Technical Memo

Responsive partner.
Exceptional outcomes.

To: Tiffany Determan, Isanti Soil and Water Conservation District

From: Jeff Strom, Wenck Associates, Inc.
Aaron Claus, Wenck Associates, Inc.

Date: October 3, 2019

Subject: Green Lake Phosphorus Diagnostic Study

Green Lake is a deep lake located in Isanti County. Historic water quality monitoring efforts for Green Lake (Attachment A) suggest the lake does not meet state water quality standards. Green Lake was placed on the State of Minnesota's 303(d) list of impaired waters in 2015 and a Total Maximum Daily Load (TMDL) study for the lake was completed in 2017. Since the completion of the TMDL study, the Isanti Soil and Water Conservation District (SWCD) and the Green Lake Improvement District (LID) have collected additional flow and water quality measurements from various ditches and streams that discharge to the lake.

The SWCD contracted with Wenck Associates, Inc. (Wenck) to review the newly collected data, compare these data to the original TMDL study, and provide further recommendations to reduce phosphorus loading to the lake. This technical memorandum presents the results of this work which includes the following components:

- Review historic and recently collected data
- Update lake phosphorus budget and model using new data
- Establish phosphorus goals and reductions based on new data
- Recommended strategies

Existing Data Review

Table 1 summarizes the data, studies and models that were compiled and reviewed for this study. All information in Table 1 was supplied by the SWCD staff or was available online.

Table 1. Data, studies and models reviewed for this study

Data/Study	Description	Source
Green Lake water quality data (2016-2018)	Includes temperature/DO profiles and surface TP, Chl-a, TSS and Secchi measurements for Green Lake	Isanti SWCD
Green Lake water quality data (pre-2016)	Includes various surface parameters (1973-2015) as well as hypolimnion TP concentrations (1988-1989, 1991, 1993, 1998)	EDA (link)
Green Lake tributary monitoring data	Includes TP, TSS, Secchi tube, DO, gauged flow and water level measurements for four tributary stations (Figure 1)	Isanti SWCD
DNR Fisheries Surveys for Green Lake	Historic DNR fisheries survey results for the following years: 2016, 2012, 2007, 2002, 1997, 1992, 1987, 1982, and 1979	MnDNR (link)
Green Lake Aquatic Plant Survey Report	Early spring (May 7-14, 2018) aquatic vegetation survey of Green Lake with focus on curly-leaf pondweed	LIMNOPRO
Green Lake Status Report (2018)	Review of historic data and recommendations for future studies and management for water quality and nuisance vegetation	LIMNOPRO

Data/Study	Description	Source
Rum River TMDL and WRAPS Reports (2017)	TMDL report includes TMDL allocations and reductions for Green Lake. WRAPS report outlines restoration strategies based on available data and TMDL results.	MPCA (link)
Rum River HSPF-SAM Model	HSPF Simulation Application Manager (SAM) tool developed by the MPCA and used in the Rum River TMDL and WRAPS	MPCA (link)
Green Lake Rural Stormwater Retrofit Analysis of North Brook	Reports providing recommendations for treatment of stormwater from tributaries and direct watershed draining to Green Lake	Isanti SWCD
Green Lake Subwatershed Retrofit Analysis		

In-Lake Water Quality

In order for Green Lake to be considered an impaired waterbody, the 10-year average growing season total phosphorus (TP) concentration and at least one "response variable" (chlorophyll-a or Secchi depth) must exceed State water quality standards. Growing season TP concentrations for Green Lake have averaged 61 µg/L over the most recent 10-year period, which is above the 40 µg/L standard for deep lakes in the North Central Hardwood Forest (NCHF) Ecoregion. Planktonic algae, which is measured by chlorophyll-a (chl-a), has averaged 25 µg/L which is above the 14 µg/L standard for deep lakes. Secchi depth, a measure of water clarity, is relatively good in Green Lake and has met the 1.4-meter Secchi depth standard in five of the seven years measured since 2009. Although Secchi depth has generally met State water quality standards over the past 10 years, Green Lake is still considered impaired since TP and chl-a do not currently meet State standards.

Tributary Flow and Water Quality

SWCD staff monitored flow and water quality throughout the watershed draining to Green Lake (Figure 1) from 2016-2018. Continuous water levels (transducers) and gauged flow were recorded and measured at two of the four stations (North Brook and Wyanett Creek). Based on review of these data, both monitoring stations demonstrated reasonably reliable stage-discharge relationships that could be used to convert the continuous water level readings to continuous flow (Attachment B).

Water quality monitoring results for the four tributaries are summarized in Attachment B. Monitoring parameters included TP, total suspended solids (TSS), Secchi tube, temperature and dissolved oxygen (DO). In general, TSS concentrations in all four tributaries are typically below the 30 mg/L State standard for streams in the Central River Nutrient Region. Old Judge's Creek (18%), North Brook (9%), and Wyanette Creek (9%) exhibited some individual exceedances of the 30 mg/L standard. Median TSS concentrations were highest in Old Judge's Ditch (24 mg/L) followed by North Brook (11 mg/L), Wyanett Creek (9 mg/L), and Bratline Creek (<2 mg/L). Elevated TSS measurements in Old Judge's Ditch, North Brook, and Wyanett Creek coincided with storm events and higher flow conditions suggesting sediment loading from upland sources and/or in-channel sources.

Median TP concentrations were highest in North Brook (170 μg/L) followed by Wyanett Creek (155 μg/L), Old Judge's Ditch (111 μg/L), and Bratline Creek (66 μg/L). In general, elevated TP concentrations for the four tributaries coincide with high TSS levels and therefore particulate phosphorus sources (i.e. phosphorus attached to sediment) are likely a major source to Green Lake. That said, there are several instances in which TSS levels were low (<10 mg/L) and TP measurements were relatively high (>150 ug/L) in North Brook and Wyanett Creek. Thus, it is recommended that ortho-phosphorus samples be collected at each tributary monitoring station to determine the presence of dissolved/soluble phosphorus during different times of year and flow conditions.

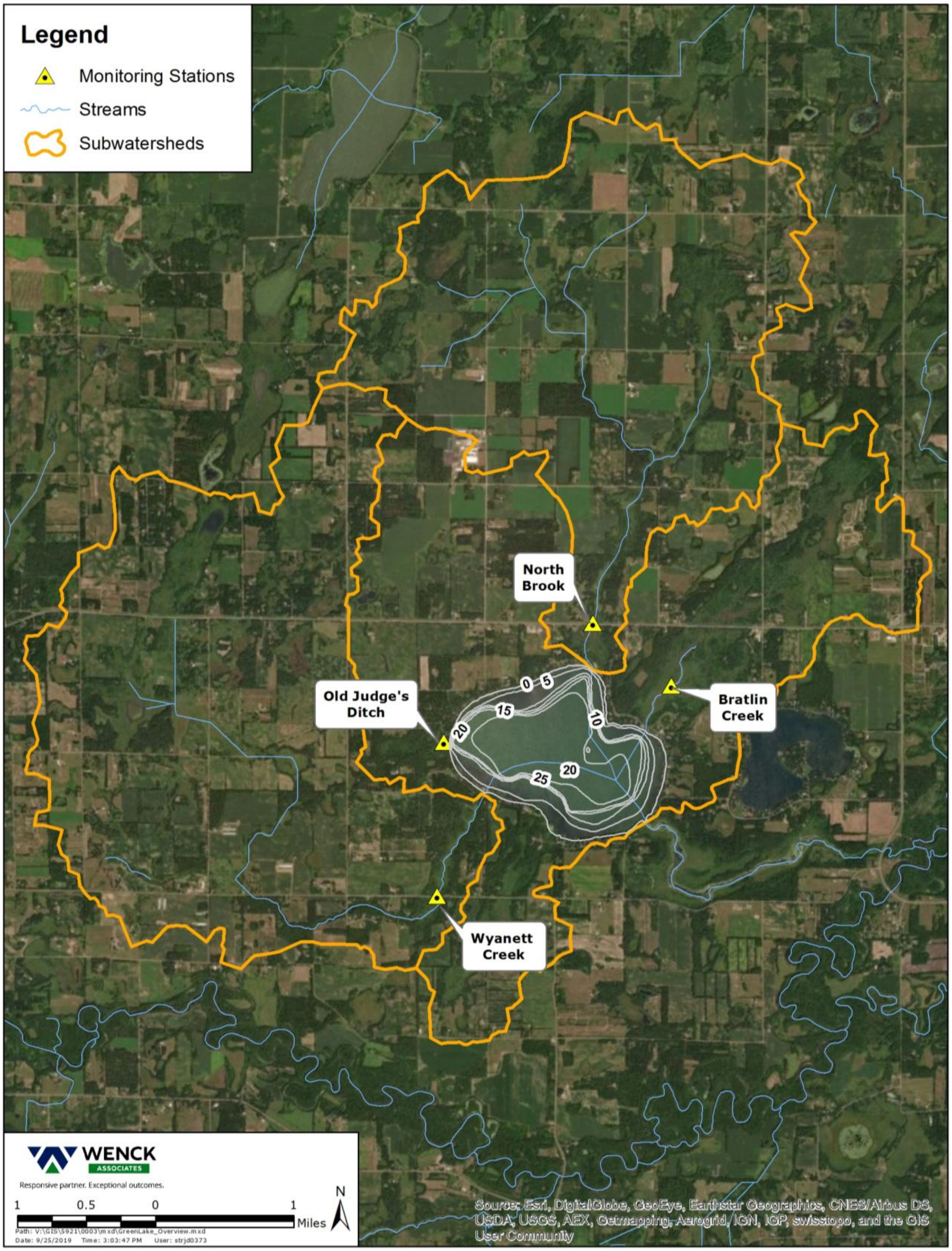


Figure 1. Green Lake subwatersheds and tributary monitoring stations.

<u>*DNR Fisheries Surveys*</u>

Abundance of fish can sometimes have strong effects on water quality through ecological interactions between fishes and the other components of the lake's food web (Noonan et al. 1994). While bottom up ecological effects (lake productivity and abiotic factors) related to nutrient loadings are usually the driving force behind a lake's stable state (algal or macrophyte dominated; Scheffer et al. 1993), other types of ecological interactions can emerge when fish abundances are relatively high (Carpenter and Kitchell 1996). The species of fish represented within the overall abundance is an important factor in attributing ecological effects as they each have different effects based on their ecological niche.

A simplified way to divide the species into functional groups is by categorizing them according to general trophic guild (a group that shares similar feeding habits). Three primary trophic guilds exist in local lakes, planktivores (includes all larval/juvenile life stages of fishes, small bodied "forage" species such as minnows and shiners, and some large-bodied specialist species: data is always lacking for this guild), piscivores (fish predators such as native game fish species: surveyed by MN DNR lake survey methods), and benthivores (specialists at feeding on/within substrates: partially/weakly surveyed by MNDNR lake survey methods). In general, each of these guilds has a different type of effect on the lake ecosystem.

Planktivorous species exert top-down effects on the ecosystem through predation on herbivorous zooplankton which are the main consumers of phytoplankton (algae). A trophic cascade is a top down effect that is manifested when higher trophic levels exert a predatory force onto successive lower trophic levels. In this way high abundance of planktivorous fish can create a trophic cascade and increase relative phytoplankton abundance (reduced water clarity).

In similar fashion piscivorous fishes can exert cascading trophic effects on the food web by predating upon and reducing the abundance of planktivorous fishes (increased water clarity). Lastly, benthivorous fishes exert very different effects on the lake ecosystem. Coined "middle-out" effects, benthivores contribute to bioturbation of sediments and uprooting of macrophytes through their feeding activities (Kaemink et al 2016). These effects are attributed to increased internal nutrient loadings in lakes with dense populations of benthivorous fishes (Bajer and Sorensen 2015; Huser et al. 2016). Often growing too large for piscivores to consume (White Sucker and Common Carp) or possessing defensive adaptations that limit predation (Black Bullhead and Common Carp); benthivorous fish populations act to sequester a large proportion of biological energy available to other organisms, held in the form of fish biomass and nutrients cycled by said biomass. This indirectly acts to reduce the available energy and "population space" for piscivorous species, reducing their relative abundance and thus the relative power of their cascading effects related to predation upon piscivorous species/life stages.

The Minnesota Department of Natural Resources has conducted surveys of fish relative abundance with standardized methods on a 5-year cycle in Green lake since 1979. These survey methods allow inference of relative abundance by comparing catch rates over time and to normal ranges for lakes with similar characteristics (lake eco-class; Schupp 1992). Figure 2 plots the trends over time for all fish species and Figure 3 plots the same trends for benthivorous species (Black Bullhead, White Sucker, and Common Carp) compared to respective normal ranges for MN lakes in class 27.

Lake survey catch per unit effort data from Green Lake suggest that overall fish abundance has varied significantly over time, has stayed mostly within normal ranges for similar lakes, and based on most recent survey in 2016 abundance is currently reaching the upper normal range in abundance. Benthivore (substrate feeding) fish populations exhibit similar trends over time in Green Lake, but account for small proportion of overall catch per unit effort (sampling bias may account for these differences).

An important note to consider with these data that standard lake survey methods (trap-nets and gill-nets) are known to ineffectively sample some species such as Common Carp and Largemouth Bass, in which case targeted sampling methods (electrofishing, capture-mark-recapture) are performed when deemed necessary. Special electrofishing surveys were performed on Green Lake for Largemouth Bass but are excluded from this analysis because normal range data is not available.

Inference about the effects of fish abundance on water quality in Green lake is limited by the lack of data on planktivorous fish abundance and Common Carp biomass density. Available data suggests that currently the state of its piscivorous game fishery is favorable for high water clarity and a macrophyte dominated stable state. The predictable occurrence of Common Carp in DNR catch data over time is indicative of a reproducing population existing within the lake and/or subwatershed, warranting specific sampling to quantify biomass density of this benthivorous species. If Common Carp biomass density is higher than 100 kg/ha (Bajer et al 2009), suppressive management of this invasive/nuisance species would be a method to increase water quality in Green Lake that is commonly employed by water managers in the region.

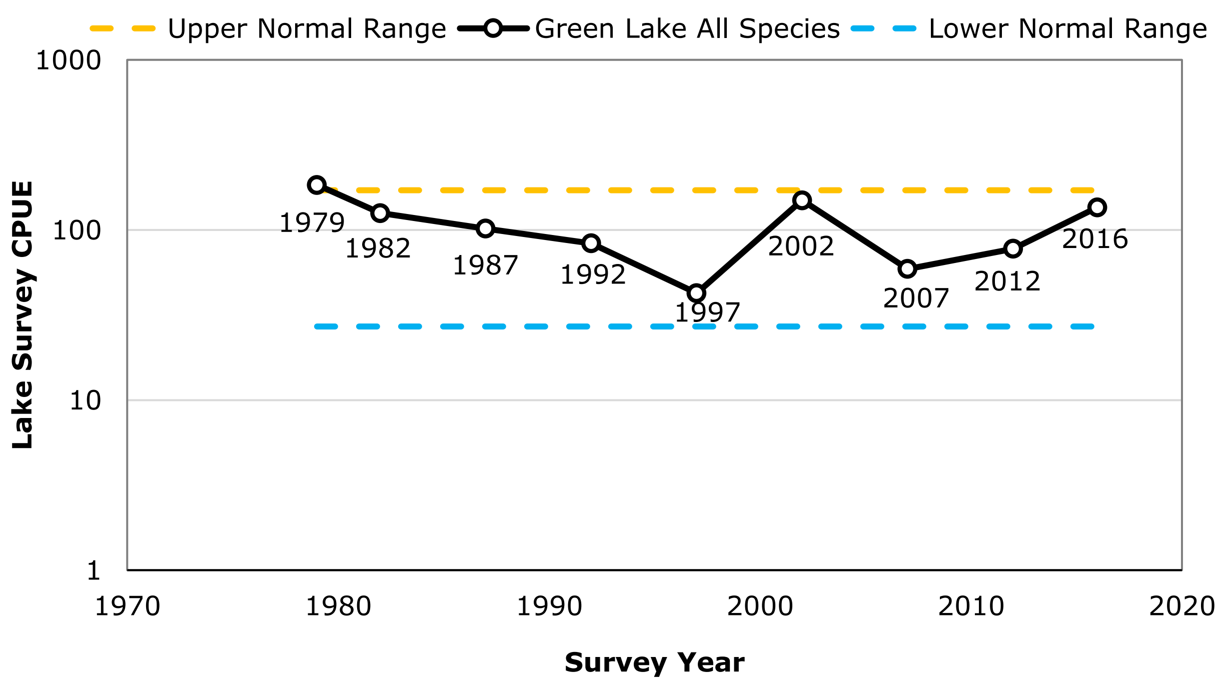


Figure 2. Trends in MNDNR lake survey catch per unit effort over time (all species).

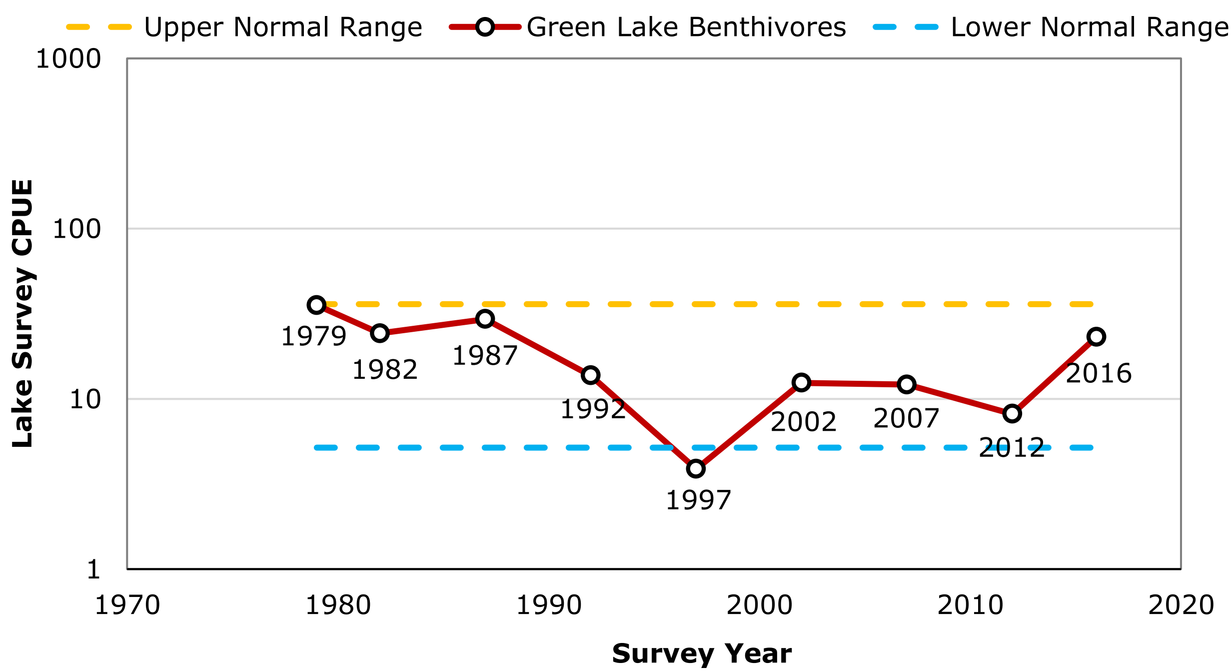


Figure 3. Trends in MNDNR lake survey catch per unit effort over time (benthivorous = substrate feeding species).

Updated Green Lake Phosphorus Budget and Model

Original TMDL Model

The Green Lake TMDL study used the Rum River Watershed HSPF model to estimate watershed flows and phosphorus loads to the lake, and a model residual approach (if necessary) to estimate internal load. The model baseline years for development of the TMDL allocations were 2006 through 2015. The original TMDL model called for watershed, subsurface sewage treatment system (SSTS), and internal TP load reduction goals of approximately 1,729 lbs/year, 110 lbs/year, and 0 lbs/year, respectively (Table 2).

Table 2. Summary of TP load reductions by source presented in the Green Lake TMDL

Source Load	Existing TP Load [lbs/yr]	Allowable TP Load [lbs/yr]	Estimated Load Reduction [lbs/yr]	Estimated Load Reduction [Percent]
C & I Stormwater	6	6	0	0%
Wyanett Creek	1,821	1,086	735	40%
North Brook	1,290	810	480	37%
Local Watershed	1,286	772	514	40%
SSTS	110	0	110	100%
Internal Load	0	0	0	0%
Atmosphere	199	199	0	0%
TOTAL LOAD	4,712	2,873	1,839	39%

As discussed previously, a significant amount of data has been collected for Green Lake since the TMDL model baseline years and the completion of the TMDL study. These data include: in-lake water quality monitoring, temperature and dissolved oxygen profiles, vegetation surveys, and tributary flow and water quality. Wenck has reviewed these data and developed an updated lake response model for Green Lake (baseline years 2016, 2017, and 2018) that reflects the newly collected data. The updated lake response model, existing TP budget, and allowable TP targets for Green Lake are presented below.

Updated Lake Response Model

To develop the updated lake response model for Green Lake, Wenck used methods similar to the lake TMDLs in the Rum River Watershed TMDL Study (MPCA, 2017) and other TMDL studies throughout the State. The four major phosphorus sources defined in the model were watershed load, internal load from lake sediments, loading from curly-leaf pondweed (CLP) senescence, loading from SSTSs near the lake, and atmospheric load.

Watershed TP loading was estimated using the tributary monitoring data described in the previous section that was collected by SWCD staff from 2016-2018. Since North Brook and Wyanett Creek were the only tributary station in which continuous flow was monitored, monitored runoff depths from these tributaries were applied to the other tributary subwatersheds (i.e. Bratlin Creek and Old Judge's Ditch) and areas immediately surrounding the lake. Results of this analysis indicate average (2016-2018) runoff depth for the entire Green Lake watershed is ~2.9 inches per year. This runoff rate is low and significantly less than the ~7.3 inches per year predicted by the Rum River HSPF model (average for model years 1997-2015). The monitored data suggests a significant portion of rainfall across the Green Lake watershed is being lost to evapotranspiration and/or deep/shallow groundwater that is not returned to the tributaries as baseflow. The average monitored TP concentration (~161 μg/L) for the entire Green Lake watershed was similar to the HSPF predicted TP concentration (~175 μg/L). Once the annual flow volumes for each tributary were calculated they were multiplied by the average monitored TP concentrations to estimate annual TP loads for each tributary.

Phosphorus loading from CLP senescence was estimated using CLP phosphorus content and areal density relationships developed by Three Rivers Park District (MPCA, 2015) for other Minnesota lakes. These relationships were combined with the percent occurrence and relative density ratings from a recent point intercept vegetation survey performed by LIMNOPRO in 2018. A CLP phosphorus content to internal load ratio of 1:½ (James et. al, 2002) was used in the Green Lake response model since not all of the phosphorus in the decaying plant matter is believed to be released to the water column.

Phosphorus loading to Green Lake from SSTSs located near the lake were estimated using methods similar to the Lower Minnesota River Watershed TMDL (MPCA, 2018). An estimate of the total number of SSTSs immediately surrounding the lake (~175 systems) was provided by Isanti County staff and assumptions were made regarding number of people per household (~2.8 people) and the number of days per year each household is occupied (~245 days/yr). It was also assumed that SSTSs that are imminent public health threats (IPHTs) or are failing to protect groundwater (FTPGW) contribute more phosphorus than SSTSs that comply with State design/performance standards. At this time, we do not know the number SSTSs immediately surrounding Green Lake that are IPHTs or FTPGW. Therefore, Wenck used the most recent county-wide SSTS failure rates for Isanti County that are reported annually to the MPCA. The county-wide estimates assume that approximately 6% of the SSTSs in Isanti County FTPGW and 0% are IPHTs.

Atmospheric phosphorus loading to Green Lake were estimated using literature rates for dry (<25 inches of rainfall), average (25-38 inches), and wet (>38 inches) precipitation years (Barr Engineering, 2004). Atmospheric loading to lakes is typically small compared to other sources and is very difficult, if not impossible, to manage.

Internal phosphorus loading for Green Lake was estimated using a model residual approach whereby the other four sources (watershed, CLP, SSTS, and atmosphere) were added to the models first, and then if necessary, additional load was added to calibrate the model. This approach assumes that the additional loads are likely attributed to internal phosphorus loading from rough fish (i.e. Common Carp) and/or lake sediments. It is also possible that a portion of the additional load needed to calibrate the model are the result of one (or more) of the other four sources being under-represented, or one or more loading source(s) that is not currently accounted for in the TP source assessment.

Internal phosphorus loading from substrate-feeding fish is extremely difficult, if not impossible to directly quantify *in-situ*. That said, Common Carp are known to uproot vegetation and re-suspend sediment through their feeding habits which, when there are high densities of carp in a lake, can lead to increase water turbidity, reduced vegetation coverage and lower waterfowl populations. Recent research suggests that these impacts begin to occur at Common Carp densities of ~100 kg of carp biomass/hectare (89 lbs/acre) (Bajer et al. 2009). As discussed above, Green lake is inhabited by a population of Common Carp but biomass density has not been quantified.

Internal phosphorus loading from lake sediments often occurs when anoxic conditions are present, meaning that the water in and above the sediment is devoid of oxygen. One way to estimate phosphorus release from the sediment is by collecting sediment cores and incubating them in the lab under anoxic conditions to measure phosphorus release over time. At this time sediment cores have not been collected or analyzed for Green Lake. Release rates can also be estimated by calculating the observed rate of change in hypolimnetic TP concentrations during the summer growing season. Based on review of available data for Green Lake in the State's EDA database, hypolimnetic TP measurements were collected in three different years (1991, 1993, and 1998; Attachment A). Analysis of these data suggest an average sediment phosphorus release rate of 10.4 mg/m^2/day. This rate is significantly higher than the release rate estimated using the model residual approach (6.0 mg/m^2/day). For the purposes of this study, the model residual rate was selected over the hypolimnetic TP release rate since neither sediment cores nor Common Carp biomass have been assessed. It is recommended that both sediment and Common Carp be evaluated to help refine the internal loading component of the updated lake response model and better inform management strategies moving forward.

Updated Modeling Results

With the watershed, CLP, SSTS and atmospheric phosphorus loads defined, the model predicted average annual TP concentrations from 2016 through 2018 were compared to available monitored in-lake TP concentrations during the same period. The model predicted TP concentration was significantly lower than monitored value, and therefore adjustments were made by increasing phosphorus loading to represent internal load (model residual approach).

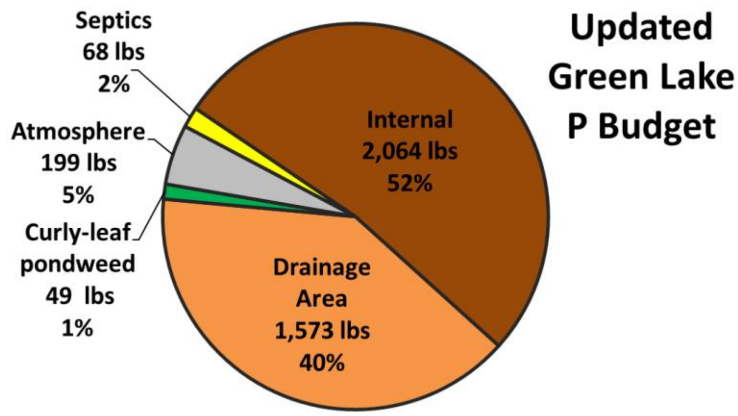


Figure 4. Green Lake Updated Phosphorus Budget (2016-2018)

The updated lake response model results suggest internal loading is likely the largest source (52%) of TP loading to the lake (Figure 4). This is a significant difference from the TMDL model which assumed minimal contributions from internal load. Watershed loading is the second largest contributor and accounts for approximately 40% of the lake's annual TP budget. Atmospheric loading (5%), septic system inputs (2%), and CLP senescence (1%) account for relatively small portions of the overall budget. Attachment C contains detailed information of the lake response model inputs and results.

Green Lake Phosphorus Goals and Source Reductions

Wenck used the updated lake response model to estimate TP load reductions (all sources) needed to meet Green Lake's 40 µg/L water quality goal. The updated model suggests TP loading to Green Lake will need to be reduced by approximately 2,142 pounds/year (54%) in order to meet this goal. Wenck reviewed each phosphorus loading source to Green Lake and performed a series of load reduction scenarios to determine which source(s) could be reduced to achieve the TP load reduction target/goal. Below is a discussion of these scenarios.

SSTS Reduction Scenario

The first scenario reviewed by Wenck was to evaluate the benefits of upgrading all "failing" (i.e. failing to protect groundwater) SSTSs immediately surrounding the lake. This scenario resulted in a TP load reduction of approximately 4 pounds/year (<1% of target/goal).

Watershed Reduction Scenario

For this scenario, TP loads from each tributary were reduced to meet the 100 µg/L standard for rivers/streams in the Central River Nutrient Region. Average monitored TP concentrations for Bratlin Creek (~87 µg/L) currently meet the Central River Nutrient Region standard, while TP concentrations for Wyanett Creek (~194 µg/L), North Brook (~171 µg/L), and Old Judge's Ditch (~193 µg/L) do not meet the standard. This scenario resulted in a TP load reduction of approximately 613 pounds/year (20% of target/goal; Table 3).

Sediment Load Reduction Scenario

The final scenario evaluated by Wenck was phosphorus load reductions benefits of internal load management via sediment inactivation and/or rough fish management. The updated lake response model suggests internal loading in Green Lake would need to be reduced by approximately 74% (1,525 pounds/year) to meet State water quality standards if the 613 pounds/year watershed load reduction scenario is achieved (Table 3). Based on our experience, chemical treatments, such as aluminum sulfate (alum), can reduce phosphorus release from lake sediments by approximately 90% (or greater) if designed and dosed correctly.

Table 3. Load reductions by source for Green Lake using updated lake response model (2016-2018)

Source Load	Existing TP Load [lbs/yr]	Allowable TP Load [lbs/yr]	Estimated Load Reduction [lbs/yr]	Estimated Load Reduction [Percent]
Wyanett Creek	753	388	365	49%
North Brook	438	256	182	42%
Bratlin Creek	120	120	0	0%
Old Judge's Ditch	193	136	57	29%
Remaining Local Watershed	70	61	9	12%
SSTS	68	64	4	6%
Internal Load	2,064	539	1,525	74%
Curly-leaf pondweed	49	49	0	0%
Atmosphere	199	199	0	0%
TOTAL LOAD	3,954	1,812	2,142	54%

Recommendations

Based on our review of available information/data for Green Lake and the updated modeling analysis presented above, we recommend the following next steps: 1) conduct review of available SSTS information 2) implement best management practices (BMPs) throughout the watershed; 3) conduct sediment internal load feasibility study; 4) conduct Common Carp population assessment; and 5) minor adjustments to current monitoring program. Each of these recommendations is described below in more detail.

Recommendation: Conduct Review of Available SSTS Information

This study uses recently reported county-wide SSTS failure rates to estimate phosphorus contributions from septic systems immediately surrounding Green Lake. The county-wide failure rates are low (0% ITPHS and 6% FTPGW) and therefore our modeling suggest SSTSs are not a significant source of loading to the lake. In order to determine if the county-wide failure rates are applicable to Green Lake, it is recommended that a review of available information be conducted for the homes/cabins/parcels immediately surrounding the lake. This could be accomplished by compiling a database with the following information for each cabin/home/parcel:

- Year home built
- Lot size
- Most recent point of sale (if applicable)
- Age of SSTS (if information available)

- SSTS inspection records (if applicable)
- Review of pump maintenance records (if available)

Recommendation: Implement Watershed BMPs

Two recent subwatershed assessment (SWA) studies were completed for Green Lake: The Green Lake Rural Stormwater Retrofit Analysis which covered North Brook and Wyanett Creek; and The Green Lake Subwatershed Retrofit Analysis which covered areas draining directly to the lake. These studies identified over 100 BMPs throughout the Green Lake watershed. Various types of BMPs were sited in these assessments, including: rain gardens, grassed swales, lakeshore restorations, permeable asphalt, hydrodynamic separators, settling ponds, land protection, grassed waterways, water and sediment control basins, filter strips, and wetland restorations. These studies estimate that if all of the sited BMPs were implemented, phosphorus loading to Green Lake would be reduced by approximately 334 pounds per year. This reduction is approximately 54% of the "updated" watershed load reduction goal (613 pound per year) for Green Lake based on the model scenarios discussed above. It is highly recommended that the SWCD and other partners continue to work with landowners throughout the watershed to implement the BMPs identified in these assessments as well as other opportunities as they are identified.

Figure 4. Example in-line wetland feature along Wyanett Creek

It is also recommended that the County assess areas within the stream/ditch corridor for potential projects that may have multiple benefits, including water quality improvement. For example, desktop review along the major tributaries to the lake, North Brook and Wyanett Creek, indicate there are several in-line ditched wetlands throughout the main channel network (Figure 4). These features can, over time, become overloaded and degraded which can lead to increased sedimentation, hydrology impacts, low dissolved oxygen, phosphorus release from the sediment, and degraded habitat. Thus, it is recommended that the SWCD establish a process to evaluate these sites and identify potential improvements where necessary. The evaluation process could include, but is not limited to, the following items:

- Upstream/downstream paired water quality monitoring
- Walking survey of channel to assess sedimentation, channel conditions, hydrology, etc.
- Wetland vegetation assessment such as the rapid floristic quality assessment (RFQA) (link)

Results of these evaluations can then be used to identify and prioritize projects such as:

- In-line or off-line settling ponds, basins, and/or filters
- Alterations to improve or restore hydrology
- Alterations to increase storage (if possible)
- Alterations to improve habitat and other wetland functions
- Stream/ditch channel restoration and/or maintenance

Recommendation: Conduct Sediment Internal Load Feasibility Study

The internal load rate used in the updated Green Lake model (6.0 mg/m^2/day) is high compared to other lakes in Minnesota where we've directly measured internal load from lake sediments. While this rate was not directly measured in the lab, it was estimated using a mode residual approach and is further supported by the large spikes in surface water TP concentrations that commonly occur in the late summer and fall when stratification weakens (Appendix A). As discussed above, phosphorus release from the sediment represents the largest source (~52%) of TP loading to Green lake and will likely need to be addressed at some point for the lake to consistently meet state water quality standards.

Based on our experience, an alum treatment to manage internal loading in Green Lake would likely cost between $0.75M-$2.00M depending on the size of the treatment area and the amount of alum needed. In order to refine these cost estimates, we recommend that an internal load feasibility study be conducted for Green Lake in which sediment cores are collected at a minimum of five sites and analyzed in the laboratory. Lab analysis of the cores should include the following parameters: sediment phosphorus release rate, moisture content-bulk density, loss-on-ignition, total iron, total aluminum, biologically-labile phosphorus and maximum allowable alum dosage. Results of these analyses will allow Wenck staff to validate and compare the internal loading rate used in the Green Lake model and develop a treatment plan to meet internal load reduction goals. The estimated cost of an internal load feasibility study for Green Lake is ~$17K and includes sediment core collection (5 sites), laboratory analysis and a final memo detailing recommended alum dosing rates, dosing schedule, treatment area and estimated treatment costs.

Recommendation: Conduct Common Carp Abundance and Density Assessment

In order to determine the likelihood that benthivorous fish abundance is contributing to internal nutrient loading, Common Carp abundance and biomass density surveys are recommended as per methods of Bajer et al. 2012. These surveys would produce baseline absolute abundance estimates that would add clarity to the source of internal nutrient loadings and add information to future Common Carp capture trends in MNDNR lake surveys. It is recommended that three individual Common Carp abundance and biomass density survey events (different days) be conducted each consisting of multiple (three or more) 20-minute electrofishing transects. Each survey event will require a MnDNR permit and follow-up modeling and data analysis of the survey results. A general cost estimate for these surveys is $5K per survey, or $15K total for three surveys.

Monitoring Recommendations

Wenck recommends the following monitoring activities to complement current lake and tributary monitoring efforts for Green Lake:

- Add ortho-phosphorus and dissolved phosphorus to the list of monitoring parameters for North Brook, Wyanett Creek, Bratlin Creek, and Old Judge's Ditch
- Conduct longitudinal surveys (4-5 events) along North Brook and Wyanett Creek to evaluate changes in water quality from upstream to downstream and pinpoint potential problem areas. Surveys should target different times of year and flow conditions and include the following parameters: TSS, TP, ortho-P, DO, temperature, pH, and flow.

- Collect hypolimnion (i.e. approx. 1 meter from bottom) TP and ortho-phosphorus samples during each surface sampling event for Green Lake
- Continue water quality sampling for Green Lake through the end of September and, if necessary, into October until the water column is completed mixed
- Perform early season (i.e. June) and late season (i.e. August) point-intercept submerged aquatic vegetation (SAV) surveys for Green Lake to track effectiveness of CLP treatments and evaluate/track health of SAV community as BMPs are implemented

References

Bajer, P. G., & Sorensen, P. W. (2012). Using boat electrofishing to estimate the abundance of invasive Common Carp in small Midwestern lakes. *North American Journal of Fisheries Management*, *32*(5), 817-822.

Bajer, P. G., & Sorensen, P. W. (2015). Effects of Common Carp on phosphorus concentrations, water clarity, and vegetation density: a whole system experiment in a thermally stratified lake. *Hydrobiologia*, *746*(1), 303-311.

Barr Engineering. 2004. (Updated 2007.) Detailed Assessment of Phosphorus Sources to Minnesota Watersheds. Prepared for the Minnesota Pollution Control Agency, St. Paul, MN

Carpenter, S. R., & Kitchell, J. F. (Eds.). (1996). *The trophic cascade in lakes*. Cambridge University Press.

Huser, B. J., Bajer, P. G., Chizinski, C. J., & Sorensen, P. W. (2016). Effects of Common Carp (Cyprinus carpio) on sediment mixing depth and mobile phosphorus mass in the active sediment layer of a shallow lake. *Hydrobiologia*, *763*(1), 23-33.

James WF, Barko JW, Eakin HL, Sorge PW. 2002. Phosphorus Budget and Management Strategies for an Urban Wisconsin Lake. Lake and Reservoir Management 18(2): 149-163

Kaemingk Mark A., Jolley Jeffrey C., Paukert Craig P., Willis David W., Henderson Kjetil, Holland Richard S., Wanner Greg A., Lindvall Mark L. (2016) Common Carp disrupt ecosystem structure and function through middle-out effects. *Marine and Freshwater Research* 68, 718-731.

Minnesota Pollution Control Agency. 2015. Elm Creek Watershed Management Commission Watershed Total Maximum Daily Load. https://www.pca.state.mn.us/sites/default/files/wq-iw11-04e.pdf

Minnesota Pollution Control Agency. 2017. Rum River Watershed Total Maximum Daily Load. https://www.pca.state.mn.us/sites/default/files/wq-iw8-56e.pdf

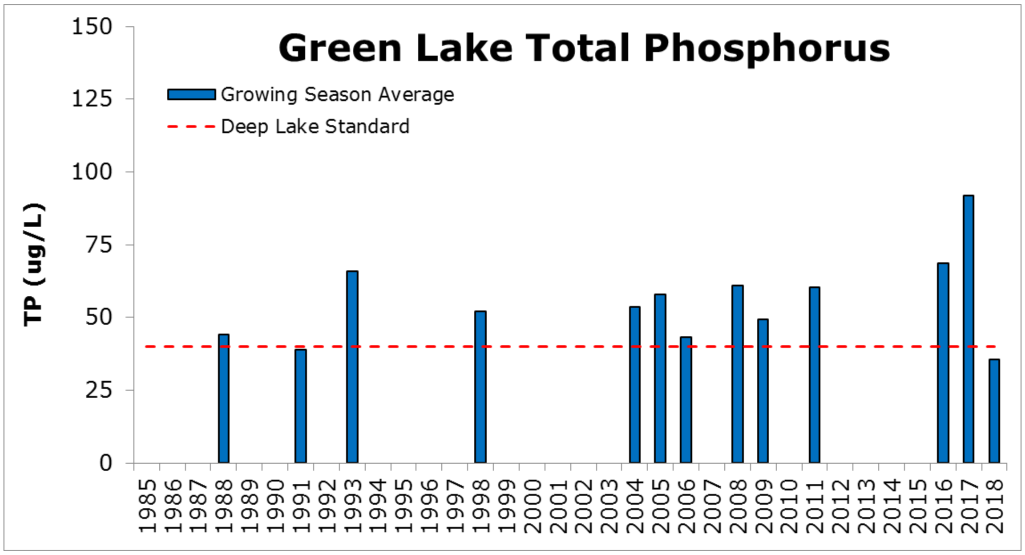
Minnesota Pollution Control Agency. 2017. Rum River Watershed Restoration and Protection Strategy Report. https://www.pca.state.mn.us/sites/default/files/wq-ws4-34a.pdf

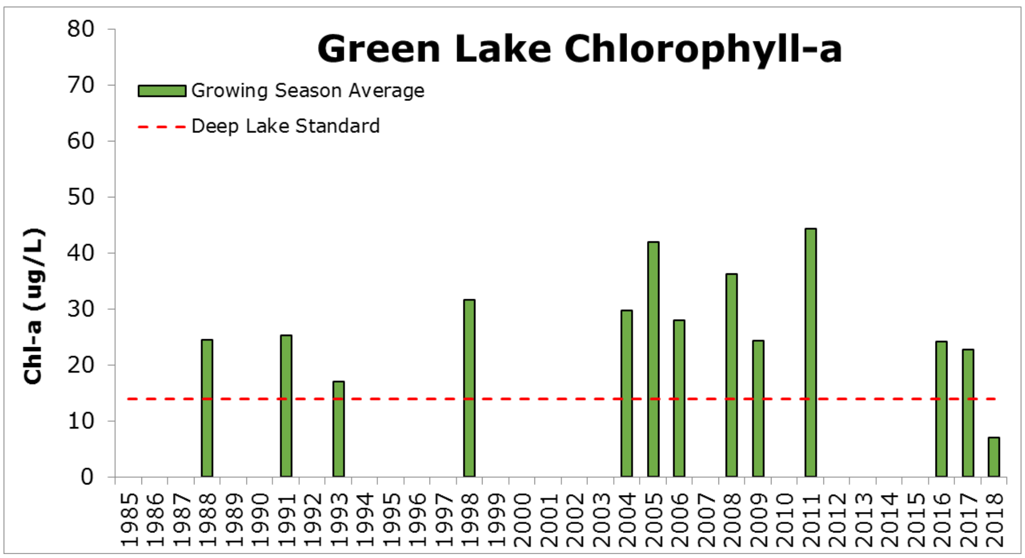
Nürnberg GK. 2004. Quantified Hypoxia and Anoxia in Lakes and Reservoirs. The Scientific World Journal 4: 42-54.

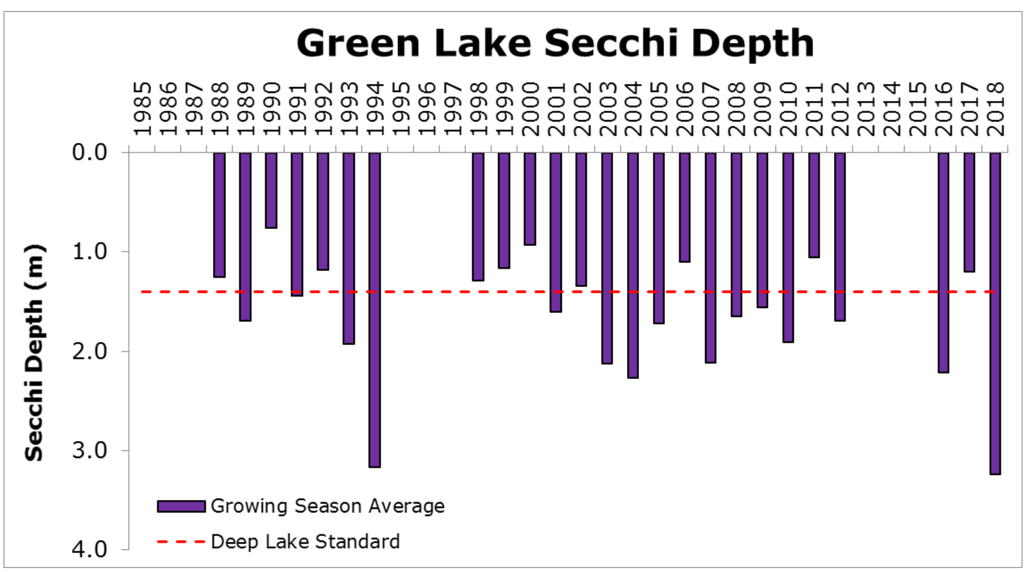
Scheffer, M., Hosper, S. H., Meijer, M. L., Moss, B., & Jeppesen, E. (1993). Alternative equilibria in shallow lakes. *Trends in ecology & evolution*, *8*(8), 275-279.

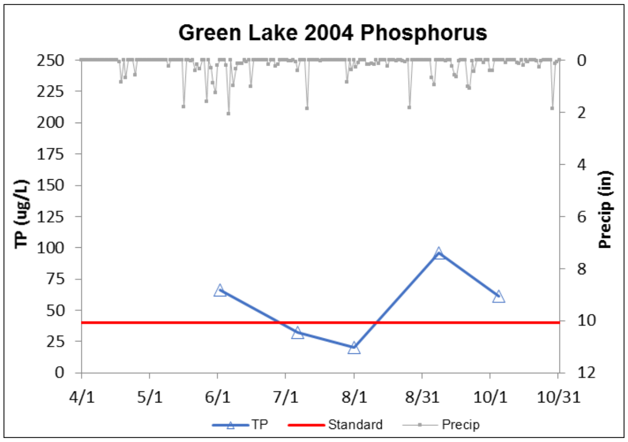
Attachment A

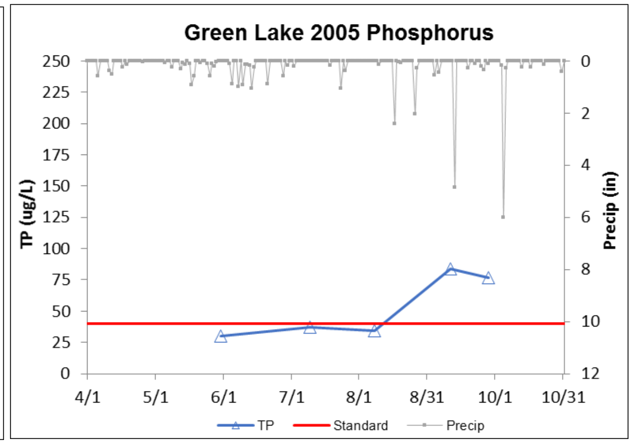
Green Lake Historic Water Quality

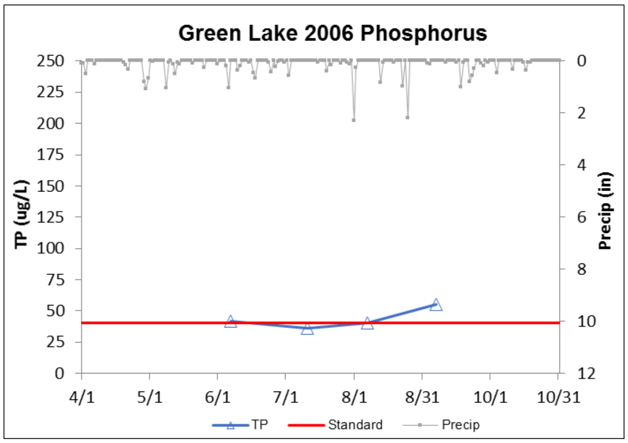

Green Lake Total Phosphorus
Growing Season Average
Deep Lake Standard
TP (ug/L)
150
125
100
75
50
25
0
1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

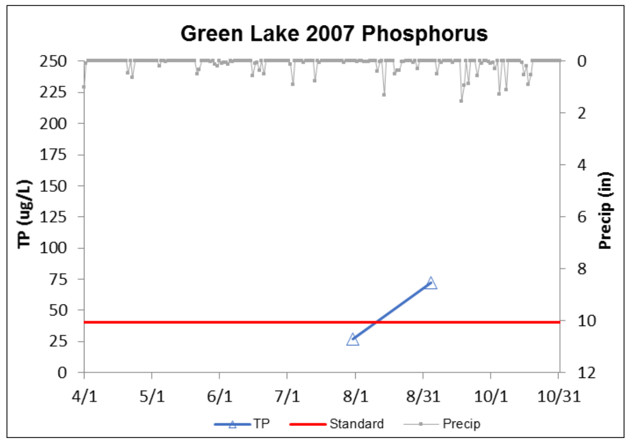

Green Lake Chlorophyll-a
Growing Season Average
Deep Lake Standard
Chl-a (ug/L)
80
70
60
50
40
30
20
10
0
1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

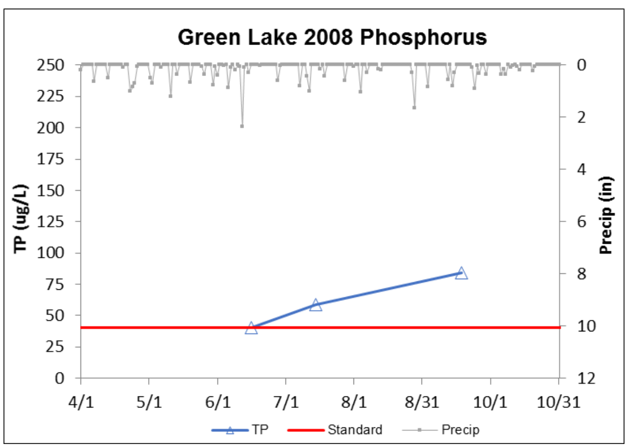

Green Lake Secchi Depth
1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Secchi Depth (m)
0.0
1.0
2.0
3.0
4.0
Growing Season Average
Deep Lake Standard

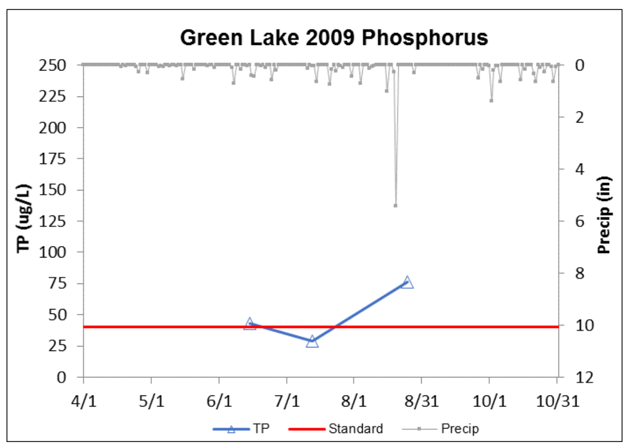

Green Lake 2004 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

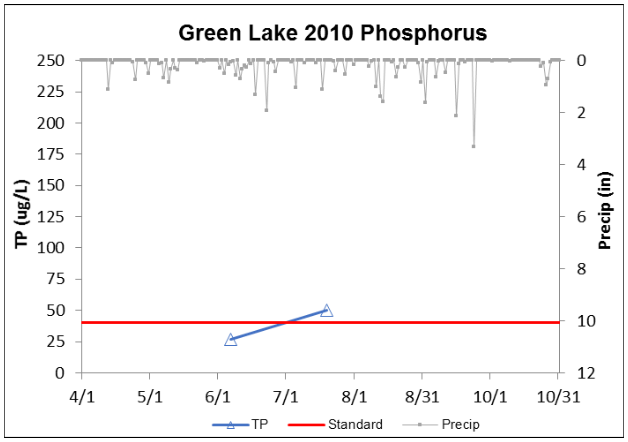

Green Lake 2005 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

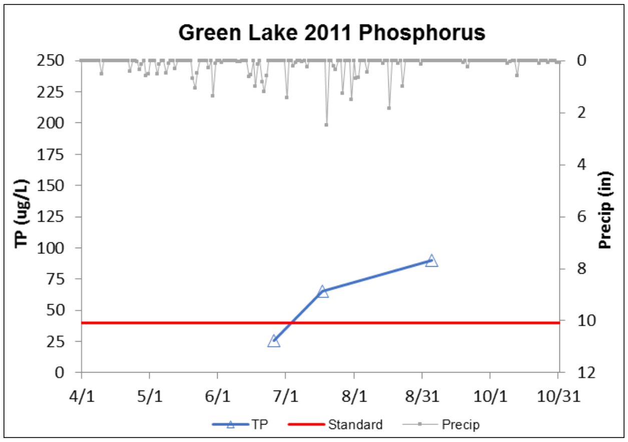

Green Lake 2006 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

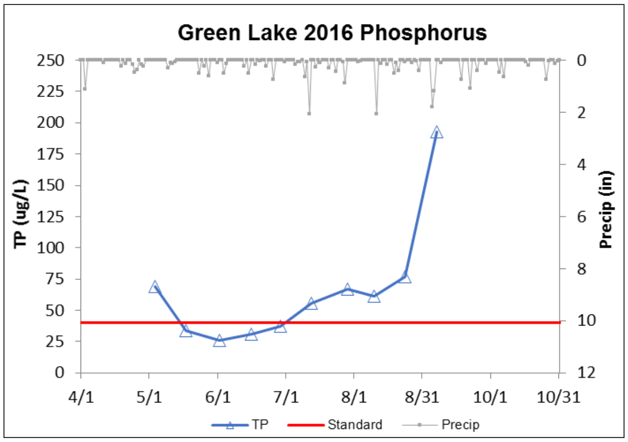

Green Lake 2007 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

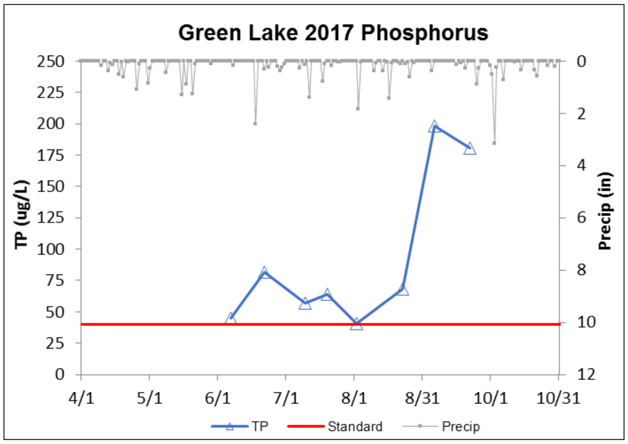

Green Lake 2008 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

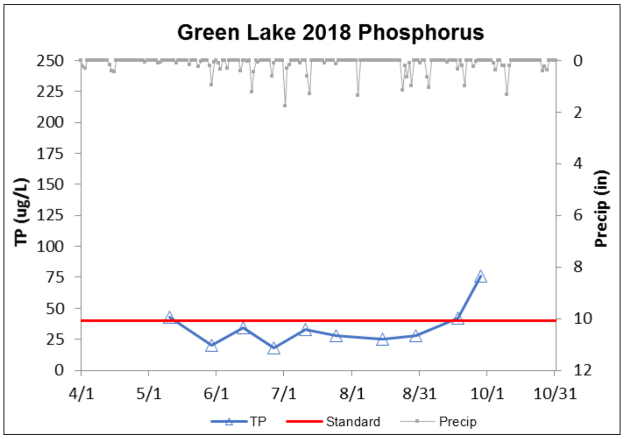

Green Lake 2009 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

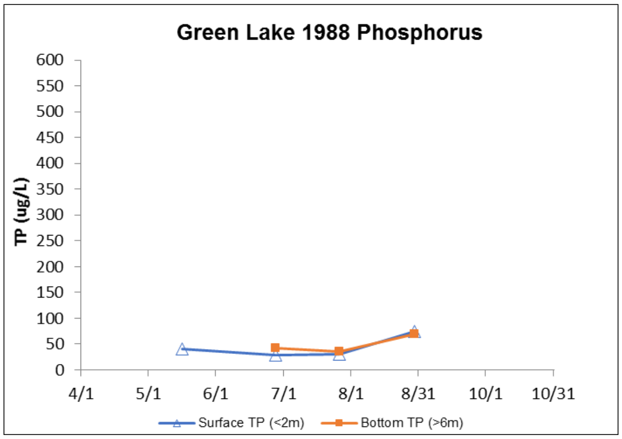

Green Lake 2010 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

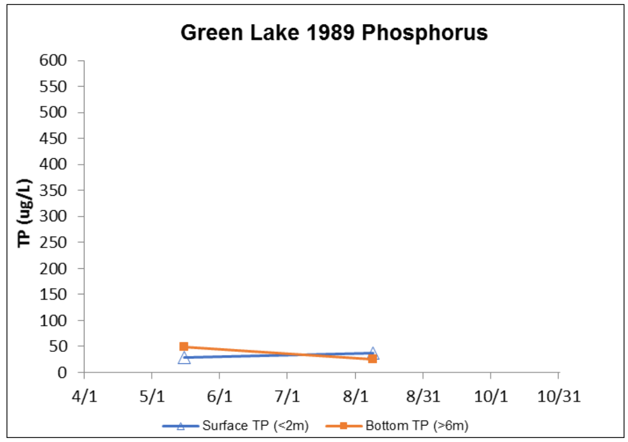

Green Lake 2011 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

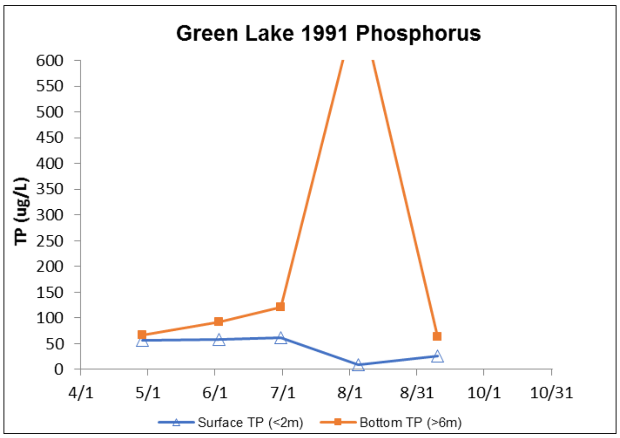

Green Lake 2016 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

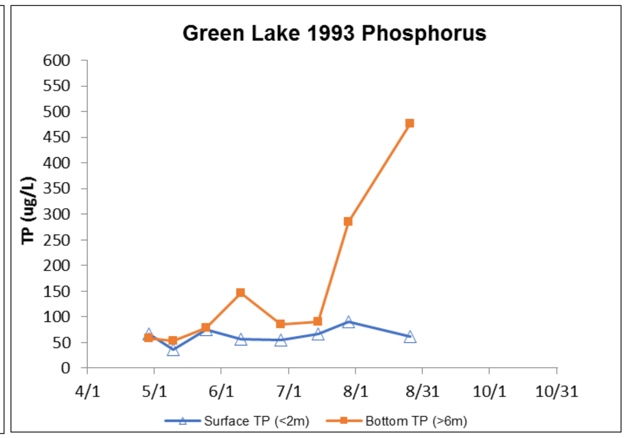

Green Lake 2017 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip

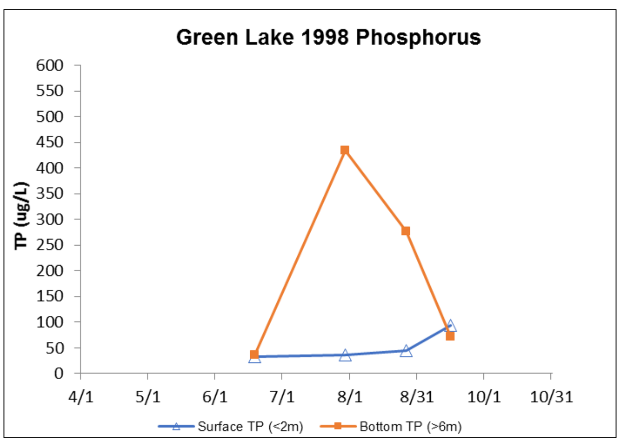

Green Lake 2018 Phosphorus
TP (ug/L)
Precip (in)
TP
Standard
Precip


Green Lake 1988 Phosphorus
TP (ug/L)
0
50
100
150
200
250
300
350
400
450
500
550
600
4/1
5/1
6/1
7/1
8/1
8/31
10/1
10/31
Surface TP (<2m)
Bottom TP (>6m)


Green Lake 1989 Phosphorus
TP (ug/L)
0
50
100
150
200
250
300
350
400
450
500
550
600
4/1
5/1
6/1
7/1
8/1
8/31
10/1
10/31
Surface TP (<2m)
Bottom TP (>6m)

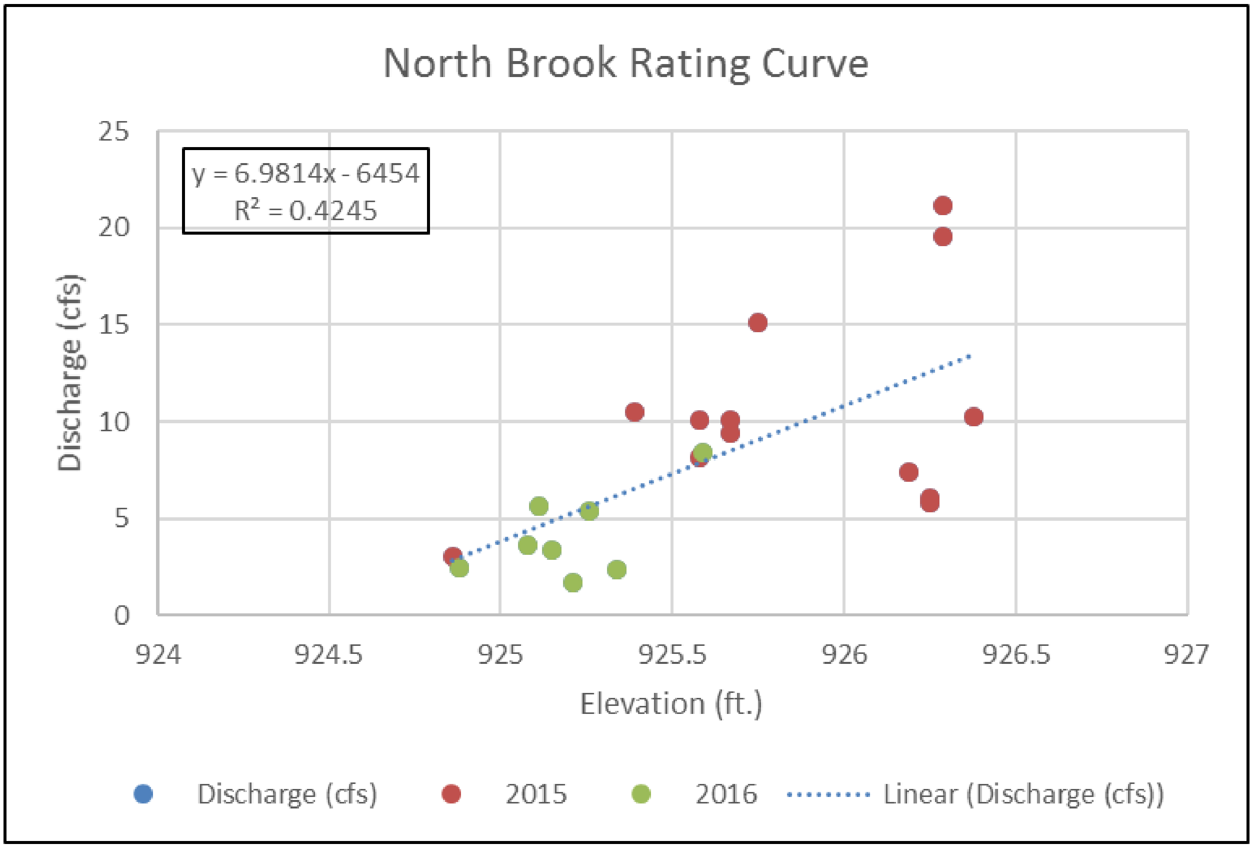

Green Lake 1991 Phosphorus
TP (ug/L)
0
50
100
150
200
250
300
350
400
450
500
550
600
4/1
5/1
6/1
7/1
8/1
8/31
10/1
10/31
Surface TP (<2m)
Bottom TP (>6m)


Green Lake 1993 Phosphorus
TP (ug/L)
0
50
100
150
200
250
300
350
400
450
500
550
600
4/1
5/1
6/1
7/1
8/1
8/31
10/1
10/31
Surface TP (<2m)
Bottom TP (>6m)

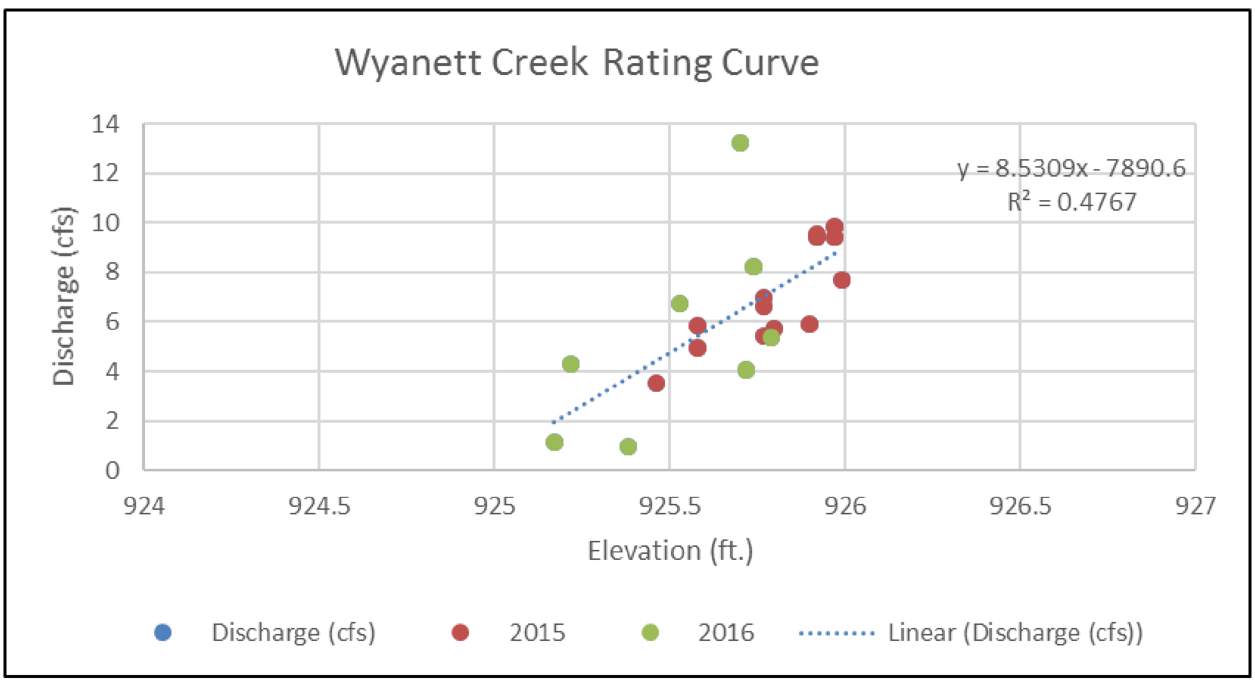

Green Lake 1998 Phosphorus
TP (ug/L)
0
50
100
150
200
250
300
350
400
450
500
550
600
4/1
5/1
6/1
7/1
8/1
8/31
10/1
10/31
Surface TP (<2m)
Bottom TP (>6m)

Attachment B

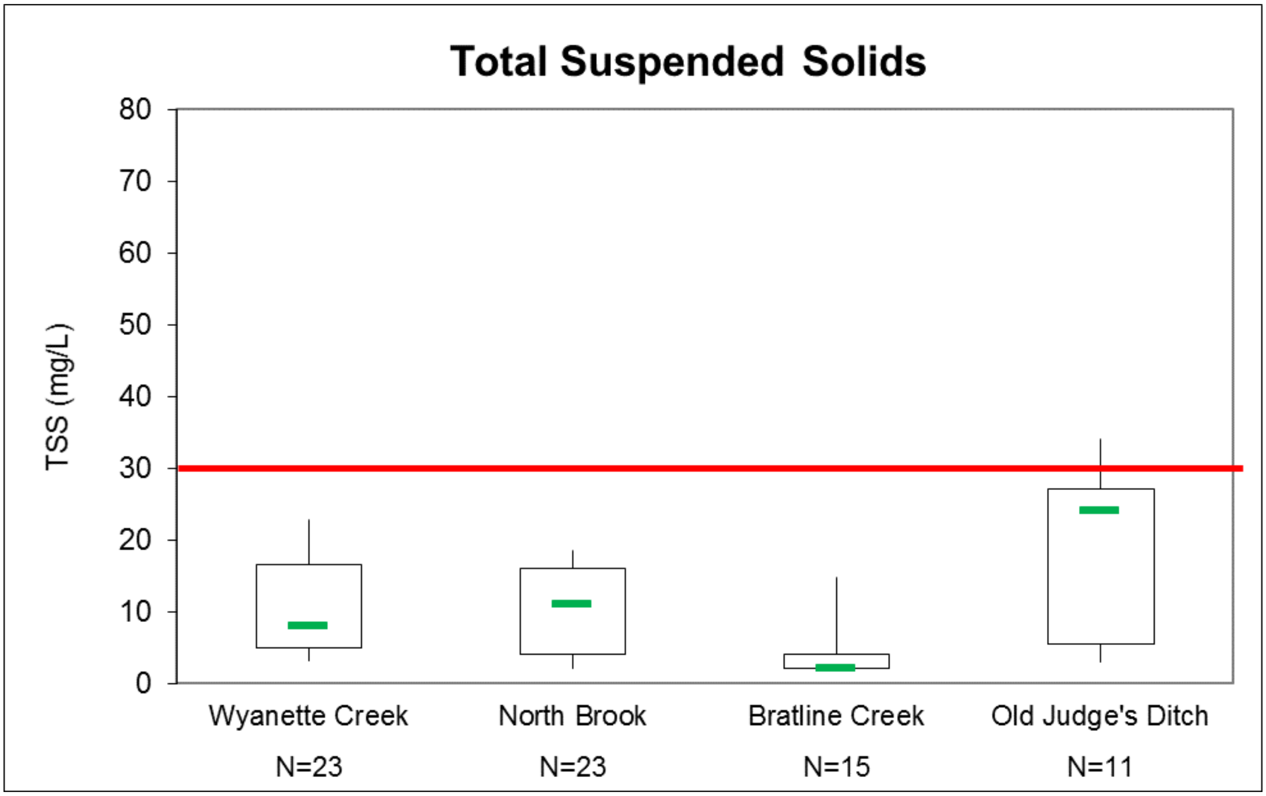
Green Lake Tributary Stage-Discharge Relationships and Water Quality Monitoring Summary

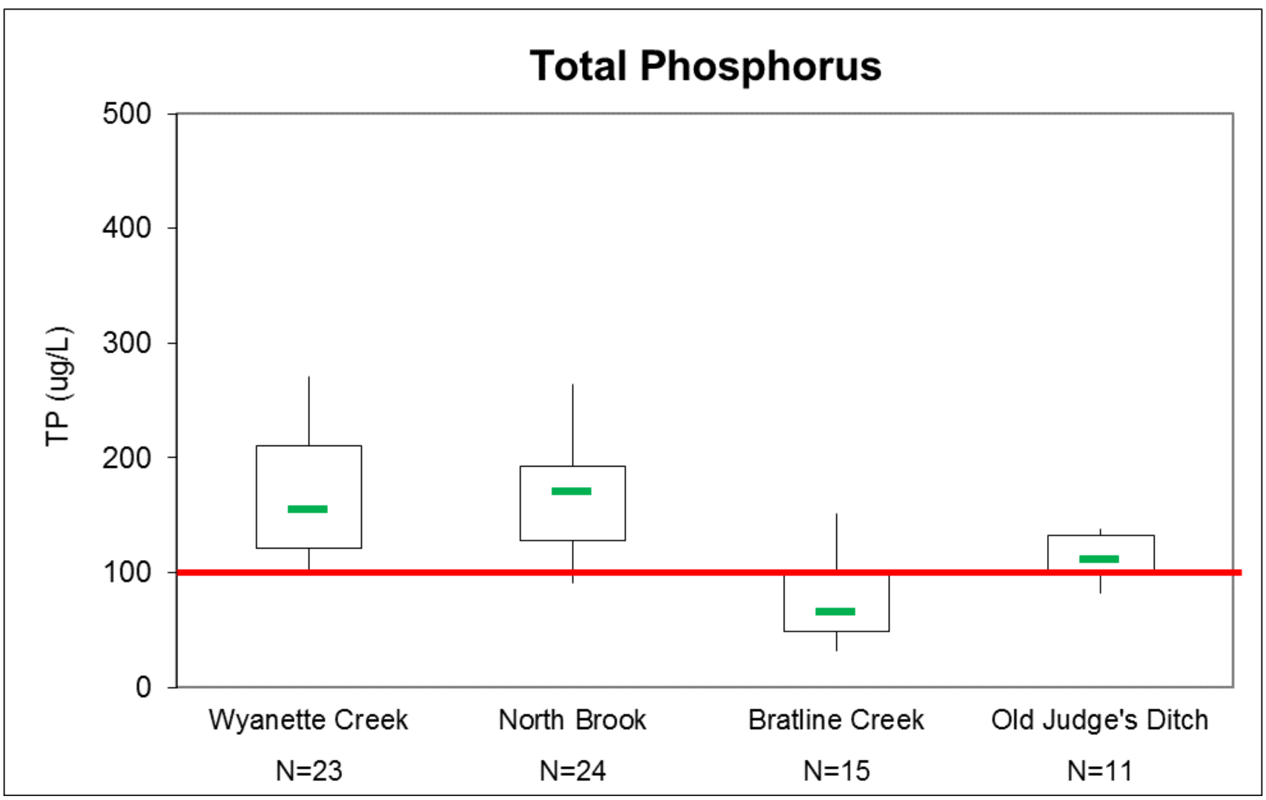


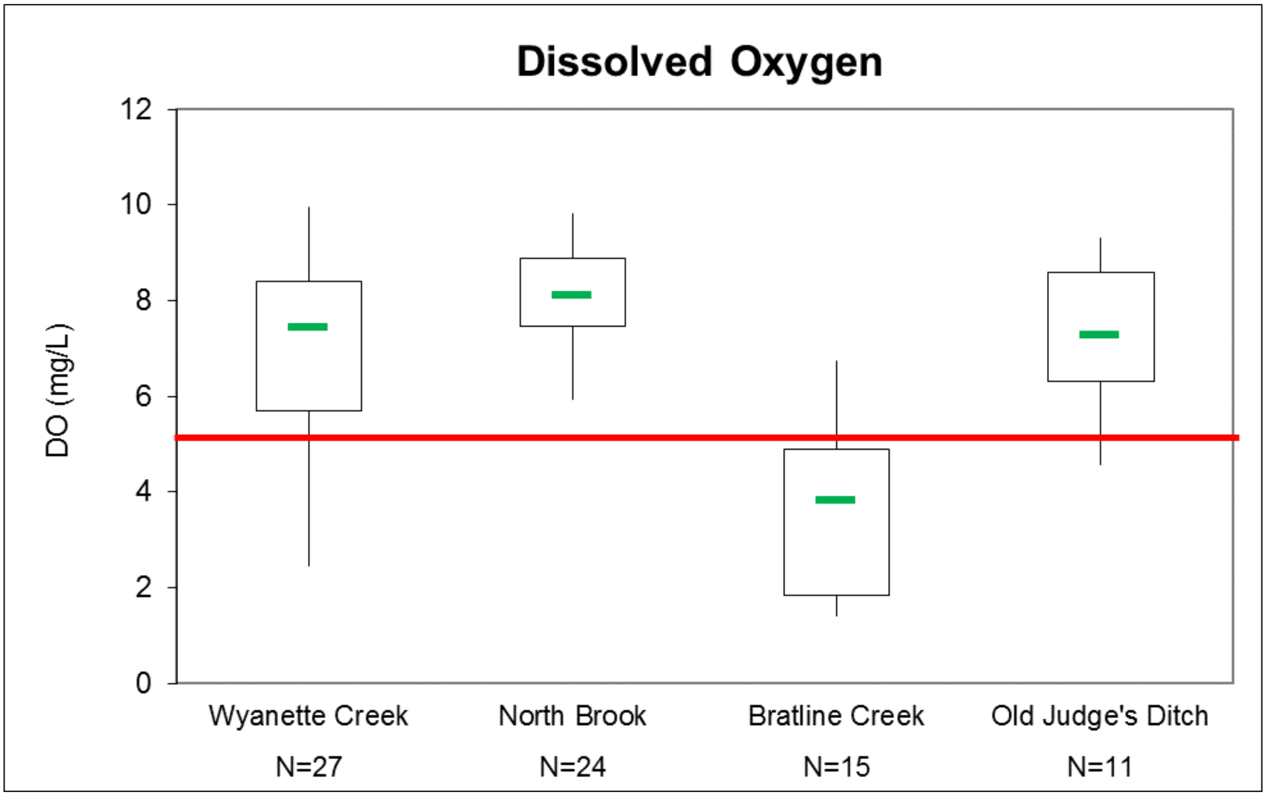
North Brook Rating Curve
y = 6.9814x - 6454
R² = 0.4245
Discharge (cfs)
0
5
10
15
20
25
924
924.5
925
925.5
926
926.5
927
Elevation (ft.)
Discharge (cfs)
2015
2016
Linear (Discharge (cfs))



Wyanett Creek Rating Curve
y = 8.5309x - 7890.6
R² = 0.4767
Discharge (cfs)
0
2
4
6
8
10
12
14
924
924.5
925
925.5
926
926.5
927
Elevation (ft.)
Discharge (cfs)
2015
2016
Linear (Discharge (cfs))


Total Suspended Solids
TSS (mg/L)
80
70
60
50
40
30
20
10
0
Wyanette Creek
N=23
North Brook
N=23
Bratline Creek
N=15
Old Judge's Ditch
N=11


Total Phosphorus
TP (ug/L)
500
400
300
200
100
0
Wyanette Creek
N=23
North Brook
N=24
Bratline Creek
N=15
Old Judge's Ditch
N=11


Dissolved Oxygen
DO (mg/L)
12
10
8
6
4
2
0
Wyanette Creek
North Brook
Bratline Creek
Old Judge's Ditch
N=27
N=24
N=15
N=11

Attachment C

Updated Lake Response Model Documentation

Input Parameters

Lake Name:	Green Lake	
Model Year:	Average	[2016, 2017, 2018]

Average Loading Summary for Green Lake

	Water Budgets				Phosphorus Loading		
Inflow from Drainage Areas							
		Drainage Area	Runoff Depth	Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name	[acre]	[in/yr]	[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1	Wyanett Creek	5,506	3.1	1,425	194	1.0	753
2	North Brook	4,779	2.4	939	171	1.0	438
3	Bratlin Creek	1,959	3.1	507	87	1.0	120
4	Old Judge's Creek	1,936	3.1	501	141	1.0	193
5	Direct (Remainder)	869	3.1	225	114	1.0	70
6							
	Summation	*15,049*	2.9	*3,598.02*			*1,572.9*

Curly-leaf Pondweed							
						Loading Calibration Factor (CF)[1]	Load
	Name					[--]	[lb/yr]
1	Curly-leaf Pondweed Load					1.0	49
	Summation						*49.4*

Failing Septic Systems							
	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1	Surrounding Lake	175	10.5	0	6%		68
2							
3							
4							
5							
	Summation	*175*	*11*	*0.0*	6%		*68.1*

Atmosphere							
	Lake Area	Precipitation	Evaporation	Net Inflow	Aerial Loading Rate	Calibration Factor	Load
	[acre]	[in/yr]	[in/yr]	[ac-ft/yr]	[lb/ac-yr]	[--]	[lb/yr]
	833	32.0	32.0	0.00	0.24	1.0	199.2
		Dry-year total P deposition =			0.222		
		Average-year total P deposition =			0.239		
		Wet-year total P deposition =			0.259		
		(Barr Engineering 2004)					

Internal (Model Residual)							
	Lake Area	Anoxic Factor			Release Rate	Calibration Factor	Load
	[km^2]	[days]			[mg/m^2-day]	[--]	[lb/yr]
	3.37	0		Oxic		1.0	0
	3.37	46.0		Anoxic	6.0	1.0	2,064
	Summation						*2,063.7*
		Net Discharge [ac-ft/yr] =		**3,598**	**Net Load [lb/yr] =**		**3,953**

Average Lake Response Modeling for Green Lake

Modeled Parameter	Equation	Parameters	Value	[Units]
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$	as f(W,Q,V) from Canfield & Bachmann (1981)			
		C_P =	1.00	[--]
		C_{CB} =	0.162	[--]
		b =	0.458	[--]
		W (total P load = inflow + atm.) =	1,793	[kg/yr]
		Q (lake outflow) =	4.4	[10^6 m^3/yr]
		V (modeled lake volume) =	16.7	[10^6 m^3]
		T = V/Q =	3.76	[yr]
		P_i = W/Q =	404	[µg/l]
Model Predicted In-Lake [TP]			**65.3**	**[ug/l]**
Observed In-Lake [TP]			**65.3**	**[ug/l]**

Input Parameters

Lake Name:	Green Lake	
Model Year:	Updated TMDL Reductions	

Average Loading Summary for Green Lake

	Water Budgets				Phosphorus Loading		
Inflow from Drainage Areas							
	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1	Wyanett Creek	5,506	3.1	1,425	100	0.5	388
2	North Brook	4,779	2.4	939	100	0.6	256
3	Bratlin Creek	1,959	3.1	507	87	1.0	120
4	Old Judge's Creek	1,936	3.1	501	100	0.7	136
5	Direct (Remainder)	869	3.1	225	100	0.9	61
6				0	0		0
	Summation	*15,049*	*15*	*3,598.02*			*960.4*

	Curly-leaf Pondweed						
	Name					Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1	Curly-leaf Pondweed Load					1.0	49
	Summation						*49.4*

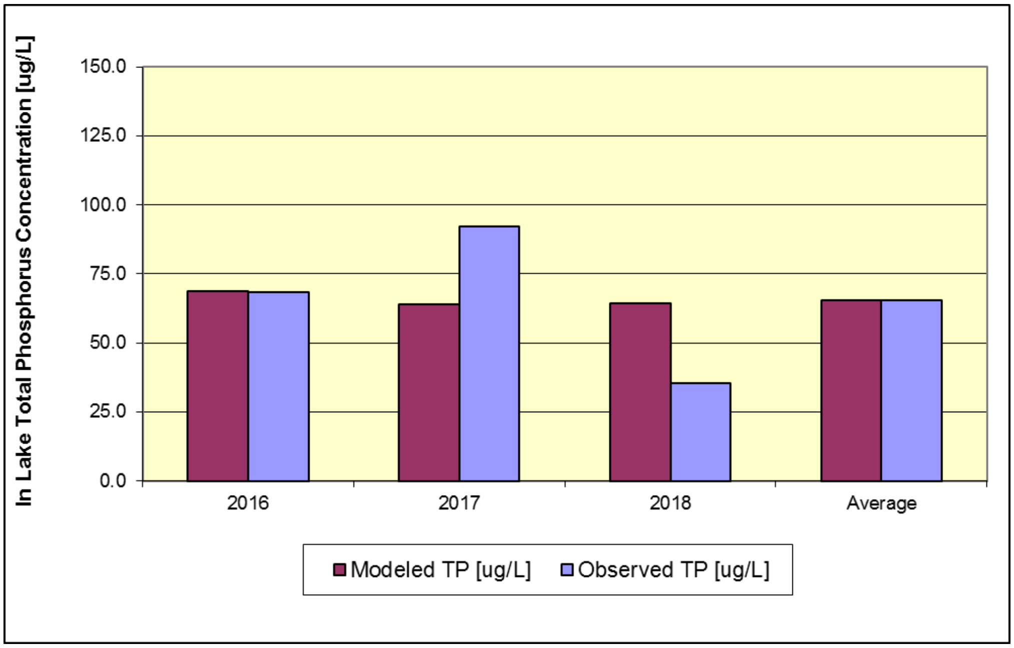
	Failing Septic Systems						
	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1	Surrounding Lake	175	0	0	0%		64
2							
3							
4							
5							
	Summation	*175*	*0*	*0.0*	0%		*63.7*

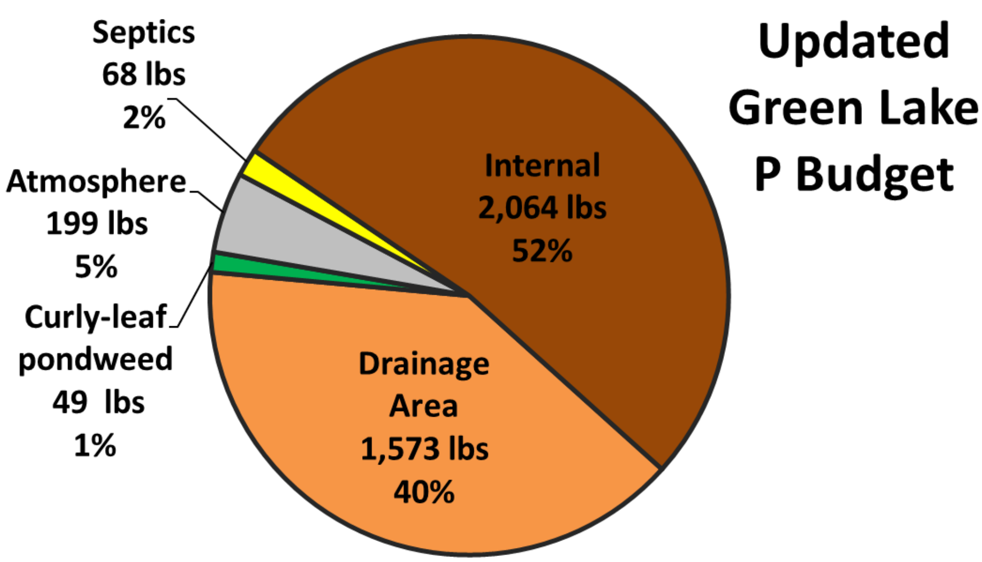
Atmosphere							
	Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
	833	32.0	32.0	0.00	0.24	1.0	199.2
		Dry-year total P deposition =			0.222		
		Average-year total P deposition =			0.239		
		Wet-year total P deposition =			0.259		
		(Barr Engineering 2004)					

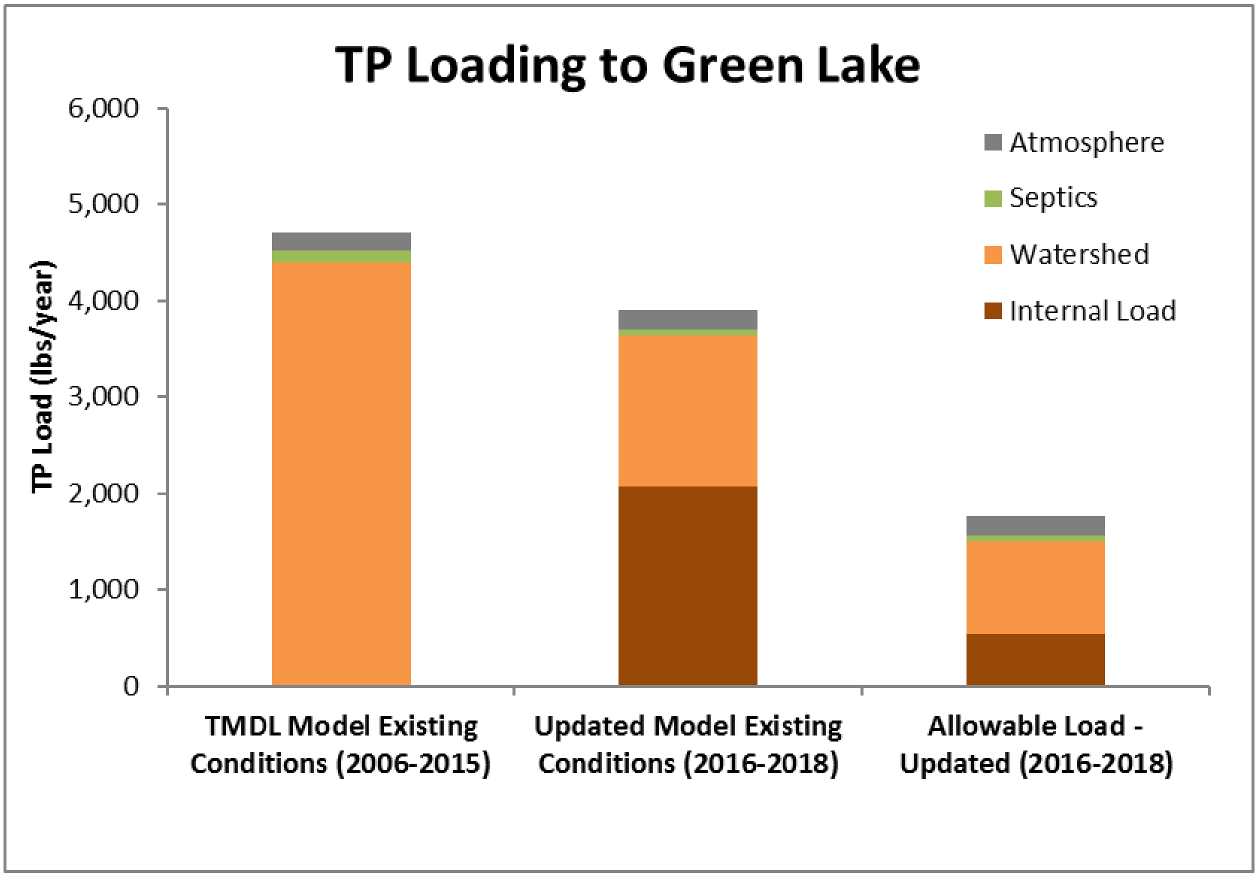
Internal (Model Residual)							
	Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
	3.37	0		Oxic		1.0	0
	3.37	46.0		Anoxic	1.6	1.0	539
	Summation						*538.9*
			Net Discharge [ac-ft/yr] =	**3,598**		**Net Load [lb/yr] =**	**1,812**

Average Lake Response Modeling for Green Lake

Modeled Parameter	Equation	Parameters	Value	[Units]
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$P = \dfrac{P_i}{1 + C_P \times C_{CB} \times \left(\dfrac{W_P}{V}\right)^b \times T}$	as f(W,Q,V) from Canfield & Bachmann (1981)			
		C_P =	1.00	[--]
		C_{CB} =	0.162	[--]
		b =	0.458	[--]
		W (total P load = inflow + atm.) =	822	[kg/yr]
		Q (lake outflow) =	4.4	[10^6 m^3/yr]
		V (modeled lake volume) =	16.7	[10^6 m^3]
		T = V/Q =	3.76	[yr]
		P_i = W/Q =	185	[µg/l]
Model Predicted In-Lake [TP]			**40.0**	**[ug/l]**
Observed In-Lake [TP]			**65.3**	**[ug/l]**


In Lake Total Phosphorus Concentration [ug/L]
150.0
125.0
100.0
75.0
50.0
25.0
0.0
2016
2017
2018
Average
Modeled TP [ug/L]
Observed TP [ug/L]


Septics
68 lbs
2%
Atmosphere
199 lbs
5%
Curly-leaf
pondweed
49 lbs
1%
Internal
2,064 lbs
52%
Drainage
Area
1,573 lbs
40%
Updated
Green Lake
P Budget



TP Loading to Green Lake
6,000
5,000
4,000
3,000
2,000
1,000
0
TP Load (lbs/year)
Atmosphere
Septics
Watershed
Internal Load
TMDL Model Existing Conditions (2006-2015)
Updated Model Existing Conditions (2016-2018)
Allowable Load - Updated (2016-2018)