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

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Objective

Shallow Long Lake (273 ac surface area) currently exhibits excessive summer cyanobacterial blooms and poor water quality (WQ) conditions (high phosphorus and chlorophyll concentrations and low water clarity) that may be linked to internal phosphorus (P) recycling from sediments. Except for two small ditch channels entering the lake, any other watershed runoff probably occurs as diffuse overland flow during high precipitation events and snowmelt periods. There is no defined surface outlet and lake level decreases during periods of drought, suggesting groundwater seepage is the primary means of lake discharge. To develop sound and effective management strategies to improve WQ in Long Lake, there is a need to quantify external and internal P sources driving cyanobacterial blooms and forecast lake response to management via empirical, steady-state modelling. Diffusive P flux from sediment (i.e., internal P loading) was quantified directly in 2014 (James 2014). However, external P loading has been difficult to estimate due to lack of tributary inputs.

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 Long 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 are several-fold:

1. re-examine the P budget and empirical steady-state models to evaluate and project water quality improvement as a result of internal P loading control
2. estimate annual and summer lakewide internal P loading from stratification and dissolved oxygen information presented in Polk County and Harmony Environmental (2013) for input into empirical steady-state models,

3. detail the development of thermal stratification using thermistors (i.e., temperature data loggers) 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 and examine bottom water dissolved oxygen dynamics to improve lakewide internal P loading estimates for incorporation into empirical models,
4. and refine Al dosage and application strategies to improve longevity.

Study Site

Long Lake, located near Balsam Lake, Wisconsin, is polymictic and has a relatively shallow (mean depth = 3.35 m, maximum depth = 5.18 m) basin with a low Osgood Index (i.e., ratio of mean depth to the square root of the lake surface area; Table 1). The lake is classified as eutrophic to hypereutrophic with Carlson (1977) Trophic State Index (TSI) values ranging between 66 and 76 based on TP, chlorophyll, and Secchi transparency for year 2012 (Long Lake Management Plan 2013). Mean summer TP, chlorophyll, and Secchi transparency in 2012 were 0.146 mg/L, 82 µg/L, and 0.64 m, respectively (Long Lake Management Plan 2013).

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.

Summer limnological data (Total P, chlorophyll, and Secchi transparency) from 1993, 1996, 2000, 2012, and 2014 (Polk County Land and Water Resources Department, Balsam Lake, Wisconsin, and Wisconsin Department of Natural Resources http://dnr.wi.gov/lakes/lakepages/LakeDetail.aspx?wbic=2478200) were combined with internal P loading information to re-construct the empirical steady-state model. Imbalances between observed and predicted lake TP represented an approximation of bulk external P loadings which can be compared with measured internal P loading to the lake. P loading reduction scenarios were explored to predict impacts of internal P loading reduction on water quality improvement.

Mean summer (June – September) concentrations of total P, chlorophyll, and Secchi transparency were calculated for the summer of 2012 (Long Lake Management Plan 2013), used to develop the lake management plan, and also from multiple years (1993, 1996, 2000, 2012, and 2014) for model input. Annual lake-wide internal P loading from sediment was estimated for the lake area below the 4-m depth contour that typically becomes anoxic during June and September using measured rates of diffusive P flux under aerobic and anaerobic conditions (James 2014). I assumed that annual internal P loading occurred only during summer and was zero during Fall, Winter, and Spring months.

The annual internal P loading rate was estimated as,

$$P_{Internal\ load} = \sum_{x=1}^{120} \frac{d\ \times\ [(P_{aerobic} \times A_{aerobic}) + (P_{anaerobic}\ \times\ A_{anaerobic})]}{A_{lake}}$$

Where $P_{internal\ load}$ = annual internal P load (mg/m^2 d); d = time interval, day (120 days in the summer); $P_{aerobic}$ = aerobic diffusive P flux, 1.06 mg/m^2 d; $A_{aerobic}$ = sediment area below the 4-m depth contour where dissolved oxygen > 1 mg/L; $P_{anaerobic}$ = anaerobic diffusive P flux, 12.9 mg/m^2 d; $A_{anaerobic}$ = sediment area below the 4-m depth contour where dissolved oxygen ≤ 1 mg/L; A_{lake} = lake surface area.

Stratification and bottom dissolved oxygen patterns

The objectives of this task were to examine stratification and bottom dissolved oxygen patterns over the summer of 2017 to document periods of anoxia above the sediment-water interface in relation to summer polymixis (i.e., stratifies and mixes several times during the summer). Since

Long Lake can exhibit polymixis, the sediment-water interface can become temporarily anoxic and drive sediment anaerobic P release for potential algal uptake during the summer. A centrally-located station was established in the lake for in situ monitoring purposes between mid-May and the end of August, 2017 (Fig. 1). Data logging thermistors (HOBO temperature loggers, Onset, Corp) were deployed at 0.5- to 1-m intervals from the lake surface to near bottom at this station to record temperature at 1-hour intervals. In addition, a YSI 6600 data sonde (Yellow Spring Instruments, Yellow Springs, OH) equipped with an optical dissolved oxygen sensor and temperature probe was deployed ~ 0.3 m above the sediment-water interface. Dissolved oxygen and temperature were recorded at 2-hour intervals. The station was disrupted and moved to the shore by vandalism in early July but returned shortly after. The in situ logging station recorded vertical temperature and bottom dissolved oxygen over the entire summer period.

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 of applying Al concentrations spread out over a period of years (i.e., 1-3 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).

The need for buffered Al was also re-evaluated by examining alkalinity concentrations in the lake in relation to Al dosage presented in James (2014). The goal was to maintain pH > 6 during application to optimize $Al(OH)_3$ floc formation and minimize soluble Al^{3+} that occurs at pH < 4.

Results and Discussion

Empirical steady-state modeling

Previous empirical modeling suggested that watershed P loading potentially accounted for ~ 52% of the annual P budget in 2012, based primarily on land use P export coefficients (Fig. 2). Annual internal P loading was estimated as ~1168 lb/y from increases in water column P during the fall of 2012 (Table 2).

In the present analysis, we estimated summer (June-September) internal P loading using measured aerobic and anaerobic diffusive P fluxes determined in 2014 (James 2014) multiplied by oxic or anoxic sediment areas, based on in situ profiles collected in 2012. Anoxia (i.e., defined as DO < 1.0 mg/L) was observed between late June and early August and late August 2012. Anoxia briefly extended to depths less than 4 m (Fig. 3). The average depth of anoxia was ~ 4.3 m and the anoxic factor (i.e., days per summer that an area equivalent to the lake surface area was anoxic) was 23 days. Summer (June-September) internal P loading based on measured diffusive P fluxes was slightly lower at 900 lb/y, compared to the Lake Management Plan estimate (Table 2).

During the summer of 2012, TP and chlorophyll concentrations increased from July through August, while Secchi transparency declined (Fig. 4). However, TP exhibited an anomalous peak exceeding 0.30 mg/L in mid-July that did not reflect variations in chlorophyll or Secchi transparency (Fig. 4). For instance, the chlorophyll concentration was very low on that date compared to the high TP concentration (Fig. 4). With the exception of mid-July, TP and chlorophyll were linearly related while Secchi transparency declined in a negative exponential pattern relative to increasing TP and chlorophyll concentration, indicating typical interrelationships between the three variables (Fig. 5). In contrast, the TP concentration in mid-

July was very high relative to chlorophyll and an apparent outlier compared to the other dates (Fig. 5).

The high TP concentration on that date also tended to skew the overall 2012 summer TP mean (Table 3). Thus, higher external P loading inputs would be needed to balance the 2012 P budget based on mean summer TP in 2012. However, when several years were considered in the estimation of summer means, TP was much lower at ~ 0.080 mg/L versus the 2012 mean (Fig. 6 and Table 3).

The Nürnberg (1998) and Canfield-Bachmann (1981) empirical models were used in conjunction with annual internal P loading determined from summer diffusive P flux to estimate annual external P loading required to predict the summer average TP concentration of 0.080 mg/L (Table 3). Both models estimated a much lower annual external P load (Table 4). Under historical mean summer TP concentrations, annual external P loading represented only 30% to 32% of the annual P inputs to the lake, compared to the 2012 summer mean TP concentration (Fig. 2). Thus, incorporation of historical means and annual internal P loading estimated from measured diffusive P flux suggested that internal P loading played a much more dominant role in the annual P budget of Long Lake.

Predicted limnological response to external P loading was much less under this latter scenario (Fig. 7). For instance, 50% reduction in external P loading resulted in only a predicted 10% reduction in summer mean TP. However, control of internal P loading via alum treatment resulted in a predicted ~50% reduction in summer mean TP from ~ 0.080 mg/L to ~ 0.039 mg/L. In addition, predicted summer mean chlorophyll declined from a current 44 µg/L to 17 µg/L with internal P loading control (~60% improvement over current conditions). Predicted Secchi transparency increased from ~ 1.8 m to 3.3 m under internal P loading control. Predicted lake response would also improve with some additional external P loading control. Finally, predicted bloom frequency of nuisance chlorophyll concentrations (i.e., > ~30 µg/L) would improve from ~ 62% of the time under current P loading conditions to only 11% of the time in the summer under conditions of internal P loading control (Fig. 8, green line).

Stratification and bottom dissolved oxygen patterns in 2017

Long Lake was polymictic during the summer of 2017 (Fig. 9). Stratification occurred in early to mid-June and the entire month of July. Complete water column mixing occurred in late July. During periods of stratification, bottom water dissolved oxygen concentrations declined to near zero. Anoxia developed in mid-June, July, and early August (Fig. 9). Reoxygenation of bottom water occurred in conjunction with the mixing period in late June. Epilimnetic expansion and fall turnover in August also coincided with increases in bottom water dissolved oxygen. During the 19 May through 29 August period, anoxic conditions occurred on 57 of the 103 dates or ~ 55% of the period. This pattern was similar to those observed in 2012. Thus, Long Lake can stratify for extended periods in the summer resulting in the development of anoxic conditions and the potential for internal P loading from anaerobic sediments.

Alum dosage and application strategy

The recommended total Al dosage reported in James (2014) was 105 g/m^2. We recommend splitting the dose into 3 lower concentrations spread out over 2 year intervals to improve Al binding efficiency (Table 5a). A higher Al dosage should be applied during year 1 to control internal P loading while a lower dose should be applied during year 3 and 5 to maintain internal P loading control. Because the first Al dose would exceed the maximum allowable to maintain lake pH greater than 6, a buffered Al (aluminum sulfate-sodium aluminate) should be applied. The second and third applications of 20-25 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. Finally, the Lake District should be made aware that an additional Al application (much lower Al concentration) may be needed several years after these applications as a maintenance measure to ensure complete internal P loading control (see James 2017). 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.

Based on dissolved oxygen profiles collected in 2012, the average depth of anoxia and potential for anaerobic diffusive P flux was ~ 14.1 ft or ~ 4.3 m below the lake surface. The depth of maximum anoxia was shallower at between 3.5 m and 4 m or ~ 12 ft below the lake surface and occurred only briefly during the summer of 2012 (Fig. 3). We recommend focusing the Al application area in Long Lake on depths greater than 15 ft at least for the initial treatment (Fig. 1), versus the 12- or 10-ft contour, because bottom anoxia and internal P loading persisted the longest in this area of the lake (Fig. 3 and 9). Given budget constraints, the Al concentration can be maximized in the area of persistent anoxia and sediment diffusive P flux by considering the 15-ft contour area. Al application over the 10-ft contour would treat those sediments briefly exposed to summer anoxia but also greatly increase the cost (see Table 5b) and potentially result in application of a lower Al concentration to meet budget constraints. Approximate costs to treat the 15-ft contour area with a buffered Al concentration of 60 g/m^2 in year 1 is $185,000. Treatment of the 15-ft depth contour in year 3 with a 25 g/m^2 Al dosage is ~ $84,500. Application of a third Al dose of 20 g/m^2 to the 15-ft depth contour in year 5 is ~ $67,600. Total estimated cost is $337,100 based on current market rates. Application area, Al concentration, and time of application can be adjusted based on monitoring and evaluation of the initial application.

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Table 1. Long Lake and watershed characteristics

Feature	Variable	Metric		English	
Watershed	Area	8.377	km^2	2,070	ac
Lake	Surface area	1,100,746	m^2	273	ac
	Volume	3,687,499	m3	2990	ac-ft
	Mean depth	3.35	m	11	ft
	Maximum depth	5.18	m	17	ft
	Osgood index	3.19			

Table 2. Estimated annual external and internal P loads to Long Lake. Annual internal P loading was estimated in 2012 via in situ increases in phosphorus in the Fall, The present study estimated annual internal P loading via measured diffusive P fluxes (James 2014) and anoxic area in the lake in 2012.

Comparison	$P\text{-}_{external}$	$P\text{-}_{internal}$	$P\text{-}_{external}$	$P\text{-}_{internal}$
	(mg/m2 y)		(lb/y)	
Lake Management Plan (2012)	513	482	1245	1168
This study	176	371	427	900

Table 3. Summer (JUN-SEP) mean limnological variables used for empirical modeling. P = phosphorus, CHLa = chlorophyll, SD = Secchi disk transparency.

Averaging period	Total P (ug/L)	CHLa (ug/L)	SD (m)
2012	106	54	1.7
1993, 1996, 2000, 2012, & 2014	80	43	1.8

Table 4. A comparison of estimated external phosphorus (P) loading required to balance the P steady-state Nürnberg and Canfield-Bachmann model. See Table 3 for a comparison of predicted and observed results.

Variable	**Nurnberg**	
	Value	**Units**
Areal water load (qs)	1.6	m/y
Flow (Q)	0.06	m3/s
Residence time (RT)	2.1	y
External P load	160	mg/m2 y
Internal P load	371	mg/m2 y
Predicted Lake TP	77	ug/L
Percent external P load	30	%
Percent internal P load	70	%
Variable	**Canfield-Bachmann**	
	Value	**Units**
Flow (Q)	0.06	m3/s
Residence time (RT)	2.1	y
External P load	176	mg/m2 y
Internal P load	371	mg/m2 y
Predicted Lake TP	75	ug/L
Predicted Lake CHLA	44	ug/L
Predicted Lake SD	1.8	m
Percent external P load	32	%
Percent internal P load	68	%

Table 5a. Approximate cost scenario to treat the upper 6-cm sediment layer in the profundal anoxic zone located below the 15-ft depth contour in Long Lake with alum.			
Variable	Year		
	1	3	5
Treatment area (acres)	89	89	89
Al dosage (g/m^2)	60	25	20
Buffered Al cost ($)	$185,000		
Al cost ($)		$84,500	$67,600
Total ($)		$337,100	

Table 5b. Approximate cost scenario to treat the upper 6-cm sediment layer in the profundal anoxic zone located below the 10-ft depth contour in Long Lake with alum.			
Variable	Year		
	1	3	5
Treatment area (acres)	167	167	167
Al dosage (g/m^2)	60	25	20
Buffered Al cost ($)	$347,135		
Al cost ($)		$158,556	$67,600
Total ($)		$573,291	

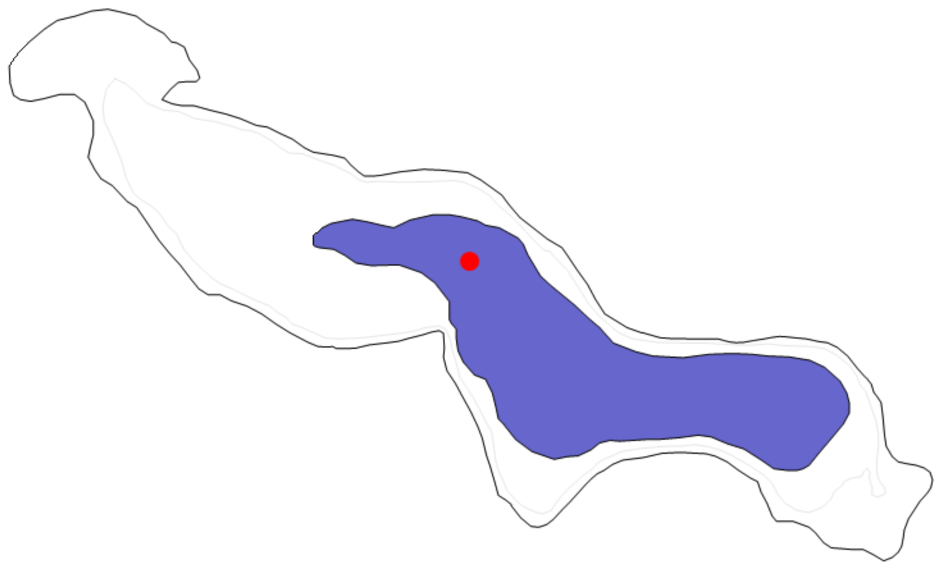

Fig. 1. Map of Long Lake, Polk County, WI. Red circle denotes the location of the thermistor string in 2017. Blue area represents the 15-ft contour and location of the proposed Al application.

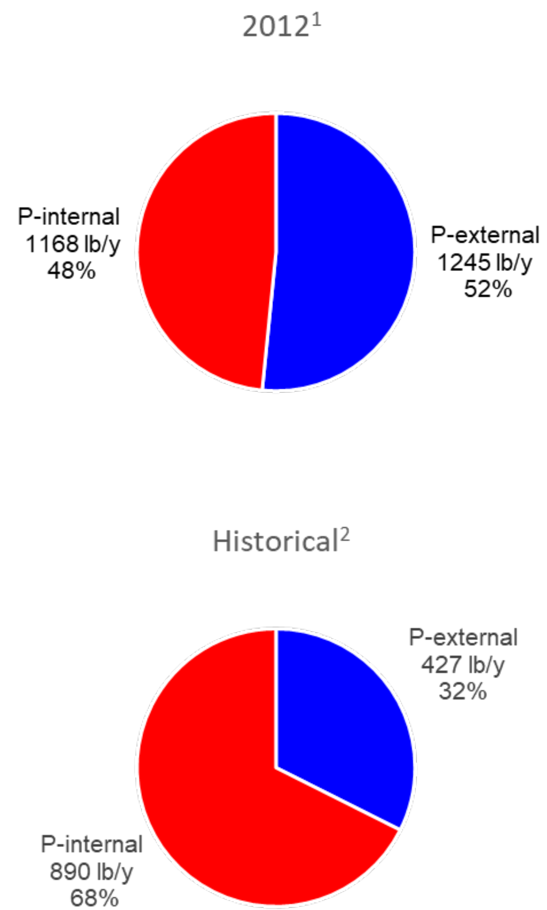

Fig. 2. A comparison of estimated annual phosphorus P inputs from external and internal P loadings based on the 2012 summer mean TP (upper) and the historical summer mean TP from several years (lower).

[1]Represents summer mean limnological conditions for 2012 only (from Long Lake Management Plan)

[2]Represents summer mean limnological conditions for 1993, 1996, 2000, 2012, and 2014 and P mass balance from Nürnberg (1998) and Canfield-Bachmann (1981) empirical models (Table 2)

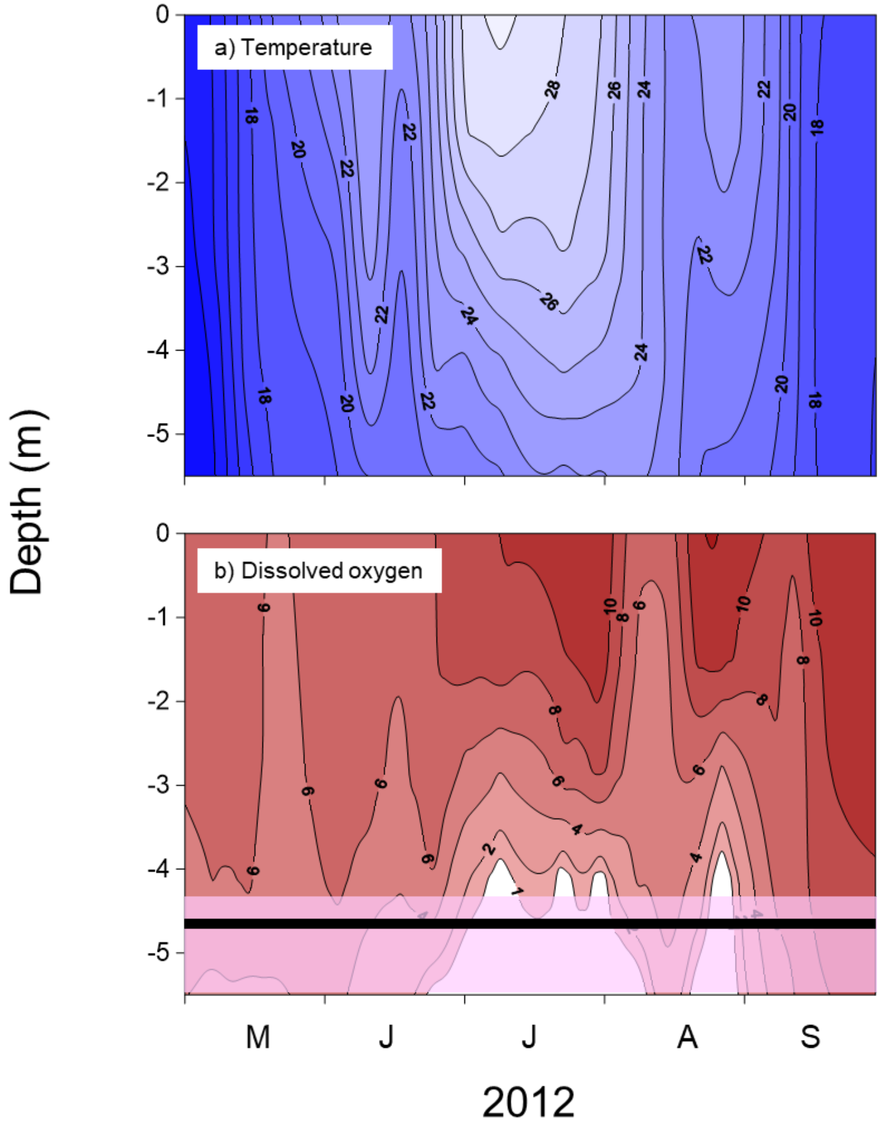

Fig. 3. Seasonal and vertical variations in a) temperature and b) dissolved oxygen in 2012 at a centrally-located station in Long Lake. White area denotes the anoxic zone. Pink transparent area represents the average depth of summer anoxia. The black horizontal line denotes the 15-ft depth chosen for Al treatment.

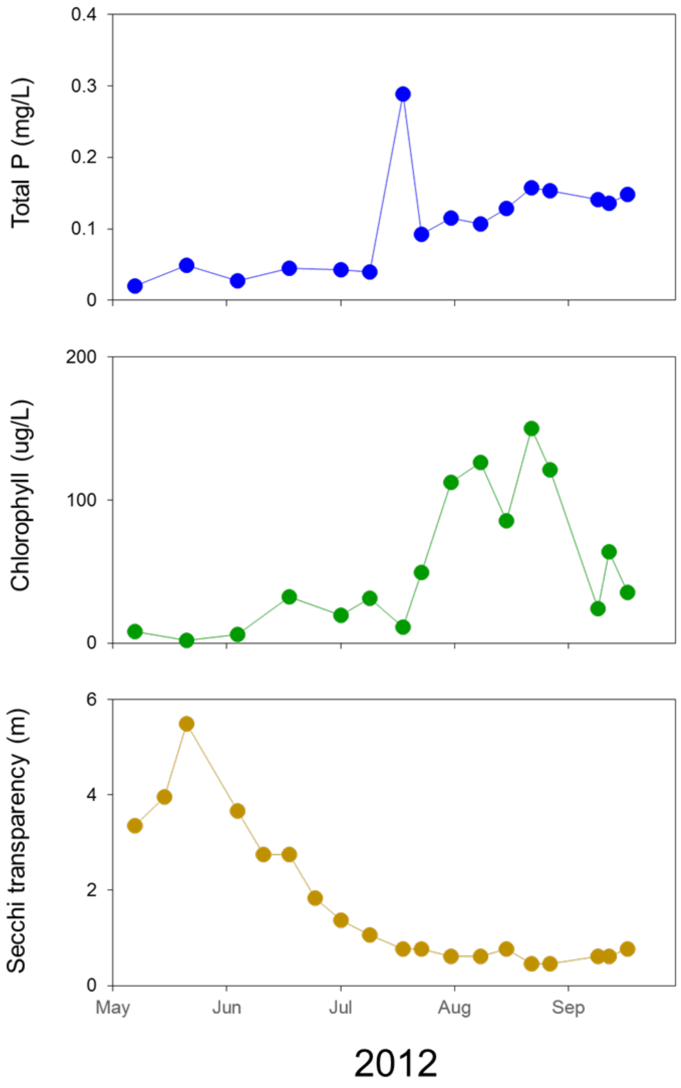

Fig. 4. Seasonal variations in surface concentrations of total phosphorus (P, upper), chlorophyll (middle), and Secchi transparency (lower) in Long Lake during the summer of 2012.

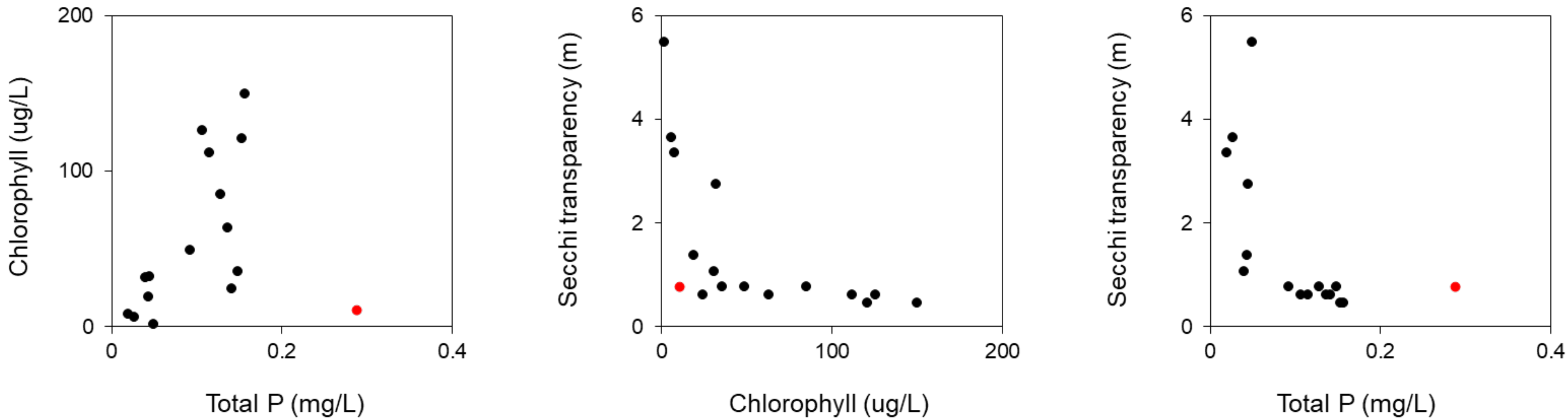

Fig. 5. Relationships between total phosphorus (P), chlorophyll, and Secchi transparency collected in 2012. Red circle represents the total P concentration collected in mid-July, 2012 (see Figure 4).

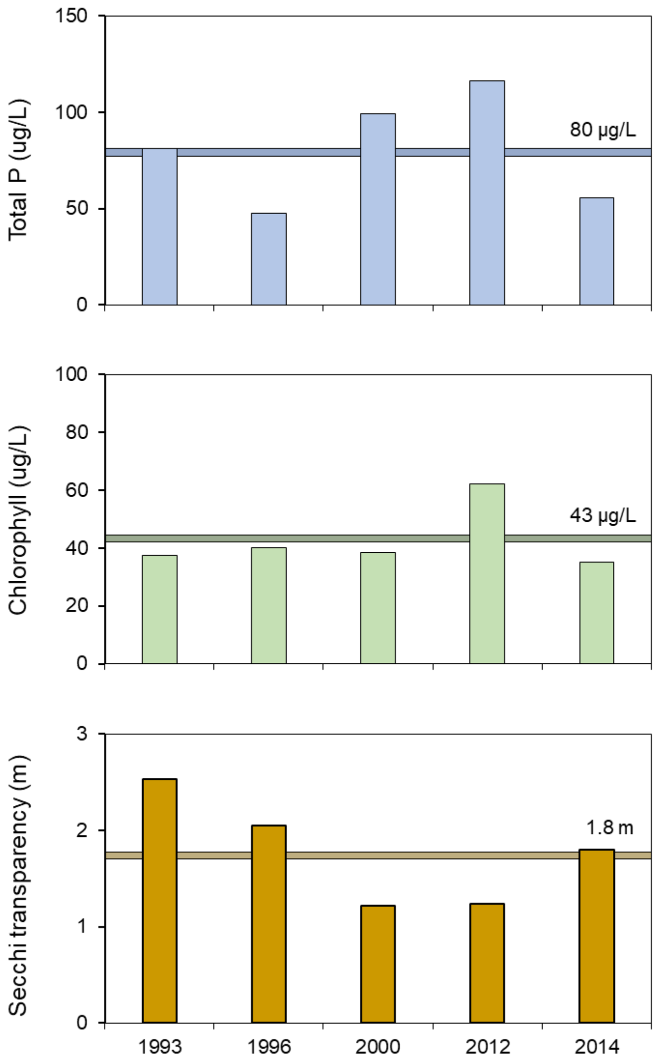

Fig. 6. Mean summer (June-September) concentrations of total phosphorus (P), chlorophyll, and Secchi transparency for various years. Horizontal bars represent the grand mean of each variable over all years.

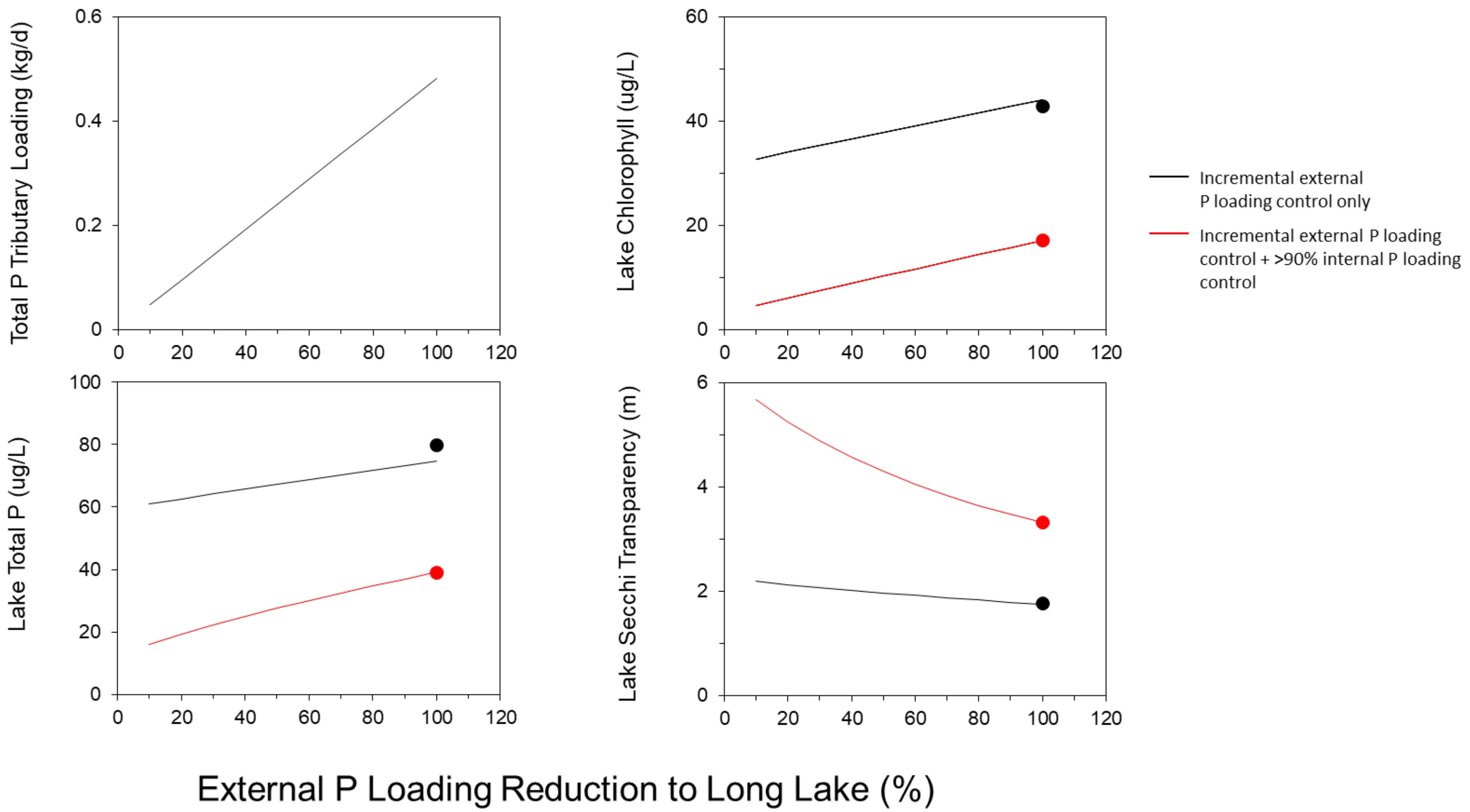

Fig. 7. Empirical model output (Canfield-Bachmann) of predicted changes in total phosphorus (P), chlorophyll, and Secchi transparency in Long Lake as a function of reducing current estimated external P loading by 20% increments. Black lines denote lake response to estimated external P loading reduction 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 3) while red circles denote lake response to internal P loading management only. 100% P load represents current estimated external P loading conditions.

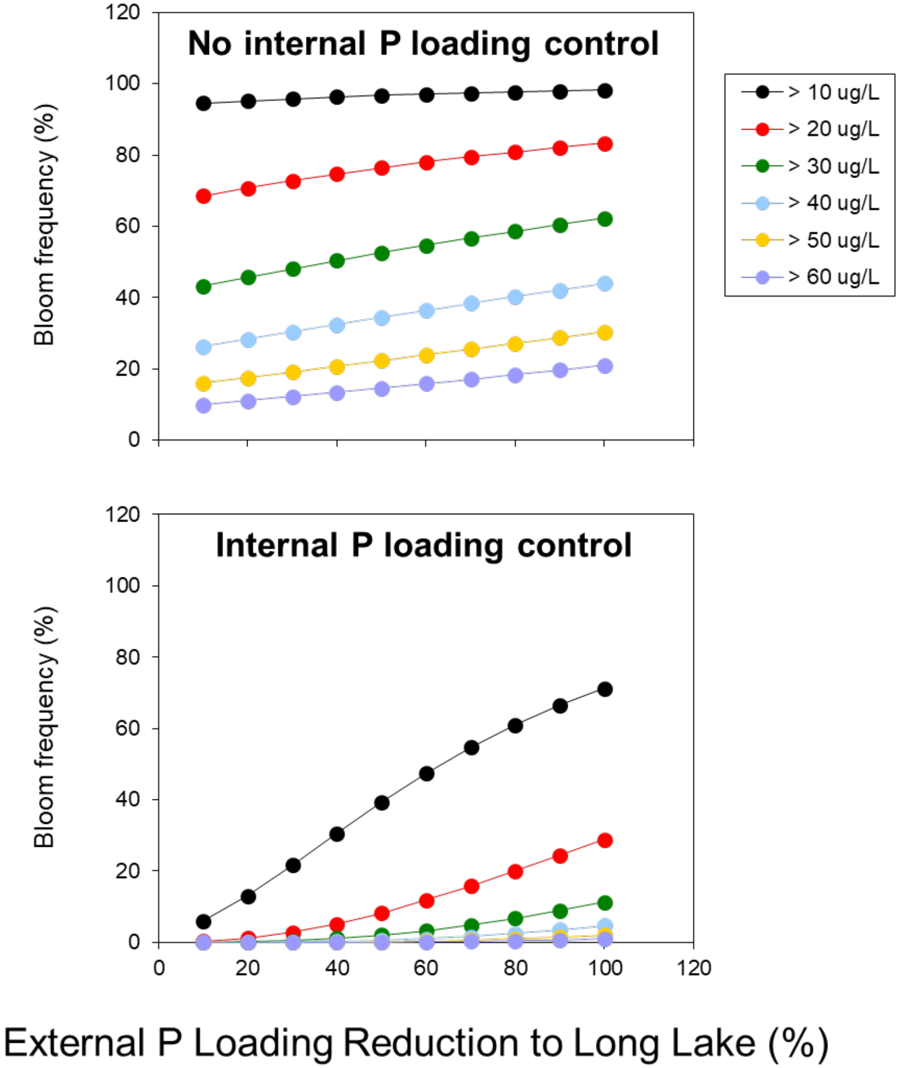

Fig. 8. Empirical model output of predicted changes in algal bloom frequency (as chlorophyll) as a function of reducing estimated external P loading by 10% increments (upper panel) and by reducing external P loading and managing internal P loading. 100% P load represents current estimated external P loading conditions.

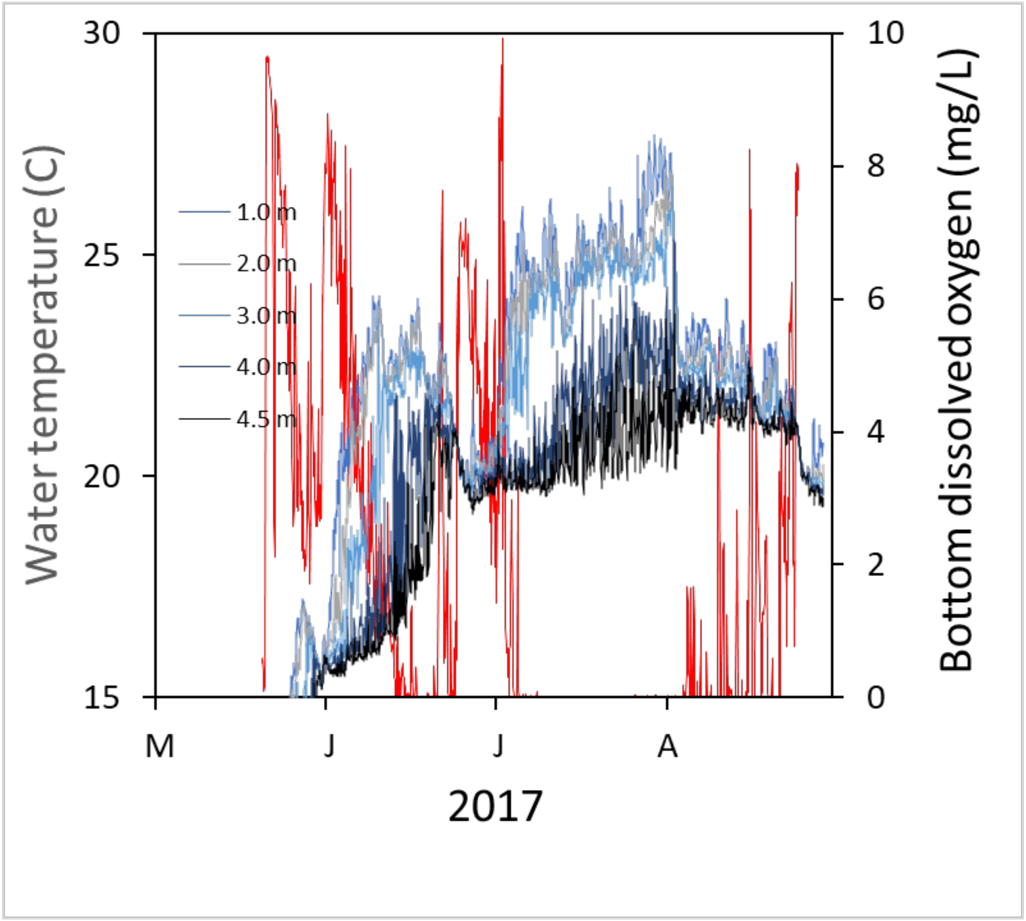

Fig. 9. Seasonal variations in water temperature at various depths and the concentration of dissolved oxygen ~ 0.5 m above the lake bottom in 2017.