Relation of phosphorus release and sediment oxygen uptake to sediment characteristics in Big Platte Lake, Benzie Co., MI

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Introduction

Sediment has an integral role in regulating the overall water quality of lakes. Nutrient cycling between sediment and the overlying water is heavily influenced by both biotic processes, such as bacterial decomposition of organic sediment, and abiotic processes, such as chemical reduction of bound metals during low oxygen levels. (Horne and Goldeman 1994; Ignatieva 1996). A major source of nutrients in lakes comes from the accumulation and decomposition of organic matter in the sediment (Horne and Goldeman 1994). Decomposed organic matter is permanently fixed in the sediment and/or recycled back into the overlying water as available nutrients (Newrkla and Gunatilaka 1982). In dimictic lakes, nutrients in the water overlying the sediment are distributed throughout the lake during spring and fall turnover (Horne and Goldeman 1994).

Phosphorus is the nutrient that most often limits lake productivity. Phosphorus can be bound to organic and inorganic sediments, and it can occur in the water column as suspended particulate phosphorus, soluble organic phosphorus, polyphosphates, and orthophosphate (Horne and Goldeman 1994). Sediment acts as both a sink and source of phosphorus in lakes (Horne and Goldeman 1994; Ignatieva 1996). When overlying water is oxygenated, phosphorus binds to ferric iron compounds, which then fall to the sediment surface as a red precipitate (Horne and Goldeman 1994). When overlying water is anoxic, phosphorus that is stored in the sediment is initially released into the sediment porewater and then gradually diffuses across the sediment-water interface into the overlying water column (Bostrom *et al.* 1982; Burley *et al.* 2001; Ignatieva 1996). The increased phosphorus in the overlying water is mixed with the rest of the water column during seasonal turnover events resulting in greater amounts of phosphorus being available for biotic uptake throughout the lake (Juracek 1998). Overall lake productivity can thus quickly rise with surges in available phosphorus (Horne and Goldeman 1994). Up to 80%

of total phosphorus additions to some lakes have been shown to come from sediment phosphorus release (Larsen *et al*. 1981).

Several factors can influence sediment phosphorus release. Some of the most well documented factors include sediment scour/resuspension, inorganic sediment composition, quantity and content of organic matter, and hypolimnetic oxygen concentration (Premazzi and Provoni 1985). Total sediment phosphorus concentrations and oxygen depletion in the water overlying the sediment are two of the primary factors that regulate phosphorus release and will be the focus of this study. Previous experiments have shown that a relationship exists between hypolimnetic oxygen depletion and sediment phosphorus release (Freedman and Canale 1977; Nurnberg 1988; Penn *et al*. 2000). Oxygen in the overlying water is consumed by sediment during chemical and biological processes, resulting in periods of anoxia during the summer and winter in deep-water zones of stratified lakes (Penn *et al*. 2000). Once oxygen is depleted from the overlying water, redox potential decreases and phosphorus, once trapped in the sediments, is released into the hypolimnetic water (Mawson et al. 1983; Ghisalberti 1998; Snodgrass 1987). In order to fully understand phosphorus cycling in a water body, sediment processes and composition need to be characterized, and phosphorus release needs to be quantified.

Platte Lake is a hard-water, marl lake located in Benzie County, Michigan. Platte Lake is currently classified as an oligo-mesotrophic lake (Clerk 2001). Platte Lake is dimictic with low dissolved oxygen concentrations in the hypolimnion during parts of the year. During the 1970’s and early 1980’s, Platte Lake received increased external loads of phosphorus, and a portion of this phosphorus was deposited in the lake sediment (Whelan *et al.* 2001). Although the increased phosphorus loading has ceased, the effects of the previous loading are still present (Whelan *et al.* 2001). Much of the added phosphorus may have been deposited in the sediments and today, these sediments may be releasing phosphorus back into the overlying water. Internal phosphorus loading from sediment release is known to persist in water bodies for years after increased external loading (Penn *et al*. 2000). Phosphorus concentrations in the water of Platte Lake and its tributaries are regularly monitored, but the amount of phosphorus deposited and released from the sediment is unknown.

Objectives/Hypotheses

The purpose of this study is to characterize the sediments of Platte Lake and determine the magnitude of internal phosphorus release. Specifically, the primary objectives of this study are to determine the role that hypolimnetic oxygen depletion and total sediment phosphorus content play in regulating sediment phosphorus release in Platte Lake. The final objective is to determine oxic/anoxic phosphorus release rates specific to Platte Lake based on sediment TP and compare the observed phosphorus release in Platte Lake to previous estimates of sediment phosphorus release.

In order to thoroughly describe the sediment throughout Platte Lake and to accurately compare Platte Lake to other lakes in similar studies, other sediment parameters also need to be measured. Therefore, sediment oxygen uptake will be measured along with other sediment parameters to better understand sediment phosphorus release in Platte Lake. Sediment oxygen uptake will be measured to quantify the oxygen consumption occurring during both biological and chemical oxidation (Bowman and Delfino 1979). The sediment parameters measured will include chemical oxygen demand (COD), total kjeldahl nitrogen (TKN), volatile solids (VS), grain size (GS), and total sediment phosphorus (TP).

The following questions will be addressed in this study: How do location and season (oxic or anoxic conditions) affect sediment phosphorus release in Platte Lake? Can phosphorus release be predicted by the total sediment phosphorus content of the sediment? Do locations with high phosphorus release rates also have a high sediment oxygen uptake? Do other sediment parameters vary similarly with location/depth in Platte Lake?

The greatest phosphorus release in Platte Lake is hypothesized to occur during anoxic periods (<2 mg O_2/L). In general, phosphorus release rates are anticipated to differ between sites and treatments. Furthermore, areas of Platte Lake that remain anoxic for the longest periods and that contain the highest TP concentrations are expected to release the greatest amounts of phosphorus. This would most likely be due to previously bound phosphate being released from reduced metals during anoxia. Seasonal variation in release rates is also expected due to changing hypolimnetic oxygen concentrations throughout the year. After spring and fall turnover, the hypolimnetic water is reoxygenated, and sediment phosphorus release is expected to be significantly lower than during anoxic periods.

Sediment oxygen uptake rates are also predicted to differ between sites. Deeper sites are expected to have higher oxygen uptake rates than shallower sites due to higher percentages of organic matter from less resuspension. Clerk (2001) stated that both particulate waste and sedimented algal material could both be possible causes of dissolved oxygen depletion in the deep-water zones of Platte Lake. Thus, the sites with the highest oxygen uptake rates are also expected to show the highest phosphorus release rates. Sediments with a high percentage of sand are expected to have the lowest oxygen uptake rates, while fine-grained sediments with high percentages of organic matter are expected to have the highest oxygen uptake rates. Sediment oxygen uptake is also expected to show a positive correlation with COD. Gardiner (1984) found that a saturation relationship existed between oxygen uptake and COD. Locations with the highest COD are expected to have the highest oxygen uptake rates.

Considerable variability in sediment composition is expected at different sites in Platte Lake. Deep-water zones are expected to have different ranges of sediment parameters than shallow-water zones. COD, TKN, TP, VS, and GS are all expected to be correlated with depth. COD, TKN, TP, and VS are expected to increase with depth due to higher concentration of organic matter in deep-water zones, while GS is anticipated to decrease with depth due to less resuspension in deep-water zones.

Methods

Before proceeding with sediment oxygen uptake and phosphorus release experiments, a general sediment survey was conducted on 9 July 2003 to determine the variability in sediment composition at different locations in Platte Lake. Thirteen sites were chosen along three transects from deep-water zones to shallow-water zones. Each site was sampled with a mini-Ponar grab sampler and COD, TKN, VS, GS, and TP were measured.

TP analysis was conducted in triplicate using 100-125 mg of dried, homogenized sediment rehydrated with DI water. Eluted phosphorus concentrations were analyzed using the molybdenum blue/ascorbic acid method and a Beckman spectrophotometer (American Public Health Association 1998). GS analysis was conducted similarly to Gardiner (1984) on a portion of the original sample by dry sieving through 1000, 425, 250, 212, 105, and 75 µm sieves and by weighing each size fraction. Sediment dry weight was determined with standard methods by calculating the difference between initial wet weight and final dried weight after drying for 24 hours at 105°C. VS analysis was conducted on a portion of the original sample after percent water determination according to standard methods by heating to 550°C for at least 2 hours. An external laboratory analyzed COD and TKN using standard methods.

Eight sites were selected for phosphorus release and oxygen uptake monitoring. These sites were selected to encompass the range of sediment types present in Platte Lake during the initial sediment survey (*Table 1*). At each site, sediment cores were collected for phosphorus release and oxygen uptake experiments using a modified Kajak-Brinkhurst corer. Mini-Ponar grab samples were collected along with sediment cores to establish sediment characteristics at the time of coring. VS, GS, and TP were measured on each set of grab samples collected with phosphorus release cores. COD was examined on the set of grab samples collected with oxygen uptake cores. Cores were collected for phosphorus release and oxygen uptake experiments in mid-summer 2003 and will be collected through December 2004 to examine seasonal changes in sediment conditions (see Time Table).

Sediment cores were transported on ice to the aquatics laboratory at Central Michigan University. Cores were transported in a vertical position with minimal disturbance and were incubated in the dark at 8°C ±1.5°C. The overlying water in the sediment cores was siphoned off and replaced with lake water filtered through a 0.45 µm Millipore filter. Replacement lake water was collected from Platte Lake just above the sediment-water interface (Ignatieva 1996; Kamp-Nielson 1974) on the same date as the cores. Each core tube was capped with a rubber cork equipped with ports for aeration and sample collection (*Figure 1*). All gas additions were performed by placing an aeration stone approximately 10 cm above the sediment-water interface (Penn *et al.* 2000).

Oxygen uptake was measured on single cores collected from the eight predetermined sites once per season. Oxygen uptake experiments were modeled after Gardiner (1984). Overlying water in each core tube was bubbled with compressed air for two hours to saturate the water with oxygen. Dissolved oxygen was measured at 15 minute intervals using a Hydrolab Mini-Sonde 4a inserted through the rubber cork and connected to a Hydrolab Surveyor 4a data logger. Dissolved oxygen in each core was monitored for approximately 8 hours or until linear dissolved oxygen depletion rate was observed. The stirring mechanism on the mini-sonde gently mixed the overlying water inside each core and prevented development of an oxycline . Sediment oxygen uptake was measured as the decrease over time in dissolved oxygen (mg/L) in the overlying water. The oxygen uptake rate should be relatively constant when the oxygen concentration in the overlying water is above 2 mg O^2/L (Gardiner 1984). Sediment oxygen uptake was converted to mg O^2/m^2/day based on the volume of overlying water and sediment surface area. One additional core was filled with deionized water during each set of experiments and served as a control. The control should indicate if an oxygen depletion rate exists in the overlying water. Cores were analyzed one at a time within two weeks of collection. The order of core analysis was randomly selected on each sampling date to eliminate any potential bias.

Phosphorus release was measured on duplicate cores collected from four sites twice during a season. The phosphorus release experiments were modeled after studies performed by Kamp-Nielson (1974) and Penn *et al.* (2000). Phosphorus release was monitored for 10 days under both oxic and anoxic conditions to mimic the seasonal dissolved oxygen extremes that naturally occur in the hypolimnion of Platte Lake. Oxic and anoxic conditions were achieved by continuously bubbling either compressed air or nitrogen into the overlying water of duplicate sediment cores collected from each site (Penn *et al.* 2000). Sediment cores were allowed to equilibrate for one day prior to phosphorus measurement. A dissolved oxygen probe was periodically inserted into each core to verify oxygen conditions.

A 125 ml aliquot of overlying water was extracted from each core with a pipette every three days for analyis of total dissolved phosphorus (TDP). An equal volume of filtered lake water was injected back into the core to maintain water volume. The extracted water sample was filtered through a 0.45 μm Millipore filter and TDP was analyzed using the molybdenum blue/ascorbic acid method and a Beckman spectrophotometer (American Public Health Association 1998). Phosphorus release was calculated as the increase in TDP over time in the overlying water divided by the sediment surface area (Ignatieva 1996). TDP was measured to avoid including any suspended particulate-bound phosphorus. Phosphorus release was converted to μg P/m^2/day based on the volume of overlying water and sediment surface area. Two additional tubes were filled with deionized water. One was bubbled with nitrogen and the other with air. Water from these control tubes was analyzed as above to determine if the experimental apparatus was a source of phosphorus.

Sediment oxygen uptake rates were compared between sites using a randomized block design ANOVA with season as the blocking factor. Phosphorus release rates were compared between locations and oxygen treatments using a 2-factor ANOVA blocking for season. Tukey-Kramer tests were performed to identify significant differences between factor levels. A simple linear regression was used to determine if phosphorus release rates could be predicted from TP concentration in the sediments. In addition, a correlation between COD and the sediment oxygen uptake rate will be conducted on samples taken on the same date to determine if an association exists. Correlations between sediment parameters (COD, TKN, TP, VS, and GS) and depth will be conducted to determine if any associations exist.

Timetable*:* 8 sites chosen from general survey. 8 cores will be taken on each date. Grab samples will be taken on the same dates as P-release cores. Grab samples will also be taken on one O2 uptake sampling date.

Approximate Sampling Date	**Sites Sampled**	**Experiment**
August 15-31 2003	Sites 1-8	Oxygen Uptake
February 2004	Sites 1-4	P-release
May 1-15 2004	Sites 4-8	P-release
May 15-31 2004	Sites 1-8	Oxygen Uptake
June 1-15 2004	Sites 1-4	P-release
June 15-30 2004	Sites 5-8	P-release
July 2004	Sites 1-8	Oxygen Uptake
August 1-15 2004	Sites 1-4	P-release
August 15-31 2004	Sites 5-8	P-release
September 2004	Sites 1-8	Oxygen Uptake
October 1-15 2004	Sites 1-4	P-release
October 15-30 2004	Sites 5-8	P-release
November 2004	Sites 1-8	Oxygen Uptake
December - January 2005	Compile and analyze data	
February - April 2005	Summarize findings and write thesis	

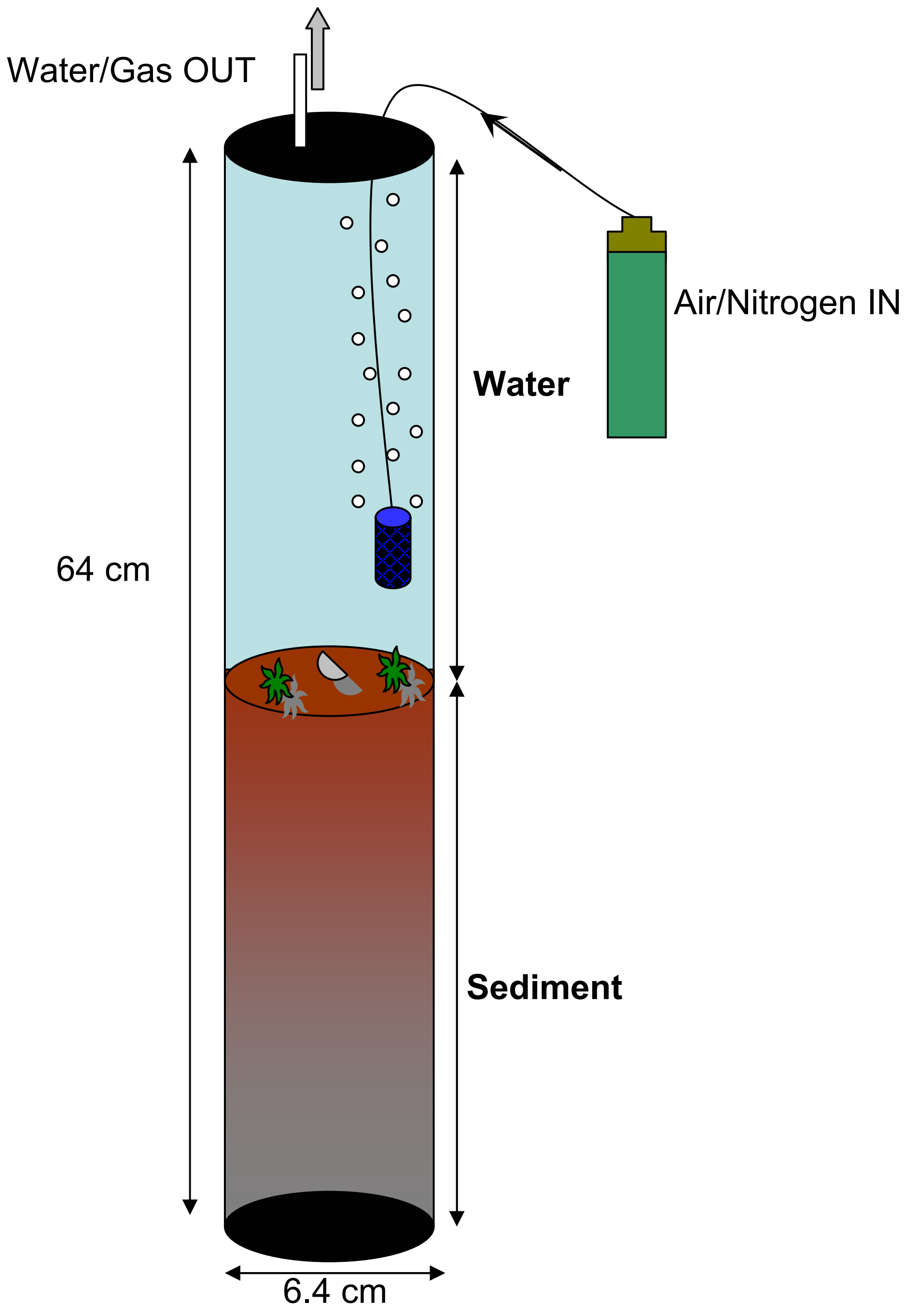

Figure 1: General Sediment Core Diagram

Results

Sediment samples collected on 7-9-03 when oxygen was absent from deep-water regions indicate that sediment quality varied with depth. In general, water content, volatile solids, TP, COD, and TKN were all found to increase with depth in Platte Lake (*Table 2*). Water content ranged from 39.53% in shallow water (site T3-2) to 78.05% in deep water (site T1-28). The range of volatile solids was from 1.79% in shallow water (site T3-2) to 13.94% in deep water (site T2-15). A correlation between volatile solids and depth yielded a Pearson correlation coefficient of 0.625 (*Figure 2*). TP varied from a low of 0.09 mg/g in shallow water (sites T1-2 and T3-2) to a high of 0.55 mg/g in deep water (site T1-28). A Pearson correlation coefficient of 0.899 was determined from a correlation between TP and depth (*Figure 3*). COD ranged from 30,000 mg/kg in shallow water (site T3-2) to 240,000 mg/kg in deep water (site T2-22). A correlation between COD and depth yielded a Pearson correlation coefficient of 0.818 (*Figure 4*). TKN varied from a low of 600 mg/kg in shallow water (site T3-2) to a high of 6,600 mg/kg in deep water (site T2-22). A Pearson correlation coefficient of 0.845 was determined from a correlation between TKN and depth (*Figure 5*).

The initial set of oxygen uptake cores were collected on 8-21-03 during *in situ* anoxic conditions in deep-water areas. The resulting oxygen uptake rates and r^2 values are presented in *Table 3* for 7 locations. The values of r^2 show the strength of the relationship between oxygen uptake and time. A sample scatter plot showing the decrease in dissolved oxygen over time and the corresponding r^2 value for site T2-5 is shown in *Figure 6*. A similar scatter plot was constructed for each site. A comparison of oxygen uptake rates between sites is shown in *Figure 7*. Sites T3-2 and T1-12 yielded the lowest oxygen uptake rates, and sites T2-22 and T2-5 produced the highest uptake rates (*Table 3*). No data are presented for site T1-28 due to data logging problems with the Hydrolab.

The first set of phosphorus release cores were collected on 2-23-04 during *in situ* oxic conditions in deep-water areas. The resulting TDP release rates and r^2 values are presented in *Table 3* for 4 locations and oxic/anoxic treatment. Phosphorus release rates were zero or negative in all cores under oxic conditions and in cores T3-10 and T1-5 under anoxic conditions (*Table 3*). Positive release rates were apparent only in cores T3-5 and T1-28 under anoxic conditions. The r^2 values indicate a strong linear relationship between TDP release and time only for the anoxic core from T1-28 (*Figure 8a*). In most cores, phosphorus release followed a non-linear pattern with time (*Figure 8b*). Often, the pattern of phosphorus release during days 0-6 was opposite to that during days 6-12.

Sites T1-5 and T3-10 were phosphorus sinks under both oxic and anoxic conditions (*Figure 9*). Site T3-5 was a sink for phosphorus under oxic conditions and a source for phosphorus under anoxic conditions. Site T1-28 was a source of phosphorus under anoxic conditions and yielded the highest TDP release rate (*Figure 9*). The other 4 sites were not sampled immediately after monitoring the first set of cores due to unsafe ice conditions.

Table 1: Data for % water, % volatile solids, TP, COD, and TKN are shown for 13 locations sampled on 7-9-03. The water depth at each site can be identified by the second part of each site designation (i.e. T1-28 corresponds to a depth of 28 M).

Site	Water Content	Volatile Solids	TP (mg/g dry)	COD (mg/kg dry)	TKN (mg/kg dry)
T1-28	78.05%	13.45%	0.55	150,000	6,200
T1-20	77.13%	12.73%	0.48	180,000	6,000
T1-12	69.88%	9.99%	0.34	110,000	4,100
T1-5	56.12%	4.37%	0.11	57,000	1,900
T1-2	59.12%	4.68%	0.09	41,000	1,700
T2-22	76.57%	13.46%	0.51	240,000	6,600
T2-15	73.26%	13.94%	0.44	140,000	6,100
T2-10	75.58%	13.38%	0.42	170,000	6,000
T2-5	57.81%	6.06%	0.31	83,000	2,700
T2-2	60.55%	5.83%	0.14	49,000	2,400
T3-10	72.66%	22.61%	0.44	160,000	5,800
T3-5	50.11%	4.71%	0.19	47,000	1,800
T3-2	39.53%	1.79%	0.09	30,000	600

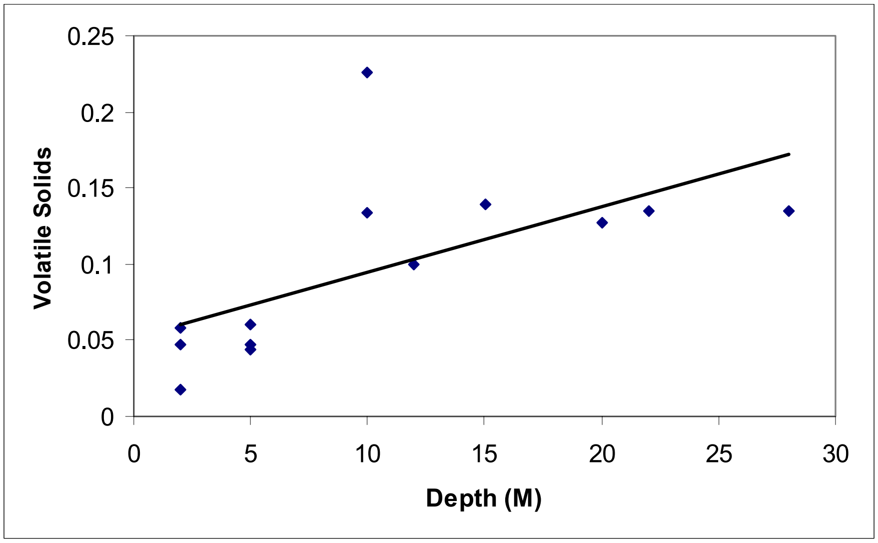

Figure 2: Scatter plot showing the positive linear relationship (r=0.625) between volatile solids and depth. Volatile solids for 13 sites were determined from grab samples taken on 7-9-03.

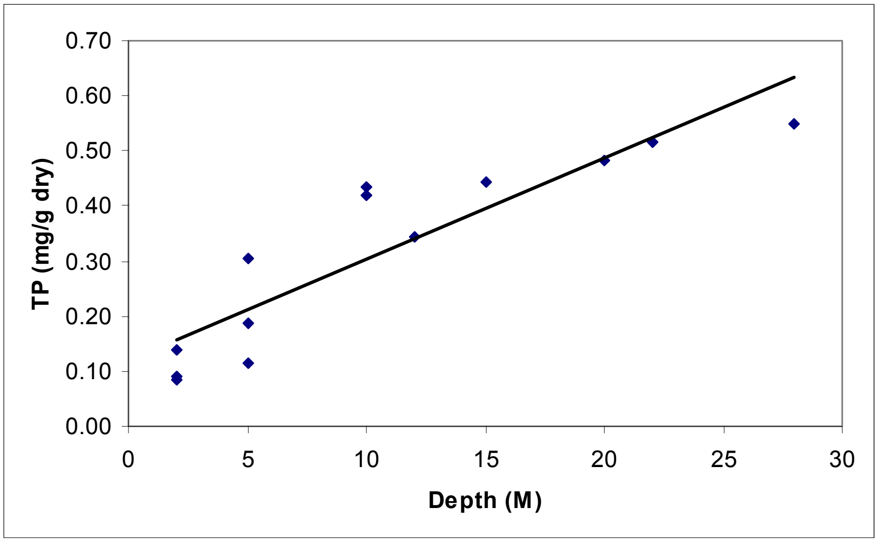

Figure 3: Scatter plot showing the positive linear relationship (r=0.899) between total sediment phosphorus and depth. Total sediment phosphorus for 13 sites was determined from grab samples taken on 7-9-03.

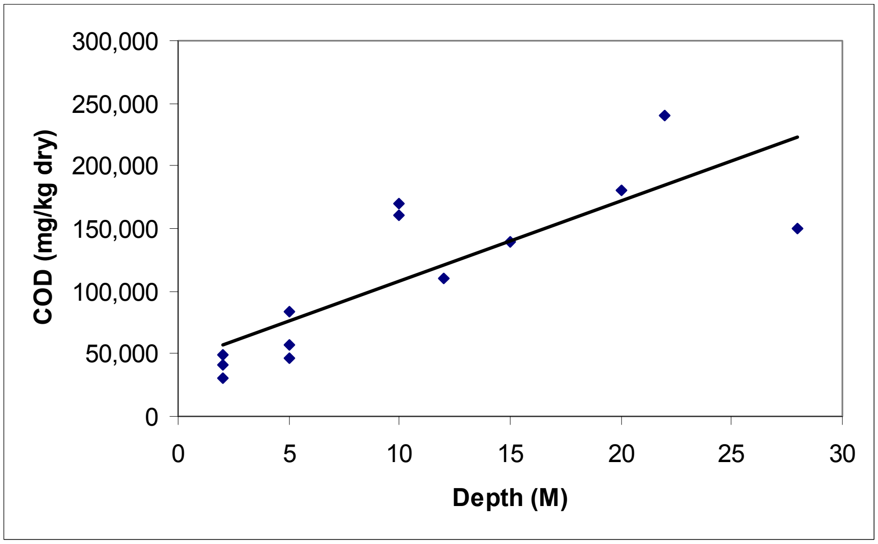

Figure 4: Scatter plot showing the positive linear relationship (r=0.818) between chemical oxygen demand and depth. Chemical oxygen demand for 13 sites was determined from grab samples taken on 7-9-03.

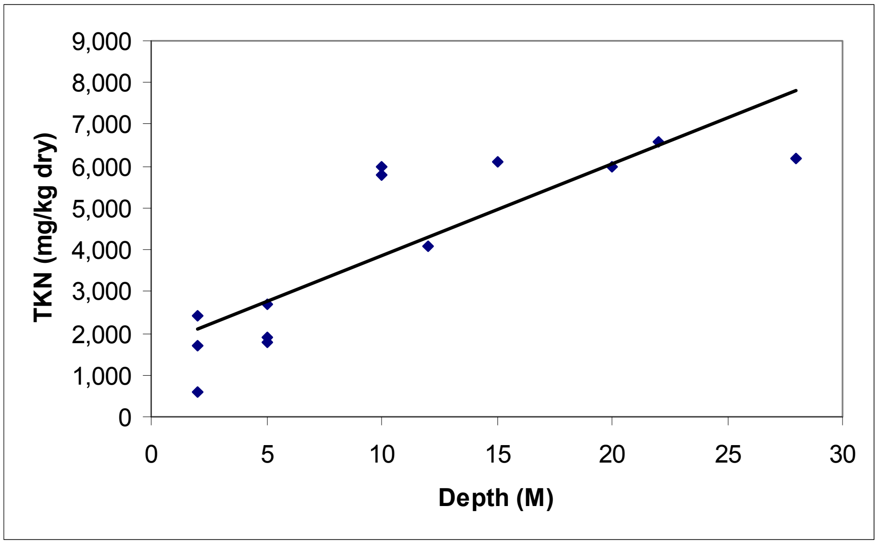

Figure 5: Scatter plot showing the positive linear relationship (r=0.845) between total Kjeldahl nitrogen and depth. Total Kjeldahl nitrogen for 13 sites was determined from grab samples taken on 7-9-03.

Table 3: Sediment oxygen uptake rates and oxic/anoxic total dissolved phosphorus release rates with corresponding r^2 values. Oxygen uptake cores were collected on 8-21-03. Phosphorus release cores were collected on 2-23-04. Negative values indicate an uptake of phosphorus. Sediment surface area was assumed to be 32.17 cm^2 in each core.

Site	Sediment Oxygen Uptake (g O^2/m^2/day)	r^2 value	Oxic TDP release (µg P/day)	r^2 value	Anoxic TDP release (µg P/day)	r^2 value
T1-28	---	---	0.0041	0.0001	1.1312	0.925
T1-5	1.42	0.985	-0.0869	0.147	0.0381	0.0062
T3-10	1.30	0.934	-0.1973	0.442	-0.2745	0.297
T3-5	1.74	0.930	-0.4037	0.260	0.241	0.196
T1-12	0.52	0.963	---	---	---	---
T2-22	1.98	0.987	---	---	---	---
T2-5	1.99	0.984	---	---	---	---
T3-2	0.66	0.921	---	---	---	---

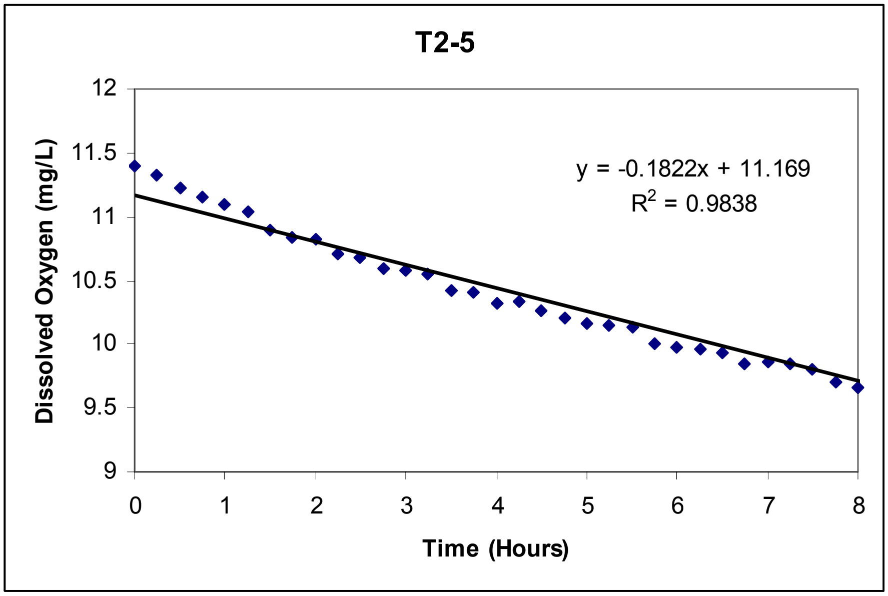

Figure 6: Sample scatter plot showing the sediment oxygen uptake rate for one site (T2-5). The equation of the best line and r^2 value are also shown.

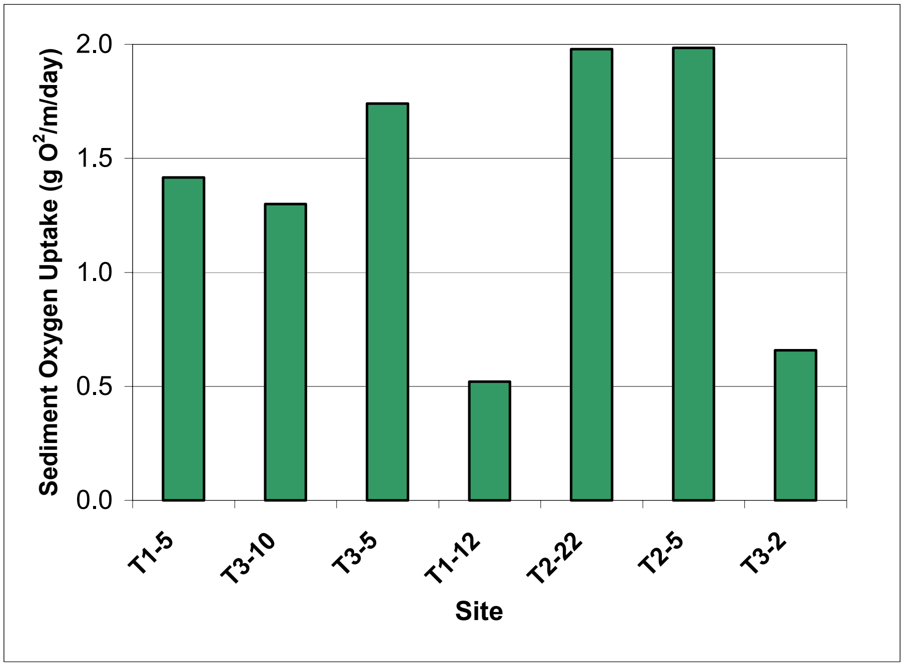

Figure 7: Comparison of oxygen uptake rates among 7 sites in Platte Lake. Oxygen uptake rates were individually determined over an 8-12 hour period from sediment cores taken on 8-21-03.

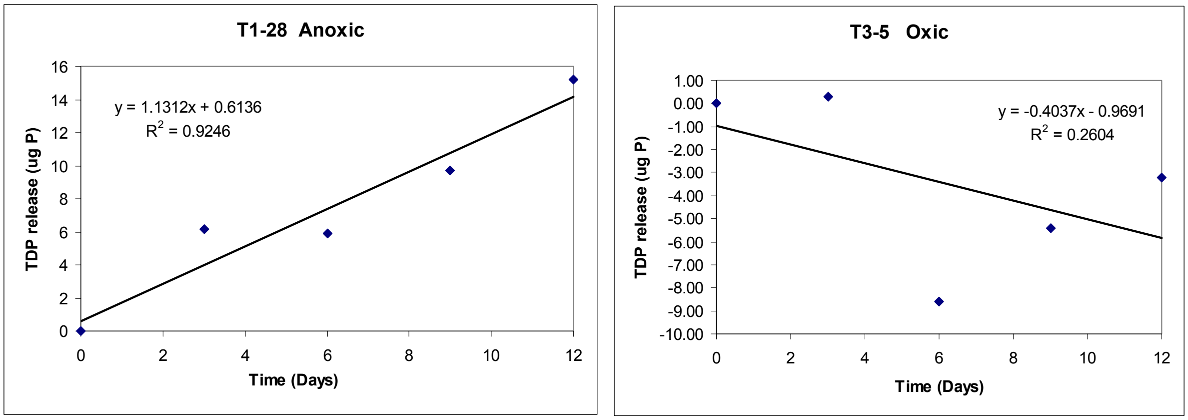

Figure 8: Sample scatter plot showing the total dissolved phosphorus release rate for core T1-28 under anoxic conditions and core T3-5 under oxic conditions. The equation of the best line and r^2 value are also shown.

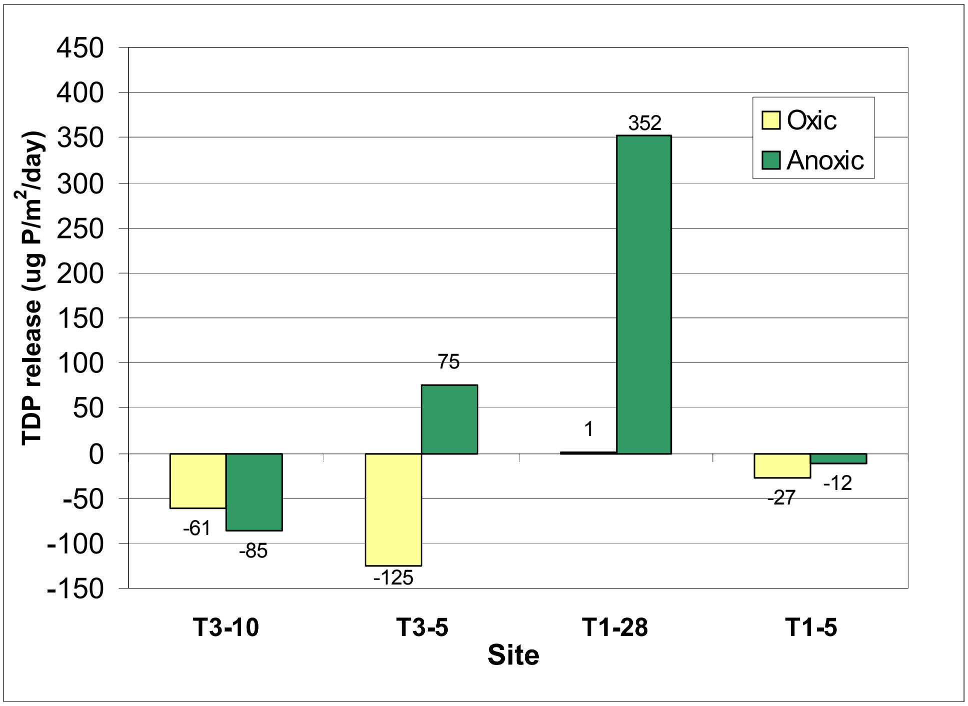

Figure 9: Comparison of oxic and anoxic total dissolved phosphorus (TDP) release rates among 4 sites. Release rates were determined over a 2 week period from sediment cores taken on 2-24-04. Negative values indicate an uptake of phosphorus.

Conclusions

Variability in some sediment characteristics between locations in Platte Lake is evident. From the general survey data, volatile solids, TP, COD, and TKN all showed positive linear relationships with depth. As expected, the values for each of these four parameters increased with increasing depth. TP was found to be the parameter that was most highly correlated with depth. An obvious difference in sediment characteristics exists between shallow-water and deep-water locations.

Furthermore, not enough data have been collected yet to assess general trends in sediment oxygen uptake and phosphorus release between locations in Platte Lake. The preliminary data show that sediment oxygen uptake rates and oxic/anoxic phosphorus release rates do differ between locations in Platte Lake. It is also promising that the range of preliminary sediment oxygen uptake rates for Platte Lake is comparable to oxygen uptake rates presented by Gardiner (1984). However, the reliability of the presented oxygen uptake data may be in question due to delayed measurement dates. The approximate two-week delay after collection was due to data logging problems with the Hydrolab. The data logging problems have been addressed to try to minimize any further sampling disturbances.

The initial set of phosphorus release cores produced some predicted and some unpredicted results. As expected, the anoxic treatment of a core taken from the deepest site yielded the highest phosphorus release rate. The anoxic phosphorus release rate from site T1-28 is likely related to the high volatile solids and TP also present at this site. Conversely, the lowest phosphorus release rate occurred in an oxic core from a shallow-water site. The negative phosphorus release rate supports the likelihood that oxic treatments fix phosphorus in some sediments. Some possible explanations for the negative release rates may be attributed to biological assimilation of phosphorus or chemical adsorption during high oxygen conditions. These phosphorus release rates are only preliminary estimates that may change upon further analysis. Several cores exhibited non-linear patterns of phosphorus change over time. Future experiments will be designed to identify time periods where linear release is evident.

Thus far, the characterization of the sediments throughout Platte Lake has progressed well. If possible, additional work on characterizing the sediments from the mid-range depths may be beneficial for making whole lake estimates. Determination of grain size distributions from previous and future sediment samples should also be valuable. For the most part, however, solid conclusions about sediment oxygen uptake and phosphorus release in Platte Lake cannot be drawn until this study has been completed.

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