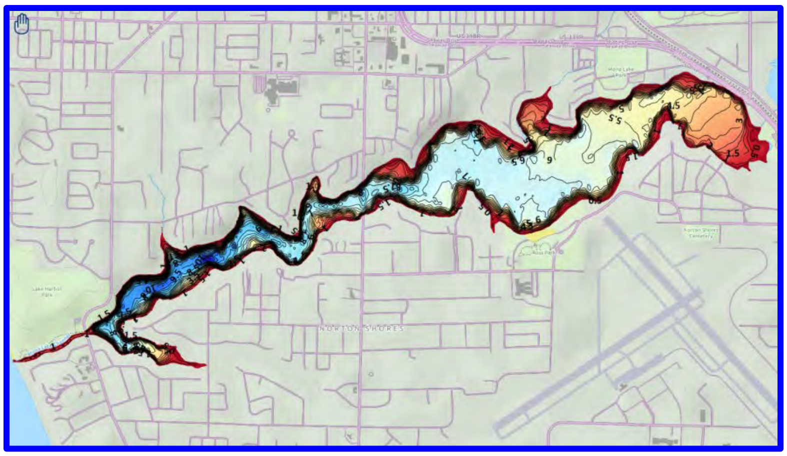
Water Quality Studies, Mathematical Modeling and Recommendations for Trophic State Management in Mona Lake, Michigan

Executive Summary

Hayden Henderson and Martin T. Auer

Department of Civil & Environmental Engineering and Great Lakes Research Center
Michigan Technological University
Houghton, MI 49931

Abstract. Mona Lake is a drowned river mouth system located in Muskegon County, Michigan. The lake is riverine in morphology and shallow, grading in depth from 4 m in the east to 11 m in the west at the channel outflow to Lake Michigan. It's shallow depth and main axis orientation parallel to prevailing winds makes it vulnerable to mixing events. The residence time of the system is seasonally variable, with fast flushing in the spring (<35 days) and slow flushing in summer (>100 days). The watershed is predominantly agricultural in its eastern portion, forested in mid-watershed and residential - commercial to the west. Two tributaries, Black Creek and Little Black Creek, account for 86% of the hydrologic input.



Mona Lake has been eutrophic to hypereutrophic for decades and remains so today, despite marked success in reducing external phosphorus loads through wastewater diversion and effluent land application. The response to management has been retarded by the presence of legacy sediment deposits of organic matter and phosphorus leading to bottom water oxygen depletion and the attendant release of phosphorus from those sediments. The wind-driven mixing of surface and bottom waters stimulating algal blooms. Water quality in spring, prior to the onset of thermal stratification, is mediated by tributary phosphorus inputs. In summer and early fall, sediment phosphorus release and mixing of the nutrient to surface waters dominates.

Field monitoring and mathematical modeling by Michigan Tech, informed by study of prior studies, have resulted in a prioritization of management options seeking to reclaim the lost beneficial uses accompanying the eutrophication process. These options include (1) testing and implementation of physical and/or chemical controls to eliminate sediment phosphorus release, design and implementation of best management practices to achieve a 25% reduction in tributary phosphorus loads, with particular focus on the Black Creek watershed and (3) remediation of a localized source of phosphorus presently discharged to Little Black Creek.

Introduction

Mona Lake is located in Muskegon County, Michigan between the cities of Norton Shores (on the south) and Muskegon Heights (on the north). The lake occupies less than 2% of its 184 km^2 watershed. The drainage basin is predominantly agricultural in its eastern portion, forested in mid-watershed and residential/commercial to the west (Figure 1). Two tributary streams, Black Creek and Little Black Creek account for 77 and 9% of the lake's hydrologic input. Inflows are greatest in the late winter and early spring and decline precipitously in summer before returning to higher flows in fall (Figure 2). Hydraulic residence time varies <35 days in high flow periods to 105-160 days during summer low flows (Evans 1992). Because of this variability in residence time, water quality in the lake is strongly influenced by tributary inputs in the spring and by in-lake processes in the summer. Mona Lake discharges to Lake Michigan through a shallow channel approximately 0.5 km in length.

Mona Lake is a drowned river mouth system. Such lakes were formed when glaciation lowered water levels in Lake Michigan and tributary scour carved out its valley. Subsequently, water levels in Lake Michigan rose (glacial rebound), 'drowning' the river mouth and leading to the conditions of morphometry and bathymetry approximating those of Mona Lake today. The lake has an average width of 0.5 km, a length of 6.5 km and is oriented east-west making it vulnerable to prevailing winds off of Lake Michigan. The riverine nascence of Mona Lake has resulted in a depth gradient proceeding from shallow depths (4-6 m) in the eastern and mid-lake portions increasing to 8-11 m in the west. The lake has mean and maximum depths of 4.5 and 8.5 m, respectively. This bathymetric gradient results spatially in two thermal regimes: completely mixed in the east and thermally stratified in the mid-portion and west (Figure 3). The completely mixed regime of the east is maintained and the water column at mid-lake and in the west de-stratified by exposure to winds off of Lake Michigan.

Mona Lake has a long history of water quality degradation related to discharges from industrial sources and, particularly, inputs of treated and untreated municipal wastewaters (Freedman et al., 1979; Steinman et al., 2007). These sources discharged phosphorus at levels stimulating eutrophication and its attendant manifestations (an abundance of algae and attendant poor water clarity in surface waters and oxygen depletion in bottom waters).

Figure 1. Land use/cover for the Mona Lake watershed, 1997.

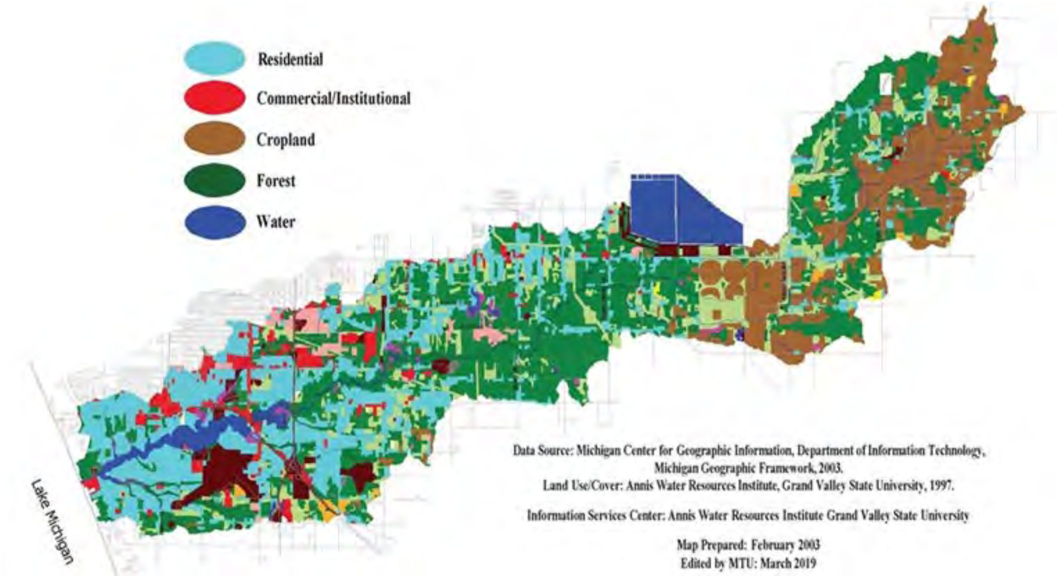


Figure 2. Total tributary flow to Mona Lake in 2017 and 2018.

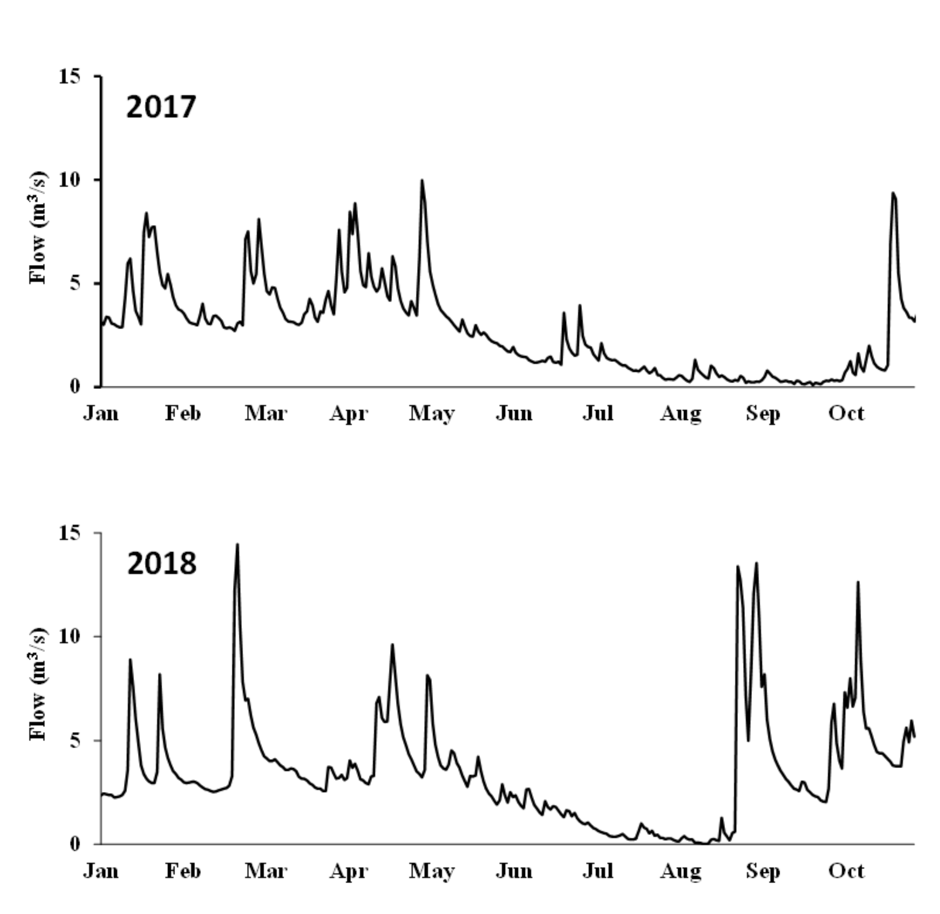
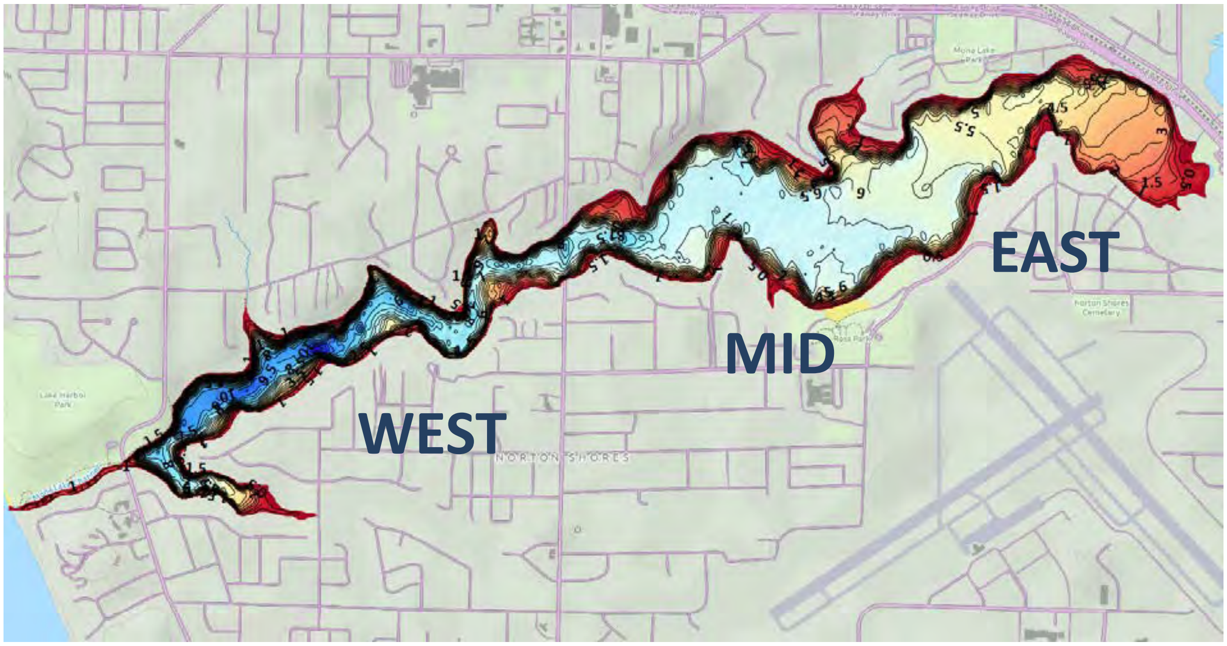


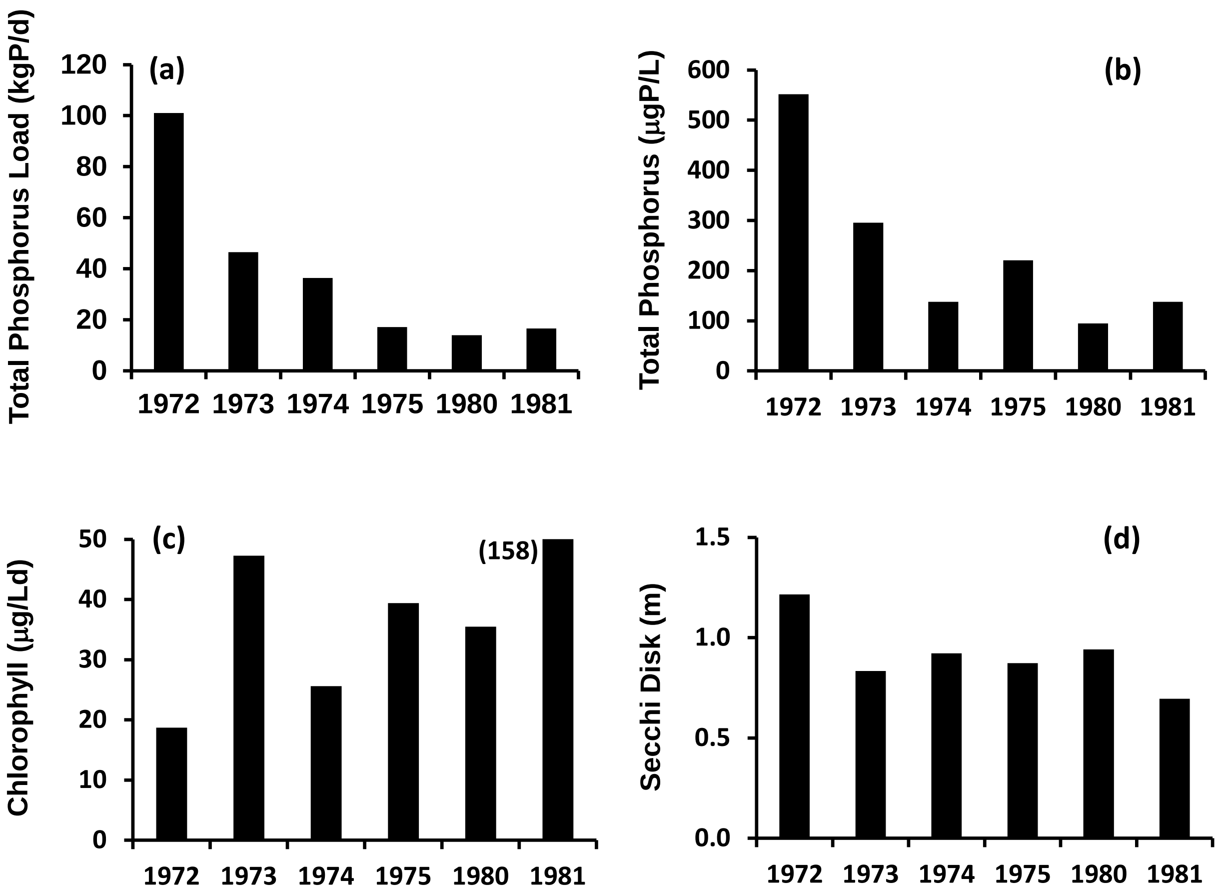
Figure 3. Mona Lake morphometry and bathymetry.



Muskegon County implemented a program of wastewater diversion – spray irrigation in 1973 (completed in 1974) to address problems with excessive algal growth in Mona, Muskegon and White Lakes. In the case of Mona Lake, diversion led to closure of the Muskegon Heights wastewater treatment plant which had discharged to Mona Lake through Little Black Creek (Freedman et al., 1979; D. Johnson, Muskegon County, personal communication). Effluent from the new, centralized facility was discharged to Muskegon Lake through Mosquito Creek (later via the Muskegon River) and to Mona Lake through Black Creek; the latter discharge was discontinued in 2010 (D. Johnson, Muskegon County, personal communication).

Prior to implementation, surface water total phosphorus concentrations in Mona Lake reached a maximum of 535 μgP/L with chlorophyll concentrations greater than 100 μg/L; well above the criteria for hypereutrophy (>50 μgP/L for total phosphorus and >22 μg/L for chlorophyll; Fuller and Jodoin 2016). The diversion resulted in a progressive reduction in total phosphorus loads to Mona Lake of 66-81% over the period 1972-1975 (Figure 4a; Limno-Tech, 1982). Yet, total phosphorus concentrations remained high in the post-diversion period, averaging 142 μgP/L for the 1974-1975 and 1980-1981 intervals (Figure 4b); well above the

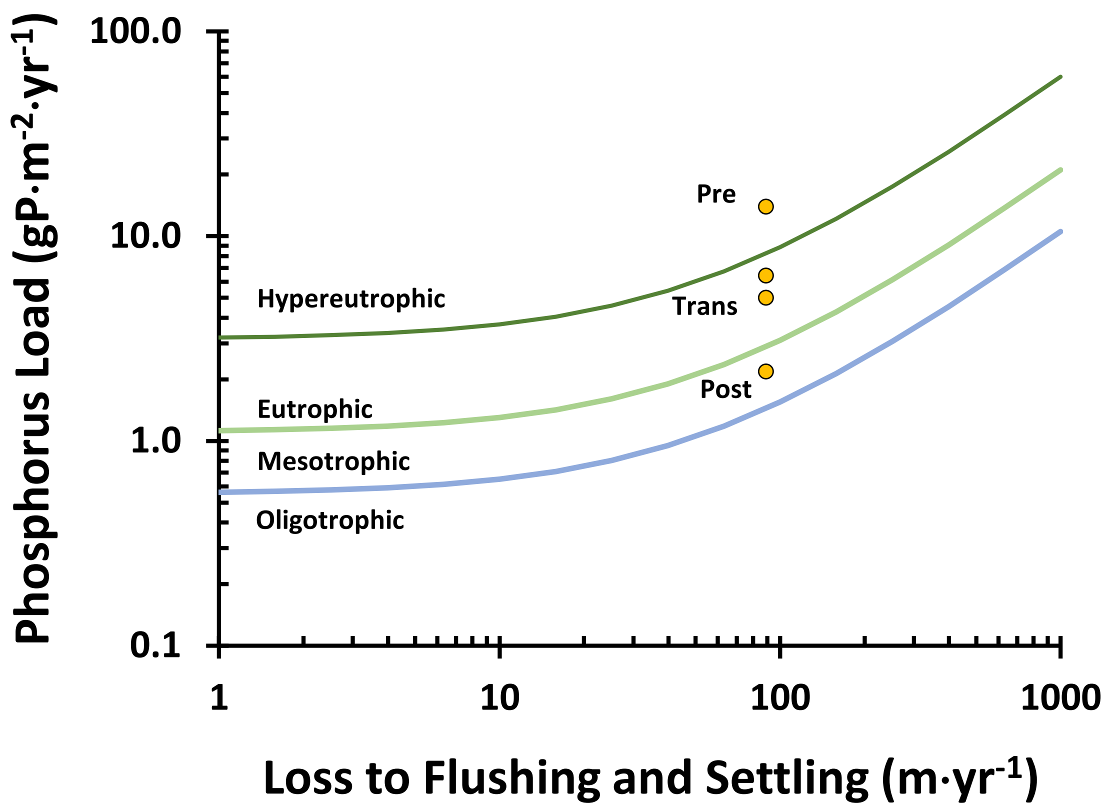
Figure 4. Phosphorus loads and water quality in the pre- and post-diversion period. Data extracted and re-drawn from Limno-Tech (1982).



lower boundary for hypereutrophy. Similarly, chlorophyll levels remained high in this period, averaging 82 μg/L, more than three times the lower boundary value for hypereutrophy (Figure 4c). Finally, water clarity worsened post-diversion, with Secchi disk transparency dropping from 1.2 m pre-diversion to 0.8 m over the post-diversion averaging period (Figure 4d).

When applied in the context of a screening model (Figure 5; Vollenweider 1975; Chapra and Tarapchak 1976), Mona Lake would be expected to move from a status of hypereutrophy, through eutrophy, to the boundary of mesotrophic conditions following diversion. It is clear that Mona Lake remained hypereutrophic in the immediate post-diversion interval. Monitoring of the lake in 2002 and 2003 (Steinman et al., 2006) determined that surface water total phosphorus concentrations, averaging 68 μgP/L, remained in the hypereutrophic range nearly three decades following diversion. With mesotrophic conditions (consistent with stakeholder

Figure 5. Screening model plot of trophic state response to changes in the external total phosphorus load to Mona Lake. Data points represent pre-diversion (1972), transitional (1973 and 1974) and post-diversion (1975, 1980 and 1981) conditions.



objectives) predicted based on external (tributary) phosphorus inputs, attention turns to internal (sediment) phosphorus release as the process retarding recovery of the system following wastewater diversion. Steinman et al. (2009) et al. determined that phosphorus loads to Mona Lake were dominated by tributary inputs in spring, but that internal sources (sediment release) contributed 68-82% of the phosphorus load in the summer and early fall seasons, periods when harmful and nuisance algal blooms typically occur. One may conclude from this that eutrophication management in Mona Lake must offer attention to both external and internal phosphorus sources.

Objectives and Approach

In 2017, Michigan Tech entered into an agreement with the Mona Lake Watershed Council to examine contemporary water quality conditions and apply mathematical models to support development of a management plan for reducing impacts of eutrophication and recovering lost beneficial uses in Mona Lake. Implementation of the landmark wastewater diversion – spray irrigation project and attendant water quality conditions are well described by Freedman et al. (1979) and Limno-Tech (1982). More recently, worked performed by the Annis Water Resources Institute has provided a solid scientific basis for understanding water quality in Mona Lake and the processes driving trophic state dynamics (see Steinman et al., 2006; 2007). The Michigan Tech project sought to build on this foundation, with the objective of prioritizing management objectives consistent with stakeholder goals for Mona Lake water quality. The approach to meeting this objective was threefold,

- Monitoring: comprehensive, eutrophication-based monitoring of Mona Lake and its tributaries was last performed more than 15 years ago. Michigan Tech conducted an event-based tributary monitoring program over the intervals Jun-Sep 2017 and Mar-Oct 2018, focusing on capturing phosphorus loads over a spectrum of flow regimes. Results from that survey were used to compare phosphorus loading rates to historical rates and to serve as drivers for mathematical model application. Lake water quality was monitored on a twice-monthly basis over these same intervals, providing a basis for examining spatiotemporal dynamics in trophic state conditions as well as data for testing model performance.

- Modeling: two model formats were applied in assessing trophic state conditions and response to management actions. The first was a total phosphorus – trophic state screening model developed by Chapra and Tarapchak (1976) in the spirit of that originated by Vollenweider (1975). The screening model is particularly useful in comparing the phosphorus load – trophic state condition of the system over a period of years, e.g., pre-diversion, post-diversion, contemporary. The second format was a one-dimensional, multilayer model (LAKE2K; Chapra and Martin 2004) that simulates vertical mass transport, temperature, dissolved oxygen, the phosphorus series (soluble reactive, (SRP, dissolved organic, DOP, particulate, PP and total, TP) and chlorophyll as driven by environmental conditions and tributary (external) sediment (internal) loads and processes. LAKE2K was tested and applied in evaluating the efficacy of a suite of engineered actions in achieving reductions in phosphorus levels and chlorophyll (algal blooms) in Mona Lake.

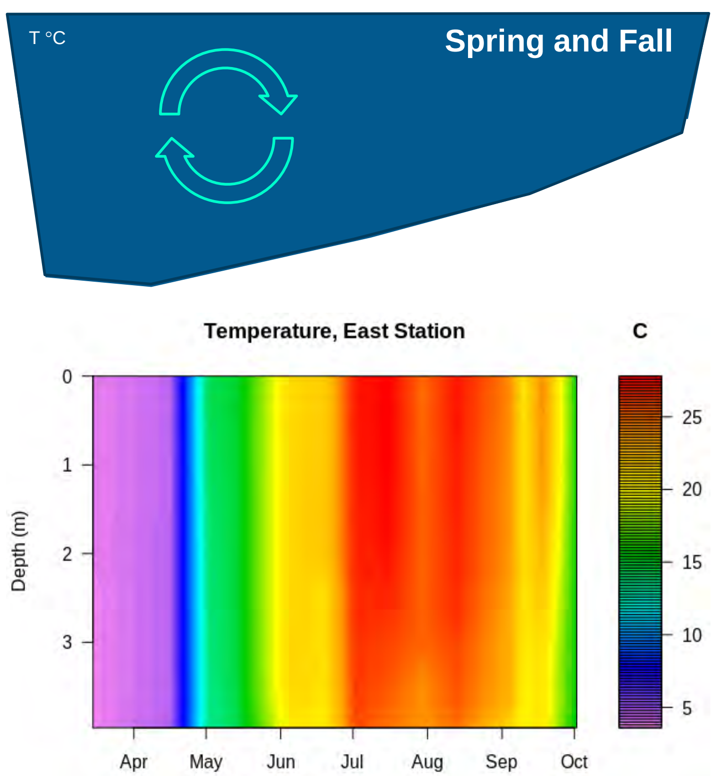
These results are then used to describe contemporary trophic state dynamics in Mona Lake, identify and characterize key processes mediating manifestations of eutrophication and prioritize management activities. Details of the methodology used for monitoring and modeling are provided by Henderson (2019).

Lake Processes and Trophic State Dynamics

Lake subject to eutrophication exhibit spatiotemporal variation in water quality, i.e., conditions that change in space (vertically over the water column and horizontally over the water body) and in time (across the seasons). The driving forces for these changes are typically meteorological, e.g., seasonal gain and loss of heat and episodic wind mixing. Here, we examine these dynamics with a focus on selected processes closely related to manifestations of eutrophication.

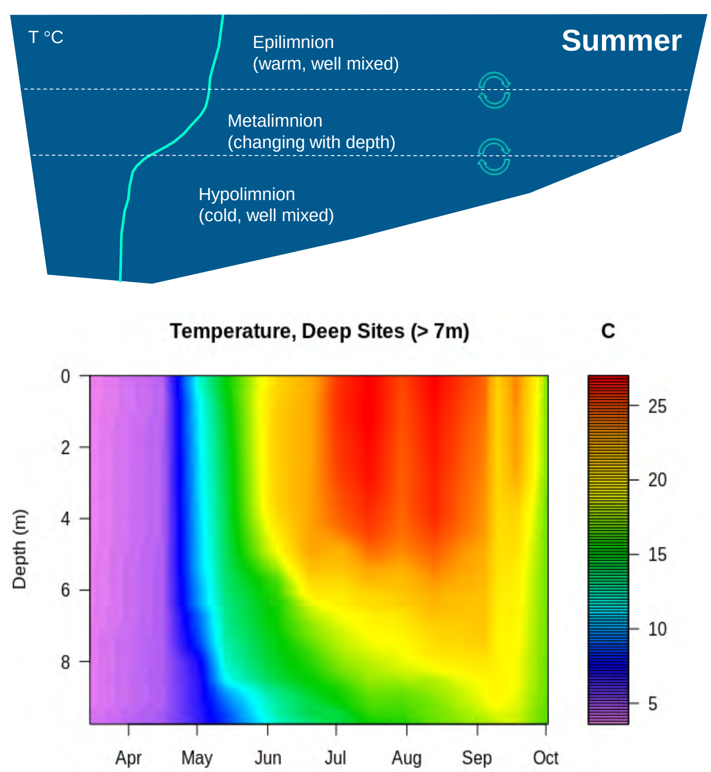
Thermal Stratification: in spring, lakes in temperate climates are cold and completely mixed vertically, i.e., isothermal (Figure 6). The lake warms as the season progresses into summer and, if the system is shallow and exposed to wind, the entire water column warms as a single body (Figure 6). Such lakes are termed polymictic as they are too shallow to resist wind-driven mixing and they remain vertically isothermal (unstratified) throughout the ice-free period.

Figure 6. The completely mixed nature of a dimictic lake in spring and fall and a polymictic lake when free of ice.



Where the system is deeper and/or less exposed to wind, warm water rides atop the cooler (more dense) water at the bottom (Figure 7). Here, the lake is said to be thermally-stratified (Figure 7), with a warm, well-mixed layer at the top (epilimnion), a layer in the middle where temperatures decline with depth (metalimnion) and a cooler, well-mixed layer at the bottom (hypolimnion). As solar input declines in fall, surface waters cool and the lake becomes near isothermal and mixes top to bottom. In winter, ice forms and the lake stratifies again, this time with the coldest (0-3 °C) and least dense water at the surface and warmer (4 °C), more dense water at the bottom because the maximum density of water occurs at 4 °C. These are termed dimictic lakes as they completely mix twice (at the summer-fall and winter spring transitions). Interestingly, Mona Lake would be considered neither wolf nor dog, exhibiting polymictic behavior in the shallow east end and dimictic behavior in the deeper mid-lake and west end (see Figure 3). This difference across the length of Mona Lake plays an important role in mediating temperature and dissolved oxygen conditions above the lake sediments.

Figure 7. The thermally stratified nature of a dimictic lake in summer. The line represents a vertical profile of temperatures ranging from ~20 °C at the surface to, typically, 4 °C at the bottom. Circling arrows indicate diffuse exchange between layers.



<u>Biogeochemical Processes:</u> overlain upon these thermal structures are a host of biogeochemical processes where microorganisms act to mediate the transformation and fate of chemical species, several of significance to eutrophication.

- *Algal Photosynthesis*: given suitable water temperatures and the availability of nutrients (phosphorus in freshwaters), algae will perform photosynthesis to the depth of light penetration (1-3 m in Mona Lake; Figure 8, upper panel). Here, the algae utilize carbon dioxide and water and use chlorophyll to capture the sun's energy (Δ), forming simple carbohydrates and producing oxygen,

$$CO_2 + H_2O + \Delta \xrightarrow{Chl} C(H_2O) + O_2$$

  The simple carbohydrates are subsequently stored for use as an energy source or used to form more complex organic matter important to plant function. Optimum temperatures, available light and an abundance of phosphorus favor photosynthesis leading to algal blooms.

- *Bacterial Respiration:* algae produced in the surface waters are ultimately flushed from the lake or settle to the bottom and incorporated in the sediments. In the sediments, the organic matter is decomposed by bacteria through the process of respiration (the opposite of photosynthesis),

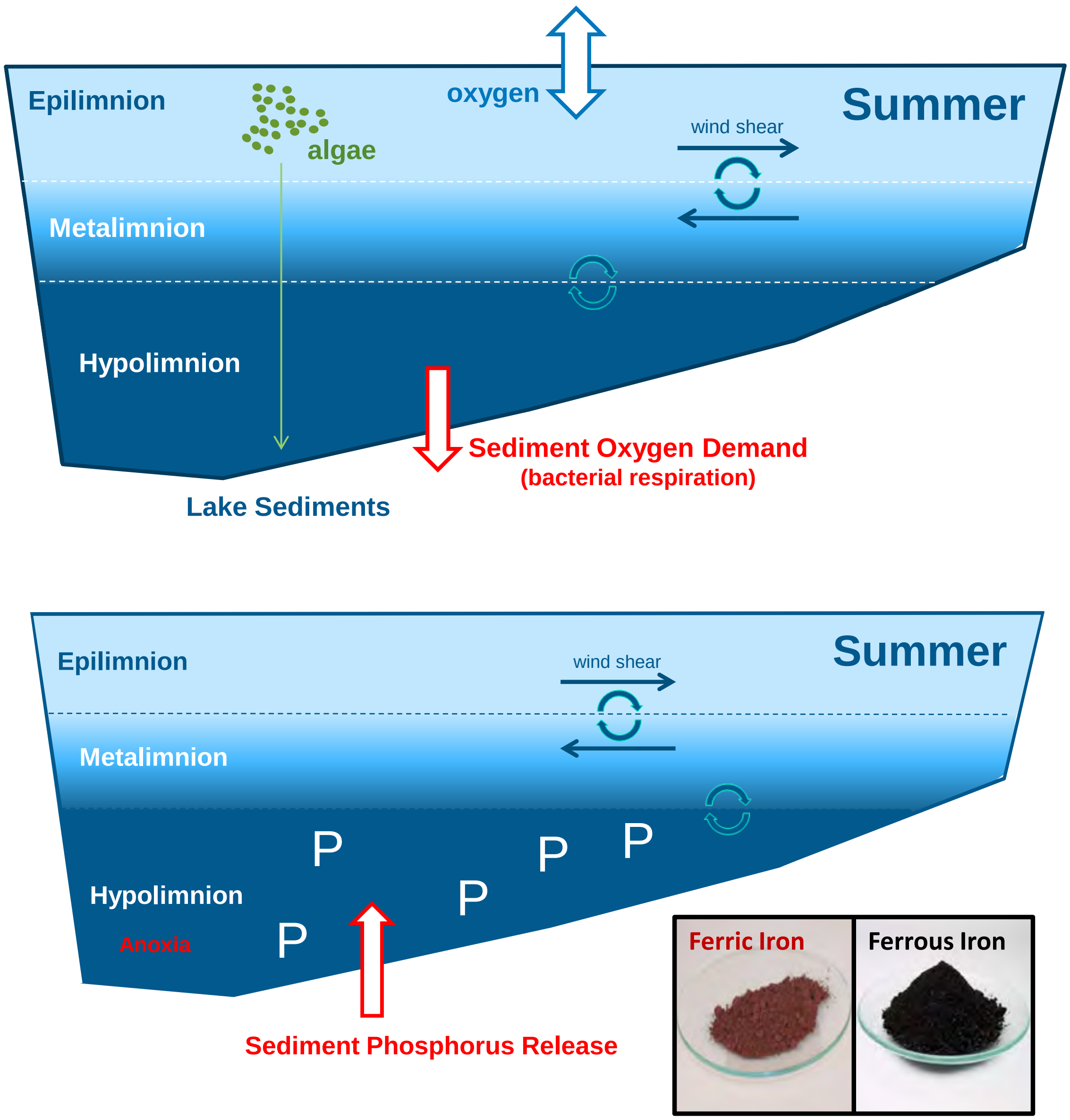
$$C(H_2O) + O_2 \rightarrow CO_2 + H_2O + \Delta$$

  Bacterial respiration in the sediment consumes oxygen which is resupplied from the water column by diffusion (Figure 8, lower panel). Where the lake muds are rich in organic matter (abundant algae) this sediment demand can consume oxygen faster than it can be replenished from the surface waters in contact with the atmosphere (limited vertical mass transport during thermal stratification). In Mona Lake, the unfavorable balance between consumption and resupply of oxygen results in depletion and, ultimately, hypoxia.

- *Iron-Phosphorus Chemistry:* phosphorus associated with algae, soil particles and detritus deposited to the bottom muds can lead to P-enriched sediment. When oxygen is present in the water overlying the sediment, phosphorus is complexed by the ferric form of iron and remains in place. In the absence of oxygen, iron is converted to the ferrous form and phosphorus is released to the sediment pore water where it can diffuse into the hypolimnion (Figure 8, lower panel inset).

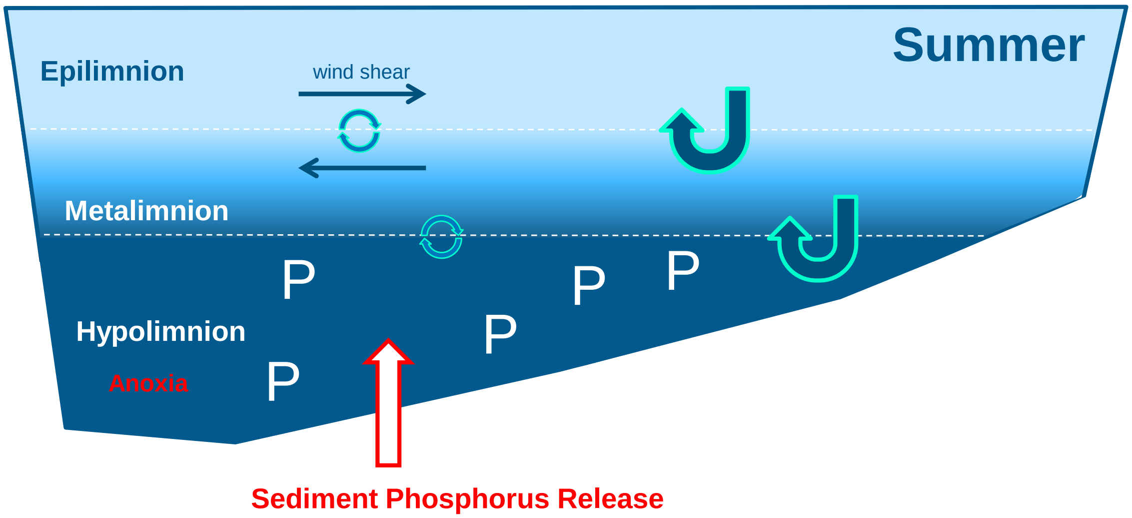
<u>Mixing and Mass Transport:</u> density (temperature) differences in the water column tend to resist mixing, maintaining the thermal structure characteristic of the stratified period. This resistance dampens mixing between the layers and limits (but does not fully block) exchange of, heat, oxygen and phosphorus. Thus the lake is well-mixed vertically during the isothermal

Figure 8. Top panel: algae growing in the surface waters settle to the bottom and are decomposed by bacteria creating a sediment oxygen demand. Oxygen enters the surface waters (reaeration) and is transported downward by wind-induced diffusion. Where sediments are rich in organic matter (algae), oxygen depletion occurs and the hypolimnion becomes anoxic (no oxygen). Bottom panel: under anoxic conditions phosphorus-binding ferric iron is converted to ferrous iron and the phosphorus is released (inset), accumulating in the hypolimnion and diffusing into the epilimnion where it can support algal growth.



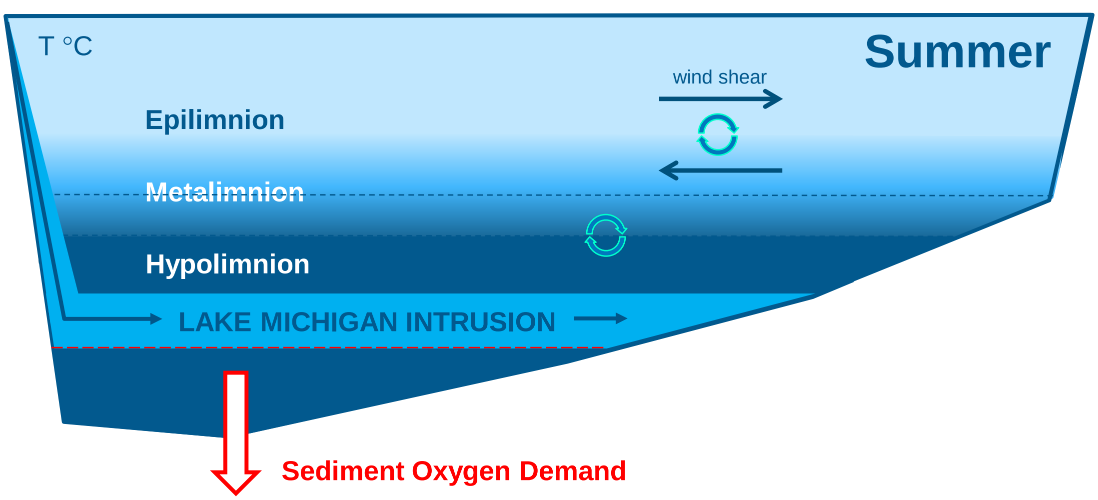
spring and fall periods and much less so during the summer stratified period. Over much of the summer vertical mixing proceeds continuously at a low intensity. In Mona Lake, with its major axis oriented with prevailing westerlies, high wind events can cause a high degree of mixing and partially or fully destratifying the lake. Both low and high intensity mixing are examples of entrainment (Figure 9) where the upper layers capture hypolimnetic water and chemical constituents, e.g. phosphorus resident there. The entrainment process can also deliver oxygen to the bottom waters, but such additions are quickly depleted by sediment oxygen demand.

Figure 9. Wind-driven vertical mass transport action through diffusive mixing (low winds) and episodic mixing across layers (high winds).



In addition to thermal stratification and entrainment, physical conditions in Mona Lake are potential influenced by intrusions. Here, cooler water from Lake Michigan migrates up the outlet channel and enters the lake, diving until it reaches a point of neutral density governed by its temperature and that of the water column (Figure 10). It is hypothesized that intrusions

Figure 10. An intrusion forming a new boundary to mixing within the hypolimnion.



place a lid on mass transport, reducing the size of the hypolimnion, hastening oxygen depletion and accumulation of phosphorus. It is the interplay of these physical phenomena and biogeochemical processes that gives rises to the spatiotemporal dynamics in causal factors and in-lake response typifying eutrophication and its manifestations.

Insights from Tributary Monitoring

Hydraulic and Phosphorus Loads

Four tributaries (Figure 11) accounted for 98% of the flow entering Mona Lake in 2017 and 2018 : Black Creek (77%), Little Black Creek (9%), Cress Drain (6%), Ellis Drain (6%) and several minor streams (2%). Flows are greatest in the Oct – May interval with markedly lower discharges in Jun – Sep (see Figure 2). Hydraulic residence time for this period ranged from 36 days under high flows to 122 days under low flows, with an annual average of 50 days. This flow regime leads to tributary dominance of phosphorus loads in spring (Figure 12) with rapid flushing of overwinter conditions from the lake. Considerable interannual variation in the total phosphorus load to Mona Lake was observed over the 2008-2018 period, driven by differences in tributary flow (Figure 13). Note, however, the similarity in magnitude of load to those more immediately following diversion (1975, 1980 and 1981; (see Figure 4a). The major contributors Figure 4a). The major contributors to the total phosphorus load to Mona Lake over the 2008-2018 interval were Black Creek at 73% and Little Black Creek at 13% (Figure 14).

Figure 11. Locations of major tributaries discharging to Mona Lake with regional partitioning of the system for lake sampling.

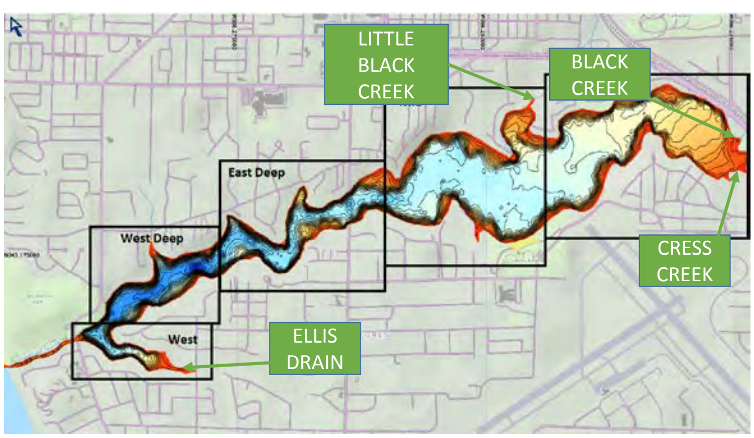


Figure 12. Total phosphorus load to Mona Lake for 2017 and 2018. Note magnitude of tributary loads in spring and fall as compared with the low-flow summer interval.

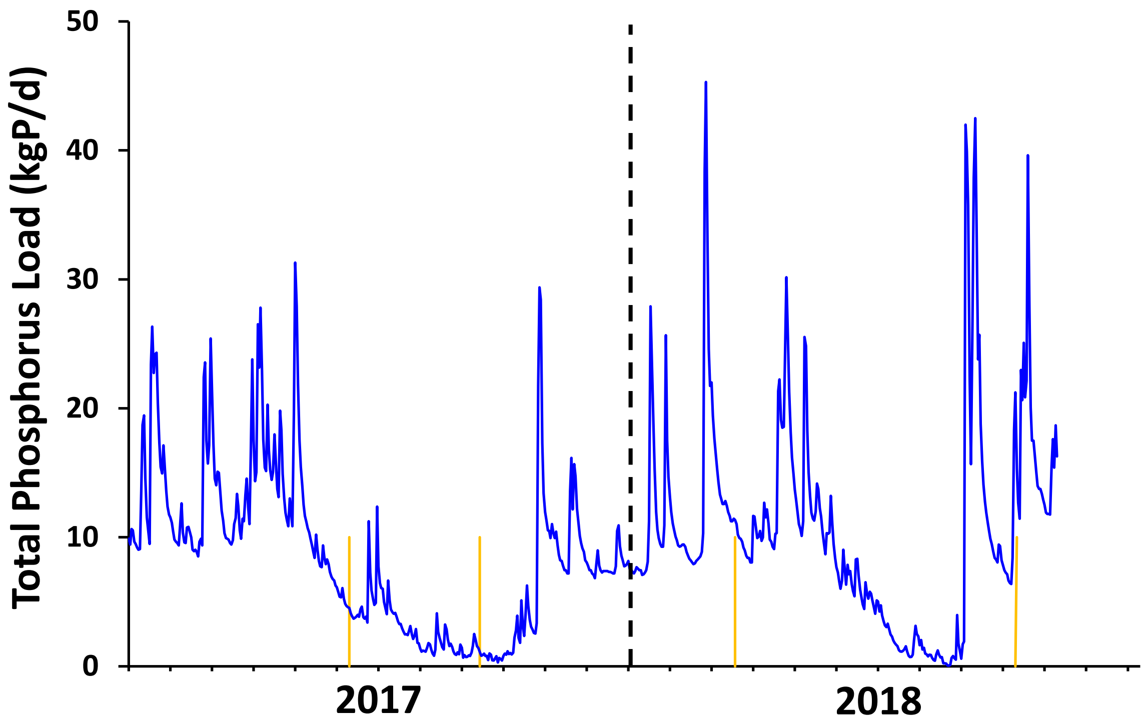


Figure 13. An 11-year calculation of total phosphorus loads to Mona Lake. Calculations are incomplete for 2018, ending in November.

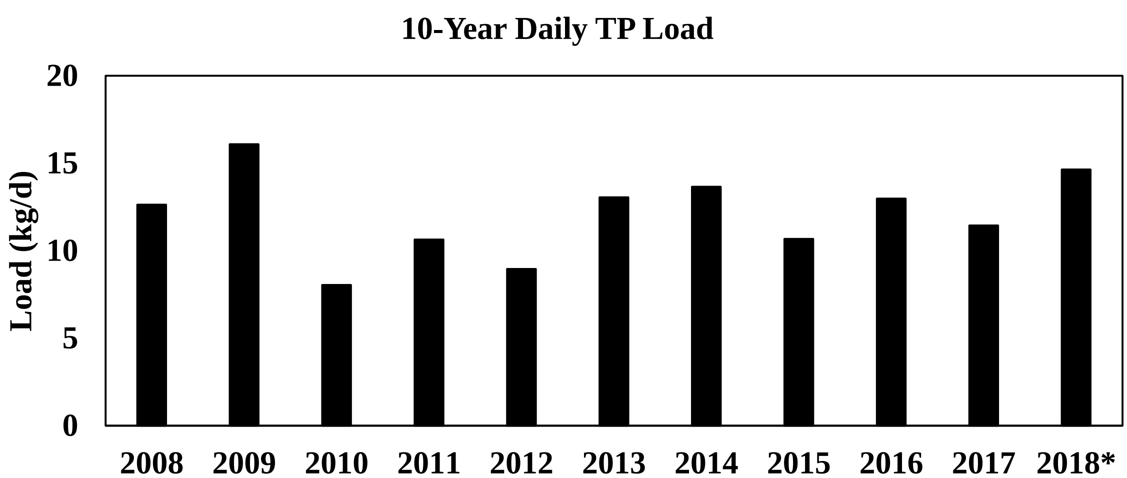
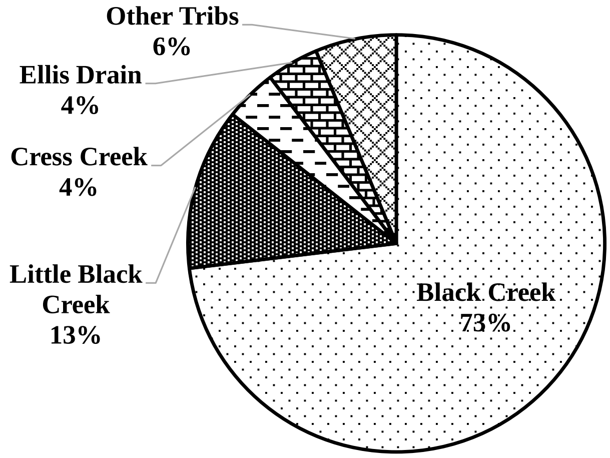


Figure 14. Contributions to the Mona Lake total phosphorus load over the 11-year period, 2008-2018.



<u>Black Creek</u>

As the largest tributary source of phosphorus to Mona Lake, Black Creek has received considerable attention with respect to remediation. Approximately 1 km upstream of its entry to the lake, Black Creek passes between two ponds (Celery Flats; Figure 15), formerly in muck farm celery production and now abandoned and flooded (Steinman and Ogdahl). The ponds have historically been drained through levee cuts providing exchange with Black Creek.

Figure 15. Location of Celery Flats relative to Black Creek and Mona Lake.

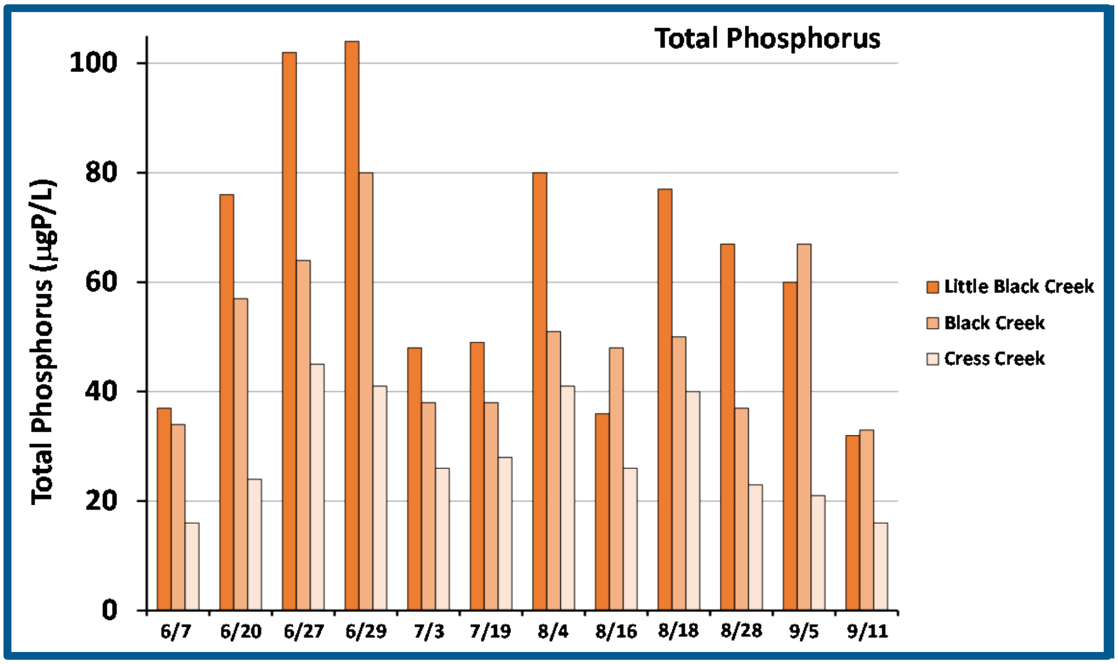
Annual mean surface water TP concentrations in the ponds ranged from 60-80 μgP/L, with bottom waters concentrations approaching 400 μgP/L (Steinman et al., 2006). Comparable total phosphorus concentrations were measured during the Michigan Tech program: 201 ± 141 and 110 ± 82 μgP/L for the North and South Ponds, respectively. Steinman and Ogdahl (2011) concluded that elevated water column levels were the result of phosphorus diffusion from Celery Flats sediments, where porewater soluble reactive phosphorus concentrations reached 1000-3000 μgP/L (Steinman and Ogdahl 2011). Total phosphorus loads from Black Creek to Mona Lake were observed to increase by a factor of 2.6 in passing along the Celery Flats levee system (Steinman and Ogdahl 2011). The increase was not attributable to changes in flow as discharge was similar at upstream and downstream sites (Steinman and Ogdahl 2011). It may be inferred, therefore, that the Celery Flats are likely to be major contributors of phosphorus to Mona Lake (Steinman and Ogdahl 2011).

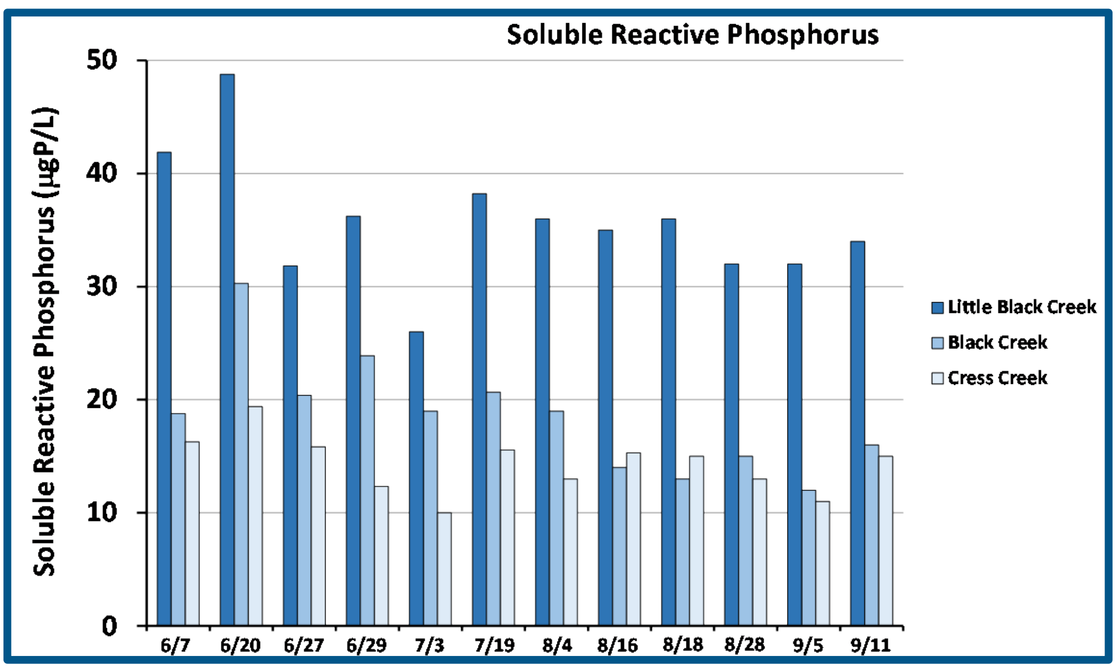
In 2015, levee cuts were filled and two discharge limiting structures were installed, one on the outlet of each pond. Measurements made during the Michigan Tech project indicated that total phosphorus concentrations averaged 40 ± 14 and 50 ± 14 μgP/L upstream and downstream of the discharge limiting structures and that this difference was not statistically significant. It could be concluded from these post-implementation measurements that the discharge limitation structures are effective in controlling phosphorus inputs from the Celery Flats to Black Creek and Mona Lake. As the Celery Flats are not continuously gaged for flow or sampled for phosphorus, we recommend implementation of continuous (flow) and flow-triggered (phosphorus) sampling to confirm the efficacy of discharge limiting structures in mitigating phosphorus loads from the Celery Flats.

Little Black Creek

At 13% of the total load, Little Black Creek represents the second largest tributary contribution of phosphorus to Mona Lake. For the 670-day period 1/1/2017 to 11/1/2018, this tributary had a soluble reactive phosphorus unit area load (kgP/ha) 31% greater than that for Black Creek and ~50% greater than that for Cress and Ellis Drains. This finding is consistent with our observations that phosphorus concentrations were regularly higher in Little Black Creek that in any of the other tributaries (Figure 16). Elevated levels of phosphorus in Little Black Creek have been noted as well in previous monitoring efforts (Freedman et al., 1979; Steinman et al., 2006).

Figure 16. Total (upper panel) and soluble reactive (lower panel) phosphorus levels in tributaries discharging to MinaLale. Note that concentrations are highest for both analytes in Little Black Creek.





Michigan Tech conducted stream surveys on Little Black Creek in an effort to identify the provenance of elevated phosphorus concentrations (Figure 17). Monitoring focused on the soluble reactive phosphorus analyte given its bioavailability to algae. As a point of reference, SRP concentrations in Black Creek and Cress Drain averaged 17 and 13 μgP/L, respectively, over the 2017-2018 monitoring. Soluble reactive phosphorus concentration ranged from 10-20 μgP/L (mean ± sd of 13.3 ± 3.6 μgP/L) over the first 550 m of Little Black Creek; comparable to background concentration in Black Creek and Cress Drain. Over the next 250 m, concentrations increase (10 → 69 → 124 → 277 μgP/L), reaching a peak just east of Roberts Street. From that point, SRP concentrations decline, presumably due to (low SRP) groundwater infiltration as Little Black Creek flows the remaining 4 km to Mona Lake.

Figure 17. Sampling stations and soluble reactive phosphorus concentrations along Little Black Creek. Markers: red > orange > yellow > blue. Green markers indicate sites identified as contaminated in MDEQ studies.

Steinman et al. (2006) referenced a number of historical sources of contamination to Little Black Creek, originally described by MDEQ (2003); however all of these sources (green dots in Figure 17) are located well downstream of observations of elevated SRP concentration. The location of peak SRP concentrations, where Little Black Creek flows under Roberts Street, has not been previously associated with any pollutant sources. However, Friedman et al. (1979) noted that Kersman Company (Coil Anodizers; presently Lorin Industries,) was one of two important sources of phosphorus to Little Black Creek; the other being the Muskegon Heights

WWTP 2 km downstream of the Roberts Street site. In and prior to 1970, Kersman Company discharged a total phosphorus load of 35.4 kgP/d to Little Black Creek via Keating Drain (Freedman et al., 1979). By comparison, that Kersman Company load was 1.4 times that of the contemporary Muskegon Heights WWTP with alum treatment in operation (Freedman et al., 1979). Subsequently, Kersman Company implemented industrial wastewater treatment, reducing its load to 1.6 kgTP/d (Friedman et al., 1979); approximately equivalent to the Little Black Creek load today (2017-18). MDEQ (2006) has reported that Lorin Industries now discharges their process wastewater to the sanitary sewer system and reportedly releases only non-contact cooling water, which is considered innocuous. Based on this information, we conclude that a significant increase in phosphorus levels is observed at Roberts Street on Little Black Creek, but that the provenance of that phosphorus is not well described.

Insights from Lake Monitoring

Monitoring was performed at an approximately twice monthly interval at 5 sites along the main axis and, in 2018, at the confluence of the lake and the outlet channel (see Figure 11).

<u>Stratification and Intrusion</u>

The portion of the lake that thermally stratifies (Mid-lake and west stations) did so over the month of May in 2018 and was fully stratified in early June; fall mixing (turnover) occurred in mid-September. Intrusions of water from Lake Michigan (cooler water with lower conductivity) were regularly observed at the lake-channel confluence (Figure 18). An intrusion (see Figure 10) was noted to have proceeded eastward within the lake as far east as the West Deep lake station on 16 July 2016 (Figure 19). Additional information on the eastward extent of intrusions (episodic events) is not available with the sampling frequency utilized here.

<u>Hypolimnetic Oxygen Depletion and Phosphorus Release</u>

Oxygen depletion in the hypolimnion (bottom waters) of Mona Lake proceeded in parallel with the development of thermal stratification, beginning in early May of 2018 and

Figure 18. Mean water column temperature at the lake – outlet channel confluence in 2018. Colder temperatures indicate the presence of intrusions from Lake Michigan.

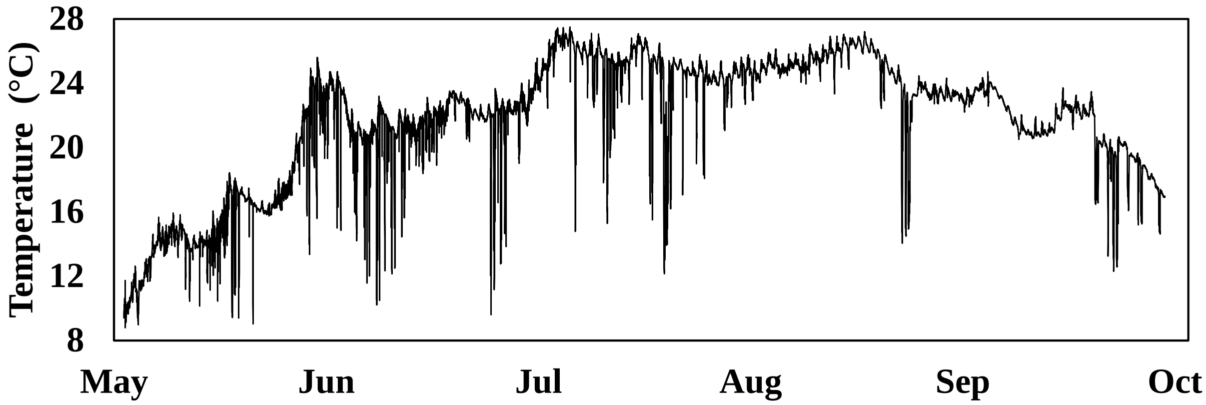
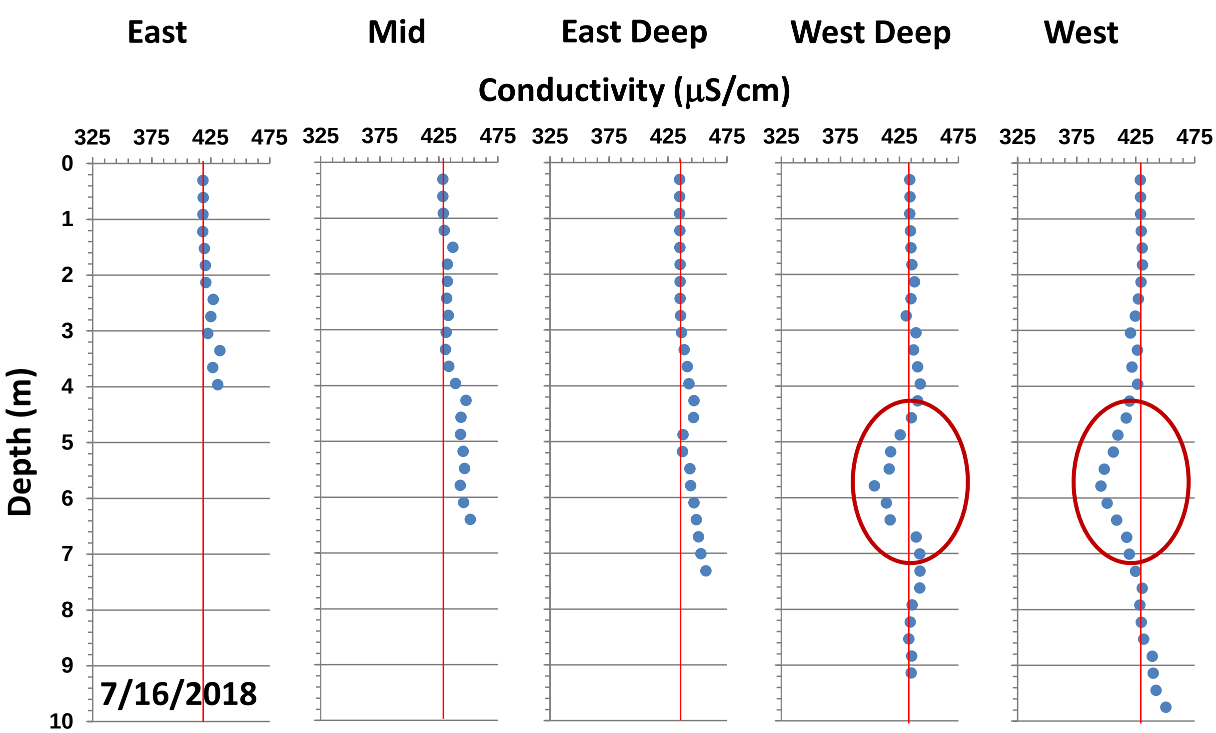


Figure 19. Conductivity profiles at the five water quality monitoring stations in Mona Lake on 16 July 2018. Red lines identify conductivity in the surface waters. Conductivities below and above those values point to intrusions from Lake Michigan and diffusion from the sediments, respectively.



achieving anoxia by mid-May of 2018 (Figure 20a). From that point anoxia moved up the water column, reaching the upper boundary of the hypolimnion (5-6 m depth) in early June and maintaining that location until turnover in mid-September. The conversion of ferric to ferrous iron, with attendant release of phosphorus from the lake sediments, occurred when conditions become anoxic (early June; Figures 20a and b), with accumulation in the hypolimnion reaching levels exceeding 500 μgP/L in August (Figure 20b). Entrainment (Figure 10) transported phosphorus from the hypolimnion to the epilimnion, making it available to support algal growth in the well-lit surface waters (Figure 20c).

Chlorophyll, Harmful Algal Blooms and Algal Toxins

Chlorophyll is the pigment common to all green plants and is used with respect to lakes as a surrogate for quantification of the abundance of algae. Chlorophyll levels in Mona Lake were largely constant from May through August of 2018 largely constant, averaging 11.4 ± 1.1 μg/L; slightly above the 20 μg/L criterion for the boundary between mesotrophy and eutrophy (Fuller and Jodoin, 2016; Figure 20c). In August, TP concentrations increased, averaging 55.6 ± 9.3 μgP/L, with a concomitant increase in chlorophyll, averaging 24.0 ± 7.8 μg/L , peaking at 33 μg/L. Both of these analytes were representative of eutrophic conditions. Mona Lake experiences harmful algal blooms (HABs) in the fall with the species composition dominated by cyanobacteria (Gillett et al., 2015). These algae produce a toxin (microcystin) potentially harmful to humans. Levels of microcystin increased in parallel with the increase in chlorophyll, reaching a peak concentration of 360 μg/L, almost 20 times the World Health Organization guideline for avoiding human health effects (Figure 21).

Insights from a Screening Model

The application of a Vollenweider type screening model (Chapra and Tarapchak 1976) in characterizing Mona Lake trophic state conditions pre- and immediately post-diversion has been presented previously (Figure 5). Here, we add results from 2017 and 2018, once again reflecting a striking response to wastewater diversion, but then conditions that have not changed significantly since immediate post-diversion in 1981 (Figure 21). The system is seen to be poised at or within the boundary for mesotrophy, a desirable outcome for stakeholders. In contrast, measurements of surface water total phosphorus and chlorophyll indicate that the

Figure 20. Oxygen and phosphorus levels in Mona Lake in 2018: (a) oxygen saturation in the hypolimnion, (b) total phosphorus in the hypolimnion and (c) total phosphorus (orange) and chlorophyll (green) in the epilimnion. Dashed line indicates time of onset of full anoxia.

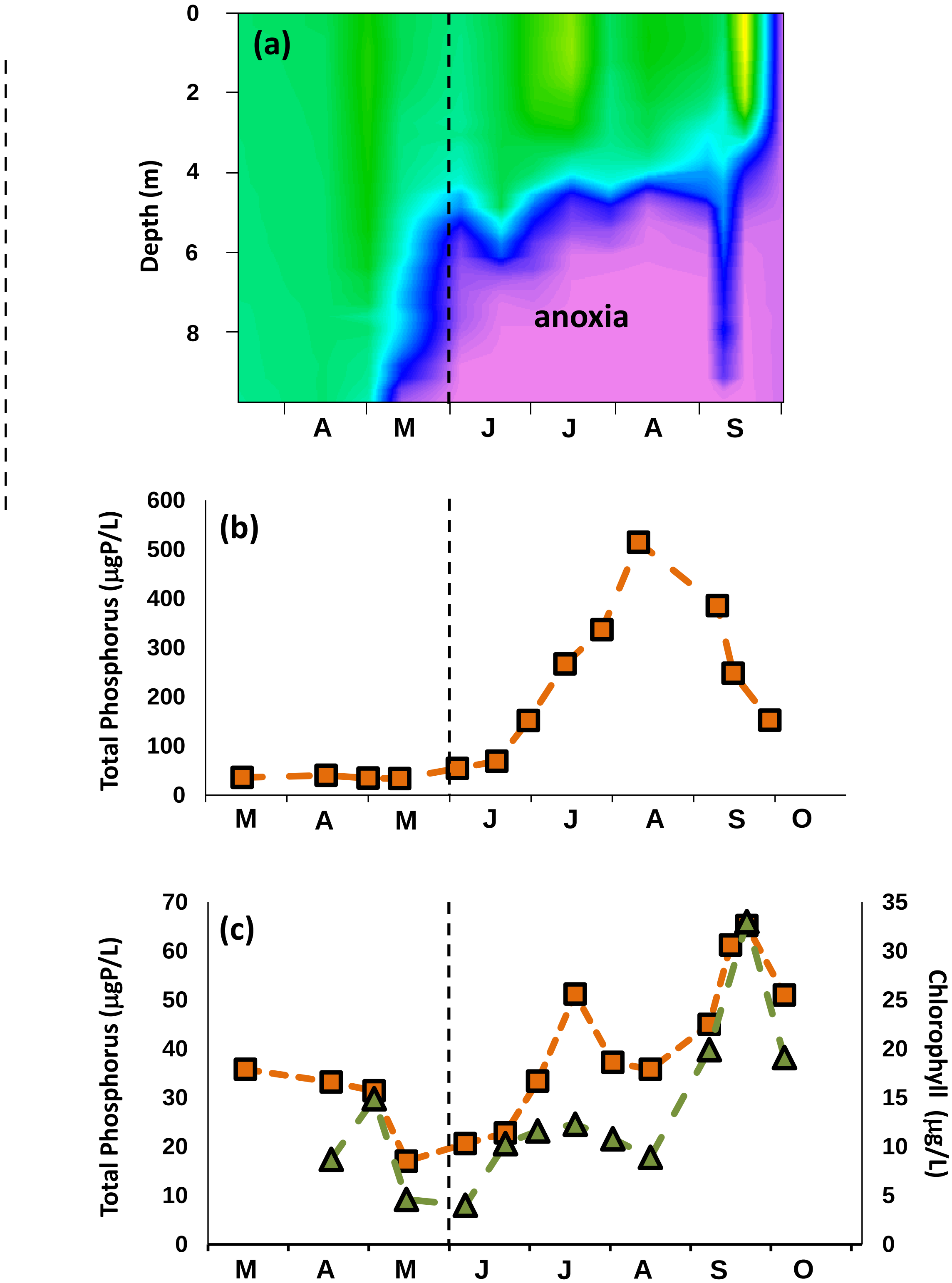
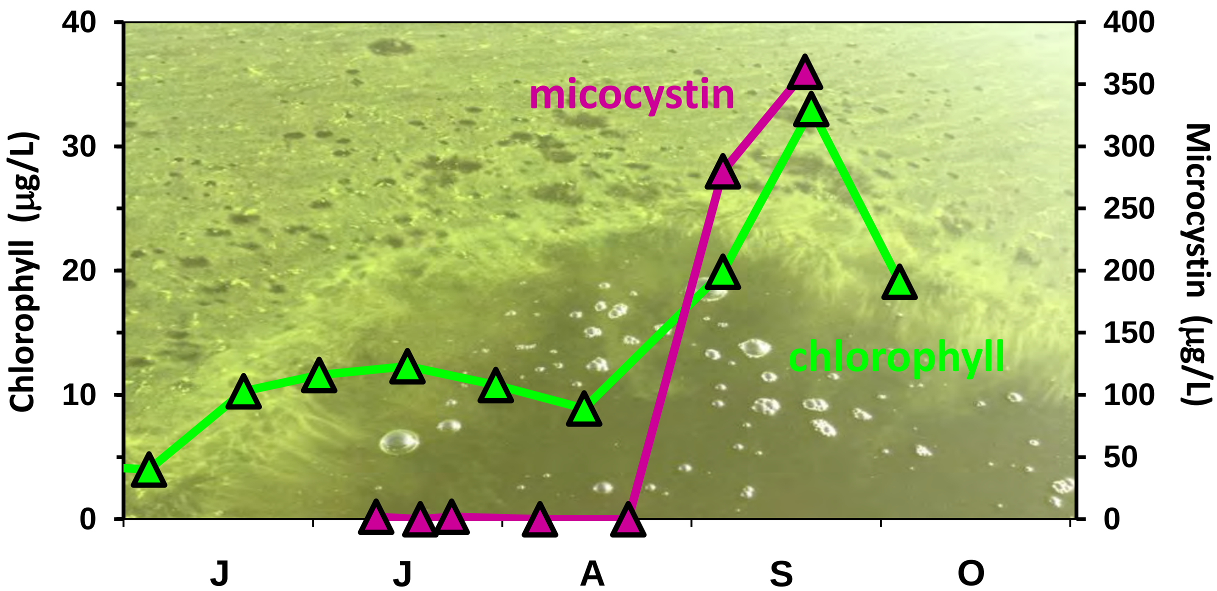


Figure 21. Levels of chlorophyll and microcystin in 2018 reflecting a harmful algal bloom (HAB) with toxins detected. Background is a surface scum of cyanobacteria (HAB) in Mona Lake.

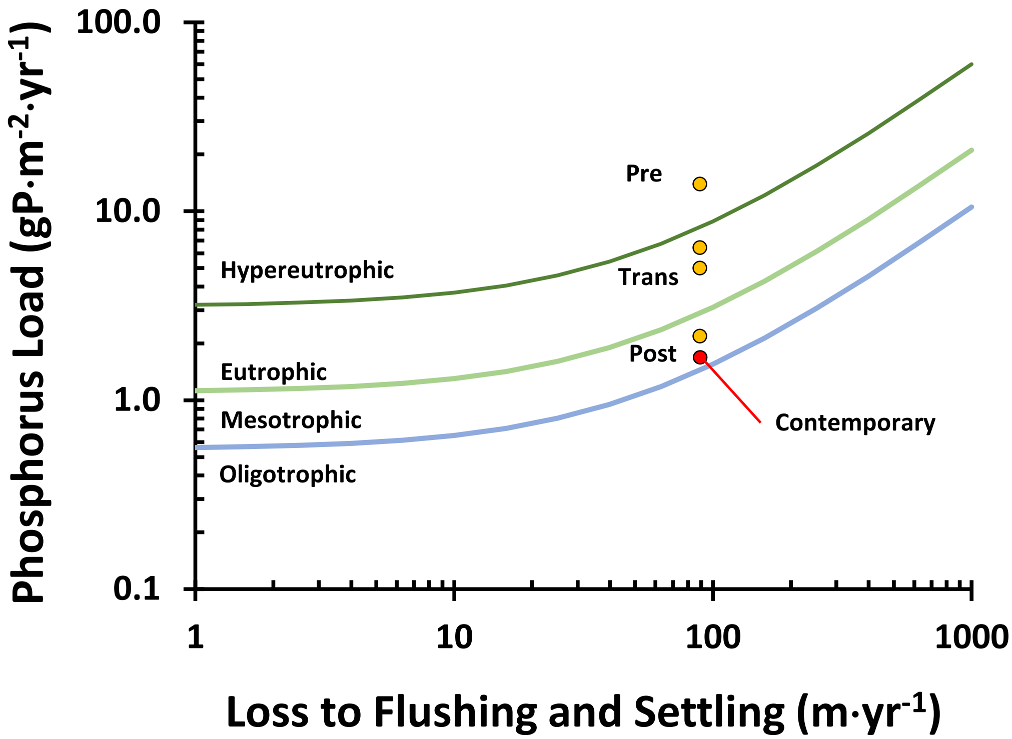


lake remained eutrophic to hypereutrophic from 1981 to today (Figure 22). The apparent disconnect between trophic state conditions predicted from external loads and those observed in the lake reflects the fact that screening models do consider internal loads, i.e., sediment phosphorus release. The significance of internal loads has been recognized in the work of others (Freedman et al., 1979; Limno-Tech, 1982; Steinman et al., 2006, 2007; and Steinman and Ogdahl, 2011) and was clearly evident in our monitoring and modeling efforts in 2017-2018.

Insights from a Management Model

The overall project objective to prioritize management actions for improving trophic state and water quality conditions in Mona Lake was met through application of a mathematical model (LAKE2K, Chapra and Martin 2004). This tool considers Mona Lake to be homogenous along its major axis (an assumption confirmed through field monitoring) and calculates water quality for surface, mid-depth and bottom waters. The model is kinetically robust, simulating spatial and temporal dynamics in water temperature, dissolved oxygen, phosphorus and chlorophyll as driven by environmental forcing conditions (e.g. solar radiation),

Figure 22. Screening model plot of trophic state response to changes in the external total phosphorus load to Mona Lake. Data points represent pre-diversion (1972), transitional (1973 and 1974) and post-diversion (1975, 1980 and 1981) in comparison to contemporary (2008-2018) conditions.



tributary phosphorus loads and sediment phosphorus release. The model was calibrated to the 2018 data set and deemed suitable for testing the impact of management actions.

Management guidance can be obtained by revisiting field monitoring results for oxygen, phosphorus and chlorophyll (Figure 20). The demarcation line placed at the end of May indicates that the full vertical extent of anoxia has been achieved. At that point, sediment phosphorus release is initiated in the hypolimnion (Figure 20b) and phosphorus migrates to the epilimnion (surface waters; Figure 20c) through entrainment. The increase in epilimnetic phosphorus is accompanied by increases in chlorophyll, i.e., an algal bloom (Figure 21). The season pattern may thus be divided into two periods: (1) that prior to the onset of thermal stratification and attendant oxygen depletion and sediment phosphorus release and (2) that following the onset of stratification and achievement of full anoxia. Water quality conditions are governed by tributary discharges in the pre-stratification period (high tributary loads, no sediment release) and by the sediments in the post-stratification interval (low tributary loads, sediment release occurring). Water quality indicates conditions of eutrophy and hypereutrophy in the pre- and post-stratification periods, respectively. Thus it will be necessary for management attention to be focused on both external and internal phosphorus load reduction.

Four sets of model runs were performed to provide guidance for management of total phosphorus concentrations in Mona Lake: (1) baseline conditions, (2) reduction of external loads, (3) elimination of internal loads and (4) combinations of external and internal loading reduction. The initial condition was specified as the total phosphorus concentration at the conclusion of the simulation and the model re-run. A target total phosphorus concentration of $\leq$20 μgP/L was set, seeking water quality conditions within the mesotrophic range. For the baseline condition, tributary phosphorus inputs were those for 2018 and the sediment phosphorus release rate was maintained at the calibration value of 25 $mgP \cdot m^{-2} \cdot d^{-1}$. To test the impact of external load management, tributary phosphorus inputs were reduced from the baseline by 10, 25, 50 and 75% and sediment phosphorus release was held at the calibration value. Here, the total phosphorus target concentration was met for external load reductions of 50 and 75% (Figure 23a); likely a bridge too far in a nonpoint source watershed management context. Next, sediment phosphorus release was eliminated (rate set to zero) and tributary loads maintained at 100%. Lake water total phosphorus levels were reduced significantly here (Figure 23b), especially in the late summer early fall interval where water quality if driven by sediment processes. The regulatory period average was 21 μgP/L, slightly above the total phosphorus criterion. Finally, two 'combo scenarios' were run, pairing elimination of sediment phosphorus release with 10 and 25% reductions in external phosphorus loads (Combo 10 and Combo 25; Figure 23c). These yielded regulatory period total phosphorus averages of 19 and 16 μgP/L, respectively.

The results for the baseline condition and 7 management alternatives are compared in Figure 24, where a preferred alternative is identified. The 50 and 75% reductions in external load meet the regulatory period target, but are deemed unfeasible in a nonpoint source watershed management context. Two additional scenarios, the no sediment release and no sediment release with a 10% reduction (Combo 10) in external load approached or met the target concentration, but with no margin of safety (16 μgP/L).

Figure 23. Results of management model runs with LAKE2K: (a) comparison of baseline and serial reductions in tributary (external) total phosphorus loads, (b) comparison of baseline and baseline with sediment phosphorus release off and (c) comparison of baseline and two combination runs, 10% and 25% reduction in tributary (external) loads and with sediment phosphorus release (internal loads) off. Solid line is total phosphorus target concentration (standard) and dashed lines define the regulatory period.

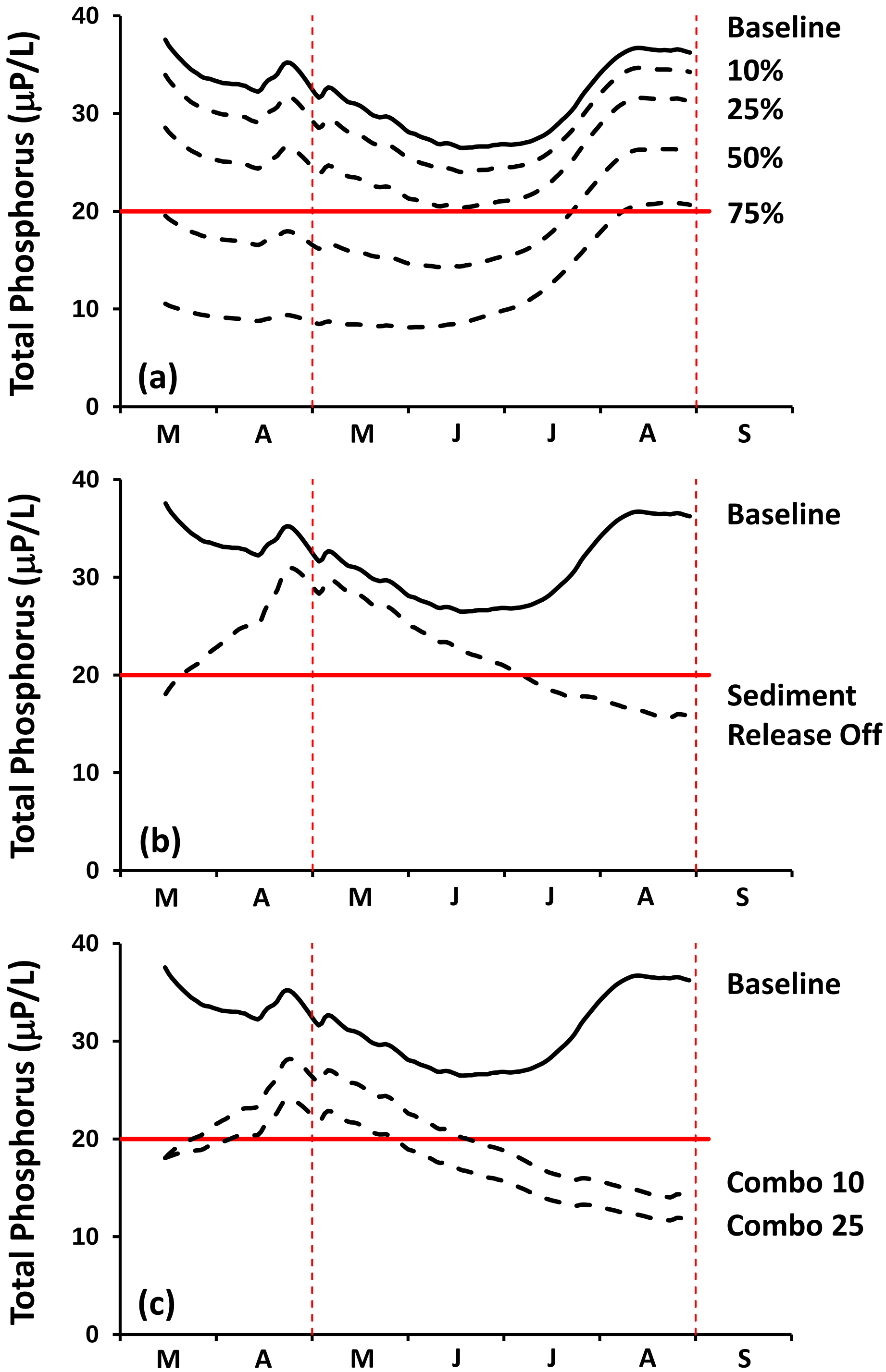
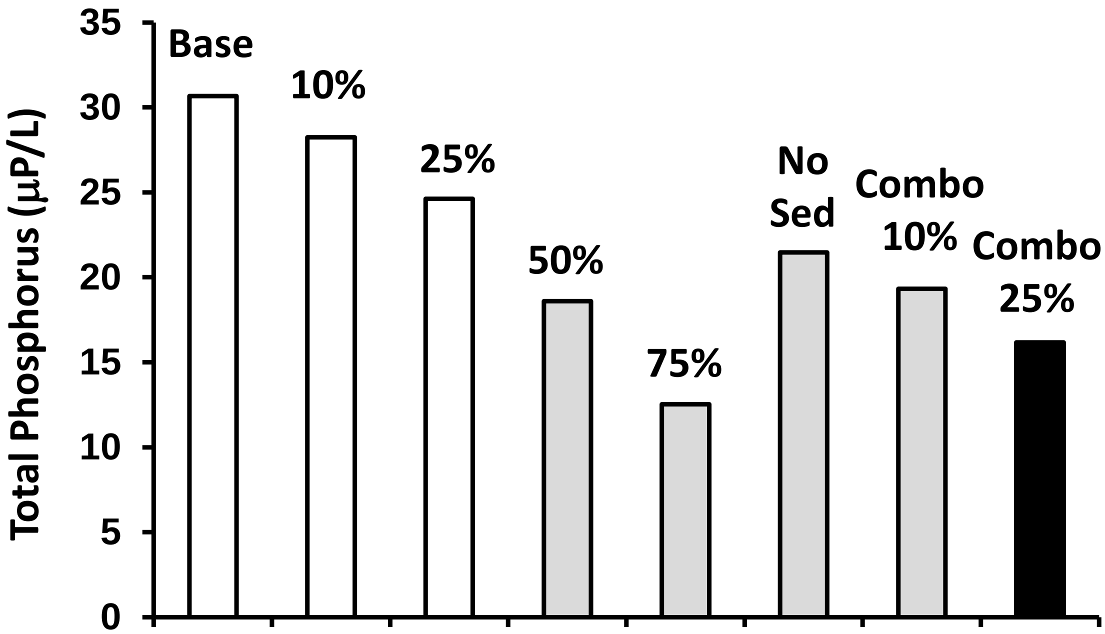


Figure 24. Baseline scenarios and management options for managing total phosphorus in Mona Lake. The response is indicated by bar color: white, did not meet the standard; gray, met the standard, but faced implementation issues or did not provide a margin of safety; and black, the preferred alternative.



Summary of Observations

Information obtained through implementation of a monitoring program in 2017 and 2018, application of mathematical models and a review of the primary scientific literature and technical reports results in the following key observations,

1) Trophic state conditions in Mona Lake are mediated by tributary phosphorus loads in the spring, pre-stratification period and by internal phosphorus loads during summer stratification;
2) The wastewater diversion – land application program, implemented in the 1970s, resulted in a striking reduction in tributary phosphorus loads, with the trophic state potential for Mona Lake approaching the condition of mesotrophy desired by stakeholders;
3) That potential has, however, not been realized. Decades of excessive phosphorus loading have left legacy deposits of organic matter and phosphorus in Mona Lake sediments. These 'sins of the mothers and fathers' continue to drive oxygen depletion and sediment phosphorus release, sustaining conditions of eutrophy and hypereutrophy.

4) Wind-driven entrainment events transport phosphorus released from the sediments from bottom waters to the warm, well-lit surface waters, stimulating harmful algal blooms (HABs) in late summer and fall.

Prioritization of Management Actions

Management actions prioritized here differ in their anticipated impact on trophic state conditions in Mona Lake, in their cost of implementation and maintenance and in the period over which an in-lake response may be expected. The actions should be integrated into a management plan which provides today's stakeholders with relief from manifestations of eutrophication while securing sustainable water quality conditions for the future. This plan must, of course, take into account the availability of resources for action plan implementation.

1) Eliminate internal phosphorus loads by implementing physical and/or chemical methods of blocking sediment phosphorus release.
2) Establish a program of best management practices contributing to achievement of the desired 25% reduction in external phosphorus loads.
3) Eliminate the source of localized elevation of phosphorus to Little Black Creek; this as a contribution to the desired 25% reduction in external phosphorus loads.

Recommendations for Future Study

The work performed here by the Michigan Tech team has served to synthesize the results of prior and contemporary scientific investigations to prioritize management actions for Mona Lake. Selection of a course of action must be guided by these results and supplemented by additional studies intended to clarify remaining questions and better target the manner in which the management plan would be implemented.

1) Engage in proof of concept testing of controls on sediment phosphorus release, taking into account the impact of physical conditions (e.g., morphometry, bathymetry, ephemeral stratification, intrusions) characteristic to Mona Lake that may impact the efficacy of such programs.
2) Review publications and conduct monitoring to partition phosphorus loads to Black Creek among those originating from the land application wastewater treatment facility, agricultural runoff and background sources associated with local soil types. Perform phosphorus bioavailability assays to prioritize specific locations for implementation of best management practices.

3) Establish flow monitoring and event-driven total phosphorus monitoring on discharges from the Celery Flats to confirm the efficacy of flow restrictors in reducing phosphorus loads.
4) Identify the source of phosphorus to Little Black Creek as a first step in eliminating phosphorus levels exceeding those of other Mona Lake tributaries.

Literature Cited

Chapra, S. C., and Martin, J.L., 2004. LAKE2K: A Modeling Framework for Simulating Lake Water Quality (Version 1.2): Documentation and Users' Manual. Department of Civil and Environmental Engineering, Tufts University, Medford, MA

Chapra, S. C. and Tarapchak, S. J. 1976. A chlorophyll model and its relationship to phosphorus loading plots for lakes. Water Resources Research, 12(6): 1260–1264.

Evans, E. D. (1992). Mona, White and Muskegon Lakes in Muskegon County: The 1950's-1980's. Michigan Department of Natural Resources, Lansing, MI.

Freedman, P.L., Canale, R.P. and Auer, M. T. 1979. Applicability of land treatment of wastewater in the Great Lakes area basin: Impact of wastewater diversion, spray irrigation on water quality in the Muskegon County, Michigan, Lakes. EPA 905/9-79-006-A, Great Lakes National Program Office, Chicago, IL, 260 pp.

Fuller, L.M. and Jodoin, R.S. 2016. Estimation of a Trophic State Index for Selected Inland Lakes in Michigan, 1999–2013. Scientific Investigations Report 2016–5023, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA, 16 pp.

Gillett, N. D., Luttenton, M. R. and Steinman, A. D. 2015. Spatial and temporal dynamics of phytoplankton communities in a Great Lakes drowned river-mouth lake (Mona Lake, USA). *Journal of Limnology*, 74(3): 453-466.

Henderson, H. 2019. The Role of Ephemeral Stratification, Anoxia and Entrainment in Mediating Spatiotemporal Trophic State Dynamics in a Michigan Drowned River Mouth System (Mona Lake, MI). M.S. Thesis, Department of Civil and Environmental Engineering, Michigan Technological University, Houghton, MI, 91 pp.

Limno-Tech. 1982. The Effect of Wastewater Land Treatment on Eutrophication in Muskegon County Lakes. Prepared for Michigan Department of Natural Resources and U.S. EPA Great Lakes Nation Program Office. Ann Arbor, MI, 171 pp.

Steinman, A.D. and Ogdahl, M.E., 2011. Does converting agricultural fields to wetlands retain or release P?. *Journal of the North American Benthological Society*, 30(3): 820-830.

Steinman, A., Rediske, R., Denning, R., Nemeth, L., Chu, X., Uzarski, D., Biddanda, B. and Luttenton, M. 2006. An environmental assessment of an impacted, urbanized watershed: the Mona Lake Watershed, Michigan. *Archiv für Hydrobiologie*, 166(1): 117-144.

Steinman, A., Chu, X. and Ogdahl, M. 2009. Spatial and temporal variability of internal and external phosphorus loads in Mona Lake, Michigan. *Aquatic Ecology*, 43(1): 1-18.