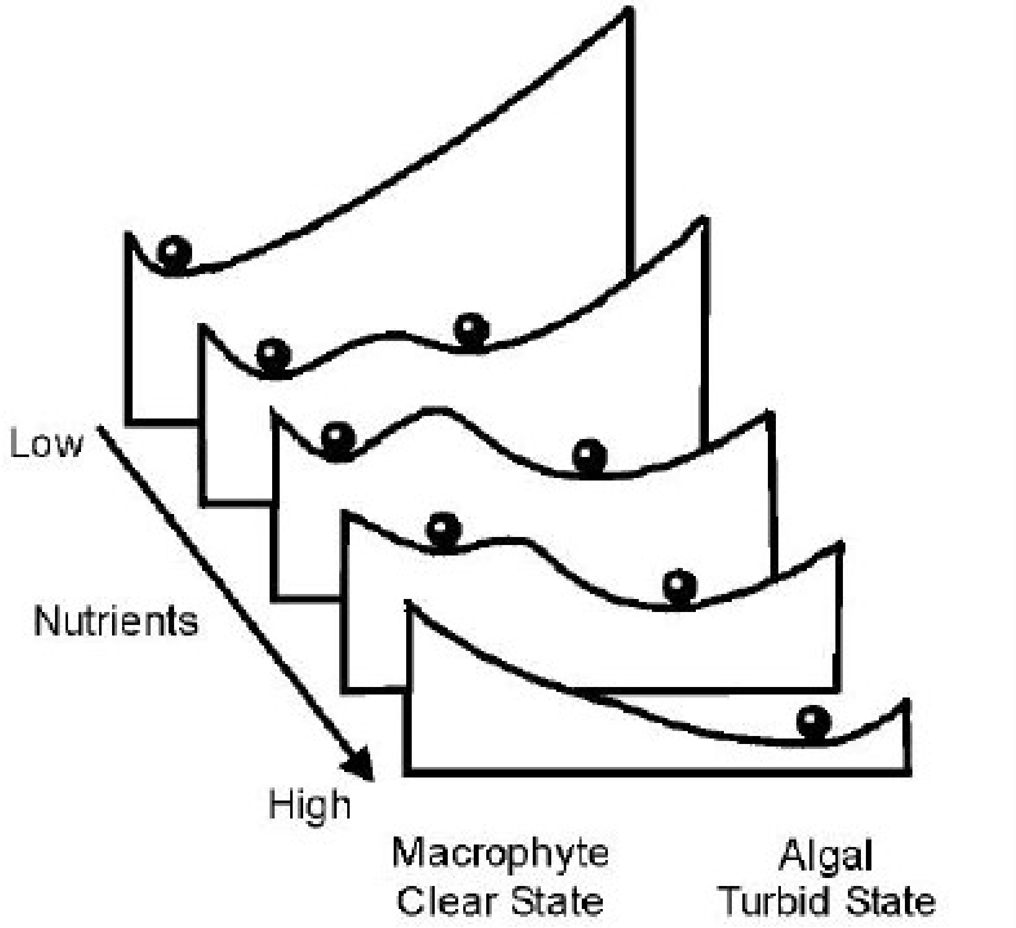

Figure 27. A graphic representation of alternative stable states in lakes. Currently Lake Noquebay is has moderate nutrient levels and remains in a clear-water state.

At some point nutrient concentrations can increase to the point where algae production is favored, but the shift from the clear-water state to a turbid-water state is often caused by some disturbance to the system (Bachman et al 1999). These disturbances have included storm events that caused turbidity through sediment resuspension, the introduction of benthic fish species such as grass carp or other changes in the fish community, or even the introduction of invasive plant species such as curly leaf pondweed (*Potamogeton crispus*). Climate change might also increase stress to lake ecosystems that could cause a shift in stable states. These might include an increase in mean lake temperatures, a longer growing season, increased severity of storm events, or increasing frequency of droughts.

Just as the clear-water regime is stable, once a lake experiences a shift to the turbid-water state, feedback mechanisms tend to keep the lake in a turbid state with high algal populations (Sheffer

1990, Sheffer et al 1993). Algae can begin growing much earlier in the season than aquatic plants and suppress aquatic plant growth through shading. A shift to an algae-dominated food web also causes shifts in the fish community that favor small fish that feed on zooplankton. Since zooplankton feed primarily on green algae, a shrinking zooplankton population can lead to increased algae and poor water clarity (Timms et.al. 1984). Increased phosphorus levels also favor the growth of nuisance blue-green algal species that float at the surface, further reducing water clarity.

The big question of course is "is Lake Noquebay in danger of a regime shift"? Currently this seems unlikely since phosphorus concentrations in Lake Noquebay are typically in the range of 12 ug/l to 23 ug/l with only a few instances of TP readings in excess of 30 ug/l, which is the level required to support nuisance algae blooms. If phosphorus concentrations continue to rise the threat will increase.

Shawano Lake, a large shallow lake located 40 miles southwest of Lake Noquebay, may offer some insight into the effects of increasing nutrient levels (Turyk, 2008). While Shawano Lake is nearly 2.5 times larger than Lake Noquebay, both lakes have artificially raised water levels and have extensive shallow areas that support dense aquatic plant growth. In Lake Noquebay, since 2000, the growing season phosphorus concentration averages 20.1 ug/l and phosphorus only rarely exceeds 30 ug/l during spring or fall turnover. In Shawano Lake phosphorus concentrations in excess of 30 ug/l during the summer months are common. As a result, Shawano Lake experiences routine algae blooms associated with mid-summer phosphorus peaks.

The primary goal in Lake Noquebay should be reducing phosphorus loading to protect against nuisance algae blooms. Protecting against even more invasive species will also ensure that Lake Noquebay remains in a clear-water phase.

RECOMMENDATIONS

1. Runoff from the lakes watershed has been identified as the major source of phosphorus to Lake Noquebay. Improving water quality, or even "holding the line" in the face of a changing climate and new invasive species, means this is where nutrient reduction efforts should be focused. Stream monitoring did not reveal any red flags or point to any one phosphorus source so nutrient reduction efforts should be watershed-wide.
    a. Shoreland runoff contributes an estimated 408 kg of phosphorus per year to Lake Noquebay. Since this area is located directly adjacent to the lake it offers some of the best opportunities to reduce phosphorus loading. Most practices involve reducing phosphorus application on the land, or intercepting and infiltrating runoff before it reaches the lake.
        i. Much of the shoreline lacks sufficient vegetative buffers to remove sediments, nutrients, and pollutants from runoff and to provide habitat for aquatic wildlife. The state standard for a functional buffer is thirty-five feet from the water. Re-

    establishment of buffers in these areas is strongly encouraged, and should include grasses, forbs, shrubs, and trees.

    ii. Existing native shoreline vegetation around the lake should be protected and efforts should be made to establish more natural vegetation in shoreline riparian areas. This vegetation provides many benefits to the lake ecosystem. The grasses and shrubs filter out sediments which flow from adjacent areas. The vegetation maintains and increases soil infiltration rates and uses nutrients that would otherwise flow to the water and provides habitat for many species of animals that use the shoreline.
    iii. Typically the soil under residential lawns has adequate phosphorus concentrations and additions are not necessary to maintain a healthy lawn. Homeowners should only apply nitrogen as needed and only add phosphorus if a soil test determines that additions are necessary.
    iv. Reduce runoff and increase infiltration by installing rain gardens and/or bioretention devices to collect and infiltrate runoff from impervious surfaces such as rooftops, driveways, and roads.

b. Agricultural sources of phosphorus include commercial fertilizers, land applications of animal waste, farmstead and feedlot runoff, and soil erosion. Although many agricultural best management practices have already been installed on watershed farms, there are still opportunities to further reduce nutrient loading.
    i. While none of the watershed streams stood out with especially high phosphorus loading, the Smith Creek/Lower Middle Inlet sub-watershed had the highest P loading rate.
    ii. All agricultural lands should be managed following a phosphorus-based nutrient management plan.
    iii. Animal waste (manure) should be managed as a resource, not a waste product. Whenever possible manure should be stored over winter and incorporated into the soil immediately after application or injected into the soil to preserve soil cover. Nutrient management plans should identify high-risk areas where manure spreading is not allowed.
    iv. Use of winter cover crops and allowing crop residuals to remain on fields over winter would help to reduce soil movement during early spring snowmelt and runoff. Conservation tillage practices should be incorporated where possible to reduce soil and nutrient runoff.
    v. New or expanding farms should incorporate agricultural best management practices during the planning phase and ensure that sufficient land is available for animal waste management needs.
    vi. Natural areas and wetlands improve water quality as they intercept and filter runoff before it reaches the streams. Efforts should be taken to restore previously drained wetlands in the lake Noquebay watershed by removing tile lines and ditches. Existing wetlands should be protected.

2. Aquatic plant harvesting removes an estimated 247 kg of phosphorus from the lake annually. While it is difficult to estimate how much of this phosphorus would be stored in the sediments versus released to the overlying waters, the amount of phosphorus removal is significant.
    a. The LNRD should continue its efforts to manage variable-leaf watermilfoil (*Myriophyllum heterophyllum*) and other nuisance species in Lake Noquebay through aquatic plant harvesting.

3. Aquatic invasive species (AIS) have been shown to disrupt lake ecosystems, leading to changes in internal loading. Efforts should be taken to prevent the introduction of new AIS to Lake Noquebay.
    a. Curly-leaf pondweed (*Potamogeton crispus*) is of particular concern due to its growth habit. CLP begins growth under the ice and outcompetes many native species. In mid to late summer CLP dies off, releasing nutrients to the lake at a time when algae can take advantage of the sudden nutrient influx.
        i. Lake residents should be educated on basic AIS identification so they can be on the lookout for "new" species in the lake.
        ii. Nobody on the lake has more hands-on experience and daily contact with the lakes plant population than the LNRD aquatic plant harvesting staff. Plant harvesting staff should receive annual training on aquatic plant identification with an emphasis on new AIS.
    b. Lake Noquebay is regionally popular with pleasure boaters and anglers, and is located close to Great Lakes waters. This puts the lake at increased risk for new invasive species and as a source water for the spread of existing invasive species. Lake Noquebay is currently ranked #132 in the top 300 AIS Prevention Priority Waterbodies by the Wisconsin DNR.
        i. The LNRD should conduct watercraft inspections and education at the main boat landings through the Clean Boats-Clean Waters (CBCW) program. The Wisconsin DNR provides 75% cost-sharing up to $4,000.00 to implement the CBCW program.
        ii. The LNRD should explore the installation of boat wash stations or other supplemental AIS prevention efforts at the Lake Noquebay Park and North Shore boat landings. AIS prevention grants can provide cost share funding for this and other containment and prevention efforts.

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