Internal Phosphorus Loading Analysis for Sediments in Eagle Springs Lake, Wisconsin

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PREFACE

This research was conducted in response to a request from the Eagle Springs Lake Association and the State of Wisconsin Department of Natural Resources (WI-DNR) to the USAE Engineer Research and Development Center (ERDC) for research assistance to determine the impacts of sediment dewatering or dredging on rates of internal phosphorus loading from sediments of Eagle Springs Lake, located in Waukesha County, Wisconsin. Funding was provided by the Eagle Springs Lake Association.

This report was written by Mr. William F. James of the Eau Galle Aquatic Ecology Laboratory (EGAEL) of the Environmental Processes and Effects Division (EPED) of the ERDC. Mr. Harry L. Eakin and Ms. Laura J. Pommier of EGAEL are gratefully acknowledged for conducting field sampling, sediment core incubation studies and analysis. I also thank Mr. Tom Day for his assistance in the field work.

BACKGROUND

Sediment resuspension via motor boat activity and wind-generated turbulence can lead to instances of high total suspend solids concentrations and turbidity in the water column and reduced transparency. Resuspension occurs when the critical shear stress of the sediment (i.e., the amount of force in the form of water currents and turbulence required to induce resuspension) is exceeded at the sediment interface. Flocculent sediments composed of silts and clays usually exhibit a high moisture content and low bulk density and are more susceptible to resuspension at low critical shears stresses versus sandy sediments. Sediments located at shallow depths in close proximity to wave action and motor boat turbulence are also more susceptible to resuspension versus sediments located in deeper portions of a lake. Submersed aquatic plants can be beneficial in reducing sediment resuspension by dissipating shear stress at the sediment-water interface (James and Barko 1994; James et al. 2004). Sediment resuspension can also be reduced by temporarily dewatering and consolidating flocculent sediment via exposure during a temporary lake drawdown (Sheffer 1998). Dewatering results in sediment compaction and an increase the force required to initiate sediment resuspension. Another means of reducing sediment resuspension is to dredge flocculent sediment down to a more compacted layer.

Dewatering and/or dredging to a subsurface sediment layer may have indirect negative (or positive) impacts on nutrient recycling that can lead to poor water quality. Completely dried sediments can release considerable phosphorus when rewetted due to death and cell lysis of microorganisms (Klotz and Linn 2001). In contrast, partial dewatering and rewetting can lead to temporary decreases in the flux of phosphorus from the sediment if phosphorus becomes bound to iron and calcium compounds as a result of desiccation (Fabre 1992; DeGroot and Van Wijck 1993). Thus, there is a need to evaluate the impacts of sediment management on nutrient recycling in order to make sound decisions regarding the best approach to take to improve water clarity without mobilizing nutrients.

Sediment dredging and/or lake drawdown to consolidate sediments are being considered to reduce sediment resuspension in Eagle Springs Lake, Waukesha County, Wisconsin. The lake was formed by impoundment of the Mukwonago River approximately 150 years ago (T. Day, personal communication). The surface area of the lake is ~ 311 acres and mean and maximum depths are 3.6 and 8 ft, respectively. The Mukwonko River is the major tributary input to the lake and it drains a predominantly agricultural watershed (62% of the land use; Hey and Associates 2002). The lake stratifies during the summer and exhibits mesoeutrophic conditions (mean TSI = 49, mean Secchi transparency = 5.12 ft, mean turbidity = 3 NTU, mean chlorophyll a = 6.8 mg m^{-3}, mean total phosphorus = 0.018 mg L^{-1}; Hey and Associates 2002). Sediments are flocculent with a mean organic matter content of 12% and a total phosphorus content of 19 µg g $sediment^{-1}$ (Hey and Associates 2002). They are also considered to contain calcareous marl deposits (T. Day, personal communication). Submersed and emergent vegetation are present throughout most of the lake. Common species include Coontail, Pondweeds, Musk Grass, Elodea, Water Lilies, Cattail, and Milfoils (Hey and Associates 2002). Eurasian Water Milfoil invaded the lake in ~ 1985 and has been subjected to management to reduce its presence in the lake. It is currently not at nuisance levels (T. Day, personal communication).

The objectives of this research were to 1) evaluate rates of phosphorus release from surface sediments and from a subsurface layer of sediment (i.e., preimpoundment soils), 2) determine variations in rates of phosphorus release from sediments as a function of sediment dewatering and rewetting, and 3) estimate compaction of sediments collected from various locations in the lake as a function on complete desiccation.

METHODS

Rates of internal P loading in the surface layer and subsurface sediment layer

Twelve intact sediment cores were collected from station D for examination of phosphorus release from sediments in the laboratory (Figure 1; Table 1). A Wildco KB Sediment Core Sampler (Wildco Wildlife Supply Co.), equipped with an acrylic core liner (6.5-cm ID and 50-cm length), was used to collect sediment. The core liners, containing both sediment and overlying water, were sealed using stoppers and stored in a protective box until analysis. Additional lake water was collected at station D for later incubation with the collected sediment.

In the laboratory, sediment cores were carefully drained of overlying water for extrusion into sediment incubation systems. Sediment incubation systems consisted of a smaller acrylic core liner (6.5-cm dia and 20-cm ht) that was sealed with rubber stoppers (Figure 2a). To one set of six sediment cores, the upper layer (maximum core length of 10 cm) was carefully extruded, intact, into a sediment incubation system using a core removal tool. To the other set of six cores collected at the same location, the upper layer of aquatic sediment was removed and discarded. This layer was ~ 24 cm in length and consisted of light-colored flocculent sediment. The remaining subsurface layer (maximum core length of 10 cm) was extruded into the sediment incubation system. The subsurface sediment layer was dark brown in color and believed to be preimpoundment soils.

Lake water was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the incubation system without causing sediment resuspension. The sediment incubation systems were placed in a darkened environmental chamber and incubated at a constant temperature of 20 C. 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 ensured complete mixing of the water column but did not disrupt the sediment. For each treatment (i.e., surface and subsurface sediment layer), 3 replicate sediment incubation systems were subjected to an oxic environment while another 3 replicates were subjected to an anoxic environment.

Water samples for soluble reactive phosphorus (SRP) were collected daily from the center of each sediment incubation system using an acid-washed syringe and immediately filtered through a 0.45 µm membrane syringe filter (Nalge). 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. SRP was measured colorimetrically using the ascorbic acid method (APHA 1998). Rates of SRP release from the sediment (mg m^{-2} d^{-1}) were calculated as the linear change in concentration in the overlying water divided by time and the surface area of the sediment core.

Variations in rates of internal phosphorus loading in the surface layer as a result of sediment dewatering

An additional 18 sediment cores were collected at station D for determination of rates of phosphorus release from the upper 10 cm of sediment as a function of sediment dewatering. The upper 8 cm of the surface layer of sediment were extruded into sediment incubation systems for desiccation (Figure 2b). The bottom of the incubation sleeve was sealed with a rubber stopper and the top of the sleeve was left unsealed. The sediments were dewatered by 33%, 66%, and nearly 100% of the original moisture content by drying in the laboratory under darkened conditions at room temperature (20 C). Changes in moisture content were monitored by measuring changes in the mass of the sediment core every other day. When the target moisture content was reached, the cores were rehydrated with filtered lake water for 2 weeks before determination of rates of phosphorus release under oxic (3 replicates) and anoxic (3 replicates) conditions using methods described above. Sediment cores typically consolidated and lost volume as they dried. To prevent exposure of the side surfaces of the core to overlying water during phosphorus release rate analysis, the sides of the core were first gently wrapped in two layers of cellophane (leaving the upper surface exposed), then fine-grain sand (prewashed in distilled water) was gently packed around the sides of the core after placement in the incubation system. After the study, sediment cores were removed from the incubation sleeves and dried to a constant mass at 105 C for moisture content determination. Sediment core height and diameter were also determined.

Vertical variations in sediment moisture content and bulk density

One intact sediment core was collected at station D for examination of vertical variations in moisture content and bulk density. In the laboratory, the sediment core was sectioned at 10-cm intervals over the upper 40 cm of sediment core sample. Sediment core sections were weighed immediately (fresh mass) and then dried at 105 C for moisture content determination (moisture content = 100 x (fresh mass-dry mass)/fresh mass)). For bulk density determination, the height and diameter of the sediment core section was measured to calculate volume. Bulk density was estimated as sediment dry mass per volume of sediment (g mL^{-1}).

Estimation of compaction due to sediment dewatering

One sediment core was collected at stations A, B, D, and F for determination of sediment compaction potential (Figure 1; Table 1). Sediment cores were collected in 5-cm diameter acrylic sleeves by 40 cm length. The length of the sediment core appeared to coincide with the layer of aquatic sediment located above preimpoundment soils in the lake. The sediments contained in the core liners were drained of overlying water and allowed to dry undisturbed at room temperature (~20 C) over a period of 3-6 months. The depth of compaction due to drying was determined at weekly intervals until complete dryness was attained (i.e., when no more measurable compaction occurred).

SUMMARY OF RESULTS

Phosphorus release as a function of sediment layer

Sediment cores collected at station D exhibited a distinct layer of light-colored aquatic sediments above darker soils that were probably of preimpoundment origin (Figure 3). The interface between the two layers was ~ 24 cm from the sediment surface at this particular station. Moisture content was very high (> 80%) and bulk density was low (< 0.25 g mL^{-1}) for both layers (Figure 4), suggesting the occurrence of fine-grained sediments.

An example of changes in phosphorus mass in the overlying water as a result of phosphorus flux from sediments is shown in Figure 5. Mean rates of phosphorus release at station D were significantly greater under both oxic and anoxic conditions for surface sediments compared to the subsurface layer (Figure 6). In general, they were very low for both sediment layers versus sediments from eutrophic lakes, which can range between 1 and > 10 mg m^{-2} d^{-1} (Nurnberg 1987). This finding is not surprising given the reported very low concentrations of total P in the sediment (19 μg g^{-1}).

Redox (i.e., oxic versus anoxic) condition did not appear to be an important factor in regulating phosphorus release from the surface and subsurface sediment layers. For other lake sediments containing iron compounds, phosphorus adsorbed to iron hydroxides under oxic (oxidation) conditions does not readily diffuse into the water column. Reduction of iron (i.e., Fe^{+3} to Fe^{+2}) by microbial communities under anoxic conditions results in the desorption of phosphorus and flux into the water column. For Eagle Springs Lake, it appeared that phosphorus flux was governed by other mechanisms such as calcium and/or organic matter degradation.

Phosphorus release as a function of sediment dewatering

An example of moisture loss from the upper 8-cm sediment layer versus time is shown in Figure 7. Overall, it took ~ 20 and 40 days to dewater sediments by 33% and 66%, respectively. 100% sediment desiccation occurred after ~ 65 days of exposure. Surface sediments dewatered 33% lost a mean 2.5 cm in height (31% compacted). When dewatered to 66% and 100% of the original moisture content, they lost a mean 3.75 cm (47% compacted) and 4.5 cm (56% compacted) in height, respectively (Figure 8). Rehydration of sediments that were dewatered by 33%, 65%, and 100% resulted in an overall lower mean moisture content compared to initial mean sediment conditions (Figure 9). As the percentage of water removed from sediment increased, there was a trend of greater rebound in mean moisture content and mean density conditions upon rehydration. Thus, drier sediments gained more water than wetter sediment during the rehydration process. However, the mean moisture content of rehydrated sediment was lower as a function of increased dewatering.

Mean rates of phosphorus release under oxic and anoxic conditions declined significantly from control levels as a result of 33% and 66% dewatering (Figure 10). Sediments that were dewatered by 100% and rehydrated exhibited increases in mean rates of phosphorus release. Under oxic conditions, the mean release rate following 100% dewatering was similar to the control rate and significantly greater than rates measured for sediment that was dewatered by 33% and 66%. Under anoxic conditions, the mean rate of phosphorus release was elevated as a result of 100% sediment dewatering and rehydration, compared to other treatments and the control mean. The high mean rate was due in large part to the results of 1 replicate (0.8 mg m^{-2} d^{-1}; see appendix). Thus, significant differences in rates under anoxic conditions could not be detected as a function of treatment due to the high variance associated with sediments that were dewatered by 100 %.

Laboratory estimates of sediment compaction

There was a linear relationship between the initial sediment core length and the total centimeters of compaction at 100% sediment dewatering (Figure 11). Implied with the initial core length was the approximate length of the aquatic sediment layer overlying preimpoundment soils, since we had difficulty coring into the subsurface preimpoundment sediment and capturing that portion in the core liner. Thus, under conditions of complete desiccation of this layer, aquatic sediments would be compacted by 1 to 5 inches, depending on the thickness of the aquatic sediment layer in the lake.

CONCLUSIONS

Laboratory-derived rates of phosphorus release from surface sediments and the subsurface layer are very low under both oxic and anoxic conditions and do not appear to represent an important flux to the water column of the lake. Laboratory results suggest that exposure of the subsurface soil layer via dredging will not result in increased phosphorus flux from the sediment into the overlying water column.

Experimental partial dewatering of surface sediments was not associated with an increase in the phosphorus release rate. Complete sediment dewatering was associated with an increase in the mean rate of phosphorus release from sediments under anoxic conditions. But, this trend was not significantly greater than the control mean due to high variability among replicates. Elevated rates of phosphorus release after complete dewatering and rehydration may be attributed to cell lysis and temporary leaching of phosphorus from decaying microorganisms killed by complete desiccation. This mean rate was not very high compared to eutrophic lake sediments. However, the anomalous rate measurement of 0.8 mg m $^{-}$2 d^{-1} is substantial and could represent an important internal flux of phosphorus to the lake.

There was a distinct layer of aquatic sediment above a darker subsurface layer at station D. This darker sediment layer may represent preimpoundment soils. If so, it could be used as a marker to reference sediment deposition in the lake. More information is needed to determine the exact origin of this layer in order to more precisely date it.

Partial and complete dewatering of sediment cores in the laboratory resulted in compaction and consolidation of sediments on the order of less than 1 inch to greater than 5 inches. Mean sediment moisture content exhibited an hysteretic pattern as a result of dewatering and rehydration. As the percentage of water removed from sediment increased, there was a trend of greater rebound in mean moisture content upon rehydration. However, the mean moisture content of rehydrated sediment was lower as a function of increased dewatering. Thus, rehydrated sediments will have a lower moisture content (and higher bulk density) due to sediment consolidation during the desiccation process.

Both the surface and subsurface sediment layers at station D exhibited a very high moisture content and low bulk density, indicating flocculent sediments composed of silts and clays. Consolidation of the surface layer via drawdown and dewatering will likely reduce the susceptibility to resususpension. An unknown is the critical shear stress required to resuspend soils in the subsurface layer, if the surface layer is removed by dredging.

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Table 1. Universal Transverse Mercator (UTM) coordinates for sampling stations in Eagle Springs Lake (16T - NAD27)

Station	UTM North	UTM East
A	381948	4745673
B	382325	4745791
D	382487	4745051
F	381999	4744861

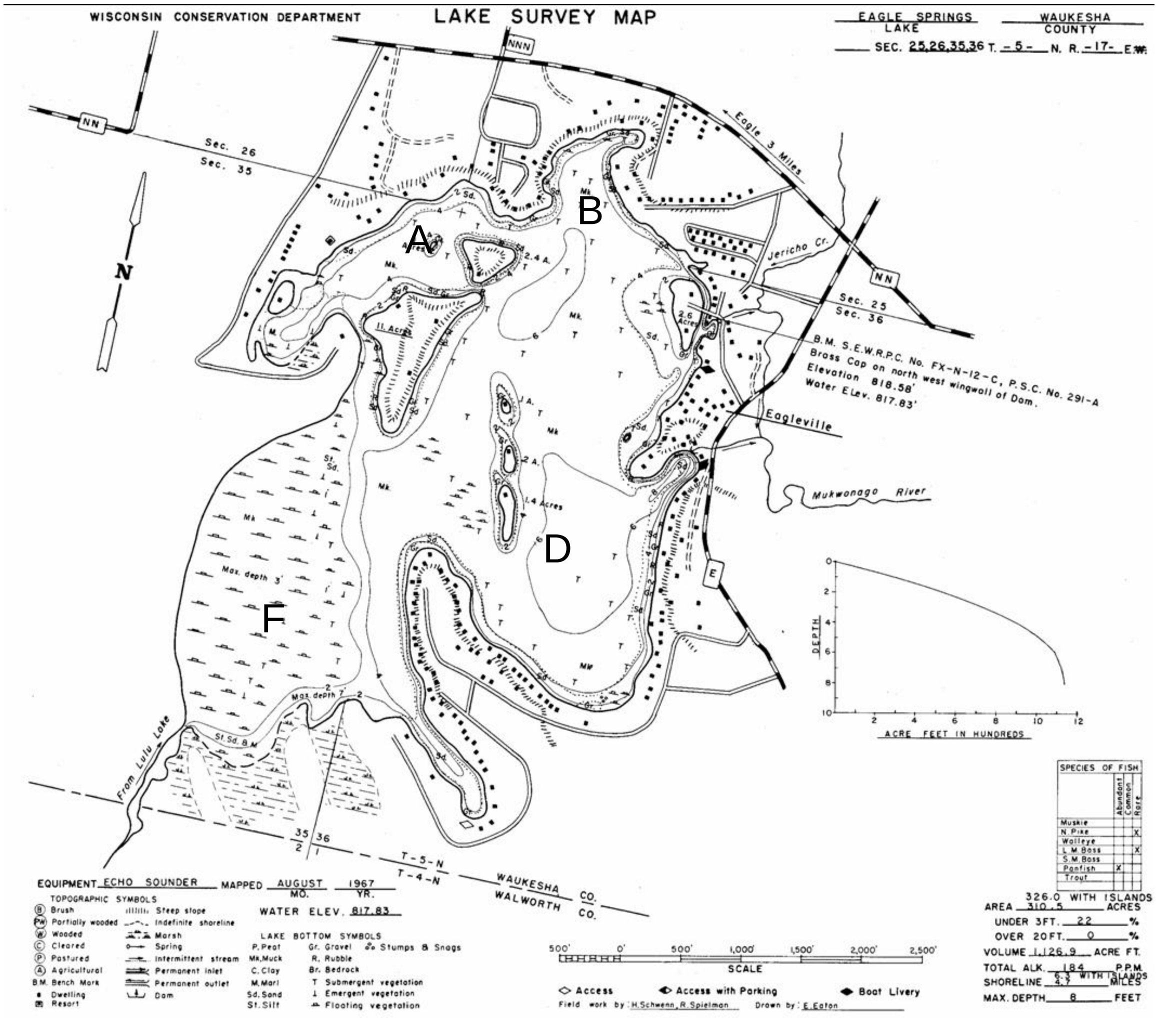

Figure 1. Bathymetric map of Eagle Springs Lake showing sediment coring station locations.

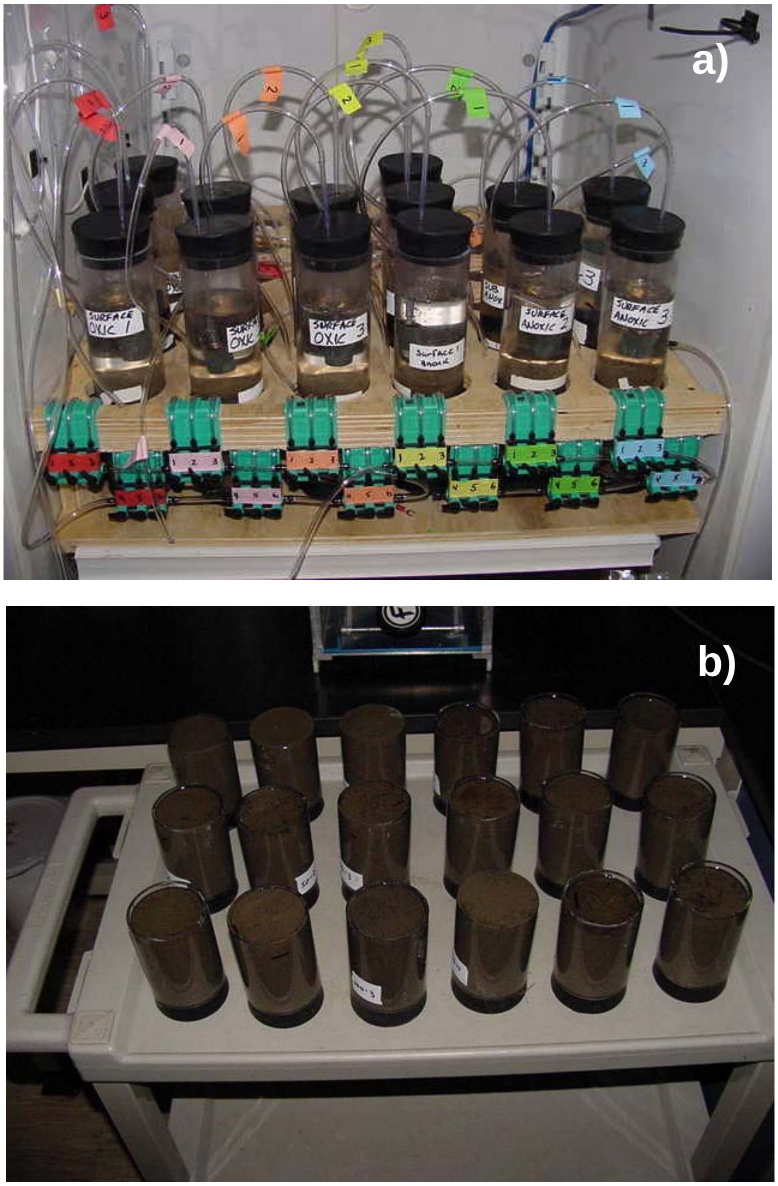

Figure 2. Sediment incubation systems used for (a) the determination of phosphorus release for surface and subsurface sediment layers and (b) desiccation of sediment to various moisture contents.

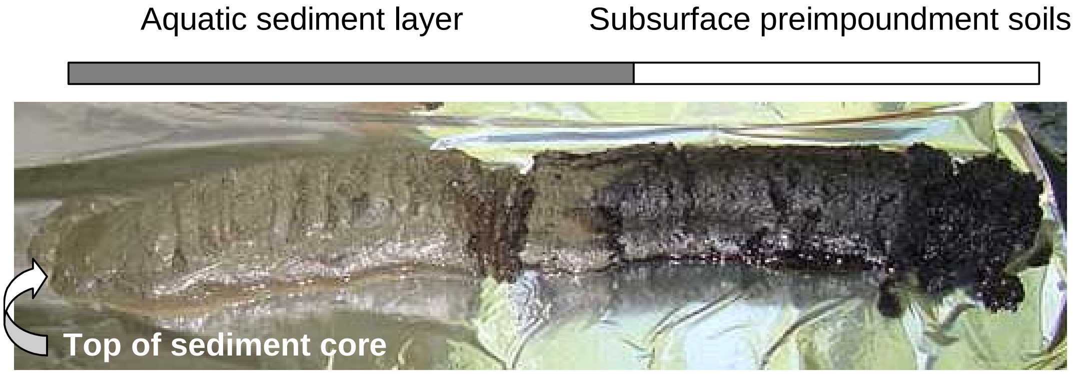

Figure 3. Sediment core collected at station D showing the aquatic sediment layer and subsurface layer.

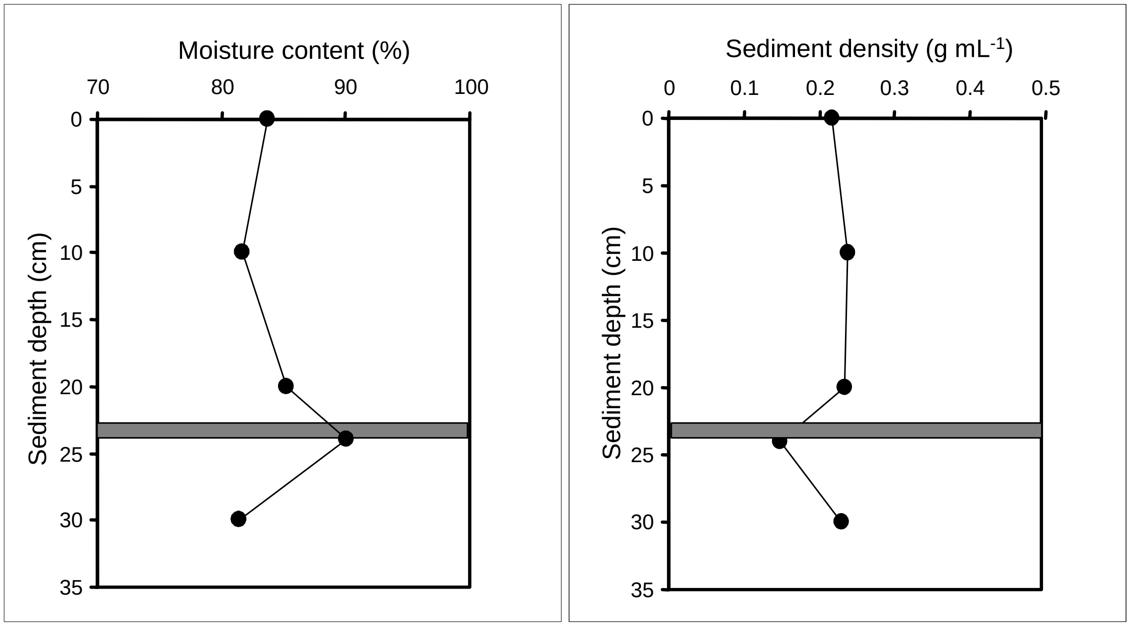

Figure 4. Vertical variations in sediment moisture content and bulk density at station D. Horizontal grey bar represents the interface between the aquatic sediment layer and soil sublayer (i.e., 24 cm or 9.4 inches from the top of the core).

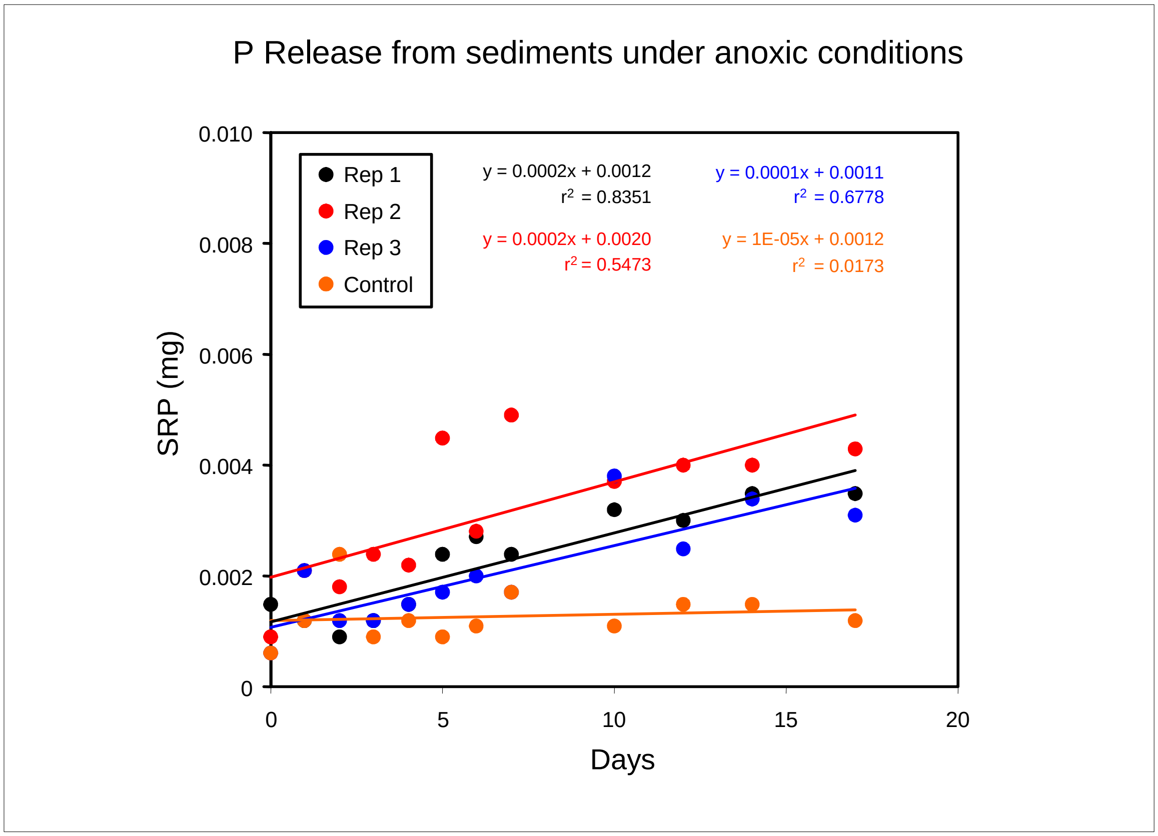

Figure 5. Changes in phosphorus mass in the overlying water under anoxic conditions as a function of time for the upper 10 cm of sediment collected at station D.

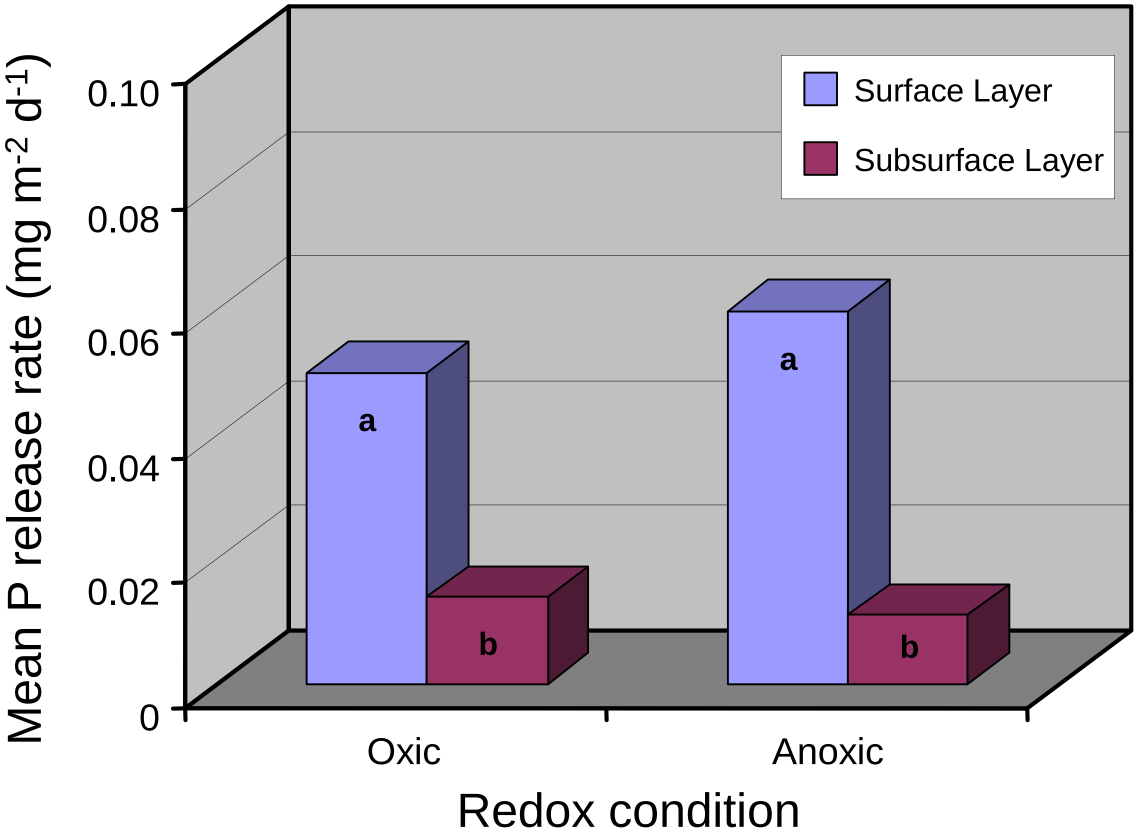

Figure 6. Mean (n = 3) rates of phosphorus release from sediment under oxic and anoxic conditions. Sediment cores were collected from station D. The surface layer represents the upper 10 cm section while the subsurface layer represents the 10 cm section or preimpoundment soils located immediately below the aquatic sediment layer (see Figure 3). Different letters represent significant differences at the 5% level or less (ANOVA; SAS 1994).

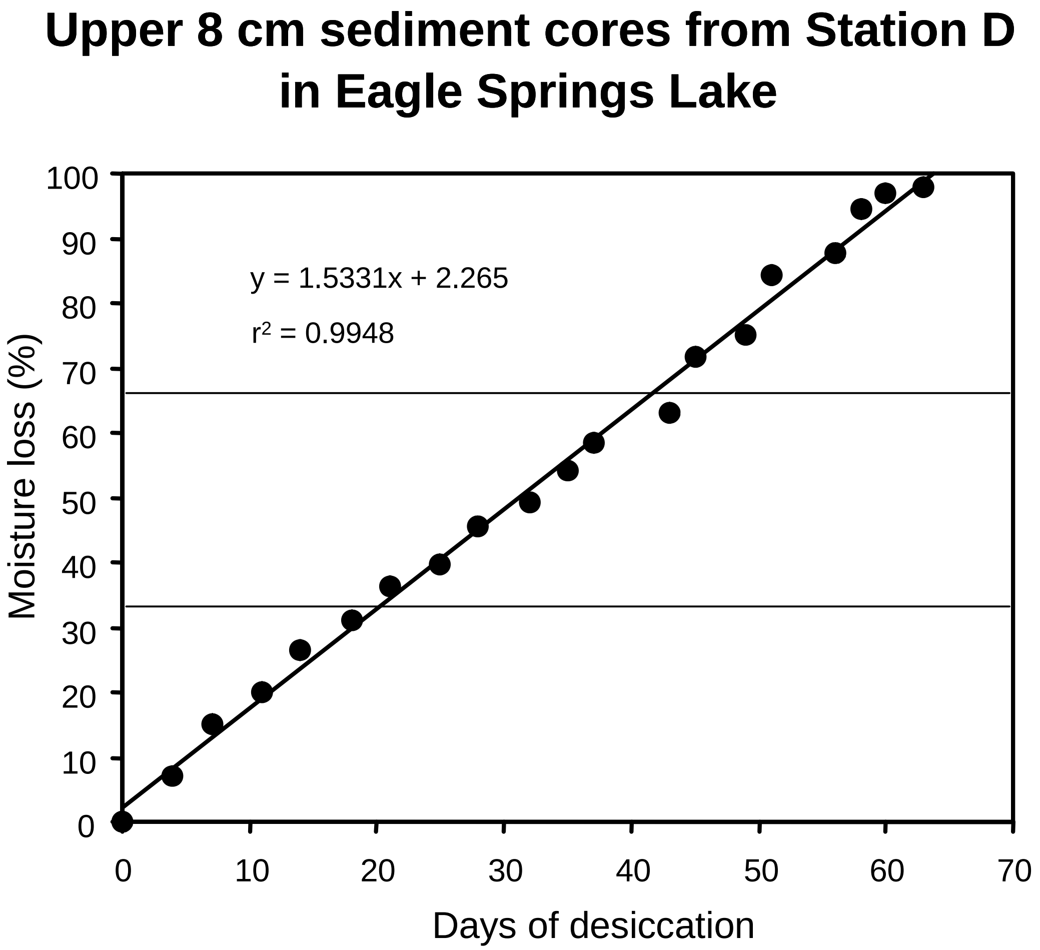

Figure 7. Loss of moisture as a percent of the original sediment moisture content versus days of desiccation.

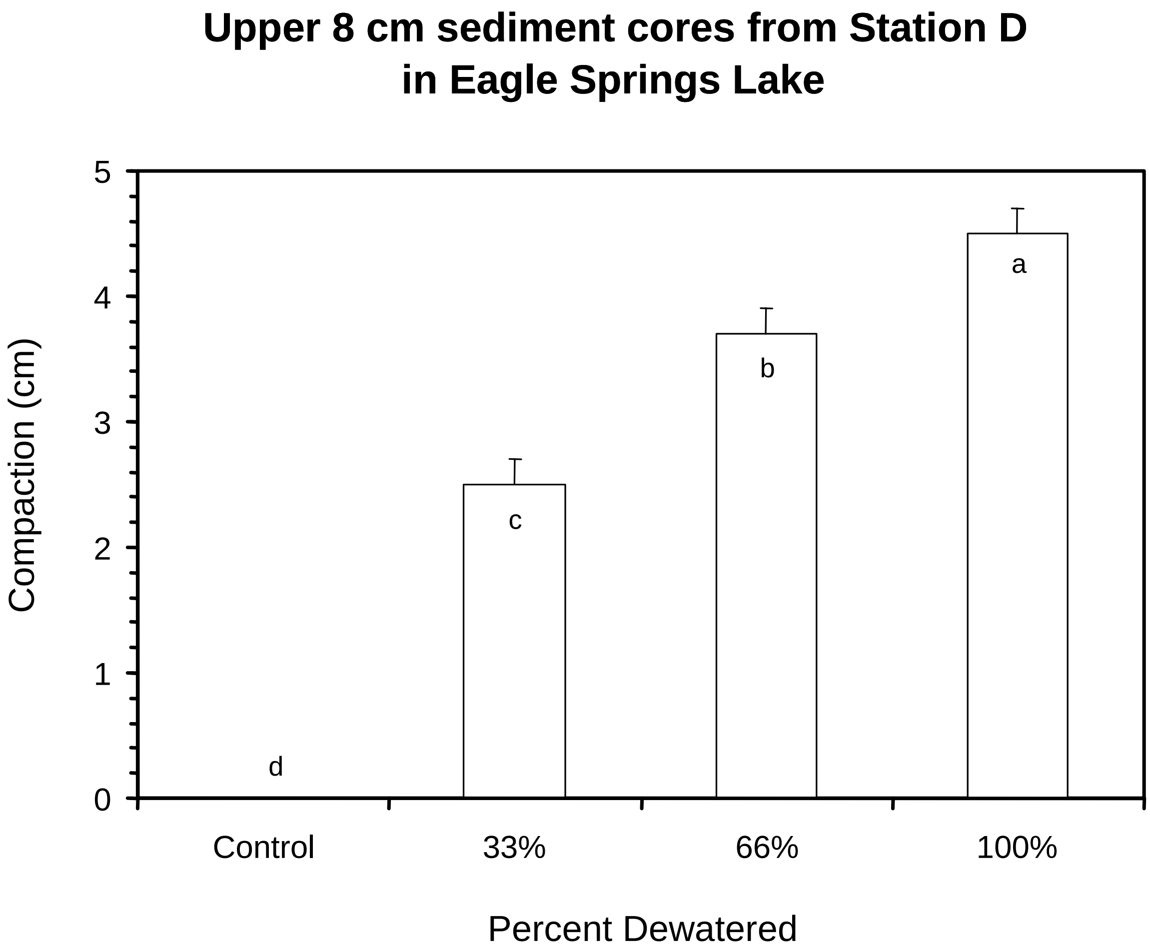

Figure 8. Variations in mean (n = 6) compaction as a function of the percent moisture loss for upper 8 cm sediment core sections collected at station D. Compaction is defined as the length of core shrinkage. Thus, sediment core sections that were dewatered by 100% (i.e., complete dryness) lost a mean 4.5 cm out of the original 8 cm core length. Vertical bars represent 1 standard deviation. Different letters represent significant differences at the 5% level or less (ANOVA; SAS 1994).

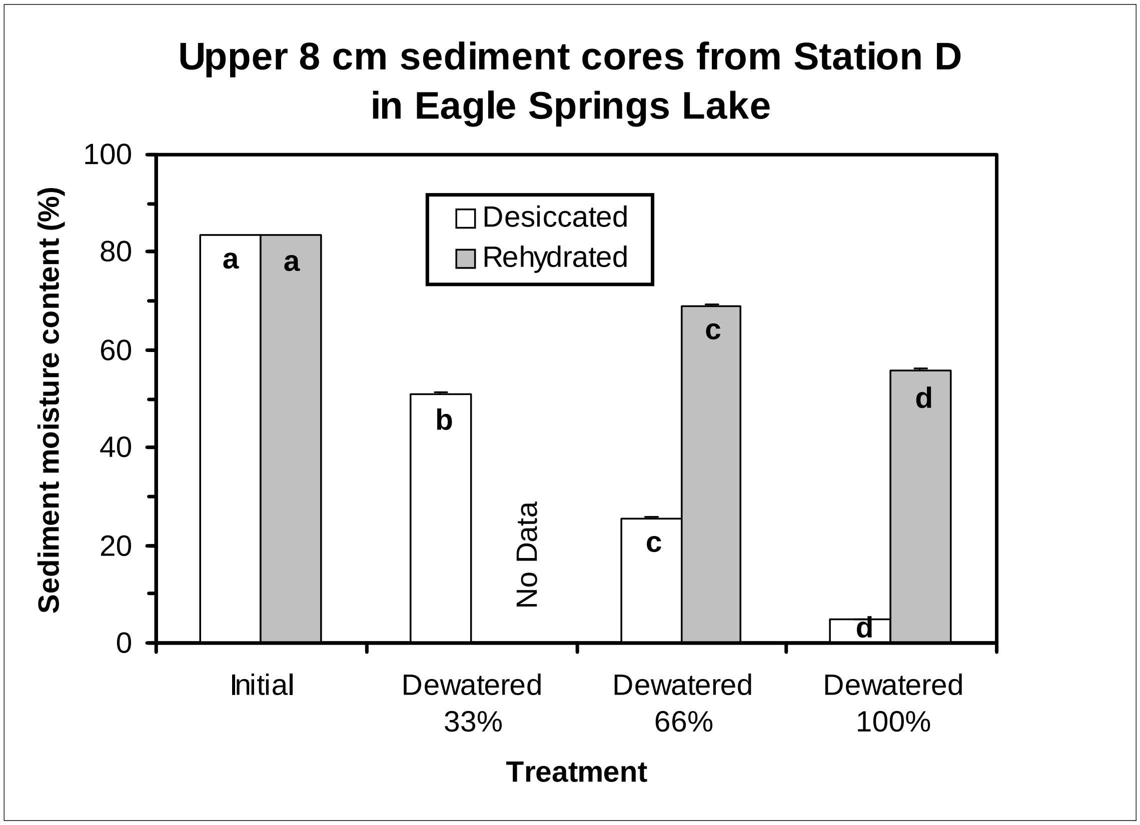

Figure 9. Variations in mean (n = 6) sediment moisture content after dewatering (open columns) via desiccation and after rehydrating desiccated sediment for 2 weeks with lake water. Vertical bars represent 1 standard deviation. Different letters represent significant differences at the 5% level or less (ANOVA; SAS 1994).

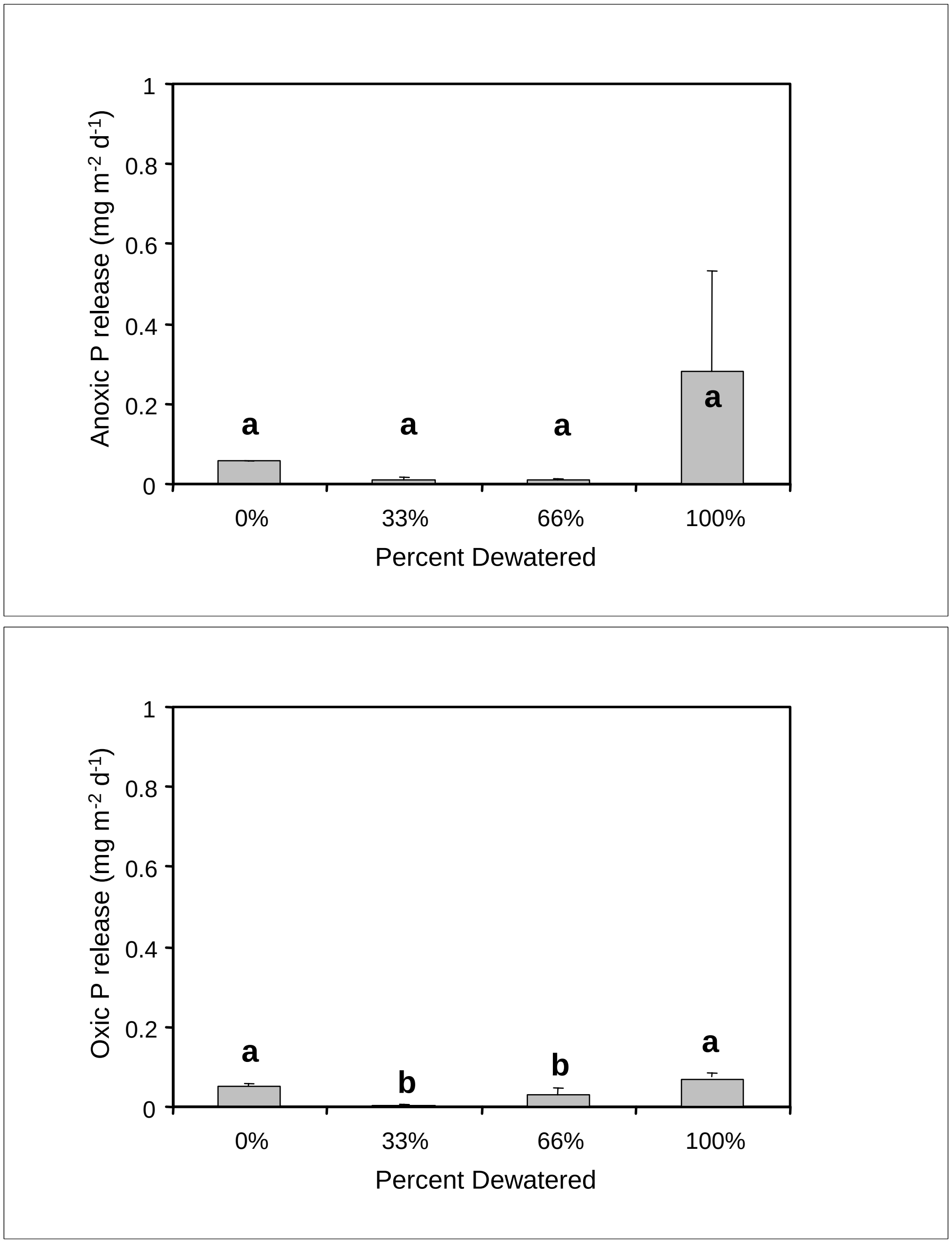

Figure 10. Variations in mean (n = 3) rates of phosphorus release from the upper 10 cm layer of sediment under anoxic (upper) and oxic (lower) conditions as a function of sediment dewatering. Sediment cores were collected from station D. Vertical bars represent 1 standard deviation. Different letters represent significant differences at the 5% level or less (ANOVA; SAS 1994).

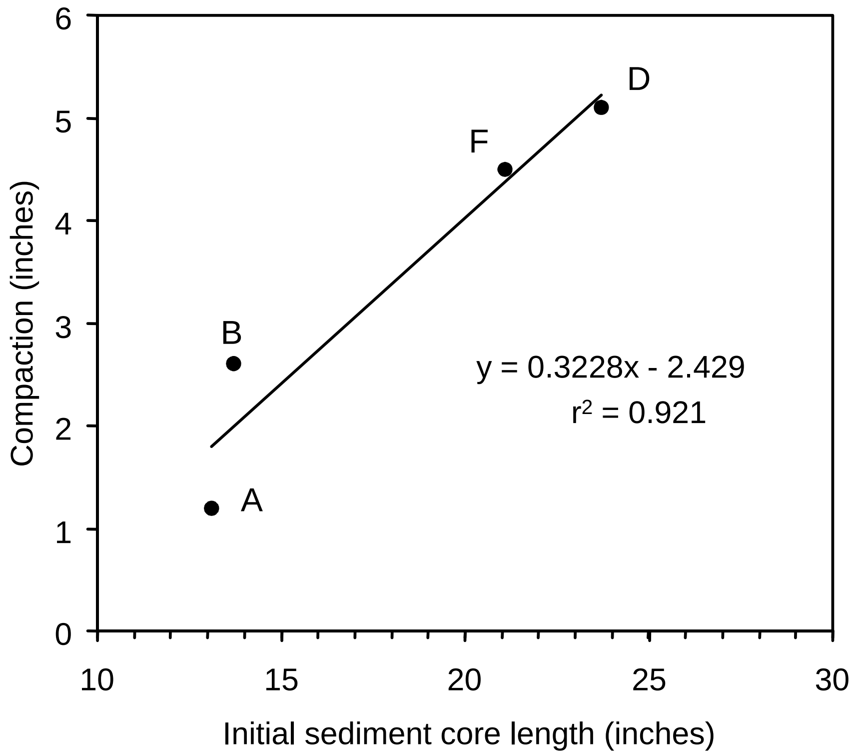

Figure 11. Relationship between the initial sediment core length and inches lost due to 100% dewatering for sediment cores collected at various stations in Eagle Springs Lake.

APPENDICES

Appendix A. Rates of phosphorus release under oxic and anoxic conditions for the surface layer of aquatic sediments (upper 10 cm) and subsurface layer of preimpoundment soils (i.e., located ~ 24 cm below the sediment surface) for cores collected at station D in Eagle Springs Lake.

Sediment Layer	Phosphorus release under oxic conditions (mg m^{-2} d^{-1})			Phosphorus release under anoxic conditions (mg m^{-2} d^{-1})		
	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Surface layer	0.06	0.06	0.06	0.06	0.06	0.03
Subsurface layer	0.02	0.01	0	0	0.01	0.02

Appendix B. Rates of phosphorus release under oxic and anoxic conditions from surface sediment layer (upper 8 cm) collected at station D in Eagle Springs Lake as a function of the percent that sediments were dewatered via laboratory desiccation.

Percent Dewatered	Phosphorus release under oxic conditions (mg m^{-2} d^{-1})			Phosphorus release under anoxic conditions (mg m^{-2} d^{-1})		
	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
0%	0.06	0.06	0.06	0.06	0.06	0.03
33%	0	0.01	0	0	0.02	0.01
66%	0.03	0	0.06	0.01	0.01	0.02
100%	0.06	0.06	0.09	0.06	0	0.78

Appendix C. Initial and final core length for sediment cores collected at stations A, B, D, and F. Compaction reprepresents the difference between initial and final sediment core length. Sediment cores were dried for ~ 4 months.

Variable	Station A (inches)	Station B (inches)	Station D (inches)	Station F (inches)
Initial Core Length	13.7	13.1	23.7	21.1
Final Core Length	11.1	11.9	18.6	16.7
Compaction	2.6	1.2	5.1	4.5