

**Little Green Lake**  
Green Lake County, Wisconsin  
**Alum Treatment Feasibility Study**  
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## EXECUTIVE SUMMARY

Little Green Lake is a shallow, eutrophic headwater drainage lake located in Green Lake County, Wisconsin. Decades of excessive nutrient input from its agriculturally-dominated watershed have resulted in degraded ecological conditions, and the lake is currently on the Wisconsin Department of Natural Resources' (WDNR) list of impaired waterbodies (303d) for excessive levels of phosphorus, chlorophyll, elevated pH, low dissolved oxygen, and degraded habitat.

Despite the implementation of successful best management practices (BMPs) within the watershed to minimize external sources of nutrients, the lake continues to be plagued by legacy phosphorus through release from bottom sediments and early-summer senescence (die-back) of invasive plant populations. The objective of this 2021 study was to 1) quantify the amount of phosphorus released from deep-water anoxic sediments, and 2) determine if the application of aluminum sulfate (alum) would be a feasible strategy for improving the lake's water quality conditions.

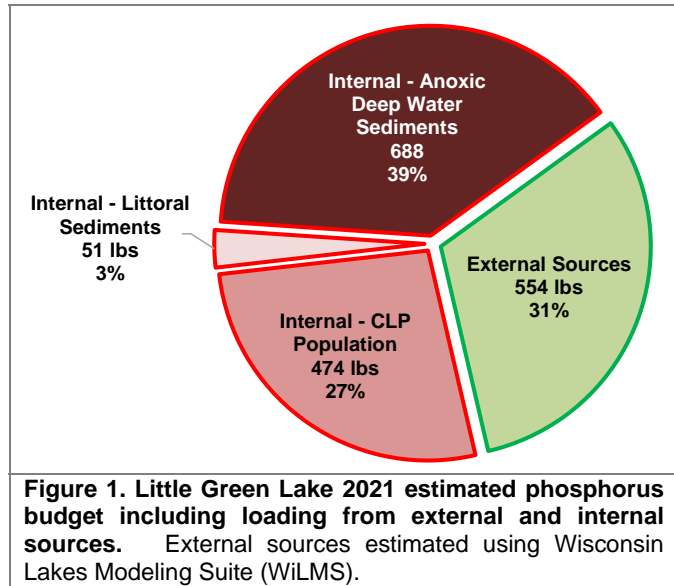
Little Green Lake has two primary sources of phosphorus: 1) external sources which originate in runoff from the lake's watershed and direct atmospheric deposition to the lake's surface, and 2) internal sources, or the annual recycling of phosphorus previously delivered to the lake from external sources. In an effort to minimize external sources of phosphorus from the surrounding watershed, the Little Green Lake Protection and Rehabilitation District (LGLPRD) has worked with county and state partners to implement BMPs, including the installation of three sedimentation basins, a barnyard nutrient reduction system, grassed waterways, contour strip cropping, and removal of a concrete seawall with shoreland habitat improvements. These mitigation efforts reduced mean (average) summer near-surface phosphorus concentrations by 57%, from a mean of 182  $\mu\text{g/L}$  (1990-2006) to 79  $\mu\text{g/L}$  (2011-2021). Mean summer chlorophyll-*a* concentrations also declined by 17%, from a mean of 59  $\mu\text{g/L}$  (1993-2006) to 49  $\mu\text{g/L}$  (2011-2021). Mean Secchi disk transparency increased by 17%, from a mean of 3.6 feet (1986-2005) to 4.2 feet (2010-2021).

Despite these improvements in water quality with external sources of phosphorus minimized, internal sources of phosphorus continue to fuel nuisance algal blooms and create degraded water quality. There are three primary sources of internally-loaded phosphorus in Little Green Lake, and they include: 1) release from deep-water anoxic sediments, 2) release from senescing invasive curly-leaf pondweed (CLP), and 3) release from shallow littoral sediments. Previous studies have concluded that internal sources of phosphorus accounted for 69% of the lake's annual phosphorus budget (Ramaker and Associates, Inc., 1997). In an effort to reduce internal phosphorus loading by minimizing stratification and bottom water anoxia, a destratification system was installed in 2003. A study led by the WDNR in 2013-2014 concluded that bottom water anoxia and phosphorus release from bottom sediments still occurred despite weakened thermal stratification created by the aeration system (WDNR, 2014).

As stated above, the focus of this study was to quantify the amount of phosphorus loaded from deep-water anoxic sediments, which in the past has been the largest source of internally-loaded phosphorus. Phosphorus released from the CLP population was derived using a case study on Big Chetec Lake (Sawyer County) and applied to the acreage of CLP mapped in Little Green Lake in 2016. Phosphorus from shallow littoral sediments, had been previously estimated by the WDNR in 2005. A summary of the study results can be found on the subsequent page, while a detailed report follows this summary.

The results of this study are as follows:

- The amount of phosphorus delivered from external sources was adjusted from past estimates, and it is estimated that external sources accounted for 31% (554 pounds) of the annual budget in 2021, while internal sources accounted for 69% (Figure 1).



- The amount of phosphorus estimated to originate from deep-water anoxic sediments in 2021 was lower (688 pounds – 39% of budget) when compared to that measured in 2013-14 (1,350 pounds). This was due to differences in thermal stratification between these years; specifically, the lake mixed during the summers of 2013 and 2014, but did not during 2021.
- Phosphorus originating from the lake’s CLP population is estimated to account for 27% (474 pounds) of the annual phosphorus budget (Figure 1).
- The WDNR’s 2005 study estimated that phosphorus release from shallow littoral sediments due to elevated pH and/or anoxia beneath dense aquatic plant beds accounts for approximately 3% (51 pounds) of the annual budget.
- An effective alum treatment would likely reduce deep-water anoxic sediment release of phosphorus by 90%. This treatment is estimated to cost \$540,000.
- An alum treatment is predicted to reduce mean near-surface phosphorus concentrations by 29% and chlorophyll-*a* concentrations by 37%. However, changes to water clarity are predicted to be minimal given the amount of phosphorus still available from the lake’s CLP population.
- To achieve measurable improvements in water clarity, it is estimated that in addition to the application of alum, approximately 80% of the CLP biomass would have to be removed prior to senescence on an annual basis.
- While an alum treatment may extend the lake’s clear-water phase in spring and improve conditions in years when the CLP population may be lower, the minimal improvement in water clarity that is predicted does not justify the cost of the alum application strategy.
- This study also provided evidence that the destratification system may exacerbate the release of phosphorus from deep-water anoxic sediments; therefore, halting its annual operation should be considered.
- It is recommended that the LGLPRD continue to monitor the lake’s water quality through the Citizens Lake Monitoring Network (CLMN) Program and the lake’s CLP population. If the CLP population is found to have declined significantly, the feasibility of an alum treatment can be revisited.

## 1.0 LITTLE GREEN LAKE

Little Green Lake (Photograph 1 and Figure 2) is an approximate 479-acre, highly eutrophic, *polymictic* drainage lake with a maximum depth of 27 feet and a mean (average) depth of 11 feet. The lake is a headwater system of the Upper Fox River Watershed, draining into the Grand River. Little Green Lake's watershed encompasses approximately 2,418 acres (3.8 square miles), of which approximately 75% of land use is row crop agriculture and pastureland (Figure 2). The northeastern area of the lake's watershed falls within the Southeastern Glacial Plains Ecological Landscape; a landscape that is largely covered by a thick layer of glacial deposits with soils derived from lime-rich tills and dominated by agriculture.



**Photograph 1.** Little Green Lake, Green Lake County, Wisconsin. Photo credit Onterra.

The southwestern portion of the lake's watershed lies in the Central Sand Hills Ecological Landscape; a landscape largely characterized by sandy soils and agriculture.

The historical and current dominance of agriculture in Little Green Lake's watershed has resulted in excessive input and accumulation of nutrients within the lake, resulting in highly-degraded water quality conditions. The lake has been on the Wisconsin Dept. of Natural Resources (WDNR) list of impaired waterbodies since 2006 for not meeting the state's water quality standards. Little Green Lake is currently listed as impaired for total phosphorus, chlorophyll (excessive algal growth), low dissolved oxygen, elevated pH, and degraded habitat. Numerous studies have been completed on Little Green Lake in an effort to quantify nutrient sources and determine the feasibility of best management practices (BMPs) to improve the lake's water quality and ecological condition. These earlier studies have shown that phosphorus from both external (watershed) and internal (sediment & senescing plants) sources were causing degraded water quality conditions.

**Polymictic Lakes** are shallow lakes which develop weak or no thermal stratification and their waters can mix multiple times from top to bottom during the ice-free season. **Dimictic Lakes** are deeper lakes which develop and maintain thermal stratification during the summer, forming a warmer upper layer of water (**epilimnion**), colder bottom layer (**hypolimnion**), and a transition middle layer (**metalimnion** or **thermocline**). Dimictic lakes mix from top to bottom twice per year, once in spring following ice-off and again in fall following cooling of surface waters.

In an effort to reduce nutrient loading from the surrounding watershed, the Little Green Lake Protection and Rehabilitation District (LGLPRD) has worked with county and state partners to implement BMPs in the lake's watershed including the installation of three sedimentation basins, barnyard nutrient reduction system, grassed waterways, contour strip cropping, and removal of a cement seawall and shoreland habitat improvements. These mitigation efforts reduced mean summer near-surface total concentrations by 57%, from a mean of 182 µg/L (1990-2007) to 79 µg/L (2011-2021). Mean summer chlorophyll-*a* concentrations also declined by 17%, from a mean of 59 µg/L (1993-2006) to 49 µg/L (2011-2021). Mean Secchi disk transparency increased by 17%, from a mean of 3.6 feet (1986-2005) to 4.2 feet (2010-2021).

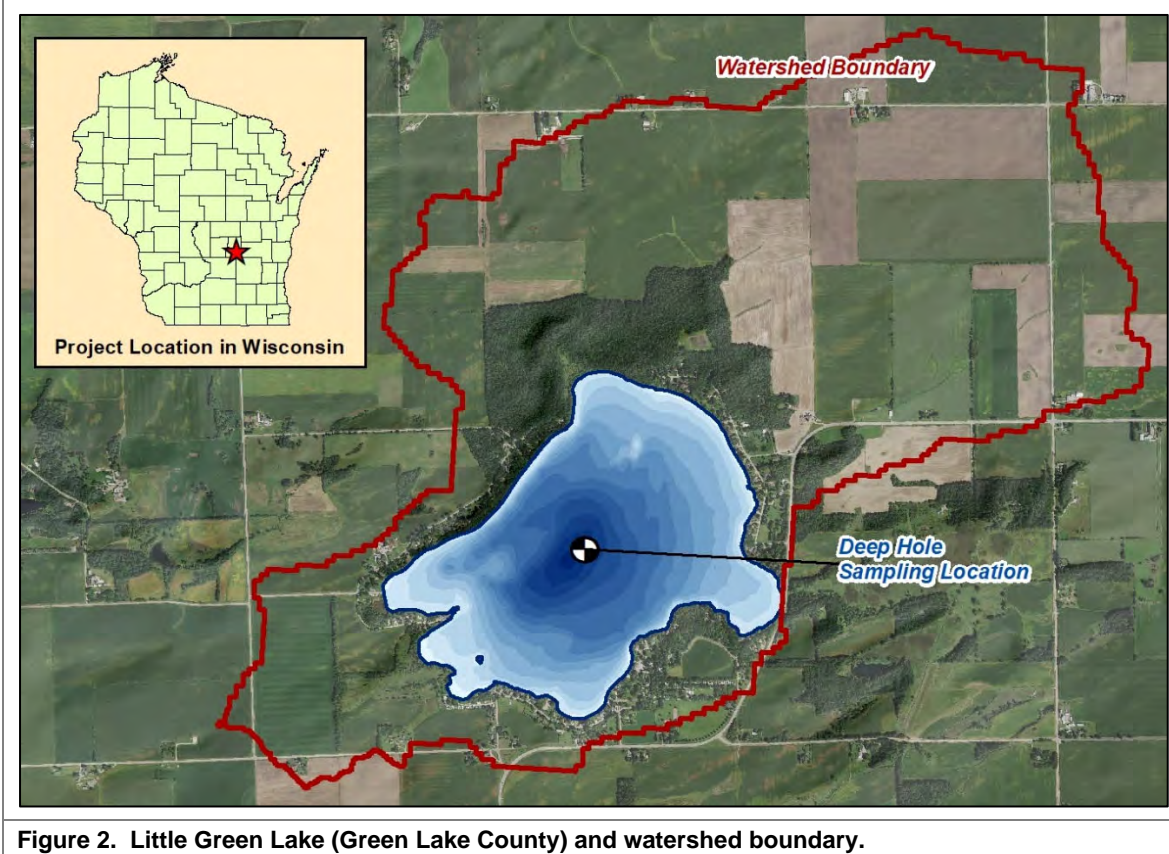


Figure 2. Little Green Lake (Green Lake County) and watershed boundary.

Despite the significant improvement in water quality, concentrations of total phosphorus and chlorophyll still exceed state standards for shallow headwater drainage lakes and the lake experiences frequent summer algal blooms and low water clarity. Previous studies have concluded that internal nutrient loading, or the internal recycling of phosphorus, accounted for 69% of the lake’s annual phosphorus load (Ramaker and Associates, Inc., 1997). In an effort to reduce internal phosphorus loading by minimizing stratification and hypolimnetic anoxia, a destratification system was installed in 2003. A study led by the WDNR in 2013-2014 concluded that hypolimnetic anoxia and phosphorus release from bottom sediments still occurred despite weakened thermal stratification created by the aeration system (WDNR, 2014).

Given the lake’s shallow morphometry, the lake does not typically develop strong thermal stratification. However, during periods of calmer weather, high rates of bacterial decomposition in deep areas rapidly consume oxygen, resulting in hypolimnetic anoxia and release of phosphorus from bottom sediments. The weak thermal gradient allows this sediment-released phosphorus to be easily mobilized to surface waters either through *entrainment* or mid-summer *mixing* events. These events act as ‘nutrient pumps’, transporting sediment-released phosphorus and other nutrients to the surface where they fuel excessive algal growth. In addition to deep-water anoxic sediment-released phosphorus, it is also believed the internal loading of phosphorus occurs in shallow *littoral* sediments due to elevated pH and/or diurnal anoxia development beneath dense

**Entrainment** is defined as the turbulent exchange of water and solutes from the hypolimnion across the thermocline to the lower boundary of the epilimnion during thermal stratification. **Mixing** is defined as complete circulation of the water column from top to bottom. The **Littoral Zone** is the area of the lake where sufficient light penetrates to support photosynthesis of larger aquatic plants.

aquatic plant beds. The lake's extensive curly-leaf pondweed (*Potamogeton crispus*; CLP) population also likely serves as a significant source of phosphorus following its natural senescence (die-back) in early summer.

In 2018, the *Little Green Lake Comprehensive Management Plan* (Onterra, LLC, 2018) was finalized and included a number of actions with an aim to improve the lake's water quality and ecological condition. In addition to continued work with agency partners to implement best management practices in the watershed, the management plan called for continued volunteer monitoring of the lake's water quality following modifications to the destratification system. If no improvements in water quality were measured after three years, the LGLPRD would initiate an alum (aluminum sulfate) treatment feasibility study. In early 2021, the LGLPRD was awarded a WDNR Management Plan Implementation Grant to aid in covering the cost of studies to determine if the application of alum is a realistic management option for improving Little Green Lake's water quality.

The feasibility study was designed to quantify the amount of phosphorus loaded from deep-water anoxic bottom sediments during the growing season, the dosage of alum that would be required to reduce this sediment phosphorus loading by 90%, and an estimated cost of implementing the alum treatment. The field sampling was completed in 2021 and involved the collection of water quality data biweekly during the growing season from March – October. Sediment cores were also collected from deep water areas and underwent phosphorus fractionization analysis to determine the amount of alum that would need to be applied to reduce phosphorus release by 90%. While a study was proposed in 2015 as part of the lake management planning development project to quantify phosphorus released from shallow littoral areas, this portion of the project was not funded by the WDNR and was not completed.

Monitoring completed as part of this study revealed that 2021 was unusual for Little Green Lake in terms of its thermal stratification. In most years, the lake maintains weak thermal stratification and experiences multiple mixing events during the summer. In 2021, above-normal temperatures in early summer resulted in the lake developing and maintaining strong thermal stratification throughout most of the summer, acting more as a dimictic system. The phosphorus loading from anoxic bottom sediments was lower when compared to the study completed in 2013-2014; however, thermocline erosion over the course of the summer allowed for the entrainment of sediment-released phosphorus to surface waters. This, in combination with loading from CLP and littoral sediments, resulted in excessive algal growth.

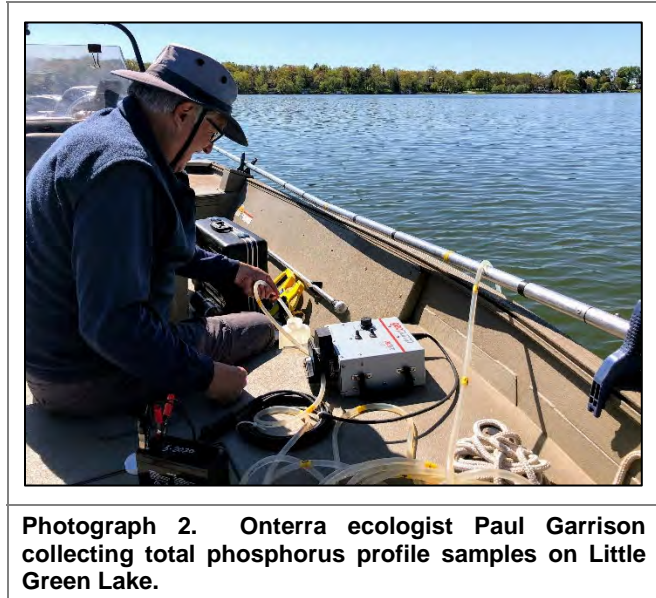
As this report details, modeling indicates that if 90% of the phosphorus released from anoxic bottom sediments were controlled with the application of alum, mean chlorophyll concentrations are predicted to decrease by 37%. Despite this reduction in chlorophyll, increases in water clarity are predicted to be minimal. There would still be sufficient phosphorus loading from the lake's CLP population and release from shallow littoral sediments to fuel excessive algal growth and create degraded conditions. In addition, the estimated cost of an alum treatment to reduce hypolimnetic phosphorus loading by 90% would be in excess of \$500,000.

This study also aligns with the WDNR 2013-2014 study that the aeration system does not improve water quality conditions and in fact, may exacerbate phosphorus release from bottom sediments. While the intent of the aeration system is to weaken thermal stratification and reduce hypolimnetic anoxia, historical data indicate that hypolimnetic anoxia still develops despite a weak thermal

gradient created by the aeration system. Weaker thermal stratification likely allows the lake to experience more frequent mixing events during the summer, allowing more phosphorus to be released and mobilized to surface waters from deep-water anoxic sediments. The aeration system was not in operation in 2021, and the lake developed strong thermal stratification. Estimates indicate that less phosphorus was released and mobilized to surface waters in 2021 compared to measurements in 2013 and 2014. Continued operation of the aeration system will likely prevent the lake from developing stronger thermal stratification in years with similar climatic conditions to 2021.

## 2.0 METHODS

To estimate the amount of phosphorus (mass) loaded from anoxic sediments, total phosphorus (TP) profiles were collected biweekly from the end of March through mid-October using a peristaltic DC pump (Geotech) (Photograph 2). In the spring prior to stratification, two samples for total phosphorus were collected – one from the near-surface (3.0 feet) and one from the near-bottom (2.0 feet off the bottom). During stratification, samples were collected for TP from the near-surface (3.0 feet) and at 6-7 incremental depth intervals within the anoxic hypolimnion, defined as the area with dissolved oxygen of  $\leq 2.0$  mg/L. Temperature and dissolved oxygen profiles at one-foot intervals were collected to determine the depth at which anoxic conditions occurred.



**Photograph 2. Onterra ecologist Paul Garrison collecting total phosphorus profile samples on Little Green Lake.**

Estimation of the amount of phosphorus loaded from anoxic bottom sediments is easier in dimictic lakes as there is typically less mobilization of phosphorus between the hypolimnion and upper layers of water. It is more difficult in shallow polymictic lakes like Little Green Lake where there is mobilization of phosphorus across the thermocline due to entrainment and/or mixing events. As mentioned previously, Little Green Lake experienced stronger thermal stratification in 2021 compared to what had been observed in the past. While bottom water temperatures remained cooler over the course of the summer, the thermocline was gradually driven deeper over the course of the summer until water temperatures were relatively uniform by late-August. During this erosion, a portion of the phosphorus from the hypolimnion was mobilized to surface waters.

In dimictic lakes, an estimate for the amount of internally loaded phosphorus can be calculated by determining the change in lake-wide mass of phosphorus between spring and fall turnover. This change in combination with an estimated input of phosphorus from the watershed and outflow from the lake over this same period can serve as a good estimate for the amount of phosphorus loaded from bottom sediments. While this method was used to provide an estimate of the total amount of phosphorus loaded from internal sources in Little Green Lake, it does not determine the proportions of phosphorus loaded from anoxic bottom sediments, the curly-leaf pondweed population, and shallow littoral sediments.

In 2005, Paul Garrison (WDNR) conducted a laboratory study to estimate the amount of phosphorus released from littoral sediments within dense plant beds under aerobic and anaerobic conditions. This study estimated that littoral sediments contribute a relatively small amount of internally-loaded phosphorus, approximately 51 pounds per year. To estimate the amount of phosphorus loaded from Little Green Lake's CLP population, phosphorus loading measurements derived from a study in Big Chetac Lake by William James at the University of Wisconsin-Stout (Short Elliot Hendrickson Inc., 2009) were applied to the curly-leaf pondweed mapping data collected in 2016 in Little Green Lake.

In 2016, approximately 260 acres of colonized CLP were mapped. For phosphorus loading estimates, the acres of only the densest areas of CLP were included (density rating of *dominant* [~50% coverage] or greater. There was approximately 166 acres of CLP delineated as *dominant* or greater in 2016. Phosphorus content of CLP in Big Chetac Lake was measured at 0.26%, and the median CLP biomass was calculated to be 245 g/m<sup>2</sup>. Researchers also indicated that not all phosphorus released from CLP makes it into the water column, with a portion likely being captured by the sediment immediately as the plants decay on the bottom. They estimated that 50% of phosphorus within the CLP makes it into the water column, while the other 50% is captured by sediments. These variables were applied to the 2016 CLP population in Little Green Lake to provide an estimate of the amount of phosphorus loaded from the population.

Wisconsin Lakes Modeling Suite (WiLMS) was utilized to estimate the amount of phosphorus being loaded annually to Little Green Lake externally from its watershed. The modeling estimated that approximately 1,500 pounds of phosphorus are loaded to the lake annually. However, this estimate over-predicted the mean phosphorus concentration measured within the lake. This is likely due to the mitigation efforts (sedimentation basins, etc.) that have been implemented within the watershed. The external phosphorus load was reduced to a level at which the model predicted an in-lake phosphorus concentration equal to the measured spring overturn concentration from 2011-2021 (34 µg/L). To achieve this in-lake concentration, WiLMS estimated that external phosphorus loading is closer to 550 pounds per year.

The lake-wide mass of phosphorus was estimated for each sampling event using volume-weighted phosphorus concentrations. The estimated net internal load ( $P_{\text{internal}}$ ) of phosphorus in pounds in Little Green Lake in 2021 (from all internal sources) was calculated using the following equation from James et al. 2015:

$$\Delta P_{\text{lake storage}} = (P_{\text{external load}} - P_{\text{outflow}}) + P_{\text{internal}}$$

Where:

$\Delta P_{\text{lake storage}}$  is the change in total phosphorus mass in pounds within the lake between spring overturn and the late-summer mixing event.

$P_{\text{external load}}$  is the external load of phosphorus in pounds from the watershed between spring overturn and the late-summer mixing events as estimated from WiLMS.

$P_{\text{outflow}}$  is the estimated outflow of phosphorus in pounds from the lake between the spring overturn and late-summer mixing events as estimated from WiLMS.

Internal phosphorus loading from deep-water anoxic sediments was estimated by calculating the change of phosphorus mass in the hypolimnion from the onset of stratification until late-summer mixing. While it was assumed that a portion of hypolimnetic phosphorus was entrained to the epilimnion during stratification in 2021, the rate of phosphorus change during the summer within the epilimnion was greater than that of the hypolimnion. It is assumed the higher rate of change within the epilimnion was due to loading from the CLP population. In addition to the Big Chetac study, this difference in the rate of loading between the hypolimnion and epilimnion was used to estimate loading from the CLP population.

In addition to TP, chlorophyll-*a* (near-surface) was measured in June, July, August, and September, while alkalinity, pH, and specific conductance were measured in June (near-surface), July (near-surface and near-bottom), and September (near-surface). All water samples were kept on ice and processed by the Wisconsin State Lab of Hygiene. Water clarity using a Secchi disk was measured during every sampling event.

Sediment cores from eight sites were collected by Onterra staff on April 15, 2021 (Figure 3). The sites were in the deeper area of the lake, which is where anoxia is expected to occur. Eight sites were sampled since phosphorus deposition and concentrations within the sediment may not be uniform. At sites 1-4, the upper 6 cm of the core was sectioned into 1 cm intervals, and the bottom 6-12 cm of the core was sectioned into 2 cm intervals. At sites 5-8, which were taken at shallower depths within the area of anoxia, a composite of the upper 5 cm of the core was collected. The sediments were analyzed at the lab of Mr. William James at University of Wisconsin-Stout to determine the amount of various sediment phosphorus fractions, especially fractions that contribute to internal phosphorus loading. The results were used to determine the dosage of alum required to reduce phosphorus loading by 90%.

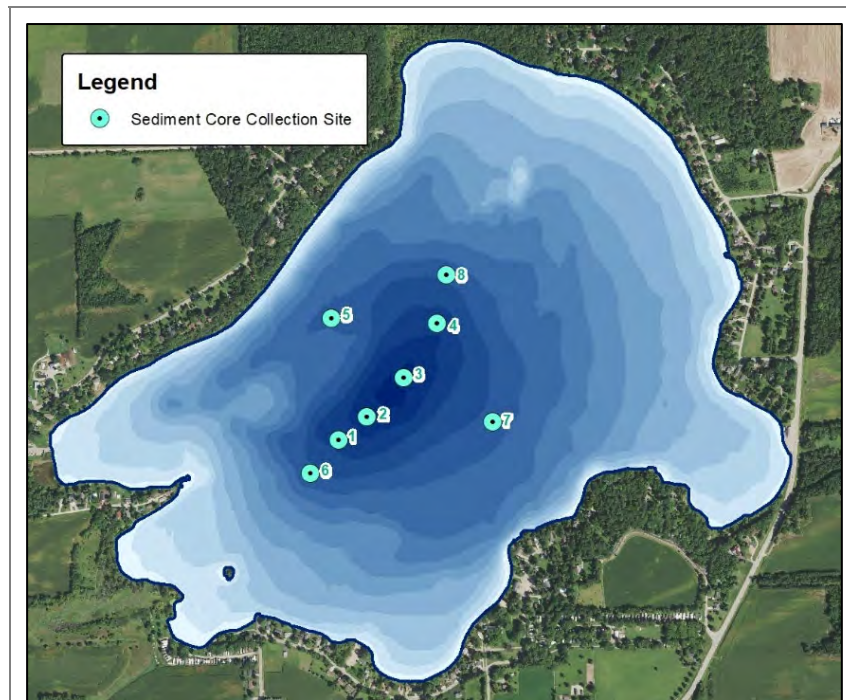
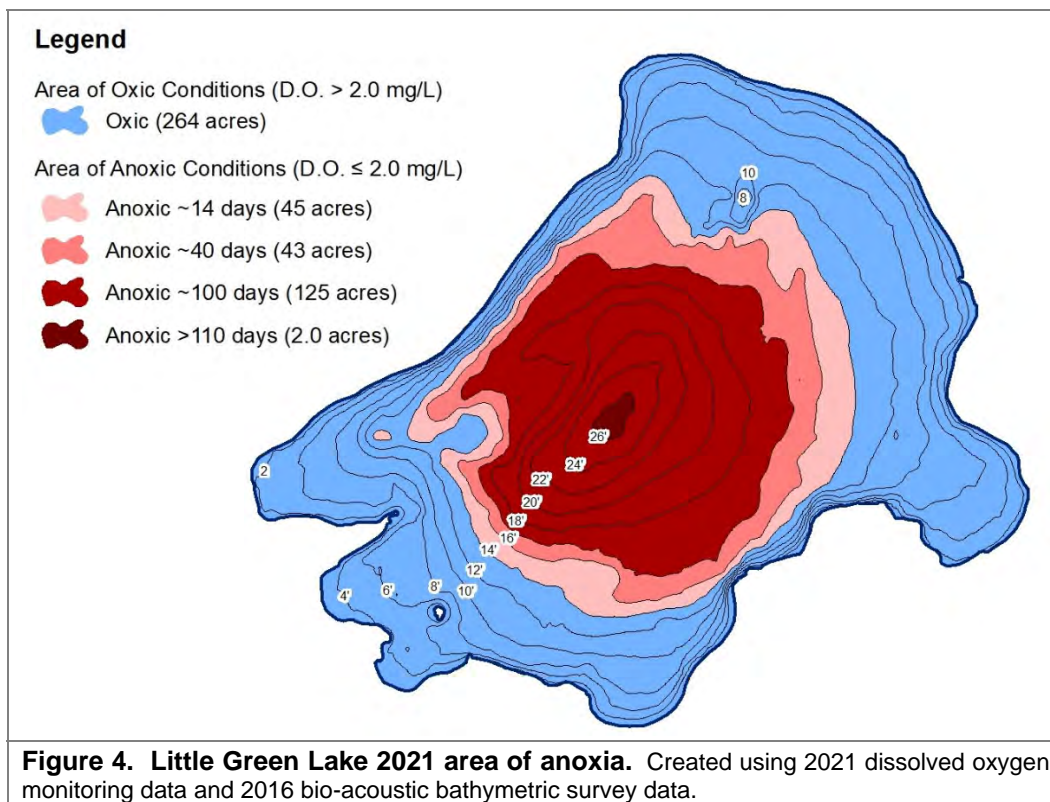


Figure 3. Little Green Lake 2021 sediment core collection sites.

## 3.0 RESULTS

### 3.1 Temperature & Dissolved Oxygen

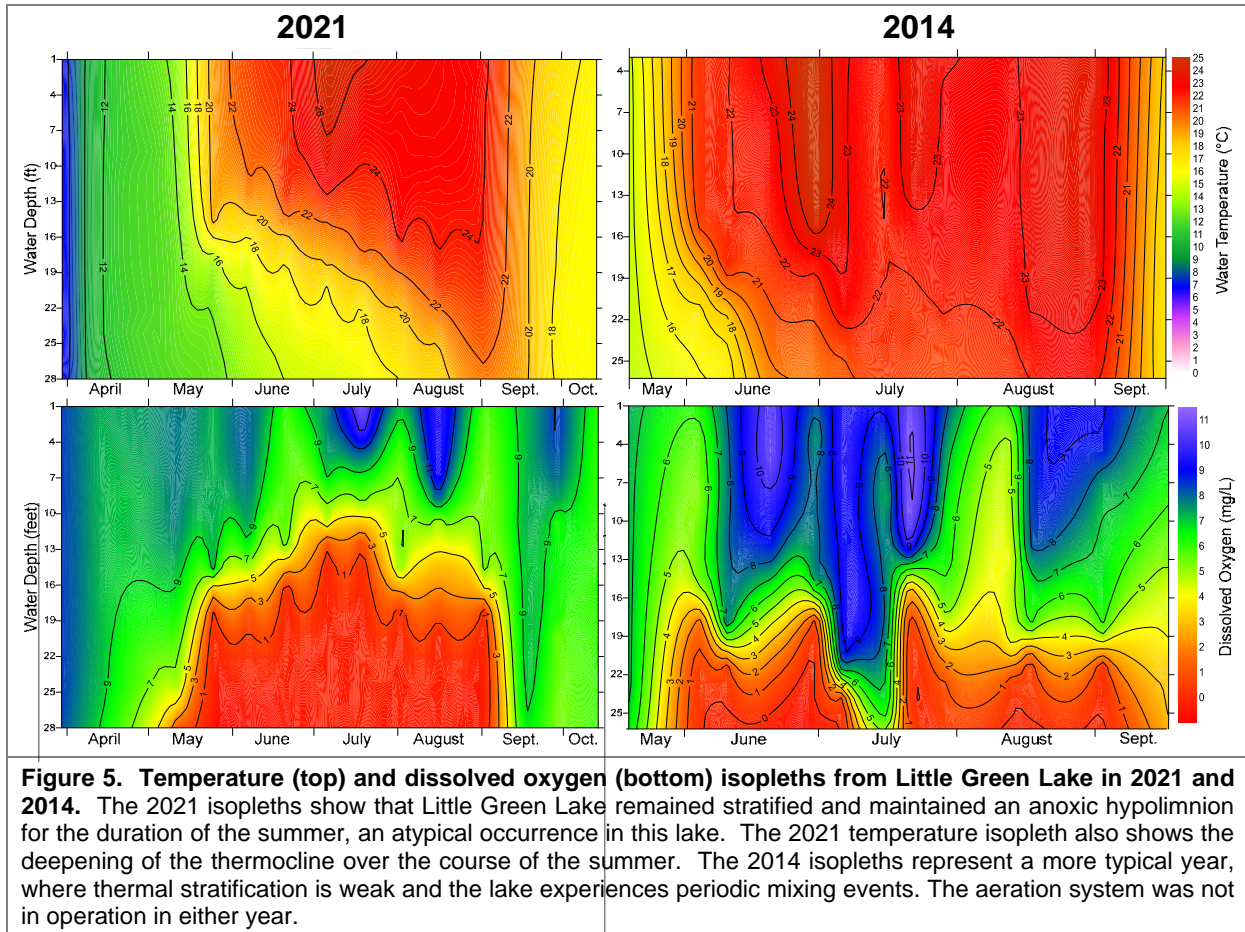
The data collected in 2021 show that it was an atypical year for Little Green Lake in terms of thermal stratification, nutrient dynamics, and water clarity. Temperature and dissolved oxygen data show that the lake developed strong thermal stratification in late-May in response to a period of above-normal temperatures. Anoxia within the hypolimnion developed with the onset of thermal stratification. The area of anoxia reached a maximum area of approximately 215 acres (12 feet and deeper) in July, and approximately 125 acres (16 feet and deeper) was anoxic for ~100 days (Figures 4 and 5). The area of anoxia increased in size despite the fact the thermocline deepened over the course of the summer. The water column reached uniform temperature in late-August/early-September, representing the only mixing event following spring turnover.



As mentioned, the stronger thermal stratification observed in 2021 in Little Green Lake is unusual. Historical temperature and dissolved oxygen data indicate that the lake typically develops weaker thermal stratification in early summer. This weaker thermal stratification allows the lake to experience multiple periods of stratification and mixing over the course of the summer. Figure 5 displays isopleths for temperature and dissolved oxygen from 2021 and 2014, years where the aeration system was not operating. The weak thermal stratification and mid-summer mixing event observed in 2014 is more representative of a typical year.

To quantify the strength of thermal stratification, water column stability,  $S$  (g/cm) was calculated using the Schmidt Stability Index (Figure 6). Schmidt Stability calculates how much energy (wind) would be needed (g/cm) to cause a complete mixing of water column without the addition or subtraction of heat energy. A Schmidt Stability value of 0 indicates the entire water column is

of uniform temperature (and density) and no energy is required to mix it. As thermal stratification strengthens and the temperature/density gradient increases between surface and bottom waters, the Schmidt Stability value increases indicating the lake is more resistant to mixing and more energy is required to mix the water column.



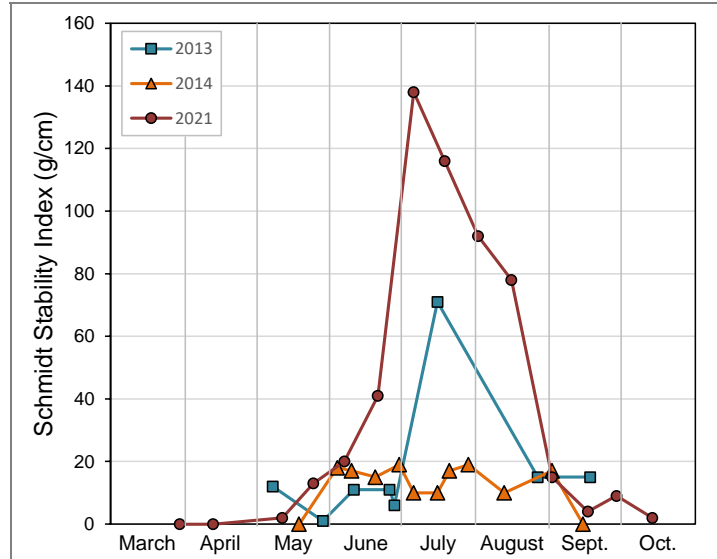
Little Green Lake’s water column stability was calculated using temperature profile data collected in 2013, 2014, and 2021. In 2013 and 2014, a more normal climatic year, the index was lower than 20 g/cm for all sampling events with the exception of mid-July in 2013 (Figure 6), indicating the lake was susceptible to mixing during wind events. In contrast, in 2021, Schmidt Stability exceeded 20 g/cm by early June and peaked near 140 g/cm in early July, indicating strong stratification and high resistance to mixing. The reduction in Schmidt Stability from early-July to September represents cooling of surface water temperatures and a deepening thermocline. Schmidt Stability was near 0 by mid-September, representing complete mixing of water column.

### 3.2 Phosphorus

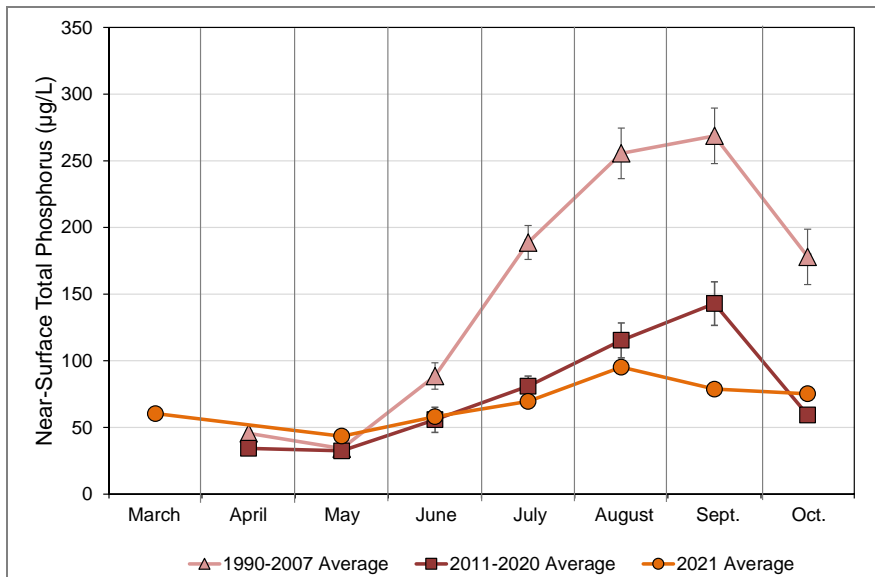
Nutrient concentrations in terms of TP were also atypical in Little Green Lake in 2021. While 2021 near-surface TP concentrations exhibited the typical pattern of increase over the course of the summer (an indicator of internal nutrient loading), concentrations in July, August, and September were below average concentrations from 2011-2020 and from 1990-2007 (Figure 7). Near-surface TP concentrations in spring of 2021 were slightly above average, likely due to rapid melting and runoff of an above-average snowpack. The lower TP concentrations in July, August,

and September indicate that the amount of phosphorus loaded from internal sources was below average in 2021.

Mass balance calculations indicate that approximately 1,200 pounds of phosphorus originated from internal sources in Little Green Lake in 2021, representing 69% of the lake’s total annual phosphorus budget (Figure 1 in Executive Summary). Approximately 700 pounds (39% of annual budget) of phosphorus were estimated to have originated from deep-water anoxic sediments. The CLP population (Photograph 3) is estimated to account for approximately 475 pounds (27% of annual budget) of phosphorus, while littoral sediments are estimated to account for approximately 50 pounds (3% of annual budget). Wisconsin Lake Modeling Suite indicates that the remaining 554 pounds (31% of annual budget) of phosphorus originated from external sources within the watershed.



**Figure 6. Schmidt stability index.** Higher Schmidt Stability Index values indicates stronger thermal stratification and more resistance to mixing during wind events. Because air temperatures were warmer than normal in June 2021, the lake maintained strong thermal stratification over the course of the summer compared to weaker stratification observed in 2013 and 2014.



**Figure 7. Little Green Lake average monthly near-surface total phosphorus concentrations from 1990-2007, 2011-2020, and 2021.** Error bars represent one standard error. Near-surface total phosphorus concentrations were below average in 2021, but still followed the pattern of increasing concentration over the summer, and indicator of internal phosphorus loading.

The 700 pounds of phosphorus estimated to have originated from deep-water anoxic sediments in 2021 is lower than estimates of over 1,300 pounds calculated in 2013 and 2014. It is believed the loading of phosphorus from deep-water anoxic sediments was higher in 2013 and 2014 (and most

years) because of the lake's more natural tendency to experience periodic stratification and mixing events over the course of the summer.

The periodic mixing and mobilization of phosphorus-rich water from the bottom to the surface creates a stronger diffusion gradient between bottom sediments and the overlying water, causing more phosphorus to be released from bottom sediments. In a more typical year like 2013 and 2014, where the lake experiences periodic mixing, phosphorus loading from anoxic deep-water sediments is the largest source of phosphorus to the lake, accounting for approximately 76% of the annual phosphorus budget.

In summary, there are three primary sources of **internal** phosphorus loading in Little Green Lake:



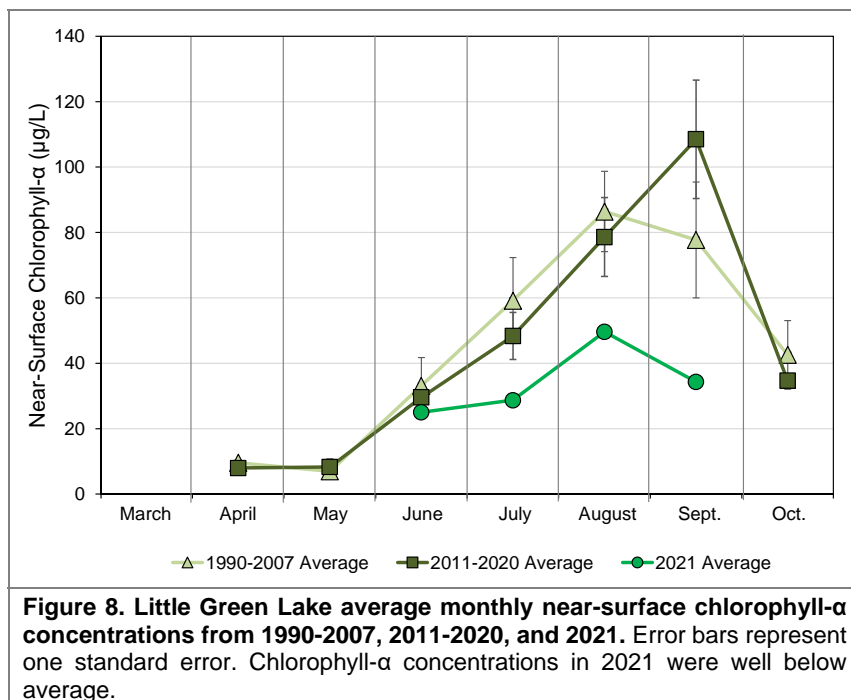
**Photograph 3. Colony of dense, surface-matted invasive curly-leaf pondweed in Little Green Lake in 2021.** Photo credit Onterra.

1. Phosphorus release from deep-water anoxic sediments. When oxygen is absent in the deep waters, phosphorus that is bound with iron in the sediments is released into the overlying waters. In 2021, this accounted for approximately 57% of internally-loaded phosphorus and 39% of the estimated total annual phosphorus budget, which includes external loading as well. It is believed in a more typical year, when the lake periodically mixes, deep-water anoxic sediment release is the largest source of annual phosphorus accounting for approximately 76% of the total internal load.
2. Decaying plant material, specifically decay of CLP. Every lake with aquatic plants experiences some level of internal nutrient loading at the end of each growing season as the lake's plants die back and decompose. However, in lakes like Little Green Lake that support a large CLP population, this plant's die-off in early-summer can elevate nutrient levels in the lake. The CLP population is estimated to account for approximately 27% of the total phosphorus budget in 2021 and 39% of the phosphorus from internal sources.
3. Diurnal release from littoral sediments within dense plant beds and/or release from elevated pH. Studies in other eutrophic Wisconsin lakes have shown that large amounts of phosphorus can be released from sediments in plant beds. Because of high photosynthetic activity in these beds, and elsewhere from algae, the pH is elevated to levels above 9.0, which can result in the release of phosphorus from the sediments. Also, in dense plant beds where water movement is restricted, the water immediately above the sediments can become anoxic, resulting in the release of phosphorus. If the architecture of the beds changes as they mature, this phosphorus may be mobilized into the deeper waters of the lake. The study completed in 2005 estimated that approximately 50 pounds of phosphorus

originate from littoral sediments each year, accounting for 3% of the annual phosphorus budget and 4% of internally-loaded phosphorus.

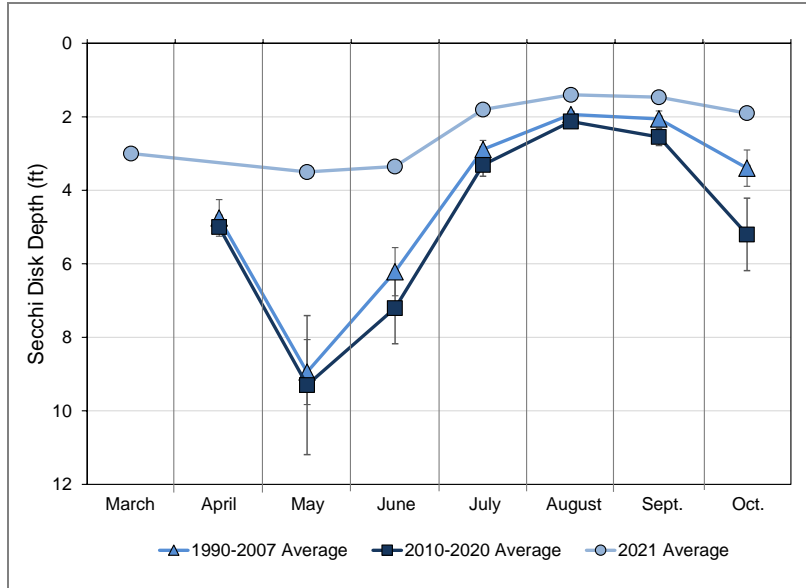
### 3.3 Chlorophyll & Water Clarity

Like TP concentrations, chlorophyll-*a* concentrations in Little Green Lake were below average in 2021, especially in July, August, and September (Figure 8). Based on the relationship between TP and chlorophyll-*a* using historical data from Little Green Lake, chlorophyll-*a* concentrations in 2021 were 35% lower than expected based on TP concentrations. Despite lower chlorophyll-*a* concentrations, water clarity as measured via Secchi disk depth, was below average across all months in 2021

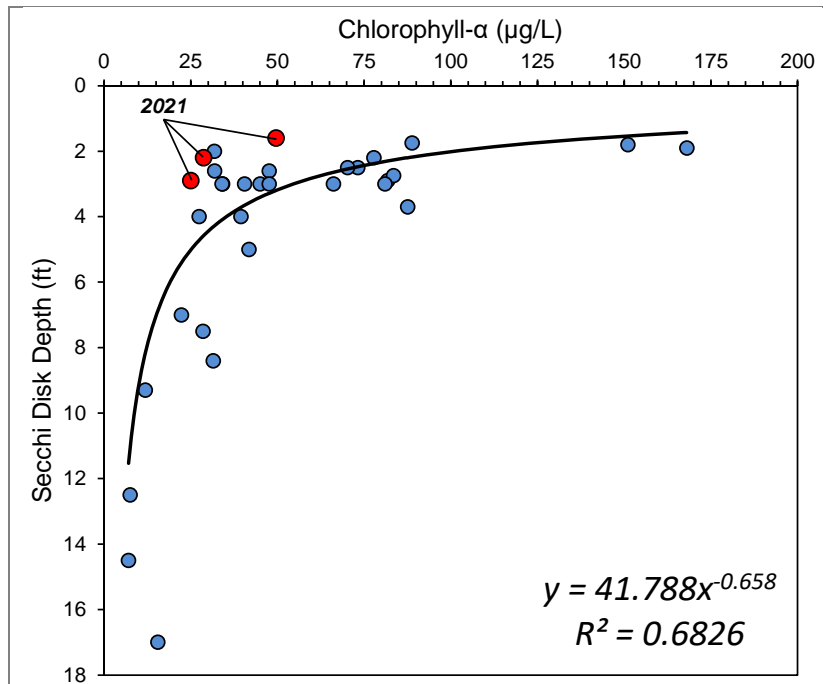


(Figure 9). In most years, Little Green Lake experiences a clear-water phase in spring, with water clarity reaching its maximum in May and June. This clear-water phase did not occur in 2021, and water clarity in May and June was approximately 6.0 feet and 4.0 feet below the 2010-2020 average, respectively. Water clarity in July, August, September, and October was approximately 1.0 foot less than the 2010-2020 average.

Overall, Secchi disk depth in 2021 was approximately 3.3 feet less than expected based on measured chlorophyll-*a* concentrations (Figure 10). It is not known why water clarity was not higher in 2021 given the below-average chlorophyll-*a* concentrations. One hypothesis is that given the stronger thermal stratification in 2021, algae may have been more concentrated immediately at the surface, above the standard 3.0-foot depth at which chlorophyll-*a* concentrations were measured.



**Figure 9. Little Green Lake average monthly Secchi disk depth from 1990-2007, 2011-2020, and 2021.** Error bars represent one standard error. Water clarity was below average across all growing season months in 2021.



**Figure 10. Little Green Lake 2011-2021 summer chlorophyll- $\alpha$  concentrations plotted against summer Secchi disk depths.** Water clarity in 2021 was lower than expected based on chlorophyll- $\alpha$  concentrations. Significant changes in water clarity would not occur until chlorophyll- $\alpha$  concentrations were reduced to  $\leq 25 \mu\text{g/L}$ . This equation was used to predict Secchi disk depth with predicted changes in chlorophyll.

### 3.4 pH

Near-surface pH was measured on three occasions in Little Green Lake in 2021; once in June, July, and August. On all three occasions, pH was between 9.0-9.4. At pH values of around 9.0 or greater, phosphorus can be released from bottom sediments even in the presence of oxygen. Given these higher pH values, it is likely that phosphorus is released from shallower sediments in Little Green Lake. The high pH is the result of high rates of photosynthesis by both algae and aquatic plants, which remove carbon dioxide from the water, elevating pH.

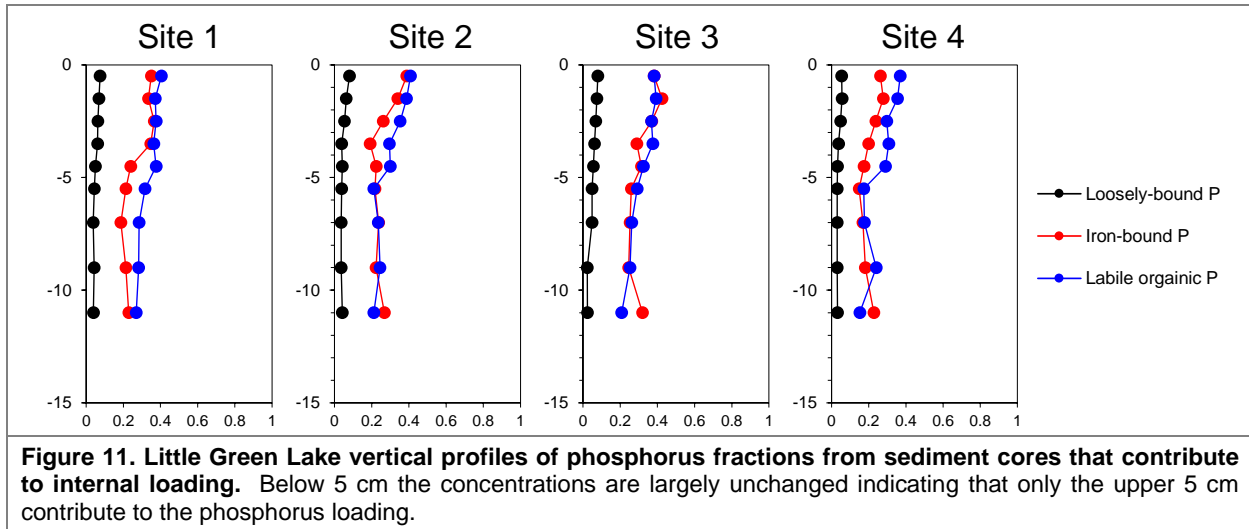
### 3.5 Sediment Cores & Alum Feasibility

Addition of aluminum salt, usually in the form of aluminum sulfate (alum), is a useful technique for reducing internal phosphorus loading in lakes. It has been used for many years including the first lake that was treated in the USA, Horseshoe Lake, WI, which was treated in 1970. Alum is effective because after binding with phosphorus, the bond of the aluminum and phosphorus is not sensitive to dissolved oxygen levels as is iron. In other words, even under anoxic conditions the phosphorus remains bound with the aluminum and does not move from the sediments into the water column.

Lake sediments contain elevated levels of phosphorus, some of which are bound with iron. When the sediments become anoxic, the iron and phosphorus bond is broken, and these elements migrate upward towards the bottom water of the lake. If the bottom waters are anoxic, phosphorus and iron migrate into the water column and when the lake mixes, or during summer wind events in shallow lakes, these elements move to the surface waters. Alum can be applied to a lake as a slurry where it precipitates to the lake bottom. This alum layer on the sediments acts a barrier to phosphorus moving into the bottom waters of the lake even in the absence of oxygen. Alum is effective because it permanently binds with the phosphorus. Unlike iron, as mentioned above, the aluminum-phosphorus bond is not affected by anoxic conditions.

In Wisconsin, over 18 lakes have been treated with alum, while over 26 lakes in Minnesota and Michigan have been treated with alum. Alum is usually applied as aluminum sulfate which reacts quickly with water to form an aluminum hydroxide floc with a high affinity for phosphate and dissolved organic P compounds. The floc quickly settles to the bottom within 24 hours and sooner in shallower lakes. Immediately after settling to the bottom, the floc is susceptible to redistribution but within months it gets mixed into the surface sediment.

In order to estimate how much alum should be added to Little Green Lake to significantly reduce internal loading, sediment cores from eight sites were collected by Onterra staff on April 15, 2021 to determine sediment phosphorus fractions, especially those that contribute to internal phosphorus loading. The most important fractions are loosely bound P and iron bound P. Below 5 cm the concentrations were essentially unchanged indicating that the source of internal loading is largely from the upper 5 cm of sediment (Figure 11). This analysis allowed for a determination of how much alum needs to be applied to reduce phosphorus loading by 90% and 75%. The required dosage varied from 105 to 191 grams of aluminum per square meter ( $\text{g Al/m}^2$ ) for a 90% reduction, and 69 to 125  $\text{g Al/m}^2$  for a 75% reduction. This results in an average application rate of aluminum of 144  $\text{g/m}^2$  and 95  $\text{g/m}^2$  for a 90% and 75% reduction, respectively.



The area to which the alum would be applied would be the area of the lake 16 feet and deeper, as this is typically the area which exhibits the longest duration of anoxia (Figure 12). This area encompasses approximately 127 acres. To reduce phosphorus release from bottom sediments within this area by 90%, approximately 67,000 kg of alum would need to be applied at an estimated cost of over \$500k (Table 1). Similarly, to reduce phosphorus loading from bottom sediments in this area by 75%, an estimated 44,000 kg of alum would need to be applied at a cost of over \$350k (Table 1).

If 90% of the phosphorus released from anoxic bottom sediments in 2021 was reduced through an alum treatment, it is predicted that growing season mean TP concentrations would have been reduced from 70  $\mu\text{g/L}$  to 54  $\mu\text{g/L}$ , a reduction in mean TP of 22% (Table 2). A reduction to a mean TP concentration of 54  $\mu\text{g/L}$  would result in a predicted growing season mean chlorophyll-*a* concentration of 32  $\mu\text{g/L}$ , slightly lower than the mean concentration of 37  $\mu\text{g/L}$  measured in 2021. Mean growing season water clarity would be predicted to increase from the measured 2.2 feet to 4.2 feet. However, given water clarity was lower than predicted in 2021, it cannot be said with certainty that water clarity would improve to this magnitude.

In a more typical years between 2010-2020, like 2013 and 2014, internal loading from anoxic bottom sediments is higher and the mean growing season TP concentration is closer to 80  $\mu\text{g/L}$ . Reducing the internal loading measured in 2013 and 2014 by 90% is estimated to result in a predicted mean growing season TP concentration of 56  $\mu\text{g/L}$ , a predicted chlorophyll-*a* concentration of 34  $\mu\text{g/L}$ , and a mean Secchi disk depth of 4.1 feet.

Estimates were also made on how water quality may improve if harvesting of 50% of the curly-leaf pondweed biomass was completed in combination with an alum treatment to reduce 90% of phosphorus release from deep-water anoxic bottom sediments. If both of these management strategies were applied in 2021, mean TP concentrations are predicted to have declined from 70  $\mu\text{g/L}$  to 47  $\mu\text{g/L}$ , chlorophyll-*a* concentrations are predicted to decline from 37  $\mu\text{g/L}$  to 27  $\mu\text{g/L}$ , and Secchi disk depth is predicted to have increased from 2.2 feet to 4.7 feet. Similarly, in a more typical year from 2010-2020, mean TP concentrations would decline to 54  $\mu\text{g/L}$ , chlorophyll-*a* concentrations would decline to 29  $\mu\text{g/L}$ , and Secchi disk depth would be 4.5 feet. To see more significant improvements in water clarity ( $\geq 5.0$  feet), mean chlorophyll-*a* concentrations would

need to decline to  $\leq 25 \mu\text{g/L}$ . To achieve a mean chlorophyll-*a* concentration of  $25 \mu\text{g/L}$ , mean TP would need to decline to  $42 \mu\text{g/L}$ . To achieve a mean TP concentration of  $42 \mu\text{g/L}$ , in addition to an alum treatment to reduce 90% of loading from deep-water anoxic sediments, at least 80% of the curly-leaf pondweed biomass would need to be harvested annually.

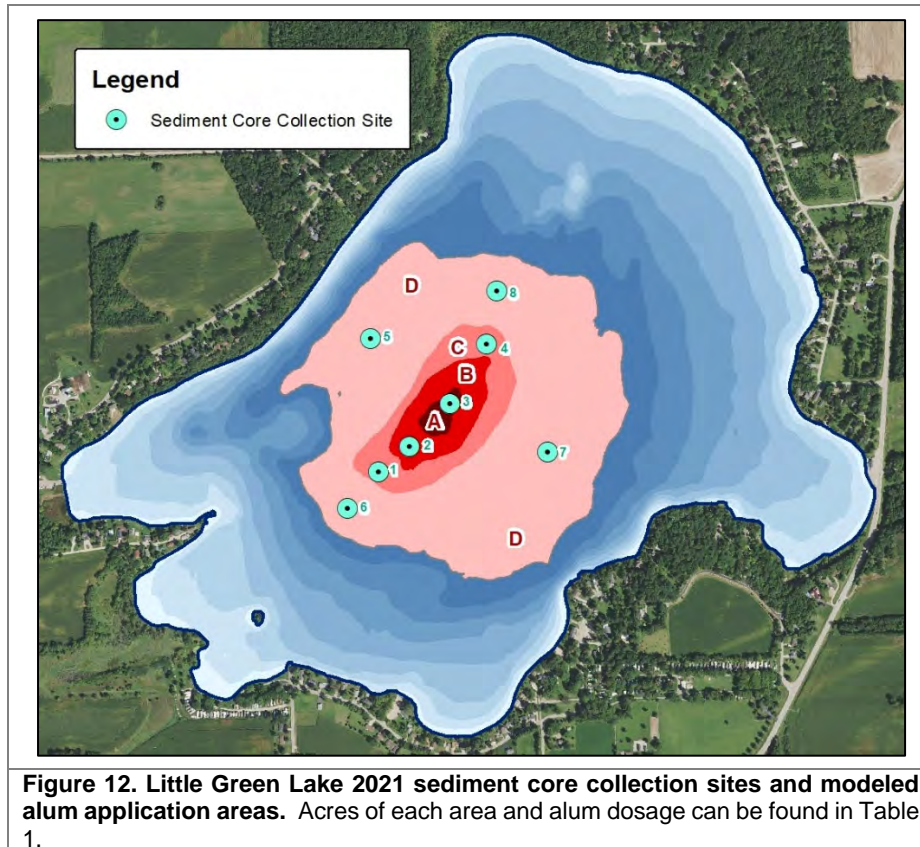


Table 1. Alum application amount for an estimated 90% and 75% reduction in internal phosphorus loading from anoxic bottom sediments (16 feet and deeper).

90% Reduction					
Area of lake bed	Lake Depth (ft)	Area to be Treated (acres)	Area to be Treated (m <sup>2</sup> )	Al dosage (kg)	Cost
A	> 26	2	7,689	1,468	
B	24-26	9	34,400	5,237	
C	22-24	14	54,635	8,559	
D	16-22	103	416,841	51,829	
<b>TOTAL</b>	<b>Below 16</b>	<b>127</b>	<b>513,564</b>	<b>67,093</b>	<b>\$539,021</b>

75% Reduction					
Area of lake bed	Lake Depth (ft)	Area to be Treated (acres)	Area to be Treated (m <sup>2</sup> )	Al dosage (kg)	Cost
A	> 26	2	7,689	962	
B	24-26	9	34,400	3,431	
C	22-24	14	54,635	5,608	
D	16-22	103	416,841	33,957	
<b>TOTAL</b>	<b>Below 16</b>	<b>127</b>	<b>513,564</b>	<b>43,958</b>	<b>355,221</b>

**Table 2. Little Green Lake predicted changes in water quality with an alum treatment designed to reduce phosphorus loading from deep-water anoxic sediments by 90% and 75%.** Predicted phosphorus concentrations obtained from Canfield-Bachmann natural lake model. Predicted chlorophyll concentrations were derived from phosphorus-chlorophyll relationship determined from historical data from Little Green Lake. Predicted Secchi disk depth was derived from chlorophyll-Secchi disk relationship determined from historical data from Little Green Lake (see Figure 10).

Parameter	Measured 2021	Predicted 2021 90% Anoxic Sediment P Reduction	Predicted 2021 75% Anoxic Sediment P Reduction
Mean Near-Surface GS TP (µg/L)	70	54	57
Mean Near-Surface GS Chl-α (µg/L)	37	32	34
Mean Secchi GS Disk Depth (ft)	2.2	4.2	4.1
Parameter	Measured Average 2010-2020	Predicted 2010-2020 90% Anoxic Sediment P Reduction	Predicted 2010-2020 75% Anoxic Sediment P Reduction
Mean Near-Surface GS TP (µg/L)	79	56	61
Mean Near-Surface GS Chl-α (µg/L)	54	34	37
Mean Secchi GS Disk Depth (ft)	4.8	4.1	3.9

Parameter	Measured 2021	Predicted 2021 90% Anoxic Sediment P Reduction & 50% CLP Biomass Removed
Mean Near-Surface GS TP (µg/L)	70	47
Mean Near-Surface GS Chl-α (µg/L)	37	28
Mean Secchi GS Disk Depth (ft)	2.2	4.7
Parameter	Measured Average 2010-2020	Predicted 2010-2020 90% Anoxic Sediment P Reduction & 50% of CLP Biomass Removed
Mean Near-Surface GS TP (µg/L)	79	49
Mean Near-Surface GS Chl-α (µg/L)	54	29
Mean Secchi GS Disk Depth (ft)	4.8	4.5

## 4.0 CONCLUSIONS

The goal of this study was to quantify the level of internal phosphorus loading in Little Green Lake and determine if the application of alum would be a feasible means of improving the lake's water quality. The water quality monitoring completed as part of this study revealed that 2021 was an atypical year for Little Green Lake in terms of thermal stratification, nutrient dynamics, and water clarity. While the lake typically develops weak thermal stratification allowing for periodic mixing events during the summer, a period of above-normal temperatures in early June of 2021 led to the development of strong thermal stratification which persisted over the course of the summer.

The sustained thermal stratification and hypolimnetic anoxia led to the release and accumulation of phosphorus within the hypolimnion from anoxic bottom sediments. Continued deepening of the thermocline over the course of the summer likely resulted in some mobilization of phosphorus from the hypolimnion to the epilimnion, but most of the phosphorus remained in the hypolimnion until mixing in early September. The rate of phosphorus accumulation within the epilimnion was higher than the rate of accumulation within the hypolimnion, indicating internal loading to surface waters comes from sources outside of anoxic bottom sediments. These additional sources are believed to be primarily from the senescence of the lake's expansive curly-leaf pondweed population and to a lesser extent the release from shallower littoral sediments from elevated pH and/or anoxia beneath dense plant beds.

The internal loading of phosphorus from all sources was estimated to account for 69% of the annual phosphorus budget to Little Green Lake in 2021, with phosphorus loading from deep-water anoxic sediments estimated to account for 39% of the total loading. Phosphorus loading from the curly-leaf pondweed population is estimated to account for 27%, loading from littoral sediments was estimated to account for 3%, and external sources (runoff and atmospheric deposition) accounted for the remaining 31%. Data collected in more typical years (e.g., 2013 and 2014) with periodic mixing indicates that internal phosphorus loading from deep-water anoxic sediments is more significant, accounting for approximately 76% of the annual budget. It is believed the periodic mixing events act as 'nutrient pumps', periodically mobilizing phosphorus-rich water to the surface, increasing the diffusion gradient between the sediment and overlying water and allowing more phosphorus to be released from bottom sediments.

The sustainment of strong thermal stratification in 2021 resulted in less phosphorus loading from deep-water anoxic sediments to surface waters. This resulted in lower near-surface phosphorus concentrations and lower chlorophyll-*a* concentrations. However, despite lower chlorophyll-*a* concentrations, water clarity was below average throughout the growing season. The typical clear-water phase in May and June did not occur. This may have been due to above-normal runoff from the rapid melting of a large snowpack. It is not clear why water clarity was not higher given the lower chlorophyll-*a* concentrations, but it is hypothesized that the stronger thermal stratification may have resulted in algae concentrating immediately at the surface, above the depth at which samples are collected. In other words, algae may have been suspended higher in the water column than the depth of 3.0 feet where standard samples are collected from.

Analysis of sediment cores indicated that most of the phosphorus released from deep-water anoxic sediments likely originates from the upper 5 cm. Using these data, alum application scenarios were developed to reduce phosphorus release from deep-water anoxic sediments (16 feet and deeper) by 90% and 75%. The application of alum over this 127-acre area to reduce phosphorus

loading by 90% and 75% would cost approximately \$540,000 and \$355,000, respectively. Even at the application rate to reduce loading by 90%, the improvements to Little Green Lake's water quality are predicted to be minimal. There is still sufficient internal phosphorus loading from the curly-leaf pondweed population and release from shallow littoral sediments to create degraded water quality conditions. While phosphorus concentrations are predicted to decline, algal blooms would still be a frequent occurrence on Little Green Lake.

Mean growing season total phosphorus concentrations would be predicted to decrease from 79 µg/L to 56 µg/L (29% decrease), mean growing season chlorophyll-*a* concentrations would decrease from 54 µg/L to 34 µg/L (37% decrease), and mean growing season Secchi disk depth is not predicted to increase significantly. The relationship between chlorophyll-*a* and Secchi disk depth in Little Green Lake indicates that to achieve a mean Secchi disk depth of 5.0 feet or greater would require mean phosphorus concentrations to be reduced to near 40 µg/L or less. To achieve this, at least 80% of the curly-leaf pondweed biomass would have to be removed annually in combination with an alum treatment to reduce deep-water anoxic sediment release by 90%.

As is discussed in the management plan, reducing CLP at the lake-wide level would require repeat, annual lake-wide treatments for at least 5-7 years to deplete the turion reserve in the sediment. During the management planning process, it was estimated that just two years of consecutive lake-wide treatments and monitoring would cost in excess of \$200,000. Mechanical harvesting to remove 80% of the CLP biomass on an annual basis is also unrealistic given the cost and extensive area that would need to be harvested. Controlling CLP on a lake-wide level on an annual basis through herbicides or harvesting is not feasible at this time. If the CLP population is found to have declined, an alum treatment could be considered; however, water quality conditions would need to be re-examined to determine if alum would still be a feasible option.

The 2021 data and examination of historical data suggest that internal loading from anoxic deep-water sediments is highest in years when the lake is weakly stratified and experiences periodic mixing and is lower when the lake remains stratified throughout the summer. While the aim of the destratification system is to prevent thermal stratification and the development of anoxia in bottom waters, data show that bottom waters still become anoxic in years with weak thermal stratification due to high biological oxygen demand. Discontinuing operation of the destratification system will allow the lake to develop stronger thermal stratification in years like 2021 where weather conditions are conducive. Sustained thermal stratification, like that seen in 2021, will reduce the amount of internal loading from deep-water anoxic sediments and exchange with surface waters through mixing events.

While an alum treatment does not appear to be a viable option for improving water quality in Little Green Lake, the management plan contains actions that the LGLPRD will continue to take in an effort to continue to improve conditions within the lake. The group will continue to monitor the lake's water quality through the Citizens Lake Monitoring Network volunteer program, and continue to work with the Green Lake County Land Conservation Department to make improvements within the watershed.

## **5.0 LITERATURE CITED**

Onterra, LLC. (2018). Little Green Lake Comprehensive Management Plan.

Ramaker and Associates, Inc. (1997). Little Green Lake Management Plan. 95.

Short Elliot Hendrickson Inc. (2009). Nutrient budget and management data analysis report. Big Chetec Lake, Sawyer County, Wisconsin. 26.

WDNR. (2014). Effects of Aeration System Operation on Water Quality Conditions in Little Green Lake, Wisconsin.

# A

## APPENDIX A

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**Wisconsin Dept. of Natural Resources Comments/Onterra Responses**

DATE: May 12, 2022 FILE REF: Little Green Lake Alum

TO: Tim Hoyman (Onterra, LLC)

FROM: Ted Johnson  
Water Resources Biologist – Eastern District

SUBJECT: DNR comments and questions on the Little Green Lake - Alum Study

We are assuming throughout this report that uncertainty is not quantifiable. This was an alum treatment feasibility study and not an updated management plan. The group recently finished a large-scale management planning project that called for this project after they completed additional monitoring. If the reader needs a refresher, they should refer back to the plan. Further, this report is intended for the lay-person, so every attempt is made to keep it as short as possible and not overly detailed. This is a very complicated subject, so including too much of a summary of the management plan, uncertainty of models, and how calculations are performed adds unneeded detail and may distract from what really needs to be understood.

- If you look at the literature, some general features that tend to make alum treatments successful for longer periods of time include:
  - pH 6-8 and alkalinity > 75 mg/L CaCO<sub>3</sub> – yes, pH is 7.3 to 9.4 and alkalinity is 130-190 mg/L
  - Watershed:Lake Area < 7.2 – yes (5.28)
  - Dimictic lakes most successful – depends on the year for Little Green, right?  
We agree that an alum treatment would likely be effective at significantly reducing deep-water anoxic sediment P release, but what is in question is if it would make a significant improvement on water quality based on loading estimated from CLP population.
  - Carp and dense plants interfere – concern for Little Green
  - After reduced external P loading – report shows Little Green still has 30% external load. How certain is this estimate and is this enough?  
We believe the group and agency partners have made efforts to minimize nutrient runoff from the watershed. The lake has seen a reduction in mean phosphorus concentration over the past decade, but the lake still experiences a rise in near-surface phosphorus concentrations over the summer, and indicator of internal loading. This group has done real work in the watershed, this is opposed to groups that want to use alum without looking at the watershed, and we believe group has minimized nutrient runoff. Regarding the uncertainty, we cannot quantify it, but to achieve the mean spring turnover phosphorus concentration of 34 µg/L, WiLMS predicts that external loading would be around 550 pounds/year.
- Important to estimate uncertainty in nutrient loading quantities and proportions. How sensitive are these estimates to the assumptions made on CLP P content, density, and coverage? What is uncertainty in WiLMS external load estimate? Having direct measurements of phosphorus content and density of CLP from Little Green Lake would be ideal, but we believe the estimate used from the Big Chetec study are sufficient for this study. The amount of phosphorus estimated using the Big Chetec data aligns with phosphorus needed in combination with phosphorus released from bottom sediments to achieve lake-wide summer concentration.
-

Link back to old reports and/or update on external source contributions, improvements to date, and what remains. Efforts that have been undertaken in the watershed are summarized in the last paragraph on page 4.

- Recognize that prior to alum treatments, many studies quantify external loads with extensive field data. This is true, but is it necessary here?
- Report emphasizes CLP as major contributor. What strategies would be recommended for CLP here and what are pros/cons of each? We went through a full alternatives and cost analysis with the group during the planning process and it is elaborated on in the management plan, but a paragraph has been added to the Conclusions section.
- Important at the end of the report to offer strategies for improvement, not only monitoring and waiting for lower CLP densities more conducive to alum treatment. Important to keep an active lake group engaged and offer solutions. The primary focus of this project was to determine the feasibility of an alum treatment, and the management plan has other actions that the group is implementing. We will reference the management plan and have summarize these ideas within the report
  - Likely possible to continue more work in the watershed, better prepare for large storm events
  - Safety practices and warning systems as lake group continues to deal with threats of HABs
- Seems like Little Green could be a good candidate for alum if the external sources and CLP are handled first. Provide more estimates on uncertainty for each of those sources and provide management action suggestions for each. We'll expand on how the WiLMS estimate was derived and how we back-calculated to mean SPO.
- Report cites a watershed area of ~1,600 acres, 2018 lake plan pegged it at 2,419 acres (WHDPlus estimate – 2,438 acres). This typo has been corrected – thank you
- Report estimates external watershed load as 554 lbs/yr, 2018 lake plan estimated external load at 1,774 lbs/yr. Need to explain the discrepancy between the two estimates. After the management plan report was sent out, we found out one of the sub-watersheds was counted twice, and this will be noted in the updated report. WiLMS estimate was around 1,500 pounds; however, this was reduced to 554 pounds to align with the mean spring overturn phosphorus concentration of 34 µg/L from 2011-2021. This has been expanded upon within the methods section of the report.
- Need to explain how the Big Chetec Lake CLP study was applied to estimate a CLP loading in Little Green. This has been expanded upon in the methods section.
- Need a better understanding on how they are calculating/defining internal loading. In the 2018 lake plan (also prepared by Onterra), they state that they are basing their numbers on “the total mass of phosphorus in the water column”, but the accompanying graphic (Fig 3.1-6) appears to show surficial data, not whole water column averages. It's acceptable to define internal loading based either on whole column or just the portion that gets into the epilimnion, but the definition needs to be clear. For example, defining it based on just the portion that makes it into the epilimnion is consistent with the reports argument that internal loading from sediments was lower in 2021 because the lake remained stratified. However, if the report is defining it based on whole water column increase, then the stratification argument would need to be better explained. We see how that's confusing in the management plan and should have rephrased the caption. In the feasibility report, internal loading is defined as a lake-wide mass of phosphorus, not solely what was estimated to be loaded to the epilimnion.
- Need to explain which lake response model(s) was chosen for the lake and why. Provide comparison of predicted and observed results including uncertainties. Same comment regarding chlorophyll-a response model(s) and Secchi predictions. Response models were added to Table 2 and Figure 10 descriptions.
- What happens if the lake loses all or most of the aquatic plants? Historic plant data indicates that the diversity and density of aquatic plants in the lake has substantially decreased over time. If the

80% reduction of CLP occurs, would you recommend alum at that point in time? This is a good point. While we allude to the fact that a large reduction in CLP, whether natural or anthropogenic would increase the effectiveness of an alum treatment, in reality, we would really have to see what the lake would be like under those conditions to determine whether an alum treatment should be completed or not. We'll elaborate on this in the report.

- Given uncertainty in external loading estimates (inherent error with models), would you recommend field sampling to establish a loading baseline? How many years would you sample? Would not be worth the money right now given how internal loading appears to be the primary contributor. If CLP is reduced, may consider doing more watershed monitoring.