



# Internal phosphorus loading and sediment characteristics in Big Lake, Wisconsin

---

31 March 2021

University of Wisconsin - Stout  
Center for Limnological Research and Rehabilitation  
Menomonie, Wisconsin 54751  
715-338-4395  
[jamesw@uwstout.edu](mailto:jamesw@uwstout.edu)

---

## 1.0 EXECUTIVE SUMMARY

- Big Lake exhibited strong stratification with a well-defined epilimnion, metalimnion, and hypolimnion throughout the summer. The bottom water immediately above the sediment surface was anoxic ( $< 1$  mg/L) from June through October 2020.
- Laboratory-measured diffusive P flux from sediment at 20 C was a mean 8.01 mg/m<sup>2</sup> d and 1.10 mg/m<sup>2</sup> d under anaerobic and aerobic conditions, respectively. Bottom water temperature was lower than the laboratory incubation temperature of 20 C, ranging between 12.3 C and 17.5 C with a summer mean of 14.5 C.
- Measured diffusive P flux was adjusted to in situ bottom temperatures using a metabolic equation. Adjusted anaerobic and aerobic diffusive P fluxes were 5.65 mg/m<sup>2</sup> d and 0.75 mg/m<sup>2</sup> d, respectively, at the summer mean bottom temperature of 14.5 C.
- Big Lake surface sediment exhibited relatively high mobile P fraction concentrations (i.e., phosphorus that contributes to internal P loading). Loosely-bound P, iron-bound P, and labile organic P concentrations were 0.095 mg/g, 1.016 mg/g, and 0.384 mg/g, respectively. These concentrations were high relative to other lakes in the region.

## **2.0 OBJECTIVES.**

The objectives of these investigations are several-fold:

1. Examine the development of thermal stratification using thermistors (i.e., temperature data loggers) deployed in the lake at ~ 1-m intervals to record temperature hourly over the course of the summer to better document temporary stratification patterns,
2. deploy a dissolved oxygen monitor near the lake bottom to record changes at 2- to 4-hr intervals to quantify periods and duration of bottom water anoxia in the lake,
3. measure rates of P release from sediment as a function of redox (i.e., aerobic and anaerobic conditions) under laboratory conditions for comparison with the P budget, and
4. examine vertical variations in sediment mobile P fractions that are active in internal P loading,

The goals of this research are to develop an estimate of summer growing seasonal internal P loading for use in P budgetary analysis and forecasting the impacts of internal P loading management on water quality.

## **3.0 METHODS.**

### *Stratification, mixing, and bottom dissolved oxygen dynamics*

Data logging thermistors (HOBO temperature loggers, Onset, Corp) were deployed at 1-m intervals from the lake surface to near bottom to record temperature at 1-hour intervals between June and September 2020, to quantify the frequency of occurrence of stratification and mixing periods (Fig. 1). A YSI (Yellow Springs Instruments) 6600 data sonde equipped with precalibrated probes was deployed in the lake approximately 0.50 m above the sediment-water interface (6-m depth) to examine seasonal changes in dissolved oxygen. The goals of this task were to quantify periods of temporary bottom anoxia to

estimate summer diffusive P flux more accurately from sediments in Big Lake. The sonde recorded bottom dissolved oxygen at 4-hour intervals.

#### *Laboratory-derived rates of P release from sediment*

Sediment in Big Lake may represent a potentially significant internal source of P recycling to the overlying water column via diffusion from porewater to the overlying water column, contributing to cyanobacterial blooms under P-limited conditions particularly when watershed point and nonpoint source loadings are nominal. During periods of temporary stratification and establishment of bottom water hypoxia or anoxia, P chemically adsorbed or precipitated to metal compounds (i.e., iron oxyhydroxides; Fe(OOH)~P) can diffuse from sediment into the overlying water column as a result of reduction reactions under anaerobic conditions (Mortimer 1971, Boström 1984, Nürnberg 1984). Under aerobic conditions at the sediment-water interface, P is typically bound to Fe(OOH) within a thin (often 1 mm or less in thickness) surface oxidized microzone, resulting much lower to negligible rates of diffusive P flux from sediment. Thus, information is needed on sediment diffusive P flux contributions (i.e., internal P loading) in Big Lake, to better understand and quantify the P budget. The objectives of this task were to evaluate rates of P release from sediment under laboratory-controlled redox (Eh; aerobic or anaerobic conditions) from intact sediment cores.

Replicate (3 per redox condition) sediment cores were collected at the centrally-located station in Big Lake for determination of diffusive P flux from sediment under controlled laboratory conditions (Fig. 1). Cores were carefully drained of overlying water in the laboratory and the upper 10 cm of sediment transferred intact to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Surface water collected from each lake was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. They were placed in a darkened environmental chamber and incubated at a constant temperature of ~20 °C. The Eh environment in the overlying water was controlled by gently bubbling air (aerobic) or nitrogen (anaerobic) through an

air stone placed just above the sediment surface in each system. Bubbling action ensured complete mixing of the water column but did not disrupt the sediment. A total of 6 cores were collected for assessment of diffusive P flux from sediment.

Water samples for soluble reactive P were collected from the center of each system using an acid-washed syringe and filtered through a 0.45 µm membrane syringe filter. The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. Soluble reactive P was measured colorimetrically using the ascorbic acid method (APHA 2005). Rates of P release from the sediment ( $\text{mg}/\text{m}^2 \text{ d}$ ) were calculated as the linear change in mass in the overlying water divided by time (days) and the area ( $\text{m}^2$ ) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Since the bottom temperature in Big Lake ranged between 12 C and 15 C while sediment diffusive P flux was measured in the laboratory at 20 C, a metabolic rate equation was used to adjust P flux for lower in situ bottom temperature (Burns 1995).

#### *Evaluation of sediment P characteristics*

The objectives of this task were to quantify vertical variations in sediment textural characteristics and mobile P fractions involved in sediment internal P loading to the overlying water column. Sediment cores were sectioned at 1-cm intervals over the upper 6 cm and 2-cm intervals thereafter for analysis of sediment physical-textural characteristics and P fractions. Sediment sections were analyzed for moisture content, sediment density, organic matter content, loosely-bound P, iron-bound P, labile organic P, and aluminum-bound P. Subsamples were dried at 105 °C to a constant weight and burned at 500 °C for determination of moisture content, sediment density, and organic matter content (Håkanson and Jensson 2002). Phosphorus fractionation were conducted according to Psenner and Puckso (1988) and Hjieltjes and Lijklema (1980) for the determination of ammonium-chloride-extractable P (1 M  $\text{NH}_4\text{Cl}$ ; loosely-bound P),

bicarbonate-dithionite-extractable P (0.11 M BD; iron-bound P), and sodium hydroxide-extractable P (0.1 N NaOH; Aluminum-bound and labile organic P).

The loosely-bound and iron-bound P fractions are readily mobilized at the sediment-water interface under anaerobic conditions that result in desorption of P from bacterially-reduced iron compounds (i.e.,  $\text{Fe}^{+3}$  to  $\text{Fe}^{+2}$ ) in the sediment and diffusion into the overlying water column (Mortimer 1971, Boström 1984, Nürnberg 1988). The sum of these fractions are referred to as redox-sensitive P (i.e., redox-P; the P fraction that is active in P release under anaerobic and reducing conditions). In addition, labile organic P (LOP) can be converted to soluble P via bacterial mineralization (Jensen and Andersen 1992) or hydrolysis of bacterial polyphosphates to soluble phosphate under anaerobic conditions (Gächter et al. 1988; Gächter and Meyer 1993; Hupfer et al. 1995). The sum of redox-P and LOP is collectively referred to a biologically-labile P. This fraction is generally active in recycling pathways that result in exchanges of phosphate from the sediment to the overlying water column and potential assimilation by algae.

## **4.0 RESULTS.**

### *Stratification and anoxia*

Overall, Big lake exhibited strong stratification between late May and late August (Fig. 2). The epilimnion was located between the lake surface and ~ 2 m. Periods of cooling mid-June, mid-July, and early August resulted in expansion of the epilimnion down to 4 m (Fig. 2 and 3). The metalimnion (i.e., region of greatest temperature change with increasing depth) was expansive, ranging between the 4- and 6-m depths. The hypolimnion was located at depths > 6 m. Periods of cooling and epilimnetic expansion did not appear to result in mixing and entrainment of hypolimnetic water. Hypolimnetic bottom temperature gradually increased from ~ 12 C in May to 17.5 C in late September. Autumnal mixing and turnover began in early October.

Bottom anoxia (defined as dissolved oxygen < 1 mg/L) developed at the centrally-located sampling station in early June 2020 (Fig. 2). Anoxic conditions above the sediment-water interface were continuous from mid-June through the onset of Autumnal turnover in October. Thus, the potential for anoxic P release from bottom sediment occurred throughout most of the lake stratification period.

### *Sediment characteristics and diffusive phosphorus flux*

Soluble phosphorus mass and concentration increased linearly in the overlying water column as a function of incubation days under both anaerobic (i.e., no dissolved oxygen) and aerobic (i.e. dissolved oxygen availability) conditions (Fig. 4). Linear mass and concentration increases were much greater under anaerobic compared to aerobic conditions, suggesting bacterial reduction of iron oxyhydroxides and desorption of phosphorus. Mean sediment diffusive P fluxes under anaerobic conditions were 8.28 mg/m<sup>2</sup> d ( $\pm 1.68$  standard error, SE) at 20 C (Table 1). Under aerobic conditions, the mean flux was much lower at 1.1 mg/m<sup>2</sup> d (Table 1). Both mean fluxes were high relative to other lake sediments in the regional area (Fig. 5). However, lake bottom temperatures were lower than the incubation temperature of 20 C, ranging between a minimum of 12.3 C and 17.5 C. The mean lake bottom temperature over the summer was 14.5 C. Thus, diffusive P fluxes were adjusted to these lower temperatures using a metabolic equation for use in more accurately estimating summer internal P loading in Big Lake (Table 1).

Sediment moisture content was relatively high in the upper 3-cm sediment layer, exceeding 95%, suggesting very flocculent sediment (Fig. 6). Organic matter content was also high in the surface layer at ~ 37%. Mobile P concentrations (i.e., loosely-bound P, iron-bound P, and labile organic P, subject to recycling pathways leading to internal P loading) exhibited maxima in the upper 5-cm layer and declined to lower concentrations below the 5-cm sediment depth (Fig. 7). These surface concentration peaks suggested the buildup of potentially mobile P in excess of burial, a pattern observed in eutrophic lake systems exhibiting internal P loading and low P burial efficiency (Carey and Rydin 2011, Rydin et al. 2011).

In particular, iron-bound P was the dominant mobile P fraction in the upper 5-cm sediment layer at 67% (Fig. 8). Labile organic P was the next dominant fraction, accounting for 28% of the mobile P. All mobile P fractions fell above the median and usually above the upper 25% quartile compared to other lakes (Fig. 8 and 9).

## **5.0 REFERENCES.**

APHA (American Public Health Association). 2011. Standard Methods for the Examination of Water and Wastewater. 22th ed. American Public Health Association, American Water Works Association, Water Environment Federation.

Boström B. 1984. Potential mobility of phosphorus in different types of lake sediments. *Int Revue Ges Hydrobiol* 69:457-474.

Burns NM. 1995. Using hypolimnetic dissolved oxygen depletion rates for monitoring lakes. *New Zealand J Mar Freshwat Res* 29:1-11.

Carey C, Rydin E. 2011. Lake trophic status can be determined by the depth distribution of sediment phosphorus. *Limnol Oceanogr* 56:2051-2063.

Gächter R., Meyer JS, Mares A. 1988. Contribution of bacteria to release and fixation of phosphorus in lake sediments. *Limnol Oceanogr* 33:1542-1558.

Gächter R, Meyer JS. 1993. The role of microorganisms in mobilization and fixation of phosphorus in sediments. *Hydrobiologia* 253:103-121.

Håkanson L, Jansson M. 2002. Principles of lake sedimentology. The Blackburn Press, Caldwell, NJ USA



Hjieltjes AH, Lijklema L. 1980. Fractionation of inorganic phosphorus in calcareous sediments. *J Environ Qua.* 8: 130-132.

Hupfer M, Gächter R., Giovanoli R. 1995. Transformation of phosphorus species in settling seston and during early sediment diagenesis. *Aquat Sci* 57:305-324.

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

Nürnberg GK. 1988. Prediction of phosphorus release rates from total and reductant-soluble phosphorus in anoxic lake sediments. *Can J Fish Aquat Sci* 45:453-462.

Nürnberg GK. 2009. Assessing internal phosphorus load – Problems to be solved. *Lake Reserv Manage* 25:419-432.

Psenner R, Puckso R. 1988. Phosphorus fractionation: Advantages and limits of the method for the study of sediment P origins and interactions. *Arch Hydrobiol Biel Erg Limnol* 30:43-59.

Table 1. Diffusive phosphorus flux as a function of aerobic (oxygen) or anaerobic (devoid of oxygen) for triplicate sediments collected at the centrally-located station in Big Lake in 2020. Fluxes were measured at 20 C and adjusted to bottom lake temperatures using a metabolic rate equation (Burns 1995).

Rep	Anaerobic				Aerobic			
	@ 20 C (mg/m <sup>2</sup> d)	@17.5 C (mg/m <sup>2</sup> d)	@14.5 C (mg/m <sup>2</sup> d)	@12.3 C (mg/m <sup>2</sup> d)	@ 20 C (mg/m <sup>2</sup> d)	@17.5 C (mg/m <sup>2</sup> d)	@14.5 C (mg/m <sup>2</sup> d)	@12.3 C (mg/m <sup>2</sup> d)
1	6.10	5.42	4.40	3.78	1.44	1.22	0.99	0.85
2	6.29	5.68	4.61	3.96	0.77	0.66	0.53	0.46
3	11.63	9.78	7.94	6.82	1.08	0.92	0.74	0.64
Mean	8.01	6.96	5.65	4.85	1.10	0.93	0.75	0.65
SE	1.81	1.41	1.15	0.98	0.19	0.16	0.13	0.11

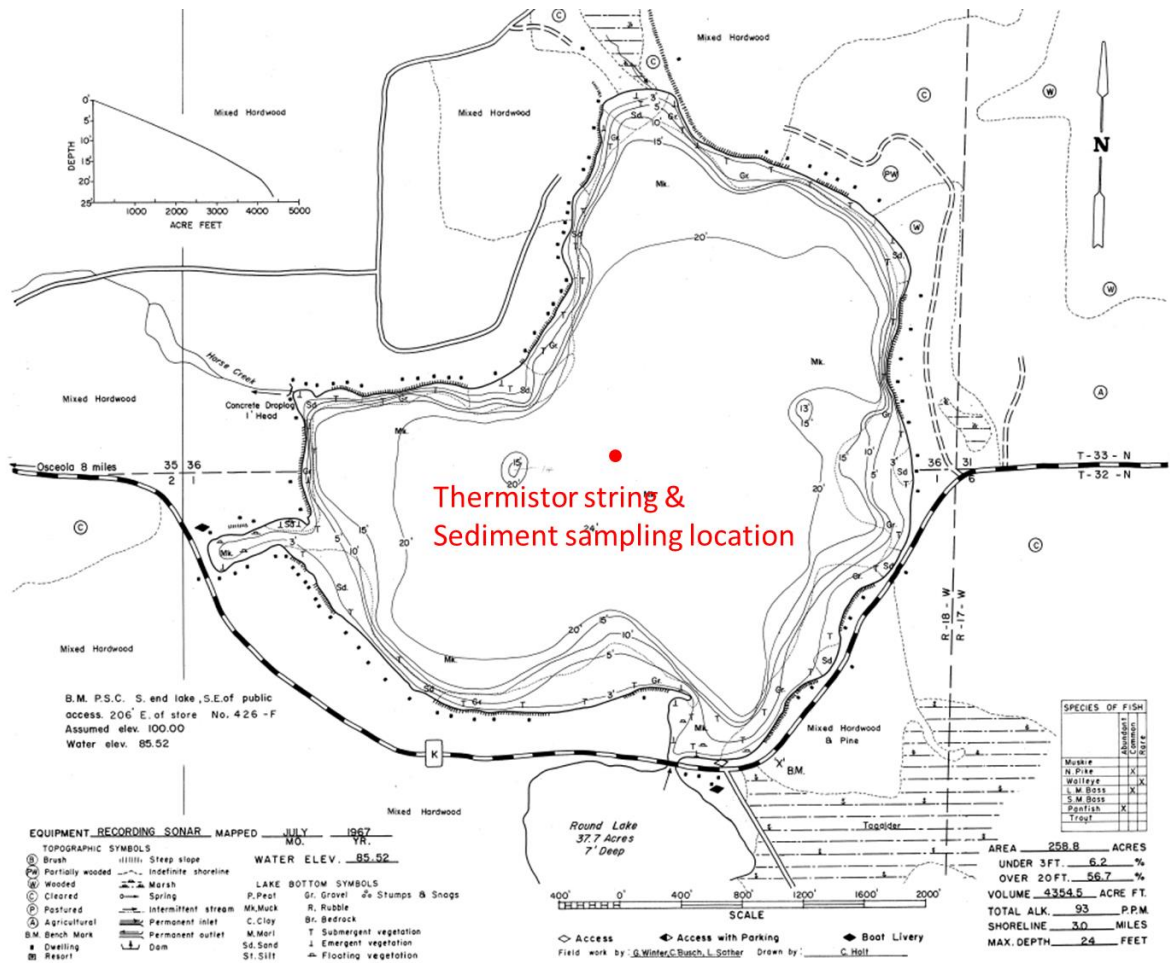
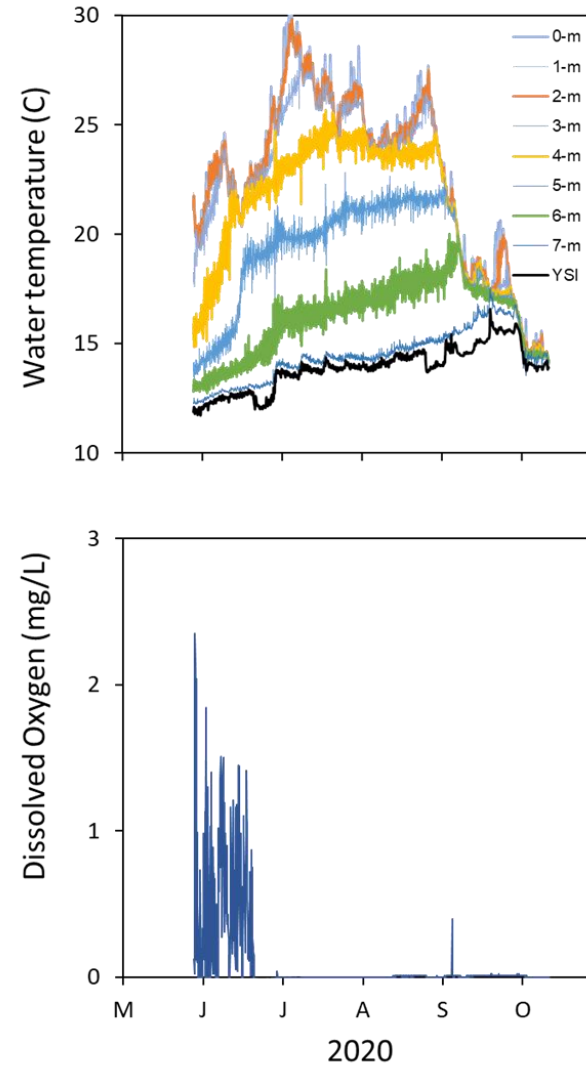


Fig. 1. Bathymetric map of Big Lake. Red dots denote the thermistor and sediment sampling stations.

Fig. 2. Seasonal variations in hourly water temperature measured at 1-m depth intervals (upper panel) and bottom dissolved oxygen (lower panel) at the sampling station located in Big Lake 2020. YSI = the independently deployed Yellow Springs Instruments (YSI) data sonde with dissolved oxygen and temperature probe.



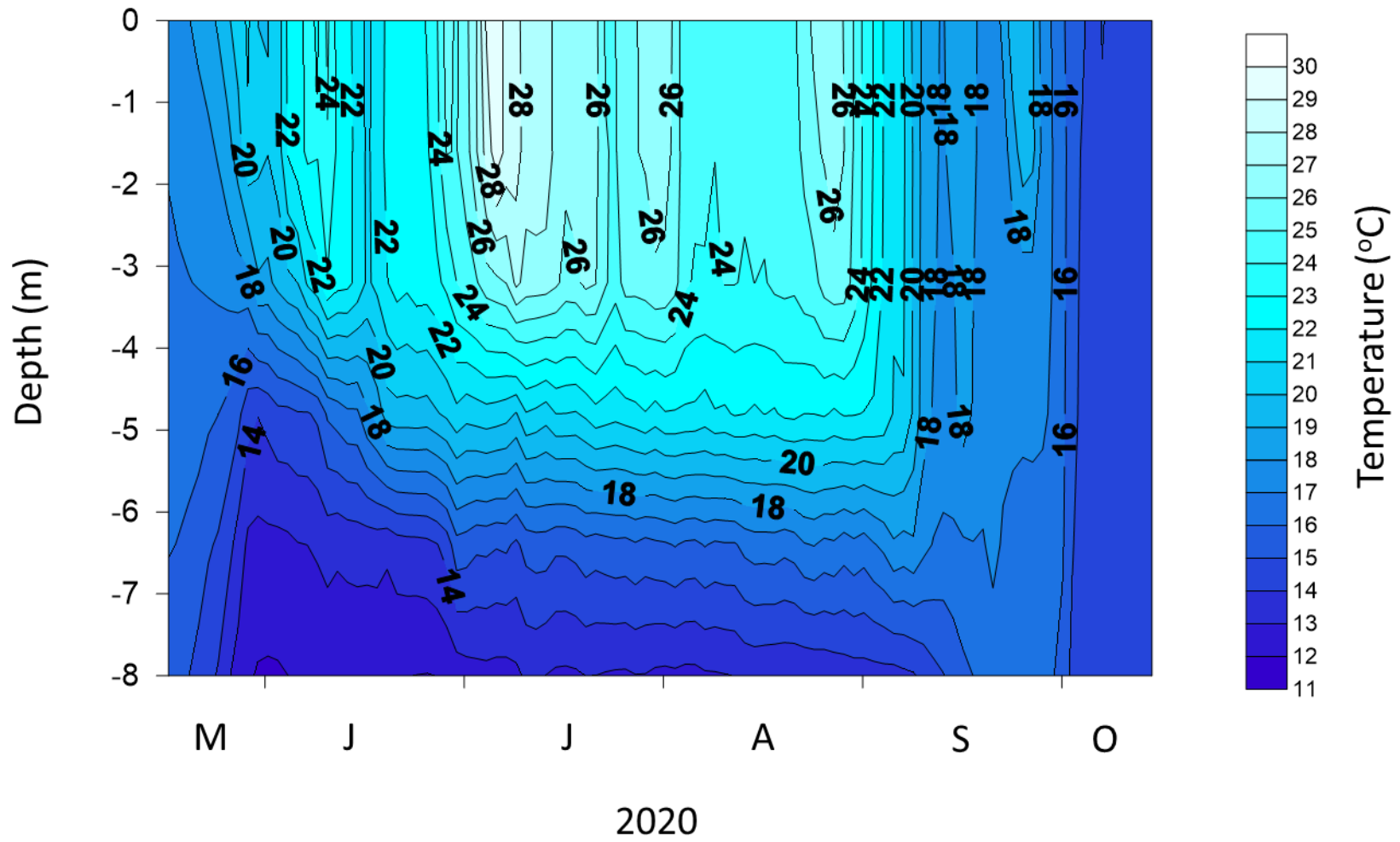


Fig. 3. Seasonal and vertical variations in water temperature.

Phosphorus in the overlying water column

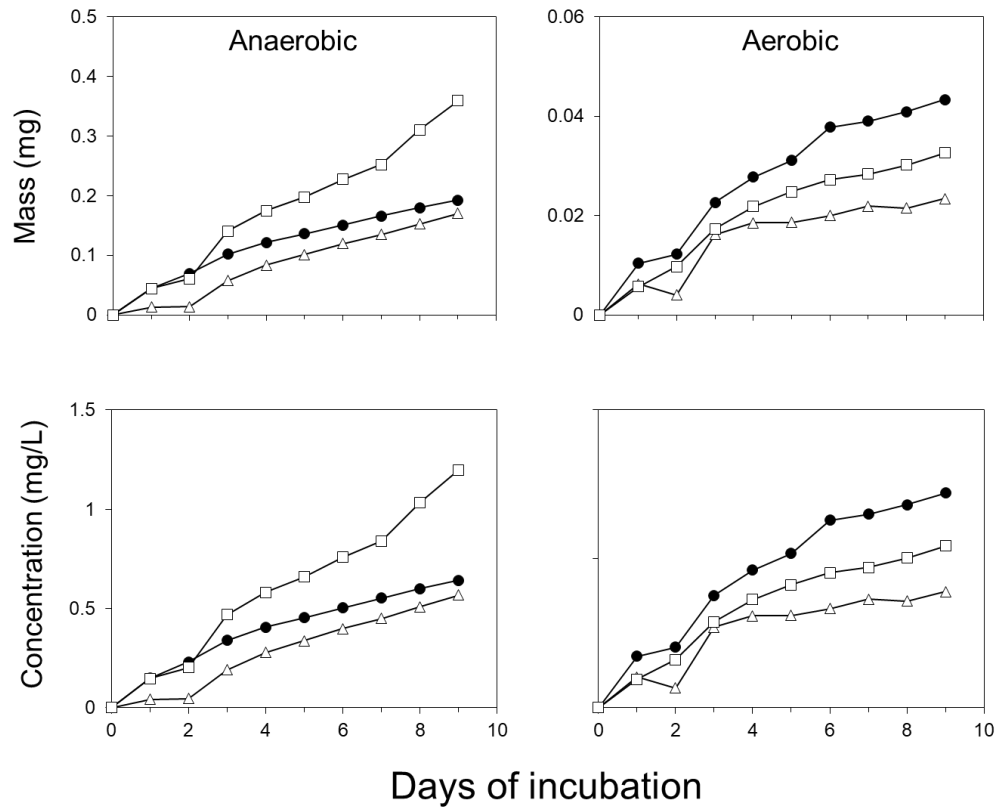


Fig. 4. Changes in soluble reactive phosphorus mass and concentration versus days of incubation in replicate sediment core incubation systems subjected to anaerobic or aerobic conditions. Please note the scale differences in phosphorus concentration and mass on the Y-axis.

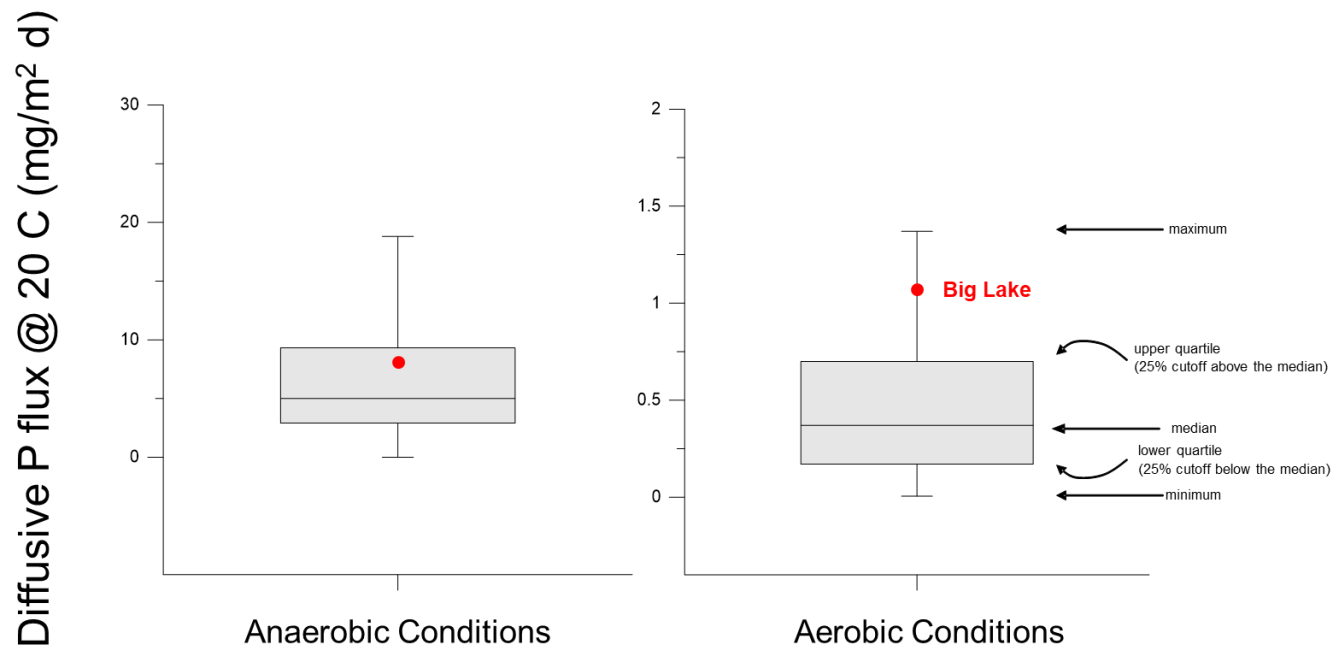


Fig. 5. Box and whisker plot comparing laboratory-derived diffusive P flux at 20 C from sediment collected in Big Lake (red circle) with other lake sediments in the region.

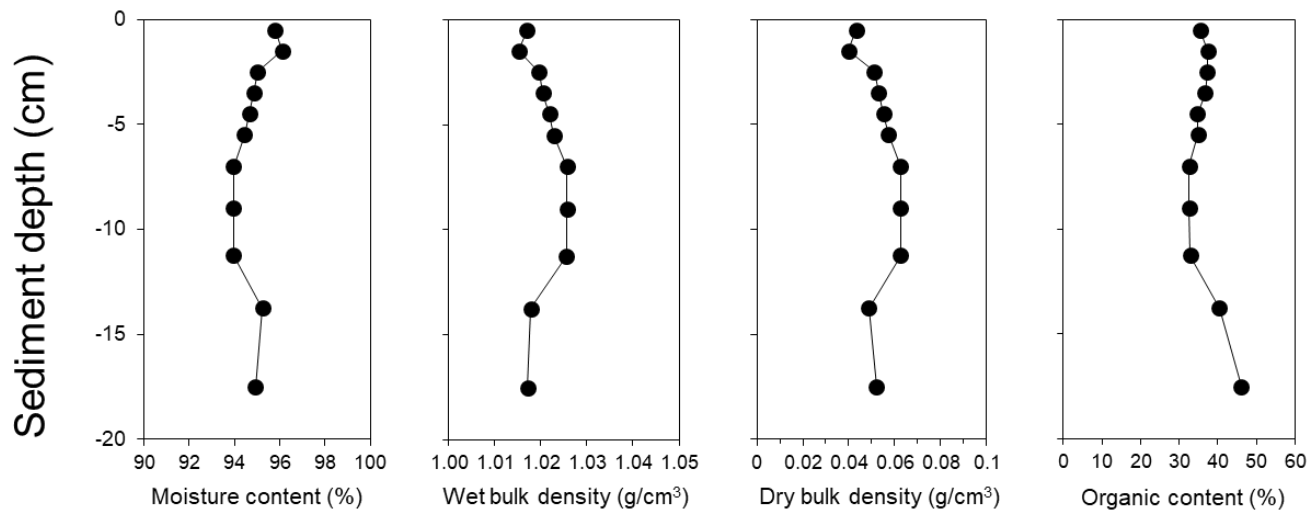


Fig. 6. Sediment core vertical profiles of physical-textural characteristics.



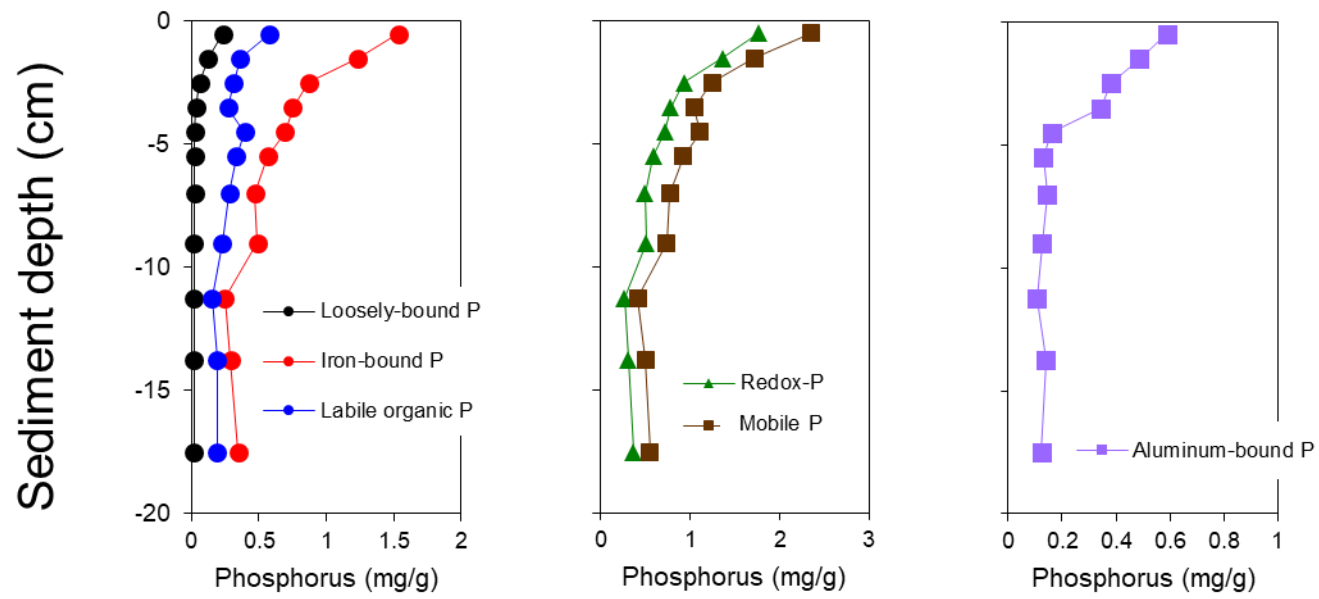
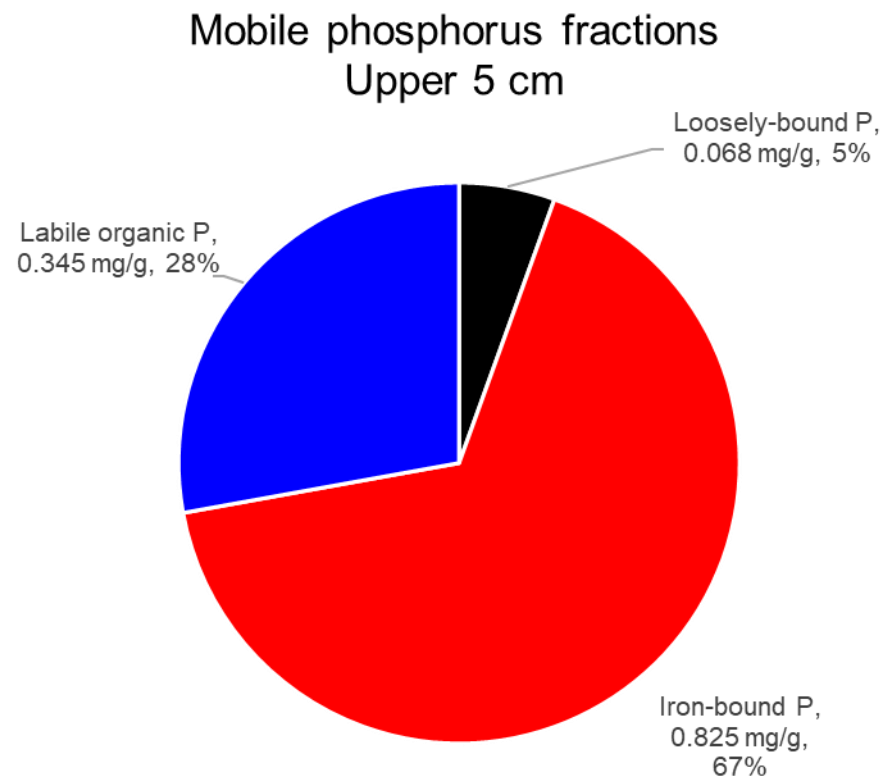
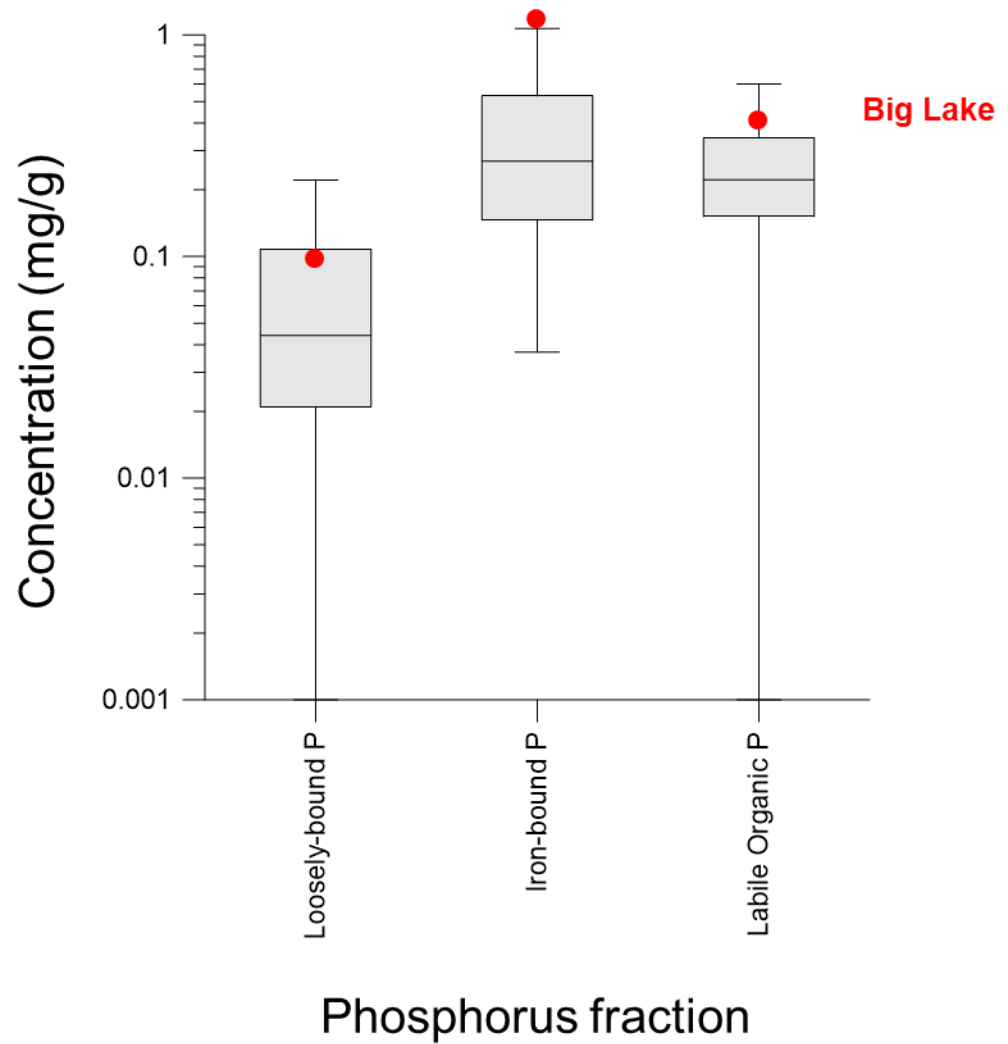


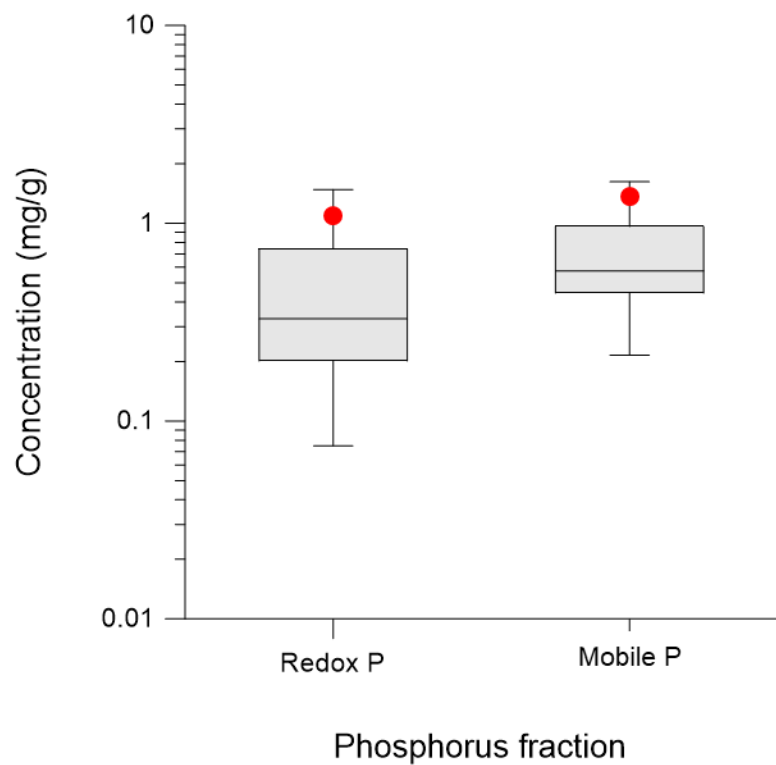
Fig. 7. Sediment core vertical profiles of various phosphorus fractions.



*Fig. 8. Percent composition of the mobile phosphorus fraction in the upper 5-cm on sediment collected in Big Lake.*

Fig. 9. Box and whisker plot comparing concentrations of loosely-bound, iron-bound, and labile organic phosphorus (P) from the upper 5-cm sediment layer in Big Lake (red circles) with other lake sediment concentrations in the region.





*Fig. 10. Box and whisker plot comparing concentrations of redox-sensitive phosphorus (i.e., loosely-bound P plus iron-bound P) and mobile phosphorus (i.e., redox P plus labile organic P) from the upper 5-cm sediment in Big Lake (red circles) with other lake sediment concentrations in the region.*