Steady-State Modeling Analysis of Big Eau Pleine Reservoir, Wisconsin River System

21 November, 2016

William F. James
University of Wisconsin – Stout
Discovery Center - Sustainability Sciences Institute
Center for Limnological Research and Rehabilitation
Menomonie, WI 54751
715-338-4395
jamesw@uwstout.edu

EXECUTIVE SUMMARY

Big Eau Pleine Reservoir, located near Mosinee, WI, currently exhibits eutrophic to hypereutrophic conditions (Carlson TSI-Phosphorus = 74). A monitoring program was conducted between 2010 and 2013 on the reservoir to examine seasonal total phosphorus (P), chlorophyll, and Secchi transparency dynamics in relation to tributary P loading for Total Maximum Daily Load (TMDL) development. Gauged tributary flow and P inputs included the Big Eau Pleine River at Stratford, Freeman Creek at Halder, and Fenwood Creek at Bradley, WI. The gauged discharge was the Big Eau Pleine River below Big Eau Pleine Dam. Four stations were established along the longitudinal axis of the reservoir for water sampling purposes. Stations were located in the headwater region, upper middle, lower middle portion, and near the dam. Surface samples were collected biweekly between April and October for total P and chlorophyll analysis. A near-bottom samples was also collected for total P analysis. Secchi transparency was determined biweekly using a 20-cm alternating black and white disk.

Mean annual inflow over the 2010-13 period was 10.22 m^3/s (± 1.61 standard error, SE), resulting in a moderately high mean annual residence time of 177 d (± 43 SE). Annual flow-weighted total P in the inflow and outflow were 0.269 mg/L and 0.102 mg/L, respectively, indicating substantial P retention. Longitudinal total P concentration gradients developed between the headwater and dam stations during the summer; the grand mean total P over 2010-13 declined from ~ 0.195 mg/L at the headwater station to 0.102 mg/L at the dam station. The reservoir-wide, area-weighted, grand mean (i.e., over 2010-13) total P was ~ 0.133 mg/L. The area-weighted grand mean chlorophyll concentration was high at ~ 69 µg/L and summer mean concentrations tended to decline from the headwater to the dam station. The area-weighted grand mean Secchi transparency was low at ~ 0.7 m. The area-weighted Carlson trophic state index (TSI, Carlson 1977) for P (TSI-P) was high at 74 and indicative of hypereutrophic conditions. The TSI based on chlorophyll (TSI-CHLA) was slightly lower at 71 and TSI based on Secchi transparency (TSI-SD) was 65.

Budgetary analysis of P loads suggested substantial P retention of loads to Big Eau Pleine Reservoir, as ~ 60% of the P input was retained. Overall, the P empirical model (Canfield and Bachmann 1981) closely predicted the observed area-weighted mean summer total P concentration. However, the model over predicted mean total P at the headwater station. Tributary P inputs entirely accounted for the summer total P budget, suggesting that internal P loading and entrainment to surface waters for algal uptake was a minor component of the P budget. The chlorophyll model (Jones and Bachmann 1976) over predicted observed means necessitating adjustment of the calibration coefficient. This pattern suggested that a portion of the total P was inorganic and not associated with algal biomass. After calibration, both the chlorophyll and Secchi transparency (based on chlorophyll concentration and nonalgal turbidity) models closely approximated observed summer grand means. A 50% reduction in P loading coincided with a 41% decline in summer total P from a predicted ~0.140 mg/L to 0.083 mg/L. Under this same P loading reduction scenario, summer chlorophyll concentrations declined by 55% from a predicted ~ 76 µg/L to ~35 µg/L. Predicted Secchi transparency increased by ~28% from 0.7 m to 0.9 m. Under current P loading conditions, chlorophyll blooms exceeding 20 µg/L and 60 µg/L occurred an estimated 89% and 41% of the time during the summer period, respectively. Using the same scenario, a 50% P loading reduction resulted in a predicted decline in the summer bloom frequency of chlorophyll exceeding 20 µg/L and 60 µg/L to 60% and 14% of the time during the summer period, respectively. Empirical steady-state models developed for Big Eau Pleine Reservoir will be used in conjunction with other decision-support tools to develop a TMDL based on predicted reservoir water quality responses to P loading reduction.

OBJECTIVES

The objectives of this investigation were to examine summer limnological conditions in Big Eau Pleine Reservoir between 2010 and 2013 and project future conditions under phosphorus loading reduction scenarios using a steady-state empirical modeling approach.

METHODS

Flow and total phosphorus (P) loadings from the Big Eau Pleine River and Freeman and Fenwood Creeks (Table 1) were combined with seasonal (April – September to early October) surface water chemistry information from four stations in Big Eau Pleine Reservoir (Table 2, Fig. 1) to construct a steady-state empirical model (Bathtub Version 6.14, Walker 1996) to forecast the response of limnological variables (total P, chlorophyll, and Secchi transparency) to future P loading reduction. Since the annual theoretical water residence time was moderate to long (range = 0.36 y to 0.84 y), an annual averaging period was used for steady-state empirical modeling analysis. Gauged hydraulic inputs included the Big Eau Pleine River at Stratford (Station ID 373325), Freeman Creek at Halder (Station ID 373411), and Fenwood Creek at Bradley, WI (Station ID 373366, Table 1). The gauged hydraulic discharge from the reservoir was the Big Eau Pleine River at Big Eau Pleine Dam (Station ID 10030620, Table 1). Monthly hydraulic flow (m^3/s) and total P loadings (kg/y) determined by the US Geological Survey (Madison, WI) were converted to mean flow (expressed as hm^3/y) and total P concentration (expressed as µg/L) over the 2010-13 period of study as input to the model. Additional hydrologic input to the model included ungauged local runoff to the reservoir from the surrounding subwatershed that was estimated using the Soil and Water Assessment Tool (SWAT) and daily precipitation records over the study period obtained from the Wisconsin State Climatology Office (Madison, WI). For the Big Eau Pleine

River and discharge from Big Eau Pleine Dam, the coefficient of variation (CV-mean) was estimated from mean January through December flows and total P concentrations between the years 2002 and 2013 reported by the US Geological Survey (Dale M. Robertson, U.S. Geological Survey, Madison, WI, unpublished data). Freeman and Fenwood Creek CV-means were estimated for the period 2010-13. The CV-mean was calculated as the standard error of the grand mean (i.e., 2002 through 2013 for the Big Eau Pleine River at Stratford and Big Eau Pleine Dam and 2010 through 2013 for Freeman and Fenwood Creek) divided by the grand mean of each constituent. This CV-mean was used for error analysis in Bathtub as recommended in Walker (1996).

Biweekly measurements of Secchi transparency and surface concentrations of chlorophyll and total P, collected in Big Eau Pleine Reservoir during the summer periods of 2010 through 2013, were averaged to estimate a mean concentration for each station segment during each year. June through September was used as the averaging period. Chemical analyses of water samples were conducted by the Wisconsin State Laboratory of Hygiene using standard methodological approaches. For in-lake morphometric inputs to the empirical model, the pool was divided into the 4 segments (i.e., headwater, upper middle, lower middle, and dam segments) corresponding to the locations of sampling stations (Table 2). The upper middle station was added in 2011.

The computer software program Bathtub was used to examine P loading reduction scenarios (Walker 1996). 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. Grand means for total P, chlorophyll, and Secchi transparency over the summer 2010-13 period were used as input into the model. The coefficient of variation for total P, chlorophyll, and Secchi transparency of the grand mean (CV-mean) was calculated as the standard error of the grand mean divided by the grand mean of each constituent. This CV-mean was used for error analysis in Bathtub as recommended in Walker (1996).

RESULTS AND DISCUSSION

Tributary Hydrology and Loading

Mean annual inflow was highest and similar in 2010, 2011, and 2013 at ~ 12.0 m^3/s and lowest in 2012 at 5.4 m^3/s (Fig. 2). The annual theoretical water residence time ranged between 130 d and 136 d during the higher flow years and was 305 d during the lower flow year of 2012 (Fig. 2). Annual total P concentration of the inflow to Big Eau Pleine Reservoir, representing a flow-weighted concentration for the combined Big Eau Pleine River, Freeman Creek, Fenwood Creek, and estimated local subwatershed runoff ranged between 0.206 mg/L in 2012 and 0.345 mg/L in 2010, following a trend similar to that of annual gauged inflow (Fig. 2). The higher annual total P concentration in 2010 versus other higher flow years may have reflected seasonal differences in the timing of precipitation. For instance, monthly P loading was unusually high during September, 2010, compared to other years (not shown). Annual total P loading followed the same inter-annual trend. It was lowest in 2012 in conjunction with lower mean annual flow and greatest in 2010, 2011, and 2013.

Reservoir Limnological Trends

In contrast to P loading, mean total P concentrations were relatively constant among years at all stations in Big Eau Pleine Reservoir (Fig. 3). In addition, they were lower than the measured inflow total P, particularly during the higher flow and P loading years of 2010, 2012, and 2013 (Fig. 3). This pattern indicated considerable P retention in the reservoir. Total P concentration gradients developed between the headwaters and dam during periods of elevated total P loading from the Big Eau Pleine River, suggesting advective transport of P loads and deposition along the longitudinal axis (Fig. 4-7). Total P was also elevated in the headwaters during periods of lower inflow, as in late July, 2012 (Fig. 6). This pattern coincided with the development of a chlorophyll maximum, suggesting incorporation of P into algal biomass. The source of this P may have been internal P loading from sediment versus watershed P loading since flows were low during this period. Alternatively, wind-driven resuspension and mixing in the headwaters could have accounted for some of the total P concentration increase in late July. Overall, grand mean total P concentrations declined from 0.269 mg/L in the combined inflow to 0.195 mg/L at the headwater station and 0.102 mg/L at the dam station (Fig. 8). Mean measured P retention over the 4-year period was 61% (Table 3).

Near-bottom concentrations of total P often exceeded surface total P at all stations during the 2010-13 period (Fig. 9-12). Vertical concentration differences tended to coincide with bottom anoxia, indicating internal P loading under anaerobic conditions (Fig. 13 and 14). Vertical concentration differences were generally greatest at the deeper dam station location (Fig. 13). In addition, seasonal and longitudinal variations in bottom water dissolved oxygen were dynamic, but did not coincide with, for instance, variations in flow (Fig. 14). Instead, bottom water patterns may have been more influenced by hydropower dam operations and withdrawal from intermediate depths which would promote interflow and underflow currents that could alter residence time distribution in the vertical water column and constituent concentration.

Mean summer chlorophyll concentrations were relatively high, ranging between 55 µg/L and 89 µg/L, and tended to decrease slightly from the headwater to the dam station (Fig. 3 and 8). Concentrations also varied longitudinally and seasonally. Usually, chlorophyll was lowest in concentration during May and increased to peaks thereafter (Fig. 9-12). In addition, blooms tended to develop shortly after periods of elevated P loading, as in August, 2010, early and late July, 2011, and early July, 2013. Concentrations also declined during periods of high inflow, as in July of 2010 and 2011 and June, 2013, suggesting potential algal cell discharge or dilution as a result of decreased residence time. Chlorophyll concentrations were high (> 120 µg/L) during a period of relatively low inflow and high residence time between June and early August, 2012 and 2013 (Fig. 6 and 7).

Although there were seasonal periods when Secchi transparency slightly exceeded 1.0 m (Fig. 9-12), these instances occurred primarily in May when chlorophyll concentrations were low. Summer means were generally lower throughout the study period (Fig. 3), ranging between 0.4 m and 0.9 m. Longitudinal variations in grand mean Secchi transparencies were also minor but tended to increase from headwaters to dam (headwater station = 0.5 m ± 0.08 SE; upper middle station = 0.67 m ± 0.04 SE; lower middle station = 0.65 m ± 0.04 SE; dam station = 0.77 m ± 0.09 SE; Fig. 8).

Grand mean summer Carlson Tropic State Index (TSI) values were greatest for total P at ~ 71 to 80 (Fig. 8), indicative of hypereutrophic conditions. Grand mean TSI was slightly lower for chlorophyll (~ 71 to 74) and Secchi transparency (~64 to 69) compared to total P (Fig. 8). Higher total P TSI suggested that a portion of the total P was inorganic P (i.e., perhaps associated with watershed P) and not incorporated into algal biomass.

Steady-State Empirical Modelling

The mean (2010-13) annual hydraulic and total P balance for measured inputs and outputs to Big Eau Pleine Reservoir are shown in Table 3. Measured mean annual P loading to the reservoir was much greater than P discharge resulting in retention of ~ 61% of the P income. The Big Eau Pleine River at Stratford, WI, overwhelmingly dominated mean annual gauged P inputs to the reservoir (Table 3). Mean flow and P loading represented 59% and 84% of the gauged mean inputs, respectively. The mean flow-weighted total P concentration was high at 0.381 mg/L. In addition, soluble reactive P represented ~ 68% of the total P at a mean flow-weighted concentration of 0.261 mg/L (U.S. Geological Survey unpublished data). Although Freeman and Fenwood Creeks represented only 14% of the gauged mean summer inflow, the mean summer flow-weighted total P concentrations were also high at 0.109 and 0.182 mg/L, respectively. Mean soluble reactive P represented 31% and 52% of the total P composition for Freeman and Fenwood Creeks, respectively. However, mean total P loading from these creek inputs represented only 8% of the measured total P load to the system. Ungauged P inputs, estimated from SWAT output, accounted for ~ 7% of the total P input. A portion of the annual total P discharge from Big Eau Pleine Reservoir was soluble reactive P (U.S. Geological Survey unpublished data). The mean flow-weighted soluble reactive P concentration over the 2010-13 period was 0.029 mg/L, representing ~ 25% of the total P concentration in the discharge. Since withdrawal depths are below the lake surface, relatively high soluble reactive P probably reflected combined sources from riverine advective interflows and entrainment of internal P loads.

The Canfield-Bachmann (1981) empirical model (option 8; Bathtub) was chosen to predict summer mean lake total P (Table 4). Because the Jones and Bachman (1976) chlorophyll-total P regression relationship was developed from and extensive northern lake data set, it was chosen for mean summer chlorophyll prediction. Finally, the default Secchi transparency model developed from relationships between chlorophyll and turbidity in reservoirs was chosen to estimate mean summer Secchi depth.

Observed versus predicted summer means of total P, chlorophyll, and Secchi transparency over the 2010-13 period are shown in Figure 15 and Table 5. Overall, the P empirical model (Canfield-Bachmann) closely predicted the observed area-weighted mean summer total P concentration in Big Eau Pleine Reservoir (Table 5). For individual segments, the model over predicted the mean total P concentration of the headwater station but closely approximated the concentration at other stations (Fig. 15). Reasons for the headwater station discrepancy are not known.

The uncalibrated chlorophyll model tended to over predict the observed area-weighted mean summer chlorophyll concentration (Fig. 15). However, standard error bars overlapped and means were not significantly different given errors in the observed chlorophyll versus the model (Walker 1996). In addition to potential error, over prediction of mean summer chlorophyll based on chlorophyll-total P regression relationships could have been related to a portion of the total P pool that was not incorporated as algal biomass. For instance, some of the total P could have been inorganic particulate P in the form of clays and colloidal metal oxyhydroxides versus algal biomass in the form of organic P. Adjustment to the observed summer mean chlorophyll concentration resulted in a calibration coefficient of ~0.65. Since the Secchi transparency model uses summer mean chlorophyll as an input variable, predicted summer mean Secchi transparency slightly underestimated the observed mean without calibration adjustment of the chlorophyll model (Fig. 15). Chlorophyll calibration resulted in improved prediction of Secchi transparency.

Phosphorus Loading Reduction

Current P loading to Big Eau Pleine Reservoir was reduced by 10% increments in Bathtub to examine predicted water quality responses to simulated future P loading reduction due to best management practices (BMP) implementation for TMDL development and goal-setting (Fig. 16). A 50% reduction in annual P loading coincided with a 41% decline in summer total P from a predicted ~0.140 mg/L (i.e., slightly higher than the observed mean total P of 0.133 mg/L). to 0.083 mg/L. Under this same P loading reduction scenario, predicted summer chlorophyll concentrations declined by 55% from ~ 76 µg/L to ~35 µg/L. Predicted Secchi transparency increased by 28% from 0.7 m to 0.9 m.

Predicted bloom frequency (i.e., percentage of the summer that chlorophyll exceeds a certain concentration) response to P loading reduction is shown in Figure 17 for various summer mean chlorophyll concentrations. Under current P loading conditions, chlorophyll blooms exceeding 20 µg/L and 60 µg/L occurred an estimated 89% and 41% of the time during the summer period, respectively. A 50% P loading reduction would result in a predicted decline in the summer bloom frequency of chlorophyll exceeding 20 µg/L and 60 µg/L to 60% and 14% of the time during the summer period, respectively. Thus, empirical models suggested that predicted reservoir trophic state indicator variables (total P, chlorophyll, and chlorophyll concentration bloom frequency) were responsive to P loading reduction.

REFERENCES

Carlson RE. 1977. A trophic state index for Lakes. Limnol Oceanogr 22:361-369.

Walker WW. 1996. Simplified procedures for eutrophication assessment and prediction: User manual. Instruction Report W-96-2, September, 1996, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, USA.

Table 1. Gauged inflow-outflow stations used in the Big Eau Pleine Reservoir empirical steady-state model.

Station ID	Gauged Inflow
373325	Big Eau Pleine River at Stratford
373411	Freeman Creek at Halder
373366	Fenwood Creek at Bradley
	Gauged outflow
10030620	Big Eau Pleine River at Big Eau Pleine Dam

Table 2. Water quality sampling station locations in Big Eau Pleine Reservoir.

Station ID	**Name**	**Surface area** (km^2)	**Mean depth** (m)	**Segment length** (km)
373137	Headwaters	4.53	5.22	16.1
373136	Upper middle	5.07	5.08	6.4
10007758	Lower middle	4.34	6.64	4.8
373135	Dam	9.16	5.5	3.2

Table 3. A comparison of mean (2010-13) annual flow and total phosphorus (P) inputs to and discharge from Big Eau Pleine Reservoir.

Component	Flow (m^3/s)	Flow (% contribution)	Total P (mg/L)	Total P (kg/y)	Total P (% contribution)
Inputs					
Big Eau Pleine River	6.1	59	0.381	72,805	84
Freeman Creek	0.7	6	0.109	2,241	3
Fenwood Creek	0.8	8	0.182	4,574	5
Ungauged inputs[1]	2.1	20	0.098	6,376	7
Precipitation	0.6	6	0.03	693	1
Total	10.2	100	0.285	86,689	100
Outputs					
Big Eau Pleine Dam	9.2		0.115	33,805	
Evaporation	0.6				
Total	9.8		0.102	33,805	
Balance	0.4			52,884	
	96%			61%	

[1]Representing local subwatershed inputs estimated from the Soil and Water Assessment Tool (SWAT)

Table 4. Algorithms used for Bathtub (Walker 1996) phosphorus loading reduction modeling of Big Eau Pleine Reservoir.

Variable	Model
Phosphorus	Canfield and Bachmann (1981)
Chlorophyll	Jones and Bachmann (1976)
Secchi Transparency	versus Chlorophyll & Turbidity

Table 5. Predicted versus observed reservoir-wide area-weighted mean concentrations of total phosphorus (P), chlorophyll, and Secchi transparency. Predicted chlorophyll represents the value after calibration. CV = coefficient of variation.

Variable	Predicted	CV	Observed	CV
Total P (mg/L)	140	0.26	133	0.05
Chlorophyll (ug/L)	76	0.44	69.4	0.09
Secchi Transparency (m)	0.7	0.24	0.7	0.06

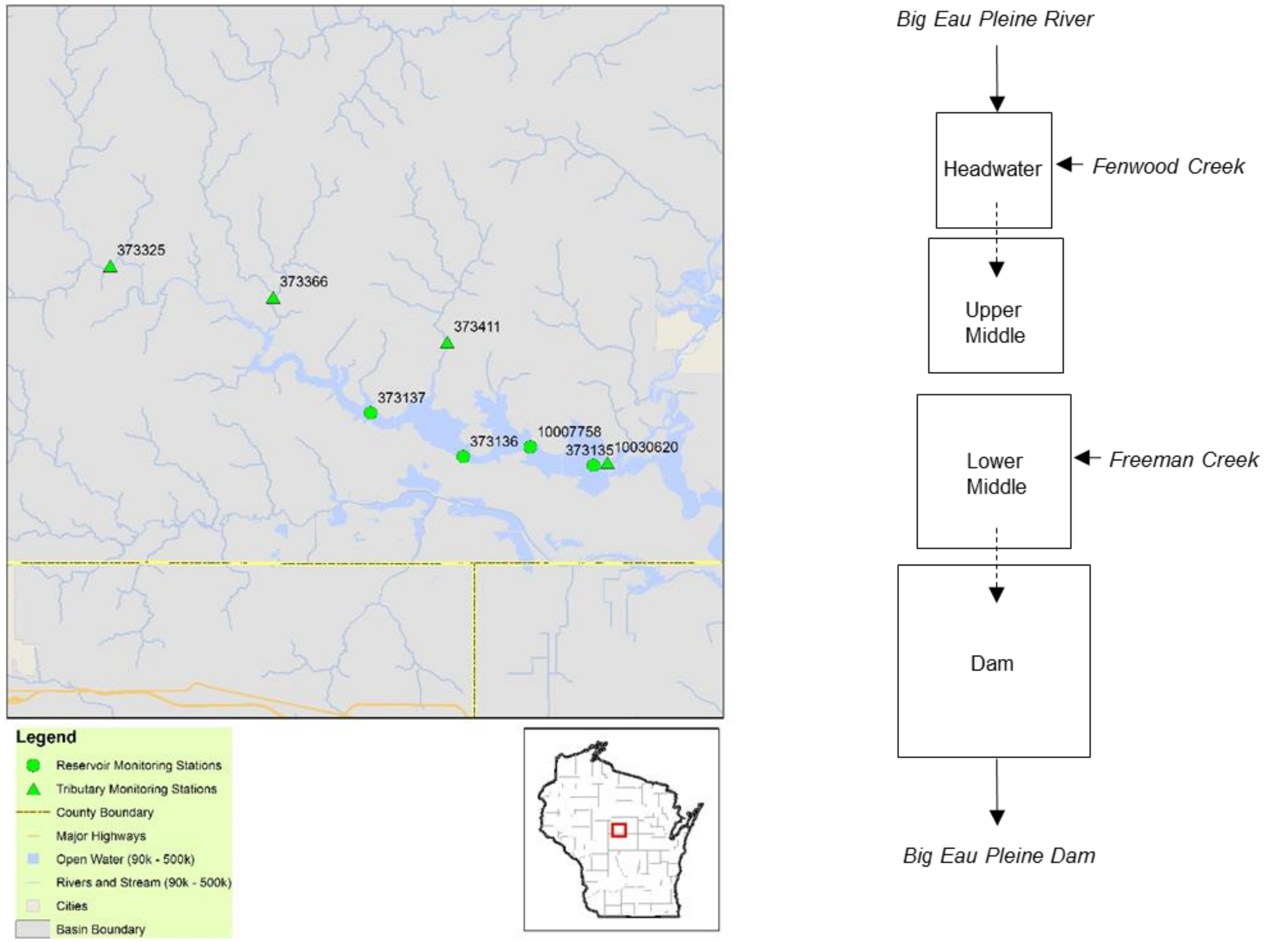


Figure 1. Water sampling station locations (left) and Bathtub conceptualization.

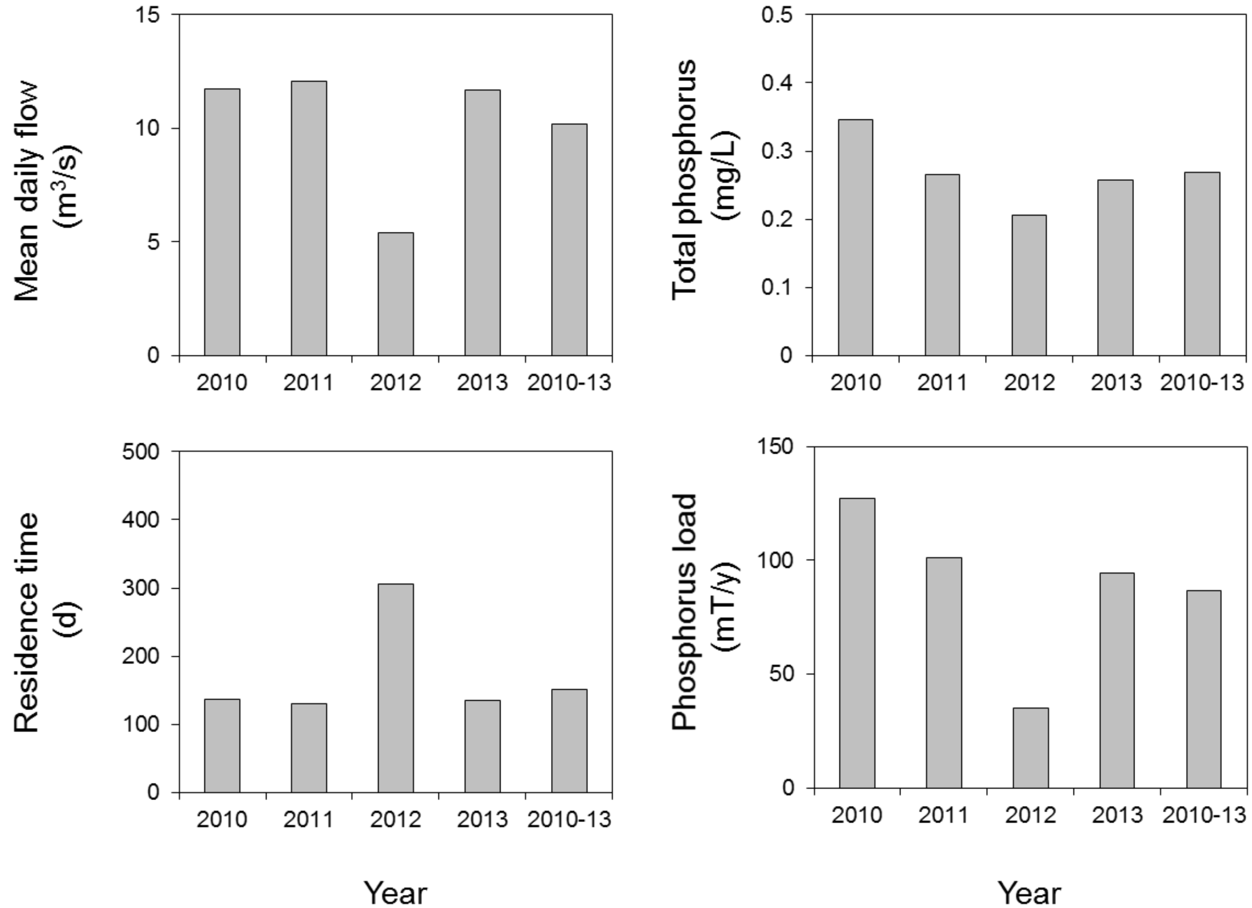


Figure 2. Annual gauged mean daily flow into Big Eau Pleine Reservoir (upper left panel), theoretical water residence time (lower left panel), flow-weighted total phosphorus concentration of the inflow (upper right panel), and total phosphorus load (lower right panel) during 2010 - 2013. The grand mean for each variable was estimated as the mean of the individual summer means.

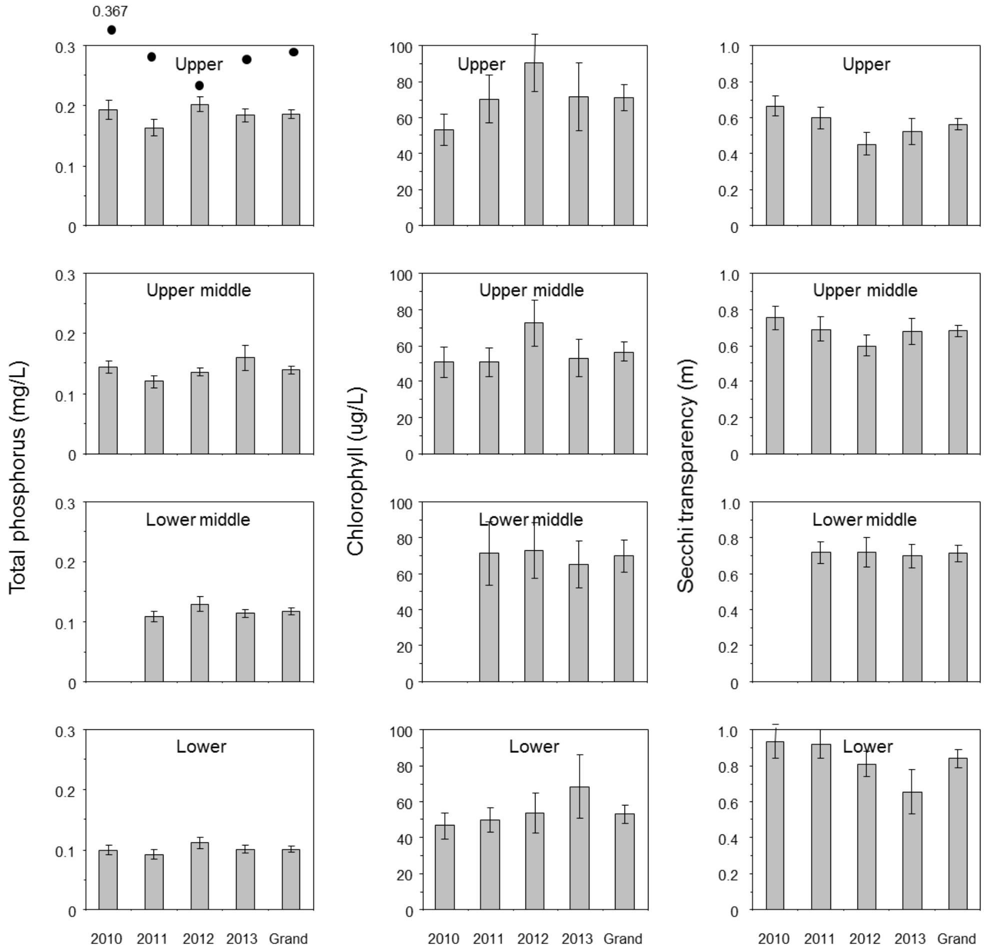


Figure 3. Summer (June – September) mean concentrations of total phosphorus (left panels), chlorophyll (middle panels), and Secchi transparency (right panels) during 2010 - 2013. The black circles denote the gauged annual inflow total phosphorus concentration (including estimated precipitation). The grand mean for each variable was estimated as the mean of the individual summer means. Vertical lines represent ± 1 standard error.

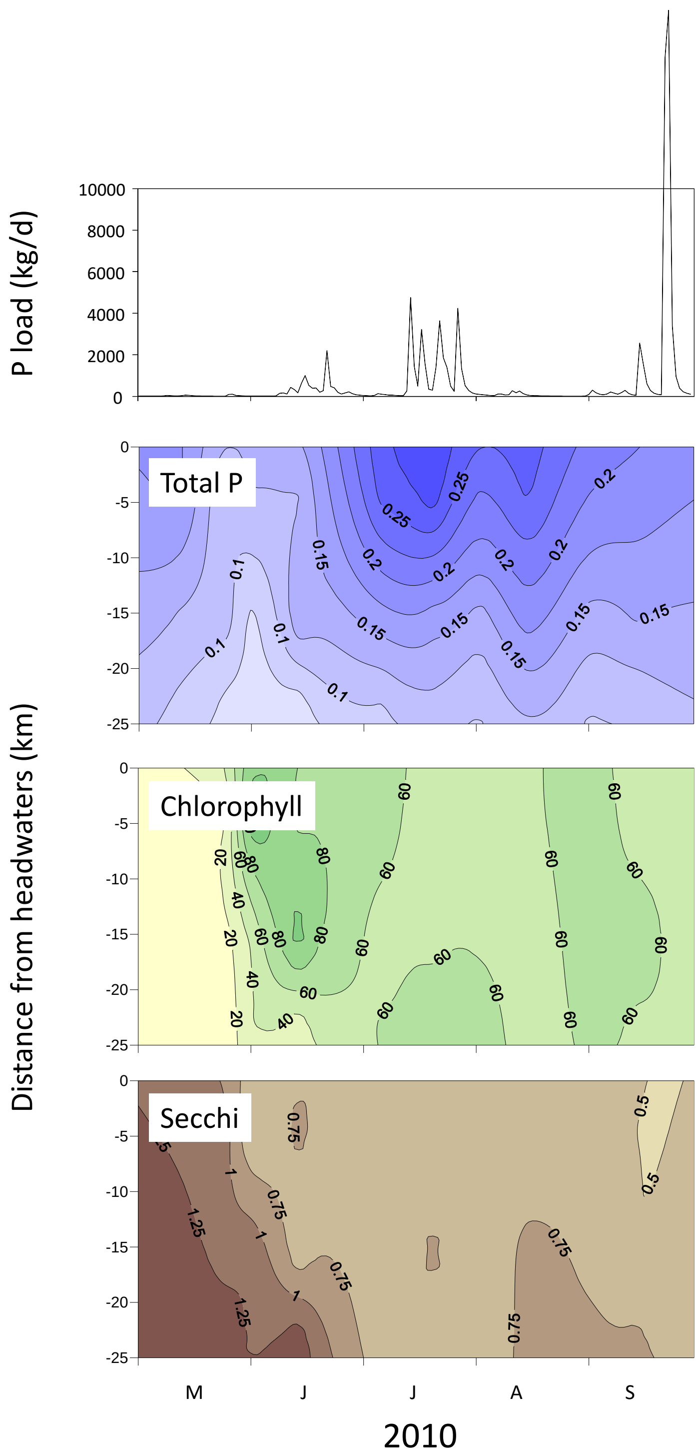


Figure 4. Summer phosphorus (P) loading from the Big Eau Pleine River (upper panel) versus seasonal and longitudinal variations in surface total phosphorus (P), chlorophyll, and Secchi transparency in 2010.

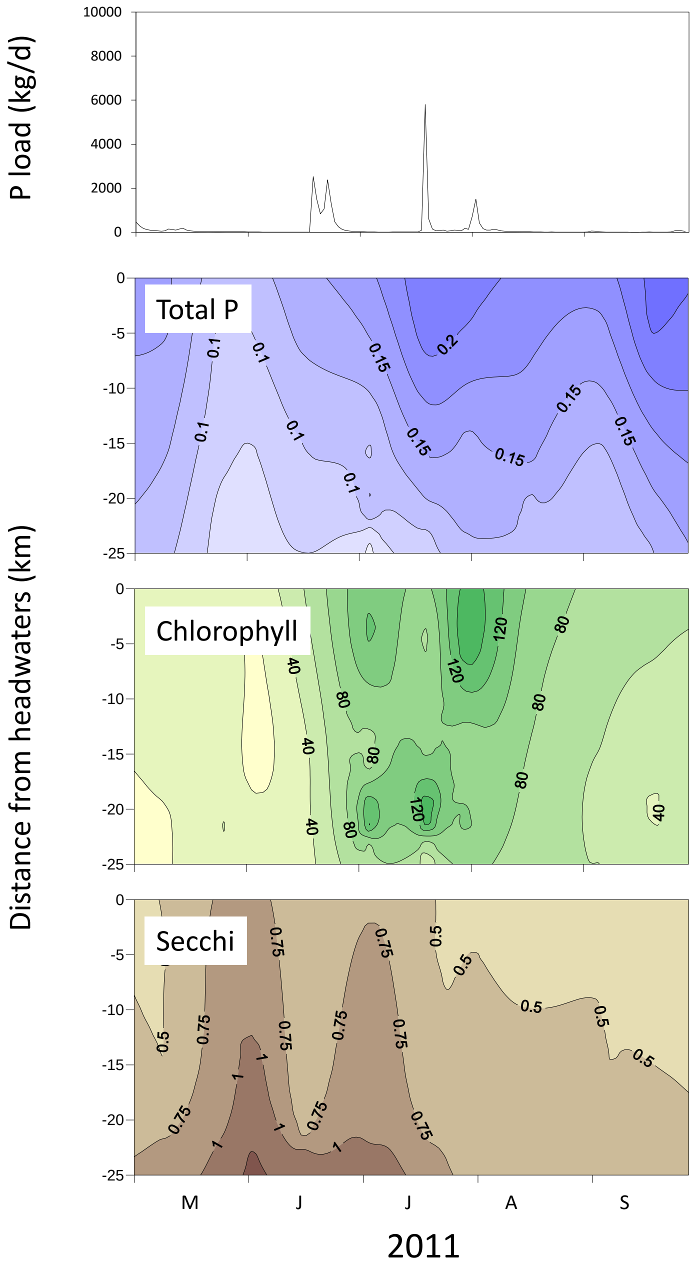


Figure 5. Summer phosphorus (P) loading from the Big Eau Pleine River (upper panel) versus seasonal and longitudinal variations in surface total phosphorus (P), chlorophyll, and Secchi transparency in 2011.

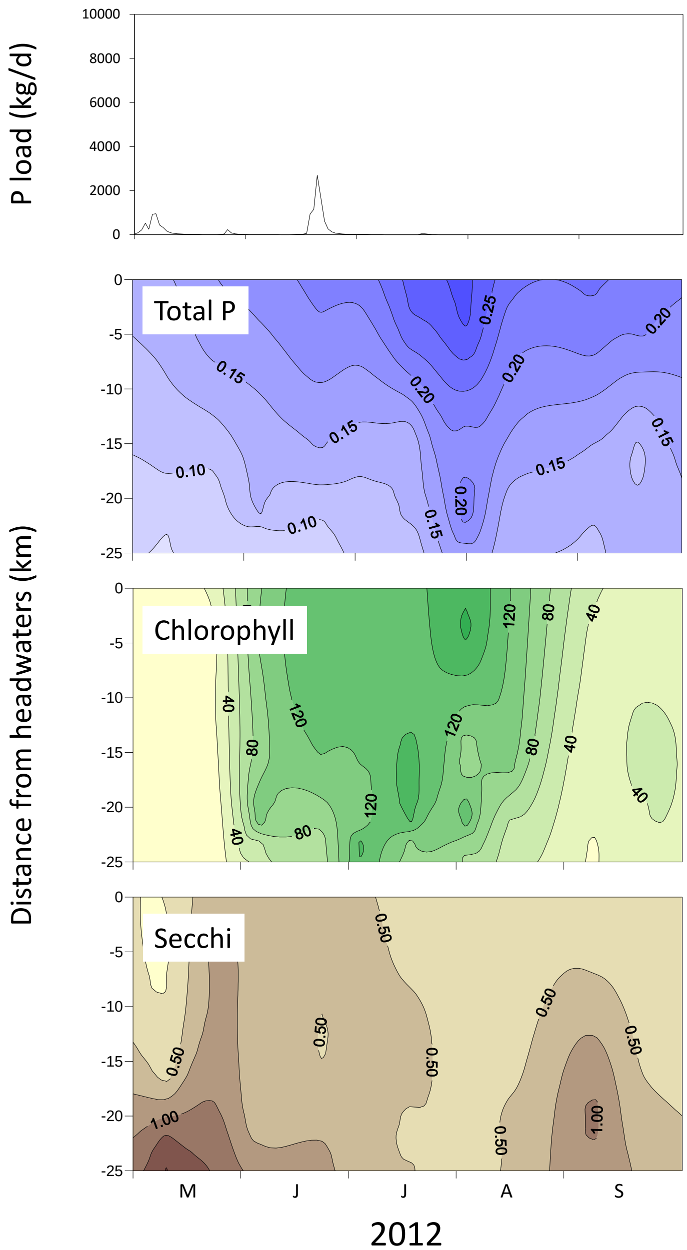


Figure 6. Summer phosphorus (P) loading from the Big Eau Pleine River (upper panel) versus seasonal and longitudinal variations in surface total phosphorus (P), chlorophyll, and Secchi transparency in 2012.

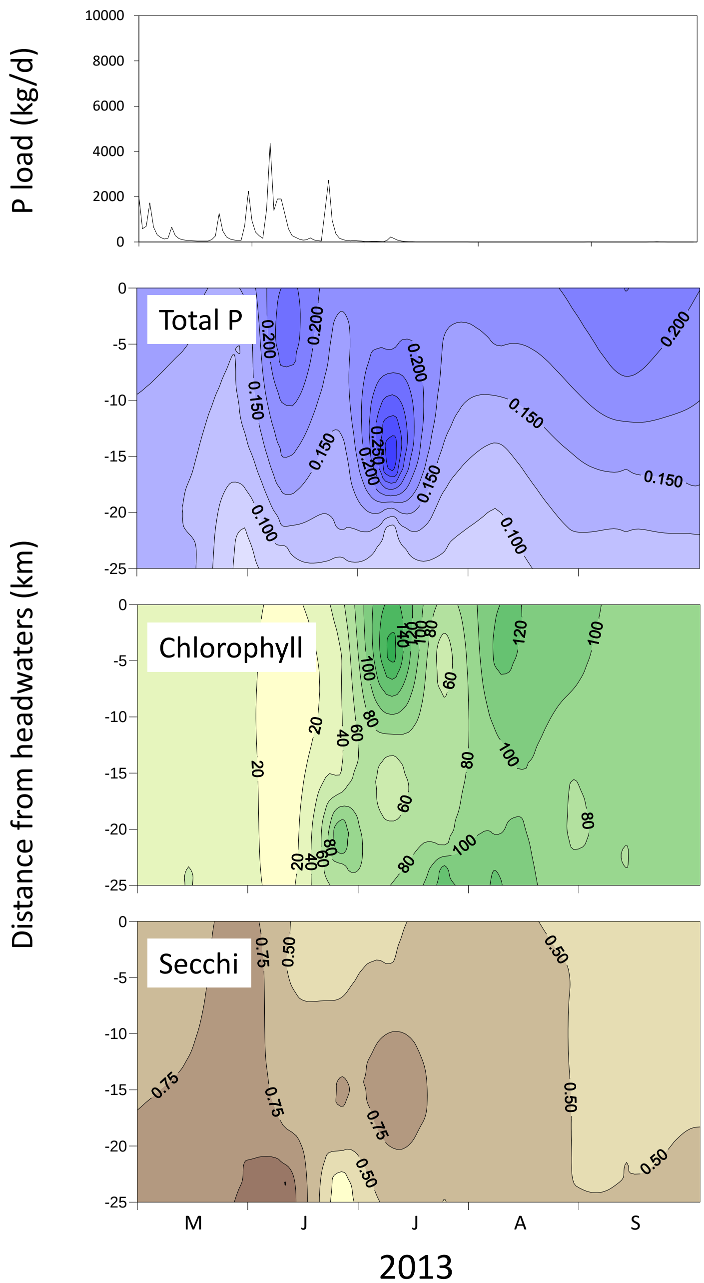


Figure 7. Summer phosphorus (P) loading from the Big Eau Pleine River (upper panel) versus seasonal and longitudinal variations in surface total phosphorus (P), chlorophyll, and Secchi transparency in 2013.

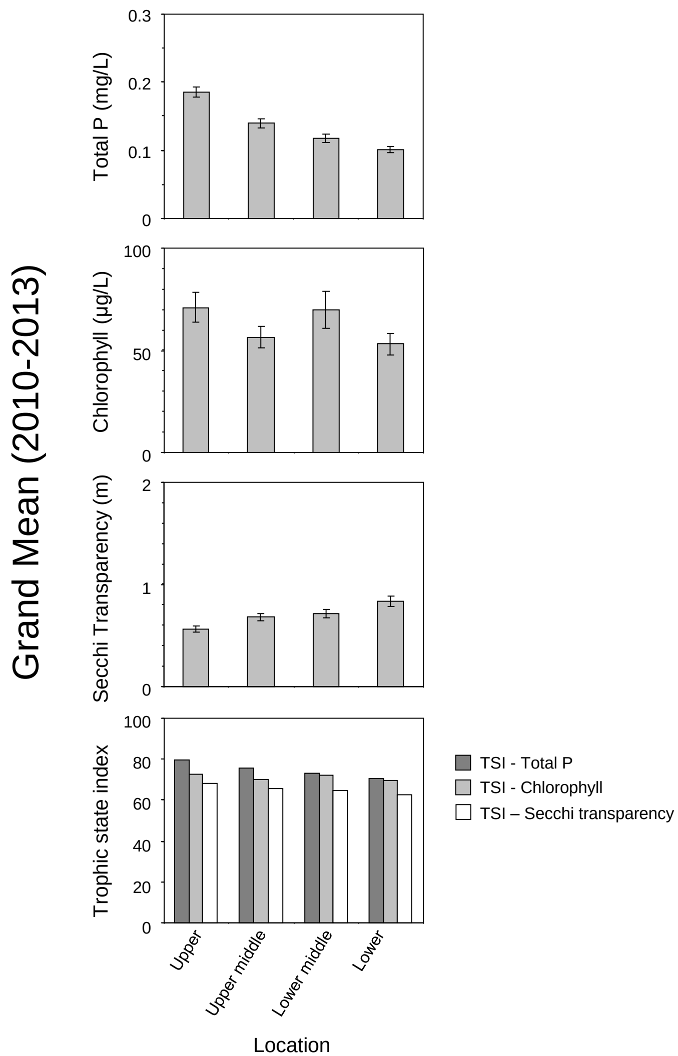


Figure 8. Variations in grand mean summer (June – September) total phosphorus (P, upper panel), chlorophyll (upper middle panel), Secchi transparency (lower middle panel), and Carlson trophic state indices (TSI) for the headwater, upper middle, lower middle, and dam stations in Big Eau Pleine Reservoir. Vertical lines represent ± 1 standard error of the grand mean.

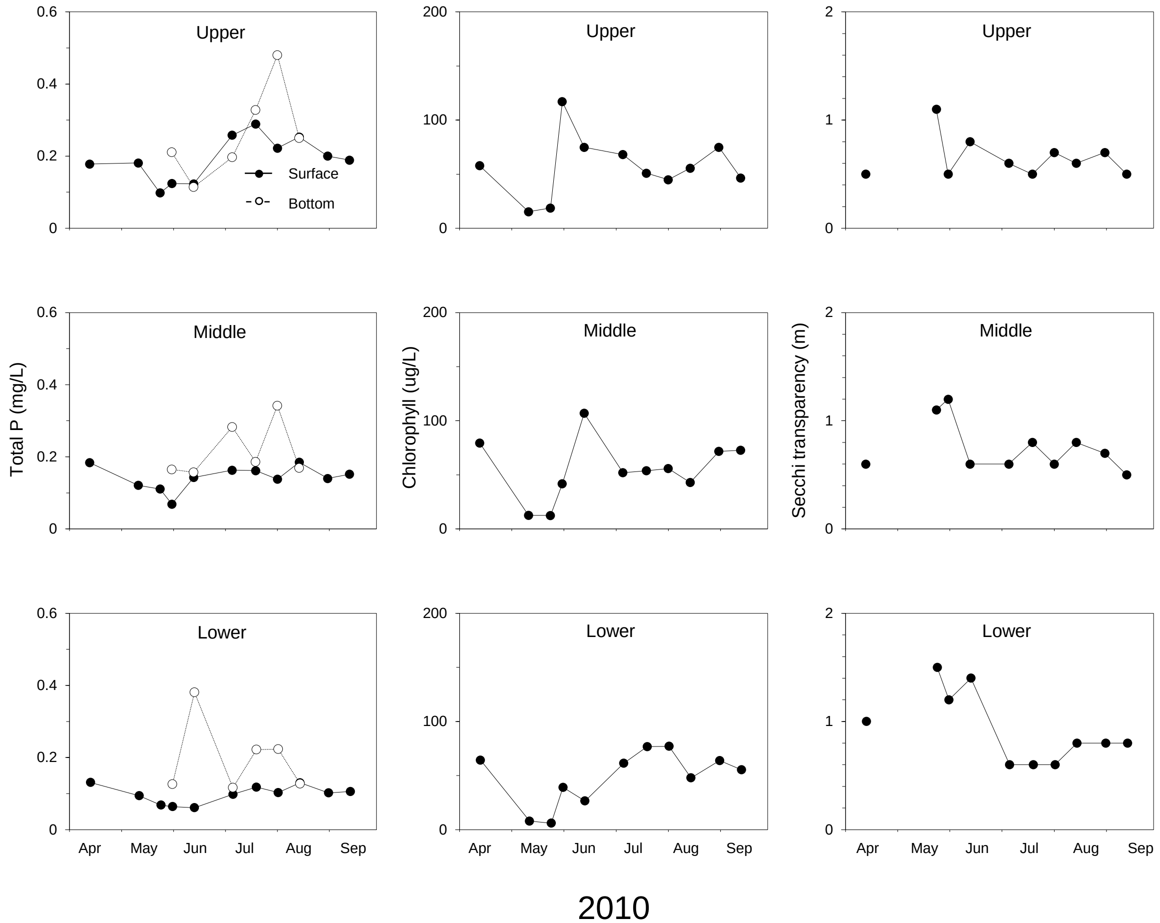


Figure 9. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, lower middle, and dam stations during 2010.

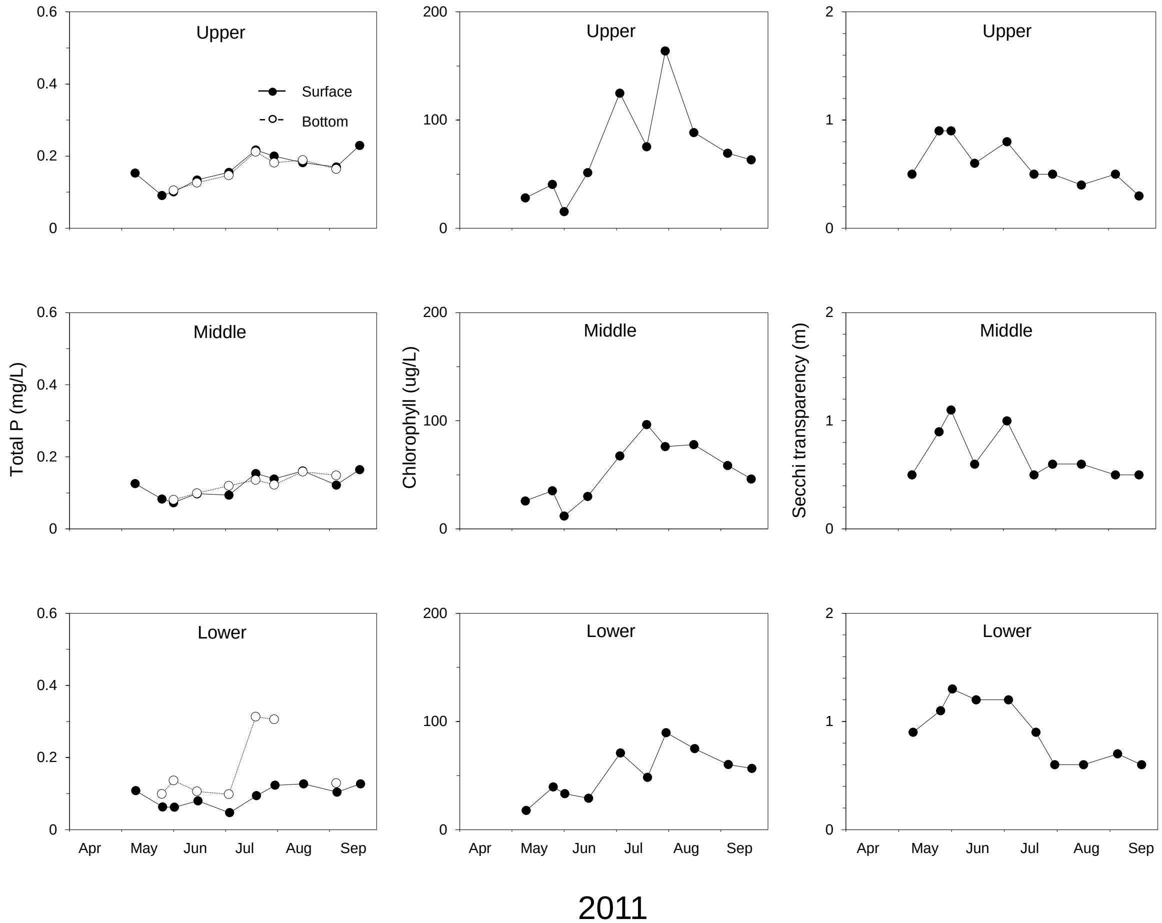


Figure 10. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, lower middle, and dam stations during 2011.

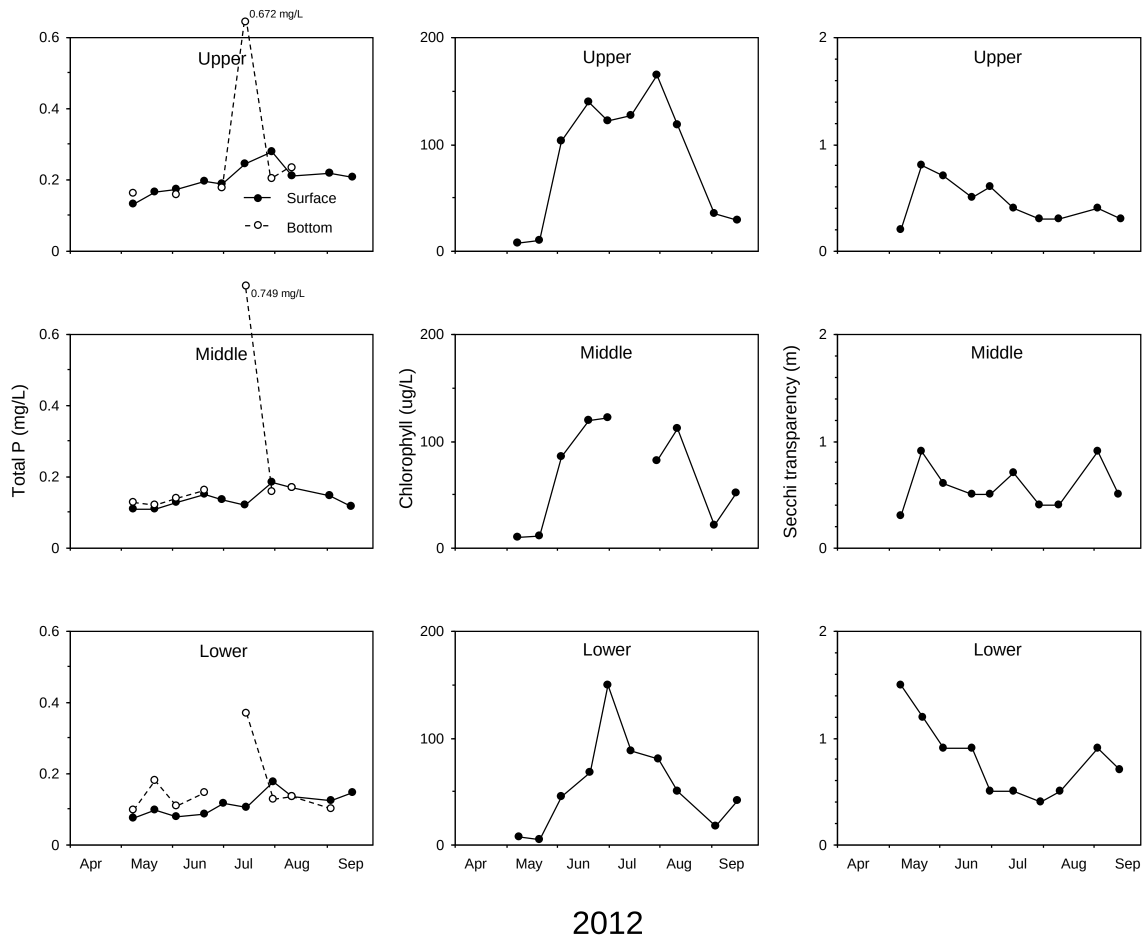


Figure 11. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2012.

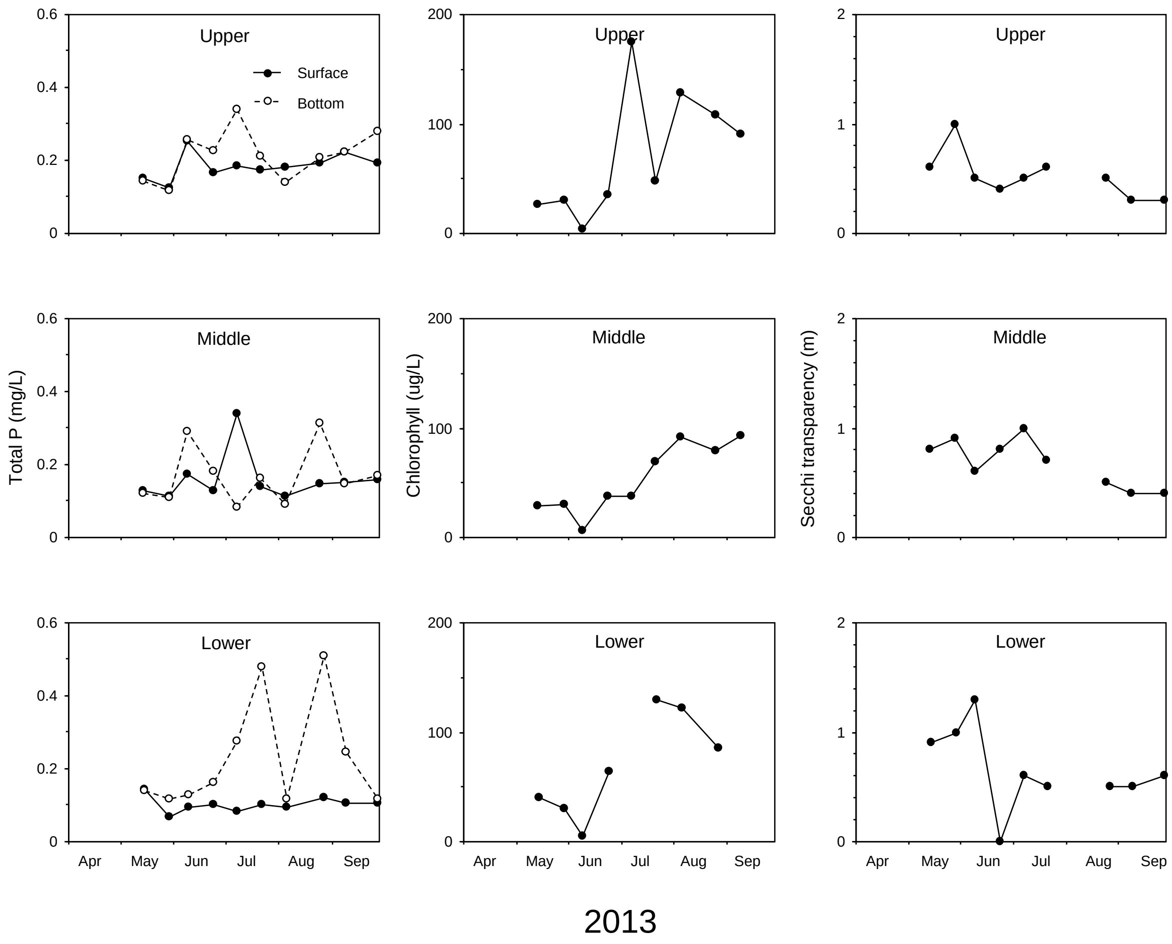


Figure 12. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2013.

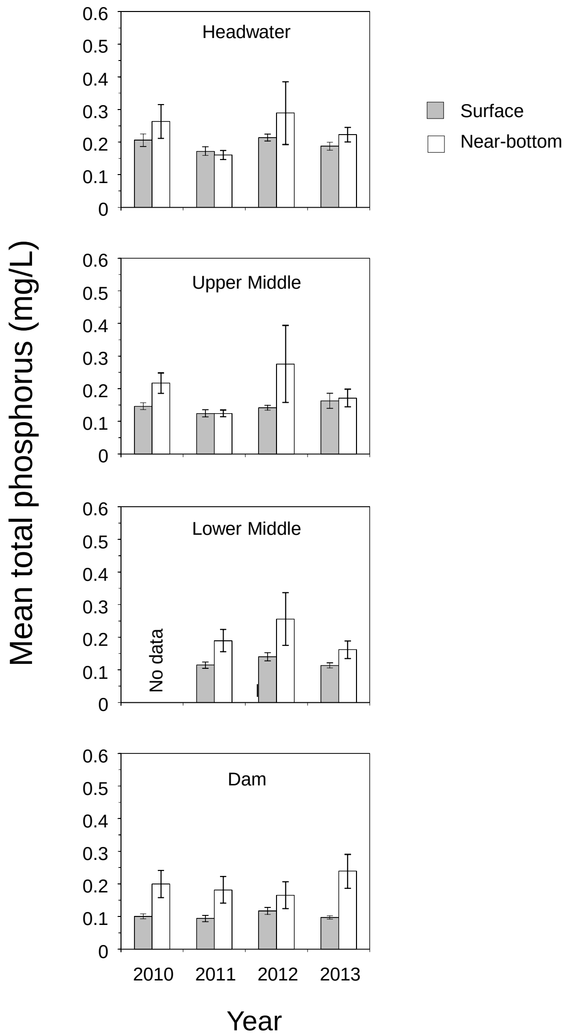


Figure 13. Variations in mean summer (June – September) surface and near -bottom total phosphorus concentrations at the headwater, upper middle, lower middle, and dam stations in Big Eau Pleine Reservoir. Vertical bars denote ± 1 standard error.

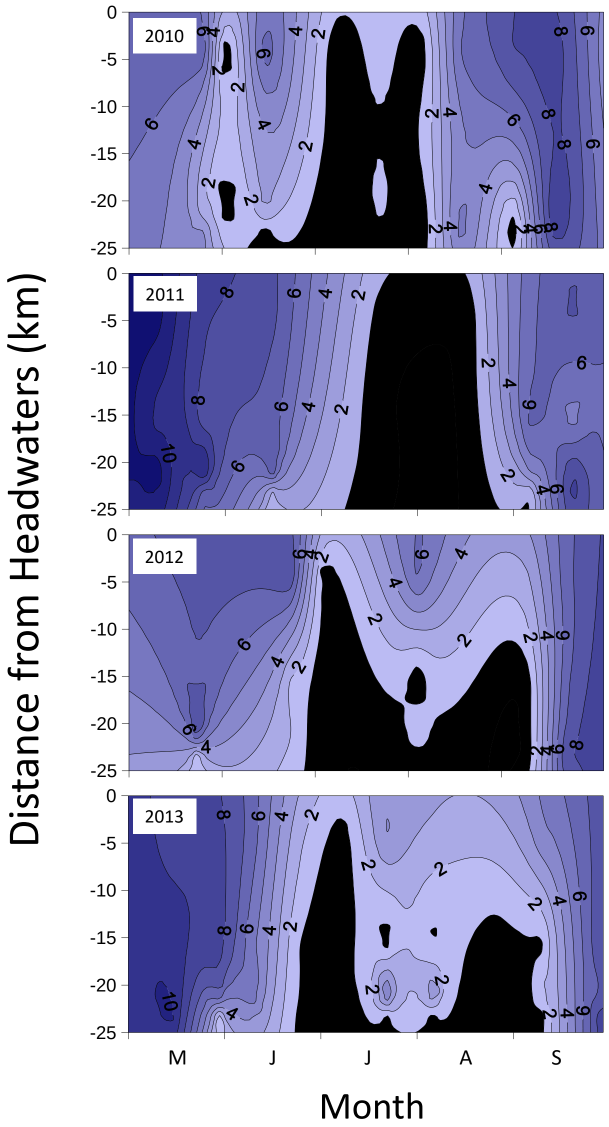


Figure 14. Seasonal and longitudinal variations in near-bottom concentrations of dissolved oxygen during 2010-2013. Black area indicate anoxic conditions (i.e., dissolved oxygen < 1 mg/L).

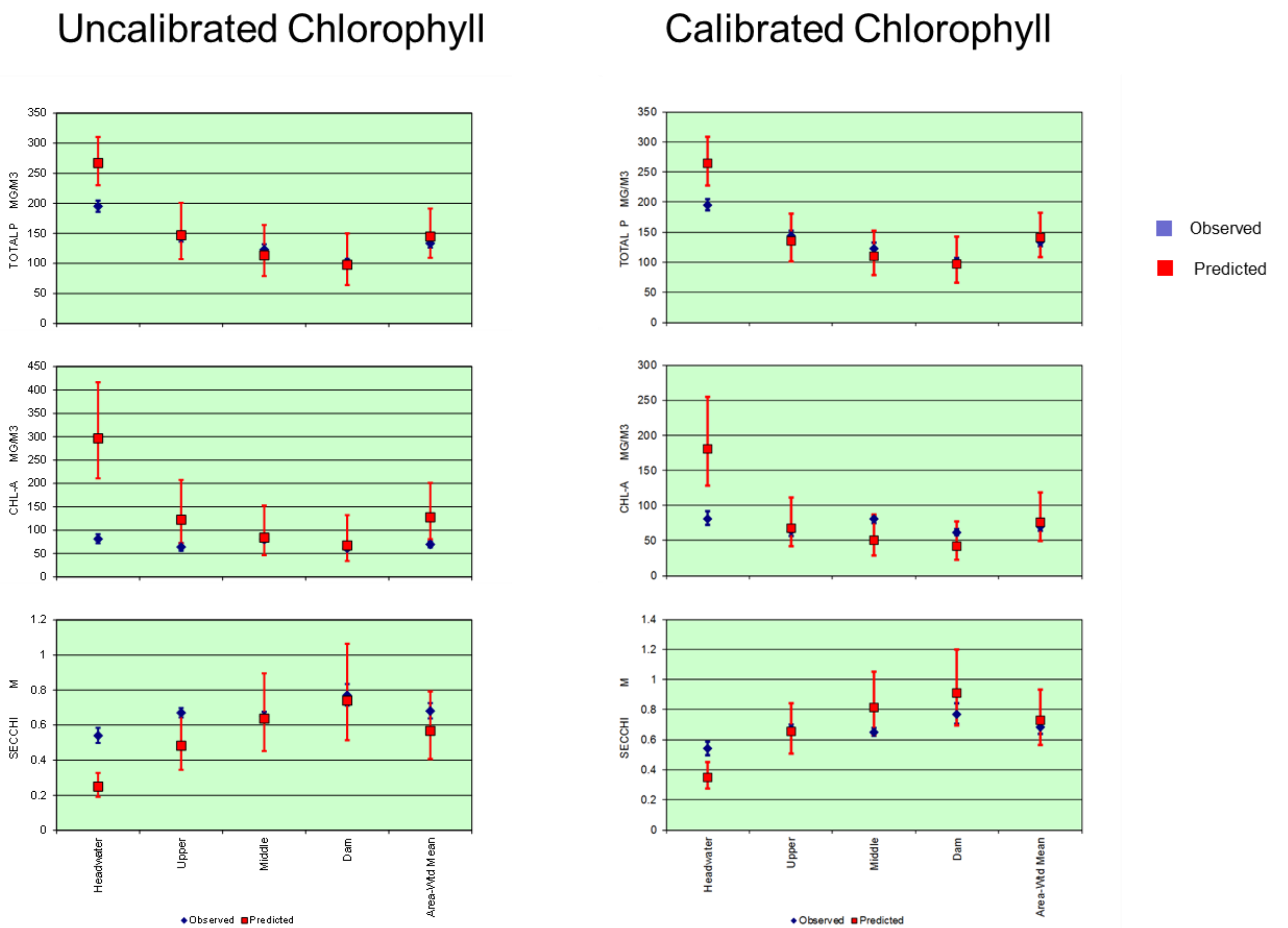


Figure 15. A comparison of mean (± 1 standard error) observed versus predicted area-weighted total phosphorus, chlorophyll, and Secchi transparency. Left panels show model output for the uncalibrated chlorophyll model while the right panels show the calibrated chlorophyll model output.

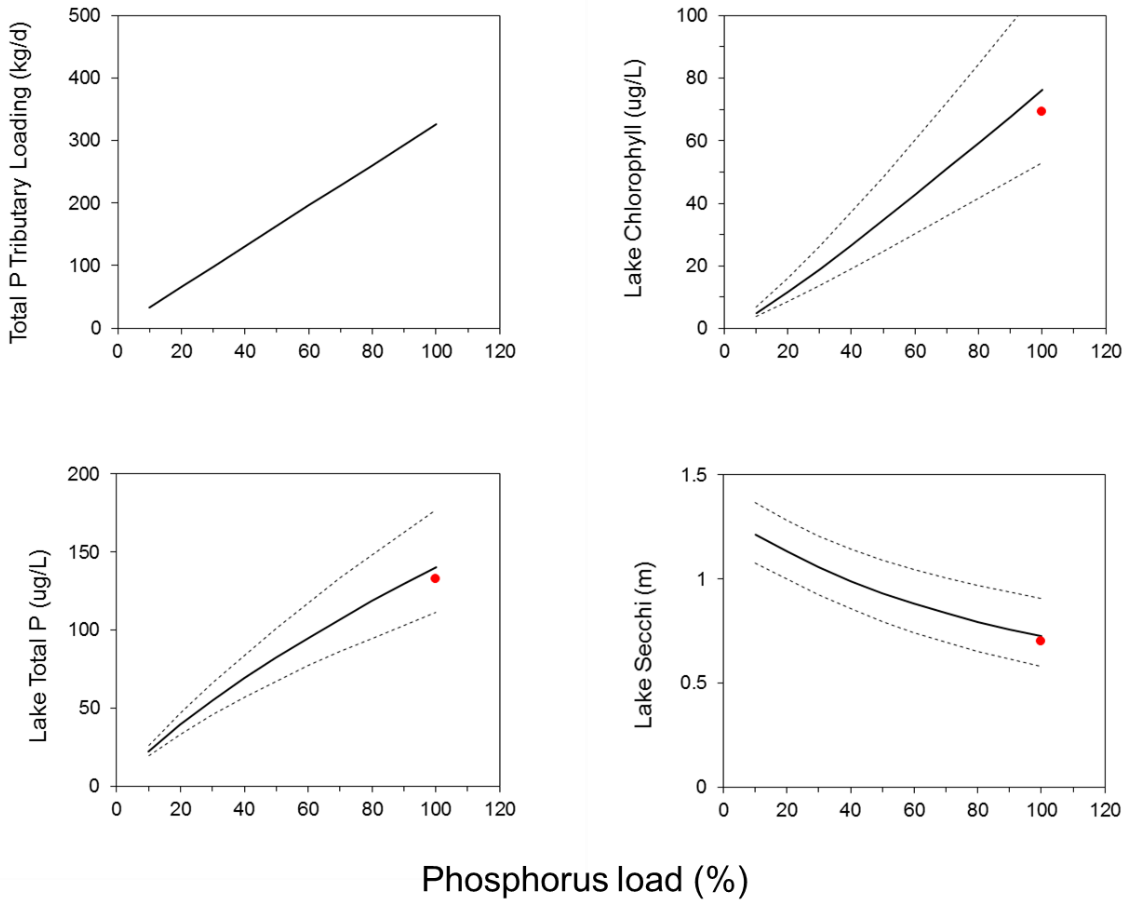


Figure 16. Bathtub (Walker 1996) model output of predicted changes in total phosphorus (P), chlorophyll, and Secchi transparency in Big Eau Pleine Reservoir as a function of reducing current mean 2010-13 mean summer P loading by 20% increments (black lines). Dotted lines denote 95% confidence intervals. Red circles represent current measured mean summer values. 100% P load represents current loading conditions.

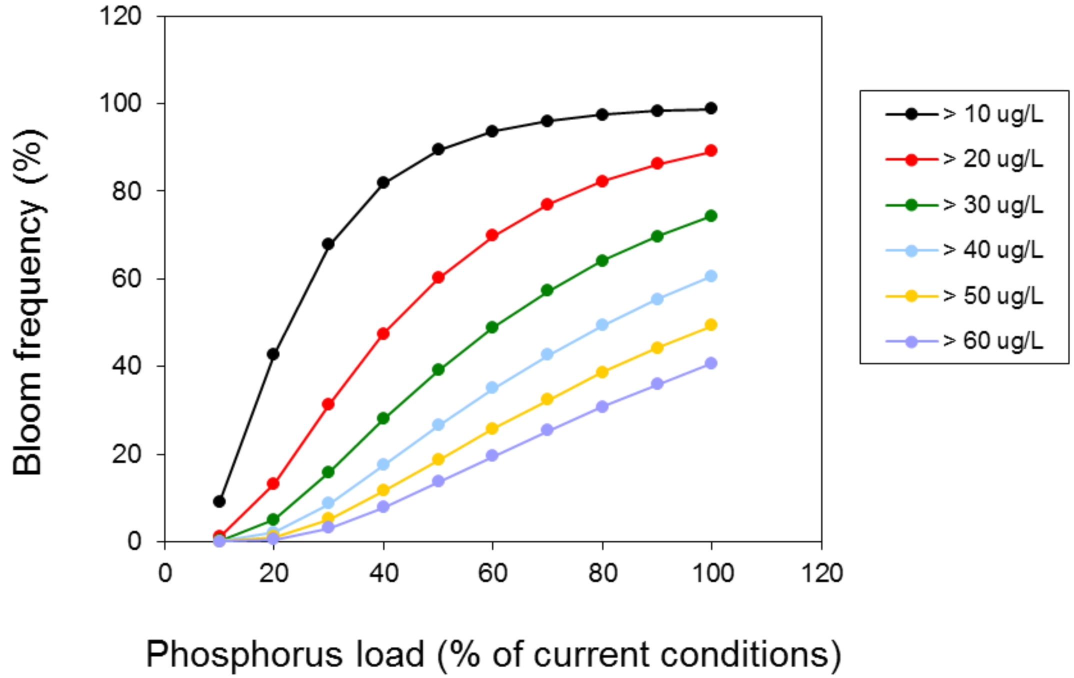


Figure 17. Bathtub (Walker 1996) model output of predicted changes in algal bloom frequency (as chlorophyll) as a function of reducing current mean 2010-13 mean summer P loading by 20% increments. 100% P load represents current loading conditions.

APPENDICES

Appendix 1a. Big Eau Pleine summer (June-September to early October) means and standard errors (SE) for the headwater station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)
2010-13					
Mean[1]	0.195	0.228	81.2	0.038	0.54
SE	0.007	0.023	7.8	0.006	0.03
2010					
Mean	0.206	0.263	60.6	0.072	0.63
SE	0.019	0.052	9.5	0.017	0.04
2011					
Mean	0.172	0.161	78.5	0.020	0.58
SE	0.014	0.014	14.5	0.004	0.06
2012					
Mean	0.213	0.289	108.3	0.027	0.44
SE	0.011	0.096	15.5	0.005	0.05
2013					
Mean	0.187	0.222	77.1	0.036	0.51
SE	0.012	0.023	20.5	0.014	0.08

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Appendix 1b. Big Eau Pleine summer (June-September to early October) means and standard errors (SE) for the upper middle station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)
2010-13					
Mean[1]	0.144	0.188	63.4	0.018	0.67
SE	0.007	0.025	5.5	0.004	0.04
2010					
Mean	0.146	0.217	56.1	0.032	0.73
SE	0.011	0.031	9.1	0.011	0.07
2011					
Mean	0.124	0.124	55.3	0.010	0.69
SE	0.011	0.010	9.1	0.002	0.08
2012					
Mean	0.142	0.276	88.2	0.013	0.60
SE	0.008	0.118	12.7	0.005	0.07
2013					
Mean	0.163	0.171	55.9	0.018	0.66
SE	0.023	0.027	11.3	0.009	0.08

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Appendix 1c. Big Eau Pleine summer (June-September to early October) means and standard errors (SE) for the lower middle station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)
2010-13					
Mean[1]	0.122	0.197	80.4	0.009	0.65
SE	0.006	0.027	9.6	0.003	0.04
2010					
Mean			No Data		
SE					
2011					
Mean	0.114	0.190	81.9	0.006	0.69
SE	0.010	0.034	20.2	0.002	0.07
2012					
Mean	0.140	0.256	89.3	0.013	0.60
SE	0.013	0.081	16.7	0.007	0.08
2013					
Mean	0.114	0.162	70.0	0.008	0.68
SE	0.008	0.027	14.0	0.004	0.07

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Appendix 1d. Big Eau Pleine summer (June-September to early October) means and standard errors (SE) for the dam station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)
2010-13					
Mean[1]	0.102	0.201	60.3	0.007	0.77
SE	0.004	0.023	5.5	0.002	0.05
2010					
Mean	0.100	0.199	53.3	0.008	0.87
SE	0.008	0.041	6.1	0.004	0.09
2011					
Mean	0.094	0.181	54.8	0.005	0.90
SE	0.010	0.041	7.2	0.001	0.10
2012					
Mean	0.117	0.165	64.6	0.008	0.69
SE	0.011	0.041	12.9	0.004	0.07
2013					
Mean	0.097	0.239	72.8	0.008	0.63
SE	0.005	0.052	20.2	0.004	0.14

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Steady-State Modeling Analysis of Lake Dubay, Wisconsin River System

21 November, 2016

William F. James
University of Wisconsin – Stout
Discovery Center - Sustainability Sciences Institute
Center for Limnological Research and Rehabilitation
Menomonie, WI 54751
715-338-4395
jamesw@uwstout.edu

EXECUTIVE SUMMARY

Lake Dubay is a run-of-the-river hydropower reservoir on the Wisconsin River near Mosinee, WI, that currently exhibits eutrophic to hypereutrophic conditions (Carlson TSI = 62 to 69). A monitoring program was conducted between 2010 and 2013 on the reservoir to examine seasonal total phosphorus (P), chlorophyll, and Secchi transparency dynamics in relation to tributary P loading for Total Maximum Daily Load (TMDL) development. Gauged tributary flow and P inputs included the Wisconsin River at Chuck's Landing, the Big Eau Pleine River below Big Eau Pleine Reservoir, and the Little Eau Pleine River near Rozellville. The gauged discharge was the Wisconsin River below Lake Dubay Dam. Three stations were established along the longitudinal axis of the reservoir for water sampling purposes. Surface samples were collected biweekly between April and October for total P and chlorophyll analysis. A near-bottom samples was also collected for total P analysis. Secchi transparency was determined biweekly using a 20-cm alternating black and white disk.

Mean daily summer measured inflow was moderate over the 2010-13 period at 126 m^3/s (± 25 standard error, SE), resulting in a low mean summer residence time of 6.6 d (±1.6 SE). Summer flow-weighted total P representing the gauged inflow and outflow was 0.107 mg/L and 0.108 mg/L, respectively, suggesting rapid flushing of P loads through the reservoir and advective dominance of total P concentrations in the reservoir. Longitudinal variation in summer mean total P concentration between the headwater and dam stations was minimal and the area-weighted grand mean (i.e., over 2010-13) total P was ~ 0.089 mg/L, similar to but slightly lower than inflow-outflow concentrations. The area-weighted grand mean chlorophyll concentration was moderate at ~ 25 µg/L and summer mean concentrations tended to increase from the headwater to the dam station. The area-weighted grand mean Secchi transparency was low at ~ 0.7 m. The Carlson trophic state index (TSI, Carlson 1977) for P (TSI-P) was high at 69 (indicative of hypereutrophic conditions). The TSI based on chlorophyll (TSI-CHLA) was slightly lower at 62 and TSI based on Secchi transparency (TSI-SD) was 66.

Budgetary analysis of summer flow and P loads indicated an approximate balance between inflow and outflow, suggesting minor P retention during the summer. Overall, the P empirical model (Vollenweider) closely predicted the observed area-weight mean summer total P concentration in Lake Dubay. Tributary P inputs entirely accounted for the summer total P budget, suggesting that internal P loading was negligible. The chlorophyll (chlorophyll:total P regression model for reservoirs; Walker 1996) and Secchi transparency (Based on chlorophyll and nonalgal turbidity) models also closely approximated observed summer grand means. Because Lake Dubay was dominated by advection, low residence time, and little apparent P retention (i.e., deposition), predicted summer total P concentration reductions coincided closely with tributary P load and concentration reductions. For instance, a 50% reduction in P loading coincided with a 50% decline in summer total P from ~0.089 mg/L to 0.046 mg/L. Under this same P loading reduction scenario, predicted summer chlorophyll concentrations declined by 50% from ~ 25 µg/L to ~13 µg/L. Predicted Secchi transparency increased by ~10% from 0.65 m to 0.7 m. Under current P loading conditions, chlorophyll blooms exceeding 20 µg/L and 60 µg/L occurred an estimated 53% and 5% of the time during the summer period, respectively. Using the same scenario, a 50% P loading reduction resulted in a predicted decline in the summer bloom frequency of chlorophyll exceeding 20 µg/L and 60 µg/L to 15% and <1% of the time during the summer period, respectively. Empirical steady-state models developed for Lake Dubay will be used in conjunction with other decision-support tools to develop a TMDL based on predicted reservoir water quality responses to P loading reduction.

OBJECTIVES

The objectives of this investigation were to examine summer limnological conditions in Lake Dubay between 2010 and 2013 and project future conditions under phosphorus loading reduction scenarios using a steady-state empirical modeling approach.

METHODS

Flow and total phosphorus (P) loadings from the Wisconsin, Big Eau Pleine, and Little Eau Pleine Rivers (Table 1) were combined with seasonal (April – September to early October) surface water chemistry information from three stations in Lake Dubay (Table 2, Fig. 1) to construct a steady-state empirical model (Bathtub Version 6.14; Walker 1996) to forecast the response of limnological variables (total P, chlorophyll, and Secchi transparency) to future P loading reduction. Since the annual theoretical water residence time was relatively low (range = 5.6 d to 10.8 d), a June through September (122 d) averaging period was used for steady-state empirical modeling analysis. Gauged hydraulic inputs included the Wisconsin River at Chuck's Landing (Station ID 10029678), The Big Eau Pleine River at Big Eau Pleine Dam (Station ID 10030620), and the Little Eau Pleine River near Rosellville (Station ID 10031106, Table 1). The gauged hydraulic discharge from Lake Dubay was the Wisconsin River at Lake Dubay Dam (Station ID 10014652, Table 1). Monthly hydraulic flow (m^3/s) and total P loadings (kg/month) determined by the US Geological Survey (Madison, WI) were converted to mean flow (expressed as hm^3/y) and total P concentration (expressed as µg/L) over the summer averaging period as input to the model. Additional hydrologic input to the model included ungauged local runoff to the reservoir from the surrounding subwatershed that was estimated using the Soil and Water Assessment Tool (SWAT) and daily precipitation records over the study period obtained from the Wisconsin State Climatology Office (Madison, WI). The coefficient of variation (CV-mean) was estimated from mean June through September flows and total P concentrations between the years 2002 and 2013 reported by the US Geological Survey. The CV-mean was calculated as the standard error of the grand mean (n = 12; i.e., JUN-SEP 2002 through 2013) divided by the grand mean of each constituent. This CV-mean was used for error analysis in Bathtub as recommended in Walker (1996). A 12-year average for flow, total P concentration, and total P loading between 2002 and 2013 was estimated from reports and data provided by the US Geological Survey (Dale M. Robertson, U.S. Geological Survey, Madison, WI, unpublished data).

Biweekly measurements of Secchi transparency and surface concentrations of chlorophyll and total P, collected in Lake Dubay during the summer periods of 2010 through 2013, were averaged to estimate a mean concentration for each station segment during each year. June through September was used as the averaging period. Chemical analyses of water samples were conducted by the Wisconsin State Laboratory of Hygiene and the University of Wisconsin – Stevens Water using standard methodological approaches. For in-lake morphometric inputs to the empirical model, the pool was divided into the 3 segments (i.e., headwater, middle, and dam segments) corresponding to the locations of sampling stations (Table 2).

The computer software program Bathtub was used to examine P loading reduction scenarios (Walker 1996). 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. Grand means for total P, chlorophyll, and Secchi transparency over the summer 2010-13 period were used as input into the model. The coefficient of variation for total P, chlorophyll, and Secchi transparency of the grand mean (CV-mean) was calculated as the standard error of the grand mean divided by the grand mean of each constituent. This CV-mean was used for error analysis in Bathtub as recommended in Walker (1996).

RESULTS AND DISCUSSION

Tributary Hydrology and Loading

Mean daily summer inflow was highest in 2010 at 185 m^3/s and lowest at 64 m^3/s in 2012 (Fig. 2). Mean daily summer flow during the summers of 2011 and 2013 were slightly above the 12-year summer average. The summer theoretical water residence time exhibited the opposite pattern. It was very low during the high flow summer of 2010 at less than 4 d and greater than 11 d during the low-flow summer of 2012. The grand mean residence time over the 4-year study period was slightly lower at ~ 6.6 d compared to the 12-y average summer theoretical residence time.

Summer total P of the gauged inflow to Lake Dubay, representing a flow-weighted concentration for the combined Wisconsin, Big Eau Pleine, Little Eau Pleine Rivers, and estimated local subwatershed runoff ranged between 0.100 mg/L in 2012 and 0.111 mg/L in 2010, following a trend similar to that of mean daily summer inflow (Fig. 2). In general, the summer total P concentration was above the 12-y average in 2010 and slightly below the 12-y average in 2012. Summer total P loading followed the same inter-annual trend. It was greatest in 2010 and 2 times higher than the 12-y average. In contrast, summer total P loading was lowest in 2012 and approximately half of the 12-y average. Summer total P loading during the summers of 2011 and 2013 were slightly above the 12-year average.

Reservoir Limnological Trends

Because summer theoretical water residence time was relatively low, even during the lower inflow period of 2012, Lake Dubay mean summer total P concentrations were only slightly lower than the measured inflow total P (Fig. 3). In addition, mean summer total P concentrations exhibited minor variation as a function of in-lake station or distance from the dam (Fig. 4). This pattern suggested that limnological patterns in the lake were largely dominated by riverine influences along its longitudinal axis. By contrast, longitudinal concentration gradients from headwaters to the dam can typically develop in larger reservoirs as a function of widening morphometry, decreasing flow velocity, and deposition of loads (Thornton et al. 1990). Mean summer concentrations sometimes increased very slightly from headwaters to the dam, as in 2010 (i.e., 0.095 mg/L at the headwater stations and 0.100 mg/L at the dam station) and 2011 (i.e., 0.078 mg/L at the headwater stations and 0.096 mg/L at the dam station, Fig. 3). In all cases, however, summer total P concentration differences were minimal between stations as indicated by grand mean trends over the study period (Fig. 4).

Variations between surface and near-bottom concentrations of total P were small throughout the study period, suggesting that internal P loading from bottom sediments likely played a negligible role in P dynamics in Lake Dubay (Fig. 5-8). There were some periods of elevated near bottom total P concentration with respect to the surface at all stations; but these concentration differences were minor and could be attributable to other mechanisms such as resuspension caused by river current shear stress or river density underflows. For instance, total P concentrations were slightly higher near bottom compared to the surface in June and July of 2010, particularly at the dam station (Fig. 5). Similar vertical differences occurred at all stations during other summers (Fig. 6-8). Overall, differences in mean summer surface versus near-bottom total P concentrations were very minor over the study period (Fig. 9).

Dissolved oxygen concentrations near the sediment-water interface generally exceeded 2 mg/L throughout the summer months at all stations (Fig. 10), indicating oxidized and aerobic conditions near the sediment-water interface that potentially suppressed diffusive P flux from sediment (i.e., internal P loading). However, there were instances of near-bottom anoxia (i.e., DO < 1.0 mg/L) throughout the study period that may have driven some anaerobic P release from sediment. While potential anaerobic diffusive P flux could have occurred from sediment during these periods, its impact on the lake P budget appeared to be negligible compared to watershed P loading (see below).

Mean summer chlorophyll concentrations ranged between 16 µg/L and 35 µg/L and tended to increase slightly from the headwater to the dam station (Fig. 3 and 4). Interestingly, means were lowest during the lower flow summer of 2012 compared to other summers. Although there were seasonal periods when Secchi transparency slightly exceeded 1.0 m (Fig. 5-8), summer means were generally lower throughout the study period (Fig. 3 and 4), ranging between 0.5 and 0.9 m. Longitudinal variations in grand mean Secchi transparencies were also minor (headwater station = 0.6 m ± 0.03 SE; middle station = 0.7 m ± 0.04 SE; dam station = 0.7 m ± 0.04 SE; Fig. 4).

Grand mean summer Carlson Tropic State Index (TSI) values were greatest for total P at ~ 69 (Fig. 4), indicative of hypereutrophic conditions. Grand mean TSI was slightly lower for chlorophyll (~ 62) and Secchi transparency (~66) compared to total P (Fig. 4). This pattern may have been related to relatively low residence time which could promote some algal biomass export if cellular doubling times are greater than residence time in the lake.

Other variables of interest are shown in Appendix 1. The grand mean total P composition was dominated by particulate P, most likely incorporated into algal biomass. Soluble reactive P was generally low and ranged from not detectable to 0.028 µg/L. The grand mean soluble reactive P concentration ranged between 0.016 mg/L (middle station) to 0.019 mg/L (dam station), accounting for~ 20% of the total P composition. Particulate N accounted for ~82% of the total N composition. Dissolved inorganic N was dominated by NO_x at a grand mean of 0.185 mg/L. The grand mean NH_x concentration was low at 0.045 mg/L and represented only 5% of the total N composition. The grand mean molar particulate N:P ratio was ~ 34:1, suggesting that algal growth was P-limited. Hillebrand et al. (2013) suggested that optimal N:P molar ratios are higher for cyanobacteria with a mean from literature values of ~26:1.

Steady-State Empirical Modelling

The mean (2010-13) summer hydraulic and total P balance for measured inputs and outputs to Lake Dubay are shown in Table 3. The measured mean summer outflow at Lake Dubay Dam accounted for 87% mean measured inflow, suggesting ungauged sources (i.e., groundwater and local surface-subsurface watershed inputs) were probably minor. Similarly, measured mean summer P loading to Lake Dubay was only slightly greater than mean summer P discharge (Table 3), suggesting minimal P retention (Table 3).

The Wisconsin River at Chuck's Landing overwhelmingly dominated mean summer gauged P inputs to Lake Dubay (Table 3). Mean summer flow and P loading represented 78% and 65% of the gauged mean summer inputs, respectively. The mean summer flow-weighted total P concentration was 0.107 mg/L. Although the Big and Little Eau Pleine Rivers represented only 12% of the gauged mean summer inflow, the mean summer flow-weighted total P concentrations were higher at 0.135 and 0.324 mg/L, respectively. Mean summer total P loading from these inputs represented 22% of the measured summer total P load to the system. Although minor but apparent P retention of inflow P loads occurred, the weighted inflow and outflow total P concentrations were nearly identical, suggesting that advective flow-through and discharge, versus deposition of total P loads, largely regulated P concentrations in Lake Dubay. Instead, differences in inflow-outflow P loads appeared to be attributed to minor differences in flow (i.e., composited inflow was slightly greater than the outflow).

Because low summer theoretical water residence time and advection dominated the P budget, a first-order P sedimentation model (σ) was chosen to predict summer mean lake total P according to the equation,

$$P_{lake} = \frac{P_{inflow}}{(1 + \sigma\tau_{\omega})}$$

Where, P_{lake} = area-weighted mean summer total P concentration (mg/m^3), P_{inflow} = flow-weighted gauged inflow total P (mg/m^3), σ = first-order sedimentation coefficient, and τ_ω = summer theoretical water residence time (y). Of the first-order P sedimentation models, Vollenweider (1976) was chosen as the P sedimentation model (Table 4). Because the Walker (1996) chlorophyll-total P regression relationship was developed from an extensive northern lake data set, it was chosen for mean summer chlorophyll prediction. Finally, the default Secchi transparency model developed from relationships between chlorophyll and turbidity in reservoirs was chosen to estimate mean summer Secchi depth.

Observed versus predicted summer means of total P, chlorophyll, and Secchi transparency over the 2010-13 period are shown in Figure 11. Overall, empirically-predicted mean summer total P, chlorophyll, and Secchi transparency were nearly identical to the observed area-weighted means for Lake Dubay.

Phosphorus Loading Reduction

Current summer P loading to Lake Dubay was reduced by 20% increments in Bathtub to examine predicted water quality responses to simulated future P loading reduction as a result of best management practices (BMP) implementation for TMDL development and goal-setting (Fig. 12). Because Lake Dubay is a run-of-the-river reservoir with low residence time and little apparent P retention (i.e., deposition), predicted summer total P concentration reductions coincided closely with tributary P load and concentration reductions (Fig. 12). For instance, a 50% reduction in P loading coincided with a 50% decline in summer total P from ~0.089 mg/L to 0.046 mg/L. Under this same P loading reduction scenario, predicted summer chlorophyll concentrations declined by 50% from ~ 25 µg/L to ~13 µg/L. Predicted Secchi transparency increased by 10% from 0.6 m to 0.7 m.

Predicted bloom frequency (i.e., percentage of the summer that chlorophyll exceeds a certain concentration) response to P loading reduction is shown in Figure 13 for various summer mean chlorophyll concentrations. Under current P loading conditions, chlorophyll blooms exceeding 20 µg/L and 60 µg/L occurred an estimated 53% and 5% of the time during the summer period, respectively. A 50% P loading reduction would result in a predicted decline in the summer bloom frequency of chlorophyll exceeding 20 µg/L and 60 µg/L to 15% and <1% of the time during the summer period, respectively. Thus, empirical models suggested that predicted reservoir trophic state indicator variables (total P, chlorophyll, and chlorophyll concentration bloom frequency) were responsive to P loading reduction.

REFERENCES

Carlson RE. 1977. A trophic state index for Lakes. Limnol Oceanogr 22:361-369.

Hillebrand H, Steinert G, Boersma M, Malzahn A, Léo Meunier C, Plum Cm Ptacnik R. 2013. Goldman revisited: Faster-growing phytoplankton has lower N:P and lower stoichiometric flexibility. Limnol Oceanogr 58:2076-2088.

Thornton KW, Kimmel BL, Payne FE. 1990. Reservoir Limnology: Ecological perspectives. John Wiley and Sons, New York.

Vollenweider RA. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem Ist Ital Idrobiol 33:53-83.

Walker WW. 1996. Simplified procedures for eutrophication assessment and prediction: User manual. Instruction Report W-96-2, September, 1996, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, USA.

WisCALM. 2014. Wisconsin 2014 consolidated assessment and listing methodology (WiscCALM) for Clean Water Act Section 305(b), 314, and 303(d) integrated reporting. EGAD#3200-2013-01, September, 2013. Wisconsin Department of Natural Resources, Bureau of Water Quality Program Guidance.

Table 1. Gauged inflow-outflow stations used in the Lake Dubay empirical steady-state model.

Station ID	Gauged Inflow	Latitude	Longitude
10029678	Wisconsin River at Chucks Landing	44.787080	89.704960
10030620	Big Eau Pleine River at Big Eau Pleine Dam	44.730816	89.759300
10031106	Little Eau Pleine River near Rozellville	44.713066	89.926285
	Gauged outflow	**Latitude**	**Longitude**
10014652	Wisconsin River below Lake Dubay Dam	44.665030	89.649981

Table 2. Water quality sampling station locations in Lake Dubay.

Station ID	**Name**	**Surface area** (km^2)	**Mean depth** (m)	**Segment length** (km)
373445	Headwaters	9.6	1.68	14.1
1003116	Middle	7.87	2.76	5.3
503163	Dam	5.79	4.02	2.5

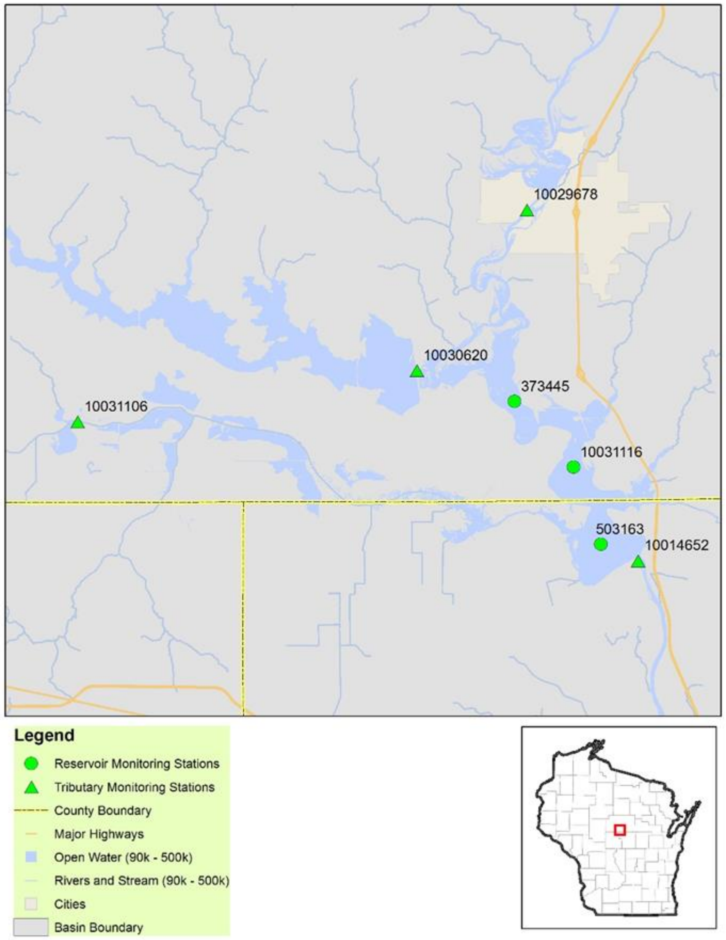
Table 3. A comparison of mean (2010-13) summer (June - September) flow and total phosphorus (P) inputs to and discharge from Lake Dubay.

Component	Flow		Total P		
	(m^3/s)	(% contribution)	(mg/L)	(kg/d)	(% contribution)
Inputs					
Wisconsin River	98.2	78	0.090	764	65
Big Eau Pleine River	11.9	9	0.135	138	12
Little Eau Pleine River	4.2	3	0.324	117	10
Ungauged inputs[1]	11.3	9	0.156	152	13
Precipitation	1.0	1	0.022	2	0
Total	126.5	100	0.107	1173	100
Outputs					
Wisconsin River at Lake Dubay Dam	109.6		0.108	1023	
Evaporation	1.0				
Total	110.6		0.108	1023	
Balance	15.9 (87%)			149.9 (87%)	

[1]Representing local subwatershed inputs estimated from the Soil and Water Assessment Tool (SWAT)

Table 4. Algorithms used for Bathtub (Walker 1996) phosphorus loading reduction modeling of Lake Dubay.

Variable	Model
Phosphorus	Vollenweider
Chlorophyll	Chla:Total P linear regression
Secchi Transparency	versus Chlorophyll & Turbidity



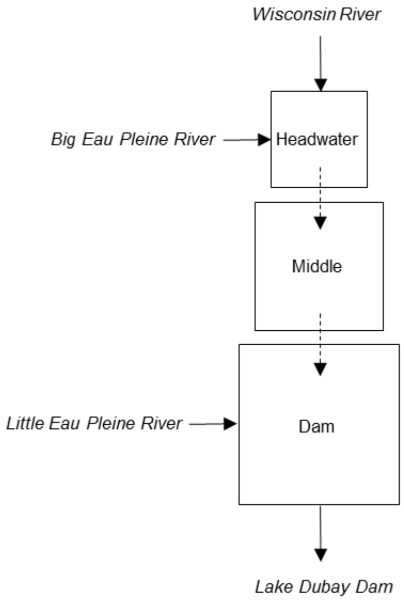


Figure 1. Water sampling station locations (left) and Bathtub conceptualization.

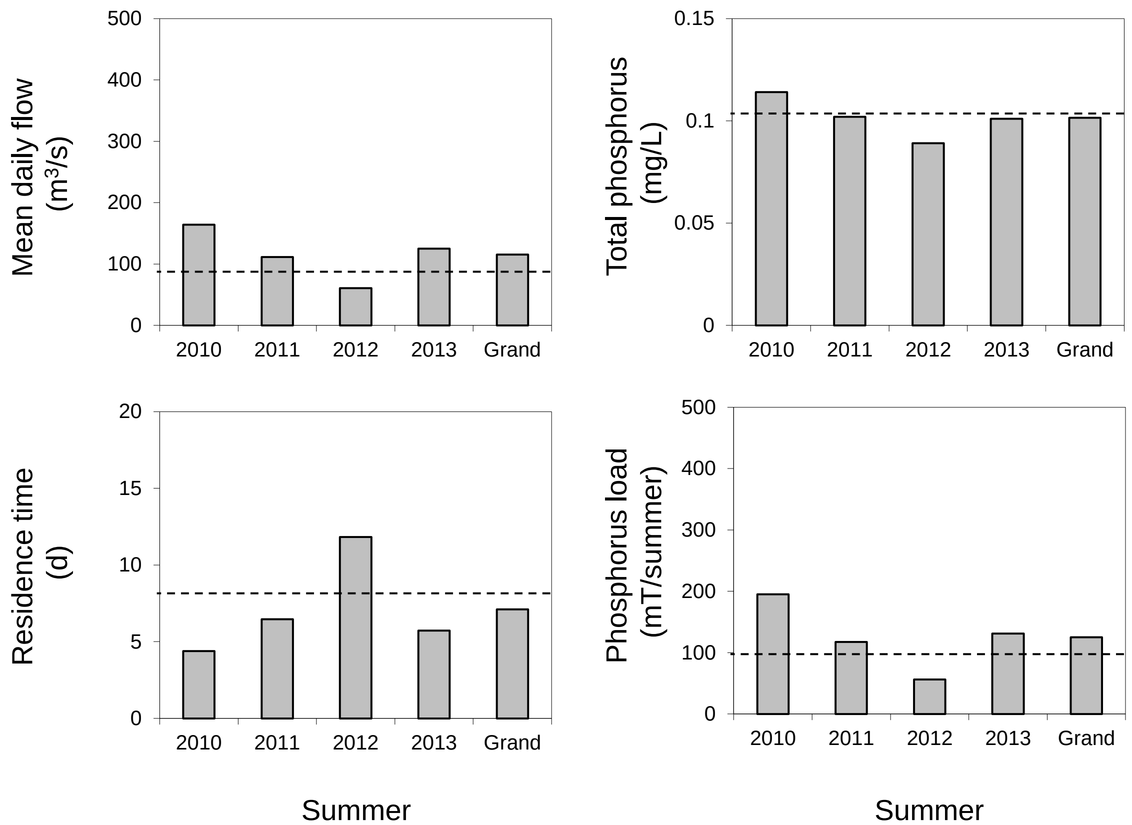


Figure 2. Summer (June – September) mean daily flow into Lake Dubay (upper left panel), theoretical water residence time (lower left panel), flow-weighted total phosphorus concentration of the inflow (upper right panel), and total phosphorus load (lower right panel) during 2010 - 2013. The horizontal dashed line denotes the 12-year average. The grand mean for each variable was estimated as the mean of the individual summer means.

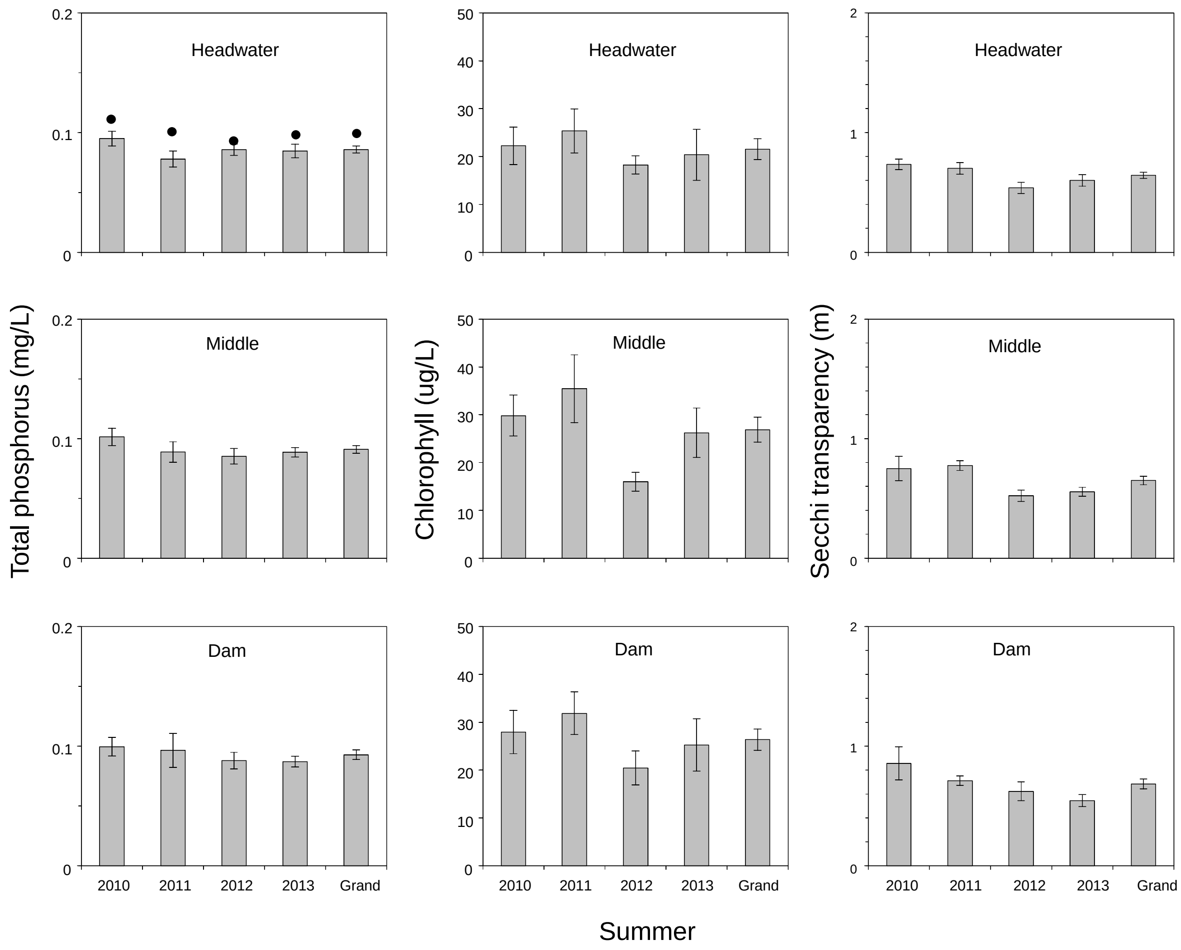


Figure 3. Summer (June – September) mean concentrations of total phosphorus (left panels), chlorophyll (middle panels), and Secchi transparency (right panels) during 2010 - 2013. The black circles denote the gauged inflow total phosphorus concentration. The grand mean for each variable was estimated as the mean of the individual summer means. Vertical lines represent ± 1 standard error.

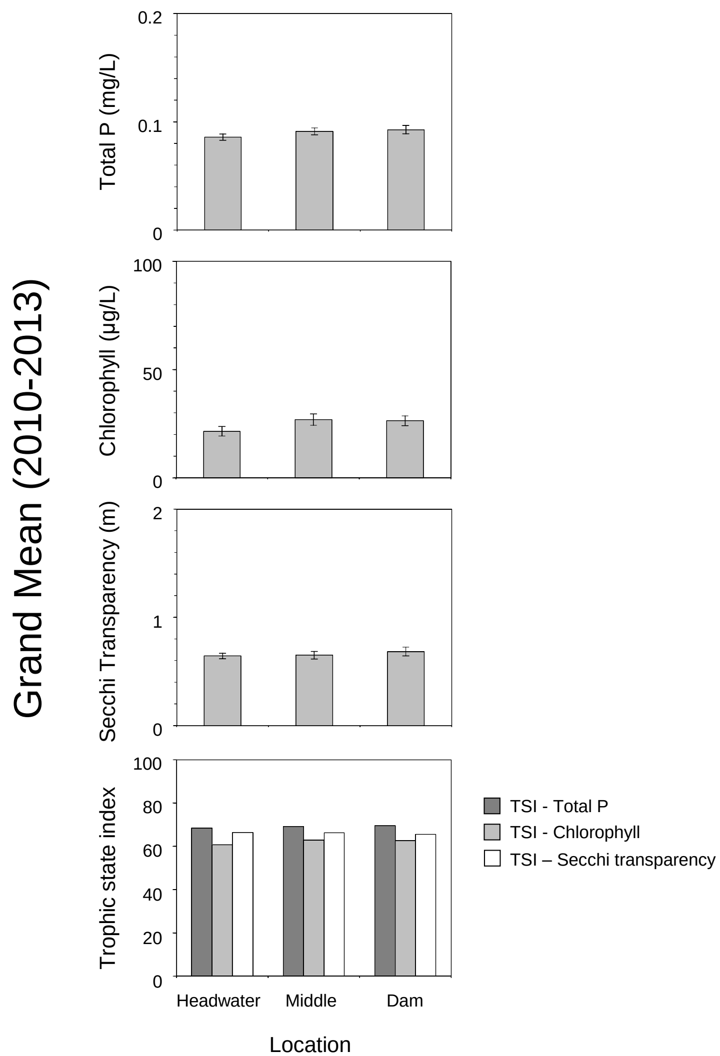


Figure 4. Variations in grand mean summer (June – September) total phosphorus (P, upper panel), chlorophyll (upper middle panel), Secchi transparency (lower middle panel), and Carlson trophic state indices (TSI) for the headwater, middle, and dam stations in Lake Dubay. Vertical lines represent ± 1 standard error of the grand mean.

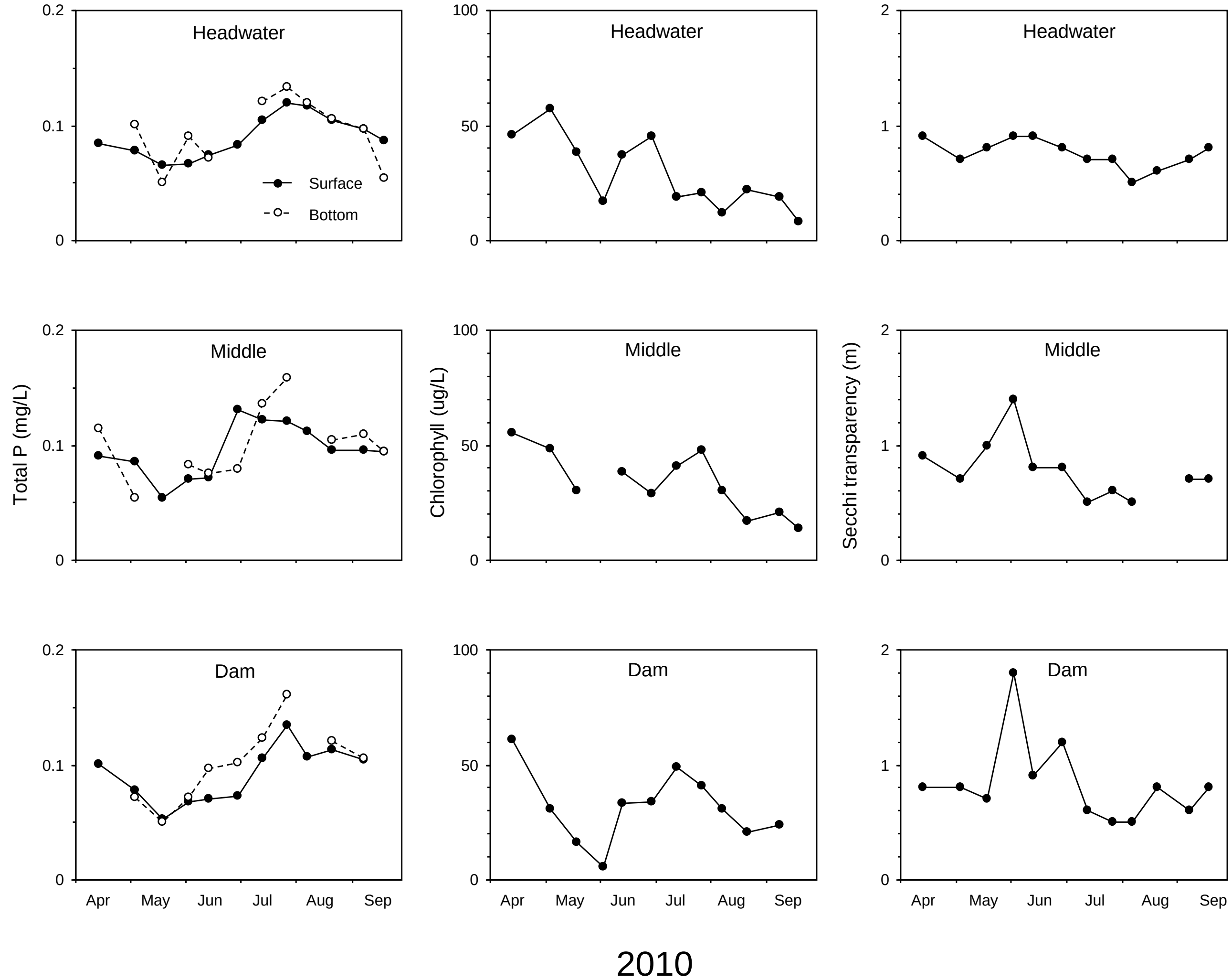


Figure 5. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2010.

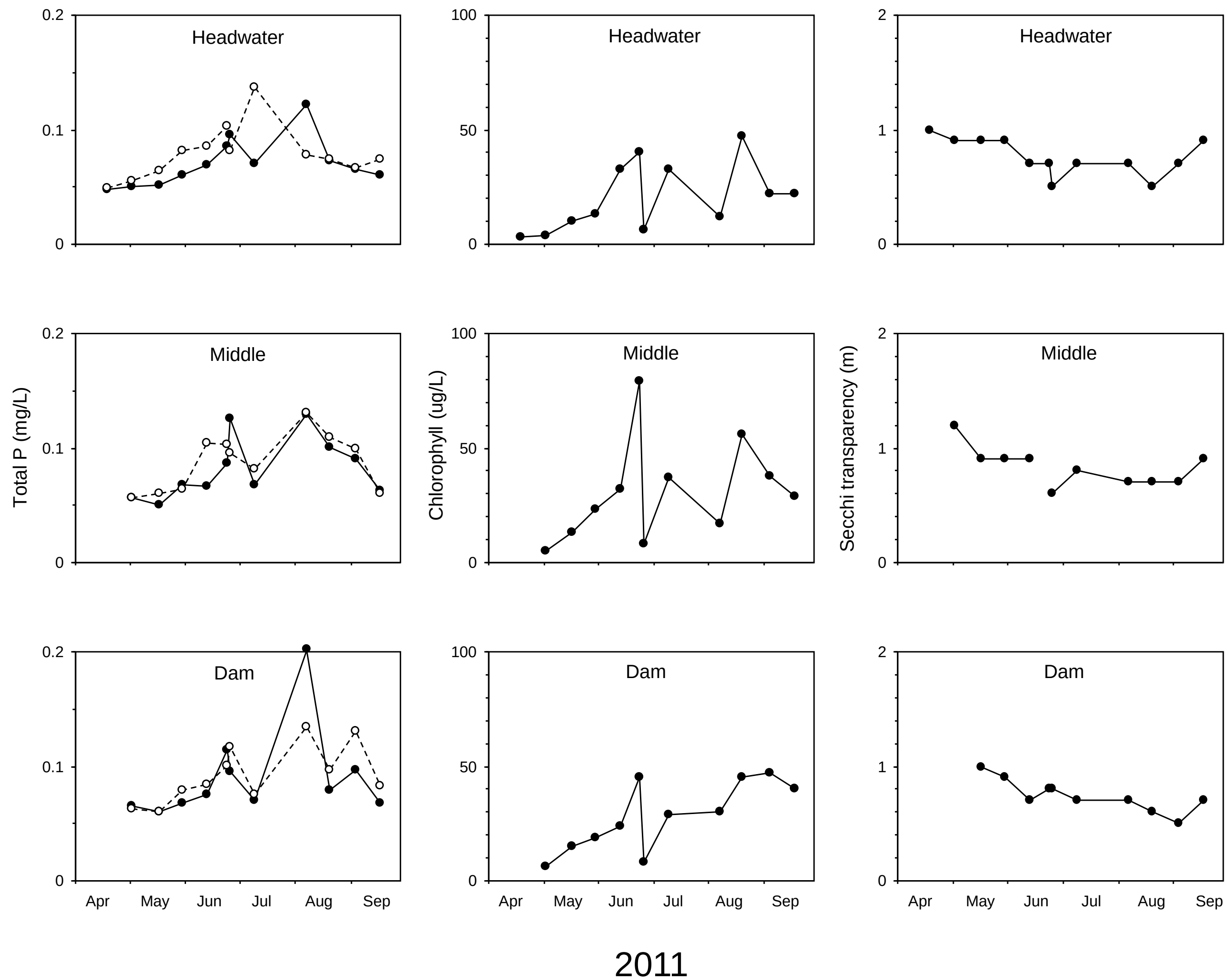


Figure 6. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2011.

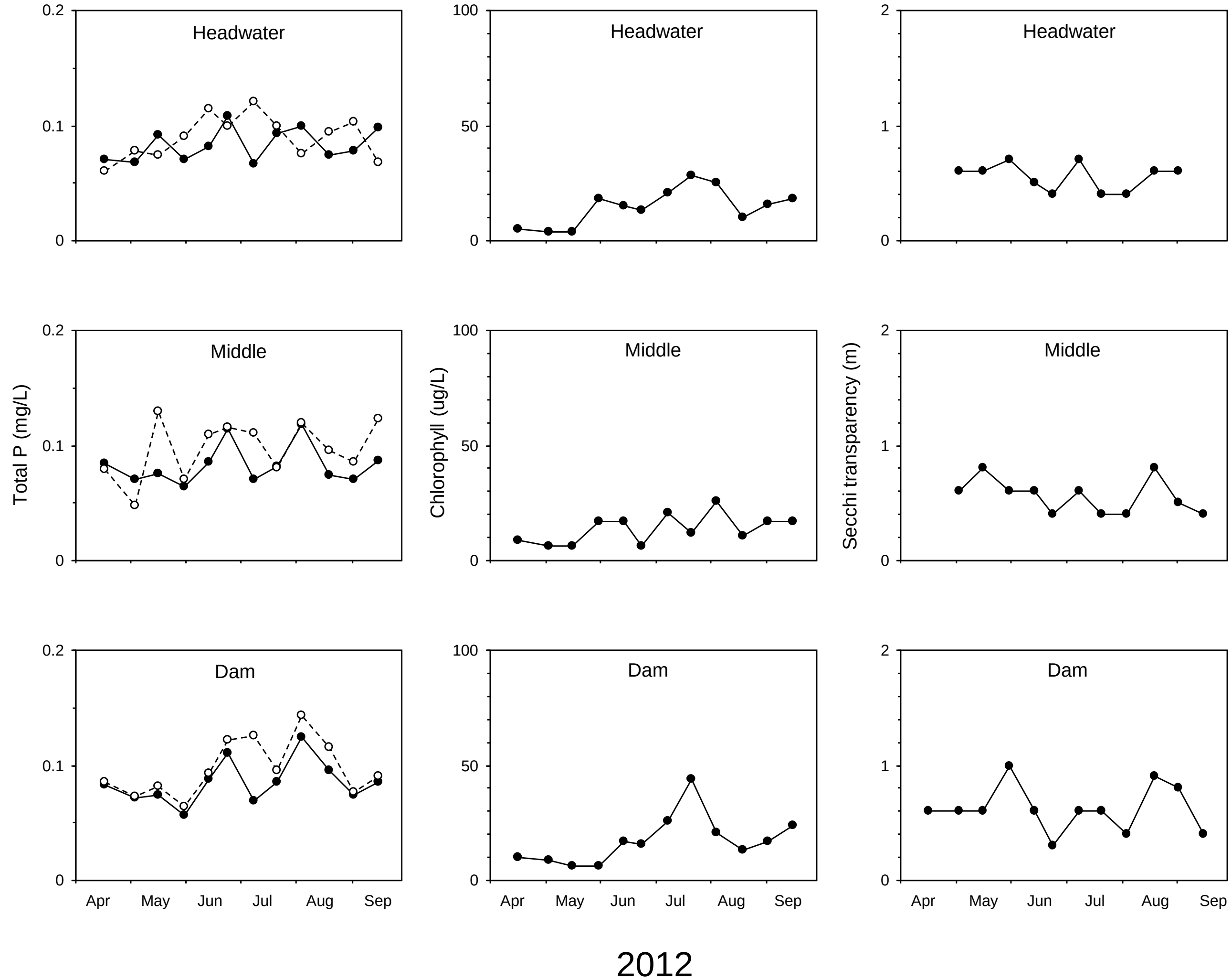


Figure 7. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2012.

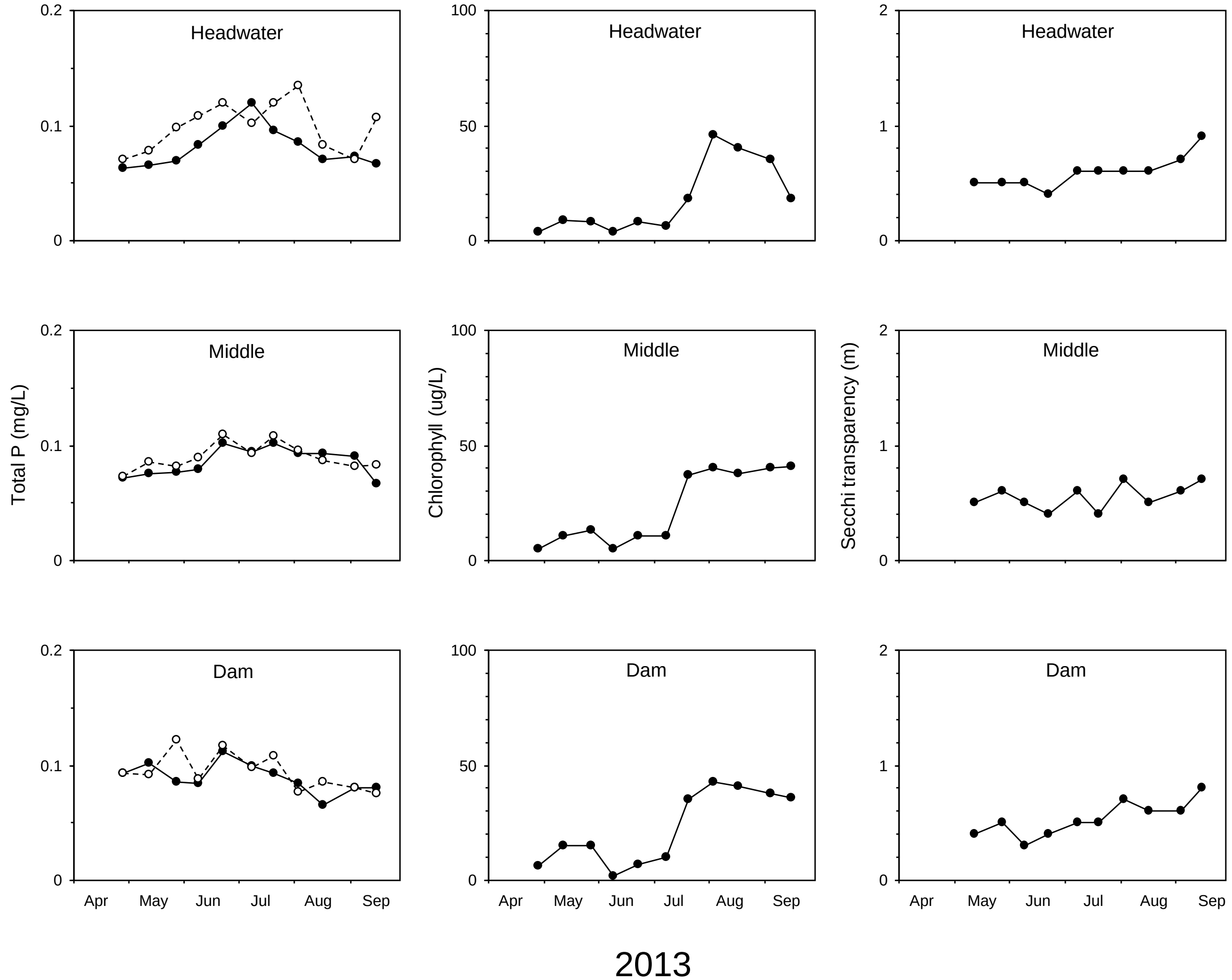


Figure 8. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2013.

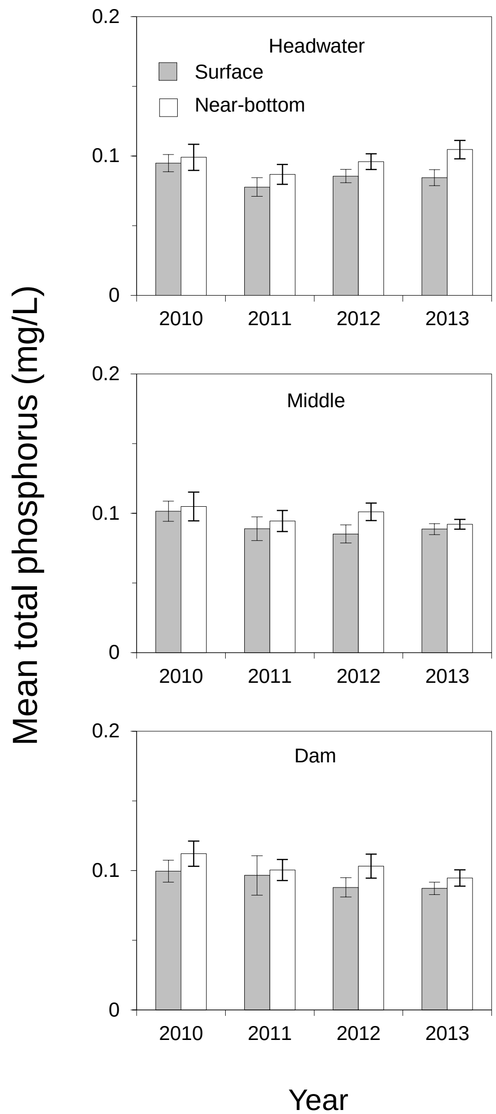


Figure 9. Variations in mean summer (June – September) surface and near -bottom total phosphorus concentrations at the headwater, middle, and dam stations in Lake Dubay. Vertical bars denote ± 1 standard error.

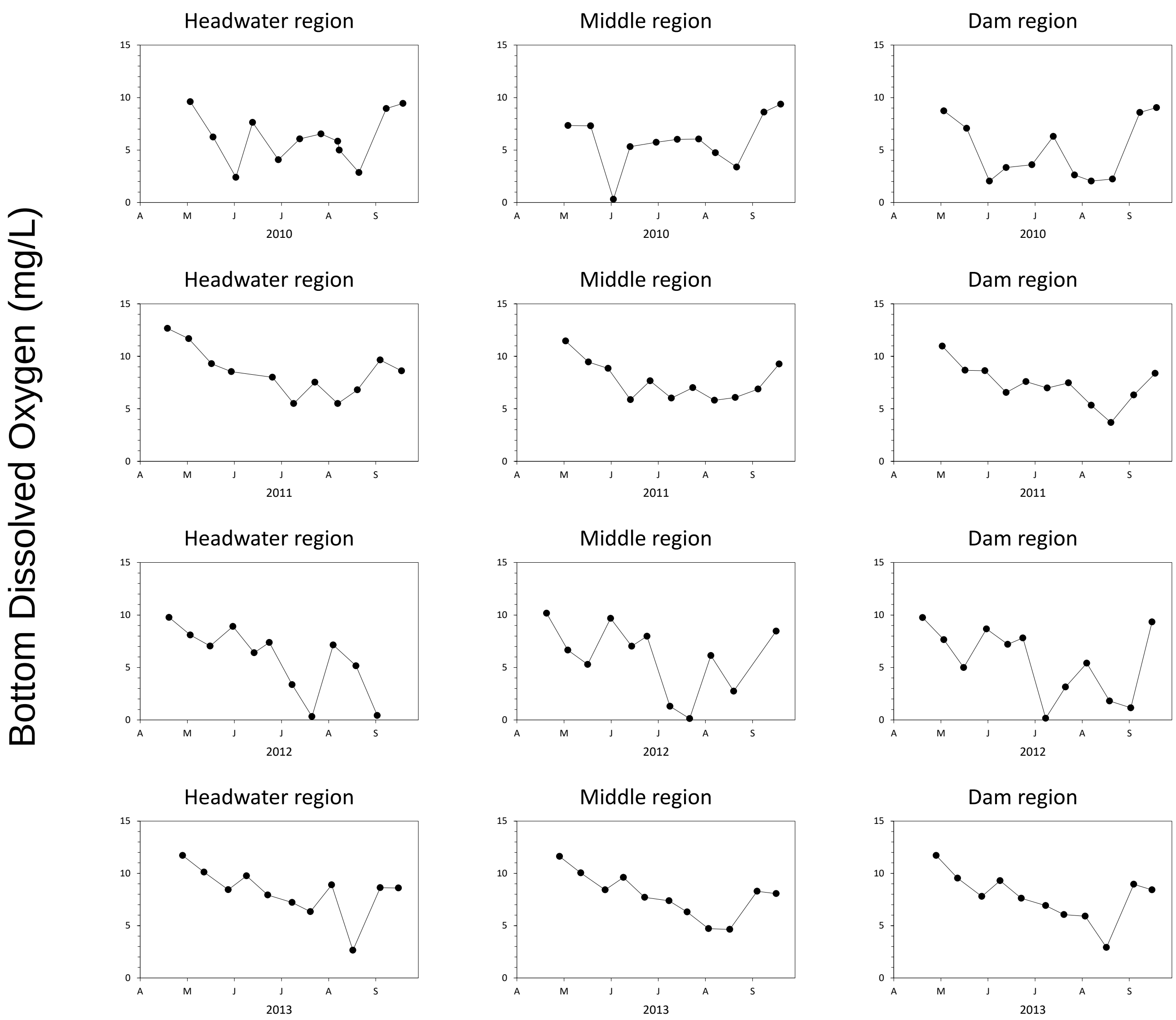


Figure 10. Seasonal variations in near-bottom concentrations of dissolved oxygen for the headwater, middle, and dam stations during 2010-2013.

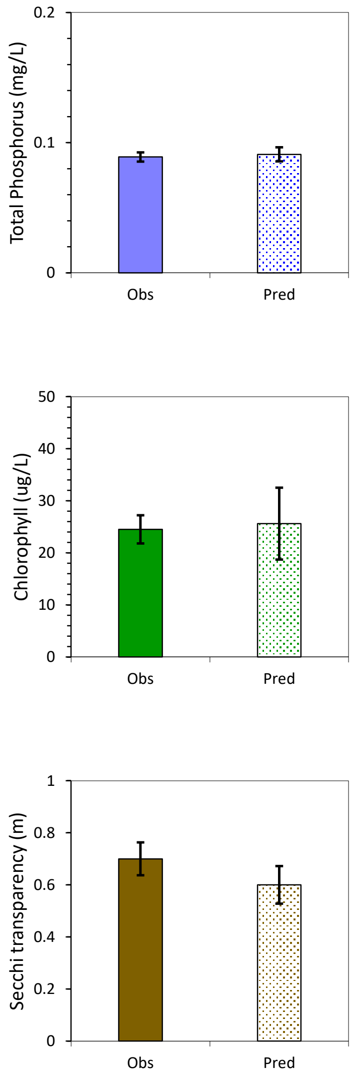


Figure 11. A comparison of mean (± 1 standard error) observed versus predicted area-weighted total phosphorus, chlorophyll, and Secchi transparency.

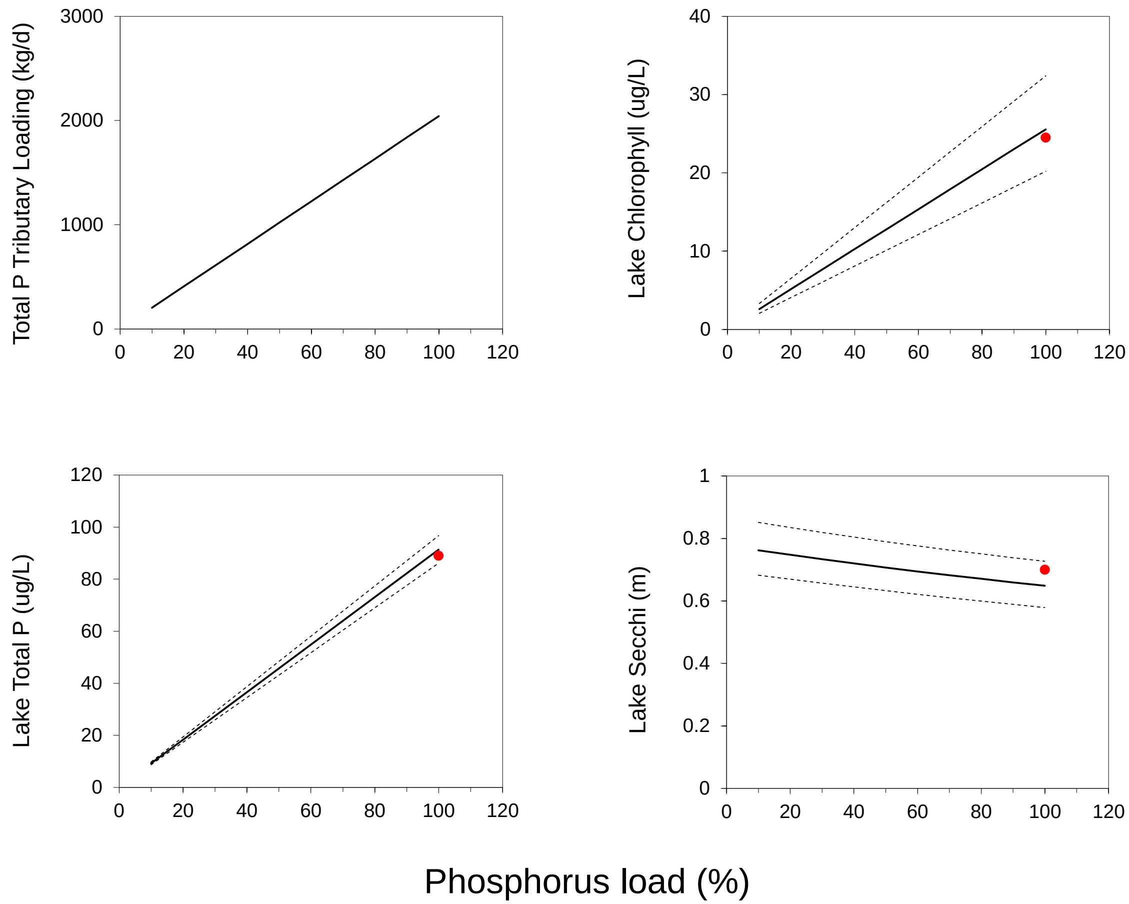


Figure 12. Bathtub (Walker 1996) model output of predicted changes in total phosphorus (P), chlorophyll, and Secchi transparency in Lake Dubay as a function of reducing current mean 2010-13 mean summer P loading by 20% increments (black lines). Dotted lines denote 95% confidence intervals. Red circles represent current measured mean summer values. 100% P load represents current loading conditions.

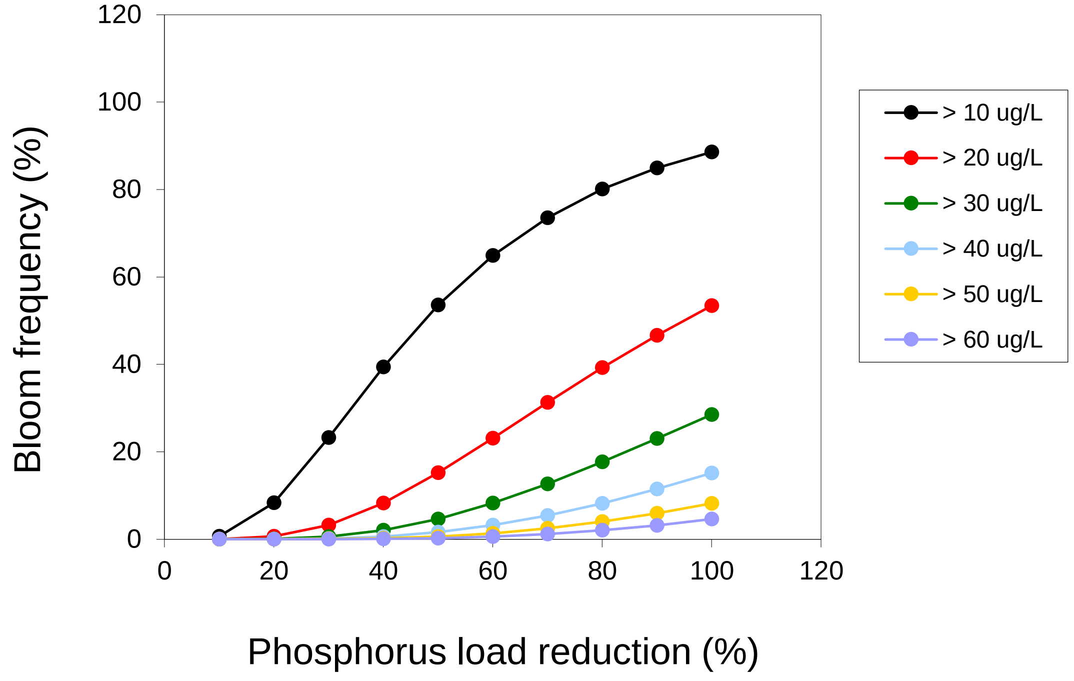


Figure 13. Bathtub (Walker 1996) model output of predicted changes in algal bloom frequency (as chlorophyll) as a function of reducing current mean 2010-13 mean summer P loading by 20% increments. 100% P load represents current loading conditions.

APPENDICES

Appendix 1a. Lake Dubay summer (June-September to early October) means and standard errors (SE) for the headwater station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi	TKN	NHx	N0x	Total N	Particulate N	Particulate P	N:P ratio	N:P ratio
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mass:mass)	(Mol:Mol)
2010-13													
Mean[1]	0.086	0.097	21.5	0.018	0.6	1.109	0.038	0.221	1.329	1.072	0.068	16.0	35.3
SE	0.003	0.004	2.0	0.003	0.03	0.028	0.006	0.028	0.041	0.027	0.002	0.4	0.8
2010													
Mean	0.095	0.099	22.2	0.028	0.7	1.250	0.069	0.293	1.543	1.181	0.067	17.8	39.2
SE	0.006	0.009	3.9	0.006	0.04	0.064	0.017	0.048	0.100	0.066	0.002	1.0	2.3
2011													
Mean	0.078	0.087	25.3	0.017	0.7	1.001	0.026	0.248	1.249	0.978	0.061	16.1	35.5
SE	0.007	0.007	4.6	0.005	0.05	0.040	0.006	0.029	0.047	0.038	0.003	0.4	0.8
2012													
Mean	0.086	0.096	18.2	0.007	0.5	1.141	0.017	0.058	1.199	1.127	0.079	14.5	32.0
SE	0.005	0.006	1.9	0.004	0.05	0.053	0.004	0.035	0.069	0.052	0.004	0.6	1.2
2013													
Mean	0.085	0.105	20.3	0.019	0.6	1.042	0.039	0.283	1.326	1.004	0.065	15.5	34.3
SE	0.006	0.007	5.3	0.005	0.05	0.030	0.011	0.066	0.062	0.029	0.003	0.5	1.0

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Appendix 1b. Lake Dubay summer (June-September to early October) means and standard errors (SE) for the middle station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi	TKN	NHx	N0x	Total N	Particulate N	Particulate P	N:P ratio	N:P ratio
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mass:mass)	(Mol:Mol)
2010-13													
Mean[1]	0.091	0.098	26.8	0.016	0.6	1.153	0.041	0.175	1.329	1.112	0.076	15.0	33.1
SE	0.003	0.004	2.7	0.002	0.03	0.032	0.008	0.026	0.043	0.032	0.003	0.4	0.8
2010													
Mean	0.101	0.105	29.8	0.026	0.8	1.284	0.091	0.243	1.527	1.194	0.076	16.0	35.5
SE	0.007	0.010	4.3	0.004	0.10	0.083	0.024	0.046	0.104	0.091	0.006	0.9	2.1
2011													
Mean	0.089	0.094	35.4	0.013	0.8	1.089	0.021	0.189	1.278	1.068	0.076	14.3	31.7
SE	0.009	0.008	7.1	0.005	0.04	0.049	0.009	0.030	0.067	0.046	0.005	0.5	1.2
2012													
Mean	0.085	0.101	16.0	0.008	0.5	1.113	0.019	0.052	1.166	1.094	0.077	14.4	31.9
SE	0.006	0.006	1.9	0.002	0.05	0.053	0.005	0.039	0.077	0.054	0.006	0.6	1.4
2013													
Mean	0.089	0.092	26.2	0.015	0.6	1.127	0.034	0.218	1.344	1.092	0.074	15.0	33.3
SE	0.004	0.004	5.2	0.004	0.04	0.053	0.011	0.065	0.047	0.061	0.005	0.6	1.3

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Appendix 1c. Lake Dubay summer (June-September to early October) means and standard errors (SE) for the dam station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi	TKN	NHx	N0x	Total N	Particulate N	Particulate P	N:P ratio	N:P ratio
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mass:mass)	(Mol:Mol)
2010-13													
Mean[1]	0.093	0.102	26.4	0.019	0.7	1.200	0.056	0.158	1.358	1.144	0.074	15.8	34.9
SE	0.004	0.004	2.3	0.003	0.046	0.030	0.008	0.024	0.040	0.031	0.003	0.4	0.8
2010													
Mean	0.100	0.112	27.9	0.024	0.9	1.303	0.077	0.206	1.509	1.226	0.076	16.3	36.1
SE	0.008	0.009	4.5	0.004	0.14	0.082	0.020	0.042	0.112	0.091	0.006	0.9	2.1
2011													
Mean	0.096	0.100	31.9	0.023	0.7	1.149	0.031	0.168	1.317	1.118	0.074	15.5	34.3
SE	0.014	0.007	4.5	0.011	0.04	0.045	0.009	0.033	0.060	0.043	0.006	0.7	1.2
2012													
Mean	0.088	0.103	20.4	0.012	0.6	1.198	0.071	0.062	1.260	1.127	0.076	15.1	33.3
SE	0.007	0.009	3.5	0.002	0.08	0.061	0.019	0.040	0.074	0.056	0.006	0.7	1.4
2013													
Mean	0.087	0.095	25.2	0.018	0.5	1.149	0.043	0.196	1.344	1.106	0.069	16.2	35.8
SE	0.004	0.006	5.5	0.005	0.05	0.038	0.013	0.060	0.041	0.048	0.003	0.8	1.3

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Steady-State Modeling Analysis of Lake Wisconsin, Wisconsin River System

21 November, 2016

William F. James
University of Wisconsin – Stout
Discovery Center - Sustainability Sciences Institute
Center for Limnological Research and Rehabilitation
Menomonie, WI 54751
715-338-4395
jamesw@uwstout.edu

EXECUTIVE SUMMARY

Lake Wisconsin is a run-of-the-river hydropower reservoir on the Wisconsin River near Merrimac, WI, that currently exhibits eutrophic to hypereutrophic conditions (Carlson TSI = 65 to 71). A monitoring program was conducted between 2010 and 2013 on the reservoir to examine seasonal total phosphorus (P), chlorophyll, and Secchi transparency dynamics in relation to tributary P loading for Total Maximum Daily Load (TMDL) development. Gauged tributary flow and P inputs included the Wisconsin River at Wisconsin Dells and the Baraboo River at Reedsburg. The gauged discharge was the Wisconsin River at Prairie du Sac. Three stations were established along the longitudinal axis of the reservoir for water sampling purposes. Surface samples were collected biweekly between April and October for total P and chlorophyll analysis. Near-bottom samples were also collected for total P analysis. Secchi transparency was determined biweekly using a 20-cm alternating black and white disk.

Mean daily summer measured inflow was relatively high over the 2010-13 period at 224 m^3/s (± 56 standard error, SE), resulting in a very low mean summer residence time of 7.2 d (±2.3 SE). Summer flow-weighted total P representing the gauged inflow and outflow to Lake Wisconsin were very similar at ~100 mg/L, suggesting rapid flushing of P loads through the reservoir and advective dominance of total P concentrations in the reservoir. Longitudinal variation in summer mean total P concentration between the headwater and dam stations was minimal and the area-weighted mean (i.e., over 2010-13) total P was ~ 0.098 mg/L, similar to inflow-outflow concentrations. The area-weighted grand mean chlorophyll concentration was relatively high at ~ 48 µg/L and summer mean concentrations tended to increase from the headwater to the dam station. The area-weighted grand mean Secchi transparency was low at ~ 0.7 m. The Carlson trophic state index (TSI, Carlson 1977) for P (TSI-P) was high at 70 (indicative of hypereutrophic conditions). The TSI based on chlorophyll (TSI-CHLA) was slightly lower at 68 and TSI based on Secchi transparency (TSI-SD) was 65.

Budgetary analysis of summer flow and P loads indicated an approximate balance between inflow and outflow, suggesting minor P retention during the summer. Overall, the P empirical model (settling velocity) closely predicted the observed area-weighted mean summer total P concentration in Lake Wisconsin. Tributary P inputs entirely accounted for the summer total P budget, suggesting that internal P loading was negligible. However, the chlorophyll model (Jones and Bachman 1976) over-predicted the observed area-weight mean summer chlorophyll concentration. Although concentrations were not significantly different given the variance in the observed chlorophyll versus the model, a calibration coefficient of 0.68 (i.e., versus 1.0) was used to adjust the predicted value to the observed mean. Because Lake Wisconsin is dominated by advection, low residence time, and little apparent P retention (i.e., deposition), predicted summer total P concentration reductions coincided closely with tributary P load and concentration reductions. For instance, a 50% reduction in P loading coincided with a 50% decline in summer total P from ~0.098 mg/L to 0.050 mg/L. Under this same P loading reduction scenario, predicted summer chlorophyll concentrations declined by 64% from ~ 48 µg/L to ~17 µg/L. Predicted Secchi transparency increased by 28% from 0.7 m to 0.9 m. Under current P loading conditions, chlorophyll blooms exceeding 20 µg/L and 60 µg/L occurred an estimated 85% and 33% of the time during the summer period, respectively. Using the same scenario, a 50% P loading reduction resulted in a predicted decline in the summer bloom frequency of chlorophyll exceeding 20 µg/L and 60 µg/L to 27% and 1% of the time during the summer period, respectively. Empirical steady-state models developed for Lake Wisconsin will be used in conjunction with other decision-support tools to develop a TMDL based on predicted reservoir water quality responses to P loading reduction.

OBJECTIVES

The objectives of this investigation were to examine summer limnological conditions in Lake Wisconsin between 2010 and 2013 and project future conditions under phosphorus loading reduction scenarios using a steady-state empirical modeling approach.

METHODS

Flow and total phosphorus (P) loadings from the Wisconsin and Baraboo Rivers (Table 1) were combined with seasonal (April – September to early October) surface water chemistry information from three stations in Lake Wisconsin (Table 2, Fig. 1) to construct a steady-state empirical model (Bathtub Version 6.14; Walker 1996) to forecast the response of limnological variables (total P, chlorophyll, and Secchi transparency) to future P loading reduction. Since the annual theoretical water residence time was relatively low (range = 4.4 d to 8.9 d), a June through September (122 d) averaging period was used for steady-state empirical modeling analysis. Gauged hydraulic inputs included the Wisconsin River at Wisconsin Dells (Station ID 573052) and the Baraboo River at Reedsburg (Station ID 573076, Table 1). The gauged hydraulic discharge from Lake Wisconsin was the Wisconsin River at Prairie du Sac Dam (Station ID 10029830, Table 1). Monthly hydraulic flow (m^3/s) and total P loadings (kg/month) determined by the US Geological Survey (Madison, WI) were converted to mean flow (expressed as hm^3/y) and total P concentration (expressed as µg/L) over the summer averaging period as input to the model. Additional hydrologic input to the model included ungauged local runoff to the reservoir from the surrounding subwatershed that was estimated using the Soil and Water Assessment Tool (SWAT) and daily precipitation records over the study period obtained from the Wisconsin State Climatology Office (Madison, WI). The coefficient of variation (CV-mean) was estimated from mean June through September flows and total P concentrations between the years 2010 and 2013 reported by the US Geological Survey (Dale M. Robertson, U.S. Geological Survey, Madison, WI, unpublished data). The CV-mean was calculated as the standard error of the grand mean (n = 12; i.e., JUN-SEP 2010 through 2013) divided by the grand mean of each constituent. This CV-mean was used for error analysis in Bathtub as recommended in Walker (1996). A 12-year average for summer flow, total P concentration, and total P loading between 2002 and 2013 was estimated from reports and data provided by the US Geological Survey (Dale M. Robertson, U.S. Geological Survey, Madison, WI, unpublished data).

Biweekly measurements of Secchi transparency and surface concentrations of chlorophyll and total P, collected in Lake Wisconsin during the summer periods of 2010 through 2013, were averaged to estimate a mean concentration for each station segment during each year. June through September was used as the averaging period. Chemical analyses of surface water samples were conducted by the Wisconsin State Laboratory of Hygiene using standard methodological approaches. For in-lake morphometric inputs to the empirical model, the pool was divided into the 3 segments (i.e., headwater, middle, and dam segments) corresponding to the locations of sampling stations (Table 2).

The computer software program Bathtub was used to examine P loading reduction scenarios (Walker 1996). 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. Grand means for total P, chlorophyll, and Secchi transparency over the summer 2010-13 period were used as input into the model. The coefficient of variation for total P, chlorophyll, and Secchi transparency of the grand mean (CV-mean) was calculated as the standard error of the grand mean divided by the grand mean of each constituent. This CV-mean was used for error analysis in Bathtub as recommended in Walker (1996).

RESULTS AND DISCUSSION

Tributary Hydrology and Loading

Mean daily summer inflow was highest in 2010 at 361 m^3/s and lowest at 92 m^3/s in 2012 (Fig. 2). Mean daily summer flow during the summers of 2011 and 2013 were slightly above the 12-year summer average (2004 – 2013) flows reported by the US Geological Survey. The summer theoretical water residence time exhibited the opposite pattern. It was very low during the high flow summer of 2010 at less than 4 d and greater than 13 d during the low-flow summer of 2012. The grand mean residence time over the 4-year study period was moderately low at ~ 7.2 d, similar to the 12-y average summer residence time.

Summer total P of the gauged inflow to Lake Wisconsin, representing a flow-weighted concentration for the combined Wisconsin and Baraboo Rivers, and estimated local subwatershed runoff ranged between 0.089 mg/L in 2012 and 0.115 mg/L in 2010, following a trend similar to that of mean daily summer inflow (Fig. 2). In general, the summer total P concentration was above the 12-y average in 2010 and slightly below the 12-y average in 2011 and 2013. Summer total P loading followed the same inter-annual trend. It was greatest in 2010 and 2 times higher than the 12-y average. In contrast, summer total P loading was lowest in 2012 and less than half the 1-2y average. Summer total P loading during the summers of 2011 and 2013 were near the 12-year average.

Reservoir Limnological Trends

Because summer theoretical water residence time was relatively low, even during the lower inflow period of 2012, Lake Wisconsin mean summer total P concentrations were only slightly lower than the measured inflow total P (Fig. 3). In addition, mean summer total P concentrations exhibited minor variation as a function of in-lake station or distance from the dam (Fig. 4). This pattern suggested that limnological patterns in the lake were largely dominated by riverine influences along its longitudinal axis. By contrast, longitudinal concentration gradients from headwaters to the dam can typically develop in larger reservoirs as a function of widening morphometry, decreasing flow velocity, and deposition of loads (Thornton et al. 1990). Indeed, mean concentrations either increased slightly from headwaters to the dam, as in 2011 and 2013, or increased to a peak at the middle station, as in 2012 (Fig. 3). In all cases, however, summer total P concentration differences were minimal between stations as indicated by grand mean trends over the study period (Fig. 4).

Variations between surface and near-bottom concentrations of total P were also small throughout the study period, suggesting that internal P loading from bottom sediments likely played a negligible role in P dynamics in Lake Wisconsin (Fig. 5-8). There were periods of elevated near bottom total P concentration with respect to the surface at all stations; but these concentration differences were minor and could be attributable to other mechanisms such as resuspension caused by river current shear stress or by river density underflows. Overall, differences in mean summer surface versus near-bottom total P concentrations were very minor over the study period (Fig. 9).

James (2014) found that laboratory-derived diffusive P flux from sediment collected in Lake Wisconsin was very high under anaerobic conditions (range = 26 – 27 mg/m^2 d) and much lower at 0.13 to 0.8 mg/m^2 d under aerobic conditions. Lower diffusive P flux under aerobic conditions was consistent with the classic Mortimer (1971) model of coupled Fe-P chemistry. Under this scenario, Fe is in an oxidized state as an Fe oxyhydroxide (Fe^{3+}~OOH) in the aerobic sediment microzone (i.e., the thin aerobic surface sediment layer often less than 1 mm in thickness) and strongly adsorbs P, resulting in its very limited diffusion into the overlying water column. Dissolved oxygen concentrations near the sediment-water interface exceeded 5 mg/L throughout the summer months at the headwater and middle stations (Fig. 10) indicating oxidized and aerobic conditions and suppressed diffusive P flux from sediment. However, there were instances of near-bottom anoxia at the much deeper dam station in June, 2010, July and August in both 2012 and 2013. Under these conditions, reduction of Fe^{3+}~(OOH) to Fe^{2+} and release of phosphate that was previously adsorbed or precipitated can result in enhanced diffusive P to the overlying water column. While potential anaerobic diffusive P flux occurred in the dam region during the study period, its impact on the P budget of the lake appeared to be negligible compared to watershed P loading (see below).

Mean summer chlorophyll concentrations ranged between 23 µg/L and 67 µg/L and tended to increase slightly from the headwater to the dam station (Fig. 3 and 4). Means were also greatest during the lower flow summer of 2012 and lowest during the higher flow summer of 2010, suggesting that summer theoretical residence time (and flushing) played an additional role in regulating algal growth. Overall, a strong positive relationship occurred between summer theoretical residence time and mean chlorophyll (Fig. 11). In particular, chlorophyll concentrations tended to be greatest in August through September, 2011-13, in conjunction with lower Wisconsin River flows. This pattern contrasted with the 2010 pattern of lower chlorophyll concentrations in August-September that were associated with higher flows, particularly in late July and September (Fig. 5-8).

Although there were seasonal periods when Secchi transparency slightly exceeded 1.0 m (Fig. 5-8), summer means were generally lower throughout the study period (Fig. 4), ranging between 0.6 and 1.0 m. Longitudinal variations in grand mean Secchi transparencies were also minor (headwater station = 0.8 m ± 0.03 SE; middle station = 0.7 m ± 0.04 SE; dam station = 0.8 m ± 0.06 SE; Fig. 5). Mean summer Secchi transparency varied inversely with summer theoretical residence time (Fig. 10) and mean summer chlorophyll (Fig. 12), suggesting linkages between longer residence time, greater algal biomass growth, and resulting reduced Secchi transparency.

Grand mean summer Carlson Tropic State Index (TSI) values for total P and chlorophyll were similar, ranging between 65 and 70 for the headwater, middle, and dam stations (Fig. 4). These ranges were indicative of eutrophic to hypereutrophic conditions. Grand mean TSI was lower for chlorophyll and Secchi transparency compared to total P (Fig. 4). Lower TSI chlorophyll relative to TSI total P may have been related to relatively low residence time which could promote some algal biomass export if cellular doubling times are greater than residence time in the lake. Lower TSI Secchi transparency versus TSI chlorophyll could have been related to dominance of filamentous cyanobacteria versus colonies or high density single cells, which tend to enhance the attenuation of solar radiation.

Other variables of interest are shown in Appendix 1. The grand mean total P composition was dominated by particulate P, most likely incorporated into algal biomass. Soluble reactive P was generally low and ranged from not detectable to 0.04 mg/L. The grand mean soluble reactive P concentration was 0.011 mg/L, accounting for~ 11% of the total P composition. Particulate N accounted for 78% of the total N composition. Dissolved inorganic N was dominated by NO_x at a grand mean of 0.242 mg/L. The grand mean NH_x concentration was low at 0.068 mg/L and represented only 5% of the total N composition. The grand mean molar particulate N:P ratio was ~ 30:1, suggesting that algal growth was P-limited. Hillebrand et al. (2013) suggested that optimal N:P molar ratios are higher for cyanobacteria with a mean from literature values of ~26:1.

Steady-State Empirical Modelling

The mean (2010-13) summer hydraulic and total P balance indicated that measured summer flow and P loading were slightly greater in the outflow than the gauged inflows to Lake Wisconsin (Table 3). Thus, additional ungauged sources of flow and P input potentially accounted for ~ 13% of the P mass imbalance. The Wisconsin River at Wisconsin Dells, WI, overwhelmingly dominated mean summer gauged P inputs to Lake Wisconsin (Table 3). Mean summer flow and P loading represented 85% and 75% of the inputs, respectively. The mean summer flow-weighted total P concentration was 0.088 mg/L. Although the Baraboo River at Reedsburg, WI, represented only 7% of the gauged inflow, the mean summer flow-weighted total P concentration was much higher at 0.247 mg/L. Mean summer total P loading from this input represented 17% of the estimated total P load to the system. Although apparent P retention was negative due to unaccounted for local total P loads, the weighted inflow and outflow total P concentrations were nearly identical at 0.099 to 0.101 mg/L, suggesting that advective flow-through and discharge, versus deposition of total P loads, largely regulated P concentrations in Lake Wisconsin.

Because low summer theoretical water residence time and advection dominated the P budget, a first-order P sedimentation model (σ) was chosen to predict summer mean lake total P according to the equation,

$$P_{lake} = \frac{P_{inflow}}{(1 + \sigma\tau_{\omega})}$$

Where, P_{lake} = area-weighted mean summer total P concentration (mg/m^3), P_{inflow} = flow-weighted gauged inflow total P (mg/m^3), σ = first-order sedimentation coefficient, and τ_{ω} = summer theoretical water residence time (y). Of the first-order P sedimentation models, Vollenweider (1976), simple first-order, and first-order settling velocity all closely predicted P_{lake} and first-order settling velocity was chosen as the P sedimentation model (Table 4). Because the Jones and Bachman (1976) chlorophyll-total P regression relationship was developed from an extensive northern lake data set, it was chosen for mean summer chlorophyll prediction. Finally, the default Secchi transparency model developed from relationships between chlorophyll and turbidity in reservoirs was chosen to estimate mean summer Secchi depth.

Observed versus predicted summer means of total P, chlorophyll, and Secchi transparency over the 2010-13 period are shown in Figure 13. Overall, the P empirical model (settling velocity) closely predicted the observed area-weighted mean summer total P concentration in Lake Wisconsin. The chlorophyll model overpredicted the observed area-weighted mean summer chlorophyll concentration (Fig. 13). However, standard error bars overlapped and means were not significantly different given errors in the observed chlorophyll versus the model (Walker 1996). In addition to potential error, overprediction of mean summer chlorophyll based on chlorophyll-total P regression relationships could have been related to 1) a portion of the total P pool that was not incorporated as algal biomass and 2) advective discharge of algal biomass due to low residence time. Adjustment to the observed summer mean chlorophyll concentration resulted in a calibration coefficient of 0.68. Since the Secchi transparency model uses summer mean chlorophyll as an input variable, predicted summer mean Secchi transparency slightly underestimated the observed mean without calibration adjustment of the chlorophyll model (Fig. 13). Chlorophyll calibration resulted in improved prediction of Secchi transparency.

Phosphorus Loading Reduction

Current summer P loading to Lake Wisconsin was reduced by 20% increments in Bathtub to examine predicted water quality responses to simulated future P loading reduction as a result of best management practices (BMP) implementation for TMDL development and goal-setting (Fig. 14). Because Lake Wisconsin is a run-of-the-river reservoir with low residence time and little apparent P retention (i.e., deposition), predicted summer total P concentration reductions coincided closely with tributary P load and concentration reductions (Fig. 14). For instance, a 50% reduction in P loading coincided with a 50% decline in summer total P from ~0.098 mg/L to 0.050 mg/L. Under this same P loading reduction scenario, predicted summer chlorophyll concentrations declined by 64% from ~ 48 µg/L to ~17 µg/L. Predicted Secchi transparency increased by 27% from 0.70 m to 0.93 m.

Predicted bloom frequency (i.e., percentage of the summer that chlorophyll exceeds a certain concentration) response to P loading reduction is shown in Figure 15 for various summer mean chlorophyll concentrations. Under current P loading conditions, chlorophyll blooms exceeding 20 µg/L and 60 µg/L occurred an estimated 85% and 33% of the time during the summer period, respectively. A 50% P loading reduction would result in a predicted decline in the summer bloom frequency of chlorophyll exceeding 20 µg/L and 60 µg/L to 27% and 1% of the time during the summer period, respectively.

Thus, empirical models suggested that predicted reservoir trophic state indicator variables (total P, chlorophyll, and chlorophyll concentration bloom frequency) were responsive to P loading reduction.

REFERENCES

Carlson RE. 1977. A trophic state index for Lakes. Limnol Oceanogr 22:361-369.

Hillebrand H, Steinert G, Boersma M, Malzahn A, Léo Meunier C, Plum Cm Ptacnik R. 2013. Goldman revisited: Faster-growing phytoplankton has lower N:P and lower stoichiometric flexibility. Limnol Oceanogr 58:2076-2088.

James WF. 2014. Sediment diffusive phosphorus flux determination in Lake Wisconsin, Wisconsin River System, 2014. University of Wisconsin – Stout, Sustainability Sciences Institute – Center for Limnological Research and Rehabilitation, Menomonie, WI 54751.

Jones JR, Bachmann RW. 1976. Prediction of phosphorus and chlorophyll levels in lakes. J Wat Pollut Contr Fed 48:2176-2182.

Mortimer CH. 1971. Chemical exchanges between sediments and water in the Great Lakes – Speculations on probable regulatory mechanisms. Limnol Oceanogr 16:387-404.

Thornton KW, Kimmel BL, Payne FE. 1990. Reservoir Limnology: Ecological perspectives. John Wiley and Sons, New York.

Vollenweider RA. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem Ist Ital Idrobiol 33:53-83.

Walker WW. 1996. Simplified procedures for eutrophication assessment and prediction: User manual. Instruction Report W-96-2, September, 1996, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, USA.

WisCALM. 2014. Wisconsin 2014 consolidated assessment and listing methodology (WiscCALM) for Clean Water Act Section 305(b), 314, and 303(d) integrated reporting. EGAD#3200-2013-01, September, 2013. Wisconsin Department of Natural Resources, Bureau of Water Quality Program Guidance.

Table 1. Gauged inflow-outflow stations used in the Lake Wisconsin empirical steady-state model.

Station ID	Gauged Inflow	Latitude	Longitude
573052	Wisconsin River at Wisconsin Dells	43.605000	89.756667
573076	Baraboo River at Reedsburg	43.532444	90.011444
	Gauged outflow	**Latitude**	**Longitude**
10029830	Wisconsin River below Prairie du Sac Dam	43.305779	89.725590

Table 2. Water quality sampling station locations in Lake Wisconsin.

Station ID	Name	Surface area (km^2)	Mean depth (m)	Segment length (km)
10031185	Headwaters	7.58	1.68	12.3
10031184	Middle	15.31	3.22	5.4
10031186	Dam	9.26	5.07	11.9

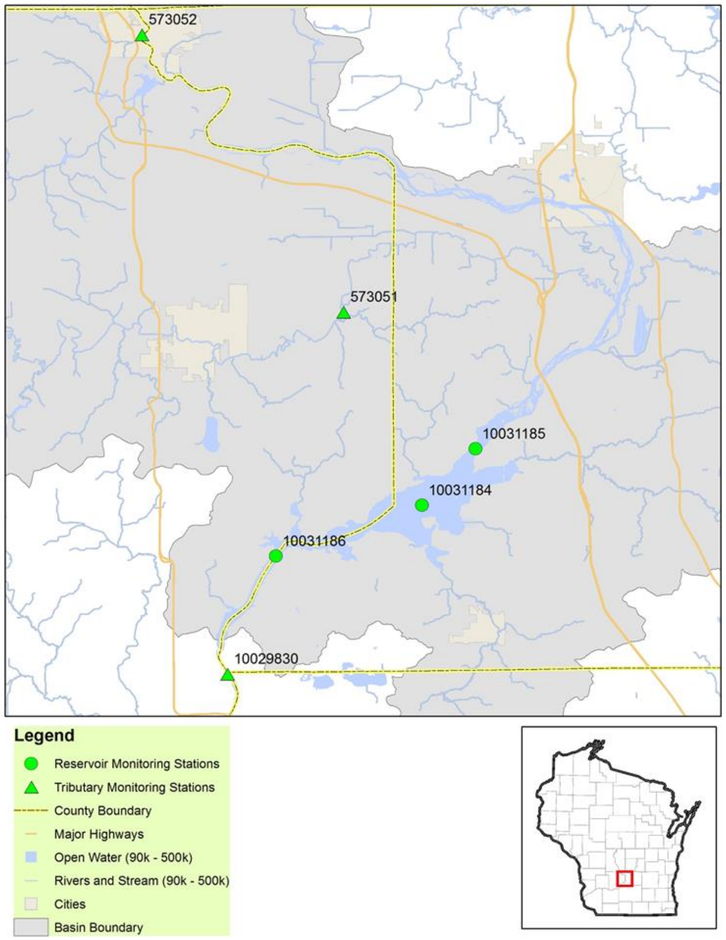
Table 3. A comparison of summer (June - September) flow and total phosphorus (P) inputs to and discharge from Lake Wisconsin.

Component	Flow		Total P		
	(m^3/s)	(% contribution)	(mg/L)	(kg/d)	(% contribution)
Inputs					
Wisconsin River at Wisconsin Dells, WI	191.2	84.8	0.088	1454	75.2
Baraboo River at Reedsburg, WI	15.6	7.0	0.247	332	17.3
Ungauged[1]	16.3	7.2	0.102	143	7.4
Precipitation	2.3	1.0	0.013	3	0.1
Total	225.3	100	0.099	1931.8	100
Outputs					
Wisconsin River at Prairie du Sac Dam	241.0		0.101	2178	
Evaporation	2.3				
Total	243.3		0.101	2178	
Balance	-17.9 (108%)			-245.9 (113%)	

[1]Representing local subwatershed inputs estimated from the Soil and Water Assessment Tool (SWAT)

Table 4. Algorithms used for Bathtub (Walker 1996) phosphorus loading reduction modeling of Lake Wisconsin.

Variable	Model
Phosphorus	First order settling velocity
Chlorophyll	Jones and Bachmann
Secchi Transparency	versus Chlorophyll & Turbidity



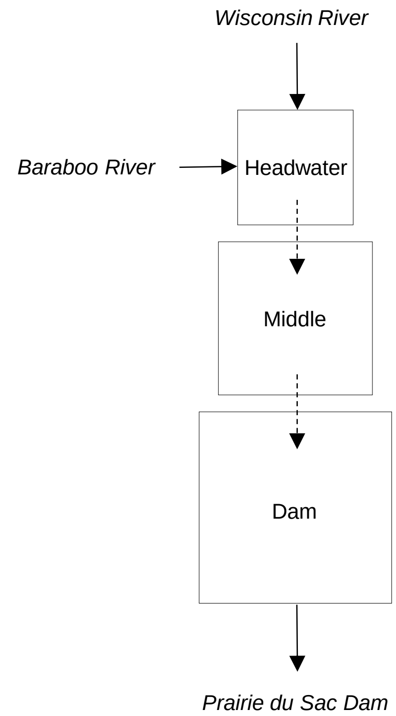


Figure 1. Water sampling station locations (left) and Bathtub conceptualization

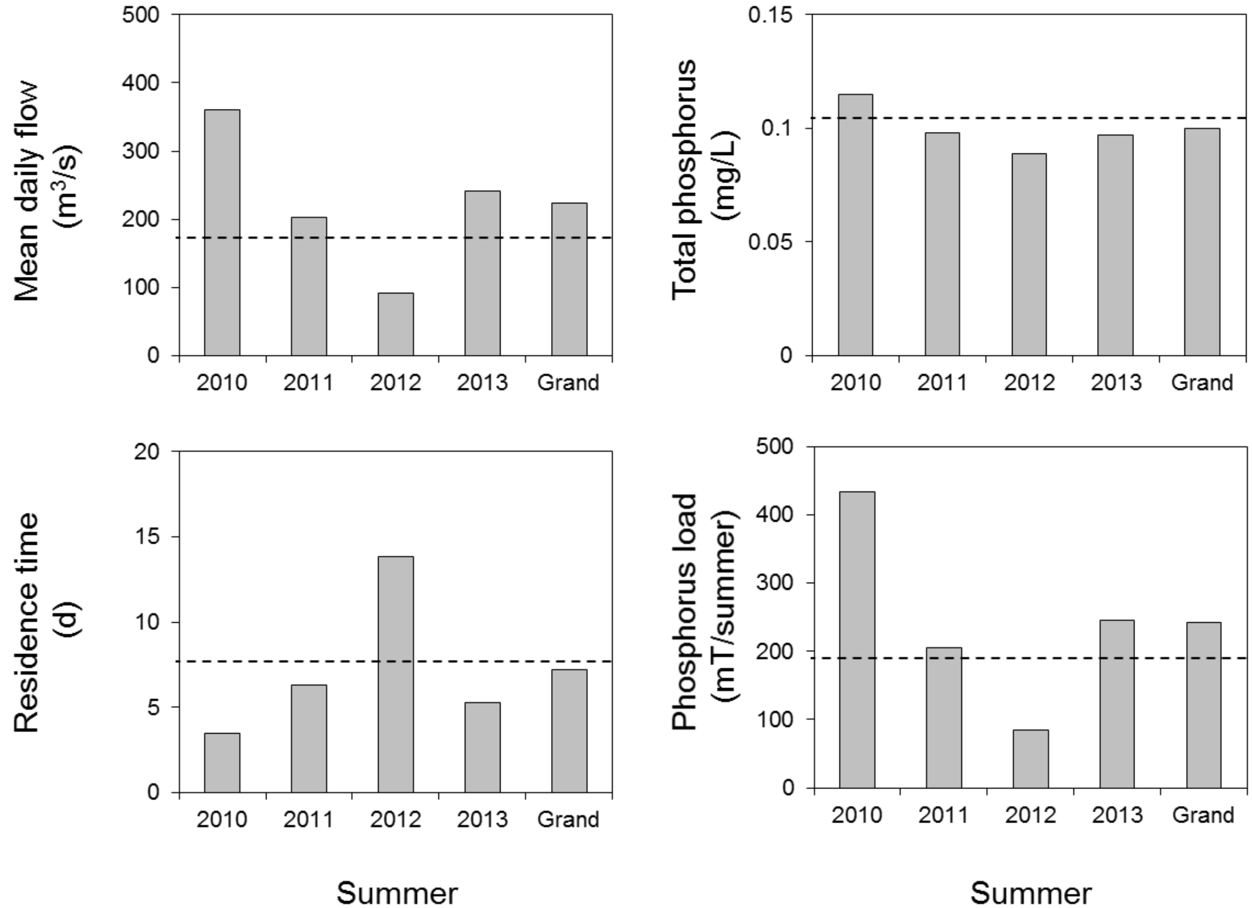


Figure 2. Summer (June – September) mean daily flow into Lake Wisconsin (upper left panel), theoretical water residence time (lower left panel), flow-weighted total phosphorus concentration of the inflow (upper right panel), and total phosphorus load (lower right panel) during 2010 - 2013. The horizontal dashed line denotes the 12-year average. The grand mean for each variable was estimated as the mean of the individual summer means.

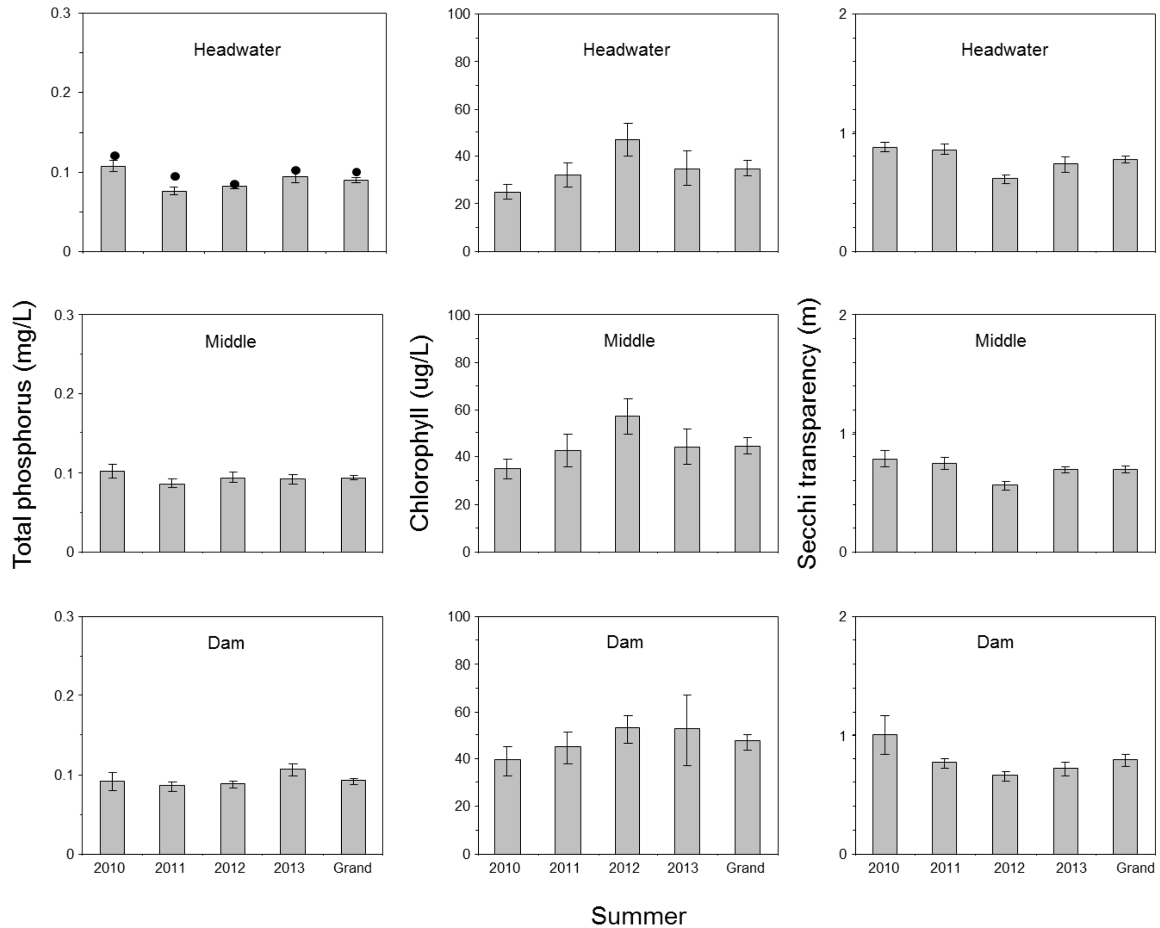


Figure 3. Summer (June – September) mean concentrations of total phosphorus (left panels), chlorophyll (middle panels), and Secchi transparency (right panels) during 2010 - 2013. The black circles denote the gauged inflow total phosphorus concentration. The grand mean for each variable was estimated as the mean of the individual summer means. Vertical lines represent ± 1 standard error.

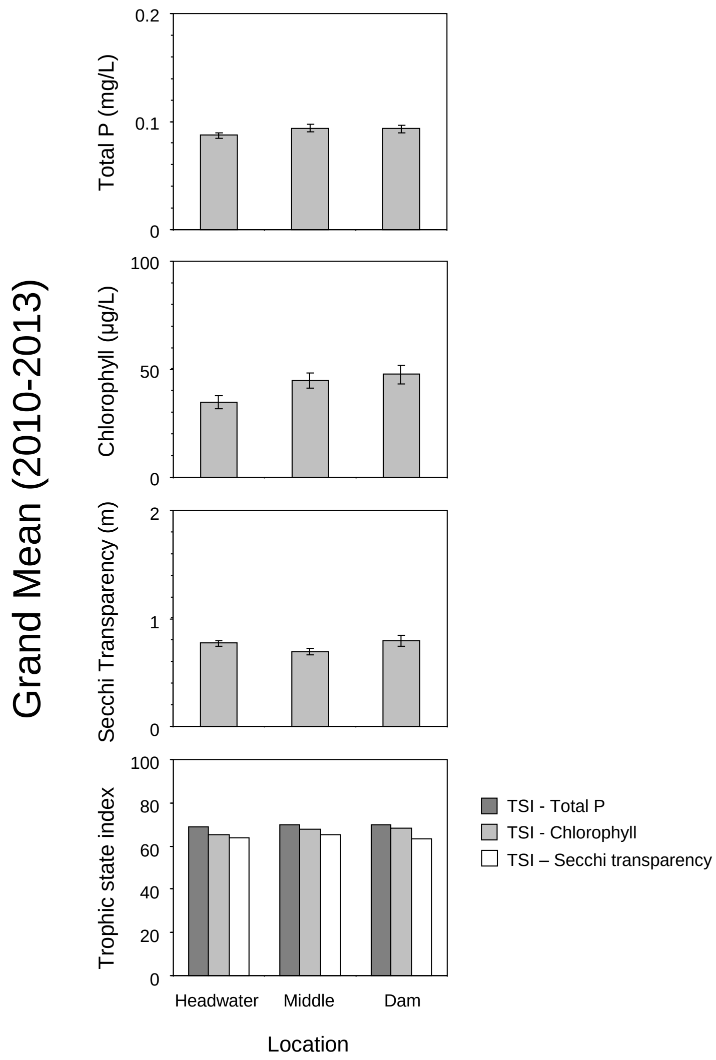


Figure 4. Variations in grand mean summer (June – September) total phosphorus (P, upper panel), chlorophyll (upper middle panel), Secchi transparency (lower middle panel), and Carlson trophic state indices (TSI) for the headwater, middle, and dam stations in Lake Wisconsin. Vertical lines represent ± 1 standard error of the grand mean.

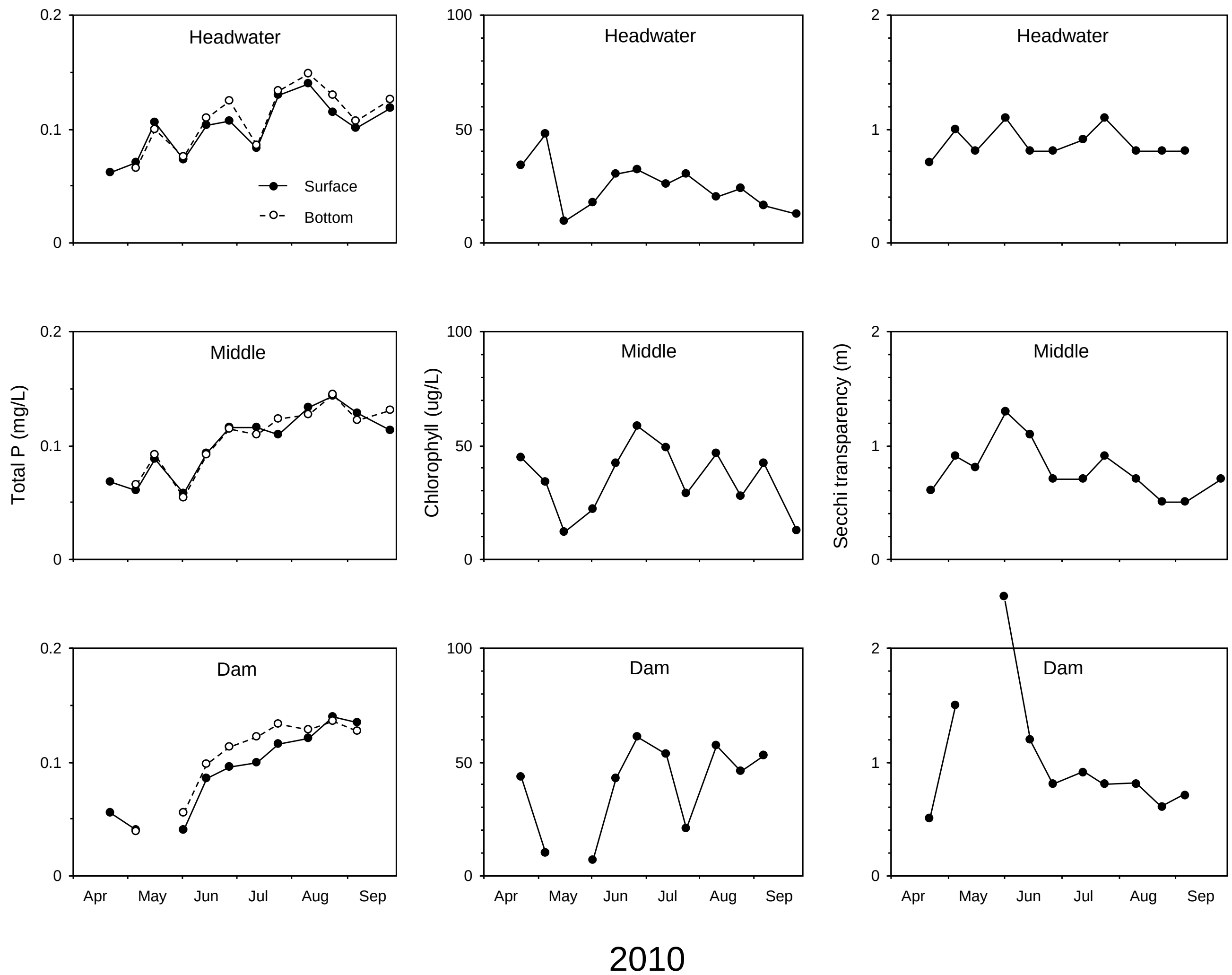


Figure 5. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2010.

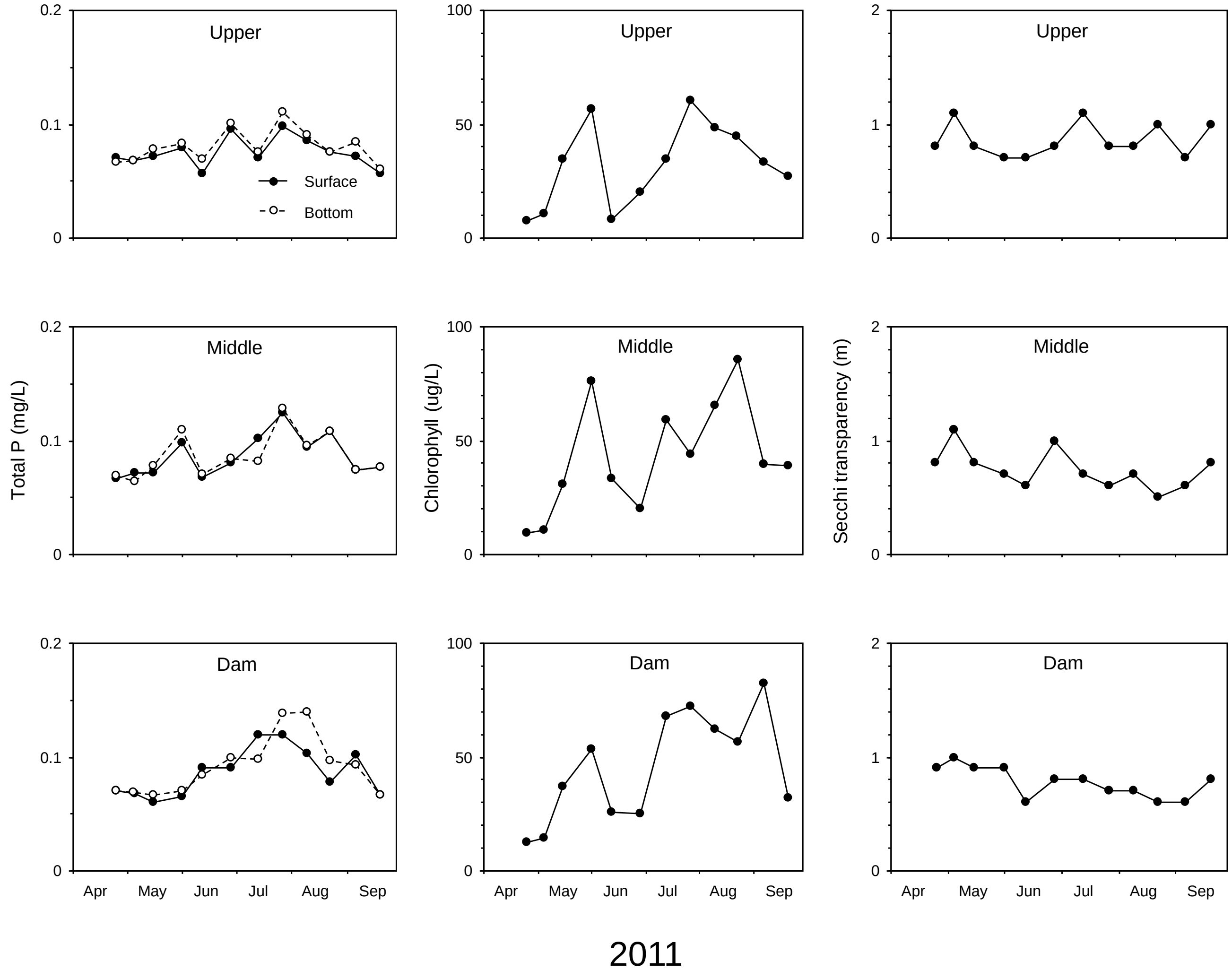


Figure 6. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2011.

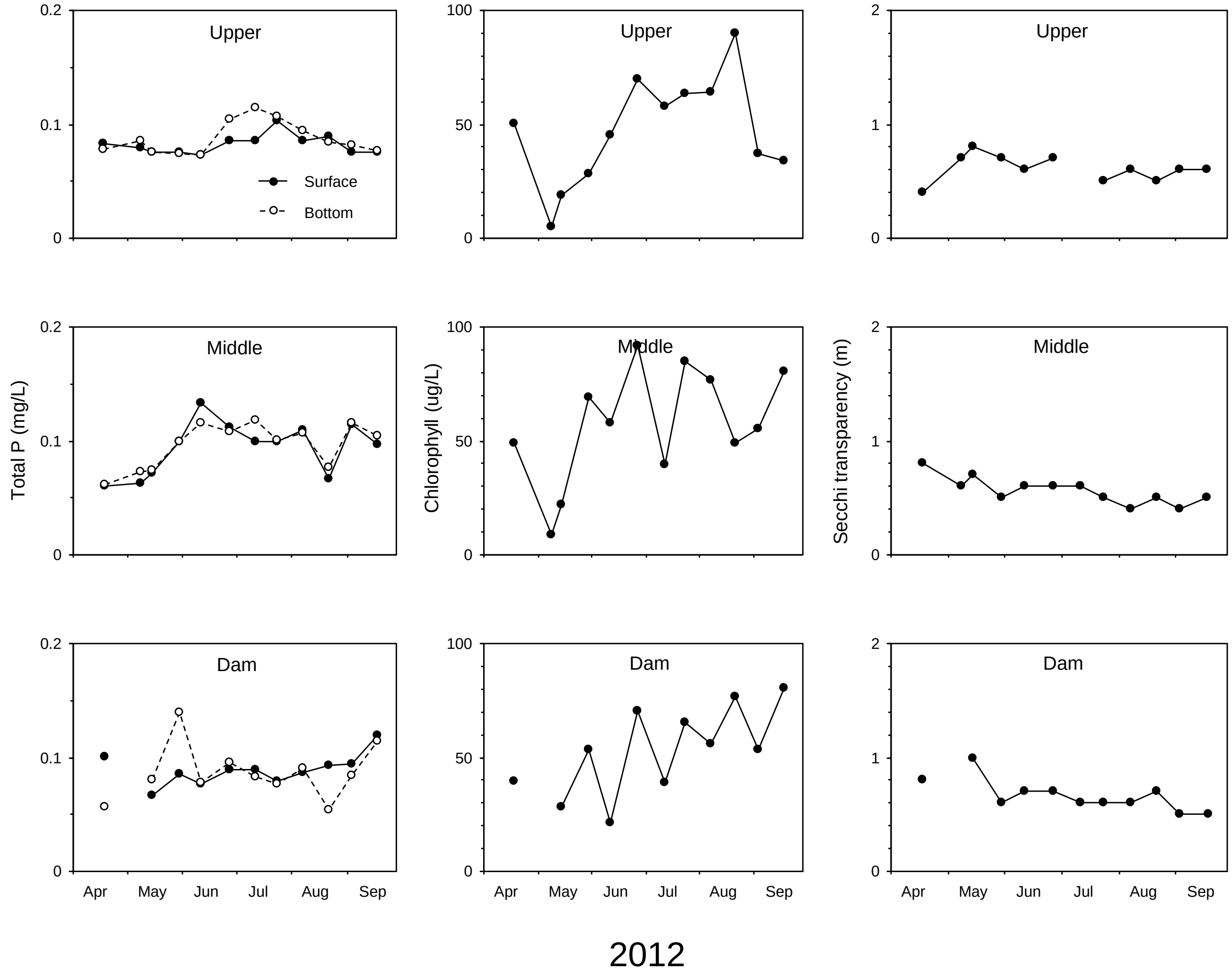


Figure 7. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2012.

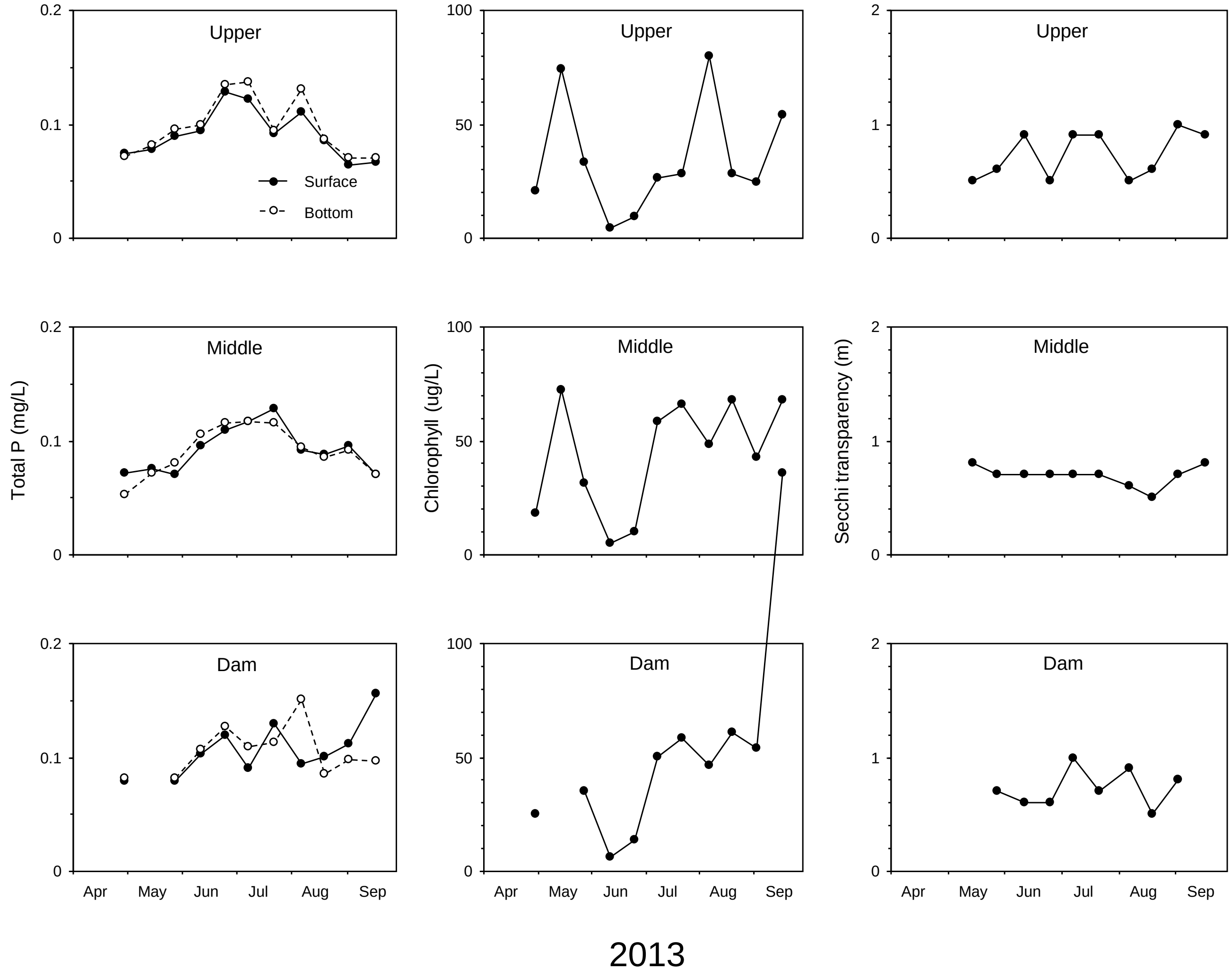


Figure 8. Seasonal variations in surface and near-bottom concentrations of total phosphorus (P, left panels), chlorophyll (middle panels), and Secchi transparency (right panels) for the headwater, middle, and dam stations during 2013.

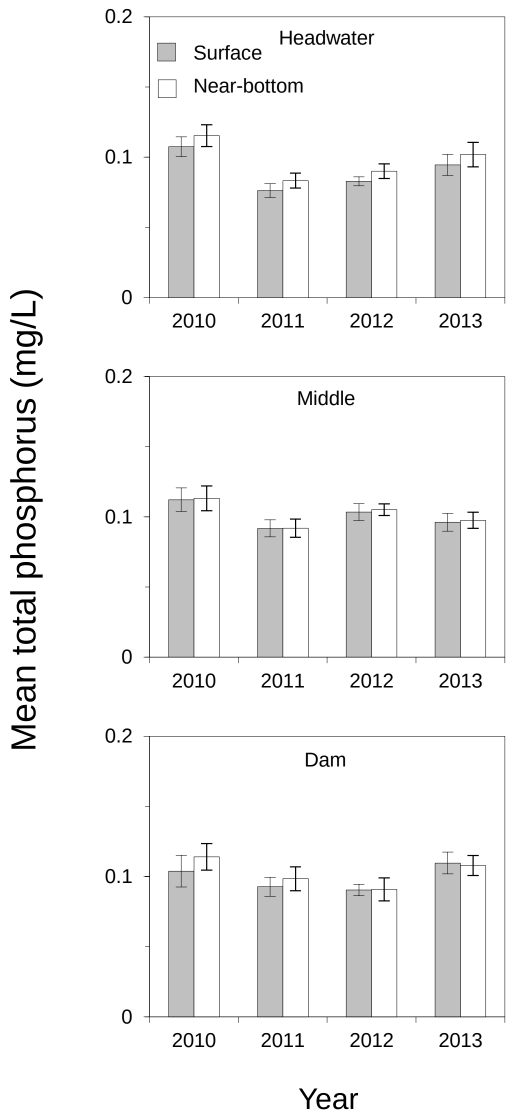


Figure 9. Variations in mean summer (June – September) surface and near -bottom total phosphorus concentrations at the headwater, middle, and dam stations in Lake Wisconsin. Vertical bars denote ± 1 standard error.

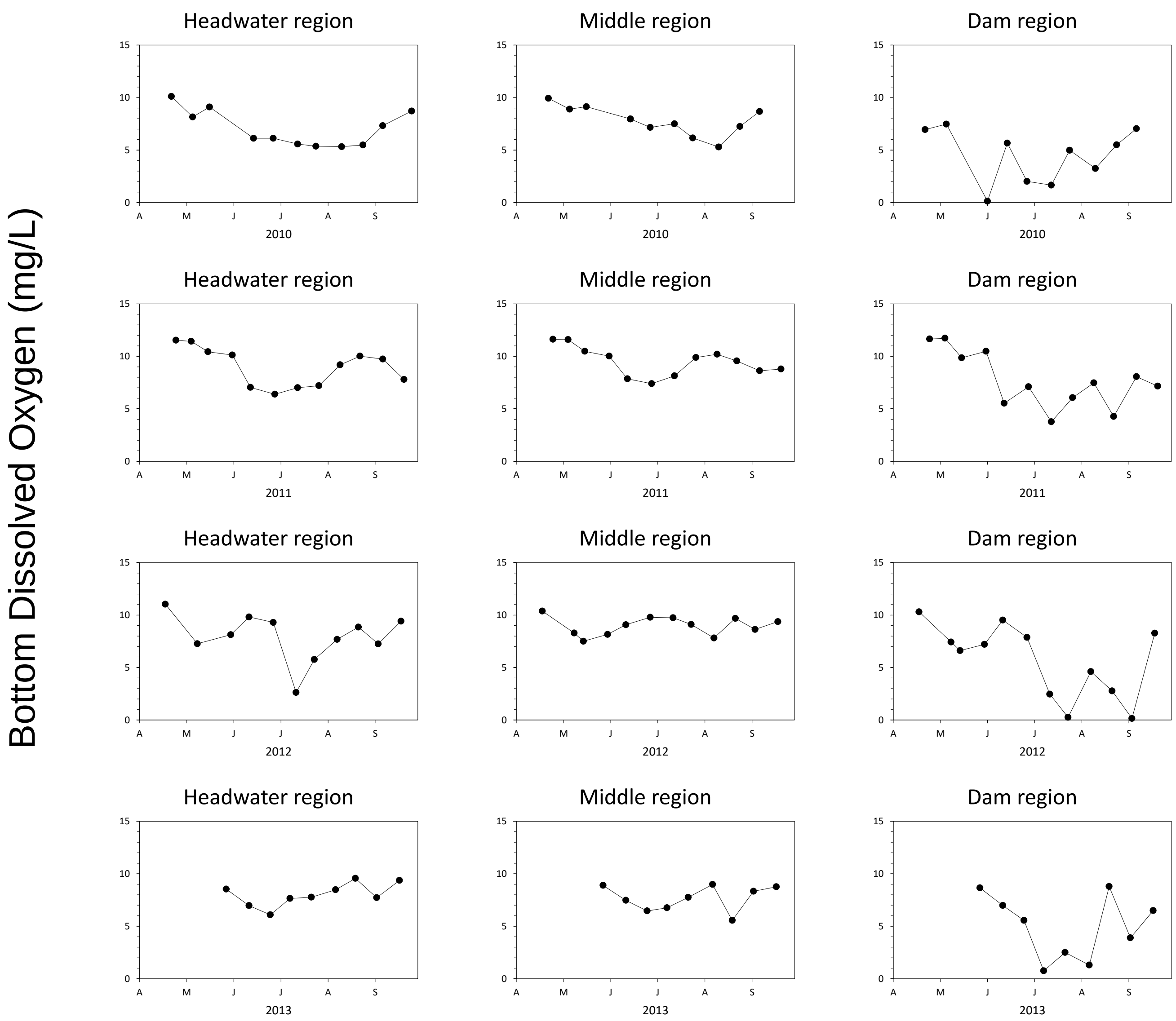


Figure 10. Seasonal variations in near-bottom concentrations of dissolved oxygen for the headwater, middle, and dam stations during 2010-2013.

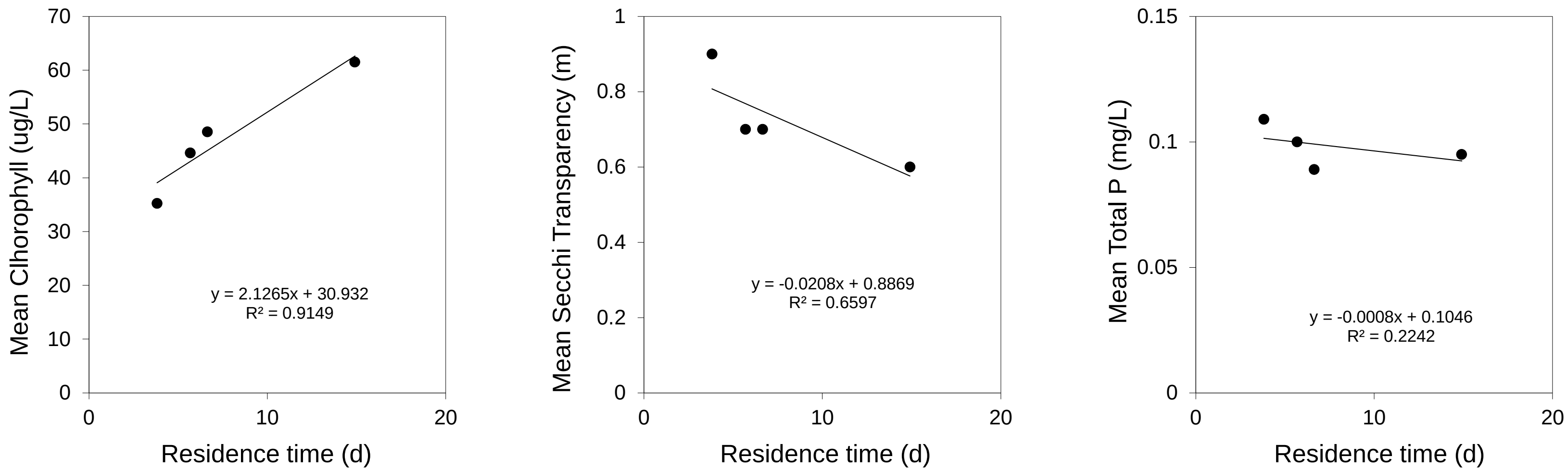


Figure 11. Regression relationships between summer (June – September) theoretical water residence time and summer area-weighted mean chlorophyll (left panel), mean Secchi transparency (middle panel), and total phosphorus (P, right panel).

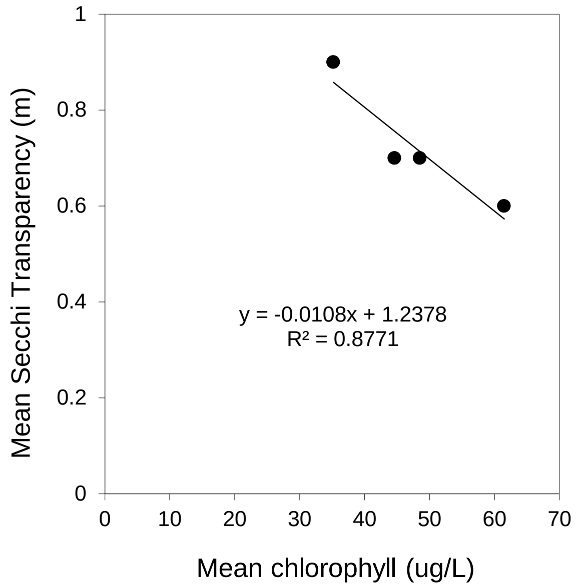


Figure 12. Regression relationships between summer (June – September) area-weighted mean chlorophyll and mean Secchi transparency.

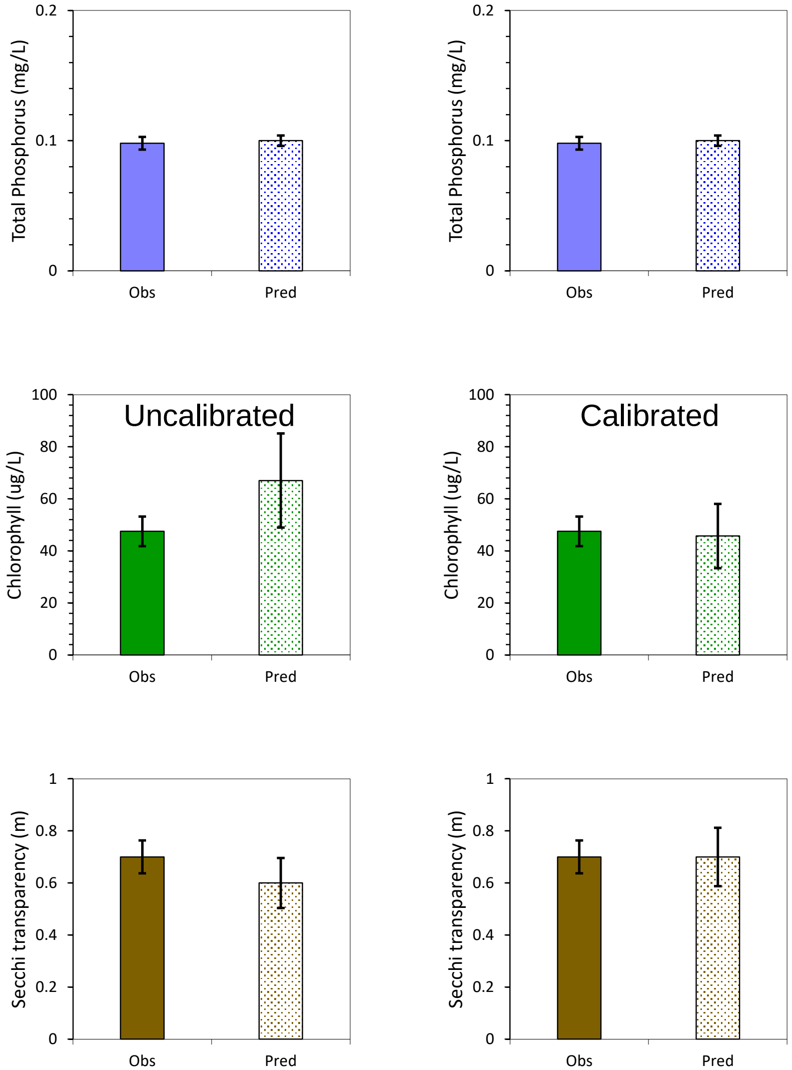


Figure 13. A comparision of mean (± 1 standard error) observed versus predicted area-weighted total phosphorus, chlorophyll, and Secchi transparency using an uncalibrated (left panel) and calibrated (right panel) chlorophyll model.

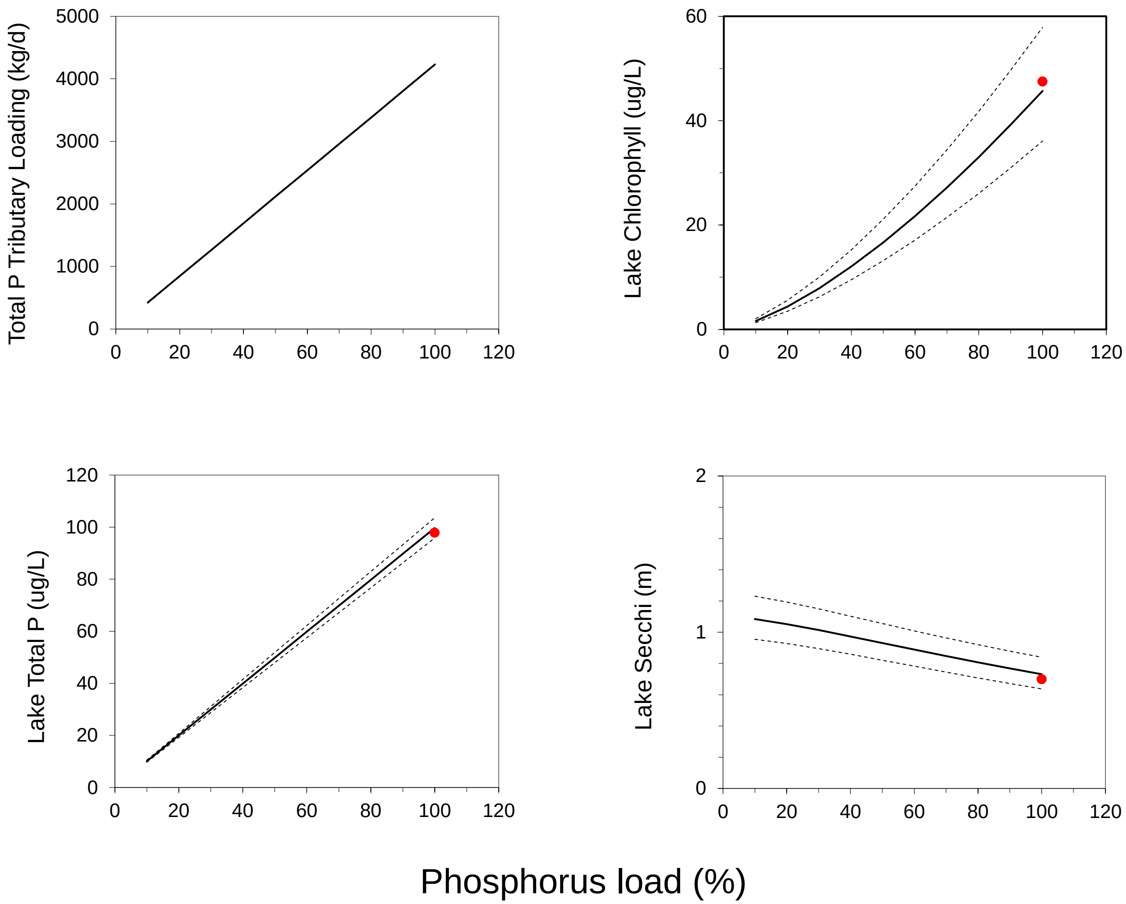


Figure 14. Bathtub (Walker 1996) model output of predicted changes in total phosphorus (P), chlorophyll, and Secchi transparency in Lake Wisconsin as a function of reducing current mean 2010-13 mean summer P loading by 20% increments (black lines). Dotted lines denote 95% confidence intervals. Red circles represent current measured mean values. 100% P load represents current loading conditions.

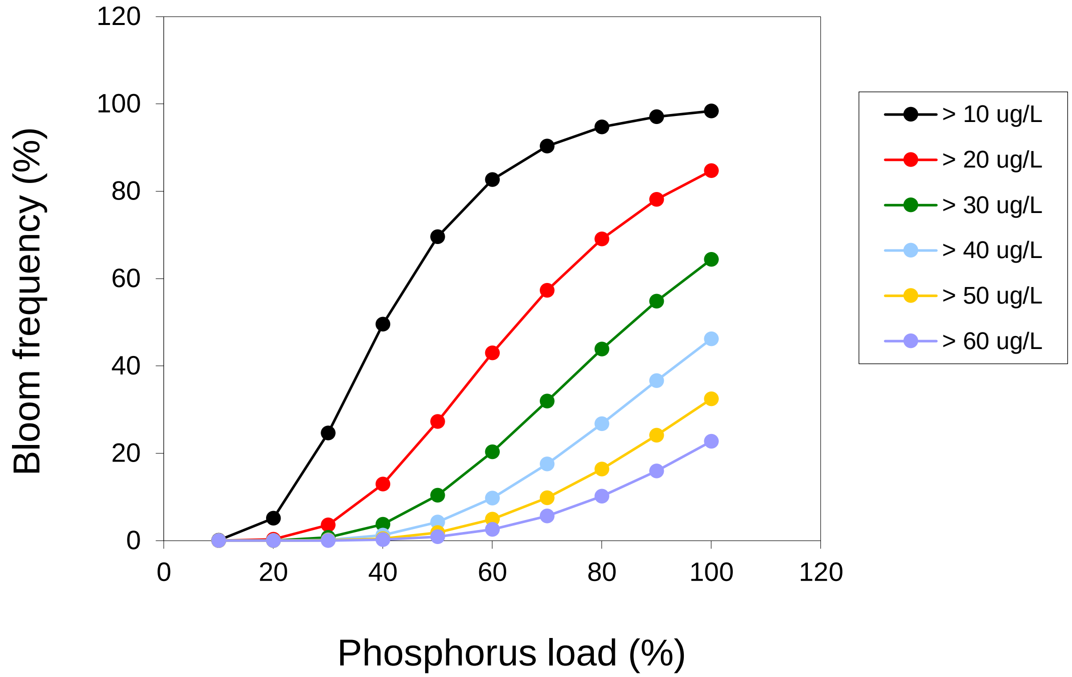


Figure 15. Bathtub (Walker 1996) model output of predicted changes in algal bloom frequency (as chlorophyll) as a function of reducing current mean 2010-13 mean summer P loading by 20% increments. 100% P load represents current loading conditions.

APPENDICES

Appendix 1a. Lake Wisconsin summer (June-September to early October) means and standard errors (SE) for the headwater station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi	TKN	NHx	N0x	Total N	Particulate N	Particulate P	N:P ratio	N:P ratio
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mass:mass)	(Mol:Mol)
2010-13													
Mean[1]	0.090	0.098	36.7	0.0142	0.8	1.072	0.025	0.299	1.371	1.047	0.076	13.8	30.6
SE	0.003	0.004	3.4	0.003	0.031	0.036	0.004	0.039	0.037	0.037	0.002	0.4	0.9
2010													
Mean	0.108	0.115	23.2	0.0298	0.9	1.043	0.036	0.397	1.441	1.007	0.078	13.1	28.9
SE	0.007	0.008	2.3	0.006	0.048	0.031	0.007	0.064	0.056	0.030	0.004	0.4	0.9
2011													
Mean	0.076	0.083	37.0	0.0077	0.8	0.949	0.017	0.335	1.284	0.932	0.069	13.7	30.4
SE	0.005	0.005	5.7	0.002	0.050	0.057	0.004	0.069	0.052	0.060	0.005	0.6	1.4
2012													
Mean	0.083	0.090	54.6	0.0022	0.6	1.157	0.011	0.132	1.289	1.146	0.081	14.2	31.4
SE	0.003	0.005	6.7	0.001	0.027	0.102	0.001	0.059	0.075	0.101	0.004	1.1	2.5
2013													
Mean	0.095	0.102	32.1	0.0171	0.8	1.138	0.034	0.331	1.468	1.103	0.078	14.4	31.9
SE	0.007	0.009	7.6	0.006	0.067	0.071	0.012	0.098	0.097	0.076	0.003	1.0	2.3

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Appendix 1b. Lake Wisconsin summer (June-September to early October) means and standard errors (SE) for the middle station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi	TKN	NHx	N0x	Total N	Particulate N	Particulate P	N:P ratio	N:P ratio
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mass:mass)	(Mol:Mol)
2010-13													
Mean[1]	0.101	0.102	49.9	0.0121	0.7	1.188	0.037	0.186	1.374	1.151	0.089	13.1	29.1
SE	0.003	0.003	3.7	0.002	0.031	0.041	0.005	0.033	0.045	0.041	0.003	0.4	0.9
2010													
Mean	0.112	0.113	36.6	0.0284	0.8	1.162	0.060	0.266	1.429	1.102	0.087	13.0	28.7
SE	0.008	0.009	4.9	0.005	0.089	0.047	0.008	0.055	0.083	0.045	0.005	0.8	1.8
2011													
Mean	0.092	0.092	51.4	0.0057	0.7	1.091	0.023	0.198	1.289	1.068	0.086	12.4	27.5
SE	0.006	0.007	7.1	0.002	0.048	0.086	0.006	0.072	0.071	0.087	0.007	0.4	0.8
2012													
Mean	0.103	0.105	67.3	0.0014	0.5	1.271	0.019	0.043	1.314	1.252	0.102	12.6	27.9
SE	0.006	0.004	5.9	0.000	0.026	0.104	0.007	0.018	0.102	0.105	0.006	1.3	2.9
2013													
Mean	0.096	0.098	44.1	0.0146	0.7	1.228	0.044	0.236	1.463	1.183	0.082	14.5	32.1
SE	0.006	0.006	8.0	0.004	0.028	0.077	0.014	0.081	0.101	0.081	0.005	0.4	0.8

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Appendix 1c. Lake Wisconsin summer (June-September to early October) means and standard errors (SE) for the dam station.

Statistic	Total P (Surface)	Total P (Bottom)	Chlorophyll	SRP	Secchi	TKN	NHx	N0x	Total N	Particulate N	Particulate P	N:P ratio	N:P ratio
	(mg/L)	(mg/L)	(ug/L)	(mg/L)	(m)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mass:mass)	(Mol:Mol)
2010-13													
Mean[1]	0.099	0.102	52.5	0.0127	0.8	1.229	0.062	0.155	1.384	1.167	0.087	13.5	29.8
SE	0.004	0.004	4.9	0.002	0.053	0.061	0.010	0.029	0.055	0.063	0.003	0.4	0.9
2010													
Mean	0.104	0.114	42.6	0.0243	1.0	1.134	0.063	0.197	1.330	1.071	0.083	13.3	29.4
SE	0.011	0.009	6.7	0.006	0.194	0.079	0.018	0.049	0.060	0.089	0.007	0.8	1.8
2011													
Mean	0.093	0.098	53.1	0.0078	0.7	1.151	0.070	0.173	1.324	1.081	0.085	12.9	28.5
SE	0.007	0.008	7.0	0.002	0.036	0.100	0.024	0.062	0.101	0.087	0.006	0.7	1.6
2012													
Mean	0.090	0.091	57.4	0.0026	0.6	1.260	0.057	0.053	1.313	1.203	0.088	13.6	30.0
SE	0.004	0.008	6.3	0.001	0.026	0.111	0.026	0.027	0.097	0.125	0.004	1.1	2.4
2013													
Mean	0.110	0.108	55.7	0.0188	0.7	1.361	0.057	0.201	1.562	1.303	0.091	14.2	31.5
SE	0.008	0.007	16.2	0.005	0.059	0.172	0.016	0.076	0.151	0.178	0.009	0.8	1.8

[1]Represents the mean of all values measured between June-September to early October over 2010-13.

Wisconsin River TMDL: Bathtub Lake Model Setup and Results for Minocqua Lake, Kawaguesaga Lake, and Redstone Lake

Introduction

This report summarizes the setup and results of Bathtub modeling for Kawaguesaga and Minocqua Lakes in Oneida County, and Redstone Lake in Sauk County. These lakes are on Wisconsin's 303(d) list of impaired waters for phosphorus related impairments and are part of the larger Wisconsin River basin Total Maximum Daily Load for total phosphorus.

Model Setup and Development

Steady-state modeling was conducted using Bathtub (Version 6.1, Walker 1996). Bathtub is a windows-based software program that provides a suite of empirical equations for predicting lake averages of phosphorus, chlorophyll, and Secchi transparency. Model outputs were only analyzed for phosphorus and no additional modeling evaluation was conducted for chlorophyll and Secchi.

Lake surface area and volume were based on values reported on WDNR lake survey maps (http://dnr.wi.gov/lakes/maps/). Mixed layer depth was based on model predictions. Redstone Lake was modeled as a single basin, while Minocqua and Kawaguesaga Lakes were modeled as two separate but connected basins. All model runs were based on annual loadings.

Table 1: Lake morphology information

Lake	WBIC	Surface Area (km^2)	Length (km)	Mean depth (m)	Mixed Layer Depth (m)
Minocqua	1542400	5.332	4.0	7.05	5.7
Kawaguesaga	1542300	2.792	2.9	5.18	4.7
Redstone	1280400	2.450	4.28	4.35	3.0

Long term annual average water and nutrient loads to each lake (Table 2) were estimated using the SWAT model developed for the Wisconsin River basin TMDL (WDNR 2016). Atmospheric loading rates were based on a precipitation rate of 0.8 m/yr and a phosphorus load of 30 mg/m^2/yr.

Table 2: Water and nutrient loading information

Lake	Watershed Area (km^2)	Mean Annual Flow (hm^3/yr)	Tributary Flow Weighted Mean TP (µg/L)	Tributary P loading (kg/yr)	Atmospheric P Loading (kg/yr)	SWAT Sub-basin(s)
Minocqua	164.51	54.3	22.8	1,240	99.0	134, 133, 168, 226
Kawaguesaga	15.63	4.99	21.4	107	51.8	135
Redstone	74.61	21.5		3,524	73.5	13, 15, 16

Surficial total phosphorus results for the modeled lakes were acquired from the department's comprehensive 2014 Lake Assessment data set developed for Wisconsin's 2014 Impaired Waters List. This data set encompassed the period from 2003 through 2012.

The total phosphorus sub-model was selected based on overall model fit. Model fit was adequate in all cases and no site-specific calibration was required.

Table 3: Monitoring and Modeling Results

Lake	Assessed Years	# Sample Results	Observed TP (µg/L)	Predicted TP (µg/L)	% diff	TP Sub-model
Minocqua	2003-2011	31	16.7	17.0	2%	Canfield Bachman - Lakes
Kawaguesaga	2003,2006, 2010-2012	14	17.7	17.3	2%	Canfield Bachman - Lakes
Redstone	2006-2012	13	57.1	61.0	6%	Canfield Bachman - Reservoirs

Loading Capacity

To determine loading capacity for each lake, upstream tributary concentrations were sequentially lowered until modeled in-lake total phosphorus matched the waterbody's phosphorus criterion under NR 102.06 Wis. Admin. Code. Atmospheric phosphorus loading rates were held constant as were hydraulic loading rates.

Table 4: Loading Capacity

Lake Name	TP Criteria (µg/L)	Tributary P loading (kg/yr)	Tributary Flow Weighted Mean TP (µg/L)	Predicted in-Lake P (µg/L)	% reduction
Minocqua	15	1,032	19	15	17%
Kawaguesaga	15	94.8	19	15	11%
Redstone	30	1,175	60	30	67%

Wisconsin River TMDL: Lake Model Setup and Results for Lake Delton

Introduction

This report summarizes the setup and results of modeling for Lake Delton in Sauk County. This lake is on Wisconsin's 303(d) list of impaired waters for phosphorus related impairments and are part of the larger Wisconsin River Basin Total Maximum Daily Load for total phosphorus.

Model Setup and Development

Steady-state modeling was conducted using Wisconsin Lake Modeling Suite (WiLMS Version 3.318.1, WDNR 2001). WiLMS is a windows-based software program that provides a suite of empirical equations for predicting lake averages of phosphorus.

Lake surface area and volume were based on values reported on WDNR lake survey maps (http://dnr.wi.gov/lakes/maps/). All model runs were based on annual loadings not seasonal loading.

Table 1: Lake morphology information

Lake	WBIC	Surface Area (acres)	Mean Depth (ft)
Minocqua	1295400	249	12

Long term annual average water and nutrient loads to each lake (Table 2) were estimated using the SWAT model developed for the Wisconsin River basin TMDL (WDNR 2016). Atmospheric loading rates were based on the default loading rates from WiLMS and comprised a minor fraction of the total phosphorus budget (30 kg/yr).

Table 2: Water and nutrient loading information

Lake	Watershed Area (km^2)	Mean Annual Flow (hm^3/yr)	Tributary P loading (kg/yr)	SWAT Sub-basin(s)
Delton	202.3	63.04	7,385	30, 31, 32

Surficial total phosphorus results for the modeled lakes were acquired from the department's comprehensive 2016 Lake Assessment data set developed for Wisconsin's 2016 Impaired Waters List. This data set encompassed the period from 2010 through 2014.

The total phosphorus sub-model was selected based on overall model fit.

Table 3: Monitoring and Modeling Results

Lake	Assessed Years	# Sample Results	Observed TP (µg/L)	Predicted TP (µg/L)	% diff	TP Sub-model
Delton	2010-2014	10	73	74	1%	Canfield Bachman – Artificial Lakes

Loading Capacity

To determine loading capacity for each lake, the WiLMS load back calculation routine was used to back calculate an annual loading to match the in-lake total phosphorus criterion under NR 102.06 Wis. Admin. Code. Atmospheric phosphorus loading rates were held constant as were hydraulic loading rates.

Table 4: Loading Capacity

Lake Name	TP Criteria (µg/L)	Tributary P loading (kg/yr)	% reduction
Delton	40	3,371	54%