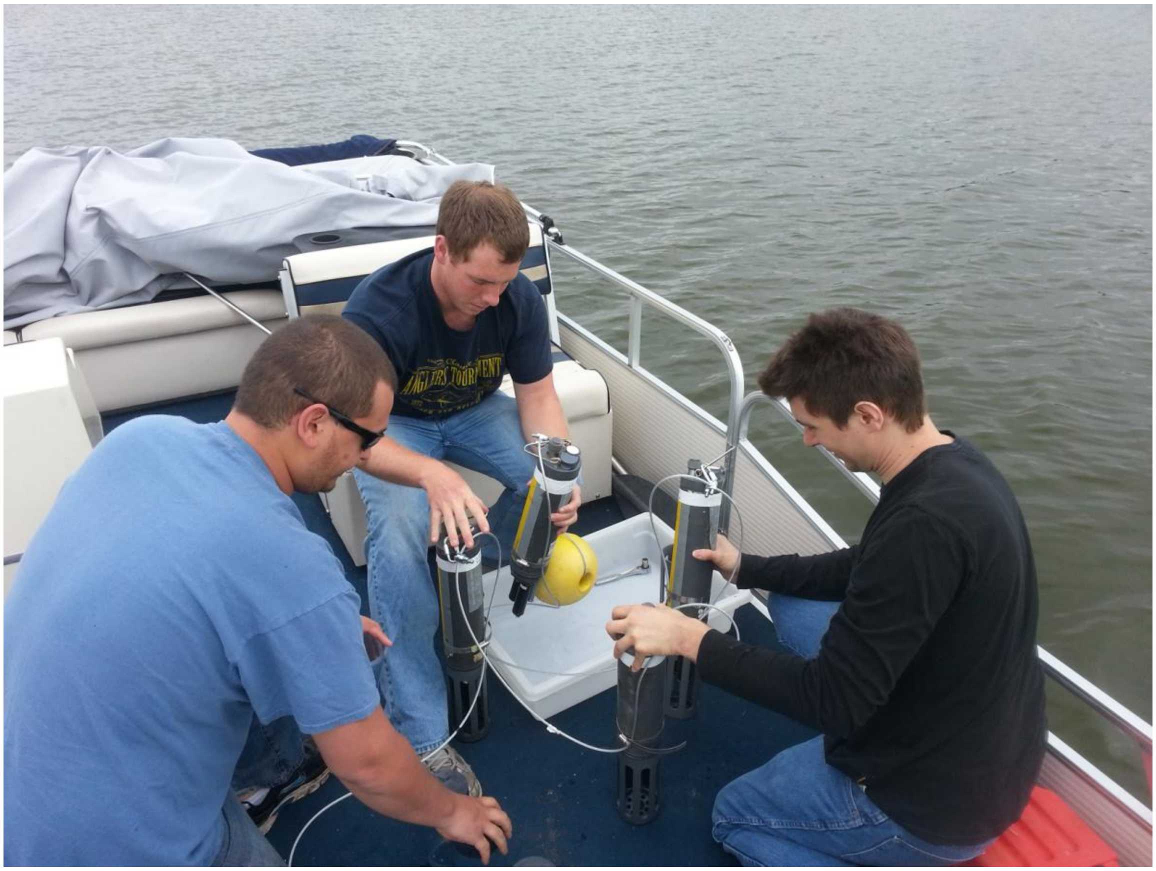
Phytoplankton and Phosphorus Dynamics in Lake Desair, Wisconsin, 2014



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OBJECTIVES

The objectives of this investigation were to examine phytoplankton dynamics in July-August in relation to phosphorus (P) gradients in Lake Desair. Specific objectives are to examine 1) phytoplankton genera assemblage to identify motile and nonmotile species and 2) the potential for phytoplankton vertical migration into hypolimnetic P gradients for biological assimilation and bloom development.

A secondary objective was to examine total and soluble P concentrations during high flows generated from spring snowmelt runoff and storms at various locations along the Northwest Creek tributary as well as other tributary inflows to Lake Desair. The goal of this objective was to better understand ranges in P concentration and composition (i.e., particulate and soluble P) in the watershed for future mitigation.

METHODS

Watershed phosphorus concentration analysis

Grab samples for analysis of total P (TP) and soluble reactive P (SRP) were collected during periods of high flow between April and June, 2014, from stations established at several bridge locations in the Northwest (2534 ac), South (880 ac), and East (84 ac) subwatersheds draining into Lake Desair (Figure 1). Overall, land cover in the Northwest subwatershed was dominated by agriculture while forested land cover accounted for the highest percentage in the South and East subwatersheds (Figure 2). Stations 1, 2, 4, and 5 were established in the Northwest subwatershed on Northwest Creek (NW Creek) from near its headwaters (i.e., station 1) to its mouth at Lake Desair (i.e., station 5; Figure 3). Station 4 represented the same location used to estimate P loading to Lake Desair in 2013 (James 2013). Station 3 was located on a subwatershed that drained into NW Creek downstream of station 4. Stations 6 and 7 were located in the South and East subwatersheds, respectively. Station 8 was the Olson detention pond outflow. Station 9 was located at the outflow of Lake Desair. Samples were frozen until analysis. SRP samples were filtered through a 0.45 µ filter upon collection before freezing.

Limnological Monitoring

Water samples and in situ profiles were collected biweekly to monthly between June and early September at a centrally-located station (Figure 4). In situ vertical profiles of temperature, dissolved oxygen, specific conductance, and pH were measured using a Hydrolab Quanta® (Hach Co., Loveland, CO) that was precalibrated against known buffer solutions and Winkler dissolved oxygen analyses. Measurements were collected at 1-m intervals between the lake surface and within 0.2 m above the bottom (maximum average depth = 9 m). Water transparency was estimated using a 20-cm alternating black and white Secchi disk. Water samples were collected between the lake surface (~0.25 m below) and 9 m using a peristaltic pump and tubing and stored in a cooler on ice in the field. Additionally, an integrated sample was collected over the 1-m water column using a schedule 40 1.25 inch PVC pipe attached to a one-way valve. For dissolved constituent analysis, samples were pumped directly into a 60-cc syringe without exposure to air and filtered through a 0.45 µm filter. All samples were analyzed for TP, SRP, total iron (TFe), dissolved iron (DFe), and viable chlorophyll. Samples for phytoplankton analysis and taxonomy were collected using the integrated sampler and preserved with Lugol's solution.

Analytical Methods

Samples for TP were predigested with potassium persulfate according to Ameel et al. (1993) before analysis. SRP samples were filtered through a 0.45 µm filter prior to analysis (Millipore MF). Phosphorus species were determined colorimetrically using the ascorbic acid method (APHA 2005). Samples for TFe were digested with nitric and hydrochloric acid according to EPA metals digestion method 3050b. TFe and DFe were analyzed using atomic absorption spectrophotometry (APHA 2005). Chlorophyll was determined via a fluorometric technique following extraction in a 1:1 solution of acetone and dimethyl sulfoxide (Welschmeyer 1994).

RESULTS AND DISCUSSION

Watershed phosphorus

Precipitation exceeding 1 inch occurred frequently between April through June, 2014 (Figure 5). Overall, daily precipitation was well above average in 2014, particularly in June. Storms were less frequent and lower in intensity in July. Early April water sampling captured snowmelt while later samples captured runoff during precipitation events. Storm concentrations of TP exceeded 1 to 2 mg/L in April at station 1, located near the headwaters of NW Creek (Figure 6). SRP was also very high at this station, ranging between 0.75 and 1.67 mg/L and representing ~ 65% of the total P. The early April concentration peak in TP was much lower at station 2, located ~ 2 km downstream of station 1, as a probable result of dilution with inflows from other upstream catchment areas. Nevertheless, TP exceeded 0.8 mg/L in early April and was greater than 0.2 mg/L in late April at this station and SRP accounted for greater than 60% of the TP. Concentrations of TP were much lower at station 3 in April, compared to those in the primary channel of NW Creek. The lower TP concentrations, ranging between 0.092 mg/L and 0.172 mg/L during April storm runoff, probably reflected forested land cover in this region of the watershed. However, SRP still accounted for 45% to 76% of the TP at this station and, thus, represented a potential source of available P to Lake Desair. Concentrations of TP and SRP declined further at stations 4 and 5 during this time period. Longitudinal concentration patterns from NW Creek headwaters to the lake declined exponentially with distance during April storms, indicating probable dilution with runoff from an increasingly larger watershed area (Figure 7). However, concentrations were still relatively high at station 5, located immediately upstream of Lake Desair, ranging between 0.10 mg/L to 0.48 mg/L TP and 0.073 mg/L to 0.29 mg/L SRP. SRP represented

~ 60% or more of the TP composition in NW Creek inflows entering Lake Desair in April.

Lake P outflow concentration at station 9 also very high during these April precipitation events (Figures 6 and 7). In particular, SRP ranged between 0.09 mg/L and 0.16 mg/L, indicating direct P availability for algal uptake. Lake inflow-outflow SRP concentrations were also very similar in April, suggesting that the residence time of Lake Desair was very low due to rapid flushing, resulting in in-lake P concentrations that reflected watershed P load concentrations. By May, SRP concentrations were substantially lower in the lake outflow compared to the inflow, accounting for only 10% of the TP composition. This pattern was probably attributed to increasing residence time, the onset of stratification, and apparent uptake of SRP by algal communities for growth.

Similar P concentration patterns occurred in the Northwest catchment basin during precipitation events in June (Figure 6). TP concentrations were greatest at the NW Creek headwaters, station 1, exceeding 2 mg/L in early June and 0.8 mg/L during the mid-June precipitation event. As in April, SRP accounted for ~ 60% and 40% of the TP concentration during these periods, respectively. TP and SRP concentrations declined in an exponential pattern from station 1 to station 5 during June rainfall periods. However, TP concentrations at the lake entrance (station 5) still exceeded 0.09 mg/L and 0.38 mg/L in early and mid-June, respectively, with SRP representing greater than 30% to nearly 50% of the TP composition (Figure 7). June SRP concentrations at station 5 were 0.094 mg/L and 0.051 mg/L during early and mid-June precipitation events, respectively.

Lake Desair P outflow concentrations at station 9 were much lower in June compared to inflow concentrations at station 5 (Figure 7). For instance, inflow TP was 0.385 mg/L while outflow TP declined to 0.05 mg/L during the mid-June event. Similar to May, Lake Desair residence time was probably higher in June, which would promote sedimentation of watershed-derived particulate P to the lake bottom. SRP concentrations were near detection limits in the outflow, versus an inflow concentration that exceeded 0.12 mg/L at the NW Creek entrance to Lake Desair. This pattern was attributed to in-lake algal uptake of SRP for growth. Indeed, surface concentrations of chlorophyll increased to a maximum that approached 200 µg/L by July (see Results below and Figure 13).

Tributary TP concentrations at stations located in the south (station 6) and east (station 7) subwatershed ranged between 0.083 mg/L and 0.174 mg/L (Figure 8). April and June mean TP concentrations were 0.018 mg/L and 0.165 mg/L, respectively, for the south subwatershed and 0.081 mg/L and 0.146 mg/L, respectively, for the east subwatershed (Table 1). These were lower than April and June mean concentrations of 0.306 mg/L and 0.240 mg/L, respectively, at station 5 (northwest subwatershed; Table 1), reflecting differences in land cover between the three subwatersheds (Figure 3). Mean SRP concentrations were also lower at station 6 and 7 versus 5 in April and June (Table 1). SRP accounted for a greater proportion of the TP at stations 6 and 7 in April compared to June (Table 1). The mean percent SRP ranged between 45% and 54% in April but only 23% to 25% in June at these stations (Table 1). By comparison, the mean percent SRP was ~ 58% in April and 41% in June at station 5 (Table 1).

The Olson Pond discharge, surprisingly, exhibited relatively high TP concentrations, ranging between 0.164 mg/L and 0.259 mg/L (Figure 8). TP concentrations were greatest in April and declined to slightly lower values in June. SRP concentrations were also high and accounted for 74% of the TP in April. The percent SRP contribution declined to 45% by late April and 26% in June. Nevertheless, the SRP concentration ranged between 0.042 mg/L and 0.193 mg/L. Inflow P concentrations need to be monitored in order to evaluate the P retention efficiency of the pond.

Mean P concentrations at all stations in April and June are shown in Figure 9. May was not included due to less frequent sample collection. In general, mean TP and SRP concentrations declined exponentially in the northwest subwatershed (i.e., station 1 to 5 and 9) during both periods. SRP represented ~ 60% of the total P in April over all NW Creek stations. This percentage declined slightly to between ~ 30%-40% of the TP at the lower NW Creek sampling sites (i.e., stations 4 and 5) in June. Mean TP concentrations were lower at station 6 and 7 compared to station 5. The mean percent SRP at these sites was ~ 50% in April, declining to ~ 25% in June. Overall, mean SRP concentrations at all inflow sites to Lake Desair were high and represented an immediately available source of P for algal uptake.

Limnological patterns in Lake Desair

As in 2013, Lake Desair exhibited strong stratification patterns during the summer of 2014 (Figure 10). The mixed layer depth between June and early September was consistently ~ 3 m in thickness (Figure 11). Thermal stability was high during this period with no apparent epilimnetic expansion and thermocline migration, which might occur during the passage of cold fronts and high wind activity (Figure 11). Hypolimnetic temperatures were very cool throughout the summer and only increased slightly between June and September, indicating little downward heat entrainment via mixing and minimal exchange and mixing between the epilimnion and hypolimnion (Figure 10).

Dissolved oxygen depletion and anoxic conditions developed rapidly in the hypolimnion in conjunction with stratification (Figure 10). Anoxia had developed at the 9-m depth in mid-June and extended up to 5 m by the end of June. In July and August, hypolimnetic anoxia extended and into the metalimnion up to the 4-m depth.

TP and TFe concentrations increased substantially in the hypolimnion throughout the summer stratified period in conjunction with the development of anoxia (Figure 12). TP concentrations above the sediment interface exceeded 1.4 mg/L while TFe was nearly 14 mg/L by mid-August. Soluble P and Fe usually accounted for greater than 60% of the total composition. Similar to 2013 patterns, there was a strong linear relationship between hypolimnetic Fe and P concentration (Figure 13) and the Fe:P ratio exceeded 5:1.

Chlorophyll concentrations were greatest in the upper 2-m water column and declined to low values in the hypolimnion (Figure 14). Unlike 2013, peaks in chlorophyll were confined to the surface waters; no secondary peaks were detected in the metalimnion which might have suggested vertical migration by motile algae. In the upper 2-m water column, chlorophyll concentrations increased to greater than 150 µg/L between June and late July following precipitation and loading events that occurred in May and June (Figure 15). A second peak in surface chlorophyll occurred in early September. Secchi transparency declined from greater than 2 m in early June to a minimum 0.6 m in early August in conjunction with peaks in chlorophyll. Strong negative exponential relationships between chlorophyll and Secchi transparency indicated algal-mediated attenuation of solar radiation (Figure 16).

<phytoplankton taxa – to be added when analyses are completed by Dr Jeff Janik>

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

An important finding of this research was that SRP concentrations were very high during snowmelt and precipitation-related runoff events, particularly in the northwest subwatershed. SRP also accounted for a substantial portion of the TP concentration, usually well over 50%. Since SRP approximates directly available P for algal uptake, its discharge into Lake Desair represented an important P source that largely explained the high chlorophyll concentrations and hypereutrophic conditions observed in the summer (James 2013).

More information is needed on soil P characteristics and runoff potential in the northwest subwatershed in order to identify critical source areas (i.e., hydrologically-sensitive areas in the watershed that exhibit high soil P concentrations) for BMP implementation. In general, soil fertilization in excess of crop P uptake requirements can lead to the buildup of excess soil P over time, referred to as “legacy P” (Sharpley et al. 2013). Numerous studies have shown positive linear relationships between soil P and P in runoff, indicating a link between soil management practices, source soil P concentrations in the landscape, and tributary P load and concentration (Sharpley 1995; Pote et al. 1996, 1999; Fang et al.

2002; Torbert et al. 2002; Davis et al. 2005). While changing soil management and agricultural behavior to achieve sustainable solutions for maintaining agricultural productivity and improving water quality is an ultimate goal, legacy P in the watershed can delay lake recovery for a long time (Kleinman et al. 2011a and b; Jarvie et al. 2013). For instance, conserving soil on the land by reducing erosion can be achieved through a variety of well-established BMPs and techniques, resulting in greatly reduced particulate P loading. However, the more challenging and difficult task facing watershed P management is reducing soluble P loading from legacy P (Klienman et al. 2011a and b). Until recently, control of soluble P in runoff has been largely ignored.

Equilibrium reactions between exchangeable P pools on soil and precipitation play an important role in soluble P transfer to runoff and edge-of-field streams. In general, P bound to metal oxyhydroxides (i.e., Fe and Al) associated with clays and minerals reach an equilibrium with aqueous P in precipitation. Disturbance of equilibrium via fertilizer addition can result in P adsorption onto soil while P removal via root uptake can result in P desorption from soil to re-achieve equilibrium conditions. Analogous to pH buffering in alkaline lakes, equilibrium reactions between aqueous and soil exchangeable P pools can buffer soluble P in runoff to a certain extent. As soil binding sites become increasingly saturated with P (i.e., via excess fertilization), buffering capacity for P weakens and soils loose more soluble P during runoff events (James et al. 2009). Reducing P additions to soils through BMPs will not usually lead to an immediate reduction in soluble P loading, particularly if the concentration of the exchangeable P pool is high (Sharpley and Rekolainen 1977), resulting in soil P desorption into runoff for long periods of time. Thus, remediation for soluble P loading reduction needs to consider hydrologic runoff from P-enriched soils, as well as erosion control.

I think an important starting point for addressing the issue of reducing soluble P loading in the niorthwest subwatershed is to identify hydrologically-sensitive areas that have agricultural soils highly saturated with P. These will be the areas to target for remediation. Hydrologically-sensitive areas can be, for instance, a sloping agricultural field with no cover crops (i.e., in the spring) that is adjacent to a headwater stream or drainage dry run. When precipitation exceeds interception and infiltration, runoff can develop that carries with it eroded fine-grained soils that are enriched with exchangeable P. These soils can equilibrate with overland runoff to produce high concentrations of SRP. In addition, precipitation splashing directly on soils can drive rapid P desorption and high SRP in the resultant runoff. Soil samples from various fields can be sent in for agricultural soil test P analysis to determine the extent of soil P saturation and equilibrium impacts on soluble P concentration.

While identification of critical source areas for soluble P in the watershed will be an important step, management for reduced soluble P in the runoff will be difficult. For instance, grassed waterways at the edge of the field may intercept some of the particulate P but not necessarily re-adsorb the soluble P in the runoff. Strategies for reducing soluble P runoff could fall into several categories, depending on site-specific needs (Table 2). One strategy is to increase soil infiltration and water capacity in order to reduce hydrological runoff. Another strategy is to attempt to detain runoff on the landscape with constructed wetlands or detention basins. The goal with this strategy is to promote complete or near complete infiltration rather than temporary detention and later discharge. Temporary detention may not remove sufficient soluble P, as suggested by the Olson detention pond. Interception and sequestration of soluble P is another strategy. This technique involves the use of materials that strongly adsorb soluble P such as oxidized Fe, Al hydroxides, or synthetic polymers. Structures placed in runways or constructed flumes containing P-adsorbing material can be placed in receiving streams draining areas with high soluble P (Penn et al. 2014). Soluble P removal systems would need to be maintained and periodically replaced as sorption sites become saturated.

While in-lake management of algal blooms is probably needed, particularly if cyanobacterial blooms with the potential for toxin development occurs in the lake, there is, unfortunately, no feasible means that can alleviate the problem with 100% certainty. Because empirical modeling indicated that tributary P loading, versus internal P loading, explained the trophic state of the lake, management targeted toward internal P loading reduction to reduce algal bloom severity and frequency would not be warranted (James

2013). Thus, even though internal P loading is high in Lake Desair, it's availability for assimilation by algae is controlled by its reactivity with oxidized Fe. Unless motile phytoplankton can directly access hypolimnetic P for uptake and growth, an alum treatment to reduce internal P loading would not be practical.

I am hesitant to recommend artificial destratification as a management tool because the outcome is not certain. Aeration or artificial destratification to reduce internal P loading during the summer would not be necessary due to reasons previously cited (also see Kleeberg et al. 2013). Although destratification to otherwise manage algal biomass has been implemented, management response may be positive (i.e., reduced algal biomass) or negative (i.e., increased algal biomass or no change). Artificial destratification minimizes density stratification and promotes mixing and exchange throughout the water column. Thus, the mixed layer essentially encompasses the entire water column and lake water gains heat throughout the mixing period. Algae can be redistributed throughout the water column and spend a significant amount of time in darkness (below the euphotic zone; Z_{mixed} depth >> $Z_{\text{euphotic zone}}$) , thereby, reducing photosynthesis. Productivity can decline via mixing-induced light limitation, or it may increase if the algal community was previously light-limited by self-shading. Under the latter scenario, mixing would disrupt surface blooms, but could also increase transparency and light penetration for stimulated growth.

Periodic mixing via artificial destratification might possibly be used in conjunction with high hypolimnetic Fe concentrations to bind SRP and reduce algal uptake. Temporary mixing would need to occur after stratification, the establishment of bottom water anoxia, and buildup of hypolimnetic DFe in order to maximize SRP binding. The goal of this strategy would be to attempt to sequester watershed-derived SRP with oxidized Fe before significant algal uptake. However, timing is an issue in that tributary SRP loads contributing to summer algal blooms typically discharge into Lake Desair in May to early June when hypolimnetic DFe concentrations are low. Thus, algae and cyanobacteria have probably assimilated SRP for later growth well before optimal conditions have been met for P binding by oxidized Fe.

Finally, artificial mixing can have other positive impacts such as reintroduction of dissolved oxygen for expanded fish habitat. But, it can also result in unintended problems. For instance, mixing can promote diffusion of important nutrients like sulfate into the sediment for bacterial anaerobic metabolism and reduction to S. This process could ultimately deplete Fe availability for P binding via reaction to inert FeS_x (Urban et al. 1994), resulting in less hypolimnetic Fe to bind all the P during periods of turnover and reintroduction of dissolved oxygen. Massive cyanobacteria bloom development in Cedar Lake, WI, was attributed to low hypolimnetic Fe and inefficient binding of internal P loads during fall turnover.

ACKNOWLEDGMENTS

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Table 1. Mean and standard error (SE) total phosphorus (P) and soluble reactive P (SRP) concentrations at various stations in the Lake Desair watershed in April and June, 2014.

	April						June					
Station	Total P		SRP				Total P		SRP			
	(mg/L)	SE	(mg/L)	SE	(%)	SE	(mg/L)	SE	(mg/L)	SE	(%)	SE
1	1.492	0.293	0.985	0.227	65.1	2.6	1.435	0.663	0.878	0.547	55.1	13.8
2	0.403	0.140	0.253	0.091	61.9	2.5	0.460	0.232	0.303	0.116	71.5	10.9
3	0.125	0.017	0.075	0.019	56.7	6.8	0.344	0.001	0.112	0.006	32.6	1.7
4	0.262	0.106	0.173	0.059	66.0	3.6	0.268	0.066	0.083	0.015	31.5	2.5
5	0.306	0.176	0.180	0.107	57.7	1.6	0.240	0.146	0.088	0.041	41.2	8.0
6	0.118	0.033	0.054	0.019	44.7	2.7	0.165	0.009	0.043	0.009	25.6	3.8
7	0.081	(n = 1)	0.043	(n = 1)	53.8	(n = 1)	0.146	(n = 1)	0.034	(n = 1)	23.3	(n = 1)
8	0.221	0.039	0.137	0.056	59.6	15.1	0.164	(n = 1)	0.042	(n = 1)	25.5	(n = 1)
9	0.216	0.023	0.126	0.036	57.2	10.4	0.051	(n = 1)	0.011	0.007	20.8	12.4

Table 2. Management approaches for reducing soluble phosphorus (P) loading to Lake Desair.

Best Management Practice	Management option
Increase soil infiltration	Tillage practices
	Increase conductivity and porosity
	Organic matter amendments
Detain a portion of the runoff on the landscape	Constructed wetlands
	Detention basins
Soluble P interception	Iron-enhanced sand benches
	Soluble P removal structures to intercept high P runoff

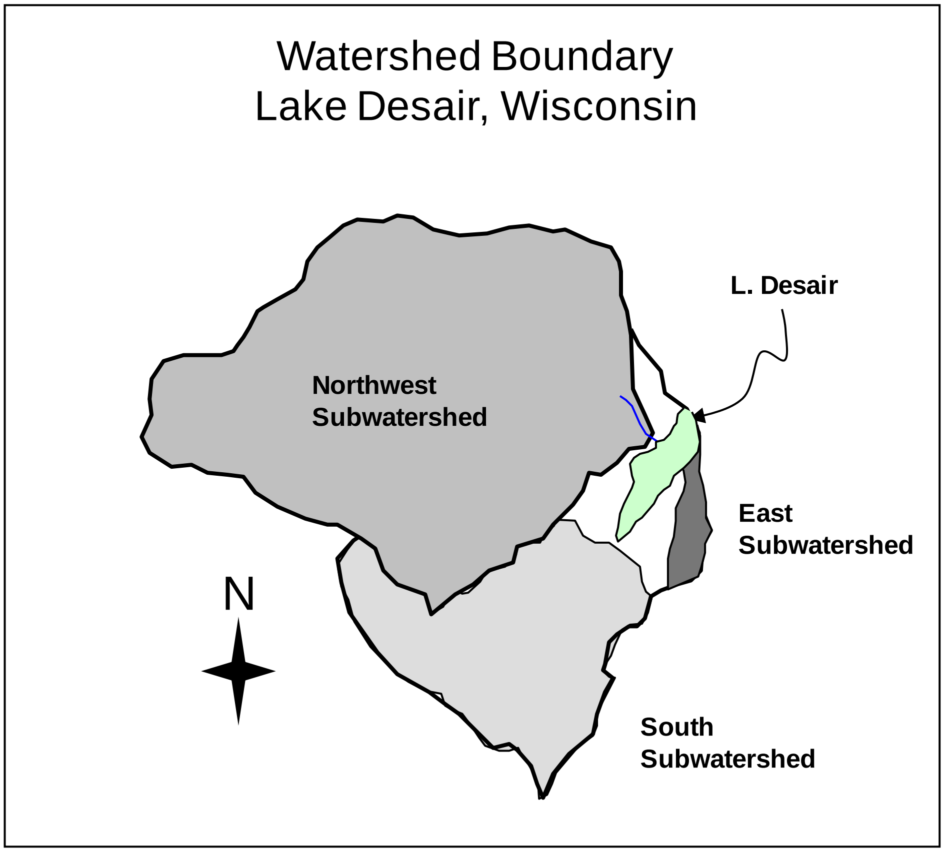

Figure 1. Catchment areas for Lake Desair.

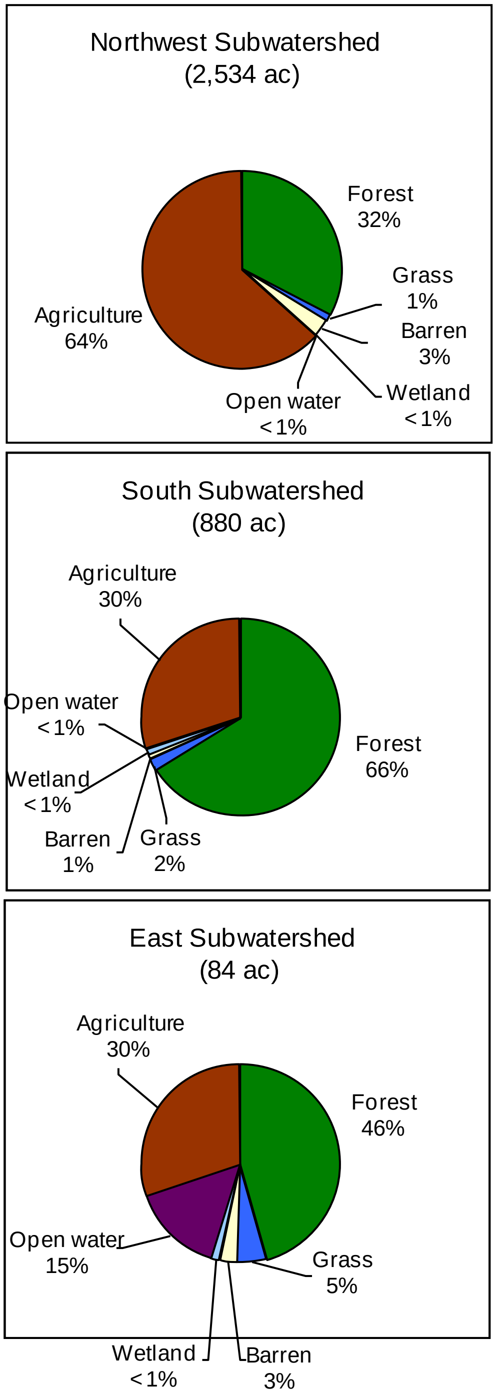

Figure 2. Percentages of various land-use practices in the Northwest, South, and East subwatersheds (Cedar Corp 2006).

Figure 3. Watershed sampling station locations.

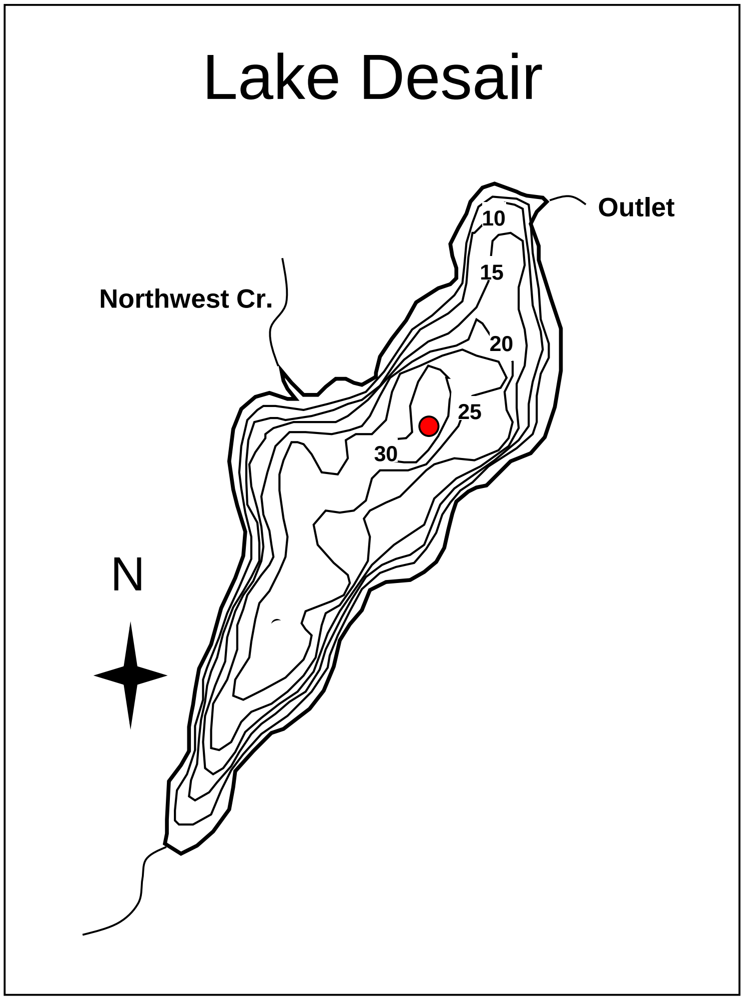

Figure 4. Bathymetric map of Lake Desair. Red circle denotes the location of the limnological sampling station.

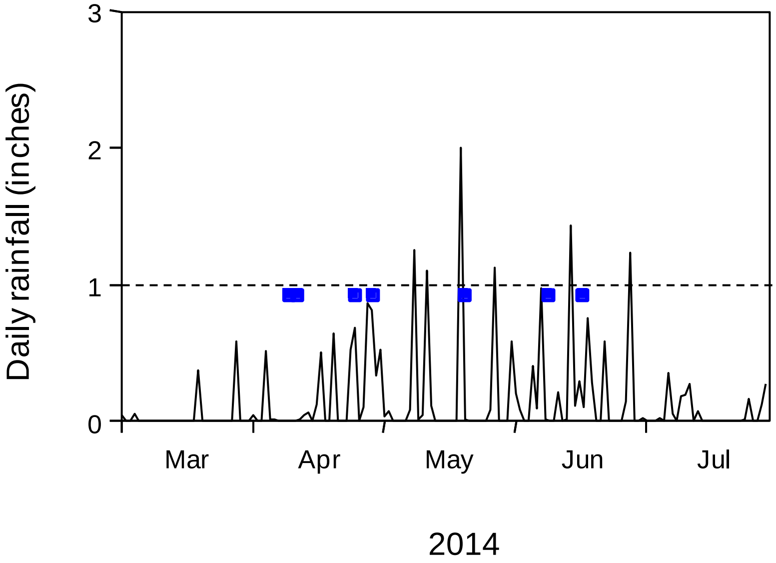

Figure 5. Time series of daily precipitation measured at the Rice Lake Municipal Airport.Blue squares represent water sampling dates for phosphorus analysis.

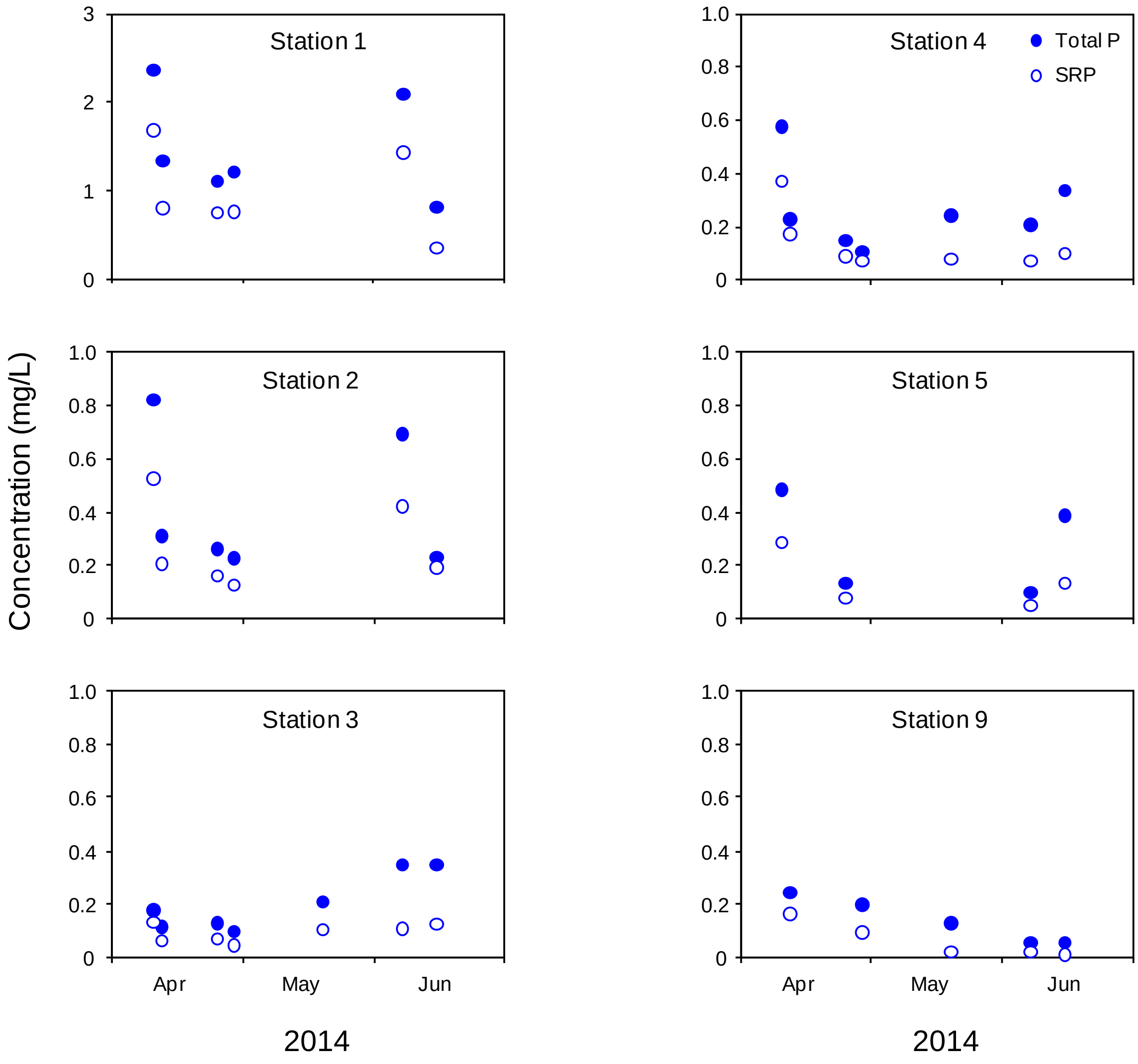

Figure 6. Seasonal variations in total phosphorus (P) and soluble reactive P (SRP) concentrations at stations located in the northwest subwatershed, including the Lake Desair outflow.

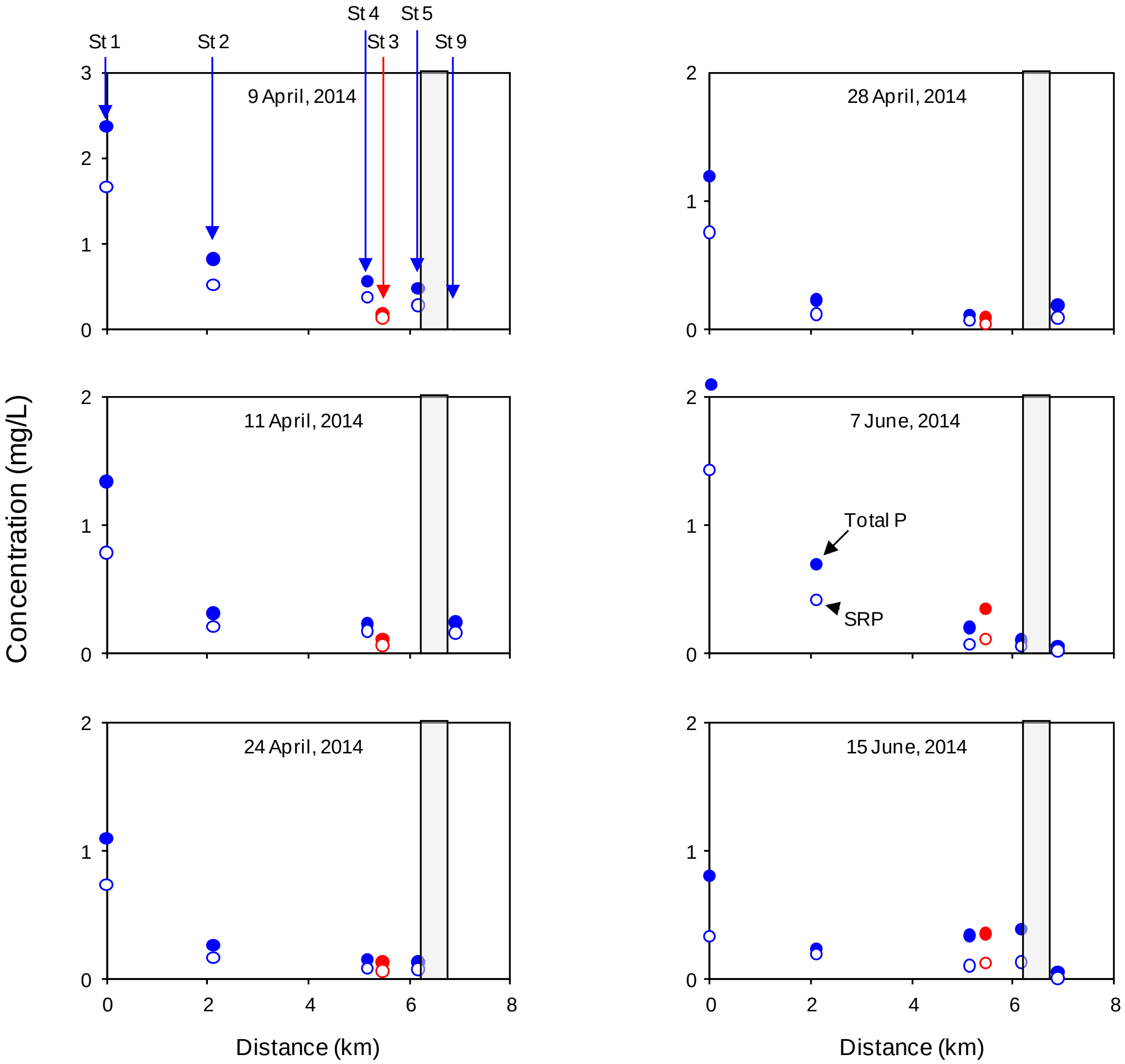

Figure 7. Spatial variations in total phosphorus (P) and soluble reactive P (SRP) concentrations on different dates at stations located in the northwest subwatershed, including the Lake Desair outflow. Red circles denote station 3 in the northwest subwatershed. This station was not located on the NW Creek tributary.

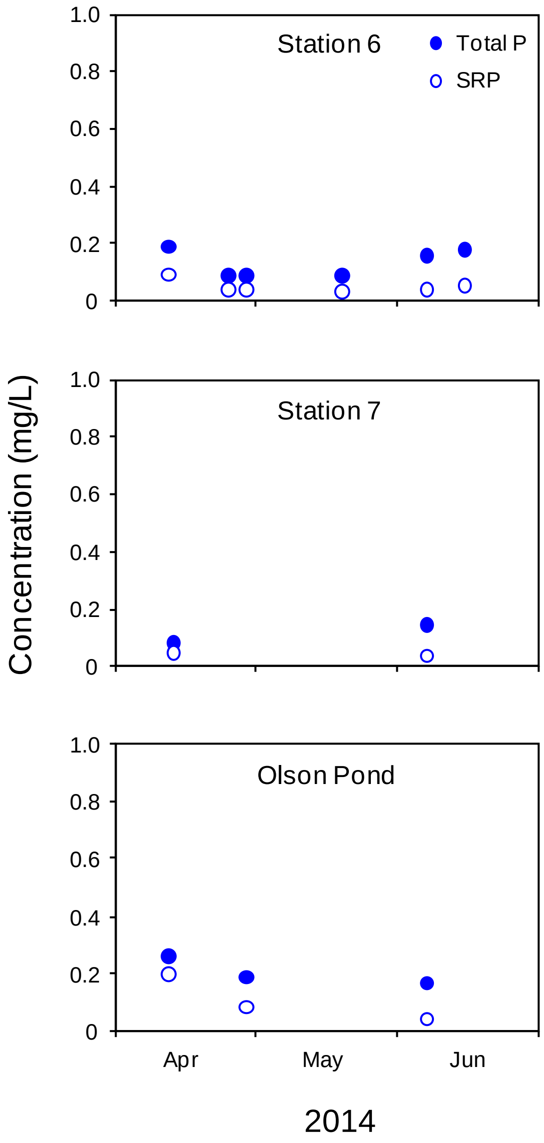

Figure 8. Seasonal variations in total phosphorus (P) and soluble reactive P (SRP) concentrations at stations located in the south and east subwatershed and Olson detention pond.

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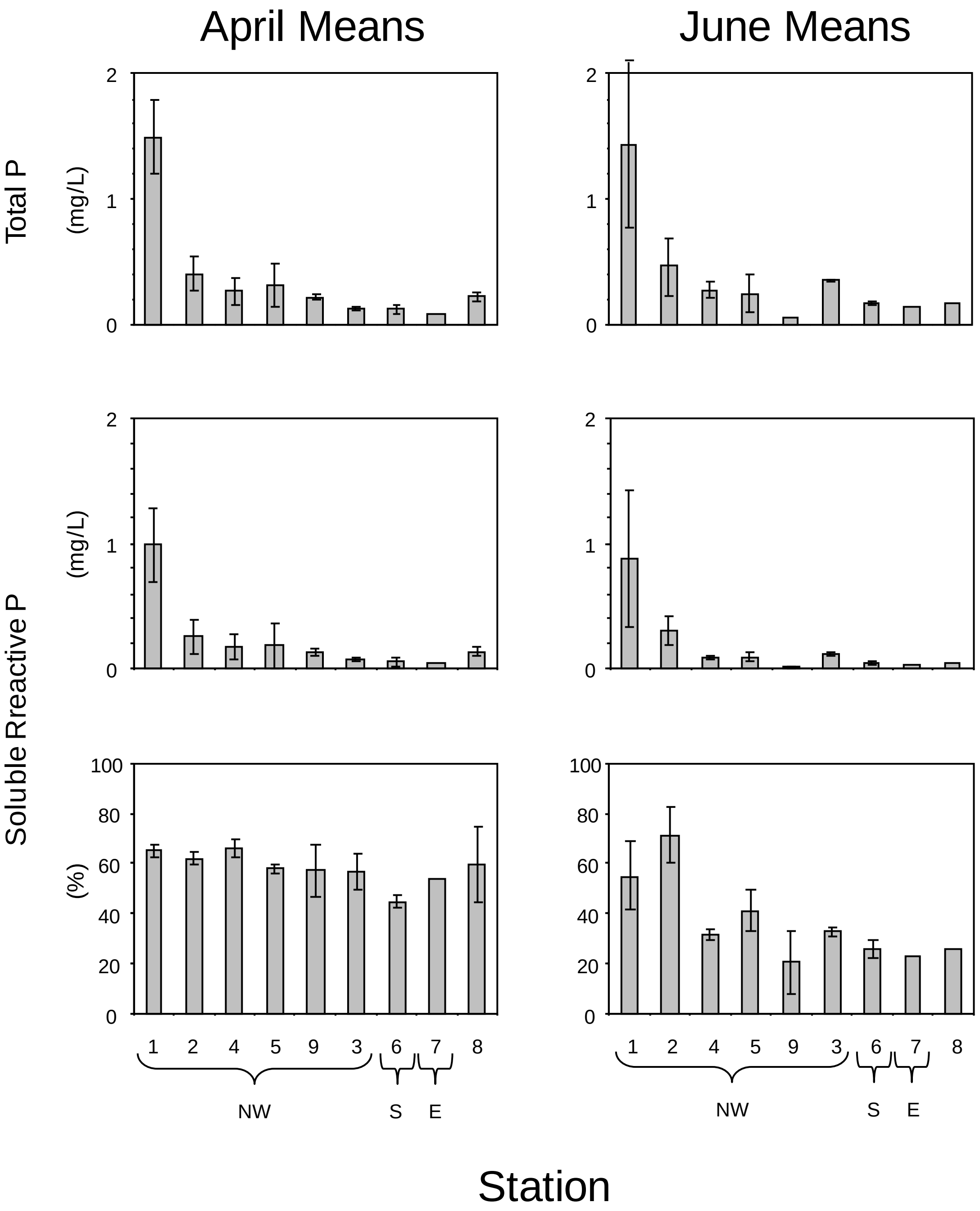

Figure 9. Spatial variations in mean total phosphorus (P) and soluble reactive P (SRP) concentrations in May and June. NW = Northwest, S = South, and E = East subwatershed.

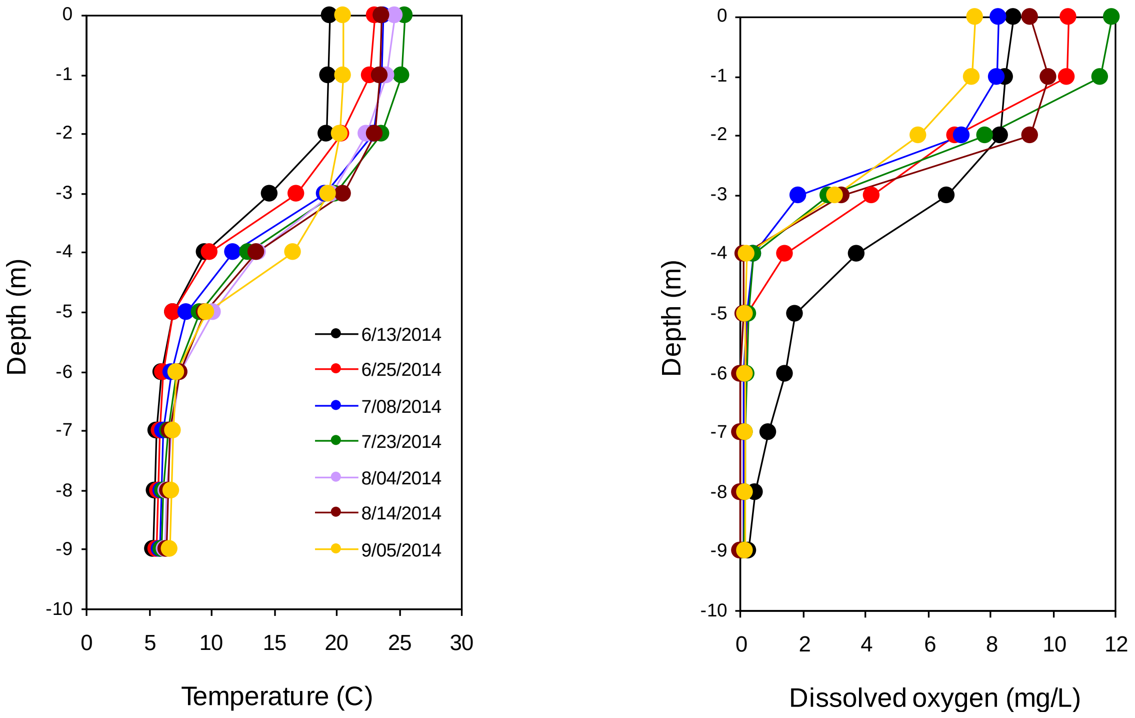

Figure 10. Seasonal and vertical variations in temperature (left panel) and dissolved oxygen (right panel) in Lake Desair.

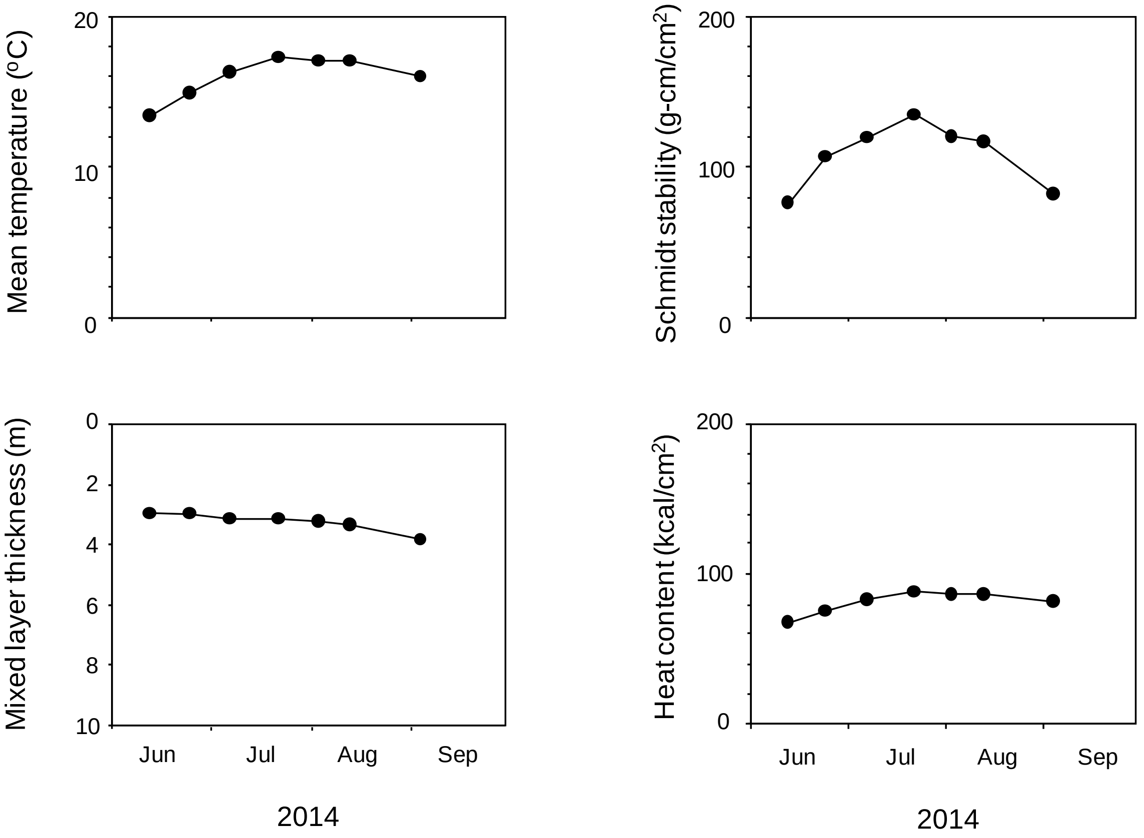

Figure 11. Seasonal variations in mean lake temperature (upper left), the mixed layer depth (epilimnion; lower left), Schmidt stability (upper right), and heat content (lower right) for Lake Desair.

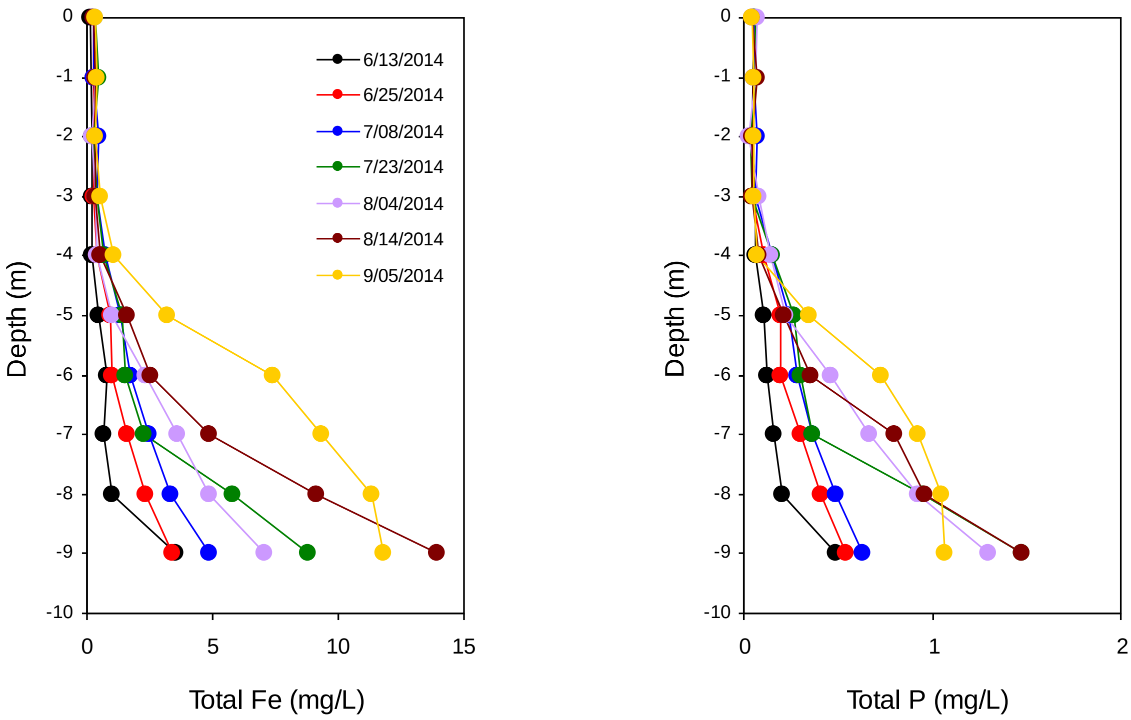

Figure 12. Seasonal and vertical variations in total iron (Fe; left panel) and total phosphorus (P; right panel) in Lake Desair.

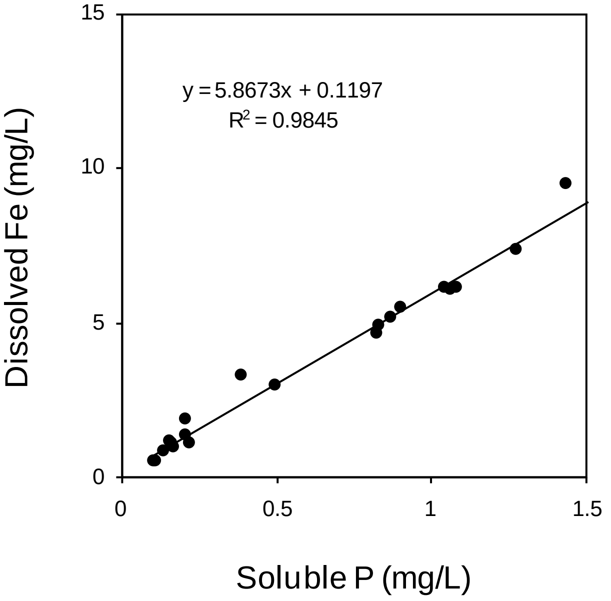

Figure 13. Linear relationships between hypolimnetic dissolved iron (Fe) and soluble reactive phosphorus (P; upper panel). The slope of the regression equation (i.e., 5.87) approximates the Fe:P ratio. An Fe:P ratio (mass:mass) greater than 3.6:1 indicates complete adsorption of PO_4^{3-} *to iron oxyhydroxides after chemical oxidation of Fe during fall turnover. For instance, at least 4 parts of oxidized iron are required to completely bind 1 part of phosphate.*

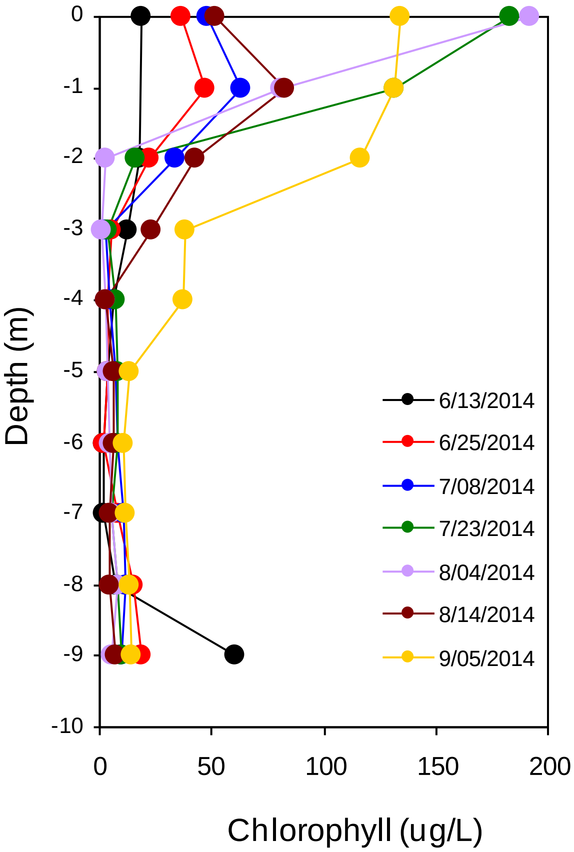

Figure 14. Seasonal and vertical variations in chlorophyll in Lake Desair.

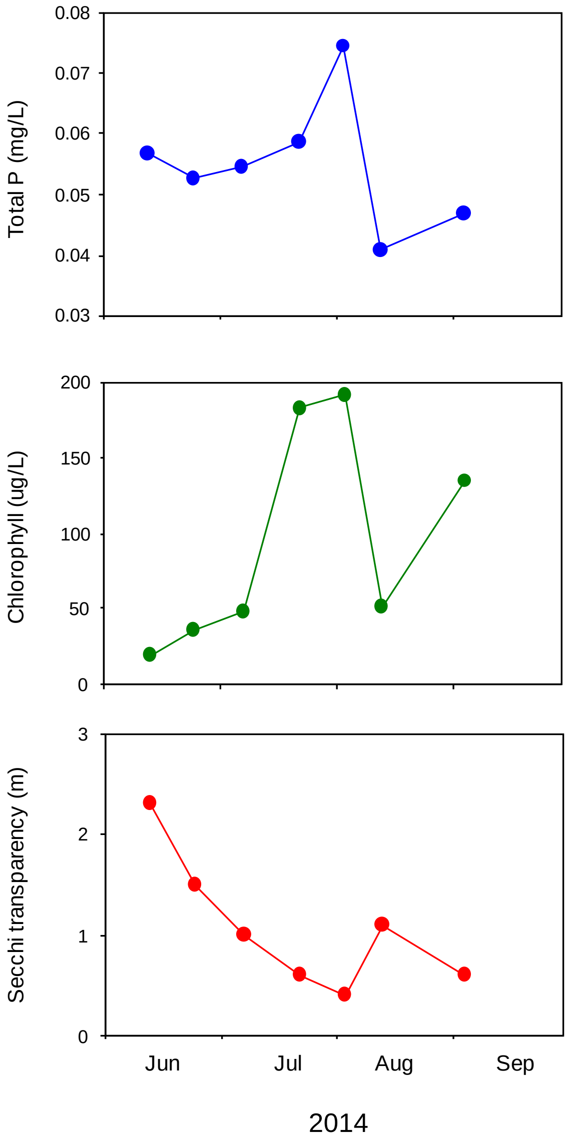

Figure 15. Seasonal variations in total phosphorus (P) and chlorophyll in the upper 1-m water column, and Secchi transparency in Lake Desair.

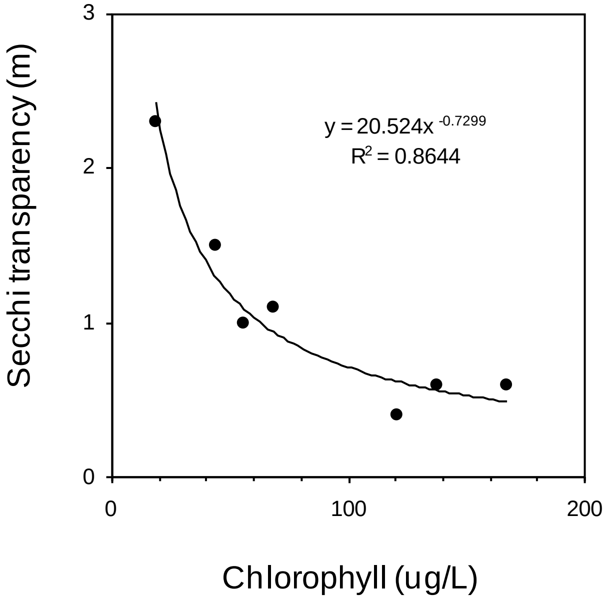

Figure 16. Regression relationships between chlorophyll in the upper 1-m water column and Secchi transparency in Lake Desair.