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

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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 ($P_{internal\ load}$, kg/summer) was estimated from changes in lake P mass during the summer of 2015 (please see *Results*) as follows,

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

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

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.

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

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

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	

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.

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.

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

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 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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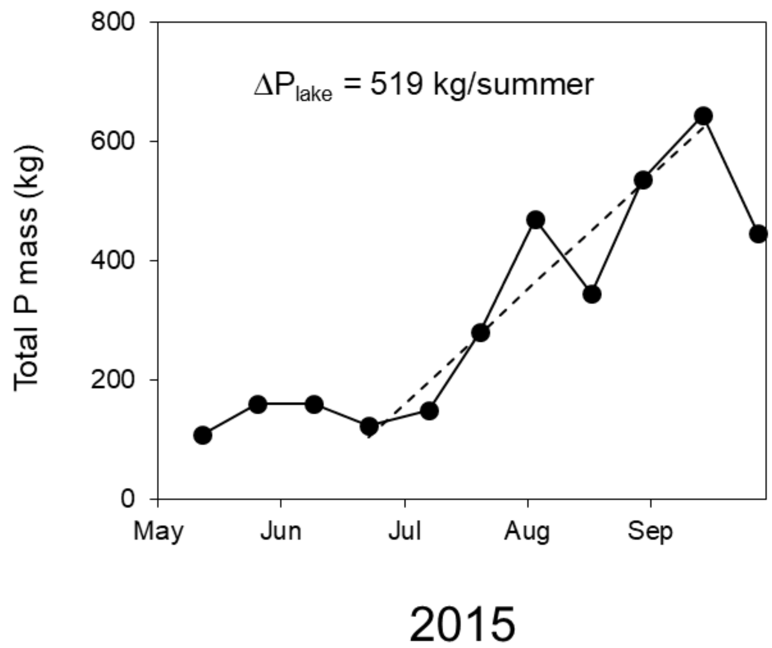

Figure 1. Seasonal variations in total phosphorus (P) mass in East Balsam Lake, WI, in 015. Dashed line denotes the linear increase in P mass between late June and September, 2015.

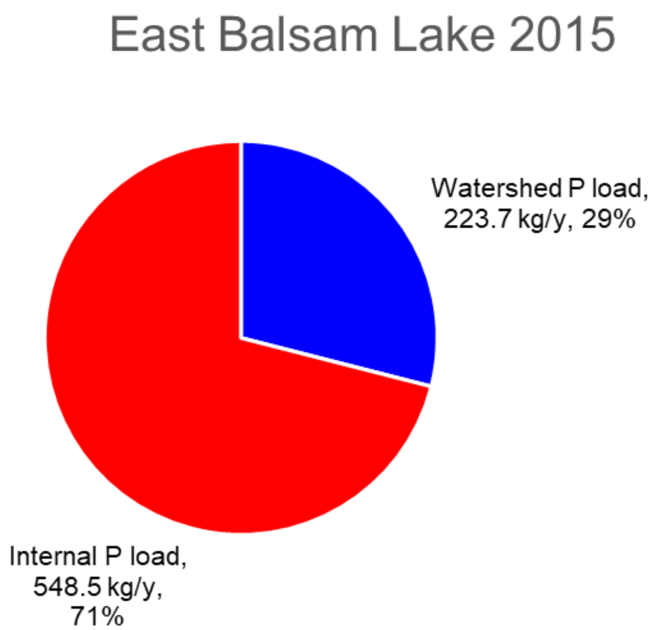

Figure 2. Estimated annual phosphorus contributions from watershed and internal loading in 2015.

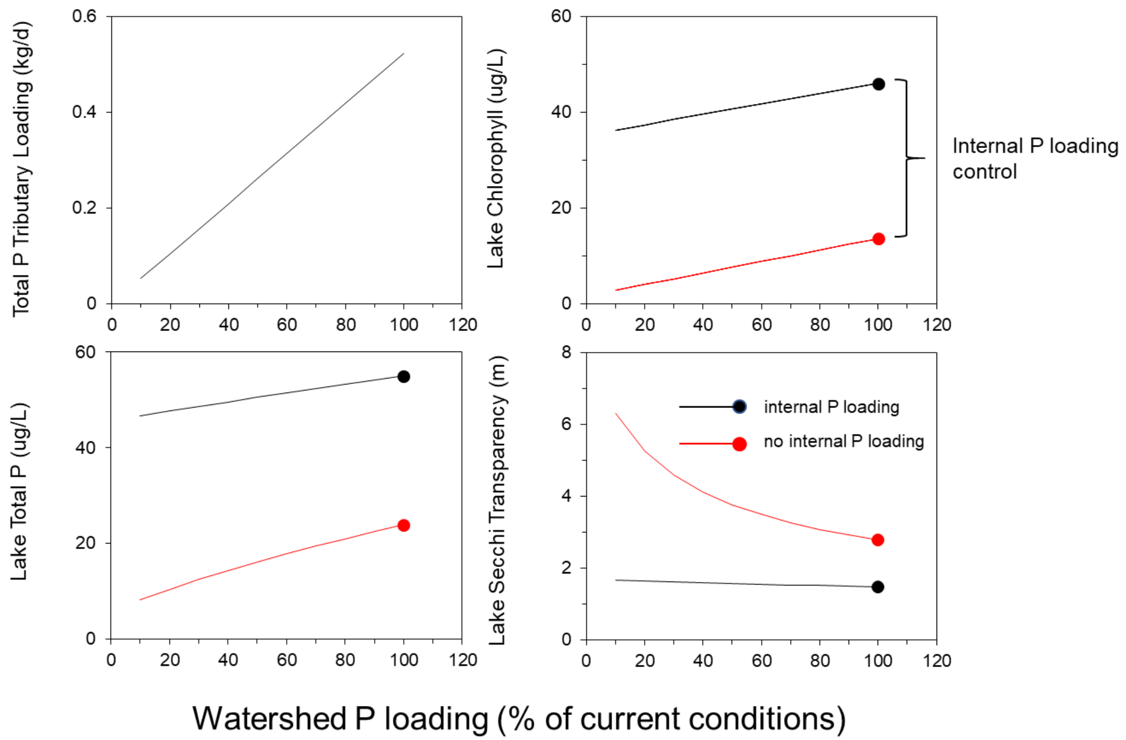

Figure 3. Empirical model output (Canfield-Bachmann) of predicted changes in total phosphorus (P), chlorophyll, and Secchi transparency in Least Balsam Lake as a function of reducing current estimated external P loading by 20% increments. 100% watershed P loading represents current conditions. Black 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.

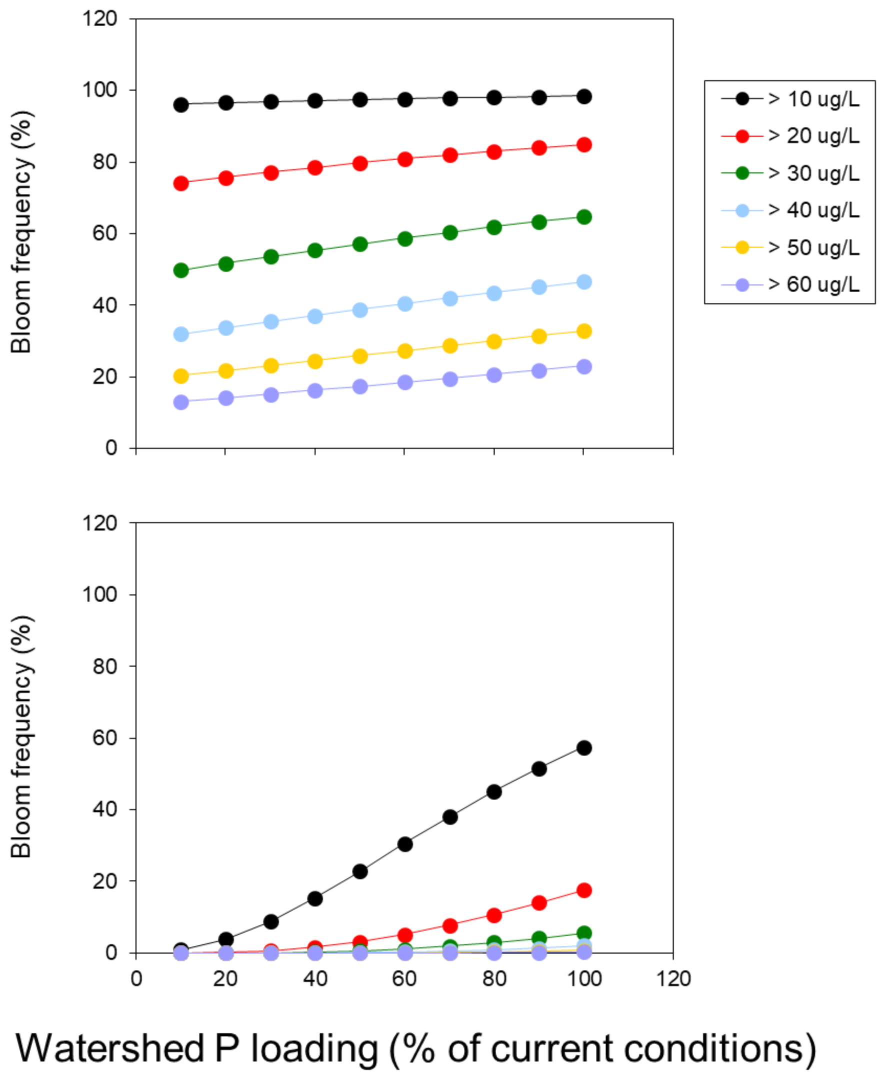

Figure 4. Empirical model output of predicted changes in algal bloom frequency (as chlorophyll) as a function of reducing estimated external P loading by 10% increments (upper panel) and by reducing external P loading and managing internal P loading. 100% P load represents current estimated external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

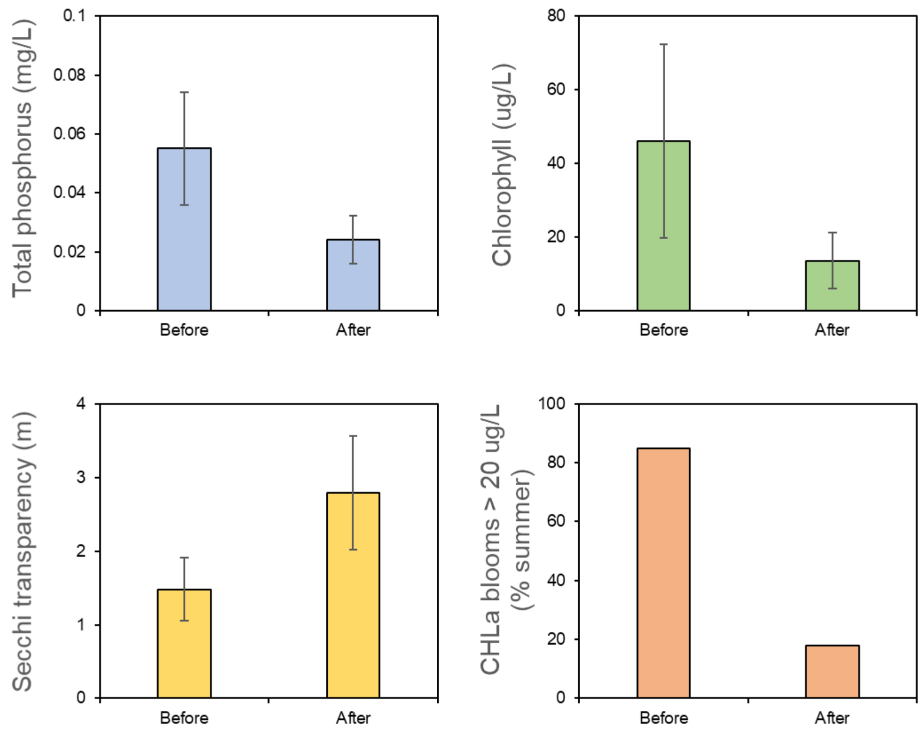

Figure 5. Projected changes in mean summer (June-September) total phosphorus, chlorophyll, Secchi transparency, and percent occurrence during summer that a chlorophyll bloom exceeds 20 µg/L as a result of alum treatment and complete control of internal phosphorus loading in East Balsam Lake, WI.

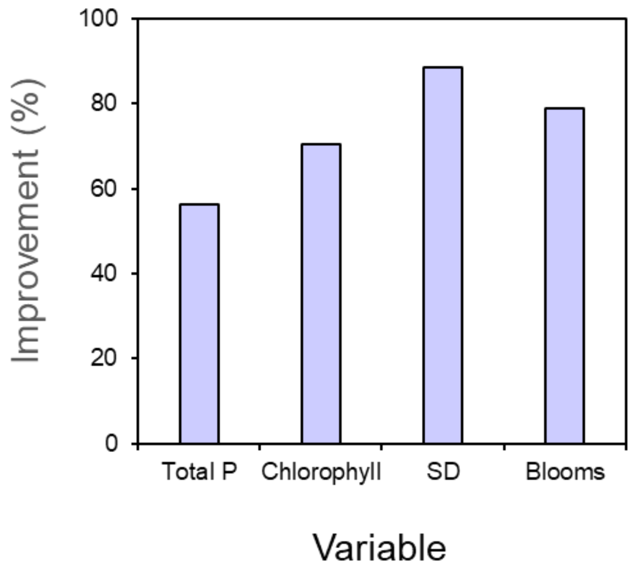

Figure 6. Projected percent improvements in mean summer lake response variables after internal phosphorus loading control in East Balsam Lake, WI. P = phosphorus, SD = Secchi disk transparency, Blooms = percent occurrence during summer that a chlorophyll bloom exceeds 20 µg/L.

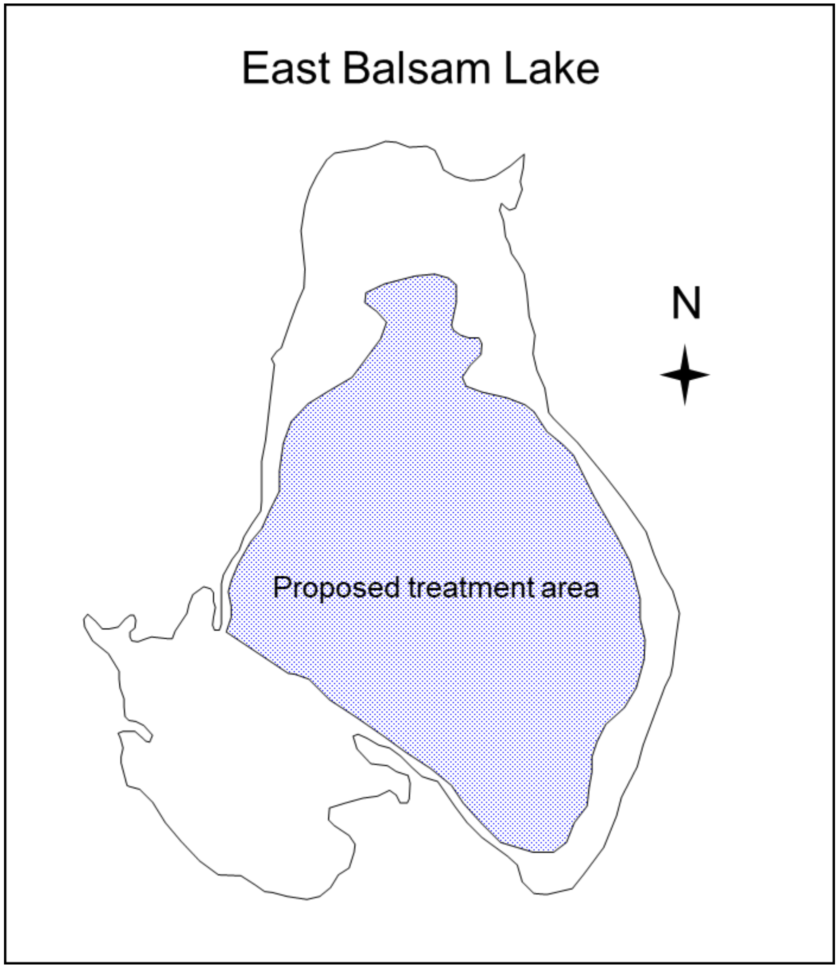

Figure 7. Proposed alum application area in East Balsam Lake. The area is ~ 300 acres and encompasses the 10-ft depth contour.

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.

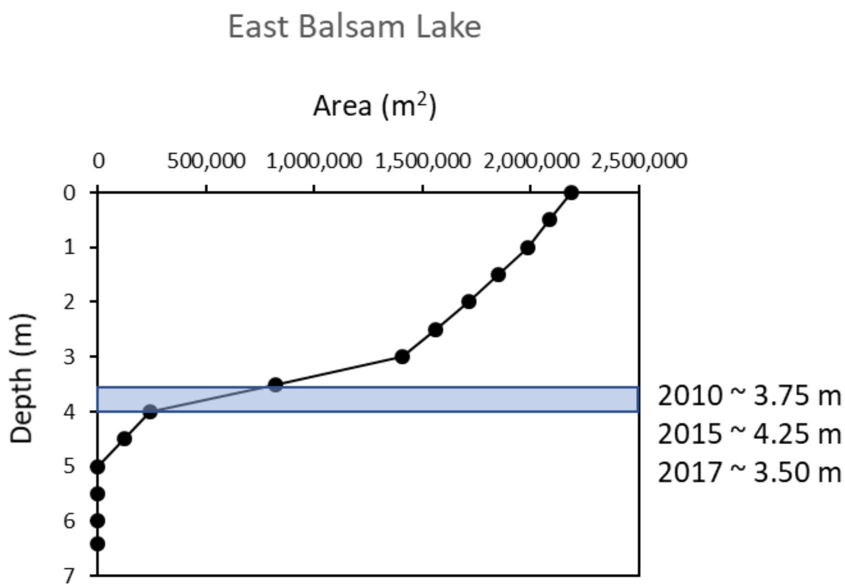

Figure 9. Changes in area as a function of depth in East Balsam Lake. Area decreases rapidly between the 3- and 4-m depth. Shaded region denotes the shallowest depth of bottom anoxia in 2010, 2015 and 2017.