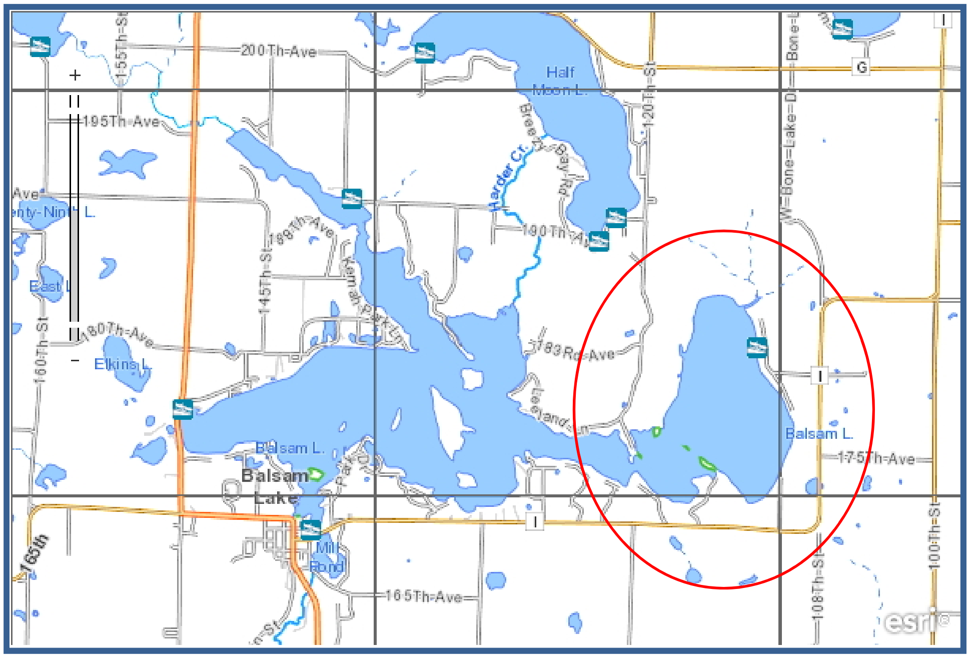
Balsam Lake Protection and Rehabilitation District

Long Range Plan

East Balsam Basin Water Quality Amendment

November 2019



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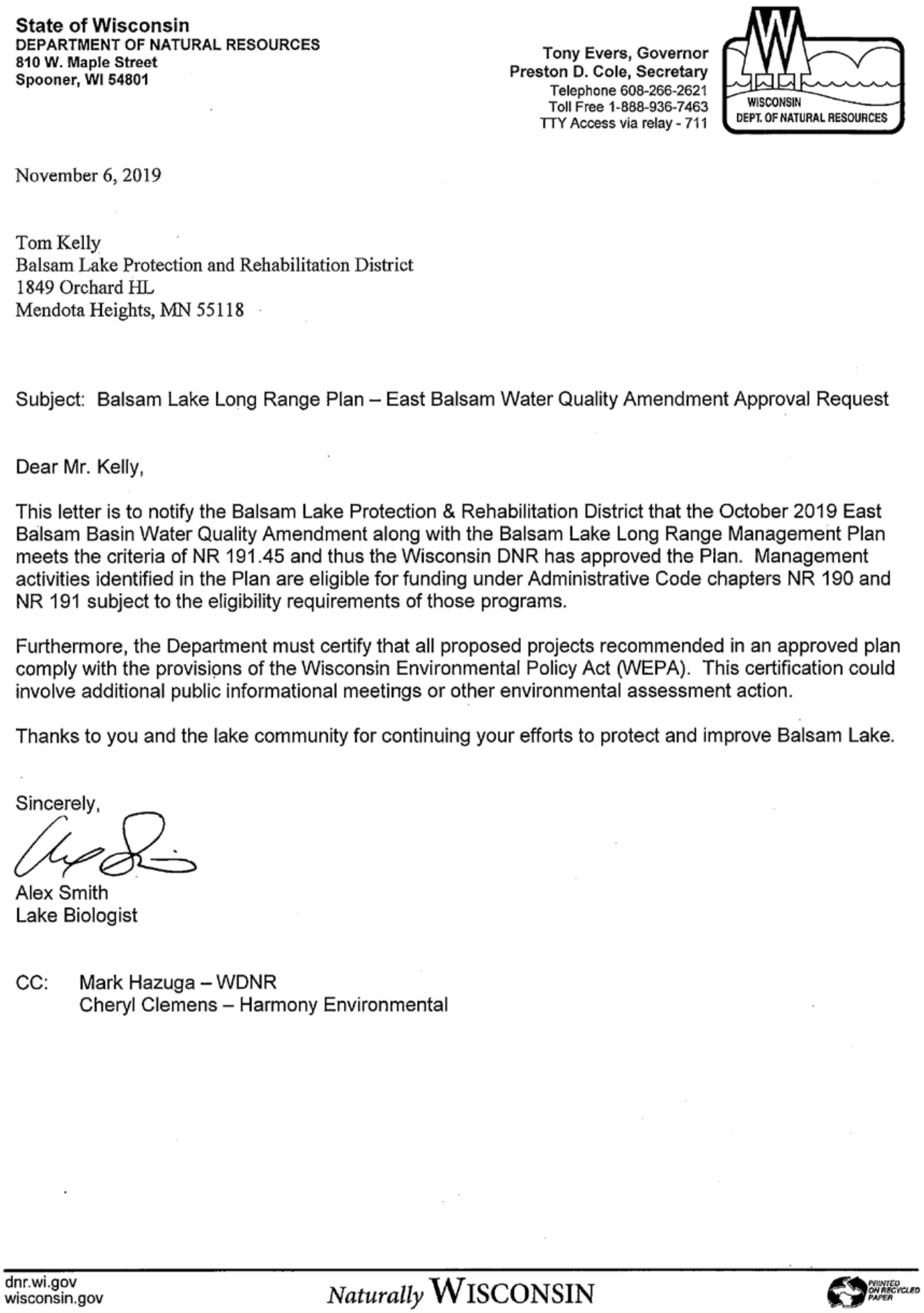

State of Wisconsin
DEPARTMENT OF NATURAL RESOURCES
810 W. Maple Street
Spooner, WI 54801

Tony Evers, Governor
Preston D. Cole, Secretary
Telephone 608-266-2621
Toll Free 1-888-936-7463
TTY Access via relay - 711

WISCONSIN
DEPT. OF NATURAL RESOURCES

November 6, 2019

Tom Kelly
Balsam Lake Protection and Rehabilitation District
1849 Orchard HL
Mendota Heights, MN 55118

Subject: Balsam Lake Long Range Plan – East Balsam Water Quality Amendment Approval Request

Dear Mr. Kelly,

This letter is to notify the Balsam Lake Protection & Rehabilitation District that the October 2019 East Balsam Basin Water Quality Amendment along with the Balsam Lake Long Range Management Plan meets the criteria of NR 191.45 and thus the Wisconsin DNR has approved the Plan. Management activities identified in the Plan are eligible for funding under Administrative Code chapters NR 190 and NR 191 subject to the eligibility requirements of those programs.

Furthermore, the Department must certify that all proposed projects recommended in an approved plan comply with the provisions of the Wisconsin Environmental Policy Act (WEPA). This certification could involve additional public informational meetings or other environmental assessment action.

Thanks to you and the lake community for continuing your efforts to protect and improve Balsam Lake.

Sincerely,

Alex Smith
Lake Biologist

CC: Mark Hazuga – WDNR
Cheryl Clemens – Harmony Environmental

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Naturally WISCONSIN

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EXECUTIVE SUMMARY

The Balsam Lake Protection and Rehabilitation District membership approved a series of alum treatments for the East Balsam Basin at its 2019 Annual Meeting. Alum treatments are expected to result in removal of East Balsam from the Wisconsin Department of Natural Resources Impaired Waters list.

The decision to complete an alum treatment followed a consideration of various alternatives to address the internal phosphorus load which drives algae blooms in East Balsam. The results of in-lake and sediment studies and modeling of anticipated results led to a BLPRD Board of Commissioners recommendation to treat East Balsam with alum. These studies are summarized in this document and included as plan appendices.

This Long Range Plan Amendment establishes new water quality objectives for East Balsam Lake.

GOAL. Improve and maintain water clarity and quality in Balsam Lake.

IMPAIRED WATERS OBJECTIVE. Remove East Balsam Lake from the impaired waters listing by achieving TP<40 ug/L and Chla<27 ug/L in the June 15 – Sept 15 period.

TOTAL PHOSPHORUS OBJECTIVE. Mean summer total phosphorus is <30 ug/L (predicted value = 24 ug/L)

CHLOROPHYL A OBJECTIVE. Mean summer chlorophyll a is <20 ug/L (predicted value = 14 ug/L)

Estimated costs and proposed treatment schedule are outlined below. The scenario includes four separate treatments at two year intervals. The total cost of the alum treatments is estimated to be $1,295,700. Interest ($51,090) and monitoring ($154,000) brings the total project cost to $1,490,790. The proposed treatment area includes the area of East Balsam 10 feet and deeper. The BLPRD will seek bids for a 2020 alum treatment based on this strategy. Monitoring results may lead to adaptations in the treatment strategy as the project progresses.

An example adaptive management scenerio approach in which the Al dose is split into smaller applications.

Variable	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Al application	30 g/m^2		30 g/m^2		20 g/m^2		20 g/m^2
Al Cost over estimate (+10%)[1]	$353,000		$388,300 [1]		$277,200 [1]		$277,200 [1]
Assessment2	▨	▨	▨	▨	▨	▨	▨

[2] Sediment core collection and vertical profile monitoring

BLPRD property owners will pay for the alum treatment through the regular assessment. The average cost to property owners from 2021 – 2028 is projected to be $24.27/year per $100,000 assessed valuation and $121.35/year per $500,000 assessed valuation. These estimates assume that the BLPRD will receive a $200,000 WDNR Lake Protection Grant for each treatment. Lake Protection Grant deadlines are currently February 1 of each calendar year. The BLPRD intends to apply for a grant February 1, 2020 following WDNR approval of this plan amendment.

The BLPRD will apply for loans so the alum treatment can be completed prior to collection of assessments and to allow for payment prior to grant reimbursement. The BLPRD is currently seeking a 3-year loan from the Trust for Public Lands which is offering an interest rate of 4 %.

EAST BALSAM BASIN WATER QUALITY PLAN AMENDMENT PUBLIC REVIEW

Following BLPRD commissioner review and tentative approval at the October 19, 2019 board meeting, this plan amendment was available for public review and comment at the Balsam Lake Public Library and on the BLPRD website http://blprd.com/. Plan amendment availability was announced in the County Ledger Press newspaper and a notice was included in the Dockside newsletter mailed to all BLPRD property owners. Comments were accepted through November 4, 2019, but no public comments were received. The BLPRD Board of Commissioners approved the amendment following WDNR favorable review at their November 16, 2019 meeting.

INTRODUCTION AND PURPOSE OF AMENDMENT

This amendment updates the August 2012 Balsam Lake Long Range Plan. The Balsam Lake Protection and Rehabilitation District (BLPRD) completed many of the plan activities following plan approval. The goals of the Long Range Plan are as follows:

TOP PRIORITY GOALS

Goal 1. Enhance Balsam Lake property owners' and visitors' understanding of lake issues and increase their involvement in protecting and improving the lake.

Goal 2. Manage native and invasive aquatic plants according to the goals, objectives, and activities outlined in the Aquatic Plant Management Plan.

Goal 3. Improve and maintain water clarity and quality in Balsam Lake.

PLAN GOALS

Goal 4. Protect, maintain, and improve fisheries and fish and wildlife habitat in and around Balsam Lake.

Goal 5. Promote the preservation and restoration of natural vegetation and scenery along the shoreline.

Goal 6. Maintain and enhance recreation and navigation.

This Long Range Plan Amendment focuses on Goal 3 - improving lake clarity and quality. East Balsam Lake has higher levels of phosphorus than other lake basins which lead to more algae growth. Because of East Balsam Lake conditions, much of the water quality implementation focused on the East Balsam watershed and basin.

OBJECTIVES RELATED TO EAST BALSAM WATER QUALITY

Objective A. Better understand lake processes to target actions.

Objective B. Improve water quality in East Balsam.

ACTIVITIES COMPLETED TO MEET EAST BALSAM WATER QUALITY OBJECTIVES

The BLPRD completed several of the activities set out in the 2011 plan to address East Balsam water quality following plan adoption. Plan activities are listed below followed by the study which addressed each. The study reports are included in appendices to this plan amendment.

Complete a sediment phosphorus release study of East Balsam in order to assess if an alum treatment is appropriate for East Balsam.

Complete additional water quality analysis for East Balsam to answer the following questions:

- a. How much does curly leaf pondweed contribute to the phosphorus load of East Balsam?
- b. How significant are changes to watershed (specifically agricultural) loading to East Balsam water quality?

James, William F. University of Wisconsin Stout Sustainability Sciences Institute – Discovery Center. *Internal Phosphorus Loading and Alum Dosage Considerations for East Balsam Lake, Wisconsin.* December 2015. (Appendix A)

James, William F. *East Balsam Lake, Wisconsin: Analysis of Phosphorus Sources, Loading Reduction Scenarios, and Alum Dosage and Application Strategies.* May 2018. (Appendix B)

Review feasibility and potential improvements to water clarity by creating an additional outflow for East Balsam.

Ayres Associates. *East Balsam Lake Water Quality Study. Feasibility of Engineered Solutions for Summer Algae Blooms.* March 2014. (Appendix C)

Reassess agricultural best management practice needs and priorities in the East Balsam and Main Basin watersheds. Identify actively cropped agricultural fields/farms, measure soil phosphorus on farm fields, and model phosphorus release using SNAP plus (an agricultural water quality model).

Wojchik, Eric. Polk County Land and Water Resources Department. *East Balsam Lake Watershed Soil Fertility and Phosphorus Index Assessment.* July 2015. (Appendix D)

Re-evaluate water quality objectives and activities based upon the results of the sediment core study, CLP analysis, and East Balsam outflow analysis along with information from the 2010 water quality study.

The BLPRD Board of Commissioners evaluated the results of the studies and recommended an alum treatment for East Balsam.

PROGRESS REPORT

An article in the fall 2018 edition of the Dockside newsletter provided a summary of the results of these studies.

East Balsam Lake Water Quality

The water in East Balsam isn't clear, we know that. The basin is listed as an impaired water by the Wisconsin Department of Natural Resources for excess algae growth. Studies of East Balsam have demonstrated that it is phosphorus in the water that leads to this growth. Our most recent estimate tells us that 70% of this phosphorus is released from sediments at the bottom of the lake. If this sediment (internal) load of phosphorus isn't controlled, we will not be successful in reducing algae growth significantly.

There are few who would argue against trying to lessen the growth of algae in East Balsam. The green swirling, smelly slime of July and August makes it undesirable for swimming, boating, and relaxing by the lake. The toxins that blue-green algae can produce threaten human and animal health.

The Balsam Lake Protection and Rehabilitation District has examined several alternatives for addressing East Balsam water quality concerns. The 2012 Lake Management Plan set this examination of alternatives for East Balsam in motion. Because lakes are complicated systems and potential fixes are expensive, the BLPRD sought professional advice. The BLPRD Commissioners have been guided by studies conducted by Barr Engineering and

UW-Stout. Ayers and Associates provided engineering analysis of alternatives in 2014. In consideration of alternatives, we need to keep the science and conditions in East Balsam in mind. Of course, we also need to think about the cost of each.

A brief science lesson will help to understand the alternatives considered. Internal sediment load in East Balsam occurs when the bottom of the lake becomes devoid of oxygen (is anoxic). This happens at depths 10 feet and greater when layers of temperature form with high-density, cold water at the bottom of the lake. When there is no oxygen at the bottom of the lake, phosphorus is released into the water from its bond with iron and other compounds in the sediment. As long as the lake stays stratified in layers, there is not a big impact on the water at the lake surface. However, in shallow lakes like East Balsam, the lake can mix and break stratification when storms bring heavy rain and strong winds. When this happens, high phosphorus waters are brought to the surface to fuel algae blooms.

If you attended the 2018 annual meeting, you know the commissioners have focused on an alum treatment as the most viable alternative. You may not be aware of other alternatives considered or the rationale for focusing on alum as the selected alternative.

Why not pursue the following alternatives?

Dredging Lake Sediments. Short answer is cost. Depending on the depth of sediments dredged, cost estimates range from $15 to $45 million to dredge the 300 acres that are 10 feet and deeper in East Balsam. There are also concerns regarding suspension of sediments and nutrients into the water column, removal of aquatic plants which provide habitat, and finding a nearby disposal site. Dredged lake sediment from 300 acres of East Balsam would cover 160 acres to a depth of 6 to 12 feet!

Aeration. This is where it is important to understand the science. An aeration system is intended to prevent the lake bottom from becoming devoid of oxygen and releasing phosphorus. Recall that iron releases its bond with phosphorus when there is no oxygen. The reverse is also true. Iron is needed to bind with phosphorous when there is oxygen present.

In order to prevent algae growth, an aeration system must be fully effective, allowing no areas to become devoid of oxygen. If only partially effective, an aerator can make the situation worse by weakening stratification and allowing phosphorus-rich waters to mix to the surface. Furthermore, there also must be iron in the water column to bind phosphorus when oxygen is present.

An aeration system installed in nearby Cedar Lake was found to make lake quality worse in a recent study. There were two reasons as described in the Cedar Lake Management Plan:

> *The lake mixed frequently, bringing phosphorus to the surface in 2011.Therefore, when combined with the limited ability of iron to bind with phosphorus [in the water column], the aerator actually increased phosphorus loading from lake sediments.*

Like Cedar Lake, East Balsam has low iron levels in the water column. If not designed appropriately, aeration could also lead to periods of low oxygen followed by regular mixing – a recipe for even higher amounts of phosphorus and algae growth.

New East Balsam Outflow

Water in East Balsam takes about two years before it flows out of the lake. There are no practical, cost-effective options to increase the flow into and therefore out of East Balsam. (You need to have more water come into the basin in order for more water to flow out.) Ayers and Associates examined alternatives to increase flow to East Balsam from Stump Bay, Harder Creek, Otter Creek, and/or Lower Rice Creek via systems of weirs, pumps, and pipes. Each option was deemed infeasible and extremely costly with not enough water to effectively improve water quality, a minimum cost reported at $50 million, and potential negative impacts on the rest of Balsam Lake.

Reducing Runoff from Homes and Farms

It is important to address the runoff of phosphorus from the watershed or land area that drains to East Balsam. The BLPRD has worked with the Polk County Land and Water Resources Department to examine agricultural lands in the watershed in an attempt to identify mitigation projects. Homeowners are encouraged to plant buffers of native vegetation along the shoreline and to capture runoff with projects such as rain gardens. Financial and technical assistance has been provided. Reducing the phosphorus load from the watershed (external load) will help to increase the longevity of the selected alternative to reduce the internal load. However, lake studies tell us that watershed reduction alone will not lead to significant water quality improvement.

What do we know about alum?

Alum (aluminum sulfate) is added to the water, forming a floc and settling to the lake bottom. It removes phosphorus from the water column, but more importantly, covers bottom sediments and prevents release of phosphorus under anaerobic conditions. Alum has been shown to be safe for fish and other living things as long as the acidity of the lake is closely monitored during application. Buffered alum is recommended for East Balsam, if higher doses are applied, to ensure that pH stays in the neutral range.

Comprehensive study of East Balsam sediments and lake conditions tell us that areas 10 feet and deeper would need to be treated at a rate of 100 grams per square meter. To maximize alum binding efficiency, the alum dose would be divided. There are options for dividing the dose, and availability of funds can play a role in the dosing decision. The rate and timing of application would ultimately be influenced by monitoring results.

Effective binding of phosphorus in lake sediments is predicted to result in significant water quality improvements and the ability to remove the basin from the impaired waters list. Lake clarity is predicted to improve throughout the growing season by an average of about 3 feet following an alum application.

There is a cost for this improvement in lake water quality. The total application cost to reach the full recommended dose is estimated at approximately $1.4 million for three treatments. Follow-up treatment will likely be needed in 15-20 years. There will also be additional investment in monitoring – at a cost of about $15,000 annually. Department of Natural Resources grants of up to $200,000 are available on a competitive basis to fund a portion of the cost of alum application It is possible to receive multiple grants over the life of the project. Grants can also support 2/3 of the cost of monitoring. Updates to the Balsam Lake Long Range Plan are needed to qualify for grant funding.

A committee of lake residents and board members will be examining options for the alum application and funding in more detail over the winter of 2018/19. The committee will bring its recommendations to the 2019 Annual Meeting. The recommendations can be used to amend the Balsam Lake Long Range plan to qualify for WDNR grants. Approval is needed at the Annual Meeting for the alum treatment to proceed.

EAST BALSAM WATER QUALITY

The Wisconsin Department of Natural Resources listed East Balsam Lake (WBIC 2620600) as an impaired water for excess algae growth in 2014. It was listed because it had chlorophyll samples that exceeded the threshold for recreational use for a shallow lowland lake. It did not exceed the total phosphorus standard at the time of the listing. Results of samples taken from June 15 through September 15 are used for the impaired waters listings.

Table 1. East Balsam Water Quality Criteria Lake Total Phosphorus (TP) and Chlorophyll-a (Chla)[1]

Stratification	Lake Natural Community	TP Criterion Aquatic Life and Recreation (ug/L)	Chla Criterion Aquatic Life (ug/L)	Chla Criterion Recreation (% days >20ug/L)
Unstratified (shallow)	Lowland Drainage	40	27	30%

MONITORING RESULTS

Citizen lake monitoring provides long-term data for East Balsam Lake. The trophic state index summarizes water quality measurements for the basin over time. Trophic state describes the degree of nutrient enrichment of a lake. Trophic states can be calculated using total phosphorus concentration, chlorophyll a levels, and secchi disc depth measurements. Oligotrohpic lakes are nutrient-poor with little growth of plants and algae with TSI readings <40. Mesotrophic lakes have intermediate nutrient levels and only occasional algae blooms and TSI readings between 40 and 50. Lakes with high nutrient levels are considered eutrophic lakes. Eutrophic lakes have low light transparency, high phosphorus concentrations, and high levels of algae growth (as measured by chlorophyll a levels) and TSI readings >50. Hypereutrophic lakes have severe algae blooms and very low water clarity. East Balsam Lake has generally been in the eutrophic category over years of monitoring.

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[1] Wisconsin Department of Natural Resources. *Wisconsin 2020 Consolidated Assessment and Listing Methodology (WisCALM)*. April 2019.

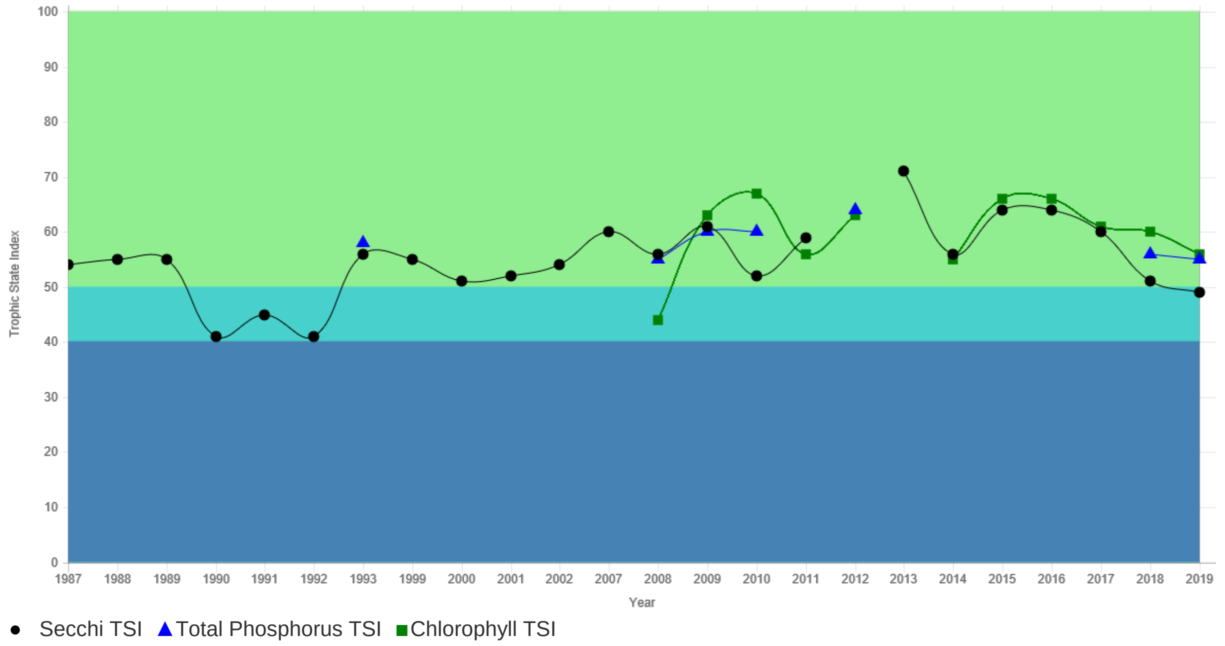

Figure 1. East Balsam Lake Trophic State Index 1987-2019[2]

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[2] Wisconsin Department of Natural Resources. Citizen Lake Monitoring Data (accessed 09/18/2019) https://dnr.wi.gov/lakes/clmn/reports/tsigraph.aspx?stationid=493058

The James 2015 study provided more comprehensive phosphorus and chlorophyll sample results for East Balsam Lake. The results in Figure 1 illustrate mean summer total phosphorus at about 0.05 mg/L (50 ug/L) and chlorophyll at about 47 µg/L.[3] Internal loading of phosphorus from lake sediments was identified as a primary source of phosphorus that fuels algae blooms in studies by Barr Engineering (2010) and William James (2015 and 2018).

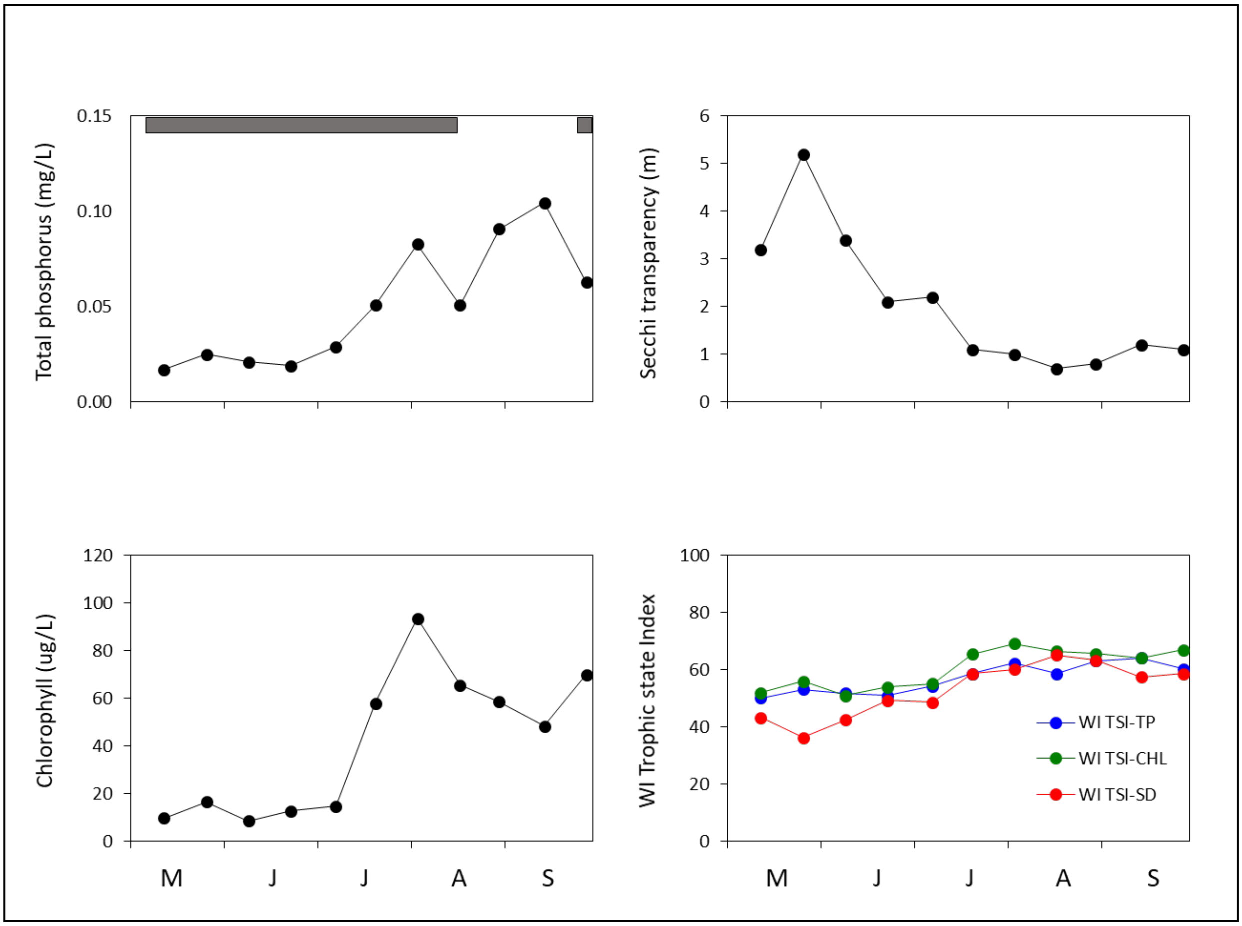

Figure 2. East Balsam Lake Monitoring Results: Total Phosphorus, Secchi Transparency, Chlorophyll, and TSI.[4]

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[3] To convert mg/L to ug/L, multiply by 1000.

[4] James. 2015.

BALSAM LAKE ALUM TREATMENT STUDIES SUMMARY

The BLPRD hired William James from UW Stout to analyze internal loading of phosphorus (P) from lake sediments and develop an alum dosing strategy in three lake studies. This summary of these studies is intended to provide an overview. Technical terms and project methodology are omitted to make project results more readily understandable. They can be found in the full reports in the plan amendment appendices.

James, William F. University of Wisconsin Stout Sustainability Sciences Institute – Discovery Center. *Internal Phosphorus Loading and Alum Dosage Considerations for East Balsam Lake, Wisconsin.* December 2015.

The study was aimed at:

1) Better understanding internal loading from East Balsam Lake sediments and where (how deep) alum should be applied.
2) Determining how much phosphorus is released from samples of lake sediments collected from deep areas of the lake, both when oxygen is present (aerobic) and when it is lacking (anaerobic).
3) Characterizing lake sediments to estimate how much alum should be applied.
4) Providing a cost estimate for the recommended alum treatment.
5) Identifying further considerations and concerns.

Sediment cores were collected from five locations in the lake and analyzed in the laboratory. The analysis identified amounts of various forms of sediment phosphorus. Sediment density, organic matter, and moisture content were also measured. The study found that phosphorus is most available for release into the water column in the top 8 cm of sediment, so this is the sediment zone that is targeted for an alum treatment.

Balsam Lake sediments release most phosphorus under anaerobic conditions - when oxygen is not present (2.3 g/m^2/day). However, some phosphorus is also released under aerobic conditions - when oxygen is present (0.27 g/m^2/day). This is significant to understanding algae blooms in the lake and the potential results of an alum treatment.

Dissolved iron released from anaerobic sediment into the bottom waters can play an important role in binding internal phosphorus loads. If dissolved iron is available during mixing and turnover, it can bind with phosphorus and return it back to the sediment where it is unavailable for algae uptake. However, without enough dissolved iron in the bottom waters during lake mixing, soluble phosphorus released from sediment can remain in the water column to fuel algae growth near the lake surface. Although some dissolved iron is released from sediment during temporary stratification and bottom anoxia in Balsam Lake, there is not enough to bind all of the soluble phosphorus during turnover periods. Thus, soluble P is available for algae uptake and growth in Balsam Lake.

If water becomes very acidic (pH falls below 4) during an alum application, aluminum toxicity can result. As a measure of safety, pH is maintained above 6 when alum is applied. Buffering agents are sometimes added to maintain pH levels, or doses can be split if low pH is predicted with an alum treatment.

A total dose of 100 g/m^2 at depths 10 feet and greater is recommended. Balsam Lake does not have the alkalinity to buffer the recommended alum dose. As a result, buffering agents would need to be used, or the alum application would need to be split into multiple treatments. Additional spring and summer testing of alkalinity in various areas of the lake would be needed to refine the maximum allowable alum dose.

Additional Considerations

Sediment from watershed runoff can reduce effectiveness of an alum treatment by covering the sediment surface.

Sediment suspended from shallow areas from wind and boating activity also has the potential to cover and reduce the effectiveness of alum floc.

Annual monitoring of sediment P movement and mobile P concentrations in the sediment following alum treatment is recommended. Future alum treatments may be needed because alum efficiency can decrease over time due to crystallization of alum and saturation of alum binding sites. Applications split over several years may increase alum binding efficiencies.

Further Analysis Recommended

The in-lake measurements taken bi-weekly didn't fully explain phosphorus levels and algae growth in 2015. Additional monitoring was recommended to better characterize stratification (hourly measurement of temperature and oxygen at 0.5 to 1.0 M depth intervals) and release of phosphorus and available iron (hourly measurements) during periods of anoxia.

Additional Notes from Bill James:[5]

Alum flocs are only slightly heavier than water. They settle to the sediment surface but may not mix immediately with the upper 8-cm of sediment. Recent studies have found that the alum floc can remain on top of the sediment rather than mixing into it. Balsam Lake sediments have high moisture and low density which should allow for some mixing and binding of sediment P.

Alum can lose its ability to efficiently bind phosphorus if it doesn't mix into the sediment within about 6 months. To overcome or compensate for this, it is recommended that the 100 g/m^2 dose be split into several smaller treatments spread out over several years. More recent studies also suggest that alum should be applied in June or later when temporary stratification and bottom anoxia develops. Application when soluble phosphorus starts to build up in the bottom waters will promote exposure of the floc to phosphorus when its binding efficiency is high.

James, William F. *Seasonal dynamics in stratification, bottom-water dissolved oxygen, and water chemistry in Balsam Lake, Wisconsin: 2016-17.* February 2018.

These investigations suggested that temporary stratification and bottom anoxia developed many times during the summer, resulting in internal P loading from sediment under anaerobic conditions. Biweekly limnological [in-lake] sampling captured the occurrence of bottom anoxia and high soluble P concentrations only twice in 2015 and once in 2017. However, bottom anoxia and potential internal P loading can develop numerous times in June and July as found by continuous monitoring. The timing of these dynamics coincided with chlorophyll increases in 2017, suggesting a strong link between algae growth and internal P loading in East Balsam Lake. Use of aluminum sulfate [alum] to bind sediment P and reduce internal P loading will tremendously improve water quality conditions in the lake.

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[5] Personal communication 04/01/2019

James, William F. ***East Balsam Lake, Wisconsin: Analysis of Phosphorus Sources, Loading Reduction Scenarios, and Alum Dosage and Application Strategies.*** **May 2018.**

This study re-evaluated the model used to estimate phosphorus loading and predict the results of an alum treatment for East Balsam Lake. The report summary and figures provide an excellent overview for this report.

Internal loading of lake sediments accounts for about 70 percent of the phosphorus in East Balsam. Significant reductions in total phosphorus and algae growth (as measured by chlorophyll a) and improvements in water clarity (as measured by Secchi depth) are predicted with an alum treatment. A split alum dose was recommended to reach 100 g/m^2 in areas of the lake 10 feet and deeper in the May 2018 report.

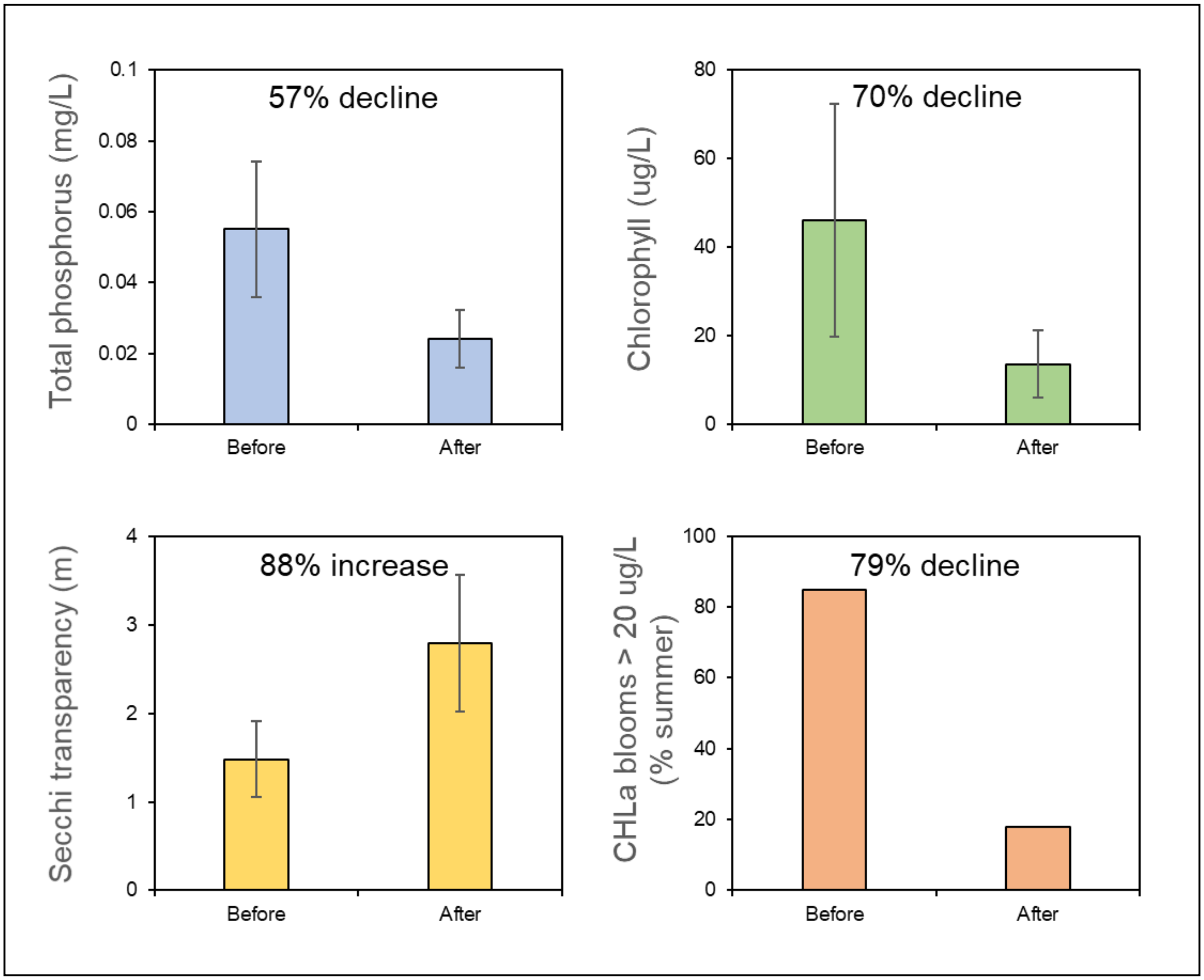

Figure 3. Modeled Changes to Total Phosphorus, Chlorophyll, Secchi Transparency, and Chlorophyll a >20 ug/L Before and After an Alum Treatment.

IMPLEMENTATION

UPDATED WATER QUALITY GOAL/OBJECTIVES/ACTIVITIES

GOAL. Improve and maintain water clarity and quality in Balsam Lake.

IMPAIRED WATERS OBJECTIVE. Remove East Balsam Lake from the impaired waters listing by achieving TP<40 ug/L and Chla<27 ug/L in the June 15 – Sept 15 period.

TOTAL PHOSPHORUS OBJECTIVE. Mean summer total phosphorus is <30 ug/L (predicted value = 24 ug/L)

CHLOROPHYL A OBJECTIVE. Mean summer chlorophyll a is <20 ug/L (predicted value = 14 ug/L)

ALUM TREATMENT STRATEGY

The BLPRD adopted an updated treatment scenario proposed by William James in April 2019. Cost estimates were also updated at this time. The updated treatment scenario and cost is shown in the table below. The scenario includes four separate treatments at two year intervals. The total cost of the alum treatment is estimated to be $1,295,700. Interest ($51,090) and monitoring ($154,000) brings the total project cost to $1,490,790. The proposed treatment area includes the area of East Balsam 10 feet and deeper. The BLPRD will seek bids for a 2020 alum treatment based on this strategy.

Table 2. East Balsam Basin Alum Treatment Strategy

An example adaptive management scenerio approach in which the Al dose is split into smaller applications.

Variable	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Al application	30 g/m^2		30 g/m^2		20 g/m^2		20 g/m^2
~ Al Cost over estimate (+10%)[1]	$353,000		$388,300 [1]		$277,200 [1]		$277,200 [1]
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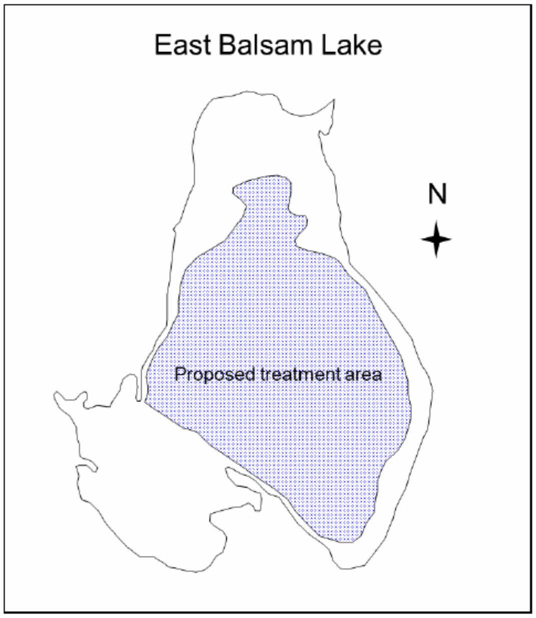

Figure 4. East Balsam Alum Treatment Area

FUNDING

BLPRD property owners will pay for the alum treatment through the regular assessment. Costs per $100,000 and $500,000 of assessed valuation are illustrated in Figure 5 below. These estimates assume that the BLPRD will receive a $200,000 WDNR Lake Protection Grant for each of four alum treatments. The average cost to property owners from 2021 – 2028 is projected to be $24.27/year per $100,000 assessed valuation and $121.35/year per $500,000 assessed valuation. Lake Protection Grant deadlines are currently February 1 of each calendar year. The BLPRD intends to apply for a Lake Protection Grant February 1, 2020 following WDNR approval of this plan amendment.

The BLPRD will apply for loans so the alum treatment can be completed prior to collection of assessments and to allow for payment prior to grant reimbursement. The BLPRD is currently seeking a 3-year loan from the Trust for Public Lands which is offering an interest rate of 4 %.

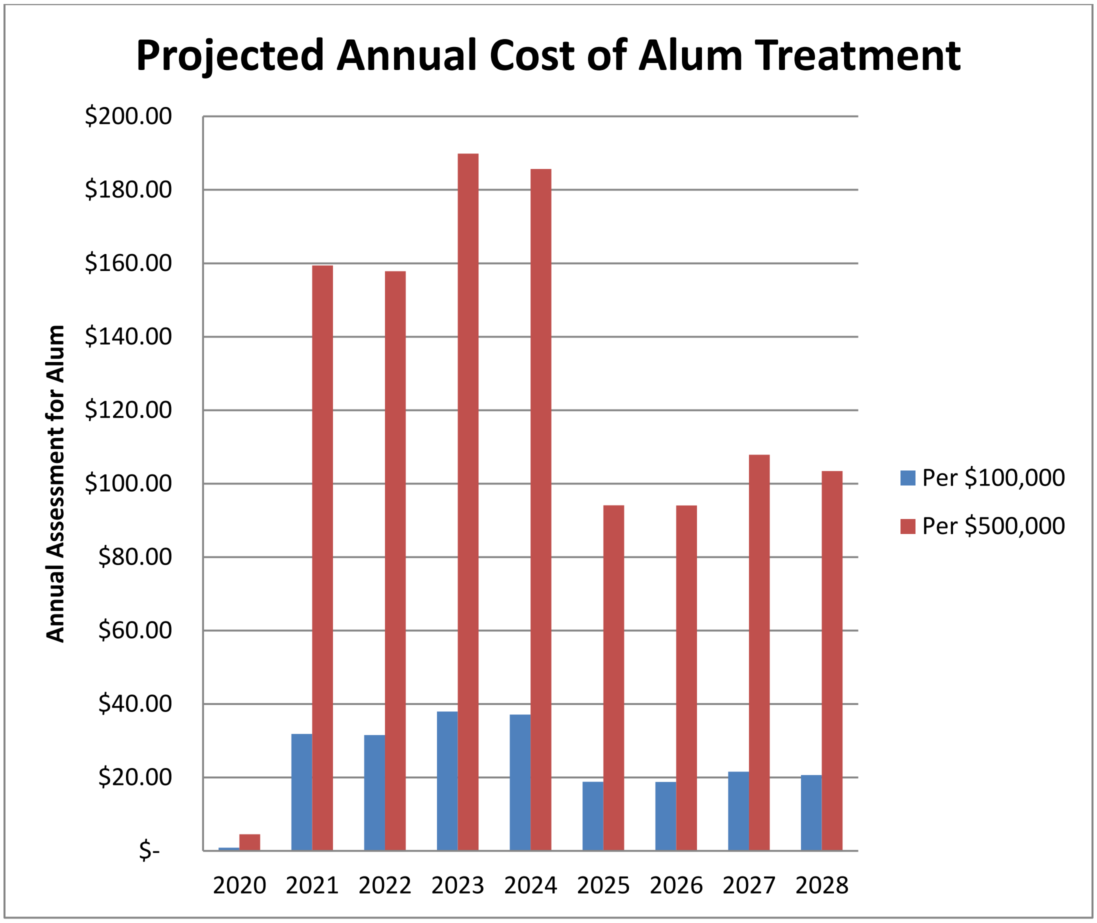

Figure 5. Projected Annual Cost of Alum Treatment to BLPRD Property Owners

MONITORING STRATEGY

Monitoring and evaluation provides critical information for adaptive management. With adaptive management, alum is applied when it is needed as evidenced by in-lake water quality and sediment characteristics. UW-Stout will complete project monitoring which will include 1) in-lake monitoring, 2a and b) Vertical and spatial variations in sediment characteristics 2b) laboratory-derived P release under aerobic conditions, and 3) a report. The total annual budget for planned monitoring is $15,400. The East Balsam Lake Post-Rehabilitation Monitoring and Evaluation Proposal is included as Appendix X. The BLPRD is applying for a Lake Planning Grant to support alum monitoring.

PUBLIC INVOLVEMENT

Information regarding East Balsam water quality and the proposed alum treatments was presented at the 2018 BLPRD Annual Meeting. The BLPRD Board of Commissioners convened an Alum Advisory Committee to review the results of the water quality and alum studies and provide guidance for communications regarding the recommended alum treatment for East Balsam. The alum advisory committee met in April and May of 2019. The committee guided the development of a public informational meeting presentation held June 8, 2019.

2019 BLPRD ANNUAL MEETING

The vote on approving and funding an alum treatment was taken at the 2019 BLPRD Annual Meeting. The planned July 20 meeting was postponed until August 24 because of severe storms in the Balsam Lake area July 19, 2019. The BLPRD presented two resolutions for votes:

Board Resolution 01-2019 (approved by a 153 to 34 vote) resolved the following:

> *The District Board of Commissioners of the Balsam Lake Protection and Rehabilitation District is hereby authorized to engage the necessary suppliers and consultants to implement the East Balsam Basin Water Quality Project and related alum treatments. The Alum Treatments and monitoring thereof are anticipated to take place over a period of eight years comprised of four phases. The funding of the four phases will be a combination of a levy upon taxable property of the District in the form of an irrepealable annual tax and WI DNR grant of $200,000 for each phase sufficient to pay both interest on the loans as it becomes due and repay the loans principal within 2.5 years of the making of each loan.*
>
> *IT IS FURTHER RESOLVED THAT, the Officers and Commissioners of Balsam Lake Protection and Rehabilitation District are authorized and directed to execute any and all actions reasonably necessary to complete such contemplated borrowing transactions and complete the alum applications and related monitoring.*

Board Resolution 02-2019 (approved by a 153 to 35 vote) authorized the first loan for the alum treatment:

> *The District Board of Commissioners of the Balsam Lake Protection and Rehabilitation District is hereby authorized to borrow the sum of* ***Three Hundred and Eighty Five Thousand and 00/100 ($385,000.00)*** *for the purpose of* ***financing the purchase of an alum treatment of the East Balsam basin subject to approval of a WI DNR grant of $200,000.00*** *AND, levy upon all the taxable property of the district a direct and irrepealable annual tax for the purpose of paying, and sufficient to pay both the interest on the loan as it becomes due and repay the loan principal within 2.5 years of making of the loan.*

EAST BALSAM BASIN WATER QUALITY PLAN AMENDMENT PUBLIC REVIEW

Following BLPRD commissioner review and tentative approval at the October 19, 2019 board meeting, this plan amendment was available for public review and comment at the Balsam Lake Public Library and on the BLPRD website http://blprd.com/. Plan amendment availability was announced in the County Ledger Press newspaper and a notice was included in the Dockside newsletter mailed to all BLPRD property owners. Comments were accepted through November 4, 2019, but no public comments were received. The BLPRD Board of Commissioners approved the amendment following WDNR favorable review at their November 16, 2019 meeting.

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James, William F. *East Balsam Lake, Wisconsin: Analysis of Phosphorus Sources, Loading Reduction Scenarios, and Alum Dosage and Application Strategies.* May 2018.

James, William F. University of Wisconsin Stout Sustainability Sciences Institute – Discovery Center. *Internal Phosphorus Loading and Alum Dosage Considerations for East Balsam Lake, Wisconsin.* December 2015.

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APPENDICES

APPENDIX A. INTERNAL PHOSPHORUS LOADING AND ALUM DOSAGE

James, William F. University of Wisconsin Stout Sustainability Sciences Institute – Discovery Center. *Internal Phosphorus Loading and Alum Dosage Considerations for East Balsam Lake, Wisconsin.* December 2015.

Internal Phosphorus Loading and Alum Dosage Considerations for East Balsam Lake, Wisconsin

University of Wisconsin – Stout
Sustainability Sciences Institute – Discovery Center
Center for Limnological Research and Rehabilitation
Department of Biology
Menomonie, Wisconsin

30 December, 2015

OBJECTIVES

The objectives of this investigation were to determine rates of phosphorus (P) release from sediments under laboratory-controlled aerobic and anaerobic conditions, quantify biologically-labile (i.e., subject to recycling via Eh, pH, and bacterially-mediated reactions in the sediment; loosely-bound, iron-bound, and labile organic P) P fractions in the sediment, and estimate aluminum sulfate (alum) dosage scenarios for East Balsam Lake, Wisconsin. Secondarily, seasonal P and chlorophyll (a surrogate of algal biomass) dynamics were examined to better understand internal P loading processes. The specific outcomes and deliverables of this research were to,

1. examine spatial and vertical variations in sediment characteristics and biologically-labile (i.e., subject to recycling via Eh, pH, and bacterially-mediated reactions in the sediment; loosely-bound, iron-bound, and labile organic P) P fractions that are potentially active in sediment internal P loading to estimate the thickness of the active sediment layer the needs to be treated with alum,
2. estimate alum (as aluminum; Al) dosage scenarios for binding redox-sensitive P (i.e., the loosely-bound and iron-bound P fractions) in the upper active sediment layer,
3. provide cost estimates for alum dosage scenarios based on treatment areas in the lake, and
4. examine seasonal P and chlorophyll dynamics in relation to internal P loading.

APPROACH

Summer limnological conditions: East Balsam Lake was sampled at biweekly intervals between May and September at centrally-located station 1 (Figure 1) to exam stratification and dissolved oxygen patterns in relation to chlorophyll, phosphorus, and iron dynamics. The goals were to quantify internal P loading from sediment and potential availability to the phytoplankton community. Specifically, information was needed to determine if oxidized iron was controlling the availability to algae of entrained internal P loading.

In situ vertical profiles of temperature, dissolved oxygen, pH, and specific conductance were collected at 1-m intervals between the lake's surface and bottom using a YSI 6600 data sonde that was precalibrated against known buffers and dissolved oxygen concentration. Water samples were collected over the same depth intervals for analysis using a peristaltic pump (Masterflex) and tubing. Samples for total Fe (TFe), total P (TP) and chlorophyll were pumped directly into a brown polypropylene 500-mL bottle (Nalgene). Samples for dissolved Fe (DFe) and soluble reactive P (SRP) were pumped directly into a 60-cc syringe without exposure to air and filtered into a 60-mL polypropylene bottle using a 0.45 µm poresize filter. Water samples for TP were digested with potassium persulfate according to Ameel et al. (1993) before colorimetric determination. Chlorophyll was determined via a fluorometric technique following extraction in a 1:1 solution of acetone and dimethyl sulfoxide (Welschmeyer 1994). Total metals were digested with a combination of nitric-hydrochloric acids and hydrogen peroxide according to EPA method 3050b. Total and soluble metals were analyzed using atomic absorption spectroscopy (APHA 2005).

Laboratory-derived rates of P release from sediment under aerobic and anaerobic conditions: Sediment cores were collected in late May, 2016, from centrally-located station 1 for determination of rates of P release from sediment under aerobic and anaerobic conditions (Figure 1 and Table 1). Cores were drained of overlying water and the upper 10 cm of sediment was transferred intact to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Surface water collected from the lake was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. Sediment incubation systems consisted of the upper 10-cm of sediment and filtered overlying water contained in acrylic core liners that were sealed with rubber stoppers. They were placed in a darkened environmental chamber and incubated at a constant temperature (20 ^{o}C). The oxidation-reduction environment in the overlying water was controlled by gently bubbling nitrogen (anaerobic conditions, 3 replicates) or air (aerobic conditions, 3 replicates) through an air stone placed just above the sediment surface in each system. Bubbling action insured complete mixing of the water column but did not disrupt the sediment.

Water samples for soluble reactive P were collected from the center of each system using an acid-washed syringe and filtered through a 0.45 µm membrane syringe filter (Nalge). The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. Soluble reactive P was measured colorimetrically using the ascorbic acid method (APHA 2005). Rates of P release from the sediment (mg/m^2 d) were calculated as the linear change in mass in the overlying water divided by time (days) and the area (m^2) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Phosphorus profiles and sediment chemistry: Additional undisturbed sediment cores were collected at five stations (Figure 1) for examination of spatial and vertical variations in sediment P fractions for alum dosage purposes. The sediment core collected at station 1 was sectioned at 1-cm intervals over the upper 6 cm, at 2-cm intervals between 6 and 10 cm, and at 2.5-cm intervals below the 10-cm depth to determine the thickness of the potentially mobile P layer (i.e., concentrations of P are typically greatest in the upper 5 to 10 cm layer, declining to background concentrations below this depth). The upper 5-cm section from additional sediment cores collected at other stations (Figure 1) were analyzed for characterization of spatial variations in sediment chemistry.

All sections were analyzed for moisture content (%), density (g/cm^3), loss-on-ignition (i.e., organic matter content, %), loosely-bound P, iron-bound P, labile organic P, and aluminum-bound P (all expressed at mg/g; Table 2). A known volume of sediment was dried at 105 ^{o}C for determination of moisture content, sediment, and bulk density and burned at 500 ^{o}C for determination of loss-on-ignition organic matter content (Håkanson and Jansson 2002). Phosphorus fractionation was conducted according to Hieltjes and Lijklema (1980), Psenner and Puckso (1988), and Nürnberg (1988) for the determination of ammonium-chloride-extractable P (loosely-bound P), bicarbonate-dithionite-extractable P (i.e., iron-bound P), and sodium hydroxide-extractable P (i.e., aluminum-bound P). A subsample of the sodium hydroxide extract was digested with potassium persulfate to determine nonreactive sodium hydroxide-extractable P (Psenner and Puckso 1988). Labile organic P was calculated as the difference between reactive and nonreactive sodium hydroxide-extractable P.

The loosely-bound and iron-bound P fractions are readily mobilized at the sediment-water interface as a result of anaerobic conditions that lead to desorption of P from sediment and diffusion into the overlying water column (Mortimer 1971, Boström 1984, Nürnberg 1988; Table 3). The sum of the loosely-bound and iron-bound P fraction represents redox-sensitive P (i.e., the P fraction that is active in P release under anaerobic and reducing conditions; redox-P). In addition, labile organic P can be converted to soluble P via bacterial mineralization (Jensen and Andersen 1992) or hydrolysis of bacterial polyphosphates to soluble phosphate under anaerobic conditions (Gächter et al. 1988, Gächter and Meyer 1993, Hupfer et al. 1995). The sum of redox-sensitive P and labile organic P collectively represent biologically-labile P. This fraction is active in recycling pathways that result in exchanges of phosphate from the sediment to the overlying water column and potential assimilation by algae. In contrast, aluminum-bound P is more chemically inert and subject to burial rather than recycling.

Al dosage determination: The upper 5-cm section of sediment collected at station 1, 2, and 3 (Figure 1) was subjected to a range of aluminum sulfate (as Al) concentrations to determine the Al dosage required to inactivate the redox-P fraction (Rydin and Welch 1999). Alum (as aluminum sulfate; $Al_2(SO_4)_3 \cdot 18\ H_2O$) was combined with 0.1 M sodium bicarbonate ($NaHCO_3$) to a concentration of 1.25 g Al/L to form an aluminum hydroxide ($Al(OH)_3$) floc. Aliquots of this solution, diluted to a final volume of 10 mL with distilled water, were added to centrifuge tubes containing the equivalent of 0.025 g dry weight (DW) of fresh sediment to obtain Al concentrations ranging from 0 (i.e., control) to ~ 50 mg Al/g DW sediment. The assay tubes were shaken for a minimum of 2 hours at 20 ^{o}C in a darkened environmental chamber, centrifuged at 500 g to concentrate the sediment, and decanted for redox-P determination (see method description above).

Al dosage was estimated as the concentration (g/m^2) required to bind at least 90% of the redox-P. The dry mass concentration of redox-P (mg/g) was converted to an areal concentration (g/m^2) as,

$$\text{Redox-P (g/m}^2\text{)} = \text{Redox-P (mg/g)} \cdot \rho \text{ (g/cm}^3\text{)} \cdot \theta \cdot h \text{ (m)} \cdot 1{,}000{,}000 \text{ (cm}^3\text{/m}^3\text{)} \cdot 0.001 \text{ (g/mg)} \qquad 1)$$

where, ρ is sediment bulk density (g/cm^3), θ is the percentage of sediment solids (100 – percent moisture content; dimensionless), and h is the thickness of the excess P layer determined from the sediment vertical profile at station 30 (m). The Al concentration (g/m^2) was estimated as,

$$\text{Al (g/m}^2\text{)} = \text{Redox-P (g/m}^2\text{)} \cdot \text{Al:P}_{90\%} \qquad 2)$$

where, Al:P$_{90\%}$ is the binding ratio required to adsorb at least 90% of the redox- P in the sediment. Gallons of alum required to treat profundal sediment and generic cost scenarios were estimated by determining the sediment area (m^2) that was probably contributing to internal P loading.

Maximum allowable Al dosage based on alkalinity and pH in the lake: Addition of aluminum sulfate to a lake leads to hydrolysis and the liberation of hydrogen ions which lowers the pH of the water column. Since Al toxicity to the biota can occur if the pH falls below ~4, maintaining a pH ≥ 6.0 as a margin of safety should also be considered in dose determination (Cooke et al. 2005). For situations where alkalinity is low or the required dosage exceeds the maximum allowable dosage to maintain pH ≥ 6.0, a buffered aluminum sulfate-sodium aluminate treatment will be needed to maintain pH near neutrality. Surface water collected from the lake was analyzed for total alkalinity and pH according to APHA (2005). A titration procedure was used to determine the maximum allowable dosage of aluminum sulfate that can be added and yet maintain pH above 6.0 (Cooke et al. 2005). A 1.25 g Al/L solution of $Al_2(SO_4)_3 \cdot 18\ H_2O$ was used as the titrant and 1.0 mL additions to 500 mL of lake water were each equivalent to 2.5 mg Al/L. Lake water was titrated with the Al solution until an endpoint of pH 6 was reached. A 1.0 mL aliquot of this solution added to 500 mL of lake water is equivalent to 2.5 mg Al/L. The total volume of Al solution needed to titrate lake water to pH 6 was multiplied by 2.5 mg Al/L to estimate the maximum allowable concentration. This calculation was then compared with estimates based on sediment redox-P to ensure that the latter was at or below the maximum allowable dosage. Caution needs to be used because a vertical alkalinity and pH profile over the entire vertical water column needs to be estimated in order to more accurately evaluate the maximum allowable dosage.

RESULTS AND INTERPRETATION

Seasonal limnological conditions

Vertical summer temperature patterns suggested that East Balsam Lake exhibited very weak stratification in early June and August, 2015 (Fig. 2a). During these periods, Schmidt stability was modestly elevated (Fig. 3a) and an epilimnion extended from the lake surface down to the 2-m depth (Fig. 3c). Mean lake temperature increased rapidly in conjunction with the development of temporary stratification in June (Fig. 3a). Periods of temporary stratification coincided with rapid dissolved oxygen depletion and anoxia above the sediment-water interface (Fig. 2b). In June, bottom anoxia was confined to depths greater than 5.5-m while in mid- through late August, anoxic conditions extended up to the 4.5-m depth (Fig. 2b). Water column mixing in mid-June probably disrupted stratification and resulted in reintroduction of dissolved oxygen to the bottom waters, as suggested by declines in Schmidt stability (Fig. 3b). Modest stratification persisted between mid- to late August, resulting in the extended period of bottom water anoxia. Heat loss from the lake between mid-August and September (Fig. 3d) was associated with water column mixing and disruption of stratification and bottom water anoxia by last August.

Total P concentrations were low throughout the vertical water column in May through the end of June, coinciding with chlorophyll concentrations less than 20 µg/L (Fig. 4a). Although bottom water anoxia developed briefly in early June, elevated concentrations of TP and SRP were not detected above the sediment-water interface, compared to patterns during extended hypolimnetic anoxia in August. However, gradients of higher P concentrations could have occurred immediately above the sediment interface that were missed by sampling. In contrast, vertical TP gradients rapidly developed above the sediment interface and extended to the 3.5-m depth by mid-August. This pattern strongly suggested that P was diffusing out of the sediment and into the overlying water column as a result of anaerobic conditions (i.e., internal P loading under anaerobic conditions). Concentrations of TP increased to a maximum of ~ 0.275 mg/L immediately above the sediment interface during this period and greater than 80% was as SRP (Fig. 4b), directly available for algal assimilation. Apparent water column mixing and reintroduction of dissolved oxygen to the bottom waters in late August resulted in disruption of hypolimnetic TP gradients and declines in SRP concentrations to low, undetectable values. Soluble P was likely adsorbed onto chemically-oxidized Fe and deposited back to the sediment during this period.

Chlorophyll increased rapidly throughout the water column between early and mid-July. (Fig. 4c). Maximum concentrations exceeded 90 µg/L in the upper 3-m water column by early August. Chlorophyll declined throughout the water column between early and mid-September in conjunction with a 5 in precipitation event (see Fig. 7). A secondary maximum developed in late September. Although not as intense as the peak in early August, concentrations nevertheless exceeded 60 µg/L in the upper 3-m by late September.

Regression analysis indicated that mean TP and chlorophyll were significantly related on all dates except late August and early September (Fig. 5). This pattern could be attributed to two factors. During most of the summer, TP explained 97% of the variation in chlorophyll, indicating that all the P was in particulate form as algal biomass. In contrast, TP was higher with respect to chlorophyll on the two anomalous dates that were associated with the period of internal P loading (Fig. 4). Thus, the mean TP concentration increased on 31 August and 15 September even though mean chlorophyll declined on the dates (Fig. 6). High mean TP with respect to mean chlorophyll during this period coincided with mixing of internal P loads into the entire water column. Thus, a portion of the TP was associated with the internal P load on those dates, specifically adsorbed to oxidized Fe (as discussed below). Otherwise, algal biomass and growth was limited by P and varied as a function of TP concentration during the summer of 2015.

In general, mean TP and chlorophyll increased rapidly to a peak between early July and early August (Fig. 6a and c). Secchi transparency was highest in May at greater than 5 m (i.e., almost to the bottom of the lake) and declined as a function of increasing chlorophyll and TP concentration (Fig. 6b). The strong negative relationship between mean chlorophyll and Secchi transparency indicated that algal biomass (i.e., not resuspended sediment) was responsible for poor water clarity in the lake (Fig. 5). The Wisconsin TSI varied from mesotrophic conditions in May to eutrophic conditions in July through September (Fig. 6d). Mean summer (June – September) values are shown in Table 4.

Seasonally, total and soluble Fe concentrations were very low in the bottom water of East Balsam Lake (Fig. 7) despite relatively high iron concentrations in the sediment (see below). Bottom water total Fe increased slightly during periods of anoxia in August. Vertically in the water column, slightly elevated concentrations of total and soluble iron were detected immediately above the lake sediment-water interface during periods of bottom water anoxia in mid- and late August (Fig. 8). Importantly, the Fe:P ratio in the anoxic bottom waters on these dates was only ~ 1.5:1. This pattern indicated that Fe flux from the sediment into the water column was low relative to SRP during periods of anoxia. Thus, during mixing periods, reoxygenation, and chemical oxidation of soluble Fe to Fe^{3+}, adsorption of soluble P and removal to the sediment was incomplete (Fe:P ratio for complete P binding is ~ 4:1), resulting in SRP availability for algal uptake.

The estimated buildup of TP mass between late June and mid-September was ~ 520 kg. Some of this TP undoubtedly originated from watershed runoff that was not quantified during the study while another portion was likely derived internally from the sediment. Barr Engineering (2011) estimated a combined P income from watershed and internal P loading of 457 kg for 2010. In particular, daily precipitation exceeded 2 in in early July, early and mid-August, and mid-September, 2015 (Fig. 9). It exceeded 5 in early September, 2015. The change in TP mass over the June-September period divided by the entire surface area of East Balsam Lake was ~ 2.8 mg/m^2 d (520 kg/ [2,187,899 m^2 · 84 d]).

Diffusive phosphorus flux and sediment spatial and vertical characteristics

P mass and concentration increased approximately linearly in the overlying water column of station 1 sediment systems maintained under anaerobic conditions (Fig. 10). The mean P concentration maximum in the overlying water at the end of the incubation period (i.e., day 10) was moderate at 0.200 mg/L (± 0.04 standard error; SE; Table 5). The mean rate of P release under anaerobic conditions was also moderate at 2.30 mg/m^2 d (± 0.46 SE; Table 5) but indicative of eutrophic conditions (Nürnberg 1988). The rate was similar to the rate of TP mass buildup of 2.8 mg/m^2 d (see above).

Although P accumulation in the overlying water column was much less under aerobic conditions, P diffusion from sediment nevertheless occurred (Fig. 10), resulting in a moderate mean P concentration maximum of 0.039 mg/L (± 0.010 SE; Table 5) in the overlying water column at the end of the incubation period. The mean rate of P release under aerobic conditions was moderate at 0.27 mg/m^2 d (± 0.04 SE; Table 5) and, thus, represented a potentially important internal source of P loading to the lake.

Typically, rates of P release are higher under anaerobic versus aerobic conditions, due to binding of P onto iron-oxyhydroxides (Fe-OOH) in the sediment oxidized microzone under the latter condition and suppression of diffusive flux into the overlying water column (Mortimer 1971). Indeed, diffusional P flux from sediment can be negligible under aerobic conditions when Fe concentrations are sufficiently high in relation to P (i.e., Fe:P binding ratio > 10:1; Jensen et al. 1992). However, East Balsam Lake sediments may act as a modest net P source even under aerobic conditions, a finding that needs to be considered in algal bloom management.

Moisture content was relatively high in the upper 5-cm sediment section at all stations, often exceeding 95% (Table 6). This pattern was indicative of fine-grained and very flocculent surface sediment. Vertically through the sediment column at station 1, moisture content was very high (i.e., the percentage of the sediment section composed of interstitial or porewater; ~ 95%), while solids content was low (i.e., the percentage of the sediment sediment composed of sediment dry mass; ~ 5%), between the sediment surface and the 15-cm depth (Fig. 11). Sediment wet bulk density (i.e., the mass of dry sediment and associated interstitial water per cm^3) was very low (Fig. 11), reflecting high interstitial water content (i.e., the density of water is ~ 1.0 g/cm^3). Ideally, moisture content should be higher while sediment density and solids content should be lower in relation to the density of the Al floc in order to promote its rapid sinking through the upper mobile P layer for maximum binding efficiency. The organic matter content was moderately high in the upper 4-cm layer, exceeding 40% (Table 6 and Fig. 11). Organic matter content increased below the 4-cm depth and approached 50% (Fig. 11). Reasons for this inverse profile pattern for organic matter content are not precisely clear but may be related to historical sedimentation from the watershed.

Loosely-bound P concentrations were relatively low in the upper 5-cm sediment layer at all stations and only represented ~2% of the redox-sensitive P concentration (i.e., the sum of loosely-bound and iron-bound P; Fig. 12). Loosely-bound P is typically lowest compared to other fractions because it reflects porewater P and P adsorbed to calcium carbonate (calcite) versus P bound to mineral and amorphous polymers. Loosely-bound P ranged between 0.006 mg/g and ~0.020 mg/g in the upper 5-cm section over all stations. Iron-bound P accounted for > 95% of the redox-sensitive P in the upper 5-cm sediment layer at all sediment sampling locations (Table 6 and Fig. 12). Concentrations were highest at station 2, which was shallower and located in the northern portion of the lake. Iron-bound P at other stations was similar at a mean of 0.493 mg/g (± 0.038 SE). Overall, loosely-bound P accounted for less than 1% of the biologically-labile P fraction (i.e., the sum of the loosely-bound, iron-bound, and labile organic P fractions; Fig. 12), By contrast, iron-bound P and labile organic P each represented ~ 50% of the biologically-labile P fraction.

Vertically in the sediment column for the core collected at station 1, iron-bound P and labile organic P exhibited concentration peaks over the upper 6 to 8 cm (Fig. 13). Concentrations of these constituents were greatest in the upper 2 cm at 0.38 mg/g and 0.49 mg/g for iron-bound P and labile organic P, respectively. In addition, labile organic P was the dominant fraction in this sediment core. Concentrations declined to background levels below the 8-cm depth and were relatively constant below that depth. This vertical concentration profile indicated the buildup of biologically-labile P and redox-sensitive P near the sediment surface in excess of breakdown and burial (i.e., potentially mobile P; Fig. 14), a pattern typically observed in eutrophic lake sediments (Carey and Rydin 2011). Others have shown that the mass of this P in the surface sediment layer closely approximated the annual gross internal P loading rate (Rydin et al. 2011; Malmaeus et al. 2012). Overall, the vertical profile suggested that inactivation of redox-sensitive P in the upper 8-cm sediment layer needed to be considered in aluminum sulfate dosage estimation to control internal P loading (Fig. 13).

Vertical profiles of total and extractable Fe are shown in Figure 14 for comparison with TP and extractable biologically-labile P concentrations. Total Fe concentrations were high relative to TP and biologically-labile P, resulting in a TFe:TP and extractable Fe:P ratios of ~ 15:1 and 35:1, respectively. High ratios suggested that Fe is probably completely binding P under oxidized conditions. Thus, oxidized Fe potentially binds and maintains P within the upper sediment during periods of mixing and dissolved oxygen entrainment. High Fe:P ratios also corroborated the finding that rates of P release from sediments were somewhat low under aerobic conditions, further suggesting Fe control of P in the sediment.

Alum dosage estimation and cost analysis

For sediment assay tubes subjected to a range of Al concentrations, the redox-sensitive P concentration declined exponentially as a function of increasing Al concentration, due to binding onto the $Al(OH)_3$ floc (Fig. 15). Exposure of a relatively low concentration of Al (~ 5 mg/g sediment dry mass) to East Balsam Lake sediment resulted in binding of ~ 60% of the redox-sensitive P. However, much more Al was needed to bind and sequester at least 90% or more of the redox-sensitive P because other constituents in the sediment (organic compounds and other anions) were also competing with PO_4^{3-} for the same binding sites.

Alum dosage was based on the Al concentration required to inactivate the redox-sensitive P fraction and 20% of the labile organic P in the upper 8-cm sediment layer. Since the labile organic P fraction represented over 50% of the biologically-labile P, mineralization of a portion of this fraction over time could contribute additional mobile P that would need to be controlled. For station 1 (i.e., the central station in the lake), the mean mobile P concentration in the vertical sediment column to be sequestered by Al (i.e., Fig. 13) was 0.275 mg/g, lower that the other station concentrations (Table 7). The Al concentration needed to sequester the mobile P in that layer was ~ 74 g/m^2 (Table 7). There was variation in that a second core collected at station 1 exhibited a higher mobile P concentration than the core that was sliced into 1-cm sections (i.e., Fig. 12). The Al dose needed for inactivation of mobile P in the surface sediments collected at the other stations ranged between 90 and 120 g/m^2 (Table 7). The mean over all determinations was ~ 97 g/m^2. A slightly higher Al dose of 100 g/m^2 is recommended to account for additional organic P breakdown and P diffusion from deeper sediments into the Al floc over time. The treatment area is shown in Figure 16. The suggested treatment area is sediment located within the 10-ft contour. The estimated treatment cost to inactivate redox-sensitive P in the upper 8-cm sediment layer within the 10-ft contour of the lake was ~$959,000, including an estimated setup fee (i.e., transport of Al to the site, labor, per diem, etc.; Table 8). To apply the full dosage and maintain pH > 6, a aluminum sulfate-sodium aluminate application would be needed (see below). Sodium aluminate buffers pH to ~ 7.0. Cost is slightly higher at ~ $1,072,000 (Table 8).

Recent lake Al dosage estimates have ranged between ~ 94 g Al/m^2 and ~145 g Al/m^2 (Table 9). These more recent Al dosage ranges are generally higher compared to historical ranges (Huser 2012) because they were targeted toward inactivation of the excess P pool in the sediment. The proposed Al dosage of ~ 100 g/m^2 to treat the upper 8-cm sediment layer is similar to these recent treatment ranges. The East Balsam Lake Al dosage is slightly lower because the mobile P concentration is lower and the moisture content is very high. Thus, the overall sediment P mass that needs to be treated is lower.

The total alkalinity at the time of sediment core sampling was moderately low at ~80 mg $CaCO_3$/L, suggesting low buffering capacity for regulating pH during alum application. Al binding of P is most efficient within a pH range of 6 to 8. As pH declines below 6, Al becomes increasingly soluble (as Al^{3+}) and toxic to biota. The maximum allowable Al dosage that could be applied and yet maintain pH at or above 6, determined via jar tests (Cooke et al. 2005), was low at only 11 mg Al/L (Table 10). Cooke et al. (2005) reported that treatment longevity (i.e., years of successful P control) generally coincided with Al dosages greater than ~ 12 to 25 g/m^3 for stratified lakes (range = 11.7 to 30 g/m^3; Table 9). The overall estimated volume-based Al dosage of 28 mg/L was much higher than the maximum allowable Al dosage. This pattern was due to the relatively low alkalinity and, thus, low buffering capacity of lake water. Thus, there would be potential concerns regarding low pH during application if the entire dosage were applied in one treatment. An additional alkalinity-pH vertical profile would need to be examined during the spring to early summer period to verify and refine the maximum allowable Al dose.

The overall desired objective of an alum application in East Balsam Lake is to have the $Al(OH)_3$ floc mix and sink through the upper 8-cm sediment layer to bind the redox-sensitive P that is contributing to internal P loading and algal bloom development. In order to meet these objectives, the Al floc needs to be denser than the upper sediment layer and sink through that layer relatively quickly (i.e., within 3 months or less). Physical disturbance and mixing caused by resuspension during spring and fall turnover periods can also distribute the Al floc into the sediment.

However, mixing of the Al floc into the sediment may likely be incomplete, resulting in the majority of the Al floc positioned on top of the original sediment surface. In that case, sequestration of mobile P will occur via upward diffusion into the Al floc over time (i.e., years). This process will be effective in controlling internal P loading but post-application monitoring will be needed to evaluate the binding efficiency of the Al floc for diffused P. Recent research has suggested that $Al(OH)_3$ binding efficiency for P decreases significantly (i.e., > 75% decrease) if it has not been exposed to and reacted with sediment redox-sensitive P within 90 days, due to changes in crystalline structure in the absence of adsorbed P (de Vicente et al. 2008a). Furthermore, as binding sites on the $Al(OH)_3$ floc become saturated with redox-sensitive P, additional P diffusing into the alum layer from deeper sediments over time can become re-adsorbed to Fe~(OOH) (i.e., redox-sensitive P; Lewandowski et al. 2003), eventually diffuse out of the sediment under anaerobic and reducing conditions, and again become an important internal P loading source years after alum treatment. Organic P mineralization to PO_4^{3-} can also contribute additional P to the Al floc over time. Thus, additional future Al applications may be needed to counteract any reduced binding efficiency. Cost and dosage estimation of a possible future application to address organic P mineralization and upward P diffusion into the alum floc would require additional analysis of sediment. A suggested maintenance Al dosage is shown in Table 8.

One current unknown is the exact $Al(OH)_3$ floc density after application, reaction with water, and deposition to the sediment. However, preliminary indications are that Al floc density is very low during the first 6 to 12 months after application. Thus, surface sediment wet bulk density should ideally be very low and moisture content high, on the order of 95% or greater, in order to promote sinking and exposure of the Al floc to redox-sensitive P. Sediments in East Balsam Lake do exhibit a very high moisture content and meet this criteria. Furthermore, periodic mixing and sediment disturbance during periods of turnover and high winds would act to promote some incorporation of the Al floc deeper into the sediments for exposure to mobile P.

To date, there is no universally accepted and proven alum application strategy to maximize P binding effectiveness and longevity. Although there have been instances of multiple applications over a period of years (Lewandowski et al. 2003), generally, lake Al treatments in the upper midwestern United States have been one-time applications. In addition to the density and sinking concerns identified above, input of new sediment from the watershed can accrete over the $Al(OH)_3$ floc over time, reducing treatment effectiveness and longevity (Lewandowski et al. 2003, Cooke et al. 2005). For shallow lakes such as East Balsam Lake, resuspension of sediments from shallower regions and focusing to deeper treated areas would also represent a significant input of new sediment that could bury the $Al(OH)_3$ floc (Huser et al. 2011). As mentioned earlier, upward diffusion of P through the alum layer from deeper sediments can eventually lead to P flux into the overlying water column, depending on the extent of binding site saturation by P on the $Al(OH)_3$ floc. Although the $Al(OH)_3$ floc continues to adsorb P for years (Lewandowski et al. 2003), its P binding efficiency apparently decreases over time (de Vicente et al. 2008a). If the $Al(OH)_3$ floc does not entirely sink through the mobile P layer and, instead, stabilizes on top of sediments with high redox-sensitive P concentration, upward P diffusion from deeper sediment layers could eventually overwhelm the capacity of the $Al(OH)_3$ floc to bind this additional sediment P source. De Vicente et al. (2008b) suggested that smaller doses spread out over several years might maintain higher P binding efficiencies. More research is clearly needed to develop effective application strategies to maximize internal P loading reduction and extend Al treatment success and longevity.

To alleviate low pH and toxicity issues during treatment and promote maximum P binding efficiency on the $Al(OH)_3$ floc, the Balsam Lake Protection and Rehabilitation District (BLPRD) should consider application of aluminum sulfate-sodium aluminate to alleviate concerns over temporary declines in pH during application. A future second maintenance treatment should be anticipated if P diffusion from deeper sediment layers into the $Al(OH)_3$ floc is not completely sequestered and instead becomes an important internal P loading source during bottom water anoxia. Since this transition may take several years, laboratory sediment P flux and sediment vertical profiles should be monitored annually to more accurately determine the optimal timing of application and Al dosage for future treatment. An example Al application and monitoring scenario is shown in Table 11.

Treatment effectiveness (i.e., maintenance of summer total P at 50% or less of pretreatment concentrations) and longevity can be projected using regression models developed by Huser et al. (2014). The current Al dosage of 100 g/m^2 is projected to be effective for ~ 46 years if carp are not present in high densities (Table 12). Carp tend to disturb sediment directly and resuspend mobile P from deeper anaerobic sediment. These factors reduce P binding efficiency and longevity of effectiveness. With carp present at moderate to high densities, projected effectiveness is 21 years. Longevity of effectiveness for a range of Al doses is shown in Table 12. This projection needs to be considered with caution, however, because it does not include critical variables such as P concentration in the sediment, changes in Al binding efficiency over time, and the possibility of additional P mineralization from organic compounds. It merely provides a comparative projection based on other treatments world-wide.

An important consideration is the potential for future maintenance applications to enhance effectiveness and extend longevity of sediment P control. Although a maximum Al dose has been estimated to sequester sediment P contributing to internal loading in East Balsam Lake, exposure to the upper 8-cm versus changes in P binding efficiency as the Al floc ages and becomes more crystalline may result in reoccurrence of internal P loading in the future as discussed above. Al binding effectiveness and control of internal P loading should be monitored annually by examining changes in sediment core mobile P and rates of P release under anaerobic conditions. If P binding effectiveness diminishes due to diffusion of P into the Al floc in excess of binding efficiency, a maintenance Al dose can be applied to sequester P that has become an important source of internal loading.

Because there is some scientific uncertainty about changes in Al binding efficiency during aging and crystallization in relation to P diffusion into the floc, an adaptive management approach is needed that includes post-treatment monitoring to assess treatment effectiveness. Under this scenario, better informed decisions can be made regarding the need for and timing of additional applications. For instance, using this approach on nearby Half Moon Lake (Eau Claire, WI) has led to the finding that another lower Al dose treatment is needed 5 years after initial application. Post-treatment annual monitoring found that P was diffusing into the Al floc from deeper sediments at a rate that was greater than the rate of P binding. Essentially, upward diffusion of very high P concentrations in the sediment (much higher than East Balsam Lake) were beginning to overwhelm the binding effectiveness of the aging Al floc.

Finally, Al application should occur in May to early June when P concentrations are relatively low in the water column. Since the Al floc sequesters P in the water column and fills binding sites as it sinks, it is best to apply Al during a period of low water column P in order to maximize available binding sites for sediment redox-sensitive P sequestration.

Conclusions and future research needs

A critical finding was detection of intermittent bottom water anoxia during the summer. Although soluble Fe and SRP temporarily increased in the water column above the sediment-water interface during these periods, the Fe:P ratio was very low. This pattern suggests that soluble Fe is reacting with other constituents in the sediment porewater (i.e., sulfur or organic matter) rather than diffusing into the water column. As a result, there is not enough Fe to bind and remove all the SRP during subsequent mixing periods. SRP buildup in the bottom waters during anoxia is, thus, directly available for algal uptake and growth. James et al. (2015) found a very similar Fe-P pattern in nearby Cedar Lake, WI.

It appeared that algal bloom development actually preceded the development of bottom water anoxia in August. However, seasonal biweekly sampling may not have provided enough resolution to detect other possible periods of temporary anoxia in July, for instance. More detailed information on dissolved oxygen patterns at the sediment-water interface and water column temperature stratification patterns is needed to better quantify relationships between temporary stratification, anoxia, diffusive P flux from sediment, and algal bloom development in order to clarify linkages between internal P loading and cyanobacteria in East Balsam Lake.

I suggest that thermistors (i.e., temperature data loggers) be deployed in the lake at ~ 0.5-m to 1-m intervals to record temperature hourly over the course of the summer to better document temporary stratification patterns. In addition, deployment of a dissolved oxygen monitor near the lake bottom to record changes at hourly intervals would be useful in better identifying periods and duration of anoxia in the lake. Finally, more information on bottom soluble iron and phosphorus concentrations during periods of anoxia would be important to verify the low Fe:P ratio found in 2015. East Balsam Lake temperature and dissolved oxygen patterns are very dynamic, requiring remote data loggers to capture periods of stratification and dissolved oxygen depletion that might occur at night. Higher resolution information on bottom water soluble iron and phosphorus during anoxia needs to be coupled with chlorophyll dynamics in order to clarify probably linkages between internal P loading and cyanobacterial bloom development.

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Table 1. Station identification and numbers of sediment cores collected for determination of rates of phosphorus (P) flux under aerobic or anaerobic conditions, biologically-labile P fractions, and the dosage of aluminum (Al) required to bind redox-sensitive P.

Station	P Flux		P fractions		Al dosage
	Aerobic	Anaerobic	upper 5 cm	Vertical profile	
1	3	3	1	1	1
2			1		1
3			1		1
4			1		
5			1		

Table 2. Sediment physical-textural characteristics, phosphorus species, and metals variable list.

Category	Variable
Physical-textural	Moisture content
	Wet and dry sediment bulk density
	Organic matter content
Phosphorus species	Loosely-bound P
	Iron-bound P
	Labile organic P
	Aluminum-bound P

Table 3. Sediment sequential phosphorus (P) fractionation scheme, extractants used, and definitions of recycling potential.

Variable	Extractant	Recycling Potential
Loosely-bound P	1 M Ammonium Chloride	Biologically labile; Soluble P in interstitial water and adsorbed to $CaCO_3$; Recycled via direct diffusion, eH and pH reactions, and equilibrium processes
Iron-bound P	0.11 M Sodium Bicarbonate-dithionate	Biologically labile; P adsorbed to iron oxyhydroxides (Fe(OOH); Recycled via eH and pH reactions and equilibrium processes
Labile organic P	Persulfate digestion of the NaOH extraction	Biologically labile; Recycled via bacterial mineralization of organic P and mobilization of polyphosphates stored in cells
Aluminum-bound P	0.1 N Sodium Hydroxide	Biologically refractory; Al-P minerals with a low solubility product

Table 4. Mean summer (JUN-SEP) total phosphorus (P), chlorophyll, and Secchi transparency with corresponding Wisconsin trophic state index values for East Balsam Lake, 2015.

Variable	Concentration	WI-TSI
Total P (mg/L)	0.055	58
Chlorophyll (ug/L)	46.2	62
Secchi (m)	1.51	56

Table 5. Mean (1 standard error in parentheses; n = 3) rates of phosphorus (P) release under aerobic and anaerobic conditions and mean P concentration (n = 3) in the overlying water column near the end of the incubation period for intact sediment cores collected at Station 1 in East Balsam Lake, WI.

Station	Diffusive P flux			
	Aerobic		Anaerobic	
	(mg/m^2 d)	(mg/L)	(mg/m^2 d)	(mg/L)
1	0.27 (0.04)	0.039 (0.010)	2.30 (0.46)	0.200 (0.04)

Table 6. Vertical variations in physical-textural characteristics, loosely-bound phosphorus (Loose-P), iron-bound P (Fe-P), labile organic P, aluminum-bound P (Al-P), redox-sensitive P (i.e., the sum of the loosely-bound and iron-bound P fractions; redox-P, and biologically-labile P (i.e., redox-P plus labile organic P) at sediment sampling stations in East Balsam Lake.

Station	Depth	Section		Moisture	Solids	Sediment Density		Organic	Loose-P	Fe-P	Labile org P	Al-P	Redox-P	Biol-labile P
		Top	Bottom	content	content	Dry	Wet	matter						
	(m)	(cm)	(cm)	(%)	(%)	(g/cm^3)	(g/cm^3)	(%)	(mg/g)	(mg/g)	(mg/g)	(mg/g)	(mg/g)	(mg/g)
1	5.6	0	1	95.5	4.5	0.046	1.016	42.7	0.012	0.405	0.507	0.097	0.417	0.924
		1	2	95.2	4.8	0.049	1.016	46.2	0.006	0.341	0.481	0.084	0.347	0.828
		2	3	95.0	5.0	0.051	1.017	43.9	0.006	0.233	0.376	0.070	0.239	0.615
		3	4	95.2	4.8	0.050	1.016	46.3	0.004	0.164	0.326	0.076	0.168	0.494
		4	5	95.2	4.8	0.049	1.015	50.0	0.006	0.150	0.288	0.070	0.156	0.444
		5	6	95.3	4.7	0.049	1.015	48.8	0.006	0.137	0.267	0.066	0.143	0.410
		6	8	95.2	4.8	0.049	1.015	49.6	0.004	0.102	0.212	0.059	0.106	0.318
		8	10	95.4	4.6	0.047	1.014	50.0	0.010	0.120	0.216	0.074	0.130	0.346
		10	12.5	95.2	4.8	0.050	1.016	48.5	0.012	0.123	0.182	0.056	0.135	0.317
		12.5	15	94.6	5.4	0.056	1.018	47.7	0.012	0.178	0.182	0.101	0.190	0.372
2	4.5	0	5	95.2	4.8	0.051	1.018	42.3	0.019	0.890	0.630	0.124	0.909	1.539
3	5.6	0	5	95.0	5.0	0.052	1.018	42.4	0.016	0.574	0.560	0.098	0.590	1.150
4	5.5	0	5	95.4	4.6	0.047	1.017	42.0	0.018	0.520	0.596	0.100	0.538	1.134
5	5.1	0	5	95.6	4.4	0.044	1.016	43.0	0.006	0.484	0.593	0.112	0.490	1.083

Table 7. Initial estimated alum (as Al) dosage to inactivate redox-sensitive P plus at least 20% of the labile organic P in the upper 8-cm sediment layer.

Station	Mobile P		Al dose
	(mg/g)	(g/m^2)	(g/m^2)
1[a]	0.275	1.067	74
1[b]	0.509	2.016	94
2	1.035	4.039	120
3	0.702	2.848	108
4	0.657	2.475	98
5	0.609	2.159	90
Mean	0.631	2.434	97
Recommended			100[c]

[a] Core 1 was sectioned at 1-cm intervals for vertical concentration profile analysis

[b] Core 2 was sectioned over the upper 5-cm and homogenized for analysis

[c] Slightly higher dose to account for release from organic sediments and deeper sediments

Table 8. Approximate cost scenario to treat the upper 8-cm sediment layer located within the 10-ft depth contour of East Balsam Lake with aluminum sulfate (alum) or aluminum sulfate-sodium aluminate.

Variable	Alum	Alum-aluminate
Treatment area (acres)	300	
Al dosage (g/m^2)	100	
Cost for initial application ($)	$959,050	$1,071,970
Cost for later maintenance application if necessary ($)[a]	$479,525	$535,985

[a] Represents 50 g/m^2 over the same treatment area

Table 9. Recent and proposed alum (as Al) dosages for various lakes. An asterisk denotes a future treatment.

Lake	Al Dose ($g\ Al\ m^{-2}$)	Reference
East Balsam Lake, WI	100	Present study
Recent treatments		
Black Hawk, MN	145	(unpubl. data)
Tiefwarensee, Germany	137	Wauer et al. (2009)
East Alaska, WI	132	Hoyman (2012)
Half Moon, WI[1]	115	James (2011)
Susser See, Germany	100	Lewandowski et al. (2003)
Green, WA	94	Dugopolski et al. (2008)
Proposed future treatments		
Big Chetac, WI	135	(unpubl. data)
Squaw, WI*	120	(unpubl. data)
Cedar, WI*[2]	116	(unpubl. data)
Halsted's Bay, Minnetonka, MN*[3]	105	(unpubl. data)
Long Lake, WI	105	(unpubl. data)
Bald Eagle, MN*	100	(unpubl. data)

[1] West and east arm dosages were 150 and 75 g/m^2, respectively

[2] Average of a stratified treatment at 130 and 100 g/m^2

[3] Average of a stratified treatment at 140 and 80 g/m^2

Table 10. A comparison of the maximum allowable Al dose, based on a titration assay and nomograph estimate presented in (Cooke et al. 2005) and the the areal sediment redox-P based Al dosage converted to a concentration for the profundal anoxic region of Long Lake. Al dosages and longevity for other unstratified and stratified lakes are from Cooke et al (2005). Numbers on parentheses denote percent reductions in in total phosphorus. Longevity = as of publication of Cooke et al. (2005).

Lake		Al Dose ($g\ Al/m^3$)	Observed Longevity (years)
East Balsam Lake	Maximum allowable	11	
	100 $g\ Al/m^2$ over the 10-ft contour	28	
Unstratified lakes	Long Kitsap County	5.5	11 (30%)
	Pickerel	7.3	<1
	Long Thurston County North	7.7	>8 (56%)
	Pattison North	7.7	7 (29%)
	Wapato	7.8	<1
	Erie	10.9	>8 (75%)
	Campbell	10.9	>8 (46%)
Stratified lakes	Eau Galle	4.5	<2
	Morey	11.7	8 (60%)
	Cochnewagon	18	6 (not reported)
	Dollar	20.9	18 (68%)
	Annabessacook	25	13 (41%)
	West Twin	26	18 (66%)
	Irondoquoit Bay	28.7	5 (24%)
	Kezar	30	9 (37%)

Table 11. An example adaptive management scenerio approach in which an initial Al dose of ~ 100 g/m^2 is applied to East Balsam Lake sediments in year 1. The second Al application and dose is determined via annual sediment profile monitoring. In this example, annual sediment core vertical profiling indicated that a second application should occur in year 5 at a dose estimated from similar core analysis.

Variable	Year 1	Year 2	Year 3	Year 4	Year 5
Al application	■				■
Assessment[1]	■	■	■	■	■

[1] Sediment core collection and vertical profile monitoring

Table 12. Projected Al treatment effectiveness longevity (i.e., years of effectiveness in maintaining reduced P in the water column) based on predictive models in Huser et al. (2014). Effectiveness is defined as maintenance of water column P 50% below pretreatment levels.

Al Dose (g/m^2)	No carp (y)	Carp present (y)
90	40	18
95	43	19
100	**46**	**21**
125	61	28
150	78	36

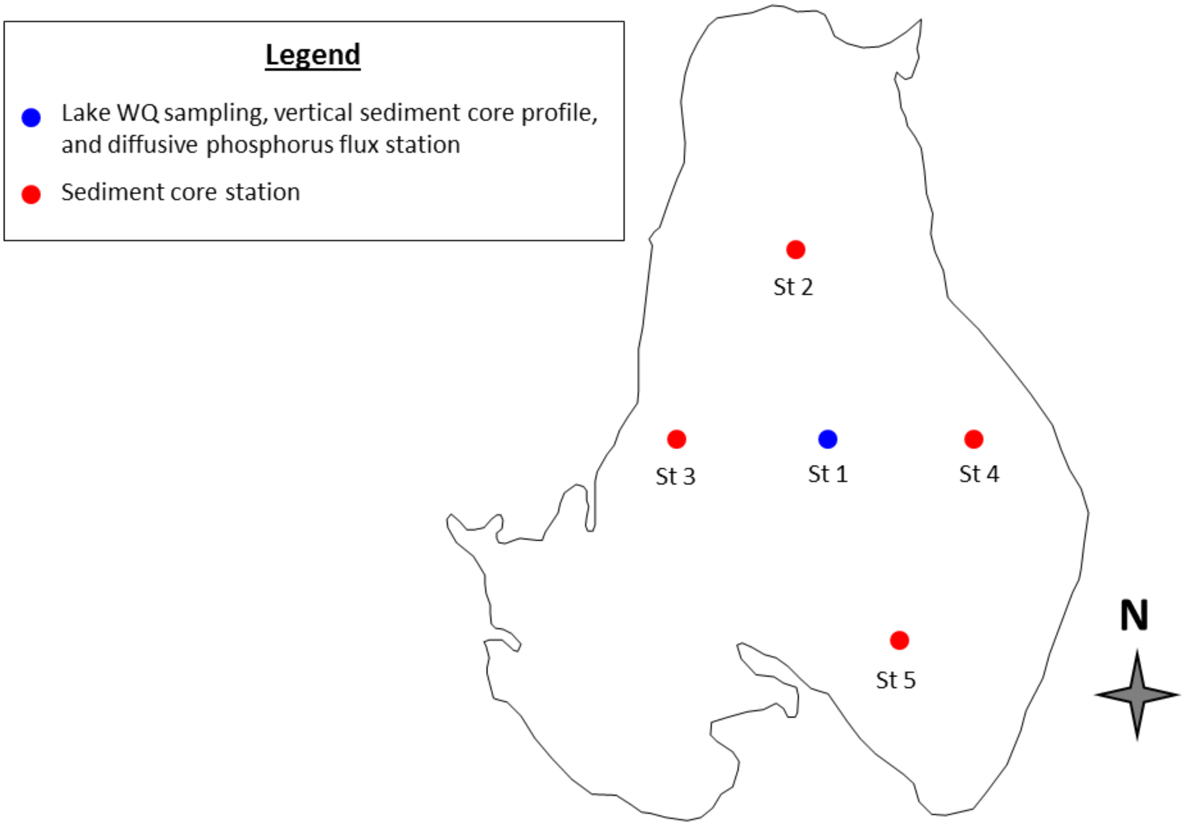


Figure 1. Station locations in East Balsam Lake.

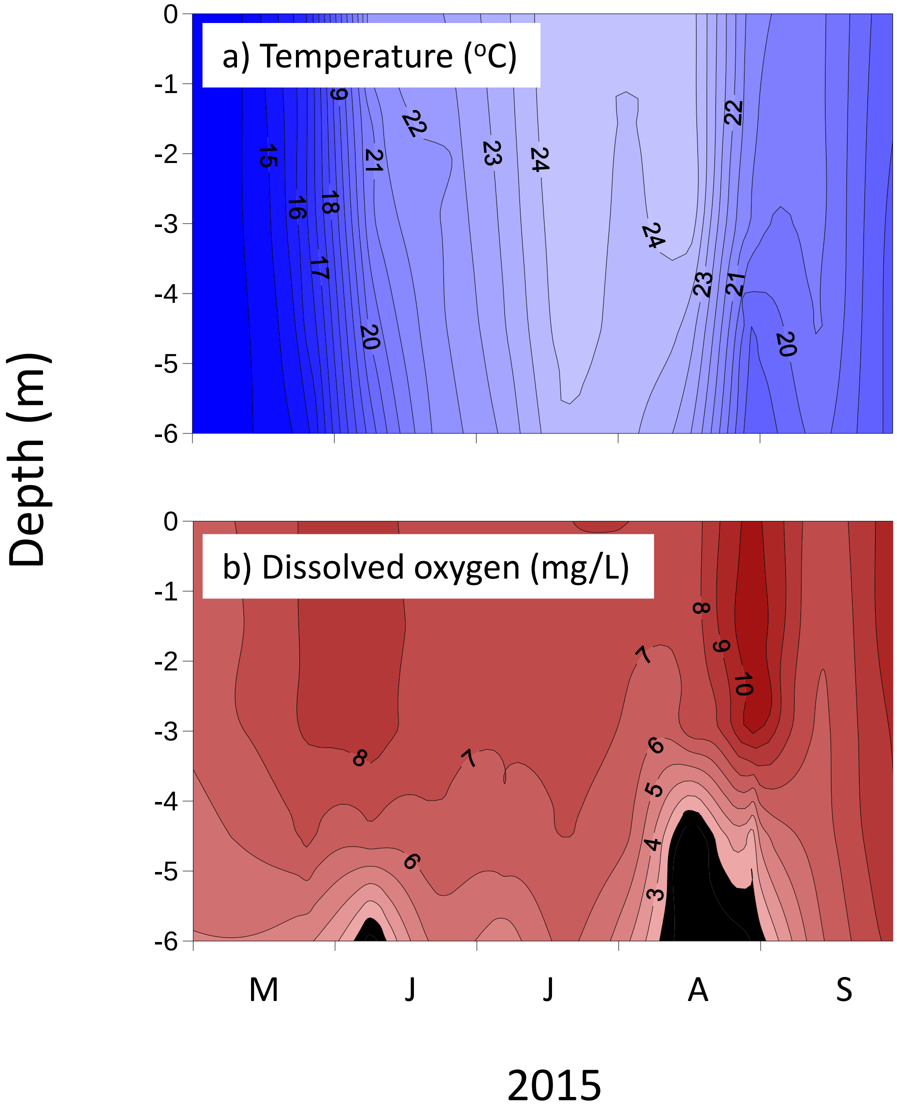


Figure 2. Water temperature and dissolved oxygen contours. The shaded black areas in panel b denote periods of anoxia.

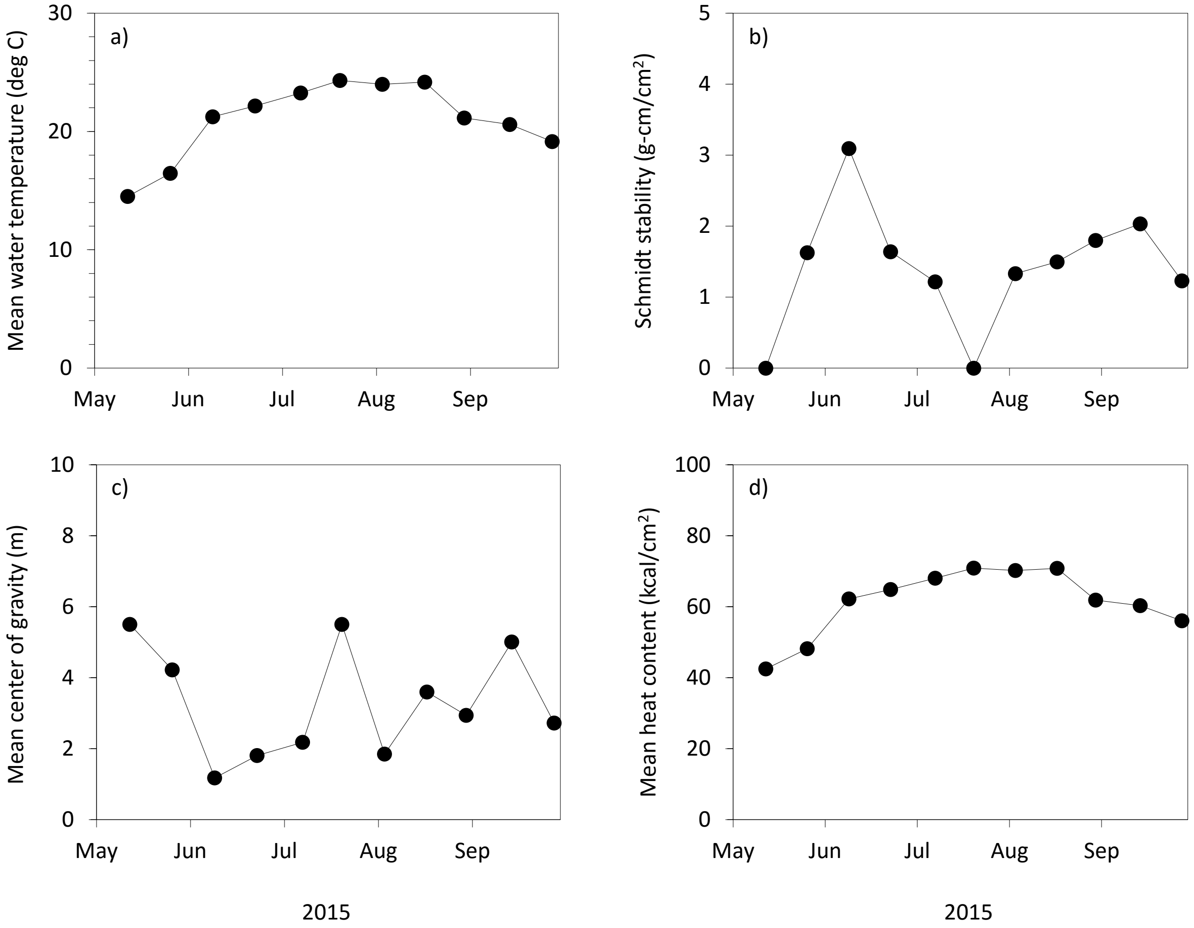


Figure 3. Seasonal variations in mean lake temperature (upper left), the center of density stratification (thermocline depth; lower left), Schmidt stability (upper right), and heat content (lower right) for East Balsam Lake.

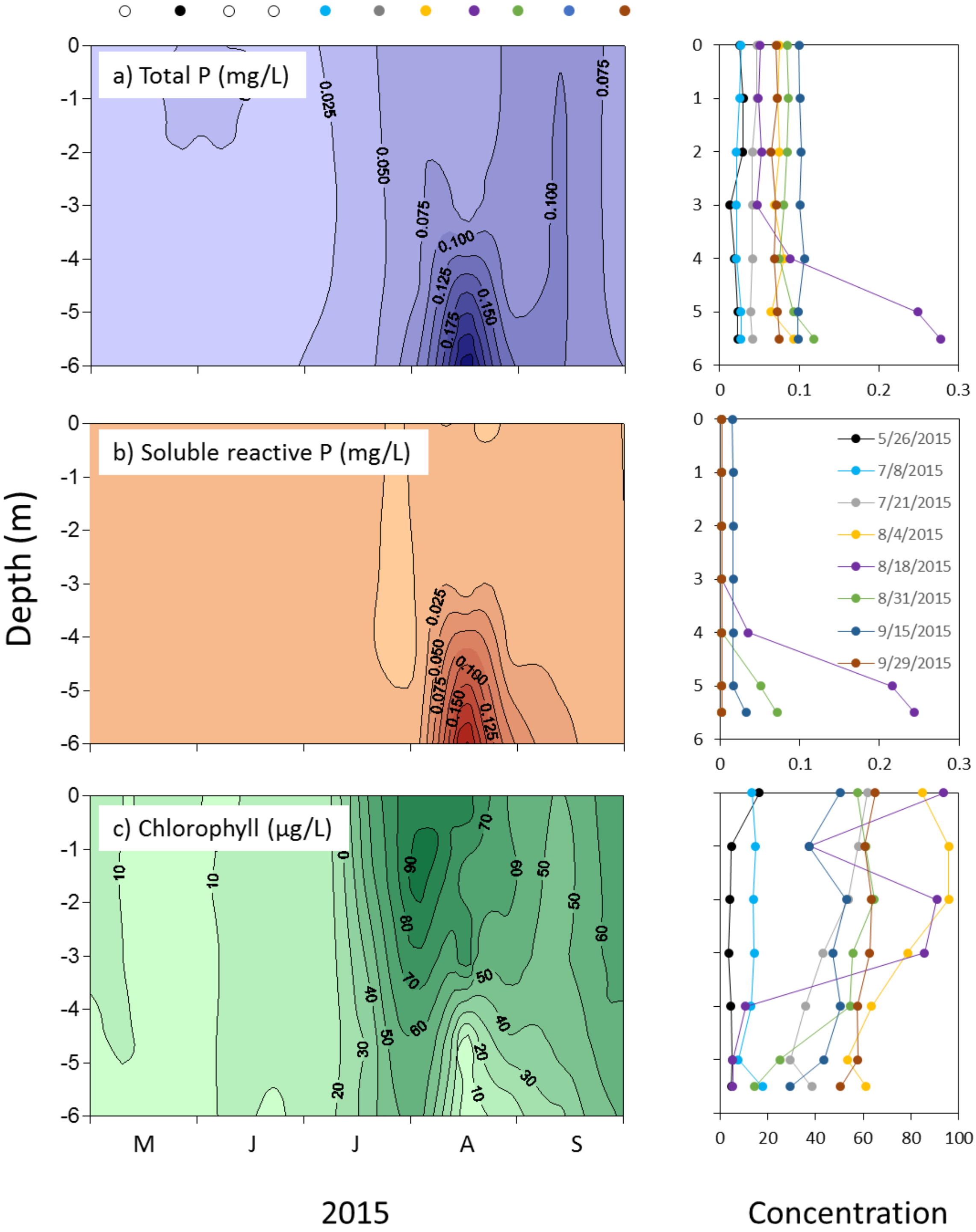


Figure 4. Seasonal and vertical variations in total phosphorus (P; upper panel), Soluble reactive P (middle panel), and chlorophyll (lower panel) in East Balsam Lake.

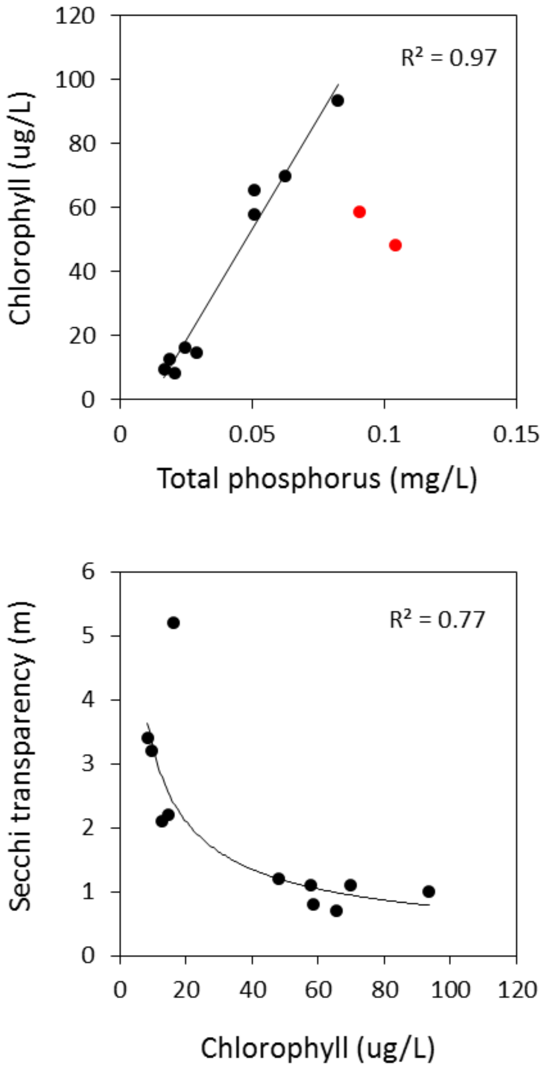


Figure 5. Relationships between total phosphorus and chlorophyll (upper panel) and chlorophyll versus Secchi transparency (lower panel). Red circles, representing sampling dates when mixing and turnover occurred, represented outliers.

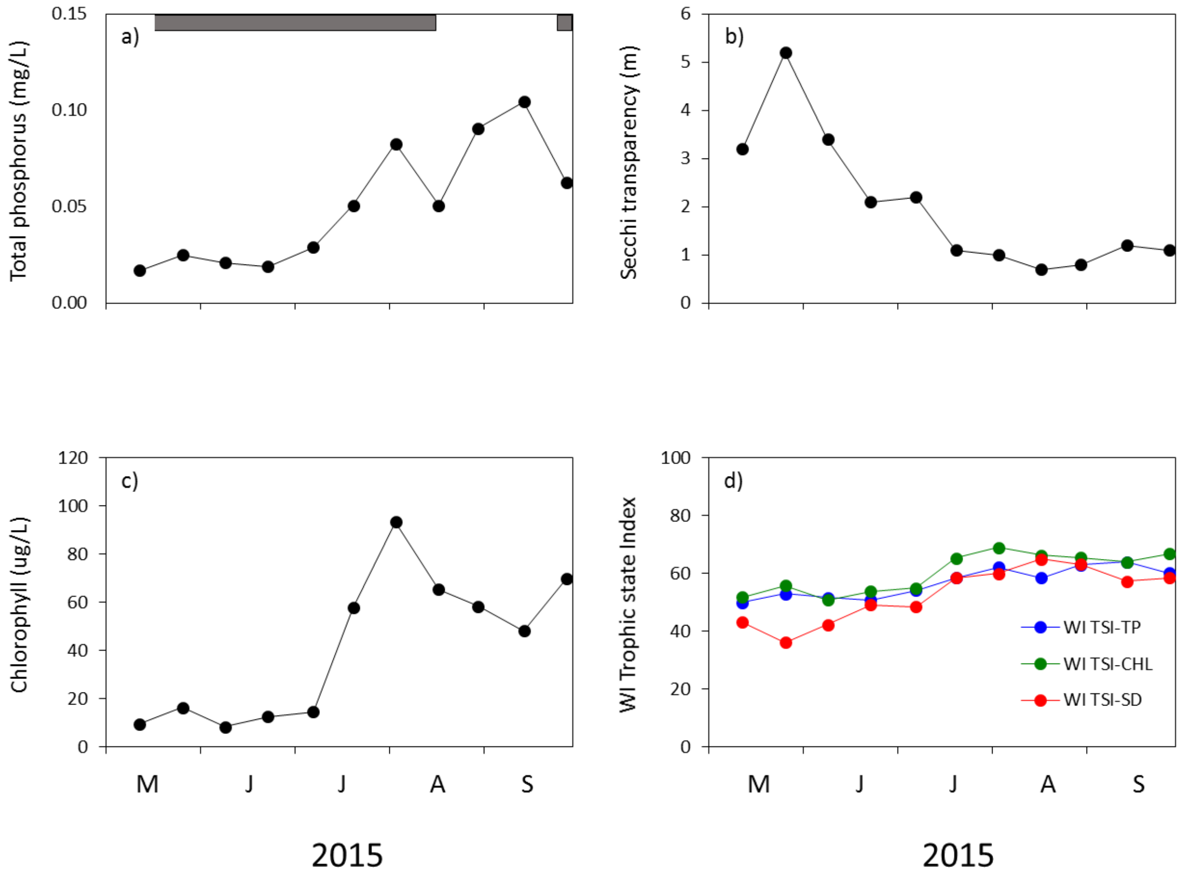


Figure 6. Seasonal variations in mean lake total phosphorus (upper left panel), Chlorophyll (lower left panel), Secchi transparency (upper right panel), and Wisconsin trophic state index (lower right panel). The grey horizontal bars represent dates used for regression analysis in Fig. 5.

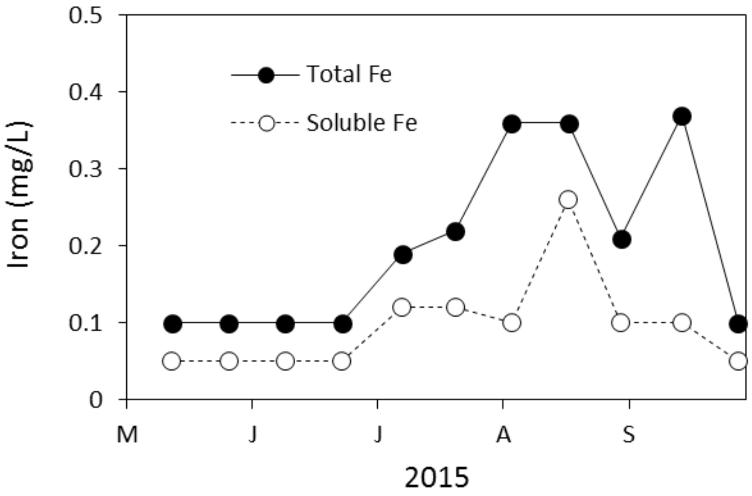


Figure 7. Seasonal variations in iron concentration in the bottom waters of East Balsam Lake.

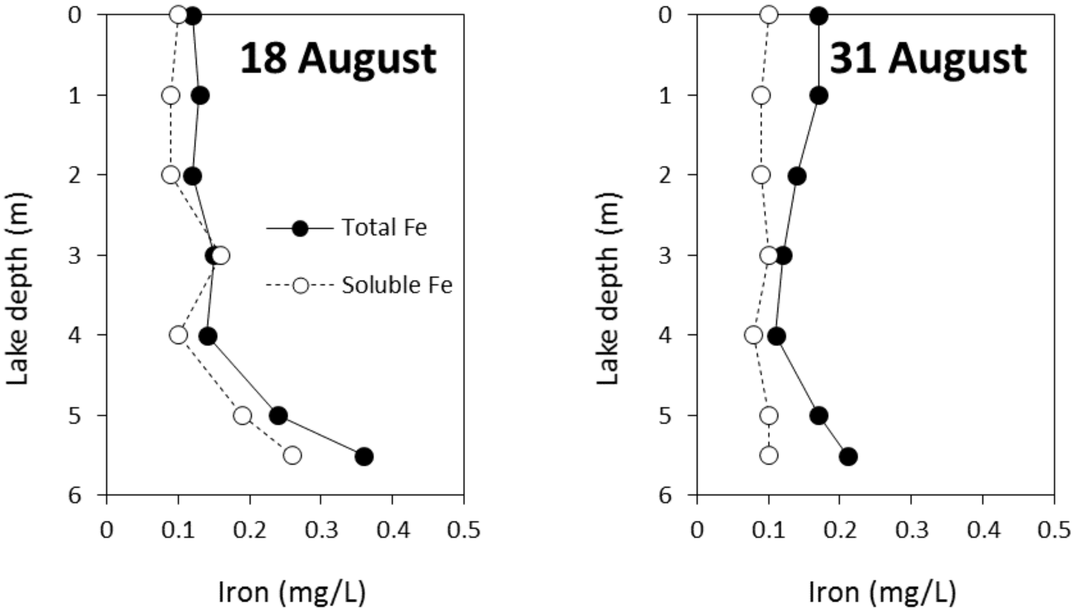


Figure 8. Vertical variations in iron and phosphorus species during periods of anoxia in East Balsam Lake.

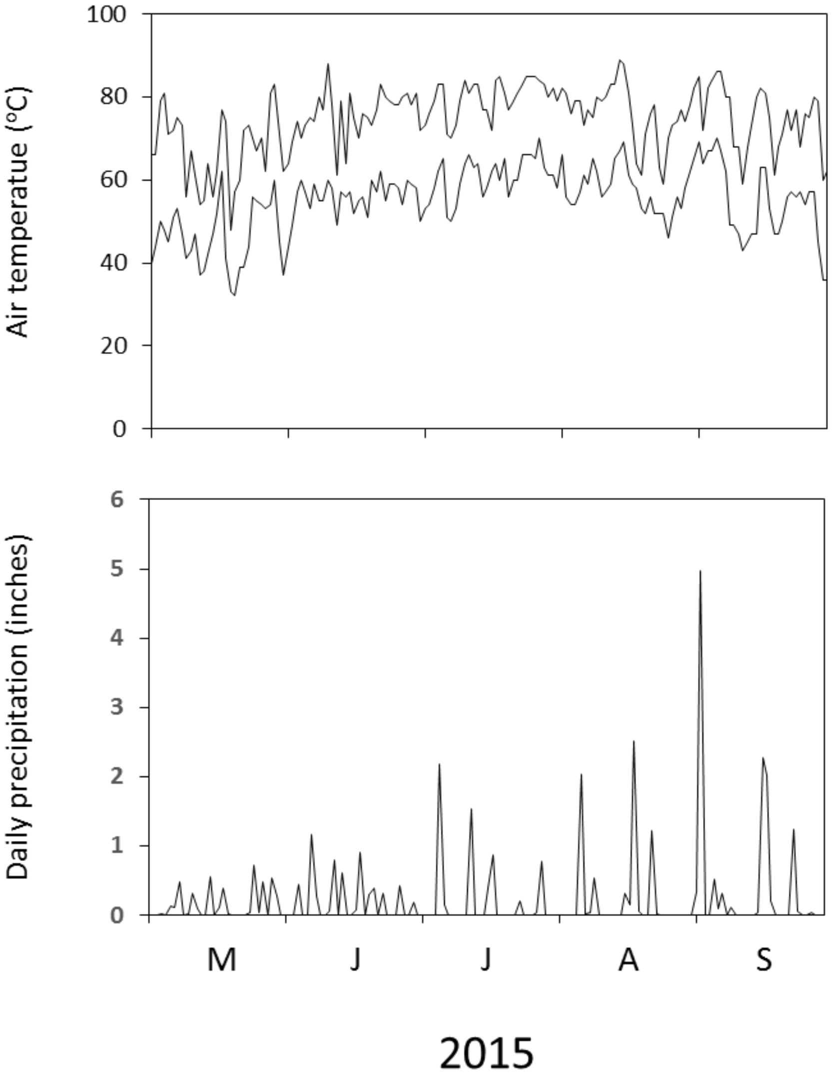


Fig. 9. Seasonal variations in minimum-maximum air temperature (upper panel) and daily precipitation (lower panel) at nearby Amery, Wisconsin.

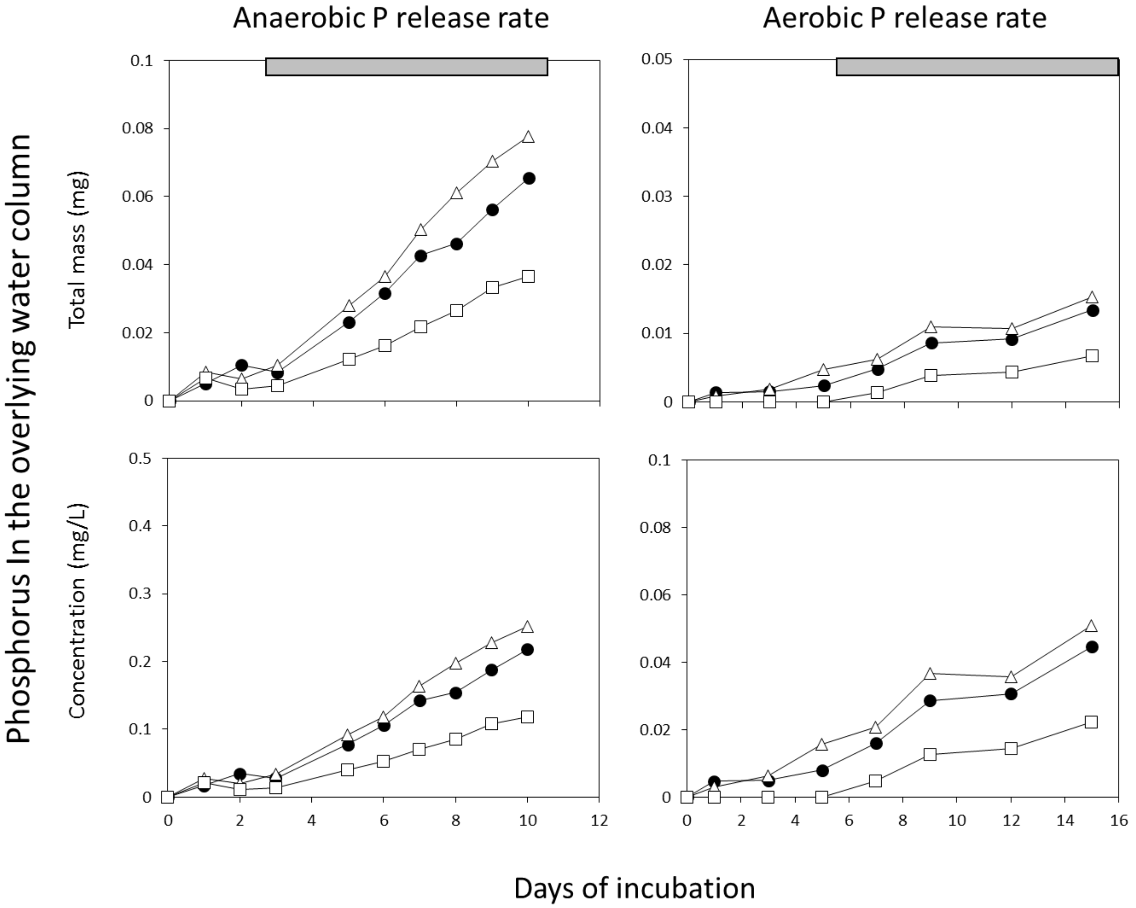


Figure 10. Changes in soluble reactive phosphorus mass (upper panels) and concentration (lower panels) in the overlying water column under anaerobic and aerobic conditions versus time for sediment cores collected at station in East Balsam Lake..

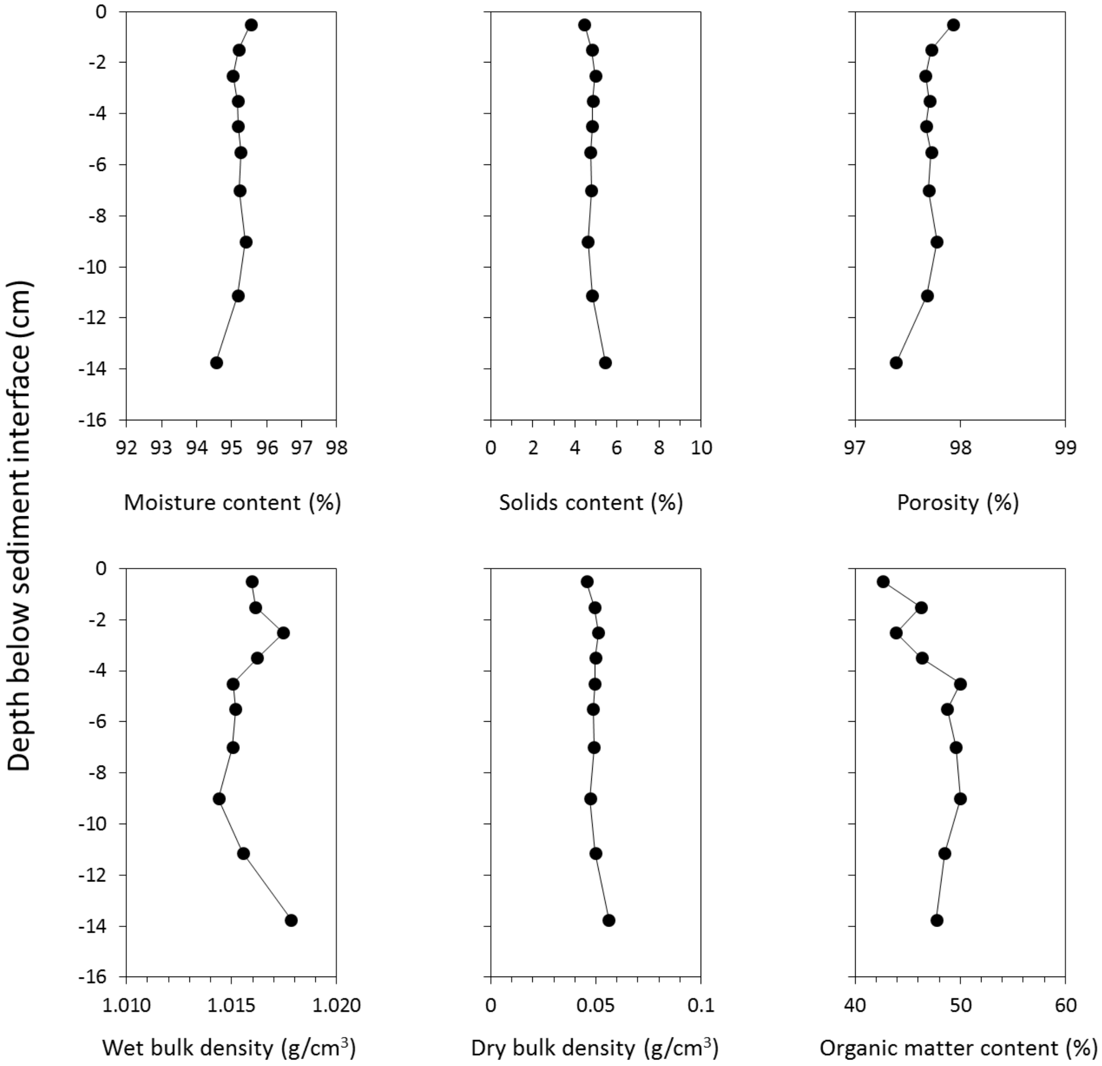


Figure 11. Variations in sediment moisture content, solids content, porosity, wet bulk density, dry bulk density, and organic matter content as a function of depth below the sediment surface for a sediment core collected at station 1 in East Balsam Lake.

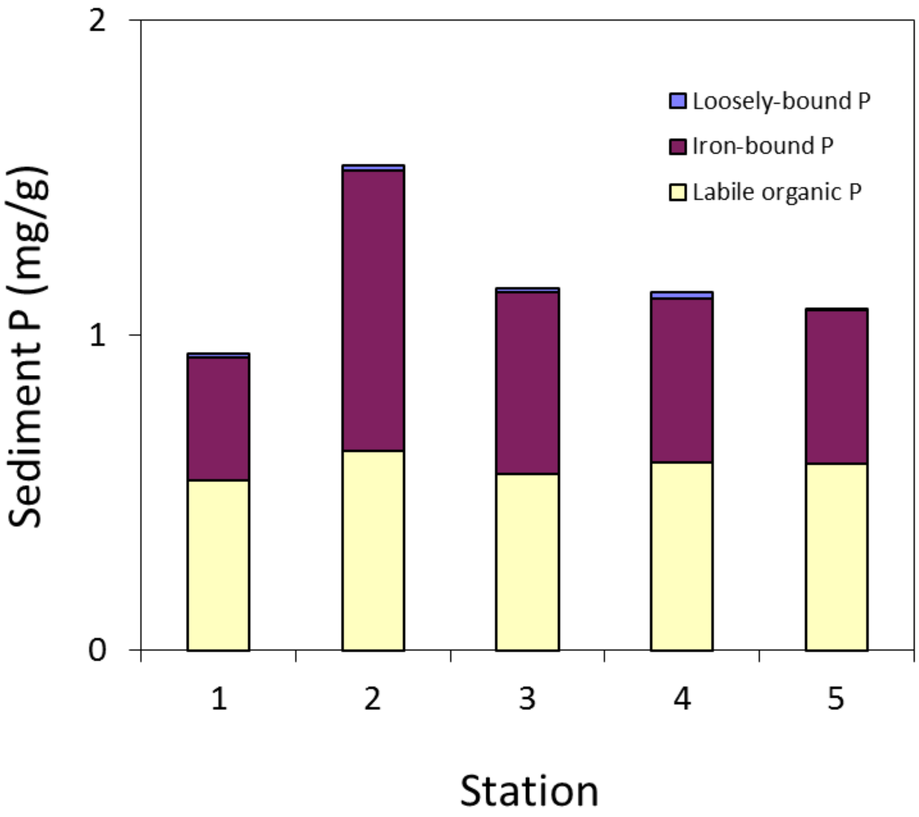
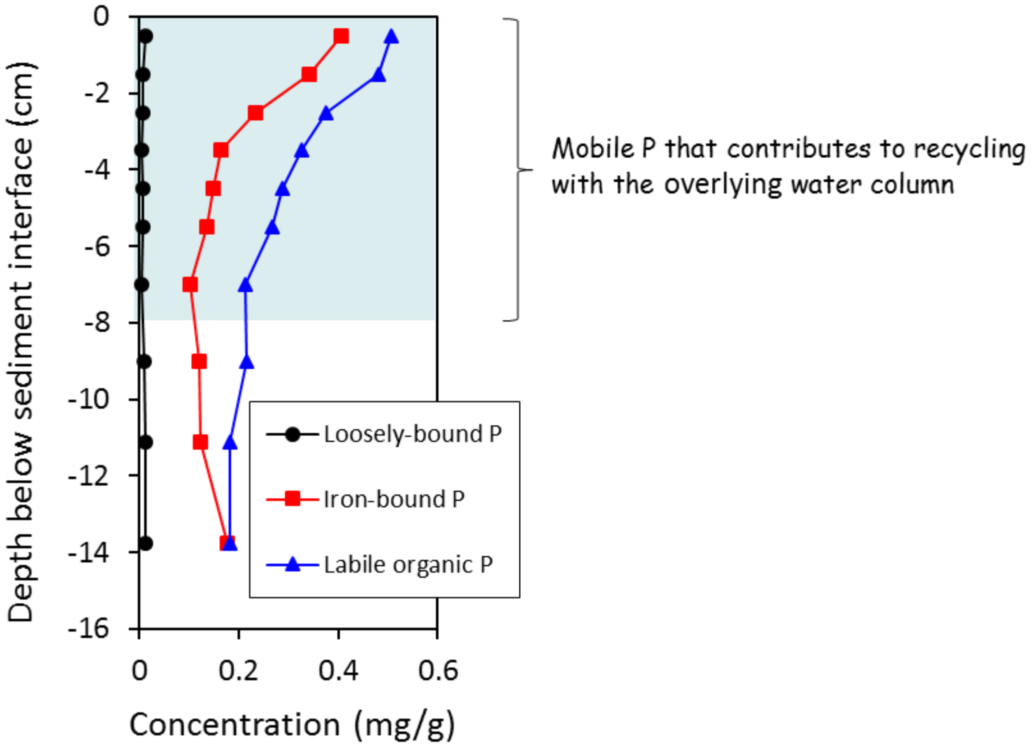


Figure 12. Variations in the composition of biologically-labile phosphorus (P; i.e., subject to recycling with the overlying water column; sum of the loosely-bound, iron-bound, and labile organic P) in the upper 5-cm sediment layer for cores collected in East Balsam Lake.

Figure 13. Variations in sediment loosely-bound phosphorus (P), iron-bound P and, labile organic as a function of depth below the sediment surface for a sediment core collected at station 1 in East Balsam Lake. The blue shaded area delineates the upper 8-cm sediment layer of redox-sensitive P in excess of background concentrations.



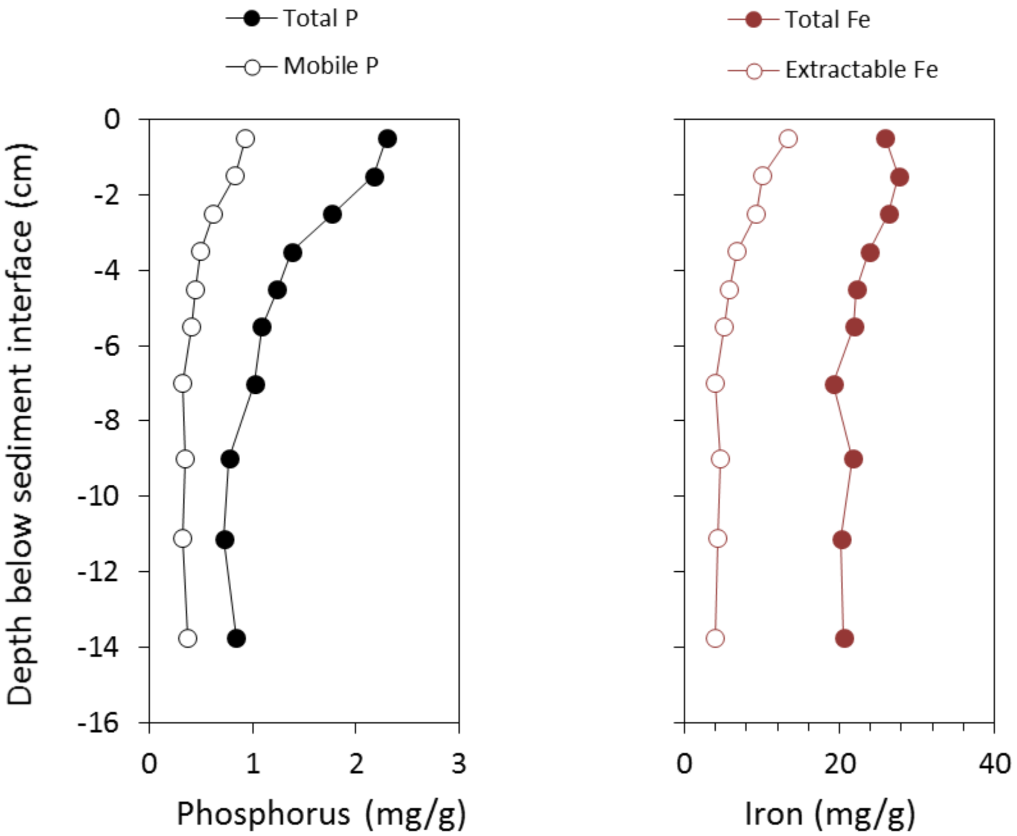


Figure 14. Variations in biologically-labile (i.e., mobile and subject to recycling and internal P loading) and total phosphorus (P; left panel) and total and extractable iron (Fe; right panel).

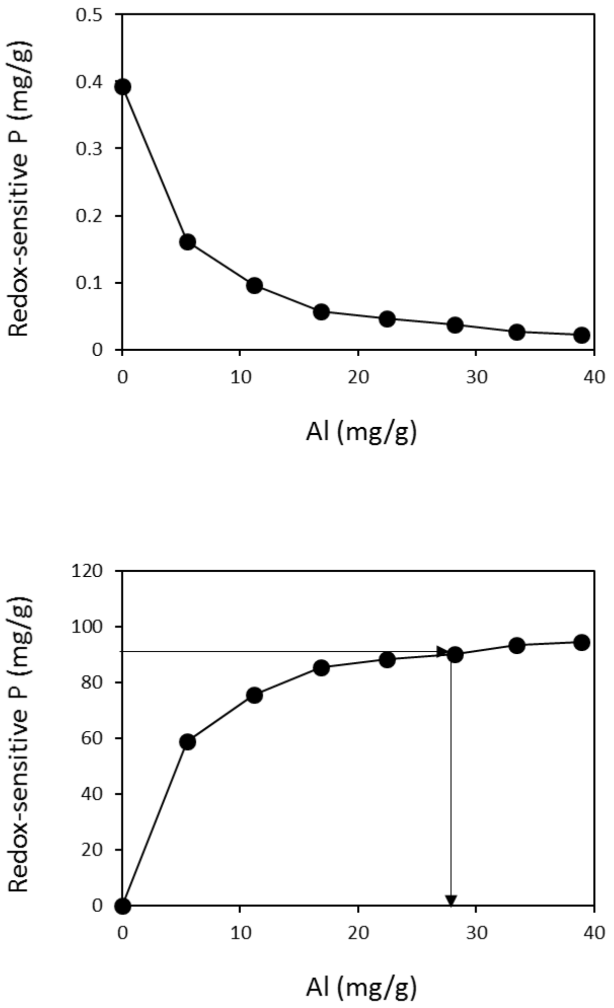


Figure 15. Variations in the concentration of redox-sensitive phosphorus (P; upper panel) and percent removed or adsorbed to the aluminum (Al) floc (lower panel) as a function of increasing Al concentration.

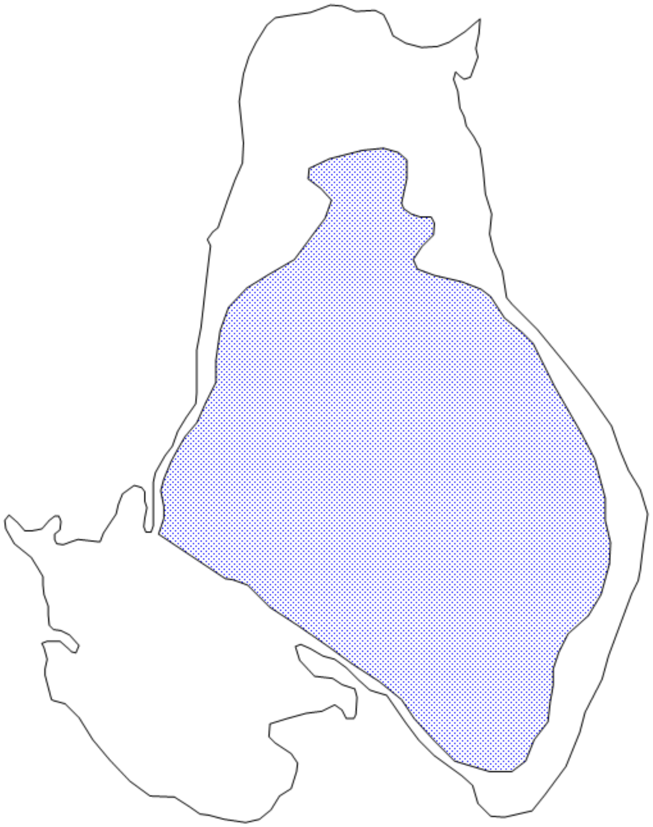


Figure 16. Suggested Al treatment area in East Balsam Lake. Blue stippled region encompasses to 10-ft contour.

APPENDIX B. ALUM DOSAGE AND APPLICATION STRATEGIES

James, William F. *East Balsam Lake, Wisconsin: Analysis of Phosphorus Sources, Loading Reduction Scenarios, and Alum Dosage and Application Strategies.* May 2018.

East Balsam Lake, Wisconsin: Analysis of Phosphorus Sources, Loading Reduction Scenarios, and Alum Dosage and Application Strategies

15 May, 2018

William F. James
Aquatic Restoration and Research, LLC
607 Pine Ave
Menomonie, WI 54751
715-338-4395
wfjames.arr@gmail.com

Summary

1. Re-evaluation of the steady-state phosphorus (P) model using lake data collected in 2015 suggested that internal P loading accounted for > 70% of the P inputs to East Balsam Lake.

2. Empirical modeling suggested that predicted mean summer total P and chlorophyll would decline to 0.024 mg/L (57% improvement) and 13.6 µg/L (70% improvement), respectively, while Secchi transparency would increase to 2.8 m (88% improvement) after control of internal P loading via aluminum (Al) sulfate application.

3. The Al dose of 100 g/m^2 should be split into lower doses applied at 2-3-year intervals. A suggested scenario is application of 60 g/m^2 in year 1, 25 g/m^2 in year 3 or 4, and 15-20 g/m^2 in year 5 or 6. Applications can occur at 2- or 3-year intervals depending on lake response to the previous application.

4. The suggested application area is 300 ac or the area roughly encompassing the 3-m or 10-ft contour.

5. The current total cost is estimated at $1.293 million dollars to treat 300 ac of sediments within the 10-ft contour. However, cost per gallon is projected to increase and become more volatile by the time of the initial application in 2020. Although the $1.293 million dollar estimate attempts to reflect future costs, an additional 10% should be added as a contingency measure for budgeting purposes ($1,422,497).

6. If funding is an issue, the Al dose can be broken into several smaller applications for affordability. For instance, 25 g/m^2 applications at 2-3-y intervals would cost ~ $ 298,867 per treatment. An adaptive management (i.e., making more informed decisions by monitoring lake response) approach should be used in conjunction with lower Al dose applications to monitor the need for and timing of future applications.

Objective

East Balsam Lake, part of the Balsam Lake chain, is relatively shallow (6.4 m max depth, 2.9 m mean depth), expansive (787 ac surface area, Barr Engineering 2011), and polymictic (Osgood index = 1.2). The lake currently exhibits excessive summer cyanobacterial blooms and poor water quality (WQ) conditions (mean summer total phosphorus ~ 0.05 mg/L, chlorophyll ~ 47 μg/L), that is linked to internal phosphorus (P) recycling from sediments (Barr Engineering 2011). With the exception of a small seasonal tributary draining forested areas, other watershed runoff probably occurs as diffuse overland flow during high precipitation events and snowmelt periods. Land use in the watershed is dominated by forest (32%) and cropland (24%). From land cover and total P runoff coefficients, Barr Engineering (2011) estimated an annual overland hydrological input of 2,579 ac-ft/y and a watershed P input of 432 lbs/y (37% of the P budget to the lake).

From information collected in 2010, internal P loading was estimated to be a codominant source in the East Balsam P budget at 50% contribution (576 lbs/y, Barr Engineering 2011). Both Barr Engineering and James (2016, 2018) found that the lake can temporarily stratify, leading to bottom anoxia and the buildup of high concentrations of soluble P above the sediment interface. James (2016) determined that laboratory-derived diffusive P flux was moderately high at 2.8 mg/m^2 d. Because the Fe:P ratio is low in the hypolimnion during periods of bottom anoxia, precipitation of soluble P back to the sediment during mixing and reoxygenation of bottom waters was incomplete, resulting in direct availability for algal uptake and bloom development. James (2016) also suggested that direct uptake of sediment P by cyanobacteria resting stages (i.e., akinetes) and inoculation of the water column under optimal conditions could represent another connection between sediment P and bloom development.

More information is needed to refine the P budget for WQ goal-setting and to better target P sources to the lake for management. Although external P loading to East Balsam Lake is currently difficult to quantify, empirical steady-state models can be used to approximate this P source if internal P loading is known. In addition, advances in Al dosage and application strategies suggest that application of lower Al dosages over multiple years and use of an adaptive management approach to monitor the effectiveness of Al in binding sediment P and controlling internal P loading will lead to improved longevity and be more cost effective.

The objectives of these investigations were several-fold:

1. re-examine the P budget and empirical steady-state models under 2015 conditions to evaluate and project water quality improvements as a result of internal P loading control,
2. estimate annual and summer lakewide internal P loading from in situ increases in total P in 2015 for input into empirical steady-state models,
3. Forecast changes in lake total P, chlorophyll, and Secchi transparency and bloom frequency as a result of controlling internal P loading,
4. and refine Al dosage and application strategies to improve longevity of internal P loading control.

Approach

Empirical steady-state modeling

While internal P loadings can be estimated and included in an empirical steady-state model, direct quantification of watershed P inputs is difficult. However, empirical modeling can be used as an heuristic tool to estimate bulk P loading from unmeasured watershed sources and then compared with internal P loading to provide more insight into P sources driving cyanobacteria blooms.

Mean summer (June – September) concentrations of total P, chlorophyll, and Secchi transparency were calculated from information collected in 2015 (James 2016) for model input. Internal P loading ($P_{\text{internal load}}$, kg/summer) was estimated from changes in lake P mass during the summer of 2015 (please see *Results*) as follows,

$$P_{\text{internal load}} = (P_{\text{watershed}} – P_{\text{discharge}}) - \Delta P_{\text{lake}}$$

where,

$P_{watershed}$ = summer inputs from the watershed (kg/summer), estimated from Barr Engineering (2011),

$P_{discharge}$ = summer discharge of total P from East Balsam Lake (kg/summer) calculated as the mean summer epilimnetic total P concentration in 2015 multiplied by the estimated inflow from Barr Engineering (2011). I assumed that inflow Q = discharge Q, and

ΔP_{lake} = the change in total P mass in the lake during the summer of 2015 (kg/summer).

$P_{watershed}$ and $P_{discharge}$ were not directly measured but estimated in 2010 via the Wisconsin Lake Modeling Suite (WiLMS, Barr Engineering 2011) and represented < 10% of the 2015 summer P budget. Thus, the ΔP_{lake} predominantly reflected internal P loading. ΔP_{lake} was estimated by multiplying total P concentration by the volume at discrete depths according to the following equation,

$$P_{lake} = \sum_{z=0}^{bottom} P \cdot V$$

Where,

z = depth (m),

P = total P concentration at depth z (mg/L or g/m^3), and

V = volume at depth z (m^3).

Steady-state phosphorus models developed by Canfield and Bachmann (1981) and Nürnberg (1998) were used to predict mean 2015 summer (i.e., June-September) total P concentration in East Balsam Lake.

The computer software program Bathtub (Walker 1996) was used predict mean summer chlorophyll concentration and Secchi transparency and to examine P loading reduction scenarios. Bathtub is a windows-based software program that provides a suite of equations for predicting lake seasonal averages of total P, chlorophyll, and Secchi transparency. Empirical model selection is shown in Table 1.

Table 1. Algorithms used for phosphorus loading reduction modeling of East Balsam Lake.

Variable	Model	Calibration coefficient
Phosphorus	Canfield and Bachmann (1981) Nürnberg (1998)	1.17 [1]
Chlorophyll	Jones and Bachman	1.63
Secchi Transparency	versus P concentration	1.75

[1] Canfield-Bachmann (1981) = 1.17; Nürnberg (1998) = 1.0

Aluminum dosage and application strategies

Other research (Berkowitz et al. 2005, 2006; de Vicente et al 2008a, 2008b; James 2017) has suggested development of an adaptive management approach to applying lower or partial applications of Al spread out over a period of years (i.e., 2-3 year intervals) and monitoring lake response for future Al maintenance applications. The goal of these approaches is to increase overall P binding efficiency and internal P loading control longevity by stabilizing $Al(OH)_3$ polymerization and enhancing P saturation of binding sites. Application of multiple Al concentrations spread out over a period of years may be more effective in saturating binding sites, lowering the Al:P binding ratio, and stabilizing polymerization for longer internal P loading control. Dose splitting can also be used as an adaptive management approach to address slower degradation of labile organic P into mobile forms as well as increased P binding efficiency onto the Al floc.

The objectives of this task were to develop an adaptive management approach timeline that laid out an application schedule and dosages that were split. The adaptive management approach included sediment and lake water column monitoring needs to evaluate the effectiveness of the current Al application and need for adjustments in future dosage and timing of application (*see attached proposal*).

Results and Discussion

Empirical steady-state modeling

Table 2. A comparison of variable inputs used for empirical modeling of East Balsam Lake.

Variable	Barr 2010	UW-Stout 2015
Annual precipitation (m)	0.93	1.3
Total P (mg/L)	0.052	0.055
Chlorophyll (ug/L)	47	46.2
Secchi (m)	1.4	1.51
Internal P load (mg/m^2 d)	0.42	0.69

As discussed in James (2016), P lake mass (kg) increased from a minimum in late June to a peak 643 kg in mid-September 2015, resulting in a ΔP_{lake} of 519 kg/summer (Fig. 1). When adjusted for minor estimated $P_{watershed} - P_{discharge}$ the summer internal P loading rate was 549 kg/summer or 0.69 mg/m^2 d. This rate was much higher than the internal P load estimated by Barr Engineering for the summer of 2010 (Table 2). Differences between years are not unusual or surprising and are likely due to variations in climate and seasonal weather patterns.

Mean summer (June-September) concentrations of total P, chlorophyll, and Secchi transparency were similar in 2010 versus 2015 (Table 2). In 2015, means were 0.055 mg P/L, 46.2 µg CHLa/L, and 1.5 m, respectively. Annual precipitation was higher in 2015 compared to 2010.

Both the Canfield-Bachmann (1981) and Nürnberg (1998) P model was used in conjunction with internal P loading determined via in situ changes in total P mass in 2015 to predict the summer average total P concentration of 0.055 mg/L (Table 2). The output indicated that summer internal P loading overwhelmingly dominated P sources to the lake at ~ 71% (Fig. 2 and Table 3). In contrast, estimated external P loading represented only ~ 29% of the inputs to the lake. Given the occurrence of temporary stratification, bottom anoxia, and low Fe:P ratio in the hypolimnion (James 2016), modeling output suggested that internal P loading played an important role in driving algal blooms in 2015.

Table 3. A comparison of estimated external phosphorus (P) loading required to balance the P steady-state Nürnberg and Canfield-Bachmann model.

Variable	Nürnberg	
	Value	Units
Areal water load (qs)	1.5	m/y
Overland flow (Q)	0.104	m3/s
Residence time (RT)	1.9	y
External P load	102	mg/m2 y
Internal P load	251	mg/m2 y
Predicted Lake TP	54	ug/L
Percent external P load	28	%
Percent internal P load	72	%

Variable	Canfield-Bachmann	
	Value	Units
Areal water load (qs)	1.5	m/y
Overland flow (Q)	0.101	m3/s
Residence time (RT)	2	y
External P load	102	mg/m2 y
Internal P load	251	mg/m2 y
Predicted Lake TP	55	ug/L
Predicted Lake CHLA	46	ug/L
Predicted Lake SD	1.5	m
Percent external P load	29	%
Percent internal P load	71	%

Predicted limnological response to external P loading reduction was minor when internal P loading was not controlled (Fig. 3). For instance, 50% reduction in external P loading resulted in only a predicted 8% reduction in summer mean TP to 0.051 mg/L, a 12% decrease in chlorophyll to 41 µg/L, and a 5% increase in Secchi transparency to 1.58 m. Thus, results suggested that substantial reductions in watershed P loadings would not meet State of Wisconsin WQ criteria for shallow lakes (WisCalm 2014).

However, control of internal P loading via alum treatment resulted in a predicted ~57% reduction in summer mean TP from ~ 0.055 mg/L to only ~ 0.024 mg/L (Fig. 3). In addition, predicted summer mean chlorophyll declined from a current 46 µg/L to only a projected 14 µg/L with internal P loading control (~70% predicted improvement over current conditions, Fig. 3). Predicted Secchi transparency increased from ~ 1.48 m to 2.79 m under internal P loading control (~ 88% improvement, Fig. 3). Predicted lake response would also improve with some additional external P loading control. Finally, predicted bloom frequency of nuisance chlorophyll concentrations (i.e., > ~20 µg/L) would improve from ~ 85% of the summer under current P loading conditions to only 18% of the summer under conditions of internal P loading control

(Fig. 4, red line). Predicted improvements in limnological variables as a result of internal P loading control are shown in Fig. 5 and 6. They suggest that WQ goals would be met or exceeded via control of internal P loading alone.

Alum dosage and application strategy

The recommended total Al dosage reported in James (2016) was 100 g/m^2 within approximately the 10-ft contour of East Balsam Lake (Fig. 7). I recommend splitting the dose into 3 lower concentrations spread out over 2- to 3-year intervals to improve Al binding efficiency (Fig. 8). For instance, a higher Al dosage should be applied during year 1 to initially suppress internal P loading while lower doses can be applied during year 3 and 5 to maintain internal P loading control. In addition, I recommend that Al application occur within 1 month or less of the development of bottom anoxia to bind P diffusing out of the sediment. For East Balsam Lake, application in early to mid-June would coincide with the development of bottom anoxia (James 2018). Finally, the Lake District should be made aware that an additional Al application (lower Al concentration on the order of 25-50 g/m^2) may be needed several years after these applications as a maintenance measure to ensure complete internal P loading control (see James 2017).

The zone of bottom anoxia needs to be considered in selection of the application area since internal P loading is greatest under anoxic conditions. Barr Engineering (2011) suggested that the depth of anoxia (i.e., < 2 mg/L dissolved oxygen) extended to ~ 3.75 m in 2010. James (2016 and 2018) found that anoxia extended to the 4.25-m depth in 2015 and the 3.50-m depth in 2017 (Fig. 9). Thus, the depth of anoxic conditions can vary annually. In all above studies, however, dissolved oxygen profiles were only measured in the approximate center of the lake; but, anoxic conditions could extend to shallower depths spatially. In addition, area decreases substantially between the 3- and 4-m contour (Fig. 9). I recommend treatment of the area encompassed by the 3-m (i.e., 10-ft, 300 ac) contour as a margin of safety to account for potentially more extensive anoxia during periods of drought and lengthy stable stratification (James 2016).

Because the first Al dose would exceed the maximum allowable to maintain lake pH greater than

6 if this scenario is followed, a buffered Al (aluminum sulfate-sodium aluminate) should be applied. The second and third applications of 15-25 g Al/m^2 would not exceed the maximum allowable dosage. Thus, aluminum sulfate alone could be applied at that Al concentration yet maintain pH above 6. Both water column and sediment monitoring will be used to assess control and the need, if any, for another maintenance Al application several years into the future.

Table 4. Approximate cost scenario to treat sediment within the 10-ft depth contour (i.e., 300 ac) in East Balsam Lake with alum.

Variable	Year		
	1	3 to 4	5 to 6
Treatment area (acres)	300	300	300
Al dosage (g/m^2)	60	25	15
Buffered Al cost ($)	$701,844		
Al cost ($)		$424,261	$167,074
Total ($)	$1,293,179		
Plus 10% contingency	$1,422,497		

Projected costs for Al treatment of 300 ac under the above application scenario (Fig. 8) are shown in Table 4. The cost for the first treatment is ~ $700,000. Treatment costs decline in subsequent years in conjunction with lower required doses. Total costs are projected to be $1,293,179. Because the future cost of alum is volatile, an added 10% contingency for budgeting purposes brought the projected total to $1,422,497.

If these projected costs are too high in relation to funding procurement, lower dose applications that fall within funding constraints should strongly be considered. Lower Al doses spread out over several years will also be very effective in controlling internal P loading in the long-term; the trade-off, however, could be limited control of internal P loading after the initial treatment and the potential for algal bloom development but at lower concentrations. Table 5 lists projected costs of alum and buffered alum at various concentrations. For instance, a 25 g Al/m^2 treatment may be more affordable and feasible under funding and lake

Table 5. Projected future costs to apply various concentrations of aluminum sulfate (alum) or buffered alum to the 300 ac treatment area in East Balsam Lake. A 10% contingency adjustment is included in these projected future costs.

Concentration (g/m^2)	Alum only ($)	Buffered alum ($)
15	$183,782	$206,282
20	$241,645	$271,013
25	$298,867	$335,578
30	$355,448	$399,278
40	$466,687	$525,426
50	$575,363	$649,733
60	$681,475	$772,028

protection grant constraints. Finally, please note that the future cost of alum has become more volatile and is rising due to increased demand.

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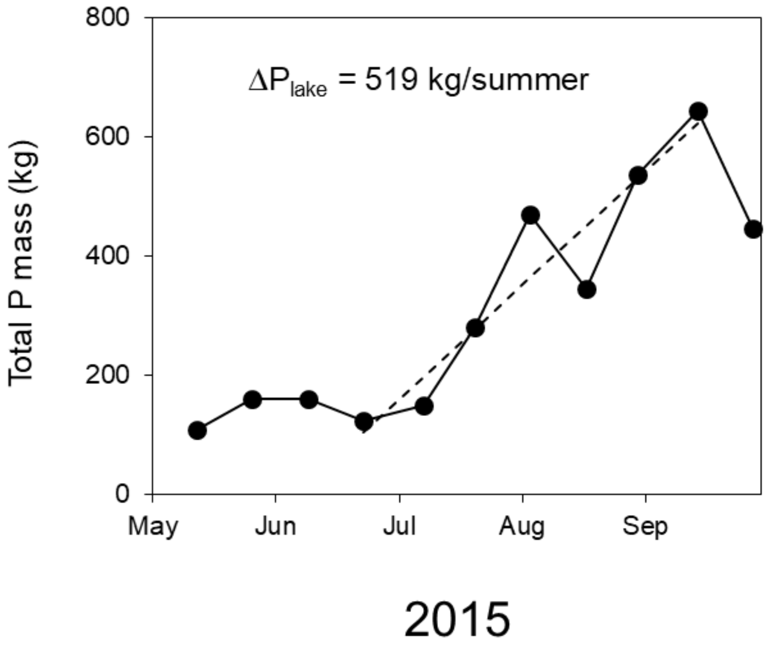


Figure 1. Seasonal variations in total phosphorus (P) mass in East Balsam Lake, WI, in 015. Dashed line denotes the linear increase in P mass between late June and September, 2015.

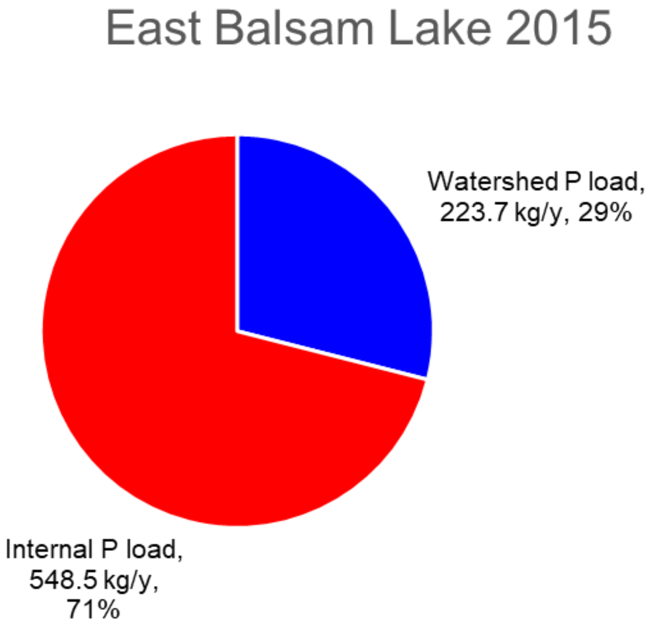


Figure 2. Estimated annual phosphorus contributions from watershed and internal loading in 2015.

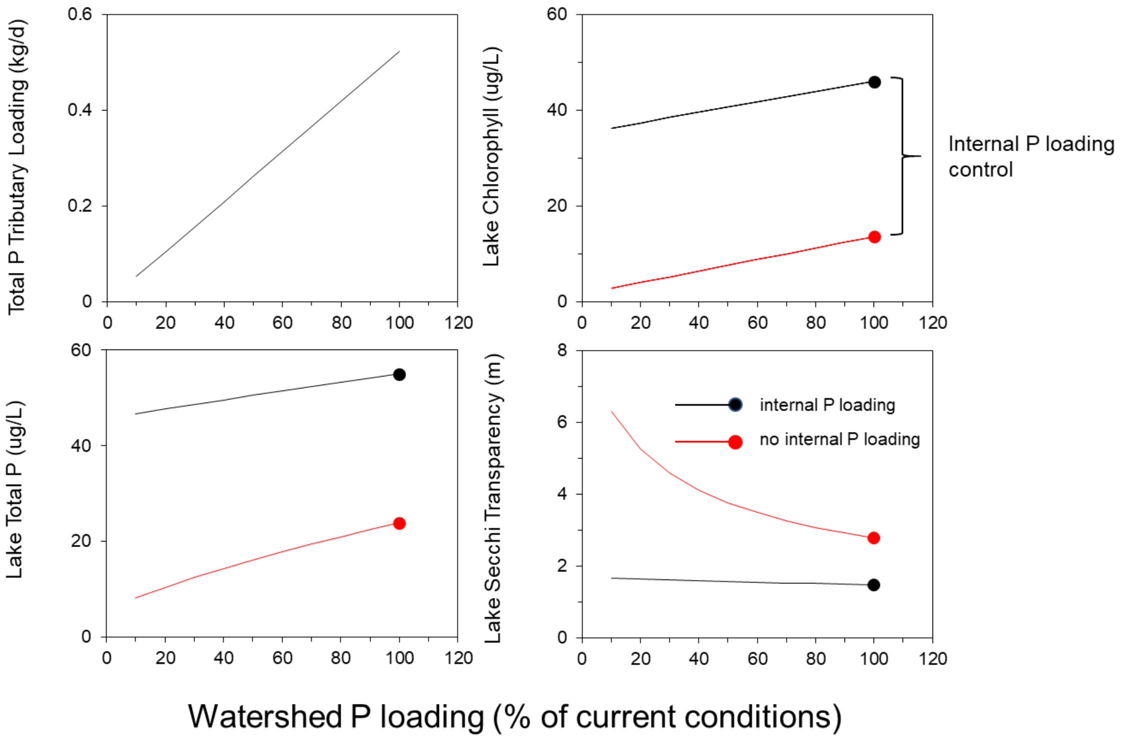


Figure 3. Empirical model output (Canfield-Bachmann) of predicted changes in total phosphorus (P), chlorophyll, and Secchi transparency in Least Balsam Lake as a function of reducing current estimated external P loading by 20% increments. 100% watershed P loading represents current conditions. Black lines denote lake response to estimated external P loading reduction but no management of internal P loading while red line denotes lake response to external P loading reduction after hypothetical management of internal P loading. Black circles represent current measured mean summer values (Table 2) while red circles denote lake response to internal P loading management only.

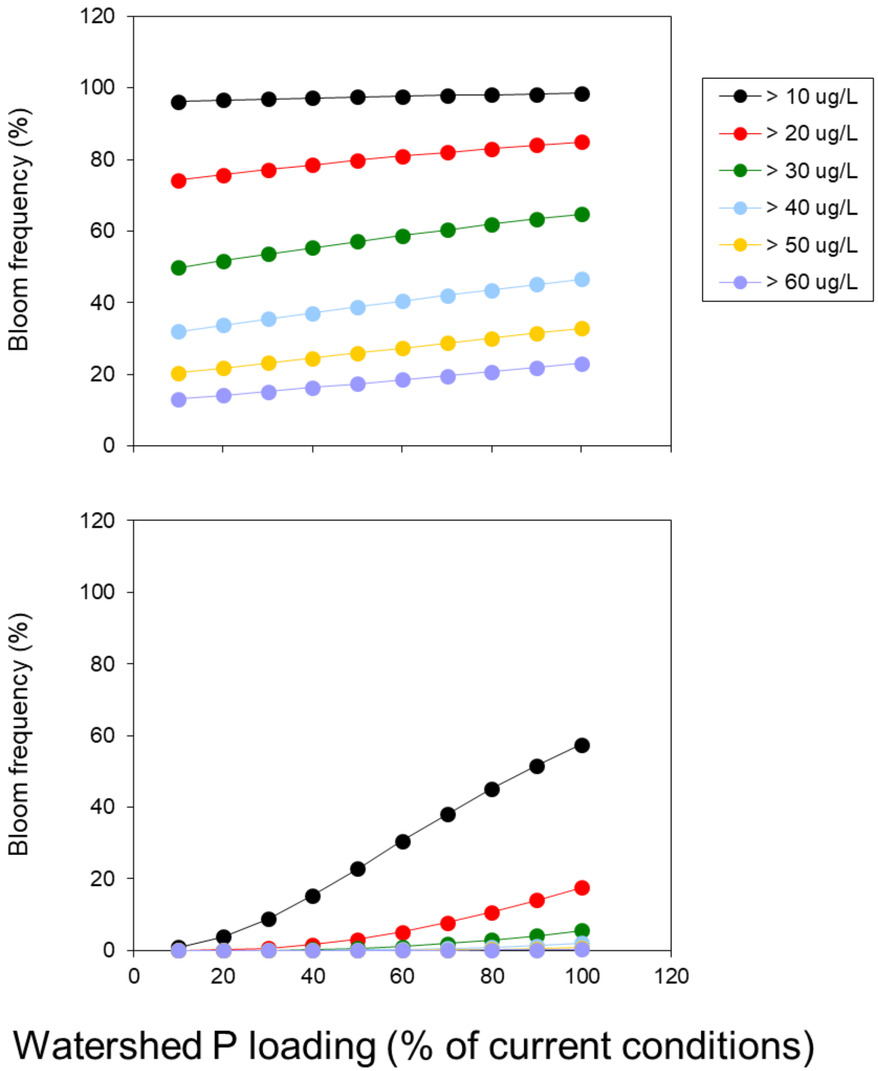


Figure 4. Empirical model output of predicted changes in algal bloom frequency (as chlorophyll) as a function of reducing estimated external P loading by 10% increments (upper panel) and by reducing external P loading and managing internal P loading. 100% P load represents current estimated external P loading conditions. Red circles represent nuisance bloom frequency threshold of 20 µg/L.

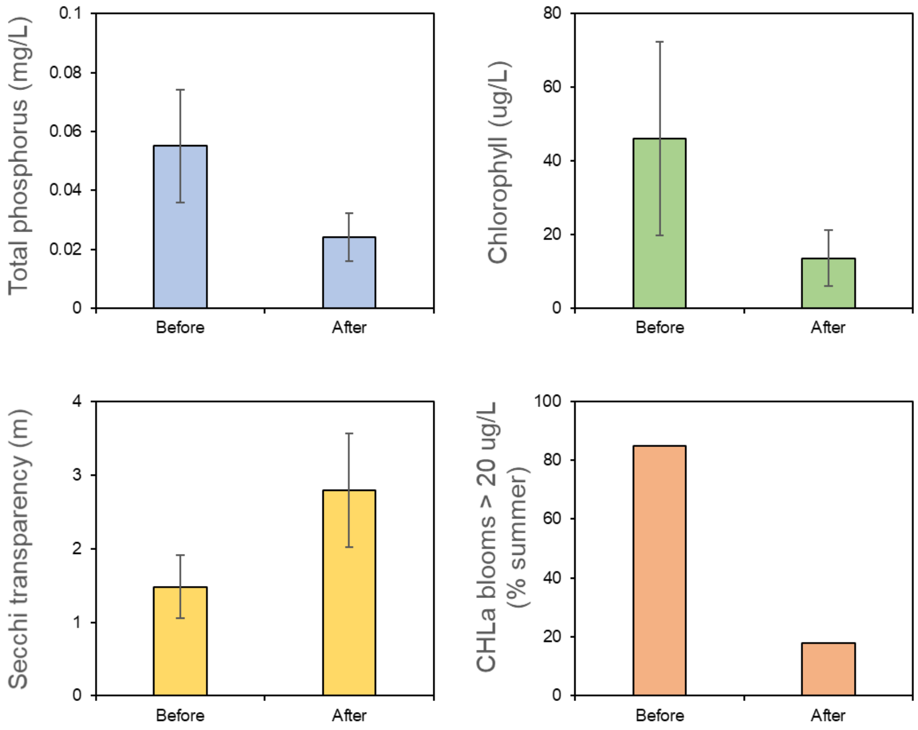


Figure 5. Projected changes in mean summer (June-September) total phosphorus, chlorophyll, Secchi transparency, and percent occurrence during summer that a chlorophyll bloom exceeds 20 µg/L as a result of alum treatment and complete control of internal phosphorus loading in East Balsam Lake, WI.

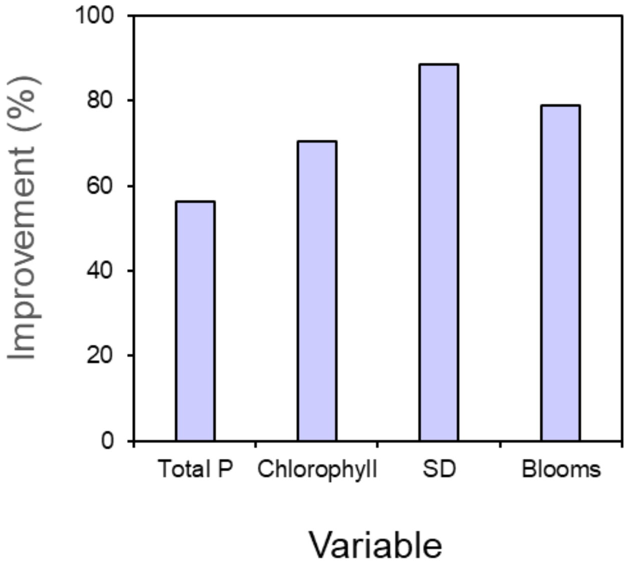


Figure 6. Projected percent improvements in mean summer lake response variables after internal phosphorus loading control in East Balsam Lake, WI. P = phosphorus, SD = Secchi disk transparency, Blooms = percent occurrence during summer that a chlorophyll bloom exceeds 20 µg/L.

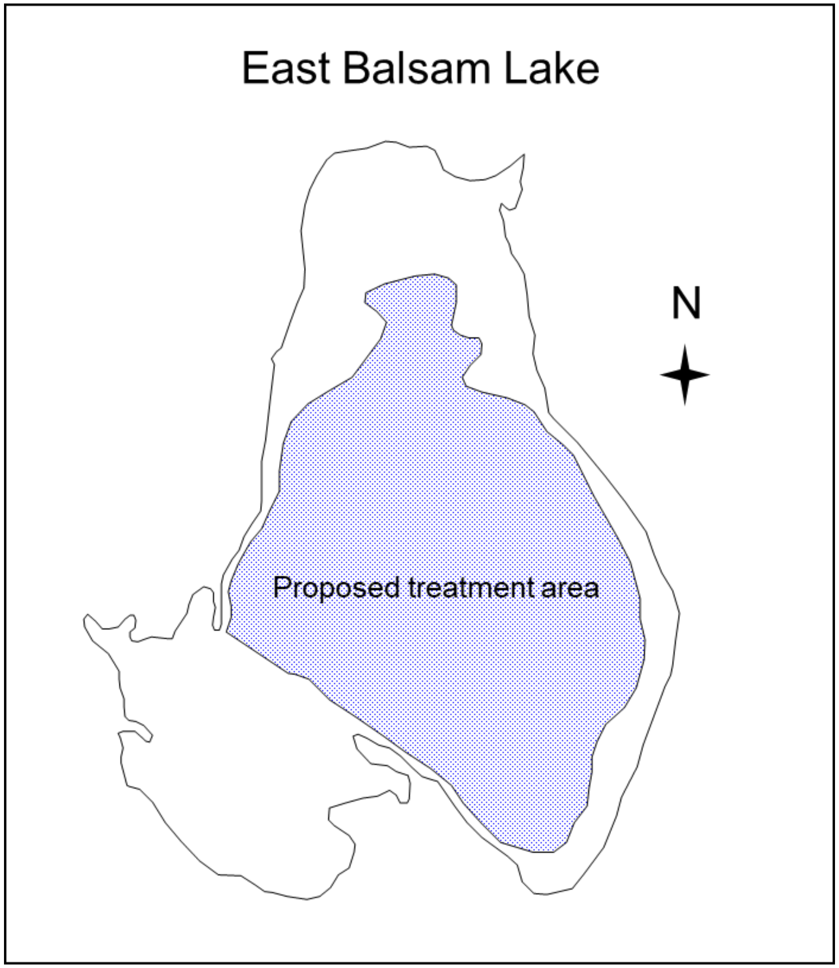
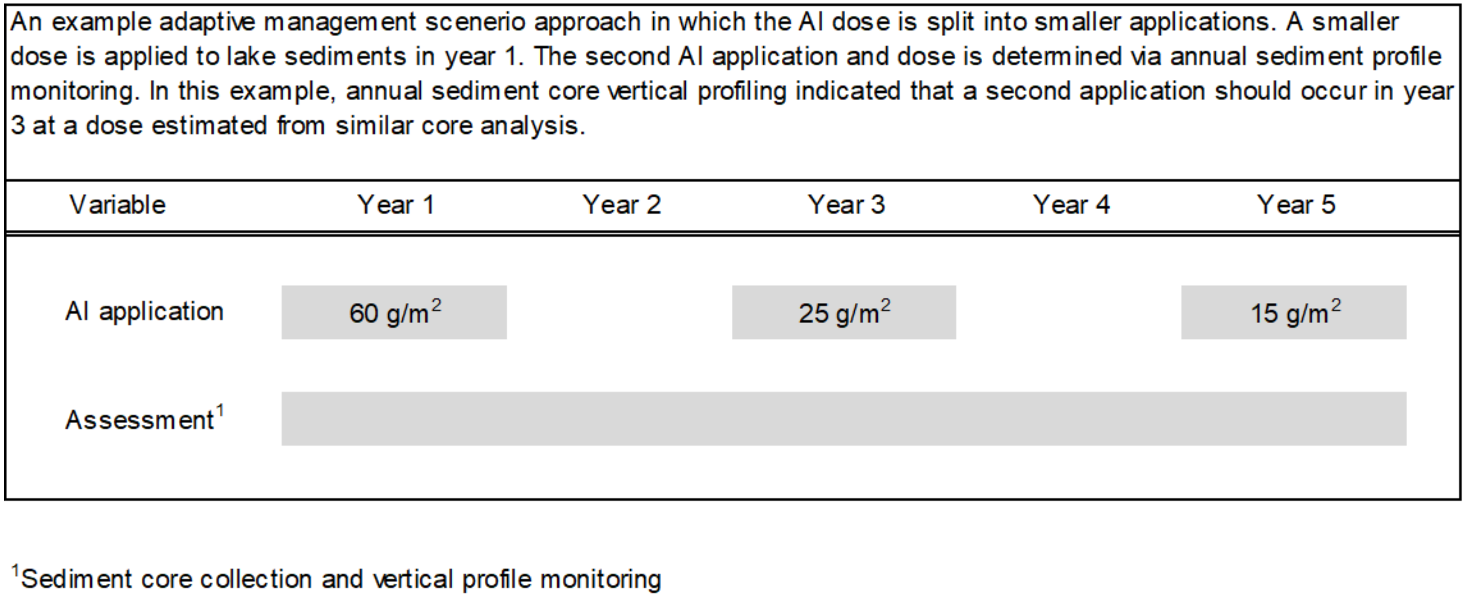


Figure 7. Proposed alum application area in East Balsam Lake. The area is ~ 300 acres and encompasses the 10-ft depth contour.



An example adaptive management scenerio approach in which the Al dose is split into smaller applications. A smaller dose is applied to lake sediments in year 1. The second Al application and dose is determined via annual sediment profile monitoring. In this example, annual sediment core vertical profiling indicated that a second application should occur in year 3 at a dose estimated from similar core analysis.

Variable	Year 1	Year 2	Year 3	Year 4	Year 5
Al application	60 g/m^2		25 g/m^2		15 g/m^2
Assessment[1]	▨	▨	▨	▨	▨

[1] Sediment core collection and vertical profile monitoring

Figure 8. An example adaptive management scenario for application and dosage of alum (Al). The 100 g/m^2 dose was split into 3 lower doses applied at 2-3 year intervals. The initial dose (Year 1) is highest to provide immediate short-term control of internal phosphorus (P) loading while subsequent lower doses in later years maintain internal P loading control as the initial Al floc layer loses binding efficiency.

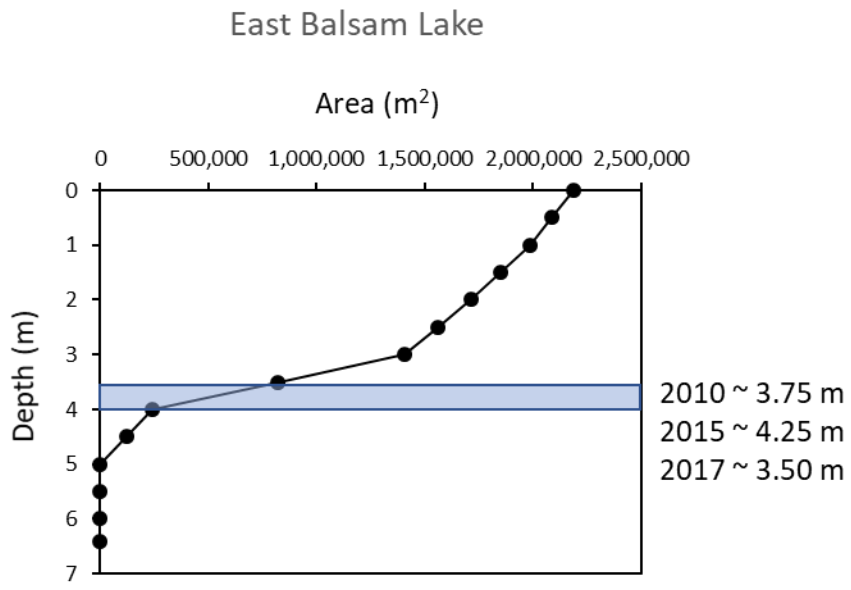


Figure 9. Changes in area as a function of depth in East Balsam Lake. Area decreases rapidly between the 3- and 4-m depth. Shaded region denotes the shallowest depth of bottom anoxia in 2010, 2015 and 2017.

APPENDIX C. ENGINEERED SOLUTIONS TO EAST BALSAM WATER QUALITY

Ayres Associates. *East Balsam Lake Water Quality Study. Feasibility of Engineered Solutions for Summer Algae Blooms.* March 2014.

East Balsam Lake Water Quality Study

Feasibility of Engineered Solutions for Summer Algae Blooms

Prepared for:

Balsam Lake Protection and Rehabilitation District
Balsam Lake, WI

March 2014

East Balsam Lake Water Quality Study

Feasibility of Engineered Solutions for Summer Algae Blooms

AYRES ASSOCIATES
3433 Oakwood Hills Parkway
Eau Claire, WI 54701-7698
715.834.3161 • Fax: 715.831.7500
www.AyresAssociates.com

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1. INTRODUCTION

This report analyzes the potential of three engineered solutions to increase the water quality of the eastern portion of Balsam Lake, East Balsam Lake, in Polk County, Wisconsin. Additional non-engineered solutions were identified throughout the process but need further evaluation. Figures 1-1 and 1-2 are location maps of East Balsam Lake. Figure 1-2 also notes the Basin delineations of Balsam Lake performed by BARR Engineering 2011.

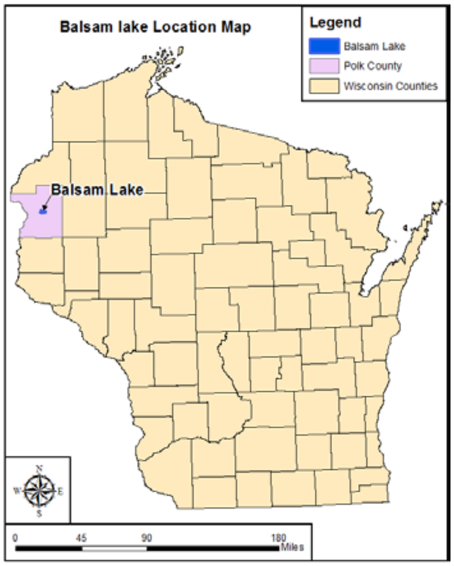

Figure 1-1: Balsam Lake Location Map

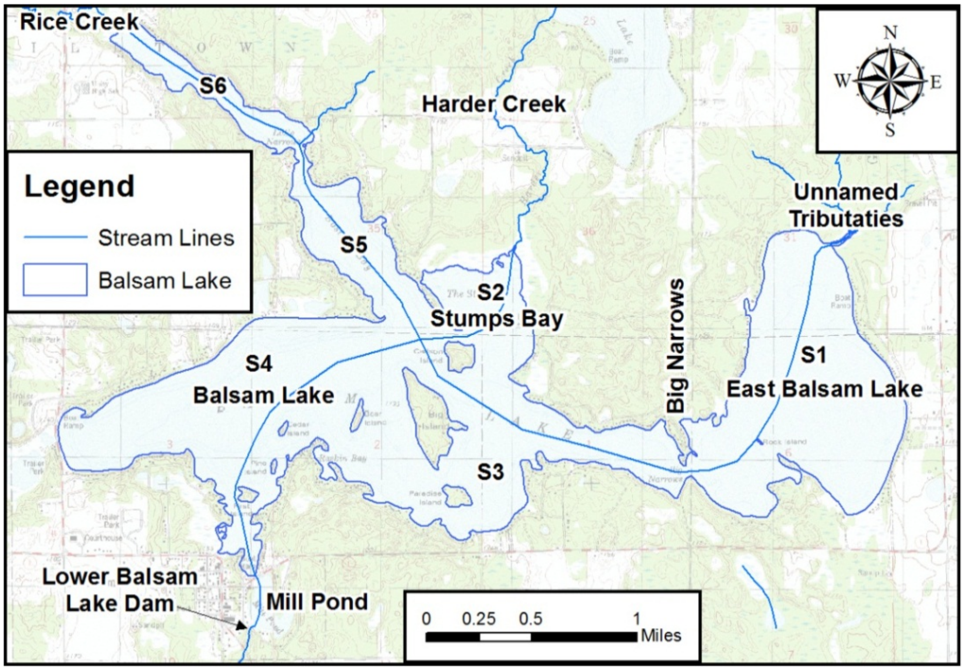

Figure 1-2: Balsam Lake Location Map and BARR Lake Basin Notation (USGS Seamless Quad Background)

East Balsam Lake is separated from the remainder of Balsam Lake due to a natural topographic feature known as the Big Narrows. The majority inflows do not directly enter East Balsam Lake; they enter the remainder of the Balsam Lake complex. Harder Creek flows into S2 and Rice Creek flows into S6. The lake's outlet is through Mill Pond at the south end of S4; Mill Pond's flow is controlled by the Lower Balsam Lake Dam.

Algae blooms are a consistent complaint from the local populous of East Balsam Lake residents. The lake has been recommended for listing as an impaired water body by the Wisconsin Department of Natural Resources, DNR (DNR, 2014). East Balsam Lake is impacted by internal and external phosphorus loading in the summer season where anoxic conditions consistently occur. The low oxygen concentration induces sediment phosphorus loading or internal phosphorus loading. This internal phosphorus loading makes up a major portion of the total phosphorus loading of East Balsam Lake and is a major contributor to algae blooms during the summer months which generally start in late June.

Five engineered solutions were analyzed to increase water quality by decreasing the phosphorus load and/or decreasing the retention time of East Balsam Lake. The engineered solutions analyzed were dredging, flushing by weir, flushing by pump, aeration, and alum capping. Viability and recommendations for each type of treatment are provided. This report is conducted under contract with the Balsam Lake Protection and Rehabilitation District.

Elevations referenced are to both NGVD 1929 and NAVD 1988 as noted per measurement.

2. HISTORICAL STUDIES OF BALSAM LAKE

The following reports are historical studies of Balsam Lake and are referenced within this report for technical content.

2.1 East Balsam Lake Water Quality Monitoring, BARR 2010

From 2009-2010, BARR Engineering (BARR) performed a water quality assessment of Balsam Lake published in 2011. This report was performed under contract with the Balsam Lake Protection and Rehabilitation District. The report examined the phosphorus loading and other common water quality measurements of Balsam Lake. The lake was split into six distinct zones for measurement and modeling.

2.2 Water and Phosphorus Budgets and Trophic State, Balsam Lake, Northwestern Wisconsin, 1987-1989, Water Resources Investigation Report 91-4125

A water budget and phosphorus loading study for Balsam Lake was conducted from 1987-1989. The water budget inflows/outflows accounted for in the report included precipitation, surface water inflow, groundwater discharge to the lake, evaporation from the lake, surface water outflow, and groundwater recharge. Precipitation was found to be the dominant water budget component followed by, in decreasing order, inflows from Rice Creek, ground water discharge, Harder Creek, and runoff from the watershed adjacent to the lake. The water budget study was performed during drier than normal years with rainfalls of 6.09 inches and 8.71 inches below normal for the first and second years respectively. Groundwater recharge was found to account for 2% of outflows where outflow through the Lower Balsam Lake Dam to Balsam Branch accounted for 98% of outflows. Over the entire year for the entire Balsam Lake complex, evaporation was determined to be insignificant. Outflows to Balsam Branch were determined to remove only 30% of the phosphorus which was carried by the inflows.

3. EAST BALSAM LAKE HYDROLOGY AND HYDRAULICS

The hydrology and hydraulics of East Balsam Lake must be understood to analyze the water quality issues and evaluate solutions to those issues.

3.1 Precipitation

The BARR report concentrated on a single water year for water quality data. Historical average hydrology is necessary for a long term solution. Precipitation is the main driver for flows into Balsam Lake including East Balsam Lake (Rose, 1993). The historical average precipitation was analyzed for East Balsam Lake using inverse distance weighting for four surrounding historical precipitation gages. The four gages have a common recording period of 43 years, 1971 to 2013. The gages are all similar in elevation and are all located within 20 miles of East Balsam Lake. Three of the gages were used in Rose, 1993 to determine historical average precipitation for Balsam Lake. The Cumberland gage was added as a surrounding gage to the east. The gages analyzed are noted in Table 3-1.

Table 3-1: NCDC Data Center Precipitation Gages Analyzed For East Balsam Lake

Gage ID	Gage Name	Latitude	Longitude	Elevation (NAVD 88)	Distance to East Balsam Lake (miles)
GHCND:USC00470175	Amery	45.301	-92.363	1070 ft	7.8
GHCND:USC00471923	Cumberland	45.533	-92.022	1240 ft	18.8
GHCND:USC00474894	Luck	45.573	-92.485	1220 ft	8.4
GHCND:USC00477464	St. Croix Falls	45.411	-92.646	770 ft	12.9

Figure 3-1 presents annual data averaging from 1971 through 2013 for the precipitation gages noted in Table 3-1. The data is weighted by inverse distance weighting to determine annual precipitation averages for East Balsam Lake. As can be seen from Figure 3-1, 2010 was a significantly wetter year than the annual averages. Therefore, flows from the BARR report will be adjusted by 0.82 for comparison. Lake water levels are controlled by the Lower Balsam Lake Dam under agreement with the DNR. This indicates that the volumes and thus retention times will vary by this discrepancy with historical average rainfall. Retention times will be adjusted by a factor of 1.22.

The average amount of rainfall per month based on the USGS gage data for the Balsam Lake area is:

- June = 4.35 inches
- July = 3.90 inches
- August = 4.31 inches
- September = 3.60 inches

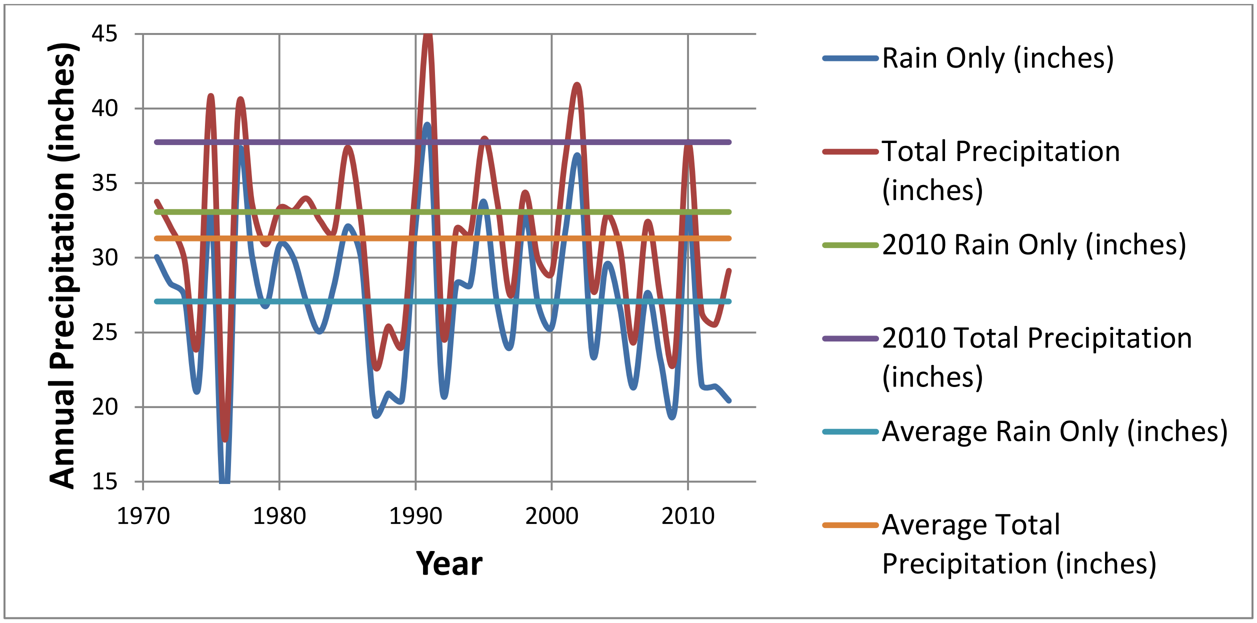

Figure 3-1: East Balsam Lake Annual Precipitation Averages

3.2 Watershed

The East Balsam Lake watershed is 3070 acres using the Big Narrows as a separation point. Figure 3-2 shows the watershed delineation for East Balsam Lake per the Purdue Long Term Hydrologic Impacts website.

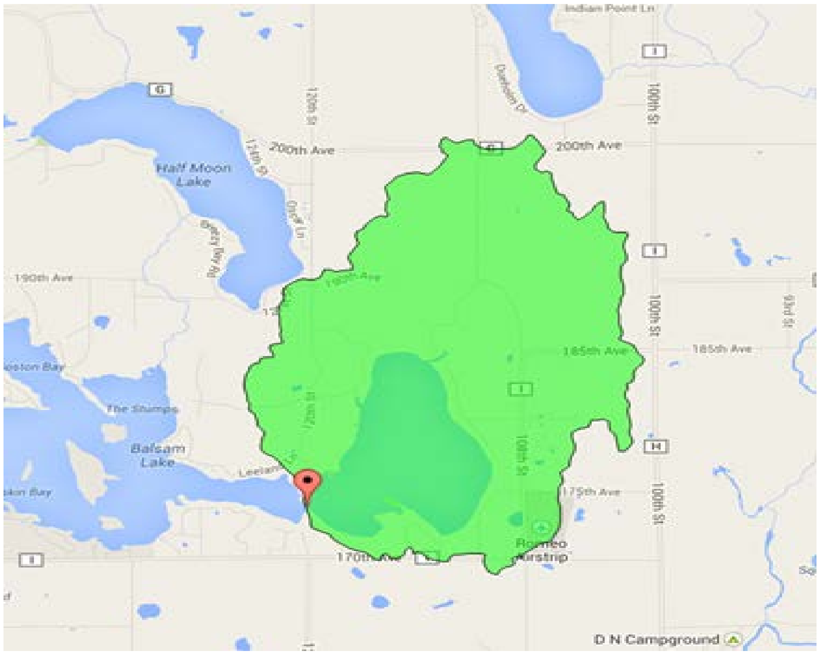

Figure 3-2: East Balsam Lake Watershed (Purdue, 2014)

The East Balsam Lake watershed has significant amounts of non-contributing area as shown in Figure 3-3. Figure 3-3 is a comparison of the watershed delineation for Balsam Lake performed by Rose for the 1993 report verses the Purdue Long Term Hydrologic Impacts digital elevation model watershed delineation. Both images were geo-referenced to obtain the overlay. As can be seen, the areas are only approximately equal. As is shown in Figure 3-3, the light green areas are considered by the USGS as non-contributing. The combined contributing boundary for the Purdue delineated watershed was found to be 2215 acres.

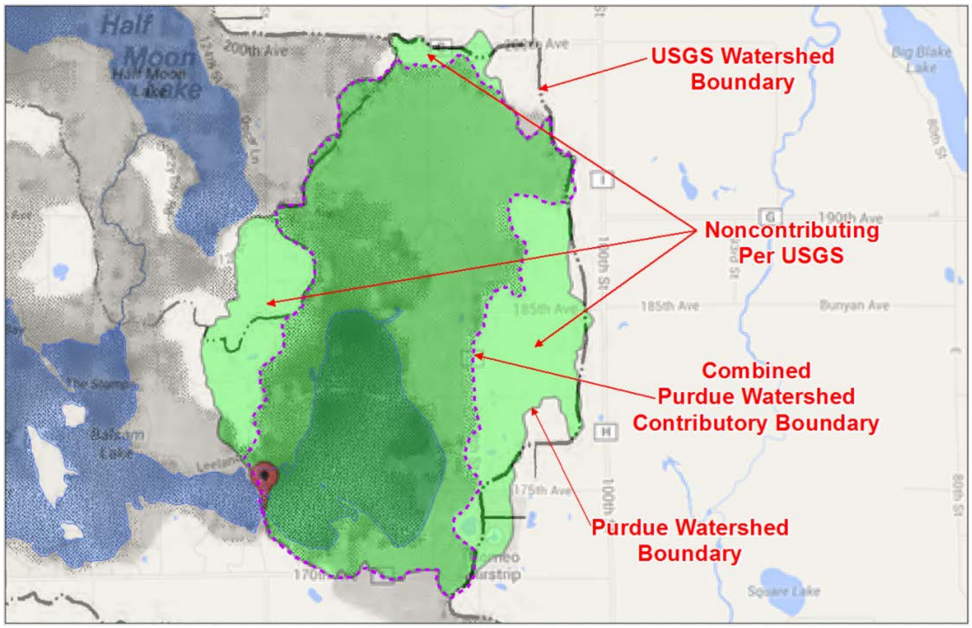

Figure 3-3: Watershed Delineation Comparison USGS vs Purdue Long Term Hydrologic Impacts

3.3 Lake Depth and Volume

East Balsam Lake is shallow averaging 9.5 feet deep (BARR, 2011, page 32). Figure 3-4 shows the depth storage curve for East Balsam Lake as derived from BARR 2011. Figure 3-5 shows the bathymetry map of Balsam Lake developed by the DNR in 1964. No water surface reference elevation was determined from the report and it is assumed that the reference elevation is determined from the USGS quadrangle map as 1133 feet elevation NGVD 1929.

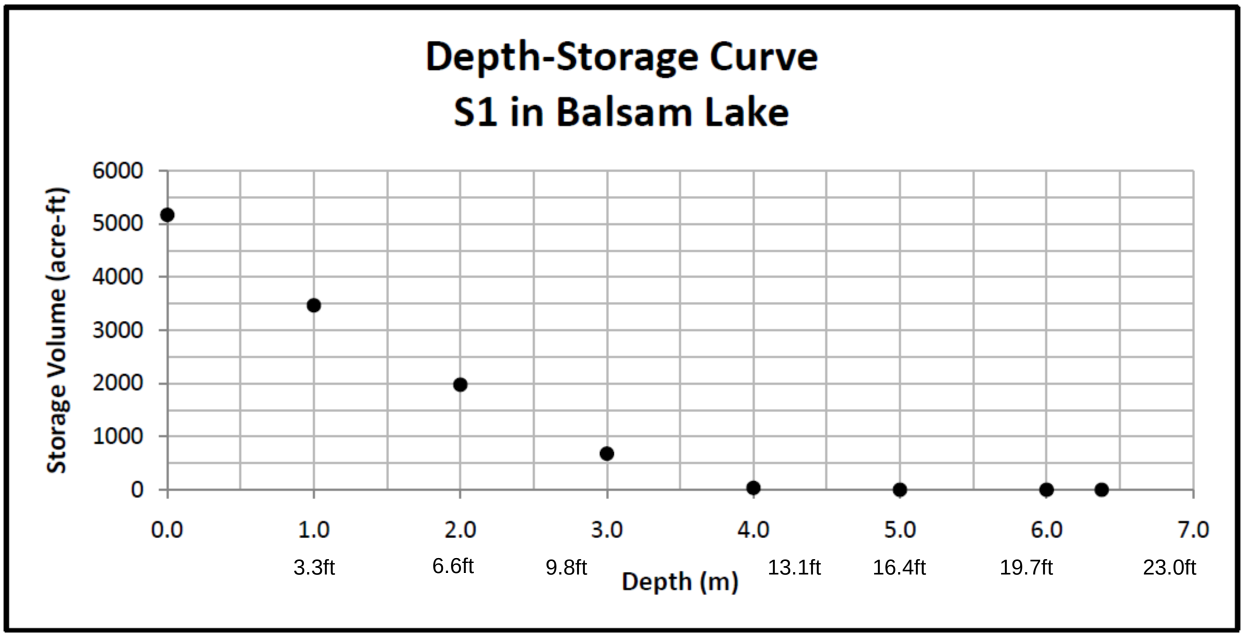

Figure 3-4: East Balsam Lake Depth Storage Curve (BARR, 2011, Appendix R-2)

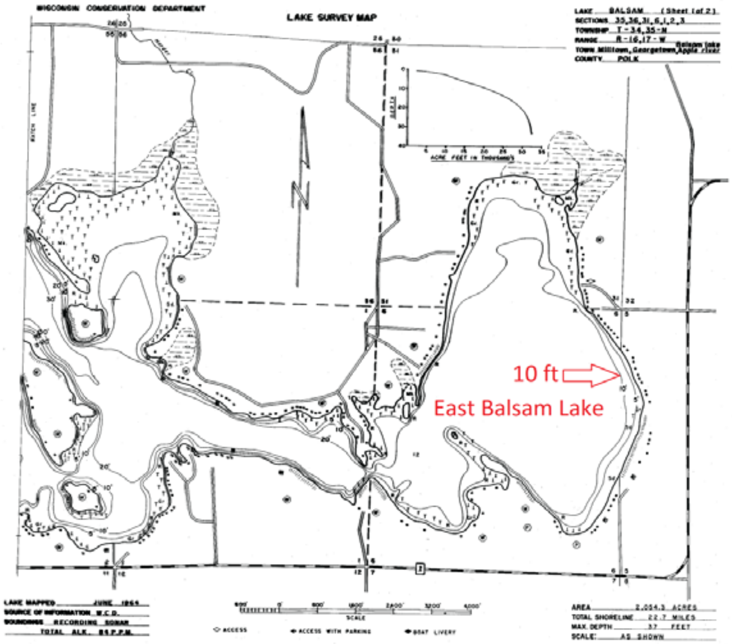

Figure 3-5: East Balsam Lake Bathymetry Map (DNR, 1964 annotated)

3.4 East Balsam Lake Summer Season Water Budget

Average precipitation rates were determined for East Balsam Lake to estimate a flow rate into the lake from precipitation. Evaporation was determined as the average of the USGS 1988, USGS 1989, and BARR 2010 reported values. These values were reported during non-average years where 1988 and 1989 had below average precipitation and 2010 had above average precipitation. The average should generate an approximate average evaporation rate during the summer. Precipitation rates for Balsam Lake were derived from inverse distance weighting to the four gages noted in Table 3-2 for the summer months of 1971 through 2013. Lake areas were derived from the National Hydro Dataset 24k resolution Balsam Lake area shape file.

Table 3-2: Balsam Lake Evaporation

Month	USGS 1988 (in./month)	USGS 1989 (in./month)	BARR 2010 (in./month)	Average (in./month)
June	6.76	4.48	2.00	4.41
July	6.73	5.11	2.90	4.91
August	5.13	4.16	2.40	3.90
September	2.96	3.35	2.30	2.87

Table 3-3: Summer Lake Average Flows Due To Net Precipitation

Month	Precipitation (in./month)	Evaporation Summer 2010 (BARR, 2011) (in./month)	Net Precipitation (in./month)	Balsam Lake Complex Flow Rate for 1900 acres (cfs)	East Balsam Lake Flow Rate for 550 acres (cfs)
June	4.35	4.41	-0.06	< 0	< 0
July	3.90	4.91	-1.01	< 0	< 0
August	4.31	3.90	0.41	1.1	0.3
September	3.60	2.87	0.73	1.9	0.6

The Lower Rice, Harder, and Otter Creek average summer flow rates were determined through analysis of available data. Rice and Harder Creek inflows were determined as averages of the USGS 1988, USGS 1989, and BARR 2010 data. Similar to evaporation these data are assumed to average out due to the below and above average years which were reported on. The Otter Creek inflow is stated in BARR 2011 data but was adjusted by 0.82 to account for the above average flows. It should be understood that flow rates are not linearly related to precipitation and the average flow in Otter Creek is probably overstated but due to the low value the overstatement is insignificant. Figure 3-6 demonstrates reported values for Rice and Harder Creeks by USGS in 1988 and 1989.

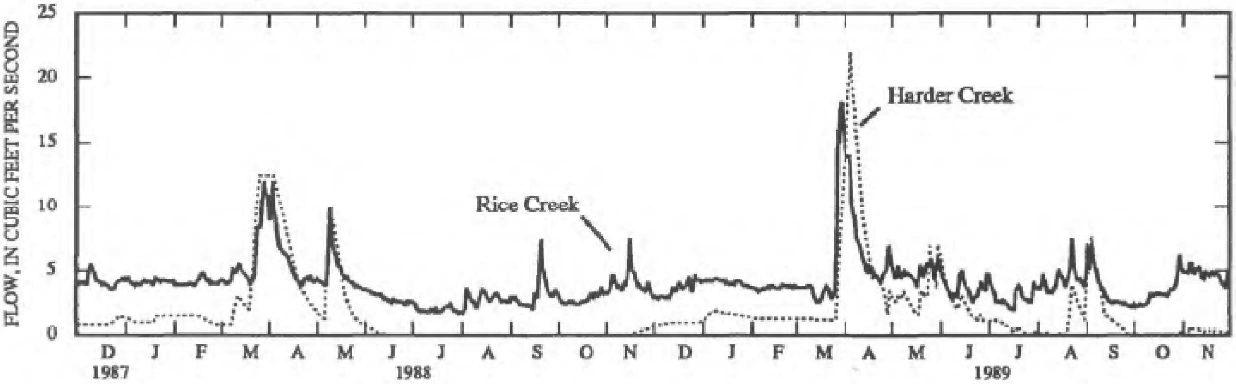

Figure 3-6: Rice and Harder Creek Flow Rates 1988 – 1989 (Rose, 1993, Figure 6b)

The average summer inflows for the three contributing creeks are:

- Lower Rice Creek and Otter Creek= 4.3 cfs
- Harder Creek = 2.6 cfs

The Balsam Lake water surface elevation is controlled by the Lower Balsam Lake Dam. Currently once the lake is at its maximum water surface elevation limit, additional flow is passed through the dam into the Balsam Branch.

4. EAST BALSAM LAKE WATER QUALITY ISSUES

East Balsam Lake has multiple water quality issues including anoxic conditions near the bottom of the lake (at certain times of year), high residence times, and net increases in phosphorus loads.

4.1 East Balsam Lake Retention Time

Table 4-1 demonstrates how East Balsam Lake has a relatively high retention time of 2.0 years compared with the other portions of the Balsam Lake complex. The other portions of the Balsam Lake complex have less severe water quality issues; therefore, improving the retention time of East Balsam Lake will have a positive impact on the water quality. It is understood that algae blooms will form in East Balsam Lake if the lake sits for 7 to 10 days. It is assumed that a retention time of 6 days or less would be required to prevent algae blooms and is presented as a unitary comparison value only.

Table 4-1: Balsam Lake Water Bodies and Retention Times
(per BARR 2011, Section 6.2 and Appendix R)

Lake Body	BARR 2010 Designation	Volume (acre*ft)	Retention Time in 2010 (yrs)	Retention Time average (yrs)
East Balsam Lake	S1	5100	1.6	2.0
Stumps Bay	S2	600	0.24	0.29
Balsam Lake (1)	S3	6100	0.55	0.67
Balsam Lake (2)	S4	12700	0.70	0.85
Boston Bay	S5	2600	0.54	0.66
Little Narrows	S6	1200	0.25	0.31

4.2 East Balsam Lake Dissolved Oxygen Concentrations

Anoxic conditions were monitored by BARR in 2010 in East Balsam Lake. “When oxygen concentrations are less than 2mg/L (anoxic conditions), sediments pump phosphorus into the lake.” (BARR, 2011, page 35). Anoxic conditions were determined to be the cause of the internal sediment phosphorus loading.

Figure 4-1 is a graph of time and depth vs dissolved oxygen for East Balsam Lake. It can be seen from Figure 4-1 that dissolved oxygen rates dip below 2 mg/L at depths greater than 3.5 m during the period of late June to late August. It is assumed that the low dissolved oxygen concentrations occur every year during the summer months. For analysis purposes and to be conservative it is assumed that this period occurs from June 15th to September 15th totaling 92 days.

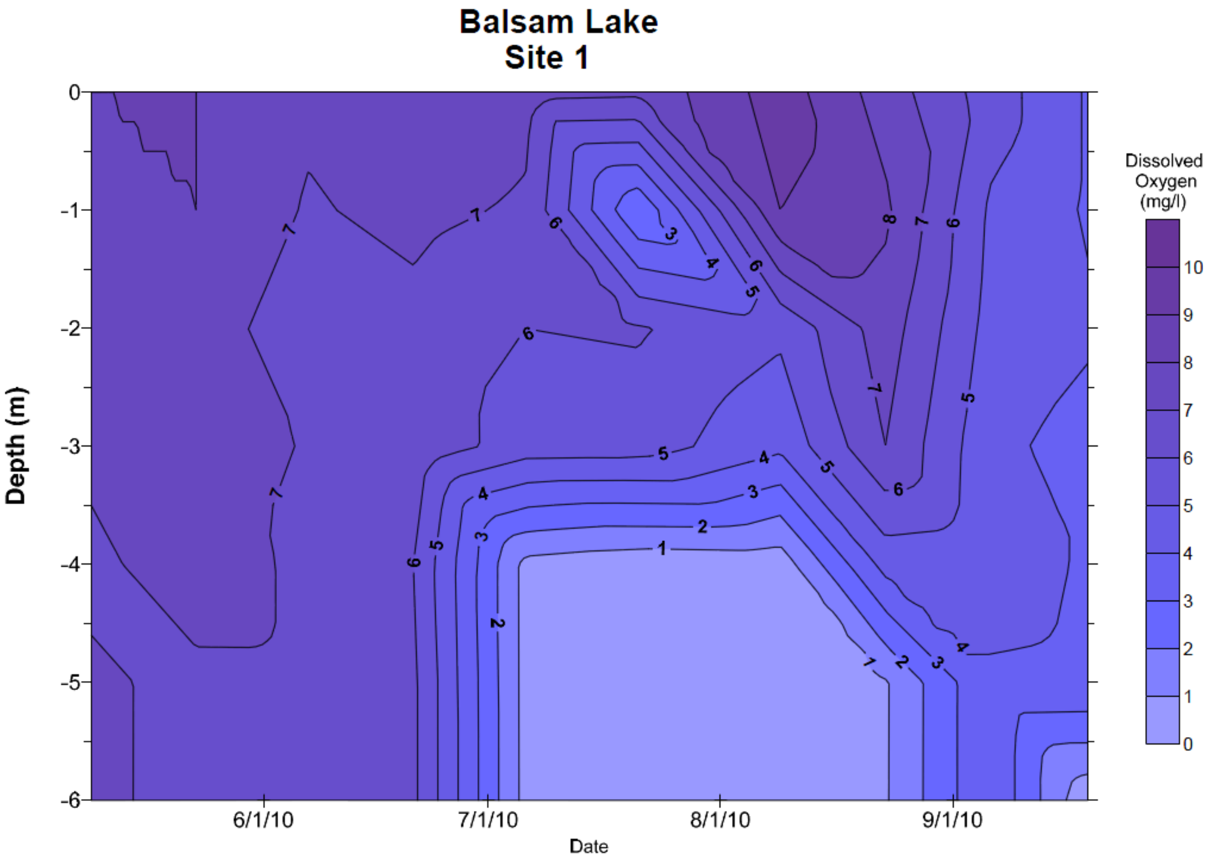

Figure 4-1: East Balsam Lake Dissolved Oxygen Isopluvial Graph
(BARR, 2011, Appendix F-2)

4.3 East Balsam Lake Phosphorus Loading

Phosphorus loading to East Balsam Lake consists primarily of runoff from upstream and internal soil loading. “In 2010 East Balsam Lake conveyed nearly 40% of its annual phosphorus load to S3 (Balsam Lake (1)).” (BARR, 2011, page 35). The East Balsam Lake watershed area consists primarily of the following: (BARR 2011, page 12)

- 17.50% Lake
- 23.76% Cropland
- 6.64% Forage/Pasture
- 31.83% Forest
- 4.26% Lake Residential
- 2.63% Rural Residential
- 10.23% Wetland

Phosphorus export rates were determined to be well within Wisconsin regulatory limitations for Otter Creek, Harder Creek, and Lower Rice Creek. The low export rates are reflective of a wellmanaged watershed (BARR, 2011). Although no specific mention is made of the unnamed tributaries to East Balsam Lake it is reasonable to assume that similar export rates are produced to these seasonal streams. Figure 4-2 presents total phosphorus concentrations vs time for East Balsam Lake in 2010. As can be seen, there is a spike in the bottom water layer in phosphorus concentrations during the summer period which coincides with anoxic conditions, indicating the validity of the soil loading theory. The time period is also consistent with Figure 4-1 and Figure 4-4. Figure 4-3 is a breakdown of the phosphorus loading sources as determined by BARR 2011 where S1 refers to watershed runoff.

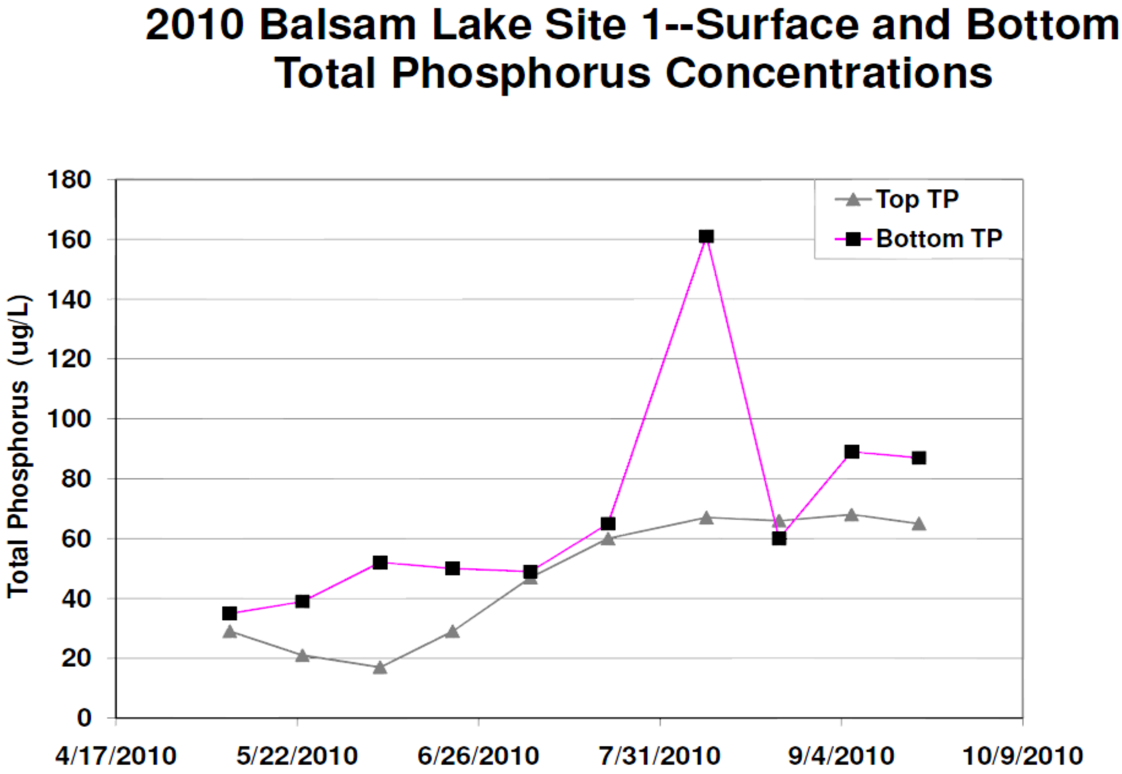

Figure 4-2: East Balsam Lake Total Phosphorus vs Time 2010 (BARR, 2011, Page 52)

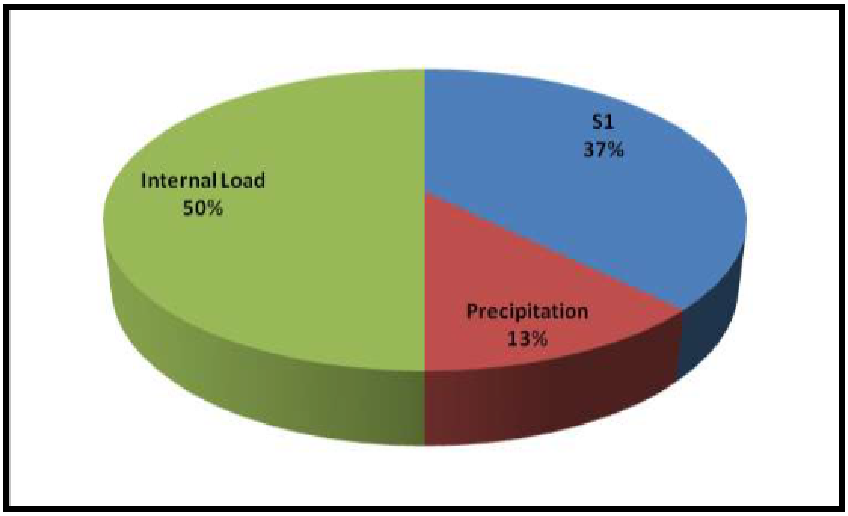

Figure 4-3: East Balsam Lake Phosphorus Budget (BARR, 2011)

4.4 Water Clarity, Secchi Depths

Water clarity is measured by Secchi depths; Secchi depths are available for Balsam Lake from historical records from volunteer measurements (BARR, 2011). Figure 4-4 presents Secchi depths vs time for East Balsam Lake during summer, 2010. It can be seen from Figure 4-4 that water clarity follows a similar time table to low dissolved oxygen levels of approximately June 15th to September 15th. Note that the other areas of Balsam Lake are all eutrophic in late summer per BARR, 2011, Figure 5-9.

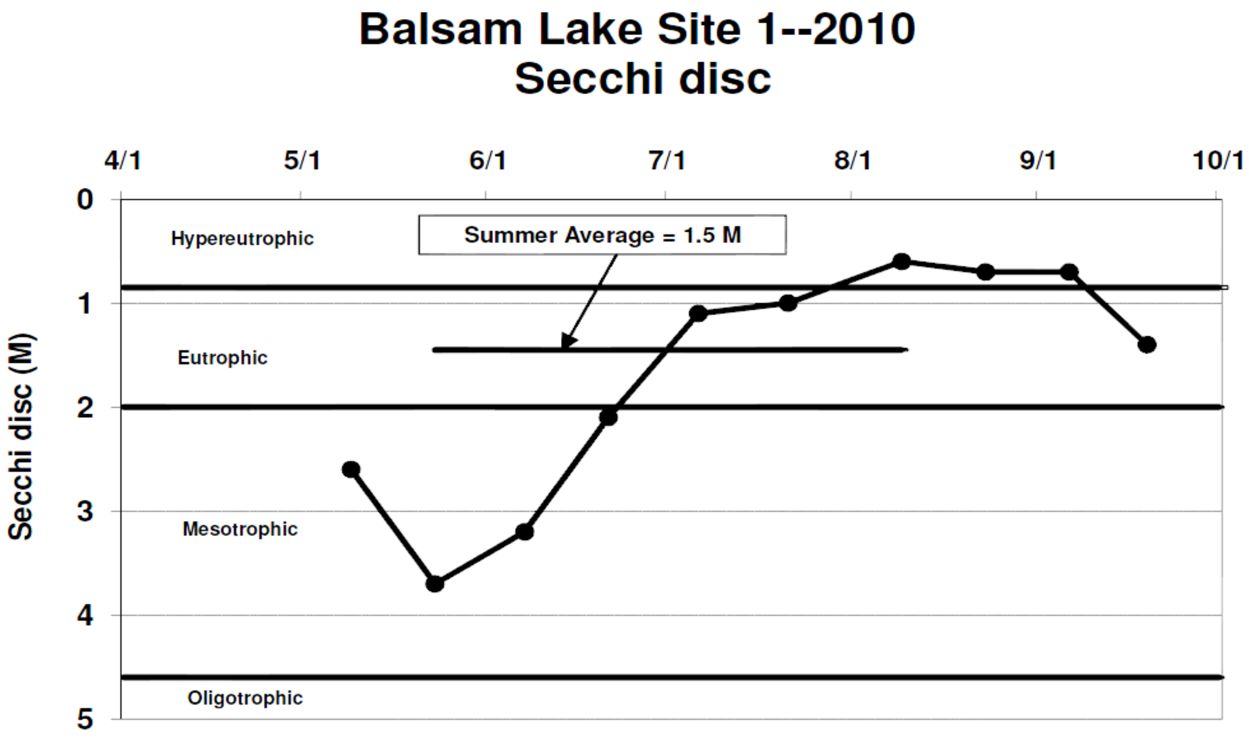

Figure 4-4: East Balsam Lake Secchi Depths vs Time, 2010 (BARR, 2011, Appendix F-8)

5. ENGINEERED SOLUTIONS TO WATER QUALITY ISSUES IN EAST BALSAM LAKE

Five engineered solutions to water quality issues in East Balsam Lake were examined for feasibility. Feasibility includes available water resources, potential cost, and ability to be permitted. The potential solutions include dredging, flushing by pumping, flushing by weir, aeration, and alum capping.

5.1 Dredging

Dredging is the removal of the top sediment layer by mechanical or hydraulic means. It is assumed that the internal phosphorus loading is generated by only the top 1 or 2 feet of sediment in the lake bottom. Dredging would remove the phosphorus laden layer and the potential for internal phosphorus loading. The soil has not been analyzed to determine the exact depth of soil needed to be removed for this process to be effective

Dredging is a heavy environmental impact solution. Removal of the bottom soil layer includes the life sustaining soil of the lake. It would take years or even decades for the lake to reestablish the existing ecosystem of aquatic plants and animal life.

East Balsam Lake is approximately 550 acres in area. Assuming 1-2 feet of soil removal is sufficient, the estimated quantity of soil removal required to successfully remove the phosphorus is from 890,000 cubic yards to 1,800,000 cubic yards of sediment. Costs to remove sediment include the mechanical removal, hauling, and disposal. Due to the quantity of sediment removal only engineering experience was used to estimate the cost and a fill site was not found. The estimated cost for dredging, hauling, and disposal is $20 per cubic yard. At $20 per cubic yard of soil removed the estimated cost of removing soil by dredging ranges from $18 Million to $36 Million. Lake bed soil should be sampled for phosphorus content by depth before any dredging project is considered to obtain a more accurate estimate of necessary soil removal.

5.2 Flushing by Weir

Flushing is a recognized technique to improve water quality. The State of Washington used flushing to improve the water quality of Moses and Green Lakes using diverted water from nearby cleaner sources (EPA, 1981). This effort relied upon the higher water quality of the Columbia River to “flush” out the lake. The lake would reach the steady state quality of a flow ratio mix of the natural inflow and diverted river inflow concentrations.

A similar potential for flushing exists for East Balsam Lake using Harder Creek, Otter Creek, an d Lower Rice Creek water diverted from its natural alignment to move south under Highway I. Rice and Harder Creeks both have higher water quality for phosphorus content than East Balsam Lake. Currently they flush the remainder of the lake complex. Figure 5-1 is a schematic showing the inflows into the Balsam Lake complex and a drawing of the flushing by weir technique for East Balsam Lake.

Balsam Lake is the reservoir created by the Lower Balsam Lake Dam; flow from the lake is controlled by the dam. Potentially, the exit weir can be redesigned to force flow through East Balsam Lake and exit south to an existing designated wetland. A culvert would need to be constructed under existing Highway I to pass the redirected flow.

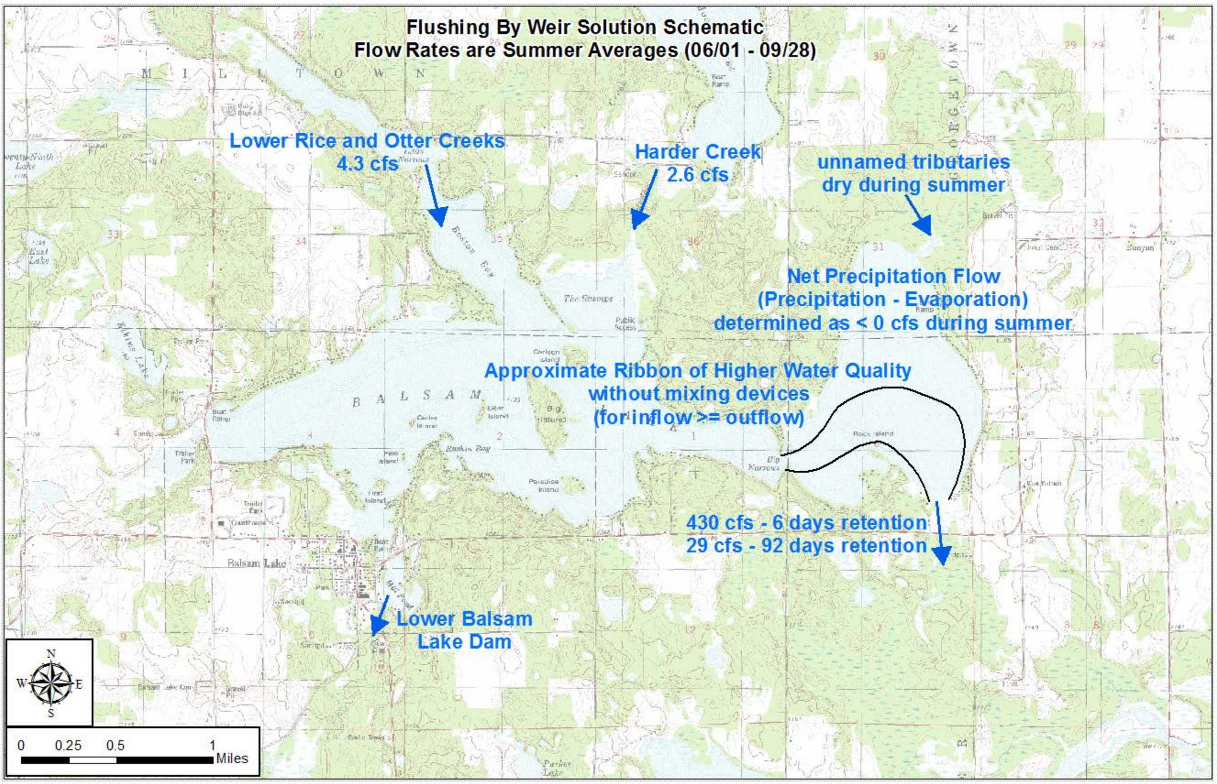

Figure 5-1: Flushing by Weir Schematic and Flow Budget (USGS Seamless Quad Background)

As can be seen from Table 3-3 net precipitation flow during the summer is not a reliable source of significant amounts of flushing flows.

Due to entrance of flow into East Balsam Lake from "Big Narrows" a ribbon of higher water quality would be generated without improving quality for all of East Balsam Lake. Figure 5-1 demonstrates the potential for a flow ribbon also known as short circuiting. Short-circuiting is described as "the last water that entered the tank is the first water drawn from the tank" and "the oldest water cannot be drawn from the tank due to the location of the outlet pipe" (Duer, 2010). Figure 5-2 demonstrates the principle of tank short circuiting where the darkest water on the edges of the tank are the worst quality and the quality improves towards the outlet. Proper mixing is generally used to prevent short circuiting but properly mixing East Balsam Lake is impractical.

Figure 5-2: Water Tank Short Circuiting (Duer, 2010, Figure 3)

It is understood that algae blooms will occur in East Balsam Lake with a retention time of greater than 6 days. The volume of East Balsam Lake at an average lake surface elevation is 5100 acre-feet. The flow required to flush, replace all the water, East Balsam Lake in 6 days is 430 cfs. This flow is greater than the average inflow of all combined inflowing creeks and would require drying out the natural outflow in addition to requiring the artificial input of 423 cfs.

To create a retention time similar to the other portions of Balsam Lake, a 92 day retention time, a flow of 29 cfs would be needed. This would still be greater than the average inflow of all combined inflowing creeks. This would require drying out of the natural outflow in addition to requiring artificial inputs. It is unknown if using a flow of 29 cfs would increase water quality, it does not follow the understood retention time recommendation. Because it does not meet the recommended retention time, other issues such as the shallow waters and internal phosphorus loading would likely still cause algae blooms.

If all 6.9 cfs or a portion of the flow entering the Balsam lake complex were rerouted through East Balsam Lake, it would reduce the retention time, but not enough to prevent algae blooms. This rerouting of flow would require drying out of the natural outflow. This is the same flow that flushes the other portions of Balsam Lake but there are many other aspects that could cause algae blooms if the recommended retention time is not met. The rerouted flow may have a negative effect on the other portions of the Balsam Lake Complex.

Additional amounts of flow may not be allowable into the wetlands mapped south of East Balsam Lake and could potentially be considered a dangerous flooding impact. Rerouting the entire combined flow of Lower Rice Creek, Otter Creek, and Harder Creek would not be easily permitted. This reroute of the flow would bypass approximately 17.8 miles of natural flow while still emptying into the same Apple River. Figure 5-3 demonstrates the bypass configuration in terms of the Apple River Watershed.

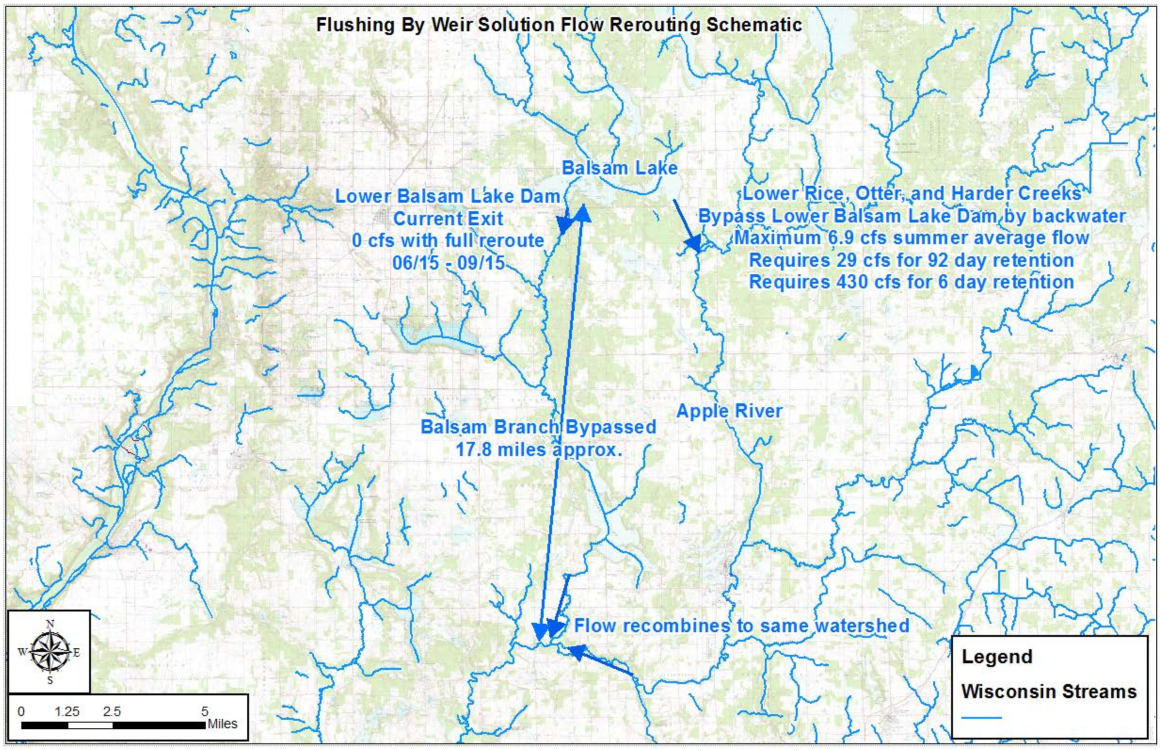

Figure 5-3: Flushing by Weir Control Reroute Schematic
(USGS Seamless Quad Background)

Due to the lack of required inflows to flush the East Balsam Lake complex the lake would actually be drained, without additional inflows, rather than flushed. In addition, rerouting of the entire inflows of Harder, Otter, and Rice Creeks would not be easily permitted as bypassing approximately 17.8 miles of Balsam Branch. If a retention time of 6 days is not met, algae blooms may still occur due to a combination of other factors. Flushing by weir is not a recommended alternative.5.3 Flushing by Pump and Pipe

5.3 Flushing By Pump And Pipe

Flushing by pump and pipe would force higher quality flow from “The Stumps” to the northern edges of East Balsam Lake where the flow would be able to interact with a larger portion of the lake before exiting through “Big Narrows” into Balsam Lake. Note that multiple outlets and baffles would be required to force all of the lake to mix with the inflow. Figure 5-4 demonstrates a schematic and preferred pipe alignment for this potential solution.

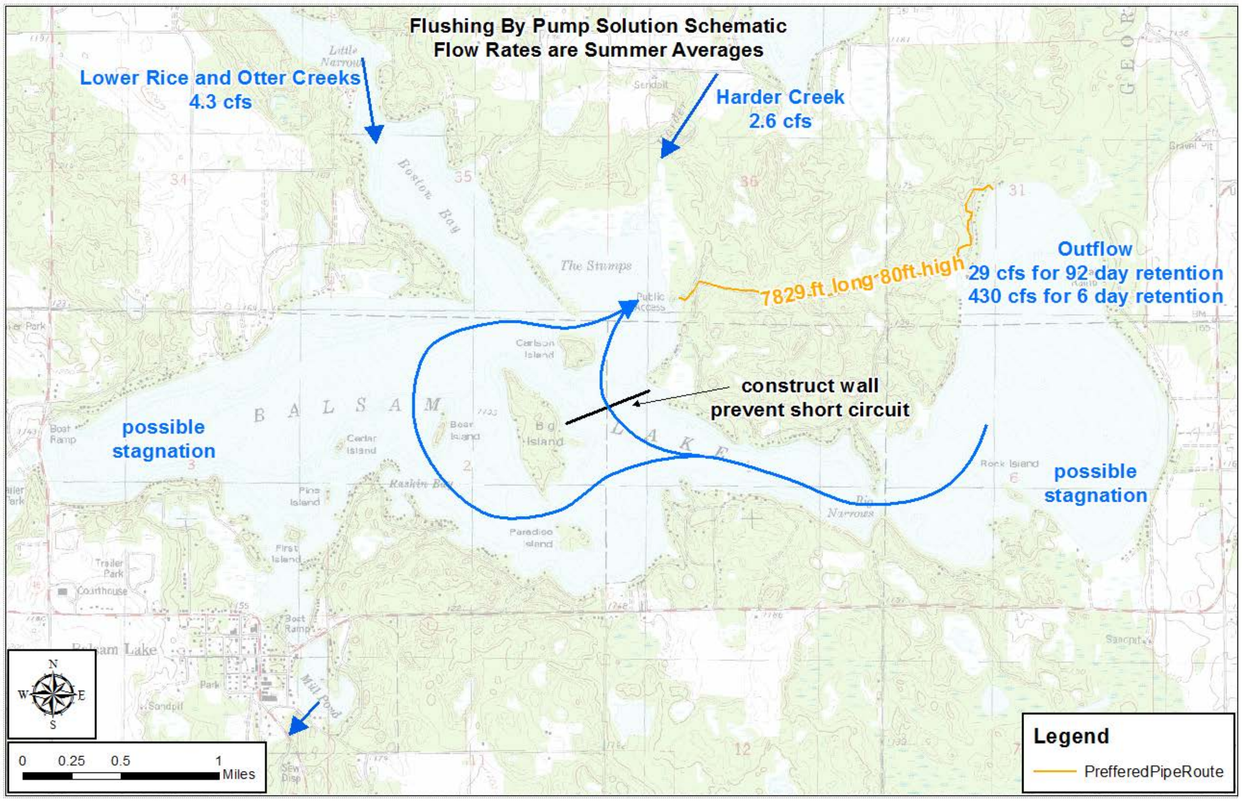

Figure 5-4: Flushing by Pipe and Pump Schematic
(USGS Seamless Quad Background)

Flushing requires removal of the entire lake within 6 days. This is the same flow rate noted in the flushing by weir option with a different method of water movement. Unlike the flushing by weir option, flushing by pumping does not require artificial water resource input to maintain lake levels as the water is recycled through the Balsam Lake complex. In addition, flushing by pipe would not require a rerouting of natural flows to Balsam Branch. Figure 5-4 shows that not as much water will inflow to the Balsam Lake complex as is being pumped. This will cause a recycle effect where the lakes will mix in an approximate steady state mixture rather than a flushing effect from the incoming sources. A baffle/wall would likely need to be constructed between Big Island and the peninsula to prevent short circuiting of flow between only East Balsam Lake and Stumps Bay.

Construction of inlets and outlets that can handle 430 cfs will cause significant suction and jetting velocities at the entrance and exit. Velocities for 430 cfs flow within a 5.5 ft. diameter pipe are approximately 18 fps. Construction of the pump and pipe system would require cordoning off areas of Stumps Bay and northern East Balsam Lake from human and boat access.

The high velocities surrounding the inlet and outlet may overpower fish near the suction flows and cause erosion in the lake bottom near the inlet and outlet. In addition to addressing human safety concerns, construction of the pump and pipe system would require addressing lake-bottom erosion and fish protection issues.

Construction of a pump and pipe system that can handle 430 cfs is a significant multi-million dollar infrastructure investment in addition to ongoing maintenance and power consumption costs. A 430 cfs pump is comparable to pumps that are used for power stations, water supplies, flood control, and desalination plants (Flygt, 2014). Pumps this large would be impractical for this application. Figure 5-5 shows a 430 cfs pump, a Flygt A-C Series Column Pump.

Figure 5-5: 430 cfs Pump, Flygt A-C Series Column Pump (Flygt 2014)

The preferred pipe alignment would be approximately 8100 feet long including additions into the lake for entrance and exit beyond the shoreline.

Figure 5-6 shows the expected annual pumping costs for the understood flow rates vs internal steel pipe diameter. Power costs are based on $0.112/kW*hr assumption which is the local average power cost. The preferred pipe diameter would minimize total installment + power consumption costs. It is assumed that pumping would occur continuously throughout the 92 day period to prevent stagnation.

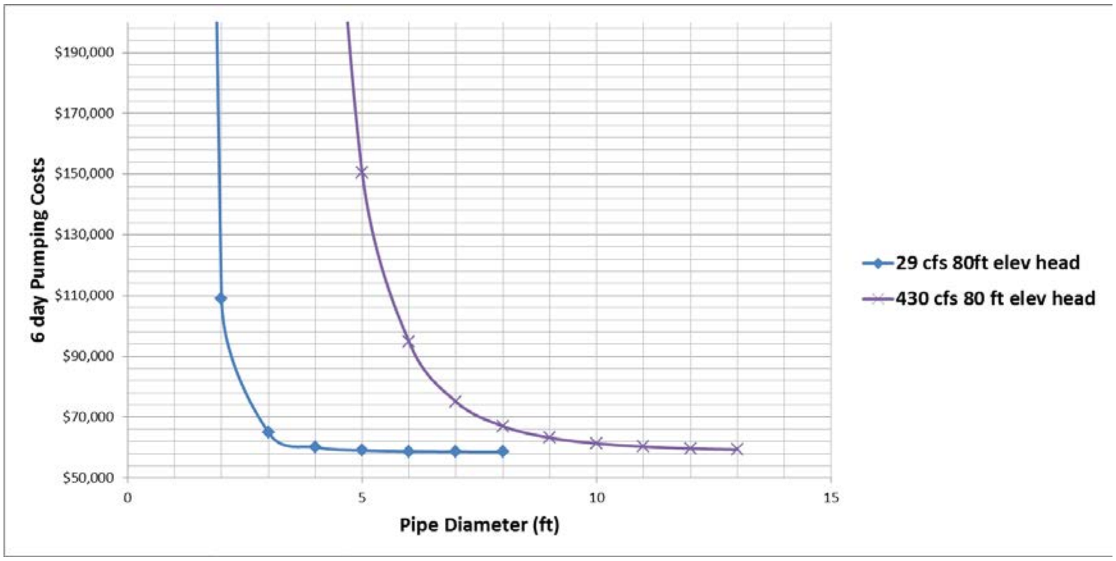

Figure 5-6: Annual Pumping Costs for Given Design Flow Rates vs Pipe Internal Diameter

Figure 5-7 demonstrates how the total 20 year cost will vary depending upon internal pipe diameter. The total cost changes per diameter by pumping power required and unit pipe installation costs. Unit installation costs are derived from www.get-a-quote.net for 2009 Wisconsin Heavy Construction Costs for welded steel pipe. Welded steel pipe is chosen based on its longevity and low seepage histories. Due to the amount of flows considered only maximum wall thicknesses were chosen for the unit cost trend analysis. Per Figure 5-6, an internal diameter pipe of 5.5ft would optimize the total 20 year cost. Due to the continuous flushing no annual pumping costs would meet the understood $100,000 annual maximum. This 20 year cost analysis does not include the construction of a pumping house, installation of the pumps, and improvement of the local electrical grid to handle the increased load. These additional costs can easily range from $2-10 Million beyond stated costs in Figure 5-7.

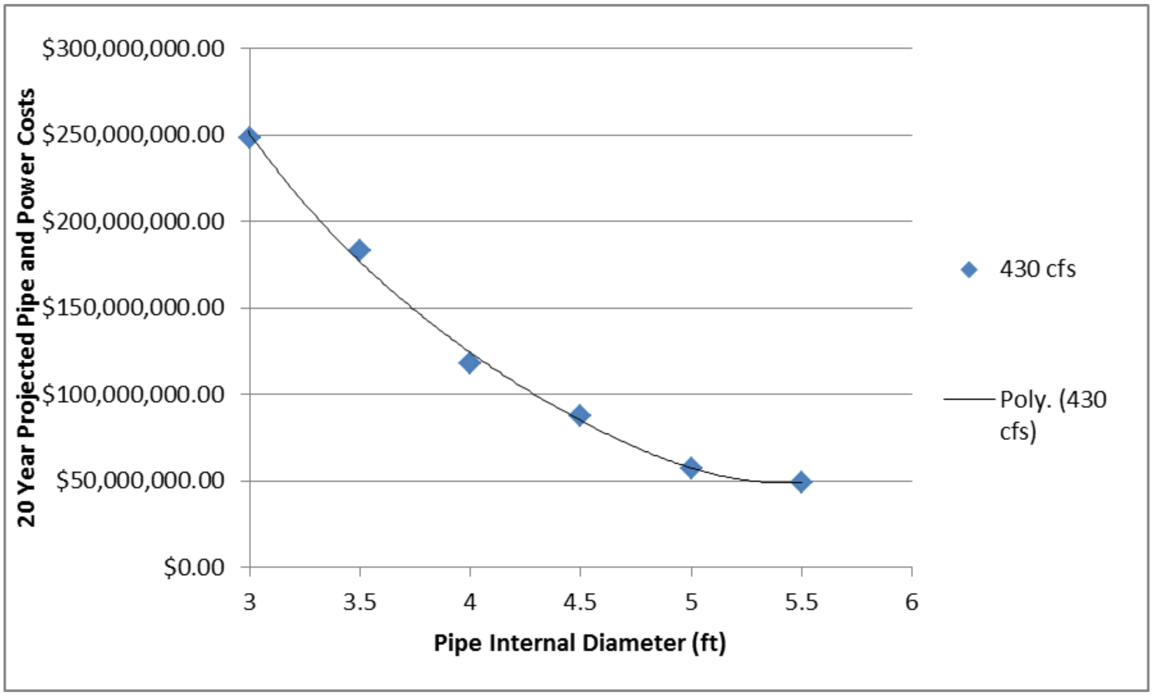

Figure 5-7: 20 Year Cost Investment (Pipe and Power Only) vs Pipe Diameter

Flushing by pump and pipe would not have sufficient inflow to the Balsam Lake complex to replace the phosphorus loaded water with fresh water within East Balsam Lake. As shown in Figure 5-4, flushing would more likely approach a steady state mixture of the entire Balsam Lake complex. This would improve the water quality of East Balsam Lake but could have negative water quality effects on the rest of Balsam Lake. As shown in Figures 5-8 to 5-10, all portions of the Balsam Lake complex are in or near a Eutrophic state during late summer. It could be detrimental to the rest of the lake to force heavy mixing of East Balsam Lake with the rest of the complex.

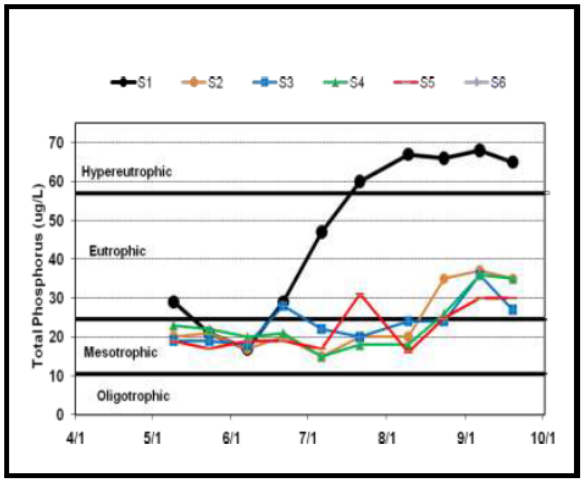

Figure 5-8: 2010 Phosphorus Concentrations for All Balsam Lake Areas (BARR, 2011, Figure 5)

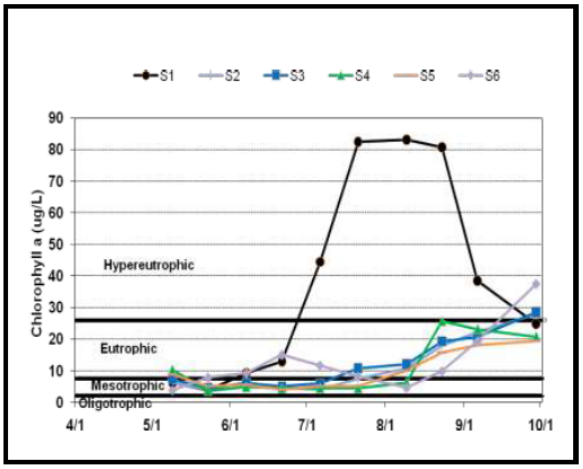

Figure 5-9: Balsam Lake Chlorophyll A Concentrations All Areas (BARR, 2011)

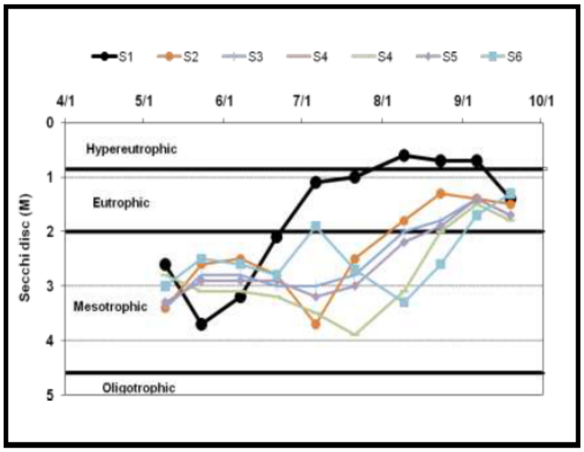

Figure 5-10: Balsam Lake Secchi Disc Depths All Areas (BARR, 2011)

Note that the measurements taken in Figures 5-8 to 5-10 were performed during an above average precipitation year and should generally reflect higher water quality than normally exists within the lakes.

Pumping 29 cfs, to obtain a retention time similar to the rest of the Balsam Lake complex, may be a feasible amount of water to pump. It would decrease the retention time but East Balsam Lake would not be completely flushed within 6 days. It is unknown if this would have an effect on the water quality because the retention time would not meet the required time. Other contributing factors such as shallower water depths of East Balsam Lake and internal loading may still cause algae blooms if the required retention time is not met.

Due to the lack of sufficient and reliable higher quality inflows, the high investment costs, the ability to negatively impact the rest of the lake, negative environmental impacts on the lake from high flows and velocities, blocking off portions of the lake from recreational activities, and dangerous conditions for residents and visitors due to high flows and velocities; flushing by pump and pipe is not a recommended alternative.

5.4 Aeration

Aeration uses pumps and perforated hoses/pipes to force air into the bottom layers of the lake. This would increase the oxygen concentrations in the anoxic layers of the lake during the summer months. Controlling the oxygen content in the soil layers may prevent the internal loading of the lake phosphorus from the sediment layers.

Aeration is a feasible option to reduce blue-green algae growth (Washington Department of Ecology). Blue-green algae are also known as cyanobacteria and are toxic. This type of algae is discouraged in growth by the use of aeration, due to the increased oxygen and de-stratification of the lake. Local lake residents have noted the existence of some blue-green algae, but it is not known if it is the predominant algae during the late summer months.

Another aeration method is forced mixing through mechanical lift devices. Several companies produce these devices commonly used for potable water tanks and reservoirs. Medora Corporation of North Dakota makes a product called the SolarBee; its website claims the SolarBee is 90-95% effective in controlling blue-green algae blooms (Medora Corporation).

Depending on the type of algae present in East Balsam Lake aeration or forced mixing may be a viable alternative. Further research into whether aeration or forced mixing would be affective in this application should be done by a limnologist more familiar with the biological process or the lake.

5.5 Alum Capping

Alum capping is the placement of alum into a lake. The Alum flocculates with the phosphorus in the water and drops to the lake floor forming an Alum layer. This layer traps the phosphorus within the soil from being released during times when minimal dissolved oxygen is present. Alum treatment would not have the same environmental impact as dredging. The addition of Alum to a lake is environmentally degrading only when the concentration causes a pH to drop below acceptable levels. Historical studies have shown that the addition of Alum does not interfere with the lake bottom ecosystem (BARR, 2009). However Alum treatment in shallow lakes is much less effective and has a shorter life span than Alum treatment in deep lakes.

A national study of Alum treatment in lakes found that treatment is much less effective in shallow lakes with significant external phosphorus loading (DNR, 2003). From Figure 3-5 it can be seen that Balsam Lake is a shallow lake with maximum depths near 10ft. From Figure 5-11, it can be seen that East Balsam Lake receives 50% of phosphorus loading from external sources (BARR, 2011).

Further investigation into the feasibility of Alum capping in this situation should be done by a limnologist more familiar with the alum treatment process.

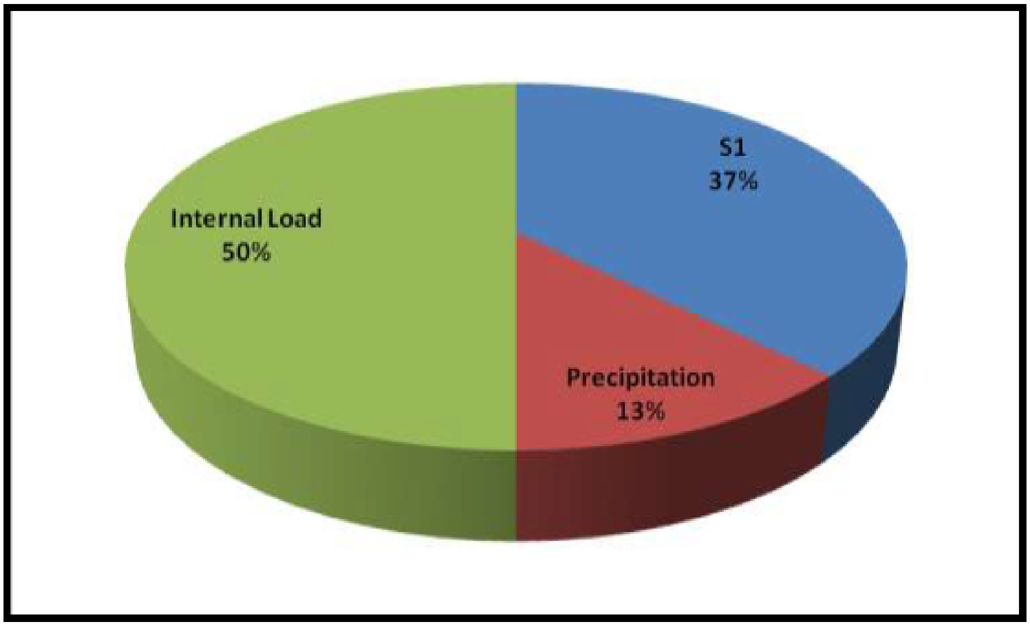

Figure 5-11: East Balsam Lake Phosphorus Budget (BARR, 2011)

6. RECOMMENDATIONS

It is recommended that none of the potential solutions be implemented as engineered solutions to East Balsam Lake water quality issues. Aeration and Alum capping could be investigated further by a limnologist. Table 6-1 summarizes each analyzed solution, a cost estimate, and the governing disadvantages as a solution.

Table 6-1: Summary of Engineered Solutions to East Balsam Lake Water Quality Issues

Engineered Method	20 Year Cost Estimate Present Value (2016 cost)	Governing Solution Disadvantages
Dredging	$18 to 36 Million	Environmentally destructive, cost prohibitive
Flushing By Pump	$50 Million	Not feasible with 6 day flush requirement, cost prohibitive with 6 day flush requirement
Flushing By Weir	Not Feasible	Not feasible with 6 day flush requirement
Aeration	Consult a limnologist	Consult a limnologist
Alum Capping	Consult a limnologist	Consult a limnologist

Twenty year cost estimates for 2016 are based on average annual inflation of 3%. The cost estimates are projected to 2016 understanding that 2016 is the earliest project start date.

7. CONCLUSIONS

East Balsam Lake has water quality issues annually over the summer months. Previous analyses have provided data that define the water quality issues and allow alternatives to improve water quality to be investigated.

The contributory watershed to East Balsam Lake is 2215 acres. The major contributing inflow for East Balsam Lake during the summer months is precipitation. Precipitation inflow for East Balsam Lake is effectively neutralized by evaporation outflow during the summer months. For an average year, there is a net loss (more evaporation than precipitation) of water from East Balsam Lake during June and July and a net gain of 0.3 cfs and 0.6 cfs for August and September.

The water quality of East Balsam Lake is poor during the summer months generally between June 15 and September 15; this is caused by various issues. East Balsam Lake has more stagnant water than the other portions of Balsam Lake; the retention time of East Balsam Lake is 2.0 years compared to 0.3 to 0.85 years for the other portions of the Balsam Lake complex. The dissolved oxygen levels in the lower depths drop below 2 mg/l during the summer months; this creates anoxic conditions that allow phosphorus to be released from the soil. The phosphorus levels in East Balsam Lake are higher than the other portions of the lake. The phosphorus loading of East Balsam Lake in comprised of 50% internal loading, 37% watershed runoff, and 13% from precipitation. The Secchi disk readings, which indicate water clarity, confirm that East Balsam Lake has lower water quality during the summer months than the other portions of the Balsam Lake complex.

Five engineered solutions were considered to improve the water quality of East Balsam Lake. The solutions considered were: dredging, flushing by weir, flushing by pumping and pipe, aeration, and alum capping.

Dredging would remove the phosphorus loaded sediment at the bottom of the lake. This is not a recommended solution due to high cost and environmental impacts of removing the lake bed material.

Flushing by weir would force the water from Lower Rice, Otter, and Harder Creeks to pass through East Balsam Lake and exit beneath HWY I. This is not a feasible option because additional flow would be needed to obtain the flow necessary to prevent algae blooms.

Flushing by pumping and pipe would pump water from “The Stumps” to the northern portion of East Balsam Lake. This would circulate the water better through East Balsam Lake improving the water quality there. This would cause the entire lake to reach a steady state and would likely decrease the water quality of the other portions of the lake. 430 cfs would need to be circulated to create the retention time of 6 day needed to prevent algae blooms. This solution is not feasible because of the amount of water that would need to be circulated to prevent algae blooms. This alternative is not recommended because of cost, safety concerns to residents and visitors, and environmental concerns. 29 cfs could be circulated to create a retention time similar to the other portions of East Balsam Lake and is presented as a unitary comparison value and not a solution. This solution is not recommended because it may not prevent algae blooms. If the recommended retention time of 6 days is not met, other factors such as shallow depths and internal phosphorus loading may still cause algae blooms.

Two other alternatives were considered but not fully developed. Aeration and forced mixing could improve water quality by de-stratifying the lake and adding oxygen near the bottom of the lake. This could be a viable option but further evaluation of this option is needed. Alum capping could be a feasible alternative. Alum capping adds alum to the lake, the alum flocculates with phosphorus, sinks to the bottom, and creates a layer that blocks the lake bed soil from releasing phosphorus. As with aeration, further evaluation and sediment sampling is needed to determine if alum capping is a feasible solution.

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APPENDIX D. EAST BALSAM WATERSHED AGRICULTURAL ANALSYIS

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East Balsam Lake Watershed
Soil Fertility and Phosphorus Index Assessment
July 2015
Polk County Land and Water Resources Dept.
Eric Wojchik-Conservation Planner

Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Project Overview

The Polk County Land & Water Resources Department (LWRD) conducted this evaluation to quantify the amount of phosphorus delivery from agriculture land uses to East Balsam Lake at the request of the Balsam Lake Protection and Rehabilitation District. This project's objective was to work with the agriculture community to gather field soil test data, model estimated phosphorus delivery from fields, identify areas of concern, and identify strategies to reduce nutrient runoff from non-point sources in the watershed.

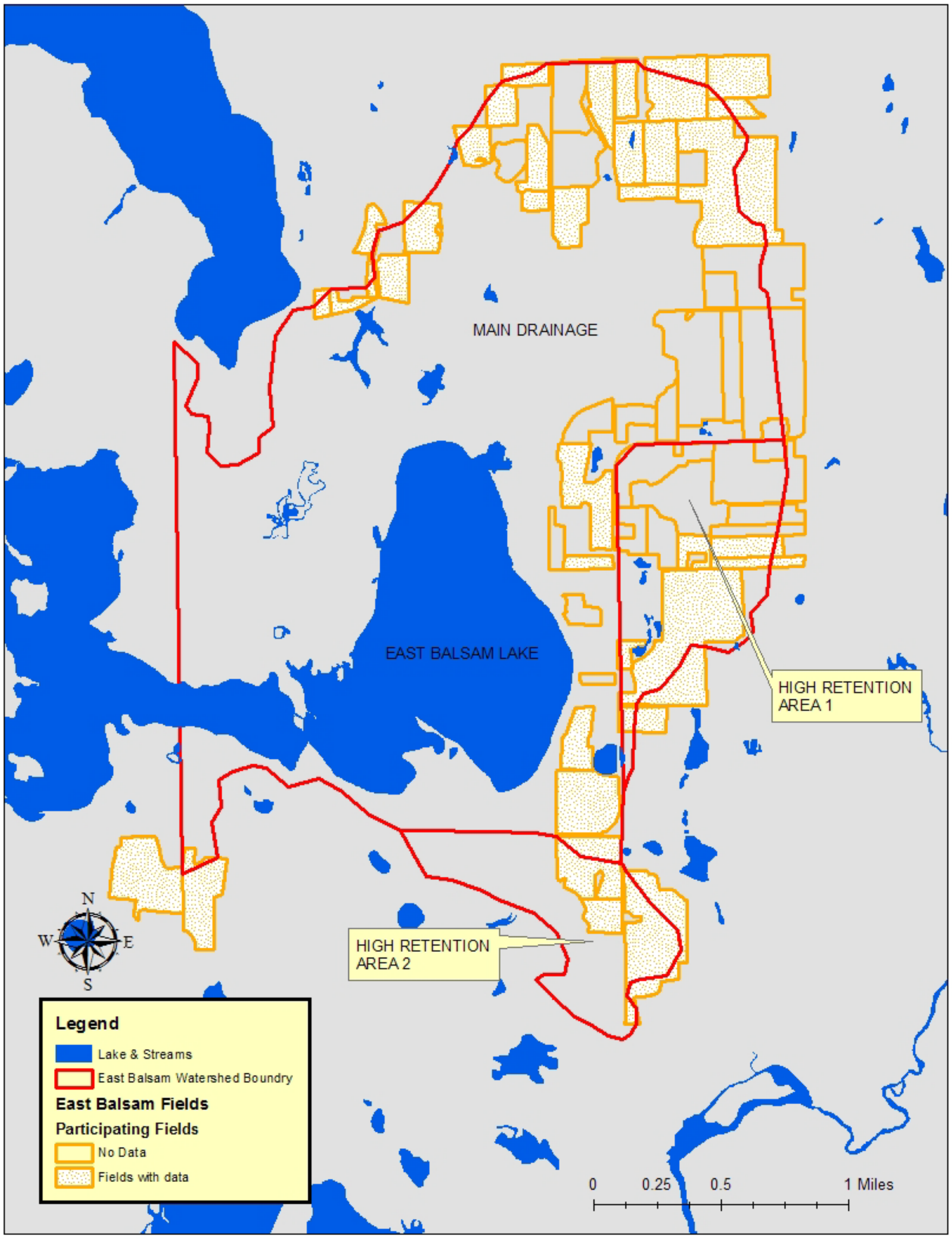


Figure 1

Project Area

The East Balsam Lake watershed encompasses 3,006 acres (Figure 1). There is a diverse mix of land use in the watershed. Agriculture makes up nearly 42% of the land use within the watershed. Row crop production makes up the majority of the farming practices within the project area. Dairy operations that were once common within the watershed have declined. There are three known active dairy farms that farm land within the watershed. Livestock from all three operations do have access to pasture within the watershed project area. Manure applications are made to many of the fields within the main drainage area. Small hobby beef and/or horse operations do exist in the watershed, but these operations were not inventoried.

For this particular study the watershed making up the main drainage to East Balsam was the priority area of concern (Figure 1). Polk County LWRD concentrated most of the data collection efforts on agriculture operations within this area. In addition to the main drainage to East Balsam, a substantial amount of field data was collected in the remaining sub-watersheds named High Retention Area 1 and High Retention Area 2 (Figure 1). These two watersheds are identified as high retention areas because their direct drainage to the lake has been interrupted by roads, resulting in the ability to retain significant amounts of water before releasing to the lake.

Methods

Collection of soil sample and crop management information for modeling estimates was the main focus of the project. With field soil tests, crop rotation, plant nutrient applications, and tillage system information, Polk County LWRD was able to determine an estimated Phosphorus Index (P Index) and soil loss for each field and averages for each watershed. The P Index is an estimation of a field's potential to deliver nutrients to the edge of the field and possibly beyond to surface waters. This value represents pounds of phosphorus delivered per acre of cropland, per year.

Soil loss was calculated with an equation known as the Revised Universal Soil Loss Equation (RUSLE 2) (Figure 2). This equation produces a numeric value in tons of soil lost per acre, per year. RUSLE 2 uses factors such as soil type, slope steepness, slope length, tillage system, and other variables to calculate soil loss. All soils have a predetermined amount of soil they can lose annually and still maintain productivity. This value is called "T" or tolerable soil loss. The RUSLE 2 equation produces a value (A) that can be compared to "T" to determine the rate at which soil is eroding. This calculation is helpful in evaluating phosphorus delivery because phosphorus bonds very strongly to soil particles. Therefore, if a producer minimizes soil erosion, phosphorus delivery off the field is also minimized.

Universal Soil Loss Equation

$$A = R\ K\ L\ S\ C\ P$$

- R - rainfall and runoff;
- K - soil erodibility;
- L - slope length;
- S -slope steepness;
- C - cover and management;
- P - support practice

~Equation used by SNAP Plus to calculate soil loss in this project

Figure 2 – Revised Universal Soil Loss Equation

To determine project P Indexes and soil loss values, all soil test information was entered into the Soil and Nutrient Application Planning software (SNAP Plus). SNAP Plus is a program that estimates P Index and soil loss per field using field characteristics, soil test analysis, crop rotation, and commercial or organic nutrient application information. This program requires a significant amount of information about the fields and the operation that must be obtained from the producer. Much of the information was collected by LWRD staff at farm visits interviewing agriculture producers in the watershed to obtain as much information to represent real management practices.

During the course of the project 13 agriculture producers were contacted to participate through multiple mailings and personal phone calls. Of the 13 possible participants, 7 agricultural producers were willing to participate and submitted soil test information and were interviewed. Of these 7 producers 4 are row crop farmers and 3 crop and dairy farm. All 7 producers provided useable soil test information covering 834.77 acres (66% of the watershed cropland acres). This was fairly high participation compared to other studies LWRD has conducted in the past.

Once data was compiled, entered, and modeled in SNAP Plus, results were entered into ArcMap GIS to spatially illustrate the findings. ArcMap is a geographic information system that can analyze data and illustrate it visually so that trends, patterns, and “hot spots” may appear. ArcMap GIS was used to make maps for reporting and creating the database where all information was stored.

Results

Soil test data was collected in all 3 watersheds within the East Balsam Watershed: Main Drainage, High Retention Area 1, and High Retention Area 2 (Figure 1, pg. 2). Soil test information permitted the calculation of average soil phosphorus levels. Soil test phosphorus throughout the entire watershed was quite variable. Soil test phosphorus on all fields ranged from 4 parts per million (ppm) to 160 ppm. According to UW-Extension Publication A2809 *Nutrient Application Guidelines for Field, Vegetable, and Fruit crops in Wisconsin*; 14% of the fields were low to very low soil test phosphorus (17 ppm or less), 8% of the fields reviewed were found to fall in the optimum category (18-35 ppm) for soil fertility, 64% of the fields fell into the high category (36-99 ppm), and the remaining 14% of the fields fell in the excessively high category (100+ ppm). It is important to mention that these fertility ranges pertain to the fertility needs of common row crops. Excessively high soil test phosphorus for crops does not mean there is an immediate threat to water quality. A fields potential to threaten water quality is dependent on a number of other factors including weather, topography, soil type, tillage, and crop management. Soil test levels are only one component of a very complex runoff risk equation.

Fields within the main drainage had the highest average soil test phosphorus levels at 59.5 ppm (Figure 3). When the field information was modeled in SNAP plus with management practices and field characteristics were factored into the equation, these fields resulted in a Phosphorus Index of 2.77 pounds of phosphorus contributed per acre, per year. Average soil loss was moderate with an estimate of 2.8 tons/acre/year soil loss (Figure 5). This information is important as these fields are part of the direct main drainage and could have high potential to contribute runoff to the lake. However, with the exception of the soil test phosphorus being slightly elevated, all other estimates are within the nutrient management requirements and the Wisconsin Department of Natural Resource threshold levels for maintaining water quality. Additionally, some of these fields have been observed to have conservation or no till cropping practices. Conservation practices recorded on fields within the main drainage showed much lower values than fields without when modeled. These numbers confirm the value of these practices in minimizing a crop field’s potential to load sediment and nutrients to surface waters. Even though elevated soil test phosphorus levels are only one component to the equation, a strategy to draw down soil test phosphorus is wise, as lower soil test phosphorus will assure lower risk of surface water impact in the absence of farming conservation practices.

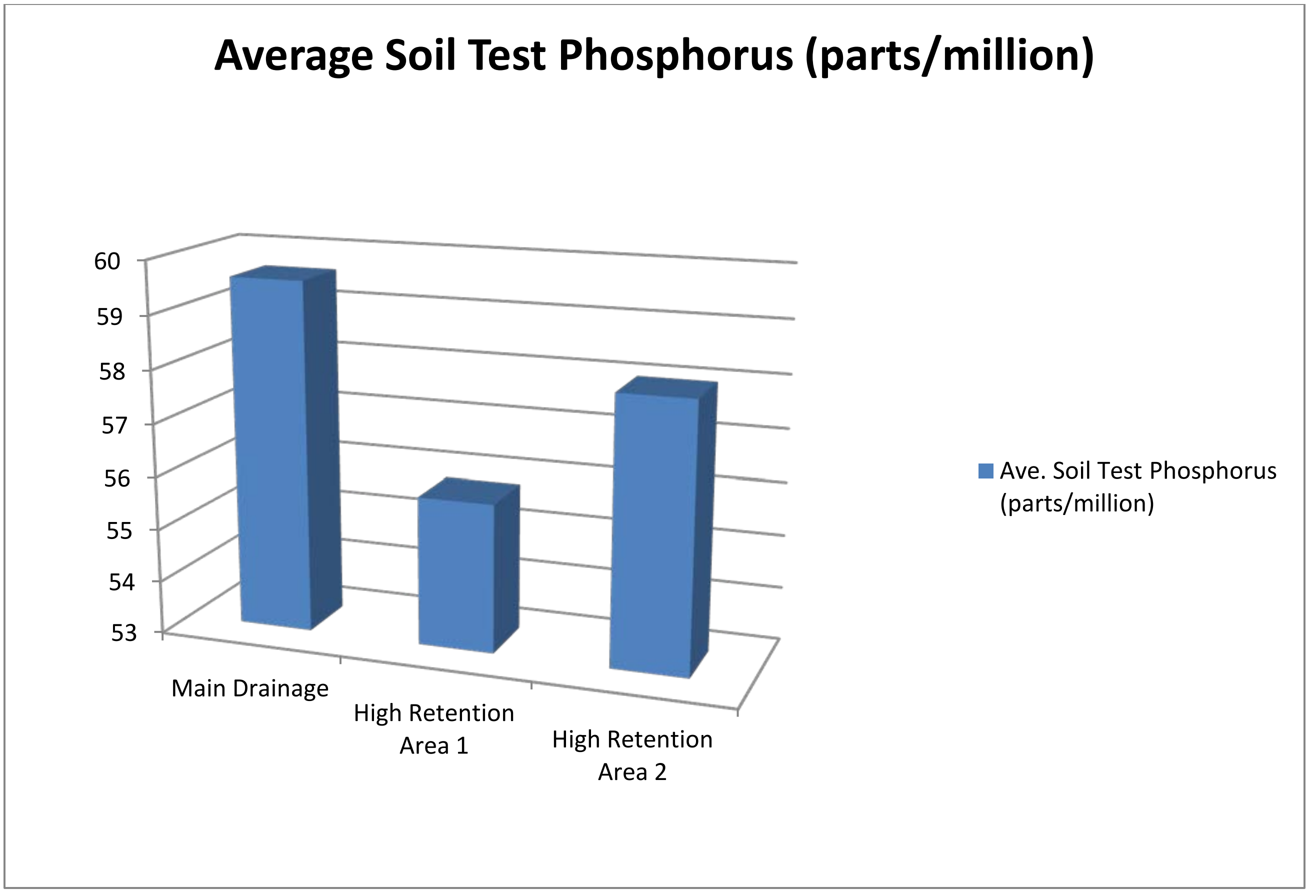
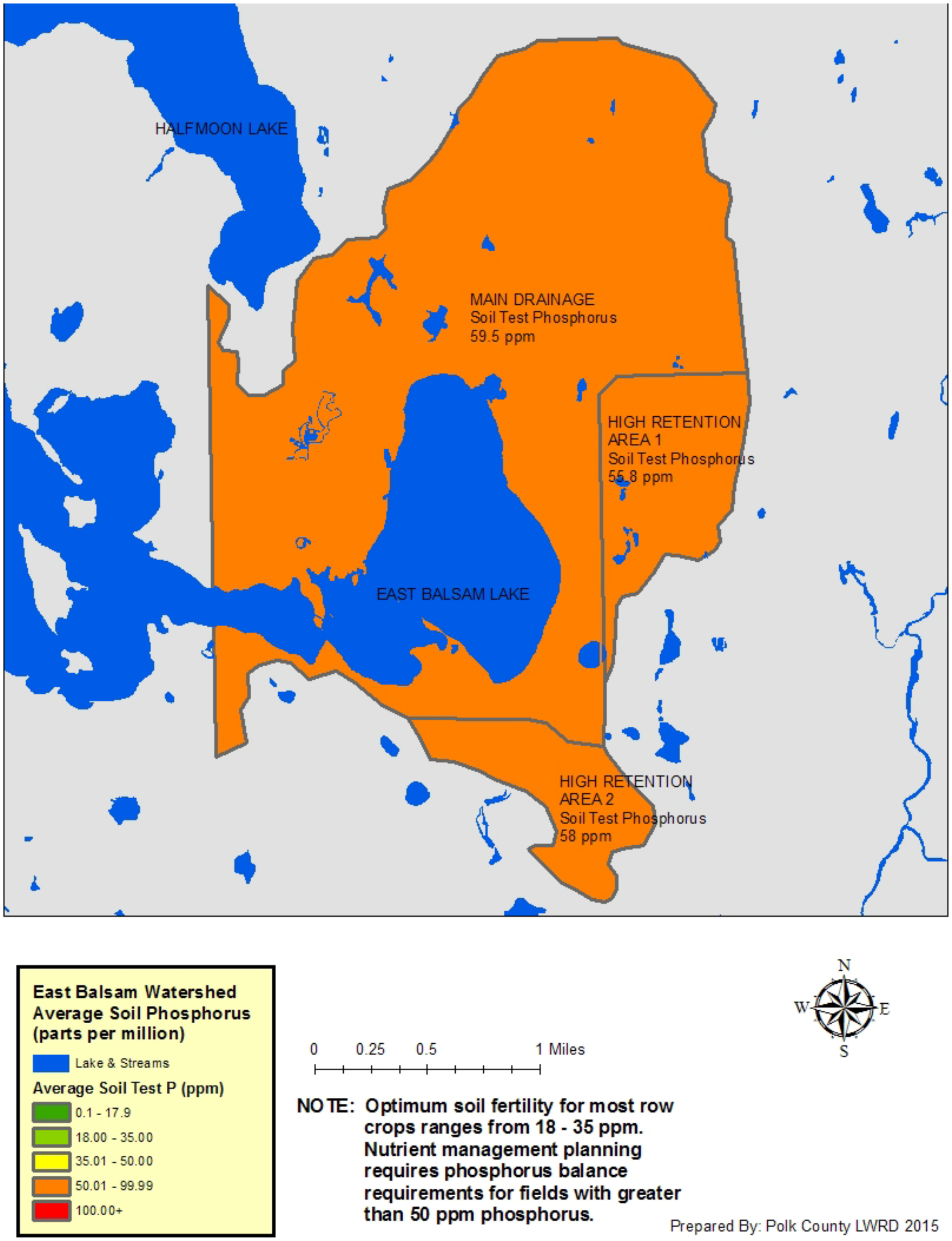

Average Soil Test Phosphorus (parts/million)
60
59
58
57
56
55
54
53
Main Drainage
High Retention Area 1
High Retention Area 2
🟦 Ave. Soil Test Phosphorus (parts/million)

Figure 3



NOTE: Optimum soil fertility for most row crops ranges from 18 - 35 ppm. Nutrient management planning requires phosphorus balance requirements for fields with greater than 50 ppm phosphorus.

Prepared By: Polk County LWRD 2015

Figure 4

The soil loss evaluation portion of this study yielded higher than expected values in some areas. However, the watershed wide averages are not above tolerable soil loss levels for the area soils. As shown on the average soil loss map all watershed averages are below the watershed wide tolerable (4 tons/acre/year) levels (Figure 6, page 8).

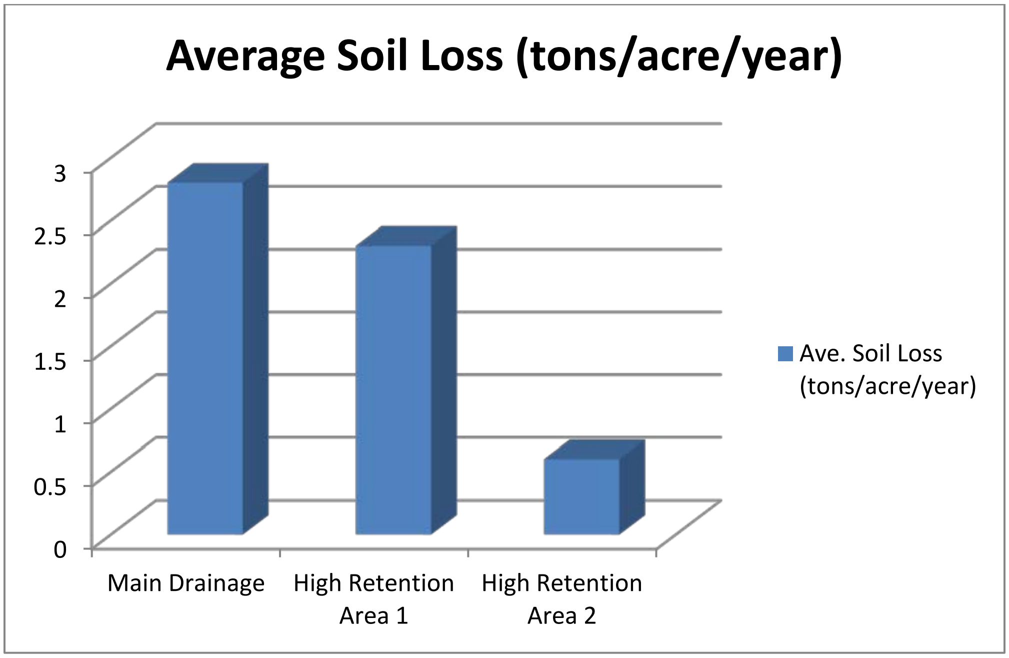


Figure 5

The estimates of soil loss should be fairly representative of the entire watershed. There has been enough data collected to achieve representative results, and all information collected during farm interviews used in the modeling process was as close to actual as possible. An average soil loss of 2.8 t/ac/yr or less in these three watersheds is quite acceptable from a conservation planning standpoint. However, fields do exist in these areas that exceed the tolerable level for their soils. Ten fields within the main drainage exceed their soils respective tolerable soil loss. These fields range from 3.1 to 8.9 t/ac/yr and make up 37% of the total fields evaluated.

Within High Retention Area 1, there are 3 fields that exceed their soils respective tolerable soil loss. These fields range from 4.2 to 7.6 t/ac/yr and make up 75% of the cropland evaluated.

Both fields evaluated within the High Retention Area 2 are well below their soils tolerable soil loss. Fields within this watershed area have had various conservation practices implemented on them, from cover crops to no-till farming practices.

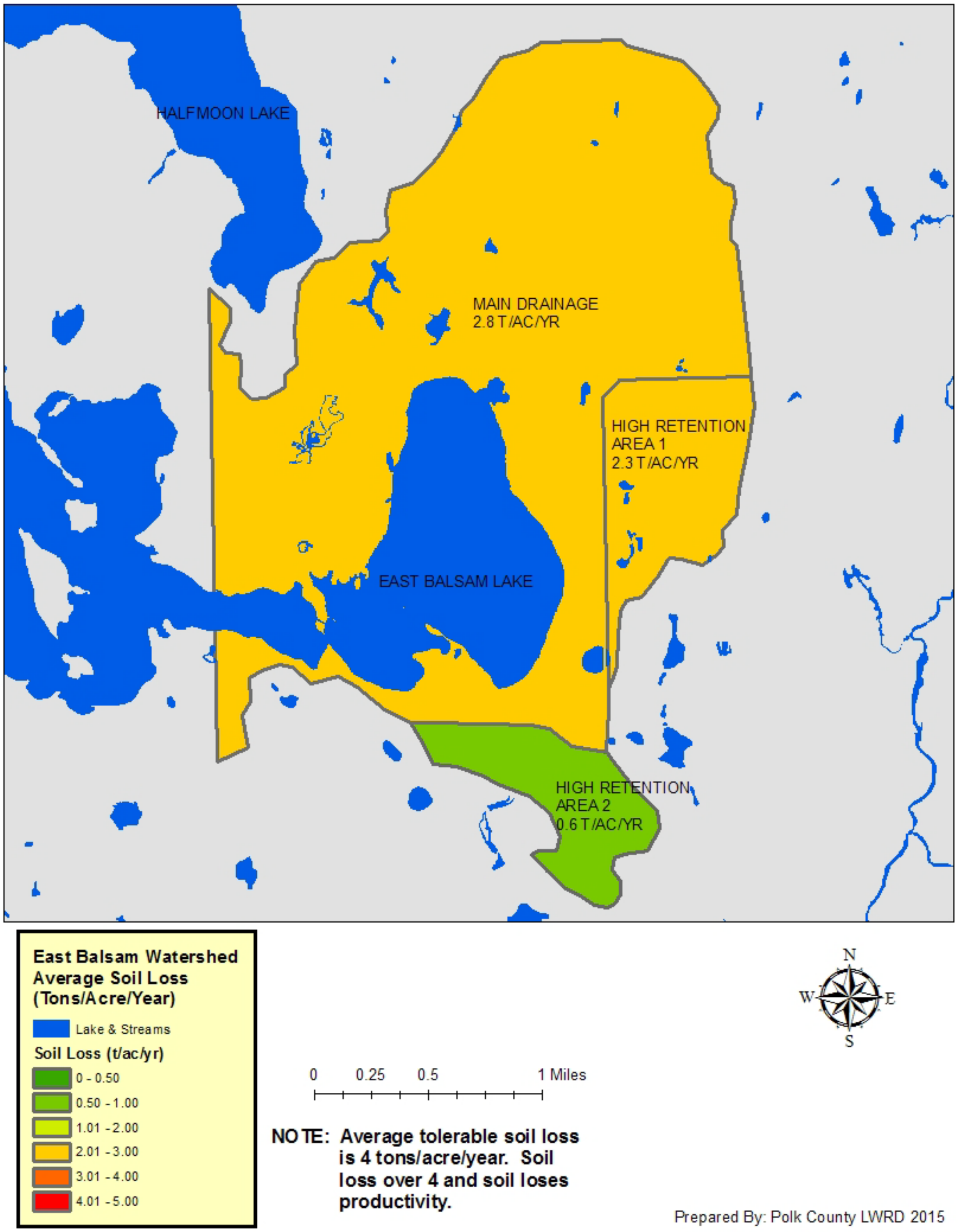
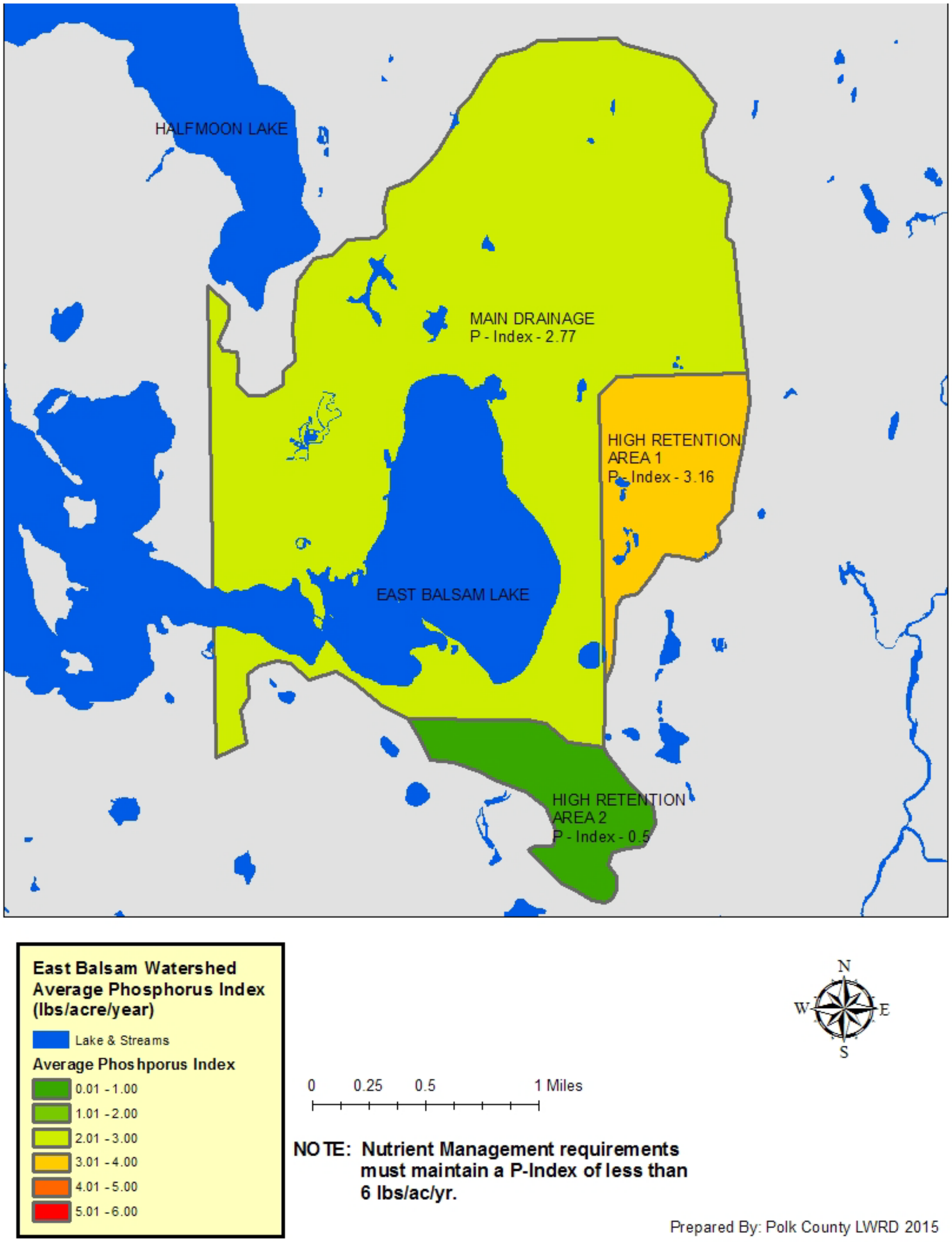

HALFMOON LAKE
MAIN DRAINAGE
2.8 T/AC/YR
HIGH RETENTION
AREA 1
2.3 T/AC/YR
EAST BALSAM LAKE
HIGH RETENTION
AREA 2
0.6 T/AC/YR
East Balsam Watershed
Average Soil Loss
(Tons/Acre/Year)
🟦 Lake & Streams
Soil Loss (t/ac/yr)
🟩 0 - 0.50
🟩 0.50 - 1.00
🟨 1.01 - 2.00
🟧 2.01 - 3.00
🟧 3.01 - 4.00
🟥 4.01 - 5.00
0
0.25
0.5
1 Miles
N
W
E
S
NOTE: Average tolerable soil loss is 4 tons/acre/year. Soil loss over 4 and soil loses productivity.
Prepared By: Polk County LWRD 2015

Figure 6

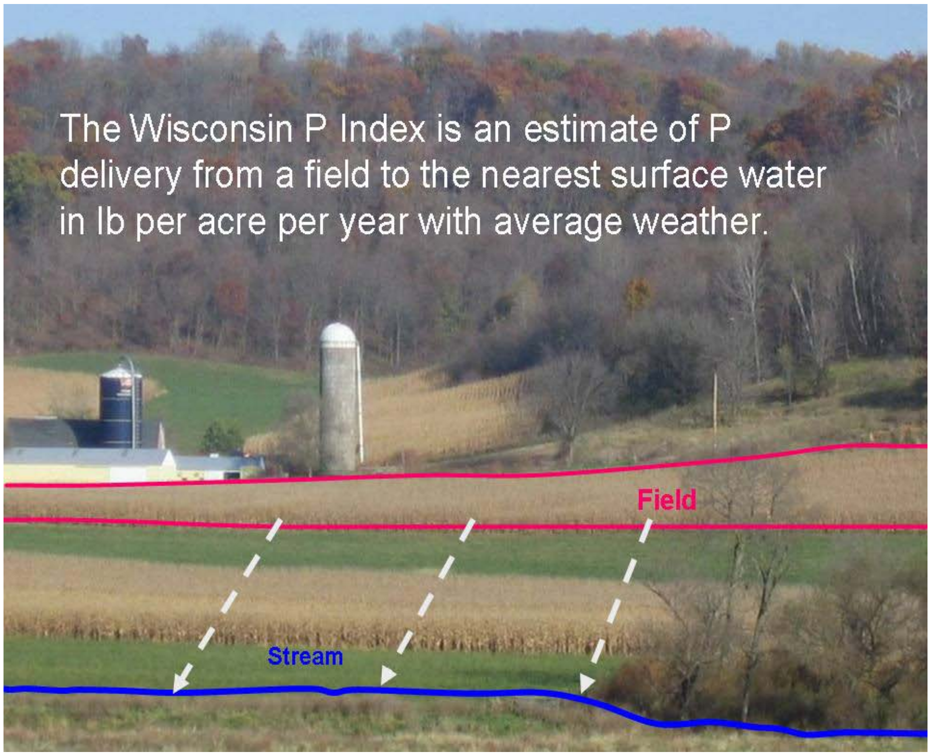


NOTE: Nutrient Management requirements must maintain a P-Index of less than 6 lbs/ac/yr.

Prepared By: Polk County LWRD 2015

Figure 7

The Phosphorus Index for the project area represents a collection of all field data obtained from soil test information and farmer interviews. The P Index represents a fields estimated potential to deliver phosphorus to nearby surface waters based on an agriculture producers planned management. The units for the P Index values are in pounds of phosphorus lost per acre, per year. The state of Wisconsin sets an upper threshold limit of 6 lbs/ac/yr. For nutrient management planning, anything over a P Index of 6 is unacceptable and may result in a change in crop management.



The Wisconsin P Index is an estimate of P delivery from a field to the nearest surface water in lb per acre per year with average weather.

Graphic Courtesy, UW-Wisconsin Madison

During this project approximately 837.77 acres were evaluated totaling 36 separate fields within the East Balsam Lake watershed. Phosphorus Index values range from 0 to as high as 9 lbs/acre/year, with a watershed wide average of 1.9, or 2 lbs/acre/year, as P Index is always reported in whole numbers. As you can see from the graph below (Figure 8) both the Main Drainage and High Retention Area 1 P-Index levels were elevated but not above the State of Wisconsin's threshold limit of 6 lbs/ac/year.

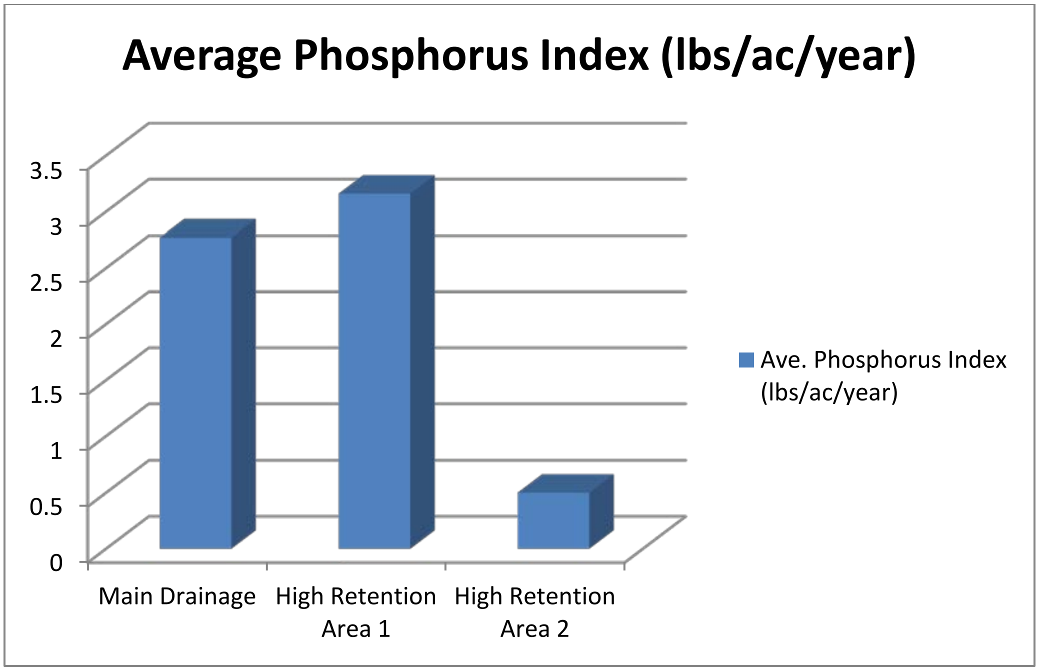


Figure 8

With the exception of a few fields, the P Index levels were low to moderate. Low to moderate P Index numbers in the Main Drainage are important as these fields have an increased surface water runoff risk. One unique feature of the East Balsam Lake Main Drainage watershed is that it is well buffered with wetlands and woodlands between the agricultural land and the shoreline of the lake. While SNAP plus models a fields potential to allow phosphorus movement to the fields edge, it does not accurately estimate phosphorus transport from the field edge to the nearby surface water. With the existence of undisturbed buffer area between the agricultural land and East Balsam Lake there is great potential to reduce the amount of phosphorus through natural processes between the field edge and the lake.

Conclusions and Recommendations

Overall this project was successful. Time and farmer participation were limiting factors. Farmer participation in projects like this takes time. Project results would have greatly improved if this was a five year study. It was a challenge to connect with every operator in the watershed. As always, not everyone is willing to participate. For the size of the watershed area we had good participation which was important in collecting enough field data to obtain good representative estimates.

Most of the information collected in this watershed project was not unlike what has been collected in similar studies where soil test and P Index information was estimated. Moderate to low P Index values were seen throughout. There were 8 fields that have a P Index of greater than 6. These fields were elevated due to a combination of high soil test phosphorus, winter applications of animal waste, and specific row crops that require intense tillage and have a shorter growing season leaving more exposed soil throughout the growing season.

With the estimated values seen from this assessment, a reduction in P Index is very likely and could be very simple with the adoption of a few specific conservation practices. However, for this reduction to be possible implementing the practices would be necessary and would result in significant changes in management for some operations. This could be challenging with some of the more expensive practices such as manure storage. However, some lower costs practices such as: nutrient management planning, no till farming, contour farming and filter strips on all fields could help towards some reduction at a lesser cost to the producer.

While obtaining nutrient management plan information it was apparent that nutrient management planning efforts need to be improved. Many of the producers that participated in this project did not have a current nutrient management plan. Many have a cropping plan for nutrient applications, but few had a 590 nutrient management standard approved plan that addresses water quality as well. Though a full 590 compliant plan is not entirely critical to achieve environmental and water quality benefit, it does help in most cases if the plan is implemented as written. Most of the growers who are actively engaged in nutrient management planning are following the plans to the best of their ability. Even though some of the recommendations are not compliant with 590, the basics of the plan are almost always understood and likely implemented. Awareness of sensitive areas, moving manure to fields that need it, and soil testing are all basics of a plan. When these basics are implemented it is less likely nutrients, including phosphorus, will be over applied to the land. With this, it appears that the educational aspect of nutrient management planning is almost more effective in minimizing risk as having a plan written.

Soil test levels within the East Balsam Lake watershed are high according to the needs of the row crops planted there. Even though the majority of the growers are doing well keeping sediment and particulate phosphorus on the land, Polk County LWRD recommends any effort to draw down these levels. With lower soil test phosphorus on these fields the risk of impacting surface water is reduced when crop or tillage management practices change in the future. Knowing these fields are trending high in phosphorus is helpful alone.   Polk County LWRD will make efforts to promote practices in this watershed that will draw down these levels. Average soil test phosphorus on fields within the East Balsam Lake watershed of 18 to 35 parts per million would be preferred rather than a watershed wide average of 57.8 parts per million.

Positive Project Outcomes

This project had many positive outcomes. Much of the challenge of implementing conservation practices is buy-in of those targeted to make a change. Polk County LWRD staff was pleased with the level of participation in the project. The agriculture producers that participated wanted to participate because they too are concerned about water quality and soil health.

This work promoted soil testing and obtained soil tests for those who may not routinely soil test. Knowing soil fertility alone can decrease fertilizer and manure applications. Once agricultural operators start soil testing they often times value the information and adjust fertilizer applications resulting in a significant cost savings. Polk County LWRD anticipates that some of the participating producers will continue to take routine soil tests as a result of this work.

In addition to soil testing the farm interview process during this project promoted awareness of conservation practices, and the value of conservation planning. Often agriculture producers are aware of soil conservation concerns on their operation and project staff was able to help with recommendations to address these concerns.

With very high costs to produce row crops and low commodity prices, agriculture producers are generally very careful in their nutrient management. The agriculture producers in the East Balsam Lake watershed are some of the most progressive with nutrient management the Polk County LWRD staff has worked with. There are a few producers that have taken fertilizer and chemical applications to the next level using Variable Rate Technology (VRT). VRT technology uses very specific soil fertility information and Global Positioning Systems (GPS) to apply chemical and fertilizers in only areas needing it, and in only amounts needed according to soil tests. It is a very precise way to apply materials to the land without applying materials in excess. This technology can also be used in seeding practices and has been known to save enough money in seed, chemical, and fertilizer to cover the costs of the equipment in just a few years. It was a pleasure learning from the producers using this technology in the watershed and the Polk County LWRD staff will be working with these producers in the future to be leaders in promoting this technology to others in the agriculture community.

With the information gathered from this study, the Polk County LWRD has identified areas that could be improved. As funding is available and affected producers are agreeable, financial and technical assistance will be offered to producers to address the areas of concern. This process is entirely voluntary. No guarantees can be made for improvements or producer participation. However, knowing improvements can be made that might have both financial and environmental benefits typically start the conversation and the process towards change.

References

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APPENDIX E. POST ALUM TREATMENT MONITORING

East Balsam Lake Post-Rehabilitation Monitoring and Evaluation Proposal. University of Wisconsin – Stout. Discovery Center – Sustainability Sciences Institute. April 2019.

East Balsam Lake Post-Rehabilitation Monitoring and Evaluation Proposal

1 April, 2019

University of Wisconsin – Stout
Discovery Center - Sustainability Sciences Institute
123E Jarvis Hall
Menomonie, Wisconsin 54751
715-338-4395
jamesw@uwstout.edu

Introduction

Multiple Al applications over a period of years are planned for East Balsam Lake to control internal phosphorus loading. It is critical to conduct post-treatment monitoring of water and sediment chemistry in order to document the trajectory of water quality improvement during rehabilitation to make better decisions regarding adjusting management to meet future water quality goals. Post-treatment monitoring will include field and laboratory research to document changes in 1) the phosphorus budget and lake water quality, 2) binding of sediment mobile phosphorus fractions that have contributed to internal phosphorus loading by alum, and 3) rates of phosphorus flux from the sediment under anaerobic conditions. Overall, lake water quality is predicted to respond to internal phosphorus loading reduction with lower total phosphorus and chlorophyll concentrations throughout the summer, lower bloom frequency of nuisance chlorophyll levels, and higher water transparency. Al application should result in the binding of iron-bound phosphorus and substantial reduction in diffusive phosphorus flux from sediments under anaerobic conditions (i.e., internal phosphorus loading).

Approach

1. In-lake monitoring

Water samples for limnological variables will be collected at a station located in the central portion of the lake on an annual basis (Figure 1). Samples will be collected biweekly between late May and the end of September (~ 10 sampling trips). An integrated sample will be collected over the upper 2-m for analysis of total phosphorus and chlorophyll a. An additional discrete sample will be collected within 0.5 m of the sediment surface for analysis of total and soluble reactive P. Secchi transparency and in situ measurements (temperature, dissolved oxygen, pH, and conductivity) will also be collected on each date.

2a. Vertical variations in sediment characteristics

A sediment core will be collected in the deepest portion within the alum-treated region of the lake annually after treatment (see Table 1) for determination of vertical profiles of various phosphorus fractions and aluminum. The goal of this task is to examine the location of the Al floc in the vertical sediment column and monitor the extent of binding of iron-bound phosphorus by the alum floc over several years. The loosely-bound (Boström 1984) and iron-bound (Nürnberg 1988) sediment P fractions are readily mobilized at the sediment-water interface as a result of eH (i.e., oxidizing and reducing conditions) and pH reactions (Mortimer 1971, Boström 1984). Labile organic sediment P can be converted to soluble P via bacterial mineralization (Jensen and Andersen 1992) or hydrolysis of bacterial polyphosphates to SRP under anaerobic conditions (Gächter et al. 1988; Gächter and Meyer 1993; Hupfer et al. 1995). The aluminum-bound P fraction approximates the concentration of P that has been bound to the Al floc and sequestered from further input to the overlying water column via diffusive flux.

Sediment cores will be sectioned at 1-cm intervals between 0 and 6 cm and 2 cm intervals down to 10 cm (8 sections) for determination of;

Moisture content
Density
Loss-on-ignition organic matter
Loosely-bound P
Iron-bound P
Labile organic P
Aluminum-bound P
Total Al

The effectiveness of the alum treatment in binding and inactivating iron-bound P will be evaluated and used in an adaptive management approach to monitor dosage and effectiveness in controlling internal P loading.

2.b. Spatial variations in sediment characteristics

Sediment cores will be collected at 4 additional stations within the Al treatment area to examine Al concentrations in the upper 5 cm composited sediment section (Table 1). This task will provide important information on the distribution and movement of the Al floc in the treatment area and an estimate of observed versus target concentrations. The results will be used to adjust and improve future Al applications (i.e., adaptive management approach). For instance, the applicator may need to concentrate more Al on an area in the lake that has a low Al concentration relative to target goals.

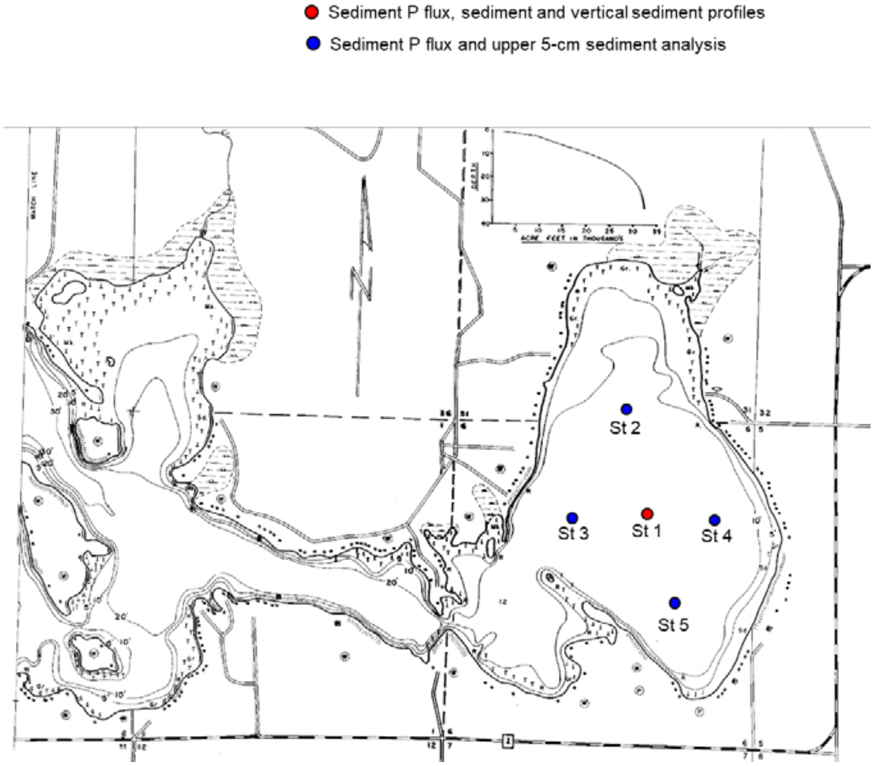

Figure 1. Sampling station locations.

The upper 5-cm will be sectioned for analysis of the following variables:

Moisture content
Density
Loss-on-ignition organic matter
Loosely-bound P
Iron-bound P
Labile organic P
Aluminum-bound P
Total Al

The information will be used to estimate spatial variations in the current Al concentration (g/m^2), Al-bound P, and the Al:P ratio.

2c. Laboratory-derived rates of phosphorus release from sediments under anaerobic conditions

Anaerobic phosphorus release rates will be measured from intact sediment cores collected in the alum-treated area on an annual basis to directly monitor alum treatment effectiveness. One intact sediment core will be collected at station 2, 3, 4, and 5 and 3 sediment cores will be collected at station 1 for evaluation of anaerobic diffusive P flux (Figure 1). The sediment incubation systems will be placed in a darkened environmental chamber and incubated at a constant temperature for 1-2 weeks. The incubation temperature will be set to a standard temperature for all stations for comparative purposes.

The oxidation-reduction environment in each system will be controlled by gently bubbling nitrogen through an air stone placed just above the sediment surface to maintain anaerobic conditions. Post-treatment rates will be compared with pre-treatment rates to evaluate the effectiveness of the Al floc in inactivating iron-bound phosphorus and controlling rates of phosphorus release under anaerobic conditions.

3. Interim report

An interim report describing results from the monitoring program will be delivered on an annual basis (data analysis and reporting @ 32 hr x $100/hr = $3,200). Results will also be presented at a technical meeting for evaluation and management recommendations.

Table 1. Cost and Timeline

Task	Cost per year	2020	2021	2022	2023
Al treatment		■		■	
1	$5,780	▨	▨	▨	▨
2a	$1,760	▨	▨	▨	▨
2b	$880	▨	▨	▨	▨
2c	$3,780	▨	▨	▨	▨
3	$3,200	▨	▨	▨	▨
Total per year	$15,400				

Water Chemistry					
Analysis		Price ($)	Depths	Unit	Cost
Field sampling		$500		10	$5,000
Nutrients	Total phosphorus	$18.50	2	10	$370
	Soluble reactive phosphorus	$15.50	1	10	$155
	Chlorophyll, fluorometric	$25.50	1	10	$255
Total					$5,780

Sediment Chemistry Task 2a, b, and c					
Variable		Unit	Cost		
			Each	Quantity	Total
Textural and Physical Characteristics	Moisture Content-Bulk Density-organic content	per sediment section	$30	12	$360
Sediment Total Metals	Digestion fee	per sediment section	$25	12	$300
	Total Aluminum	per sediment section	$30	12	$360
Sediment Phosphorus Extractions	Mobile Phosphorus	per sediment section	$135	12	$1,620
Sediment Flux or Internal Loading	Incubation for rates of soluble reactive P release	per 10 cm core	$540	7	$3,780
Total					$6,420