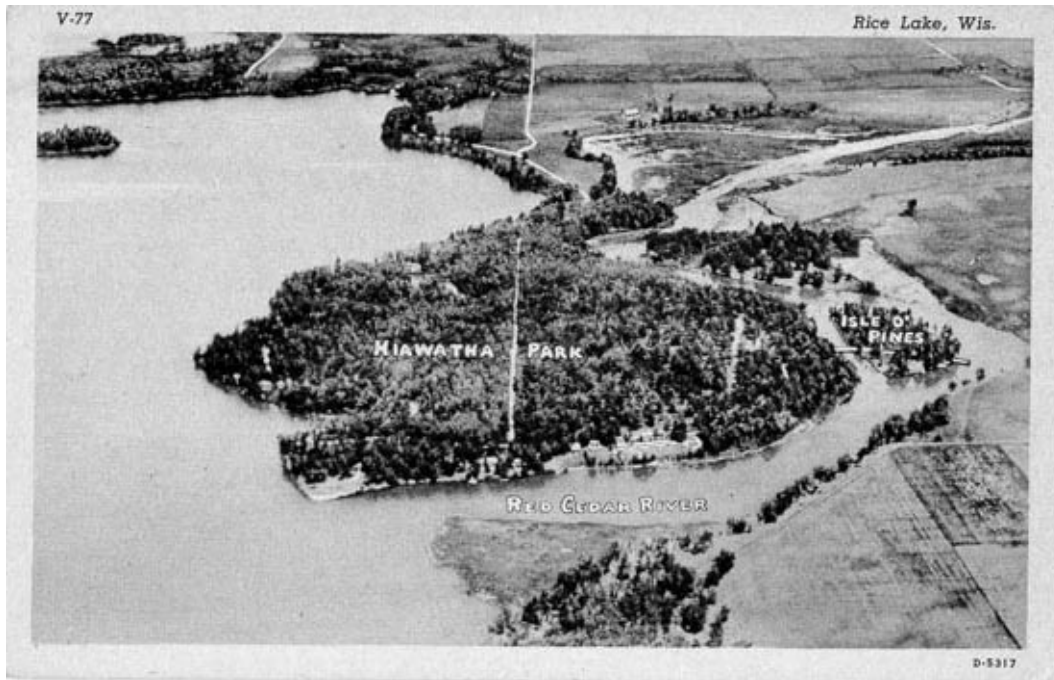


Limnological Analysis of Rice Lake, Wisconsin



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PREFACE:

This study was conducted in response to a request from the State of Wisconsin Department of Natural Resources (WI-DNR) to the U.S. Army Engineer District (USAED), St. Paul, for planning assistance under Section 22 of the Water Resources Development Act (Public Law 93-251). Funding was provided by the WI-DNR and USAED, St. Paul. The study coordinator for WI-DNR was Mr. Daniel Simonson. The Section 22 coordinator for the USAED, St. Paul, was Mr. Terry Engel.

This study was conducted and the report written by Mr. William F. James, Dr. John W. Barko, and Mr. Harry L. Eakin of the Eau Galle Aquatic Ecology Laboratory (EGAEL) of the Environmental Processes and Effects Division (EPED) of the Environmental Laboratory (EL), WES. We gratefully acknowledge Mss. Laura Blegen, Allysa Boock, Tiffany Brunner, Susan Fox, Emily Gillis, and Stephanie Sweeney, and Messrs. Dale Dressel, Allan Lamphere, Mathew Pommier, and Eric Secrist of the EGAEL for water and sediment sampling, chemical analyses, and execution of studies on phosphorus release from sediments.

ABSTRACT:

We examined external constituent loadings from tributary inflows, internal phosphorus fluxes from profundal sediments, and water quality conditions in Stump and Rice Lake in 2001. Water samples for external loadings were collected from the Red Cedar River and Bear Creek. Four stations were established in the main basin of the lake complex (1 in Stump Lake and 3 in Rice Lake) for limnological profiling during the summer (May through September). Sediment cores were collected at these same stations for laboratory determinations of phosphorus release from sediment as a function of eH and pH.

There were a number of storm inflow periods to the lake complex during the summer period. During periods of storm inflow, the hydraulic residence time of the lake complex declined to < 10 days (often less than 5 days). During periods of nominal inflow the hydraulic residence time was usually > 15 days. The Red Cedar River contributed 50% or more of the measured external suspended sediment and nutrient load to the lake complex.

Internal loading of P via release from oxic profundal sediment, measured in laboratory incubation systems, ranged between undetectable and $0.9 \text{ mg m}^{-2} \text{ d}^{-1}$, while P release from anoxic sediment was very high (range = 2.7 to $12 \text{ mg m}^{-2} \text{ d}^{-1}$). Increasing the pH in oxic systems resulted in greater rates of phosphorus release from sediments under oxic conditions at 2 of the stations (i.e., Stump Lake and Rice Lake Station 1). Lake-wide rates of P release from oxic and anoxic sediment, estimated via laboratory incubation techniques that were extrapolated over the summer period (May through September), averaged only $0.4 \text{ mg m}^{-2} \text{ d}^{-1}$, versus a summer external phosphorus loading rate of $9.4 \text{ mg m}^{-2} \text{ d}^{-1}$. This budgetary comparison indicated that external phosphorus loads were probably much more important in regulating algal productivity in the lake complex than internal phosphorus loads during the summer of 2001.

Station 3, located in the more isolated southern lobe of Rice Lake, exhibited an extended period of thermal stratification between mid-June and early August. Associated with stratification in this region of the lake complex was the occurrence of dissolved oxygen depletion and development of anoxia in the bottom waters. Coincident with hypolimnetic anoxia was the development of elevated concentrations of phosphorus in the bottom waters, indicating some internal loading of phosphorus from the sediments at this location. Other stations in Rice Lake, located closer to the influences of the Red Cedar River and Bear Creek, exhibited only very brief periods of stratification and bottom water anoxia due, presumably, to the flushing influences of the tributary inflows. Phosphorus increases in the bottom waters were much less at these stations. The Carlson and Wisconsin Trophic State Indices for Secchi transparency, viable chlorophyll *a*, and total phosphorus ranged between 47 and 63, indicative of meso-eutrophic conditions in the lake complex during the summer during the summer.

We evaluated the impacts on algal biomass and water clarity of incremental reductions and increases in external P loading to the lake complex using the water quality model *Bathtub*. Seasonal (May through September) measured external phosphorus loads (i.e., from the Red Cedar River and Bear Creek) were varied between 25% and 200% of current (i.e., 2001) loading conditions. *Bathtub* results indicated that the lake complex is very sensitive to phosphorus loading reductions and increases. Reducing external P loading by 50% resulted in an

approximately 58% reduction on chlorophyll concentrations. In contrast, increasing external P loading by 50% resulted in an estimated 62% increase in chlorophyll concentration. These results suggested that managing external P loads will improve chlorophyll in the lake complex.

INTRODUCTION:

The overall objectives of these investigations were to examine water quality conditions and constituent fluxes of Rice Lake, Wisconsin. The relative importance of various internal and external nutrient (primarily phosphorus) loadings were evaluated in relation to water quality conditions and phytoplankton biomass (chlorophyll) in the lake. Predicted impacts of P loading reduction on viable chlorophyll *a* concentrations in the lake were examined using the model *Bathtub* (Walker 1996). The report summarizes results from 2001.

METHODS:

External Loading

Stage elevations on the Red Cedar River at 23rd Street and Bear Creek at County Road SS (Barron County) were monitored using continuous stage height recorders (ISCO Model 730 and Model 6700). Stage elevations were converted to volumetric flow using a rating curve (i.e., stage height versus flow relationships) generated over a range of flow regimes. Rice Lake pool elevation fluctuations were obtained from the City of Rice Lake. Grab samples were collected from tributary inflows at biweekly intervals and analyzed for the variables listed in Table 1. For total suspended sediment analysis, suspended material retained on a precombusted glass fiber filter (Gelman (A/E)) was dried to a constant weight at 105 °C (APHA 1992; Method 2540 D). Samples for total nitrogen and phosphorus were predigested with potassium persulfate according to Ameal et al. (1993) before analysis. Water samples for analysis of soluble constituents were filtered through a 0.45 µm filter (Gelman Metricel) prior to analysis of nitrate-nitrite-N, ammonium-N, and soluble reactive phosphorus. Nitrogen and phosphorus constituents were measured colorimetrically on a Lachat QuikChem automated water chemistry system (Zellweger Analytics, Lachat Div., Milwaukee, WI). Loadings by various external sources were estimated using the computer model *Flux* (Walker 1996). Loadings were estimated via either weighting concentrations with respect to flow (Method 2) or via a regression algorithm (Method 6).

Internal Loading

Nine replicate intact sediment cores were collected from the profundal sediments of four stations in the Rice Lake complex (Fig. 1), for determination of rates of soluble reactive phosphorus release from the sediment. Sampling depths were 1.5 m at Stump Lake, 4.6 m at Rice Lake Station 1, 4.5 m at Rice Lake Station 2, and 5.4 m at Rice Lake Station 3. Sediment cores were collected using a Wildco KB sediment core sampler (Wildco Wildlife Supply Co.) equipped with an acrylic core liner (6.5-cm ID and 50-cm length). Additional lake water was collected from the epilimnion for incubation with the collected sediment. Overall, a total of 36 sediment cores were collected for examination of P release from sediments in the lake complex.

Sediment systems, constructed according to the methods of James and Barko (1991), were incubated in an environmental chamber at 20° C for 1-2 weeks. One set of 3 replicate sediment incubation systems was subjected to an oxic environment while another other set (3 replicates) was subjected to an anoxic environment for each station. The oxidation-reduction environment in each system was controlled by gently bubbling either air (oxic) or nitrogen (anoxic) through an air stone placed just above the sediment surface. Bubbling action insured complete mixing of the water column but did not disrupt or resuspend the sediment. The third set of three replicate sediment incubation systems was subjected to an oxic environment and high pH (~9.0) by bubbling with CO₂-free air. Water samples were collected daily from the overlying water of each sediment system, filtered through a 0.45 µm membrane filter, and analyzed colorimetrically for soluble reactive phosphorus using the ascorbic acid method (APHA 1992). pH was measured using a pH probe calibrated against known buffer solutions. Rates of phosphorus release from the sediment (mg m⁻² d⁻¹) were calculated as the linear change in phosphorus mass in the overlying water (corrected for dilution effects due to daily replacement of lake water) divided by time and the surface area of the incubation system (0.00332 m²).

Limnological Monitoring

Four stations were established in the Stump-Rice Lake complex for limnological monitoring purposes (Fig. 1). During the ice-free period, water samples were collected biweekly at 1-m intervals from the surface (i.e., 0.1 m) to within 0.5 m from the bottom for the water quality variables listed in Table 1. For soluble constituents (i.e., soluble reactive phosphorus), samples collected from anoxic water in the lake were filtered immediately without exposure to oxygen. Samples for chlorophyll were extracted in dimethyl-sulfoxide (DMSO)-acetone (50:50) at < 0 °C for a minimum of 12 hours. Viable chlorophyll *a* was determined fluorometrically (Turner model TD-700) according to Welschmeyer (1994). In conjunction with the water sampling schedule, measurements of water temperature, dissolved oxygen, pH, and conductivity were collected using a Hydrolab Surveyor III that was precalibrated against Winkler titrations (APHA 1992) and buffer solutions. The Carlson Trophic State Index (Carlson 1977) was estimated using Secchi transparency values and total phosphorus and viable chlorophyll *a* concentrations weighted with respect to water column depth and area (*Profile*; Walker 1996). In addition, the Wisconsin Trophic State Index was estimated using equations described in Lillie et al. (1993). The computer model *Bathtub* (Walker 1996) was used as a management tool to forecast the trophic response of Rice Lake to reductions and increases in P loading.

RESULTS:

Hydrological Conditions

During the period May through September, storm-related peaks in Red Cedar River and Bear Creek flow occurred in mid-May, mid-June, mid-July, and early August (Fig. 2). The hydraulic residence time of the lake complex (i.e., Rice and Stump Lakes) was usually < 10 days during these storm inflow periods. Extended periods of lower flow, occurring in mid-May through early June, early July, and mid-August through September, resulted in much higher lake hydraulic residence times, ranging between 12 and > 30 days (Fig. 2). Overall, average flows for the Red

Cedar River (7.6 cms) were 2.2 times greater than average flows for Bear Creek (3.4 cms) during the summer. The average lake hydraulic residence time of the lake complex was 15 days.

Sediment and Nutrient Sources and Sinks

External Loading. The Red Cedar River contributed greater than 60% of the measured total suspended sediment, total nitrogen, total phosphorus, nitrate-nitrite-N, and ammonium-N load to the lake complex (Table 2). Soluble nitrogen species (nitrate-nitrite-N and ammonium-N) accounted for 35% and 54% of the total nitrogen load from the Red Cedar River and Bear Creek, respectively. In contrast, particulate phosphorus dominated the phosphorus load to the lake complex, as soluble reactive phosphorus represented only 16% and 26% of the total phosphorus load from the Red Cedar River and Bear Creek, respectively.

Internal Loading. Rates of phosphorus release from profundal sediments, measured in the laboratory, were substantial under anoxic conditions, ranging between a mean (n=3) of 2.7 and 12.0 mg m⁻² d⁻¹ for the 4 in-lake stations (Table 2). Mean rates of phosphorus release under oxic conditions were substantially lower at Stump Lake and Rice Lake Station 1 and undetectable at Rice Lake Stations 2 and 3. Elevating the pH of the sediment systems resulted in the occurrence of greater rates of phosphorus release under oxic conditions for profundal sediments collected from Stump Lake and Rice Lake Station 1. In general, there appeared to be a gradient in rates of phosphorus release from sediments in the lake complex, as they were greatest in the north region at Stump Lake and station and Rice Lake Station 1 and much lower in the southern region.

Limnological Conditions

Stratification was strongest at Rice Lake Station 3 (Fig. 3), which is isolated from the direct influences of the Red Cedar River by a channel (Fig. 1). At this station, a thermocline was observed between the 2- and 4-m depths from late June through early August. Stratification was much weaker and more intermittent at Rice Lake Stations 1 and 2, due presumably to the flushing influences of the Red Cedar River and Bear Creek (Fig. 3). Stratification occurred briefly in mid- through late July. Isothermal conditions were established at the three Rice Lake stations in early September.

Coincident with periods of stratification was the occurrence of rapid dissolved oxygen depletion in the bottom waters and the development of anoxic conditions (Fig. 4). Dissolved oxygen depletion and anoxic conditions in the bottom waters were most pronounced at Rice Lake Station 3, coinciding with the development of strong stratification. Concentrations of dissolved oxygen were < 2 mg/L in the bottom waters of this station between mid-May and mid-September. Anoxia extended to the 4-m depth at this station in late July. At Rice Lake Stations 1 and 2, the occurrence of anoxia in the bottom waters occurred very briefly in late July and early August. During other periods, dissolved oxygen was > 4 mg/L throughout the water column at these stations. In the surface waters of all Rice Lake stations, dissolved oxygen was > 8 mg/L throughout the summer, often reaching 10 mg/L. Stump Lake exhibited dissolved oxygen concentrations > 4 mg/L throughout the study period (not shown).

Chlorophyll was very low throughout the summer in Stump Lake compared to stations located in Rice Lake (Fig. 5). This pattern may be related to the occurrence of macrophyte dominance in this shallow lobe of the lake, which compete with algae for light and nutrients. In Rice Lake, chlorophyll was low in May and reached a peak in mid-July. In early August, concentrations declined at Rice Lake Stations 1 and 2, but remained high at Station 3 (Fig. 5). This pattern was related to a large storm inflow in early August that reduced lake hydraulic residence time substantially, resulting in flushing of algae from the main basin of the lake. Because Rice Lake Station 3 was located in the more isolated southern lobe of Rice Lake, flushing of this water and removal of algae was probably much less. A secondary peak occurred in early September at the three stations located in Rice Lake. Concentrations declined in October in conjunction with autumnal overturn.

Phosphorus exhibited a complex pattern that was related to the occurrence of storm inflows, internal loading from sediment under anoxic conditions, and algal blooms (Fig. 6). For instance, peaks in total phosphorus occurred in the lake complex in early August, which coincided with a large storm inflow that occurred during the same period (Fig. 2). Peaks in total phosphorus also often coincided with the occurrence of algal blooms (see Fig. 5), particularly at Station 3, suggesting incorporation of P as algal biomass. In the bottom water of all stations, total phosphorus increased in concentration under conditions of anoxia (Fig. 7). Increases in total P in the bottom waters were most pronounced at Rice Lake Stations 1 and 3. These patterns suggested the occurrence of some phosphorus release from profundal sediments under anoxic conditions.

Overall, mean total phosphorus was greatest in Stump Lake and lower in Rice Lake (Table 4). This pattern was probably related to concentration gradients observed between the inflows of Bear Creek and the Red Cedar River (Table 2). Stump Lake exhibited very low mean concentrations of chlorophyll relative to total phosphorus (for reasons described above), compared to mean patterns in chlorophyll observed in Rice Lake. Trophic state indices suggested that Rice lake exhibited meso-eutrophic conditions. during the summer months (Table 4).

Budgetary Analysis and Bathtub Modeling for the Summer Period of 2001

Budgetary Analysis. External phosphorus loadings, calculated for the period May through September using the program *Flux* (Table 2), were used as input for the model *Bathtub*. The estimated lakewide rate of external phosphorus loading was $9.4 \text{ mg m}^{-2}\text{d}^{-1}$ (Table 5). We estimated lakewide internal phosphorus loading from sediments using laboratory-based rates, measured for different regions of the lake complex, and *in situ* changes in dissolved oxygen and pH in the water column. In general, pH ranged between 6.8 and 9.1 for all stations, suggesting that elevated pH could enhance phosphorus release from the sediments (Table 3). However, the estimated lakewide rate of phosphorus release from sediment for the summer period was only $0.4 \text{ mg m}^{-2}\text{d}^{-1}$ (Table 5). Thus, external phosphorus loadings appeared to dominate phosphorus dynamics in the lake complex, based on budgetary comparison of measured external and internal phosphorus loadings (Table 5)

Bathtub Modeling. We used the default models and coefficients provided in the model *Bathtub* to explore algal response to loading variations. External phosphorus loading via the Red Cedar River and Bear Creek was incrementally increased and decreased under 2001 summer flow

conditions to examine effects of changes in phosphorus loading on chlorophyll concentrations in the lake complex. Since lakewide internal phosphorus loading was low relative to external sources, we did not add this component to the model, but instead relied on adjustments in the phosphorus calibration coefficient to account for internal phosphorus loading impacts. We also used concentrations representing the weighted mean for the entire water column of the lake complex in the *Bathtub* analysis. Our justification for using the entire water column (rather than the upper euphotic zone) was that the system was generally shallow and mixed, and viable algal were usually distributed throughout the water column and sometimes higher in concentration at mid- and lower depths.

Both total phosphorus and chlorophyll varied linearly as a function of changes in phosphorus loading, while Secchi transparency responded in an inverse manner (Fig. 8). With 50% phosphorus loading reduction, chlorophyll concentrations were reduced by ~ 58%, while Secchi transparency increased by ~ 24%, over 2001 nominal levels (Fig. 8). In contrast, increasing external P loading 100% over 2001 levels via, for example changing land use patterns (increasing agricultural land use and urbanization coupled with declining forested lands, wetlands, and buffer strips), resulted in a 62% increase in estimated summer chlorophyll levels over current conditions to nearly 40 mg/m³ (Fig. 8).

Changes in the estimated frequency of bloom for 2001 summer flow conditions are shown in Fig. 9. The model suggested that the algal bloom frequency in the lake complex could respond dramatically to changes in phosphorus loading. Currently, it is estimated that algal blooms > 30 mg/m³ can occur ~ 23% of the time in the summer. A 50% increase in external phosphorus loading would result in an estimated increase in this level of bloom frequency occurrence to 51% of the time in the summer. Conversely, a 50% reduction in external P loading would result in an estimated bloom frequency occurrence of chlorophyll > 30 mg/m³ only 2% of the time in the summer.

CONCLUSIONS:

Overall, Rice Lake is a moderately eutrophic reservoir exhibiting the occurrence of algal blooms and hypolimnetic anoxia in deeper portions of the lake during the summer. External phosphorus loading reduction via BMPs, development of vegetated shoreline buffer strips, and restoration of wetlands may be important avenues for controlling chlorophyll and the frequency of algal blooms in Rice Lake during the summer, as suggested by *Bathtub* results. *Bathtub* modeling results indicated that the lake complex is susceptible to deteriorating water quality conditions as external phosphorus loadings are increased above current conditions. Model results demonstrated that both concentrations of chlorophyll, and a greater frequency of occurrence of algal blooms of higher concentrations (resulting in lower transparency), could occur as external phosphorus loading increases.

Rates of phosphorus release from sediments were high under anoxic conditions and comparable to those rates measured for other eutrophic systems (Nürnberg et al. 1986). Anoxia was observed in the bottom waters at several stations during May through August, suggesting that reducing conditions in the hypolimnion were important in the regulation P release of the bottom sediments during these periods. One mechanism of P release under reducing conditions is

iron-phosphorus disassociation (Mortimer 1971). Under oxidized conditions, iron has a high binding affinity for phosphorus (Lijklema 1977). However, phosphorus bound to iron hydroxides can desorb and diffuse into the sediment porewater and the water column as iron compounds are reduced from Fe^{+3} to Fe^{+2} under conditions of hypolimnetic anoxia.

The pH also appeared to play an important role in affecting the rate of phosphorus release from sediments under oxic conditions at some stations in the lake complex, as the rate was elevated at higher pH. Others have demonstrated this relationship between phosphorus release from sediments and pH (Boers 1991; James et al. 1996). Enhanced phosphorus release at high pH (and high hydroxyl ion (OH^-) concentration) is thought to occur via ligand exchange and replacement of PO_4^- with an OH^- ion on oxidized Fe compounds (Drake and Heaney 1987). Photosynthesis by aquatic plants and algae, which is primarily responsible for driving pH up in aquatic systems, provides a mechanism of enhancing phosphorus release from sediments under oxic conditions.

An indirect impact that we did not explore using *Bathtub* is the likelihood that dissolved oxygen demand could increase if external phosphorus loading and storage of oxygen-demanding materials in the sediment increases, particularly under conditions of higher lake hydraulic residence time. This scenario could further aggravate dissolved oxygen demands in the bottom waters, leading to enhanced phosphorus recycling from the sediment via anoxic phosphorus release. Greater productivity as a result of increases in external phosphorus loading could also exacerbate phosphorus release from the sediments indirectly by increasing the pH in the water column. This new internal source of phosphorus, in combination with greater external phosphorus loading, could result in higher algal concentrations and more frequent algal blooms.

Currently, however, it appears that low lake hydraulic residence times, caused by inflows from the Red Cedar River and Bear Creek, are important in regulating hypolimnetic anoxia to a certain extent by promoting exchange, mixing, and thermal instability. Only in the more isolated southern lobe of Rice Lake did we observe the development of persistent anoxia. Mid-summer drought conditions, increases in lake hydraulic residence time, and stronger stratification patterns could, however, result in the development of bottom water anoxia and subsequent recycling of phosphorus in other regions of the lake complex. Thus, reductions in watershed phosphorus loading, would have an added indirect benefit of reducing the rate of dissolved oxygen depletion in the bottom waters, and phosphorus release from profundal sediments, via an overall reduction in productivity and subsequent sedimentation of organic matter to the hypolimnion of the lake complex.

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TABLES

Table 1. Variable list for tributary loadings

FLOW, cms
TOTAL SUSPENDED SEDIMENT, mg/L
TOTAL NITROGEN, mg/L
NITRATE-NITRITE NITROGEN, mg/L
AMMONIUM NITROGEN, mg/L
TOTAL PHOSPHORUS, mg/L
SOLUBLE REACTIVE PHOSPHORUS, mg/L

Variable list for limnological monitoring

WATER TEMPERATURE, °C
DISSOLVED OXYGEN, mg/L
pH
CONDUCTIVITY, $\mu\text{S}/\text{cm}^2$
SECCHI TRANSPARENCY, cm
TOTAL SUSPENDED SEDIMENT, mg/L
TOTAL NITROGEN, mg/L
NITRATE-NITRITE NITROGEN, mg/L
AMMONIUM-NITROGEN, mg/L
TOTAL PHOSPHORUS, mg/L
SOLUBLE REACTIVE PHOSPHORUS, mg/L
VIABLE CHLOROPHYLL <i>a</i> , $\mu\text{g}/\text{L}$

Table 2. Summary statistics for summer (May-September) external loads to Rice Lake. CV represents the coefficient of variation.

Tributary	Total Suspended Sediment			Total Nitrogen			Nitrate-Nitrite Nitrogen			Ammonium Nitrogen		
	LOAD kg summer ⁻¹	CONC. mg L ⁻¹	CV	LOAD kg summer ⁻¹	CONC. mg L ⁻¹	CV	LOAD kg summer ⁻¹	CONC. mg L ⁻¹	CV	LOAD kg summer ⁻¹	CONC. mg L ⁻¹	CV
Red Cedar River	4.4 x 10 ⁵	4.4	0.350	89978	0.902	0.044	51916	0.520	0.083	6001	0.060	0.256
Bear Creek	2.5 x 10 ⁵	5.5	0.1256	34476	0.766	0.037	12869	0.286	0.079	3072	0.068	0.389

Tributary	Total Phosphorus			Soluble Reactive Phosphorus		
	LOAD kg summer ⁻¹	CONC. mg L ⁻¹	CV	LOAD kg summer ⁻¹	CONC. mg L ⁻¹	CV
Red Cedar River	3782	0.038	0.113	620	0.006	0.184
Bear Creek	2453	0.054	0.102	643	0.014	0.209

Table 3. Mean (\pm 1 S.D.) rates of phosphorus release from the profundal sediments ($\text{mg m}^{-2} \text{d}^{-1}$) of various stations measured under oxic and anoxic conditions.

Station	Oxic Rate (pH ~ 7.5)	Oxic Rate (pH ~ 9.0)	Anoxic Rate
Stump Lake	0.3 (0.1)	1.5 (0.4)	12.0 (2.4)
Rice Lake Station 1	0.2 (0.1)	0.9 (0.2)	10.1 (3.2)
Rice Lake Station 2	not detected	not detected	4.0 (1.2)
Rice Lake Station 3	not detected	not detected	2.7 (0.2)
Lakewide Summer Average		0.4	

Table 4. Estimates of Carlson and Wisconsin Trophic State Index (TSI) values for Stations located in Stump and Rice Lakes. Concentrations of chlorophyll *a* and total phosphorus (TP) and Secchi transparency represent means (CV) for the period May through September.

Station	Variable			Carlson TSI			Wisconsin TSI		
	Secchi, m	Chla, $\mu\text{g/L}$	TP, $\mu\text{g/L}$	TSI _{SD}	TSI _{chla}	TSI _{TP}	WTSI _{SD}	WTSI _{chla}	WTSI _{TP}
Stump L.	1.6 (0.08)	5.3 (0.09)	56 (0.08)	53	47	62	53	47	59
RL1	1.3 (0.09)	23.6 (0.17)	47 (0.14)	56	62	60	56	59	58
RL2	1.4 (0.08)	20.5 (0.14)	39 (0.14)	55	60	57	55	58	57
RL3	1.8 (0.15)	26.3 (0.18)	38 (0.16)	52	63	57	52	60	56
Lake Mean	1.5 (0.10)	20.7 (0.16)	43 (0.13)	54	60	58	54	58	57

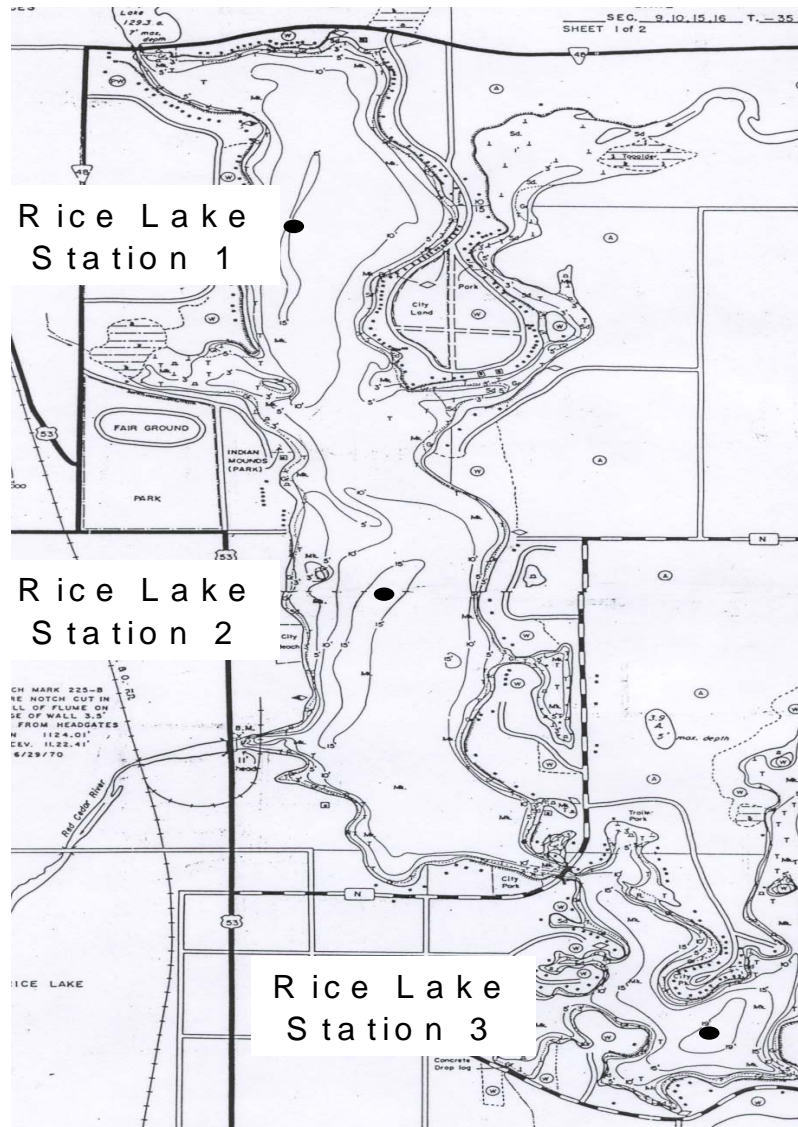


Figure 1. Location of water and sediment sampling stations in Rice Lake, Wisconsin. Stump Lake, located immediately north of Rice Lake, is not shown.

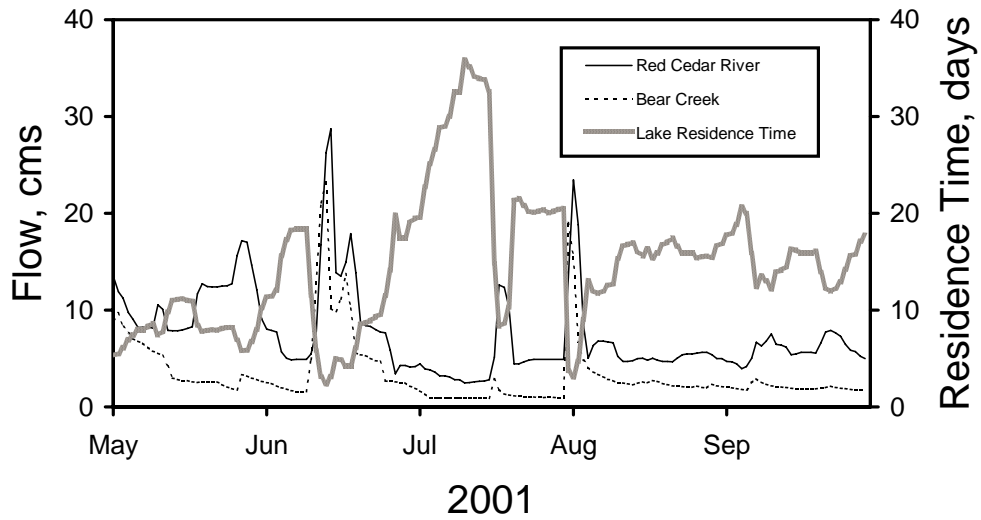


Figure 2. Seasonal variations in measured flow (cms = cubic meters per second) from the Red Cedar River and Bear Creek and the theoretical hydraulic residence time of the lake complex (i.e., Stump and Rice Lakes).

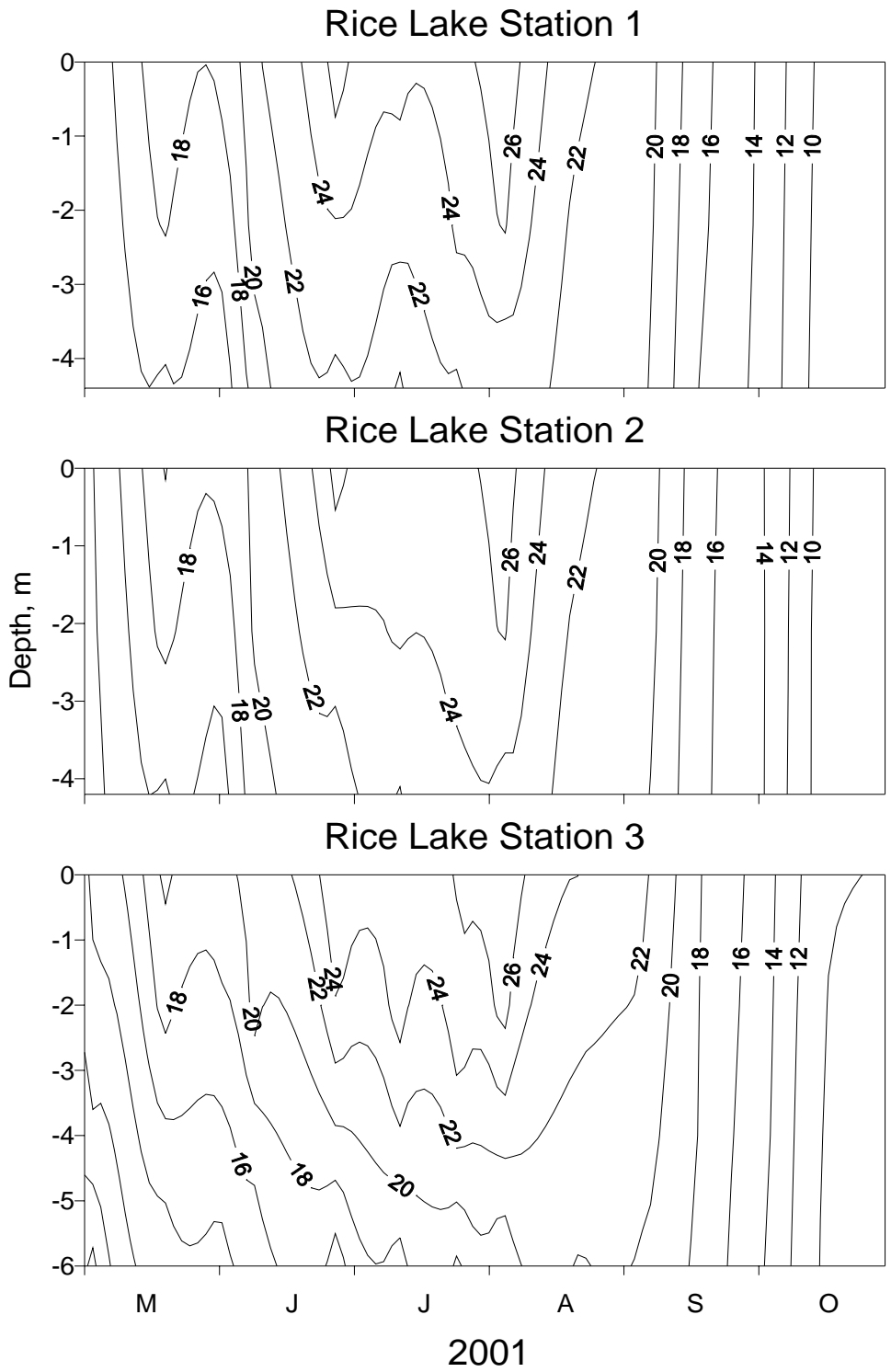


Figure 3. Seasonal and vertical variations in temperature ($^{\circ}\text{C}$) contours at Rice Lake Stations 1, 2, and 3 between May and September, 2001.

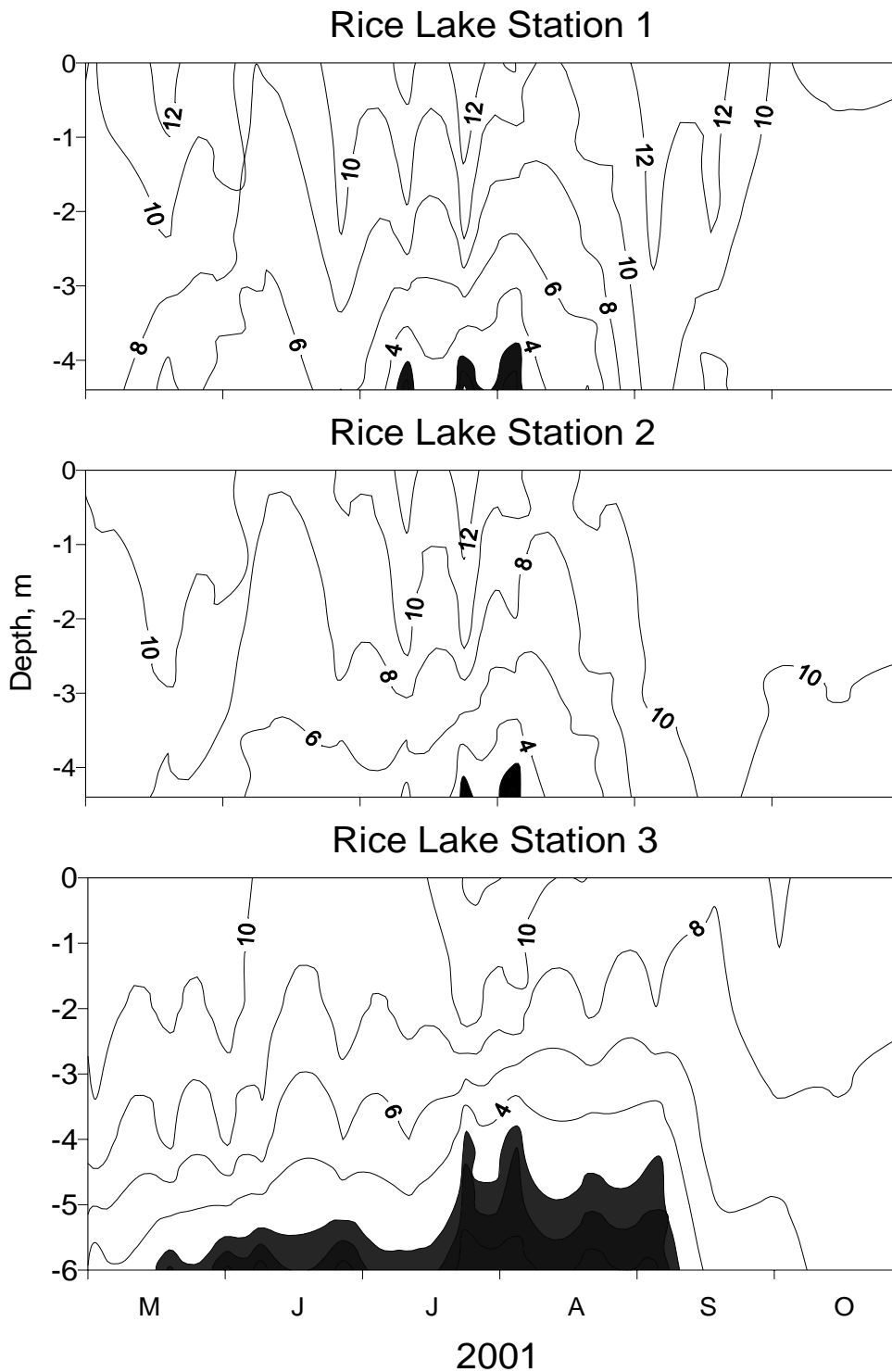


Figure 4. Seasonal and vertical variations in dissolved oxygen (mg/L) contours at Rice Lake Stations 1, 2, and 3 between May and September, 2001. Blackened areas represent depths where dissolved oxygen was < 2 mg/L (i.e., near anoxic conditions).

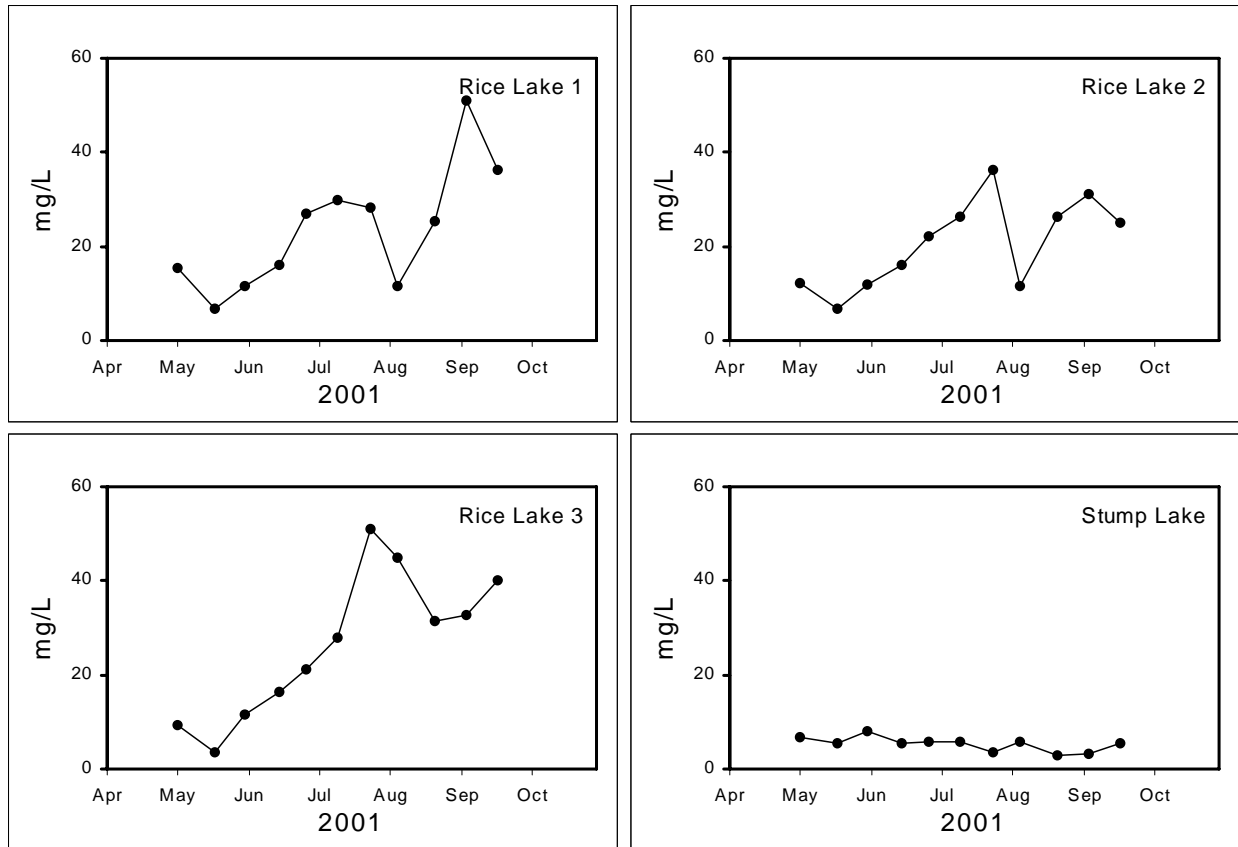


Figure 5. Seasonal Variations in water column viable chlorophyll concentrations in Rice Lake Stations 1, 2, and 3, and Stump Lake, between May and September, 2001.

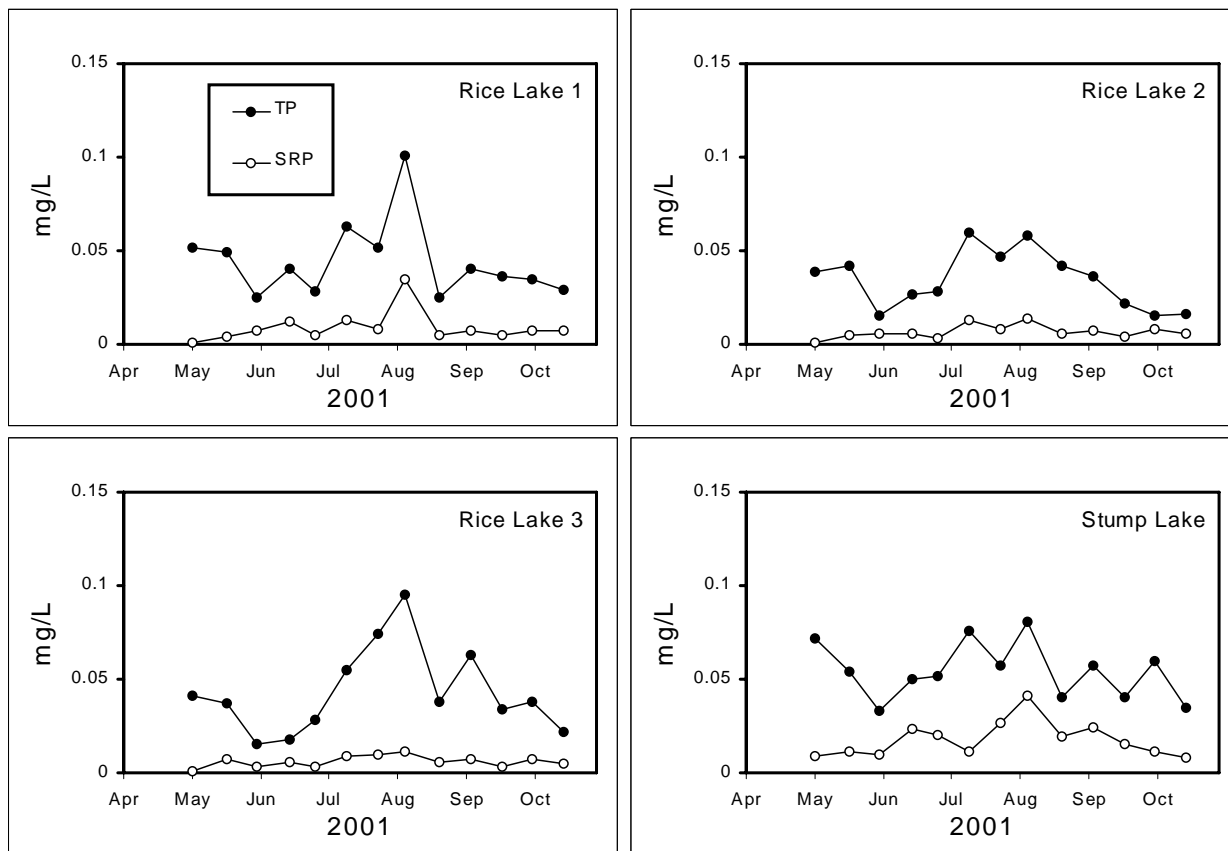


Figure 6. Seasonal Variations in water column total and soluble reactive phosphorus concentrations in Rice Lake Stations 1, 2, and 3, and Stump Lake, between May and September, 2001.

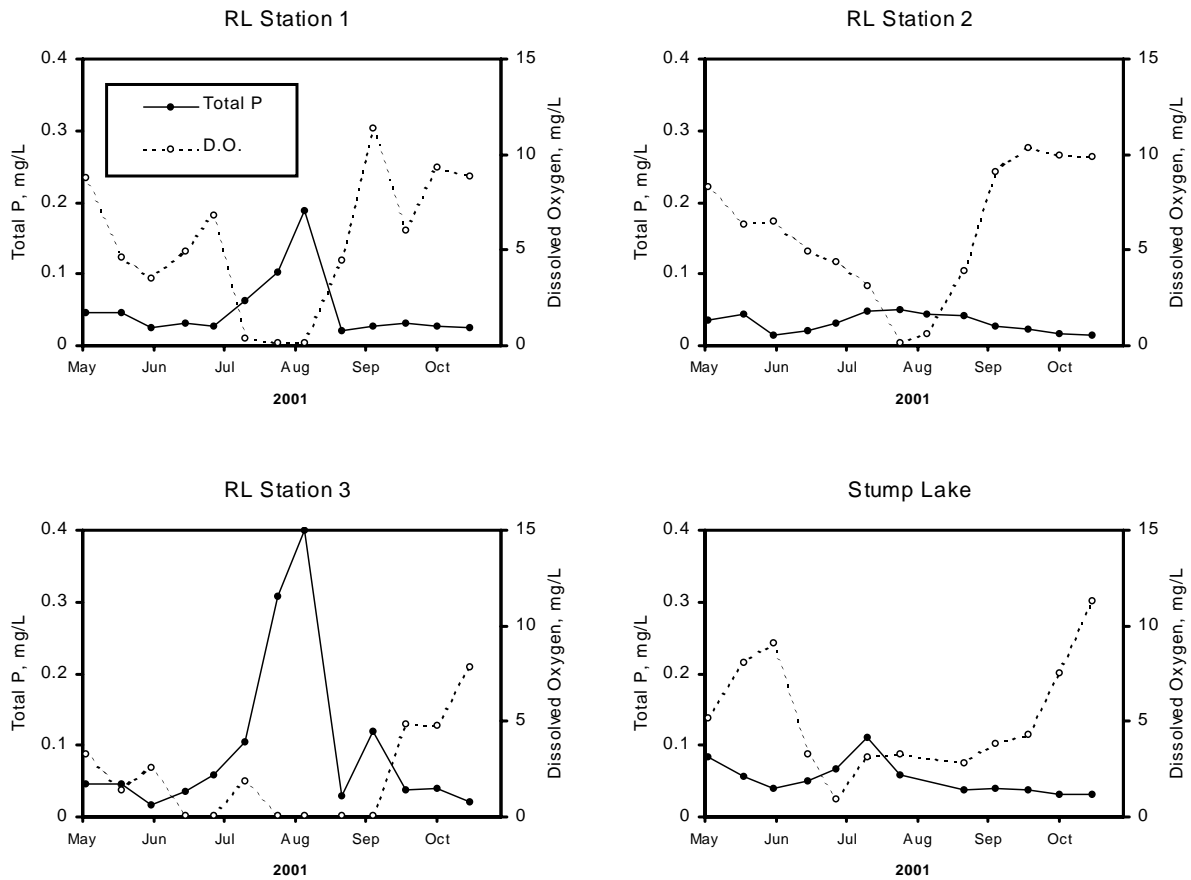


Figure 7. Seasonal Variations in total phosphorus and dissolved oxygen concentrations in the bottom waters (within 0.5 m of the sediment surface) of Rice Lake Stations 1, 2, and 3, and Stump Lake, between May and September, 2001.

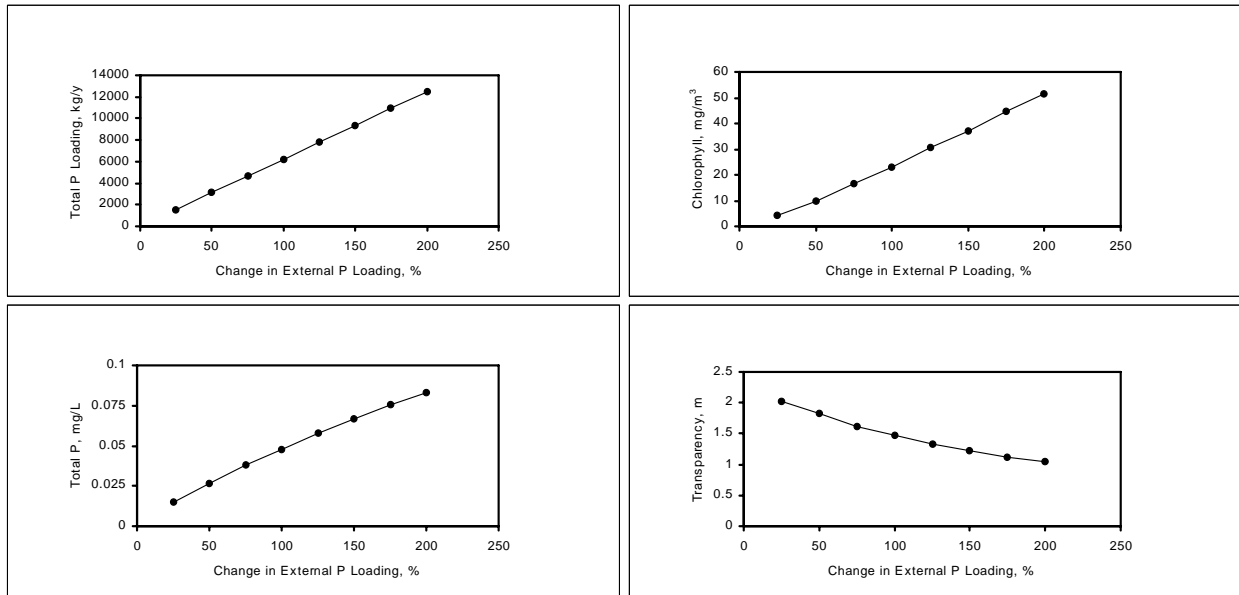


Figure 8. Incremental changes in external phosphorus loading above (i.e., greater than 100% or 2001 loading conditions) and below (i.e., less than 100% or 2001 loading conditions) current 2001 loading conditions (upper left panel), and corresponding changes in chlorophyll (upper right panel), total phosphorus (lower left panel), and Secchi transparency (lower right panel) determined in the lake complex (i.e., Stump and Rice Lakes) using the water quality model Bathub .

ESTIMATED BLOOM FREQUENCY Rice Lake

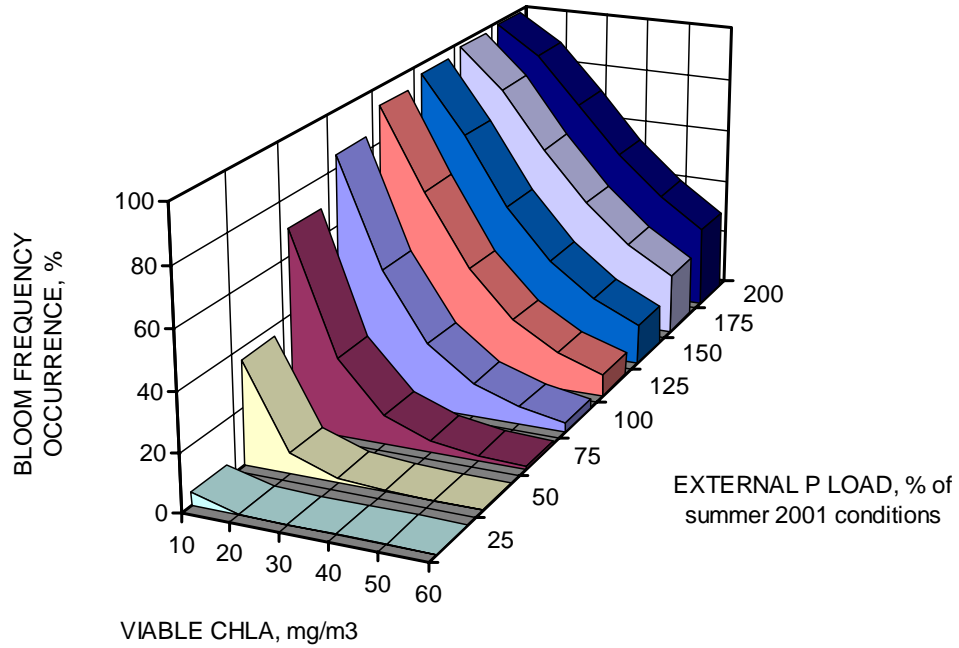


Figure 9. Estimated changes in the frequency of algal bloom occurrence of different concentrations of chlorophyll as a function incrementally increasing or decreasing external phosphorus loads to the lake complex (i.e., Stump and Rice Lakes). 100% represents current loading conditions.