

Utah Lake Sediment–Water Nutrient Interactions

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Executive Summary

This report presents findings from laboratory experiments where sediment cores from Utah Lake were subjected to phosphorus spiking under different conditions. The objectives of this project were to: (1) understand the role of aerobic/anaerobic conditions in nutrient release or retention over a range of P concentrations; (2) understand the role of pH (pH = 7 and 9.5) in nutrient release or retention; and (3) quantify the sediment oxygen demand and N release from sediments under current conditions. Sediment cores were collected from two sites in Utah Lake (Provo Bay and State Park Buoy, each with a different trophic status) and incubated at room temperature in the dark. In addition to evaluating sediment dynamics and ambient P concentrations, P concentrations in the water column were adjusted to the level of 0.5X, 2X and 4X of ambient concentrations to simulate varying conditions of point source loading. **The experiments showed that P release mainly occurred at ambient and 0.5X concentrations, with increasing P concentrations in the water column over time, while at the 4X level P concentrations in the water column tended to decrease over time. P release was more prevalent under aerobic conditions relative to anaerobic conditions.** The highest release and sink were observed under aerobic_0.5X (201.6 mg/m²/d) and anaerobic_4X (-51.84 mg/m²/d), respectively. However, the anaerobic experiments were confounded by a concomitant increase in the pH to nearly 10, probably due to CO₂ stripping by bubbling nitrogen gas and resulting in the loss of the buffering capacity of the system. A significant loss of calcium from the water column was also observed under anaerobic conditions, suggesting the potential formation of calcium carbonate mineral species (i.e., calcite) that may have scavenged P either by sorption or co-precipitation. The pH experiments also proved difficult because the water tended to quickly return to the ambient pH of ~8.5, regardless of the addition of acid or base, likely due to the natural buffering capacity in the sediments. Nevertheless, **the Buoy site showed higher ambient P concentrations when the pH was maintained at neutral (pH = 7, 0.09 - 0.53 mg/L) compared to the condition when the pH was kept in the alkaline range (pH = 9.5, 0.02-0.13 mg/L).** Because of the difficulty of maintaining the adjusted pH, the pH = 7 experiment was not conducted for the Provo Bay site. The flux rates were in the range of -17.28 to 14.4 mg/m²/d at the neutral pH for buoy site and -4.32 to 2.88 mg/m²/d at the high pH for both sites.

As for the N species, the ammonium-N, and nitrate-N were present at concentrations of 0.001-0.658 mg/L, and 0-0.239 mg/L, respectively, while nitrite-N was non-detectable in most samples. A significant variation of ambient concentrations was only observed for ammonium-N. Generally, the Provo Bay site had higher ambient ammonium-N concentrations (0.001 - 0.658 mg N/L) relative to the Buoy site (0.010 - 0.266 mg N/L). Aerobic conditions generally resulted in a higher ammonium sink (-3.6 to -37.44 mg/m²/d) relative to the anaerobic conditions (-8.64 to 0.144 mg/m²/d). The loss of ammonium-N under aerobic conditions likely is not related to autotrophic nitrification given the high pH of water. Rather, it could be related to loss of free

ammonia under high pH conditions and/or chemical precipitation of ammonium-N with other minerals.

Sediment oxygen demand (SOD) was evaluated at the two sites using in-situ chambers. The raw results, when normalized to temperature, were calculated as $-0.052 \text{ g/m}^2/\text{day}$ at the Provo Bay site ($T=55.5^\circ\text{F}$ and $\text{pH}=8.98$) and $-2.965 \text{ g/m}^2/\text{day}$ at the Buoy site ($T=58.7^\circ\text{F}$ and $\text{pH}=8.42$). Relatively lower SOD at the Provo Bay site was unexpected given that the site is richer in organic matter, but may reflect severe temperature effects on SOD at this site because Provo site is much shallower than the Buoy site.

Overall, the results suggest that Utah Lake sediments are active in terms of nutrient release and uptake depending upon the P concentrations, redox conditions, and pH in the water column. Further experiments may be necessary to maintain the ambient pH under anaerobic experiments and to maintain neutral or alkaline pH in the experiments over time. Further, the experiments were only run for 72 hours, while these processes may take longer than 72 hours to reach equilibrium.

1 Introduction

The Utah Division of Water Quality (DWQ) recently initiated Phase 2 of the Utah Lake Water Quality Study (ULWQS) to evaluate the effect of excess nutrients on the lake's recreational, aquatic life, and agricultural designated uses and to develop site-specific nitrogen and phosphorus water quality criteria to protect these uses. Understanding the cycling of nutrients within Utah Lake will help describe the current state of the lake with respect to nutrients and ecology, and sediments are an important component of the nutrient cycling within the lake. Available reports and initial information on sediment oxygen demand (SOD) and nutrient release from sediments in Utah Lake provide some insight into sediment phosphorus characteristics and fluxes but stop short of describing the mechanisms of nutrient release or of converting bulk measurements into mobile or bioavailable fractions.

Based on these past research efforts and the need to better understand the fate of P in the water column under different environmental conditions, the Utah Division of Water Quality issued a request for proposals (RFP) in the summer of 2019, which included the following questions:

1. What is the role of anoxia in nutrient releases and sediment dynamics over a range of phosphorus conditions?
2. What is the role of pH in water column-sediment interactions and nutrient releases? How do phosphorus concentrations change over a range of water column pH?
3. What is the sediment oxygen demand of, and nutrient release from, sediments in Utah Lake under current conditions?

To address these questions, we conducted the following experiments using sediment cores and water collected from two sites in Utah Lake:

1. Aerobic conditions at ambient, 0.5x, 2x, and 4x ambient phosphorus concentrations.
2. Anaerobic conditions at ambient, 0.5x, 2x, and 4x ambient phosphorus concentrations.
3. Aerobic conditions with a pH of 7 at ambient, 0.5x, 2x, and 4x ambient phosphorus concentrations.
4. Aerobic conditions with a pH of 9.5 at ambient, 0.5x, 2x, and 4x ambient phosphorus concentrations.

Additionally, the sediment oxygen demand was measured in situ at the two sites.

2. Methods

Note: Please refer to the SOP (provided in the appendix) for details on field and laboratory methods. Here we provide a summary of the methods.

2.1 Site selection

The RFP suggested studying two sites in Utah Lake. After discussion with UDWQ and the Utah Lake Science Panel, the two sites selected for sediment core collection were in the middle of Provo Bay and near the State Park Buoy. The Provo Bay site is representative of the shallow, hypereutrophic bay on the east side of Utah Lake. The Buoy site is representative of the relatively deep, eutrophic open water of the lake. The sites and coordinates are shown in Figure 1.

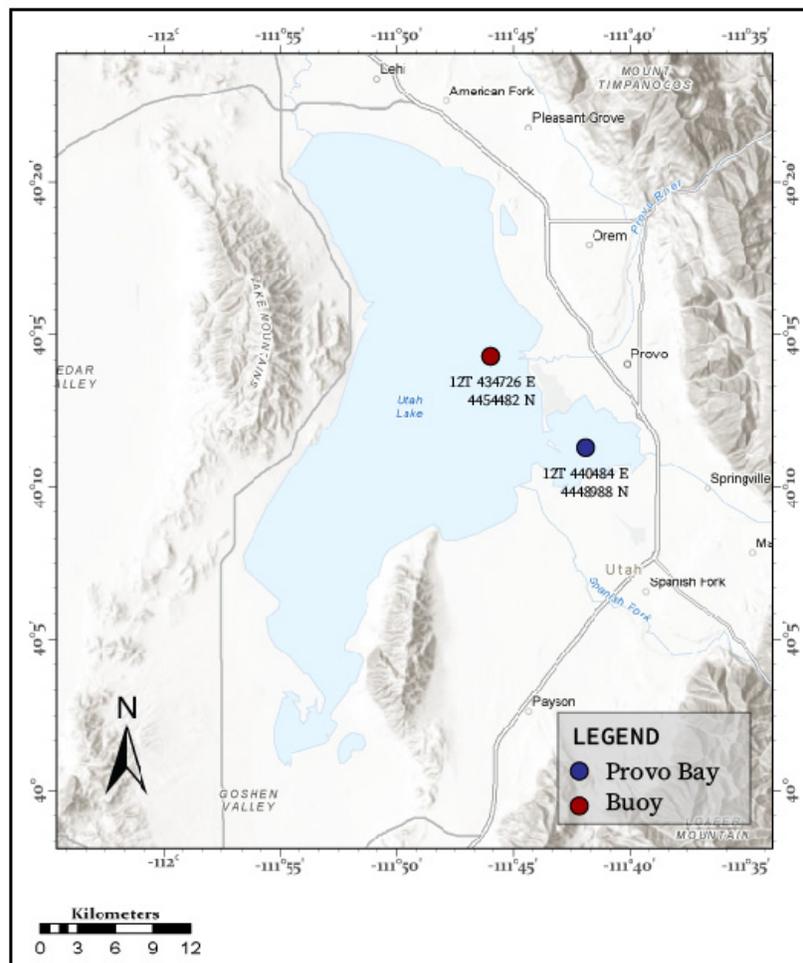


Figure 1: Map of sampling sites in Utah Lake.

2.2 Sediment core collection

A total of 72 sediment cores were collected over six trips to the lake. The dates of core collection and experimental conditions tested are listed in Table 1. Each time in the field, we collected 12 sediment cores from one of the sites and processed them immediately upon returning to lab. Each sediment core was collected with about 10 cm of sediment and 30 cm of overlying water to maintain appropriate physicochemical conditions (Figure 2). The cores were collected using a percussion corer. A drilling platform attached to a boat was used to support the sediment corer and make the process more efficient. The cores were capped, covered, and stored upright in a cooler to prevent sediment disturbance and limit microbial activity. A detailed SOP, which was initially approved by the UDWQ and Science Panel for sediment core collection, is included in the appendix of this document.

We also collected 2 gallons of surface water during each collection trip to be used as replacement water for spiking the water in the tubes. As suggested by the Science Panel, the initial overlying water was siphoned out of each core in the lab and replaced with 590 mL of lake water (~30 cm height), that was filtered (0.45 µm nylon) to remove plankton and adjusted to desired P concentrations. Field parameters (pH, dissolved oxygen, specific conductance, temperature) were measured in situ at the time of water collection using a YSI Quatro multiparameter probe, which was calibrated each field day.

Table 1. Sediment core collection details.

Site 1: State Park site near DWQ buoy		
Date	# of cores	Experiment
August 14 th , 2019	12	Neutral pH
September 12 th , 2019	12	Aerobic and anaerobic experiments
September 26 th , 2019	12+2 (prepared for low pH detect)	pH=9.5
October 1 st , 2019	3 chambers (1 control +2 experiment)	Sediment oxygen demand
Site 2: Provo Bay		
Date	# of cores	Experiment
September 4 th , 2019	12	Aerobic and anaerobic experiments
September 17 th , 2019	11(1 fewer for control)	pH=9.5
September 27 th , 2019	12(experiment not conducted)	Neutral pH
October 3 rd and 14 th , 2019	3 chambers (1 control +2 experiment)	Sediment oxygen demand

2.3 P spiking experiments under aerobic and anaerobic conditions

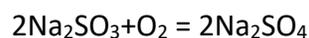
Cores were wrapped in aluminum foil and mounted on a wooden stand (Figure 3). The overlying water was gently drained and was replenished with ambient water or water spiked with different concentrations of total P to achieve 0.5X, 2X and 4X times P relative to ambient P concentrations. The ambient P was based off of historical data measured using ICP-OES in 2018 Summer provided by the BYU. Each treatment was conducted in triplicate. Stock P solution of 10 mg P/L was prepared to spike as needed. For the dilution of lake water to 0.5X, a major ion solution was prepared to simulate the natural conditions. To maintain aerobic conditions (7.5 mg/L DO) air was purged intermittently through the water column using an aeration stone placed 5 cm from the sediment water interface. The pH and DO in the water column were measured during sample collection (t=0, 12, 24, and 72 hours). Both pH and DO meters were calibrated before their usage. For DO, we used a HACH luminescent DO probe which measures DO to the accuracy of 0.1 mg/L. The pH meter was calibrated using three different pH standard solutions of 4, 7 and 10. Samples of overlying water were analyzed for ammonium-N, nitrate-N, nitrite-N, soluble reactive phosphorus (SRP), total dissolved phosphorus (TDP) after filtering through 0.45 µm nylon syringe filters.

At each sampling time, 40 mL of water was collected from each core and filtered (0.45 µm nylon syringe filter). With samples taken at 12, 24 and 72 hours, the total sampling volume was approximately 120 mL. Water loss was compensated with the initial replacement lake water. The t=0 sample was collected from the spike water rather than from the sediment cores.



Figure 3. Lab setup showing sediment cores.

The same cores used for aerobic experiments were also used for anaerobic experiments. For anaerobic incubation experiments, first, the overlying water from top of each column after the aerobic experiments was removed and replaced with new lake water. To achieve initial anaerobic conditions, a sodium sulfite solution containing trace amount of cobalt chloride (as a catalyst) was added to quickly remove oxygen.



Based on the above equation, to remove 7mg/L O₂, 55 mg/L Na₂SO₃ was initially added. Hence, no residual sulfide was present to cause any effect on system pH. Anaerobic conditions were maintained by intermittently purging with pure nitrogen gas. Additionally, a small flow of nitrogen was maintained constantly as not to allow aeration at the air-water interface in the column. A high flowrate was kept when taking samples and a low flow rate was used in between. Air or nitrogen flows were regulated using an electronic timer and a solenoid valve. Water samples from the column were collected and analyzed in similar fashion as the aerobic experiments.

2.4 P spiking experiments at pH=9.5 and pH=7

The mounting of sediment cores and preparation of P stock solutions followed the same procedures detailed in section 2.3 for aerobic and anaerobic experiments. Sediment core incubation at high pH was kept under aerobic conditions using the same strategy described earlier for the aerobic experiments. Filtered lake water was adjusted to pH= 9.5 using 1 N NaOH prior gently pouring into the sediment cores. During the experiments, NaOH was intermittently added to each column because the pH quickly returned to ambient values of ~8.5. Sediment core incubation at pH =7 was conducted by adjusting the pH with 1 M (H₂SO₄) to filtered lake water prior to adding to water to the sediment cores at the beginning of experiment. After adding water to the sediment, we observed an increase in the pH over time. Once mixing and aeration started, the pH returned to the initial value of ~8.5. The high pH experiment was conducted at both sites, while the low pH experiment was conducted only at the Buoy site. (The cores were collected at the Buoy site for low pH experiments but based on difficulty maintaining low pH and conversations with the Science Panel, the experiments were not completed).

2.5 Nutrient flux measurement

To better understand the flux between sediment-water column, nutrient flux (TDP, SRP, and ammonium-N) was calculated with the following equation:

$$\text{Nutrient flux (mg/m}^2\text{/d)} = \frac{dC_e}{dt} \times \frac{V}{A} \times 1000 \text{ mg/g} \times 24 \text{ hr/d}$$

Where, dC_e = change of nutrient concentrations in sediment core (mg/L= g/m³)

$\frac{dC_e}{dt}$ = change of nutrient concentrations along with time (g/m³/hr)

V = volume of water within the chamber (m³)

A = sediment surface area within the chamber (0.00785 m²). The area was not used in calculation because the volumetric flux rate (e.g mass/L³/time) was directly divided by the water column depth in sediment cores to obtain nutrient fluxes.

$$D = \frac{V}{A} = \text{depth of ambient water (0.3 m)}$$

$$\text{Loading (kg/d)} = \text{area (km}^2\text{)} * \text{nutrient flux (mg/m}^2\text{/d)}$$

2.6 Sediment Oxygen Demand (SOD)

For the SOD test, a control (water only) and two experimental SOD chambers were installed at the sediment-water interface at each site. The control chamber was closed at the bottom and measured DO consumption in the water column only. The testing chambers were open at the bottom and measured DO consumption due to activities in the water column and sediments. Chambers were made opaque to prevent any phytoplankton photosynthesis. The data sonde in each chamber made measurements of DO during the two-hour experimental period every 5 for Provo Bay to 15 min for Buoy (We directly used the calibrated SONDE from DWQ). A professional scuba diver was used for installing SOD chambers in-situ. The depth of each site at the time of experimentation was recorded. The top section of each SOD chamber consisted of a lid that contained the pump, plumbing, water sampling tube, water quality probe connection, and attachments for ropes used to lift the SOD chamber out of the sediments and water. A submersible pump was mounted on each chamber to internally circulate the water inside the SOD chamber at a predetermined flow rate of 11 L/min. The Control SOD chamber had a working volume of 44 liters and the Testing SOD chambers a working volume of 38 liters. This discrepancy in volumes is a result of the additional space provided in the Control chamber due to closed bottom which prohibits this control chamber to lose almost 1½" of vertical length into the sediments. The construction and design of these chambers is based on SOD chambers used by Georgia EPA Sediment Oxygen Demand (507)AF.R4.

The SOD rate for each chamber were calculated based on the following equations:

$$\text{SOD} = 1.44 \left(\frac{V}{A}\right)(b-bc)$$

Where, SOD = sediment oxygen demand (g/m²/day)

V = volume of SOD and WC chambers

A = sediment area within the chamber (0.16 m²)

b = slope of oxygen depletion curve (mg/L/min)

bc = slope of the water column (mg/L/min)

WC = 1440*bc

WC = water column depletion (g/m³/day)

bc = slope of the water column (mg/L/min)

Measured SOD can be corrected to 20 °C using a standard Van't Hoff equation:

$$SOD_{20} = \frac{SOD}{1.065^{(T-20)}}$$

Where SOD₂₀ is the rate at 20 °C, and T is in degrees Celsius.

For calculating SOD, the DO data (Y-axis) was plotted as a function on time (x-axis). For the Buoy site, the DO data for the sediment testing chamber was very consistent and enabled a good trend (e.g., consistent decrease over time). Hence, initial slope of the DO-time curve was considered for the Buoy site. However, for the Provo site, the DO trend was initially consistent with a sharp decrease towards the end. To confirm this sharp decrease and to obtain more consistent results, we again visited the Provo site with a scuba for the second time.

2.7 Analytical methods

The instrument, detection limit, and methods used for water chemistry analysis are detailed in Table 2. The spiked concentrations or standards were utilized by each method to make sure about the QA/QC. Specifically, standards for major/minor ions, nitrite/nitrate and low concentrations of ammonium-N spike were prepared for ICP-OES, IC and HACH ammonium kit measurement. New calibration curve with R²> 0.99 was used for ICP-OES, IC and SRP measurement. Ammonium-N concentrations were obtained by the barcode reading by the Hach spectrophotometer DR 5000. The accuracy of HACH spectrophotometer for ammonium nitrogen was checked by measuring the concentration of spiked standards. While preparing standards, autoclave and acid wash glassware were used. The standards for SRP were 0, 0.02, 0.04, 0.06, 0.08, and 0.1 ppm P. Stock P solution was prepared by dissolving anhydrous KH₂PO₄ in milli Q water. The calibration curve and reagents were made fresh for each run on a 96-well spectrophotometer for SRP and the same spectrophotometer was used for all samples.

Table 2. Data analysis-analytical instruments and their detection limits.

Parameters	Instrument	Detection limit	Methods
P, Ca, K, Mg, Si, Fe, Pb...	Thermo Fisher iCAP 7400 Duo ICP-OES	Depend on major and minor ions	EPA method 200.7
SRP	Spectrophotometer for 96 well plate	0.001 mg/L	Modified Murphy and Riley, 1962.
Ammonia-N	Hach spectrophotometer Dr5000	0.015 mg/L NH ₃ -N	Hach ammonia TNT 830 Salicylate based ammonia chemistry
Nitrate-N, Nitrite-N	Metrohm 883 Basic IC plus	Depend on calibration curve, 0.1 mg/L in this case	EPA method 300.0 Determination of Inorganic anions by IC

2.8 Data analysis

The change of nutrient concentrations in ambient water during each sampling interval was calculated as the difference between the final and initial concentration in the water column. The variations among samples of varying treatment groups were compared with one way-ANOVA using R studio v3.4.0 (R Development Core team, 2013). The rates of nutrient release or sink (nutrient flux) were also calculated to reflect the amount of nutrient change due to water-sediment interactions. For example, the concentrations change between 0 and 12 hours was calculated as final concentrations (12 hour) -initial concentrations (0 hour).

3. RESULTS AND DISCUSSION

3.1 TDP and SRP concentrations

Throughout the 72-hour experiment, TDP concentrations were higher for aerobic (0.05 - 1.64 mg/L) than the anaerobic conditions (0.03 - 0.94 mg/L). The Provo Bay site generally has higher TDP concentrations (0.07-1.64 mg/L) than the Buoy site (0.03 - 0.35 mg/L). At the Buoy site, the treatment with low pH generally had higher ambient TDP concentrations (0.09-0.53 mg/L) than the higher pH (0.02-0.13 mg/L). This is probably due to the redox change that changes the particle aggregations, making P easily released from the compounds (Illés and Tombácz, 2006). Similarly, Provo Bay site had relatively higher SRP (0.02-0.53) than the Buoy site (0-0.39 mg/L). Under all conditions, SRP accounted for an average 40% and a median 38% of TDP. This would imply that nutrient cycling associated with other forms (such organic P) of P could be major sources of TDP to the water column.

The ambient and 0.5X TDP concentrations tends to increase while the concentrations of 2X and 4X tend to decrease overtime. The spiked phosphorus concentrations (2X and 4X) typically do not decrease below initial pre-spiked concentrations (Table 1). Similar to TDP, the SRP ambient concentrations in some treatment scenarios did not decrease to the initial lake water concentrations. It may indicate different conditions of exogenous loading or diluting (0.5X,2X or 4X of ambient P concentrations after loading) and the response of sediment to varying initial conditions as to release or hold P. The decrease of lake ambient P concentrations may enhance P release from the sediment, while the input of more P may potentially bind to sediments to reach equilibrium.

Table 3. Initial and final P concentrations after 72 hours

Site	Groups	Initial lake ambient TDP (mg/L)	TDP concentrations-72hour (mg/L)	Initial lake ambient SRP (mg/L)	SRP concentrations-72hour (mg/L)
Provo_aerobic	Ambient	0.40-0.51	0.38-0.56	0.22-0.26	0.04-0.17
	0.5x		0.48-0.88		0.10-0.22
	2x		0.48-1.30		0.13-0.31
	4x		0.80-1.64		0.08-0.50
Provo_anaerobic	Ambient	0.38-0.41	0.21-0.25	0.25-0.28	0.09-0.22
	0.5x		0.18-0.25		0.05-0.16
	2x		0.17-0.21		0.12-0.14
	4x		0.18-0.29		0.04-0.10
Buoy_aerobic	Ambient	0.05-0.06	0.09-0.12	0.03	0.08
	0.5x		0.12-0.14		0-0.02
	2x		0.14-0.20		0.02-0.04
	4x		0.29-0.32		0.11-0.15
Buoy_anaerobic	Ambient	0.06-0.10	0.04-0.08	0.02-0.04	0.01-0.04
	0.5x		0.06		0.01
	2x		0.10-0.17		0-0.1
	4x		0.09-0.22		0.03-0.05
Provo_high pH	Ambient	0.16-0.19	0.10-0.12	0.05-0.08	0.05-0.10
	0.5x		0.11-0.13		0-0.03
	2x		0.18-0.21		0.05-0.07
	4x		0.17-0.30		0-0.08
Buoy_high pH	Ambient	0.06-0.07	0.05-0.08	0.01-0.02	0.01
	0.5x		0.04-0.07		0-0.03
	2x		0.04-0.06		0.01-0.02
	4x		0.06-0.07		0.01

3.2 TDP fluxes to/from the sediment under different conditions

Significant differences in P release/retention was detected at different spike concentrations (ambient, 0.5X, 2X and 4X) or environmental conditions (aerobic, anaerobic, pH =9.5 and pH = 7) (p<0.05, ANOVA). Phosphorus flux from/to the sediment was also calculated (Table 4). The methods used for nutrient flux, per Hogsett et al., 2019, where flux values equal to the depth of water column (d, m) times the slope of P concentration with changing time ($\frac{dc}{dt}$, g/m³/d). The positive values indicate P release while the negative values indicate retention.

For example, the Provo_aerobic at ambient conditions = $(0.0007 \text{ g/m}^3/\text{hr} - 0) \times 0.3\text{m} \times 1000\text{mg/g} \times \frac{24\text{hr}}{1\text{d}} = 5.04 \text{ mg/m}^2/\text{d}$, the lake area is 384.4 km^2
 Load = $5.04 \text{ mg/m}^2/\text{d} * 384.4\text{km}^2 = 1937 \text{ kg/d}$

The results were consistent with the dynamics of water phosphorus concentrations throughout the 72-hour experiment, as the P sink was more observed at 2X and 4X spiked columns than the ambient (e.g. no spike) or 0.5X spikes. Also, the release was detected more at aerobic and neutral pH, while retention was at anaerobic or high pH. Provo Bay generally had higher release/sink flux (-51.84 to 201.6 mg/m²/d) than the buoy site (-5.76 to 5.76 mg/m²/d), partly due to the differences in initial ambient P concentrations and eutrophication status (Herrmann et al., 2009; Hou et al., 2013). The highest release and sink were observed at Provo_aerobic_0.5X (201.6 mg/m²/d) and Provo_anaerobic_4X (-51.84 mg/m²/d), respectively. As for the environmental conditions, anaerobic generally observed more P sink (-51.84 to 1.44 mg/m²/d) than the aerobic conditions (-13.68 to 201.6 mg/m²/d). Sediment has high potential to release P at lower pH; the buoy site has the highest release at 0.5X_low pH followed by aerobic, high pH and anaerobic conditions with the same initial conditions (0.5X). P release from sediments was more significant at 0.5X concentrations (-7.2 to 201.6 mg/m²/d) than under any other condition. Under all conditions, net P sink to sediments occurred at 4X P concentrations. Anaerobic P release could be associated with iron reduction and/or P release by polyphosphate accumulating organisms. As for the total P load from/to the lake, higher flux estimates are still well within the realm of organic matter decay or exude from phytoplankton /bacteria in the water column.

Table 4. TDP flux to/from sediment.

Site	Groups	K value	R square	TDP flux (mg/m ² /d)	Load (Kg/day)
Provo_aerobic	Ambient	0.0007	0.0248	5.04	1937
	0.5x	0.028	0.381	201.6	77495
	2x	0.0008	0.0087	5.76	2214
	4x	-0.0019	0.0649	-13.68	-5259
Provo_anaerobic	Ambient	-0.0013	0.0837	-9.36	-3598
	0.5x	0.0002	0.0077	1.44	554
	2x	-0.0038	0.263	-27.36	-10517
	4x	-0.0072	0.3744	-51.84	-19927
	Ambient	0.0006	0.7332	4.32	1661

Buoy_aerobic	0.5x	0.0008	0.7599	5.76	2214
	2x	-0.0002	0.035	-1.44	-554
	4x	-0.0002	0.0493	-1.44	-554
Buoy_anaerobic	Ambient	0.00005	0.0057	0.36	138
	0.5x	-0.00007	0.0228	-0.504	-194
	2x	-0.000007	5.00E-05	-0.0504	-19
	4x	-0.0008	0.1191	-5.76	-2214
Provo_high pH	Ambient	-0.0007	0.1679	-5.04	-1937
	0.5x	-0.001	0.0803	-7.2	-2768
	2x	0.0001	0.0156	0.72	277
	4x	-0.0018	0.1487	-12.96	-4982
Buoy_high pH	Ambient	7.00E-05	0.0205	0.504	194
	0.5x	0.0004	0.4436	2.88	1107
	2x	-3.00E-07	6.00E-07	-0.00216	-1
	4x	-0.0006	0.4108	-4.32	-1661
Buoy_low pH	Ambient	0.0015	0.7319	10.8	4152
	0.5x	0.002	0.7687	14.4	5535
	2x	0.0009	0.3065	6.48	2491
	4x	-0.0024	0.3296	-17.28	-6642

Note: The water column depth (d) is 0.3m. K is the slope of TDP concentrations along with time.

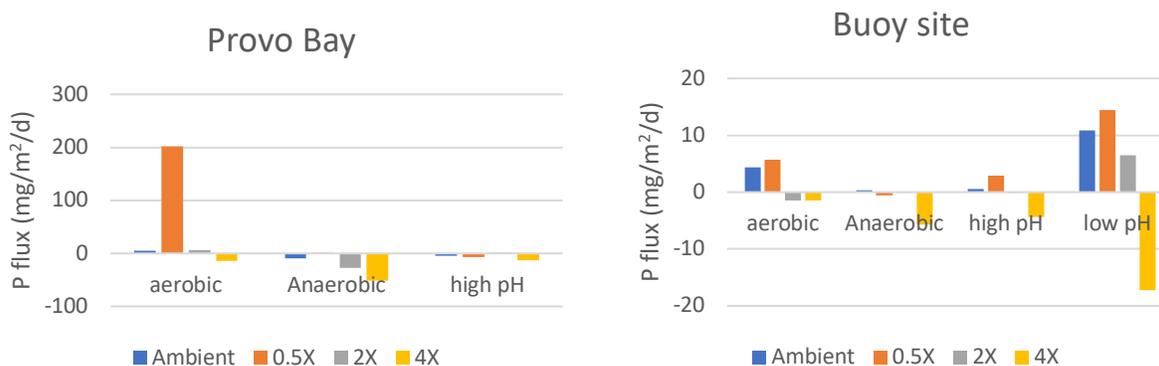


Figure 4. TDP fluxes under different conditions at two sites.

Endogenous inputs of nutrients from point and non-point source discharges are important in lake nutrient management but internal cycling of nutrients also plays a great role in supporting surface water eutrophication. However, P loads from exogenous sources have a significant influence on dissolved P concentrations in streams and sediment-water column dynamics (Ekka et al., 2006). In terms of implications for Wastewater Treatment Plants (WWTPs) loadings, the improvement of Utah Lake water quality may be delayed in response to decreased external loading and ambient concentrations because of internal recycling of P (Hogsett et al., 2019;

Randall et al., 2019). The 0.5X ambient concentrations generally enhanced P release compared to that of the ambient conditions. Previous studies also found that it may take nearly 10-15 years to reach a new equilibrium after exogenous nutrient reduction (Jeppesen et al., 2005). Also, with increased loadings, a lake may act as a self-cleaning system to remove P from the water column by mineral precipitation in calcite (Brimhall & Merritt, 1981; Hogsett et al., 2019; Randall et al., 2019). However, it may not reduce spiked concentrations to the initial levels, as the high loads (2X and 4X of ambient water) result in P sink but still remain relatively high ambient P concentrations under aerobic conditions after 72 hours (Table 4). For example, under aerobic conditions for Provo Bay the final (72 hours concentration) for ambient, 0.5X, 2X and 4X were 0.38-0.56, 0.48-0.88, 0.48-1.29, and 0.80-1.64 mg/L respectively, while the initial lake P concentrations were in the ranges of 0.40-0.51 mg/L. For the buoy site, under aerobic conditions, the final (72 hours concentration) for ambient, 0.5X, 2X and 4X were 0.09-0.12, 0.12-0.14, 0.14-0.20, and 0.27-0.32 mg/L respectively, while the initial lake P concentrations were in the ranges of 0.05-0.06 mg/L.

3.3 SRP flux to/from sediment

The equation for SRP flux was the same as TDP. More negative fluxes were observed for SRP compared with TDP. Specially, the positive fluxes were observed for Provo_aerobic_0.5X (1.44 mg/m²/d), Buoy_anaerobic_ambient (0.144 mg/m²/d), Provo_pH9.5_ambient (2.16 mg/m²/d) and Buoy_pH9.5_0.5X (1.44 mg/m²/d). The negative release was detected at 2X or 4X treatment similar to the TDP flux. The most negative flux was detected at Provo_anaerobic_4X (-21.6 mg/m²/d). Compared with TDP, there could be some other forms of P release from sediment during the experimental period.

Table 5. SRP flux to/from sediment.

Site	Groups	K value	R square	SRP flux (mg/m ² /d)	Load (Kg/day)
Provo_aerobic	Ambient	-0.0016	0.2642	-11.52	-4428
	0.5x	0.0002	0.013	1.44	554
	2x	-0.0015	0.1594	-10.8	-4152
	4x	-0.0006	0.0299	-4.32	-1661
Provo_anaerobic	Ambient	-0.0005	0.0226	-3.6	-1384
	0.5x	-6.00E-05	0.001	-0.432	-166
	2x	-0.0016	0.1546	-11.52	-4428
	4x	-0.003	0.2712	-21.6	-8303
	Ambient	-0.0003	0.6897	-2.16	-830

Buoy_aerobic	0.5x	-0.0005	0.5321	-3.6	-1384
	2x	-0.0015	0.6154	-10.8	-4152
	4x	-0.0025	0.8113	-18	-6919
Buoy_anaerobic	Ambient	2.00E-05	0.0023	0.144	55
	0.5x	-0.0004	0.5655	-2.88	-1107
	2x	-0.0013	0.3384	-9.36	-3598
	4x	-0.001	0.5615	-7.2	-2768
Provo_high pH	Ambient	0.0003	0.2739	2.16	830
	0.5x	-0.0011	0.1732	-7.92	-3044
	2x	-0.0001	0.0348	-0.72	-277
	4x	-0.0022	0.3295	-15.84	-6089
Buoy_high pH	Ambient	-4.00E-05	0.0461	-0.288	-111
	0.5x	0.0002	0.3277	1.44	554
	2x	-0.0002	0.2917	-1.44	-554
	4x	-0.0005	0.6003	-3.6	-1384

Note: The water column depth (d) is 0.3m. K is the slope of SRP concentrations along with time.



Figure 5. SRP fluxes under different conditions at two sites.

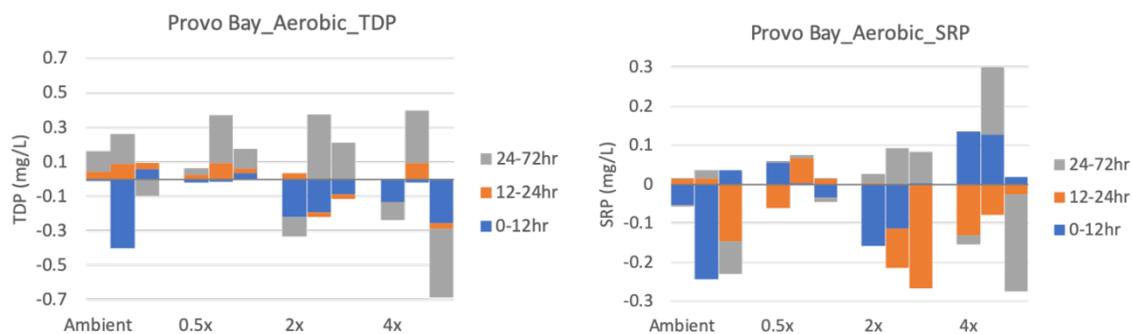
3.4 P dynamics under different conditions in terms of absolute concentration

3.4.1 P dynamics under aerobic conditions

Under aerobic conditions, both the Provo Bay and Buoy sites showed similar trends of P concentrations, with the only notable difference being the overall higher initial TDP and SRP concentrations in Provo Bay (Figure 5). DO was maintained at about 7.5 mg/L. The pH at buoy site stayed about 8.6, the pH at the PB site fluctuated between 8.53 and 8.82. Increasing P concentrations was mostly observed in the ambient and 0.5X spiked columns, with 0.5X spiked columns showing the highest increase in P concentrations over time. In contrast to the ambient and 0.5X columns, P concentrations tended to decrease over time in the 2X and 4X spiked

columns, with the greatest decrease in P concentrations observed in the 4X columns. For the Provo Bay site, TDP concentrations (triplicates measurement) increased from 0.40-0.51 mg/L to 0.38-0.56 mg/L in the control column (no spiking) and 0.40-0.53 mg/L to 0.48-0.88 mg/L in 0.5X spiked column from 0 to 72 hours. On the other hand, decreasing trends in TDP were observed in some sediment cores of each spiked column. Specifically, TDP changed from 0.77-1.14 mg/L to 0.48-1.30 mg/L in 2X spiked column and from 1.24-1.48 mg/L to 0.80-1.64 mg/L in 4X spiked columns after 72 hours for Provo Bay based on triplicate measurements. Despite the decrease in TDP overtime in the 2X and 4X columns, final concentrations (0.48-1.30 mg/L for 2X and 0.80-1.64 mg/L for 4X) were still higher than initial ambient concentrations (0.40-0.53 mg/L), indicating that the increased P in the water column did not completely sink into the sediments of Provo Bay site.

Similar trends were observed at the Buoy site. Generally, the variations of SRP also observed a tendency to decrease at 2X and 4X spiked, but at smaller quantities compared with TDP (Figure 5) for both sites. Figure 5 mostly provides an overview about P concentrations to and from sediments. Larger negative fluxes were observed for SRP than TDP for some sites (e.g., Buoy_aerobic) probably due to the sink of ortho-P while release of other forms of P from sediments. The change of water P concentrations was probably due to a state of dynamic equilibrium between particulate and soluble phases as well as between the water and surface sediments (Jenkins, 2005). Generally, soluble P is released more under anaerobic conditions (Bates & Neafus, 1980) when Fe(III) reduction occurs under anaerobic conditions at the sediment-water interface, after which the P bound to Fe(III) oxides is released into pore water (Moore and Reddy, 1994). Other reason of P release under anaerobic conditions could be due to the release of sorped P on oxyhydroxides present in the water column (Bostrom et al., 1998). However, in this case, experiments were conducted under aerobic conditions and P release during these experiments under some specific concentrations is intriguing and warrants further investigation.



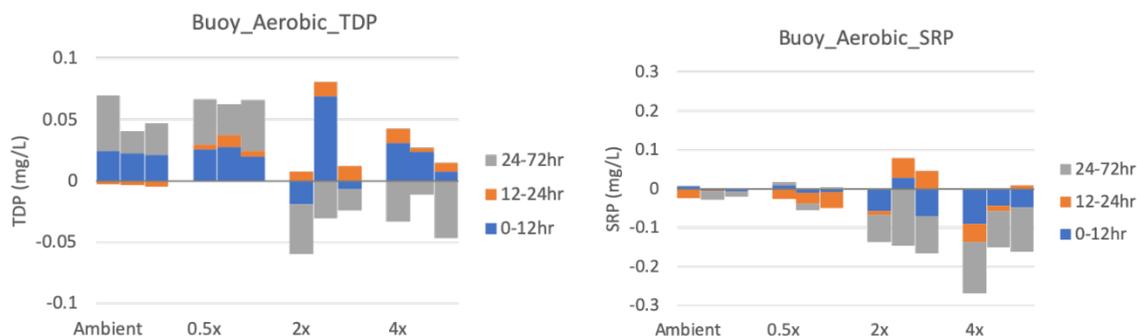


Figure 5. Relative change in TDP and SRP concentrations between sampling periods (0-12hr, 12-24hr and 24-72 hr) in the water column under aerobic conditions.

3.4.2 P dynamics under anaerobic conditions

Under anaerobic conditions, P concentrations decreased in the water column in nearly all cores from both the Provo Bay and Buoy sites over the 72-hour experiments (Figure 6). In general, P concentrations decreased more in anaerobic conditions relative to aerobic conditions. Similar to aerobic conditions, more substantial P decrease occurred in the 2X and 4X columns at both sites, for TDP and SRP. However, there was a confounding factor because over the 72-hour anaerobic experiments as the pH increased from initial values of 8.5 to 10. This was unexpected because the redox conditions should not cause a change in the pH. A possible reason for the increase in pH could be that the continuous purging of N₂ gas to maintain oxygen free conditions could have removed dissolved CO₂ from the water column, thus altering the bicarbonate buffering system, as well as some possible microbial activities. In future experiments, the pH problem may be solved by purging with N₂ gas containing 5% CO₂.

As further evidence of calcite precipitation in the columns, Ca²⁺ concentrations also decreased over time in cores from both sites. Calcite may have scavenged P as a co-precipitate or by sorption. Precipitation of calcite mostly occurs under alkaline conditions in which pH ranges from 8.7 to 9.5 (Stocks-Fischer et al., 1999). Typically, phosphorus is released under anaerobic conditions, because of the gain of previously Fe³⁺, Al³⁺ and Ca²⁺ bound phosphorus or the decomposition of organic matter (Baggie et al., 2005; Shen et al., 2013) but this was not the case in these experiments. The storage of poly-P by PAOs could be one reason decreasing P from the ambient environment (Hirota et al., 2010). The sink of phosphorus seen in our anaerobic experiments could be caused by the increased pH or anaerobic conditions, which allowed P to be absorbed on to precipitated CaSO₄, Ca(OH)₂, and CaCO₃ compounds.

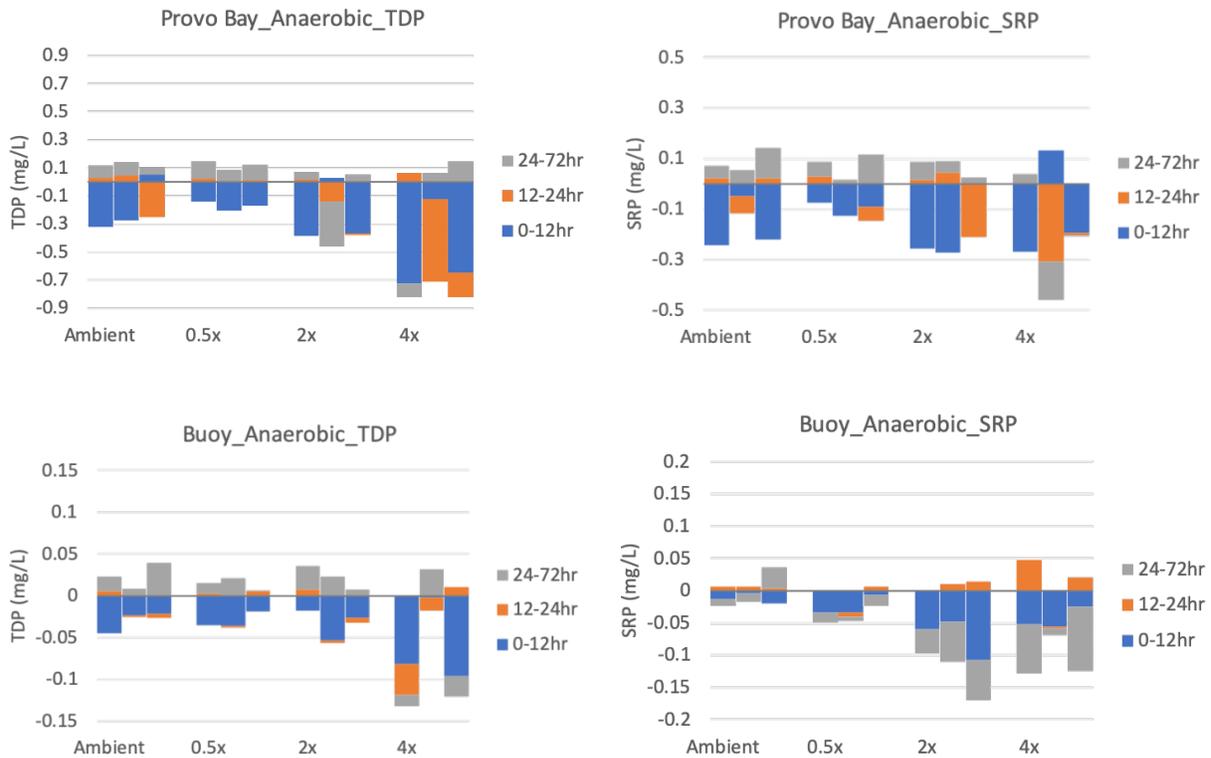


Figure 6. The change in TDP and SRP concentrations in the water column under anaerobic conditions.

3.4.3 P dynamics at neutral and alkaline pH

At the Provo Bay site, TDP and SRP concentrations were similar throughout the experiments for all treatments. At the Buoy site, TDP and SRP concentrations decreased over time, particularly in the 4x experiments. Similar to aerobic conditions, DO was maintained around 7.5 mg/L throughout the incubations during pH experiments. At both pH = 9.5 (high pH) and pH = 7.0 (low pH), the lake's strong buffering system decreased (when adjusted to high pH) or increased (when adjusted to low pH) pH towards the initial values of 8.6 ± 0.2 . Continuous addition of acid or base was required to maintain the targeted pH. As shown in the Figure 7, the trend of TDP is similar to that of the SRP except for water SRP concentrations at both sites, which were lower than the TDP concentrations. P concentrations in the low spiked columns (ambient, 0.5X) tended to increase over time, while P concentrations in the high spiked columns (2X, 4X) tended to decrease over time, ultimately reaching an equilibrium in the water column. Greater P release at lower water P concentrations was observed, while P sink was mostly observed at the 4X concentrations (Figure 7). As for the Buoy site, TDP concentrations were much higher for the neutral pH (0.09 - 0.53 mg/L) than under alkaline conditions (0.02-0.13 mg/L).

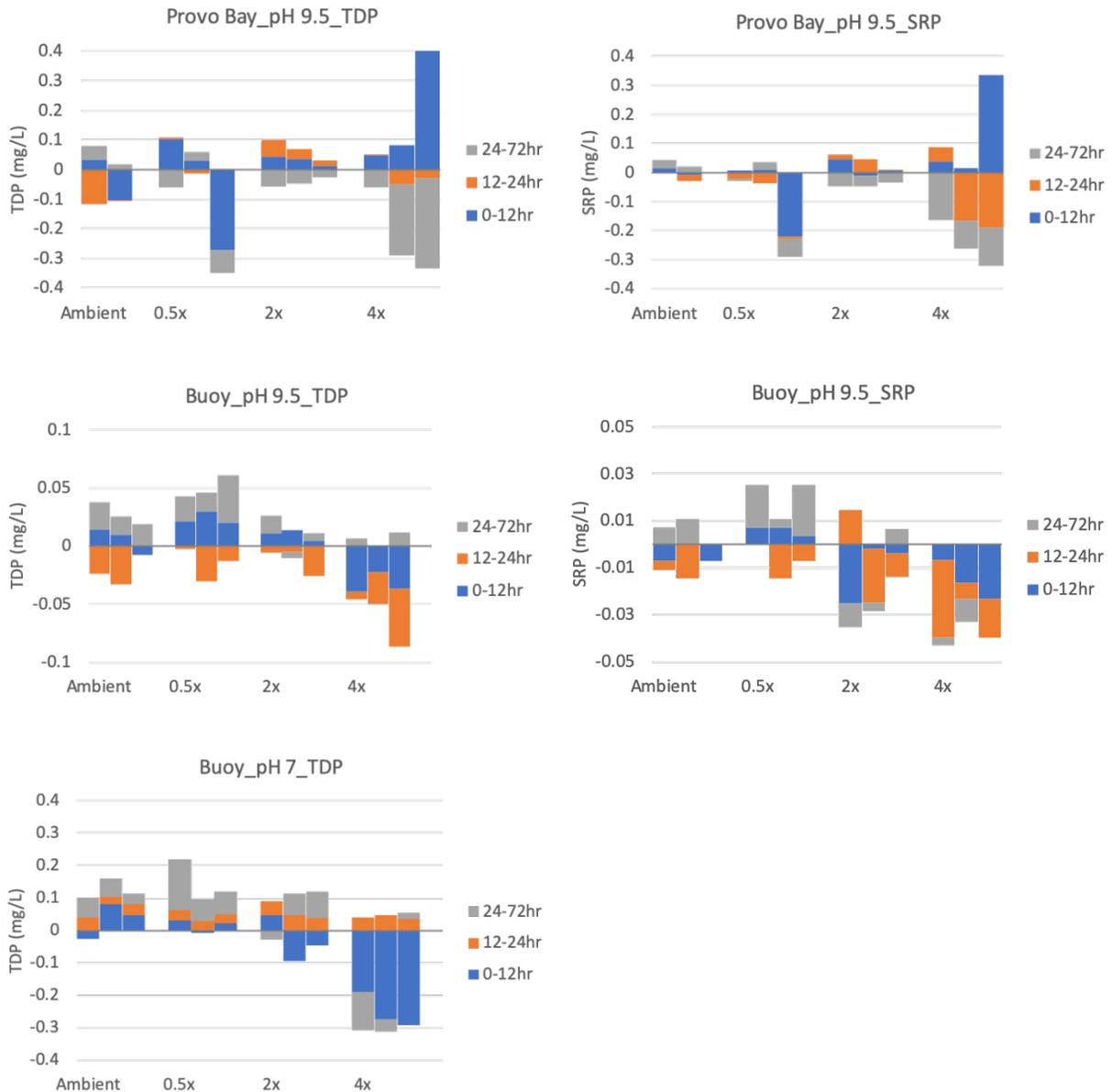


Figure 7. The TDP and SRP change with pH = 9.5 and pH =7.

A previous study found that the variation of pH can change the particles aggregation/cohesion behavior by altering their surface charge properties (Illés and Tombácz, 2006). At neutral to high pH (7- 9), P is difficult to release from the sediment as a layer of $\text{Fe}(\text{OH})_3$ protective film could be formed on the surface of Fe-P, which have a stable Fe-P complex (Li et al., 2013). While the reduction of Fe(III) to Fe(II) that enhanced P release from sediment occurs more strongly under extremely low redox potential and low pH (5.5) and/or anaerobic conditions (Moore and Reddy, 1994), the Fe phosphate precipitation or adsorption of P by Fe oxides or hydroxides could result in low P solubility in the lake. These discussions are consistent with our

results that there was a tendency to release P when pH was decreased (Gomez et al., 1999). As the ambient lake water is deficient in iron compared to calcium, the hypothesis could be that the formation of calcium-phosphate precipitation or adsorption of P by calcite species result in low P solubility in the lake. Formation of these compounds requires neutral to high pH, while the solubility of complex is determined by the pH, alkalinity, and reacting compounds. The dissolution of these compounds under extremely low pH (< 3) or with acid may increase their release from the sediment (Gao, 2012).

3.4.4 Relative change of calcium and phosphorus concentrations in the water column

To further investigate into the role of calcium in P sink, calcium and P concentrations in water were compared for each treatment (Table 6). The calcium sink occurred mostly under anaerobic (-49.04 to -14.14 mg/L) or high pH (-32.29 to 14.54 mg/L) conditions for both sites, followed by low pH of the buoy site and aerobic conditions. The greater calcium precipitation under anaerobic conditions could be due to higher pH or microbial-mediated activities. For example, the denitrification activities could occur under anaerobic conditions, increasing the pH by consuming H⁺ and producing CO₂, which favored carbonate precipitation (Zhu & Dittrich, 2016). Although not a part of this project, we have observed significant denitrification activities in Utah Lake sediments. In addition, anaerobic oxidation of methane favored the precipitation of calcium carbonate, while the aerobic oxidation of methane caused more dissolution of calcite by increasing acidity (Reeburgh, 2007). These could be reasons causing more calcium sink under anaerobic condition rather than high pH. Under neutral pH conditions, ambient water tends to have a greater release of P from the sediment than under natural conditions or the high pH for the buoy site (Table 6). This could be a result of P speciation in combination with metal oxides or hydroxides and their solubility was affected by pH (Van Nguyen & Maeda, 2016). However, calcium sink was also mostly observed under adjusted pH rather than the normal conditions (Table 6). The lowered pH generally caused less calcium sink with less precipitation and more possibility of Ca-P dissolution (Huang et al., 2005). Under all conditions, the amount of P release or sink is not comparable to the sink of calcium. There could be a larger amount of calcite species precipitation than Ca-P precipitation or attachment to the surface of minerals based on the water column Ca:P concentration ratios. The formation of calcite species reduces the free Ca concentration, thereby reducing P precipitation. However, with the large amount of Ca²⁺ in the alkaline lake, the reduction effect is eligible.

Table 6. The relative change (between 0 and 72 hours) of calcium and phosphorus concentrations in the water column (units of concentrations are mg/L).

Treat- ment	Category	Provo_ aerobic	Provo_ anaerobic	Buoy_ aerobic	Buoy_ anaerobic	Provo_ aerobic	Buoy_ aerobic	Buoy_ anaerobic
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						high pH	high pH	low pH
Ambient	P	0.005	-0.692	0.049	-0.008	-0.0624	0.0056	0.1157
	Ca	-6.08	-49.04	1.12	-14.14	14.54	-24.39	-12.08
0.5X	P	0.192	-0.050	0.065	-0.017	-0.0848	0.0345	0.1420
	Ca	2.08	-36.42	0.98	-28.69	-22.91	-18.36	-5.38
2X	P	-0.014	-0.161	-0.004	-0.076	0.0232	0.0031	0.0516
	Ca	-6.61	-45.08	0.65	-8.60	-19.33	-13.16	-10.62
4X	P	-0.180	-0.354	-0.002	-0.014	-0.0461	-0.055	-0.257
	Ca	-2.81	-47.35	0.16	-10.72	-32.29	-26.53	-8.18

Note: The positive values represent release and negative values represent sink.

4.0 Nitrogen dynamics

4.1 The dynamics of N species and ammonium flux

The ammonium-N, nitrite-N and nitrate-N were presented at concentrations of 0.001-0.658 mg/L, 0-0.048 mg/L, and 0-0.239 mg/L, while nitrite-N was undetectable most of the time. A significant change in ambient concentrations was only observed for ammonium-N. One-way ANOVA was used to compare the differences among different treatments. No significant difference in ammonium-N concentration was found among samples with different orthophosphate concentrations (e.g., the concentrations treatment for Provo_aerobic). Under all P concentrations tested, there were significant differences among treatment groups (<0.05, ANOVA). Specially, average ammonium-N concentrations throughout the 72-hour period were higher under aerobic conditions (0.07 - 0.24 mg N/L) than that under anaerobic conditions (0.03-0.09 mg N/L). For pH changes, the average ammonium-N concentrations throughout the 72-hour period were also higher for Provo Bay (0.06-0.21 mg N/L) than that for the Buoy site (0.05-0.08 mg N/L) likely due to different mineralogy compositions. No significant difference was found for nitrate-N concentration changes. The nitrate-N concentrations mostly remain in the range of 0.124-0.156 mg N/L as detected.

The ammonium flux was also calculated under different conditions following the same methods as phosphorus (Table 7). Generally, ammonium sink (negative values) was observed for most of the locations with different treatments. Provo Bay observed higher sink of ammonium (-30.24 to -0.72 mg/m²/d) than the buoy site (-12.96 to 0.144 mg/m²/d). Aerobic and high pH conditions generally have higher ammonium sink (-37.44 to -3.6 mg/m²/d) than the anaerobic conditions (-8.64 to 0.144 mg/m²/d). Even with similar high pH, the ammonium loss under anaerobic condition is not comparable to aerobic condition. Similar to ANOVA analysis, no significant

difference of ammonium sink was observed among treatments with different initial P concentrations.

Table 7. Ammonium flux to/from sediment.

Site	Groups	K value	R square	Ammonium-N flux (mg/m ² /d)	Load (Kg/day)
Provo_aerobic	Ambient	-0.0024	0.1346	-17.28	-6642
	0.5x	-0.0012	0.1027	-8.64	-3321
	2x	-0.0014	0.5333	-10.08	-3875
	4x	-0.0042	0.3455	-30.24	-11624
Provo_anaerobic	Ambient	-0.0012	0.3266	-8.64	-3321
	0.5x	-0.0006	0.1561	-4.32	-1661
	2x	-0.0009	0.3541	-6.48	-2491
	4x	-0.0001	0.0026	-0.72	-277
Buoy_aerobic	Ambient	-0.0014	0.6298	-10.08	-3875
	0.5x	-0.0013	0.4608	-9.36	-3598
	2x	-0.0018	0.4926	-12.96	-4982
	4x	-0.001	0.2355	-7.2	-2768
Buoy_anaerobic	Ambient	2.00E-05	0.0019	0.144	55
	0.5x	-0.0002	0.3140	-1.44	-554
	2x	-0.0001	0.1013	-0.72	-277
	4x	-0.0002	0.1980	-1.44	-554
Provo_high pH	Ambient	-0.0052	0.5338	-37.44	-14392
	0.5x	-0.0032	0.2135	-23.04	-8857
	2x	-0.0008	0.1494	-5.76	-2214
	4x	-0.0037	0.2607	-26.64	-10240
Buoy_high pH	Ambient	-0.0007	0.2720	-5.04	-1937
	0.5x	-0.0008	0.3199	-5.76	-2214
	2x	-0.0013	0.2005	-9.36	-3598
	4x	-0.0005	0.2000	-3.6	-1384

Note: The water column depth (d) is 0.3m. K is the slope of ammonium-N concentrations along with time. R square measures how close the slope fits values.

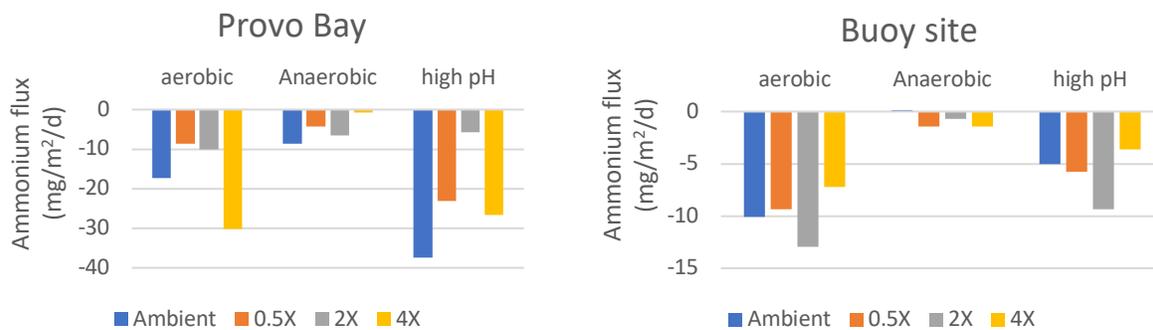


Figure 8. Ammonium-N fluxes under different tested conditions at two sites.

4.2 The absolute concentrations of ammonium under different treatment

Under aerobic conditions, ammonium was mostly released before 24 hours. Generally, Provo Bay has higher surrounding ammonium-N concentrations (0.001 - 0.658 mg N/L) than the Buoy site (0.010 - 0.266 mg N/L) (Figure 9). However, significant loss of ammonium was observed between 24 and 72 hours. In contrast to aerobic conditions, continuous ambient ammonium concentration decrease was observed under anaerobic conditions. In general, ammonium was lost from the system, likely due to ammonia volatilization with the high pH (8.5 to 10) that probably affected nitrifying bacterial activities (EPA, 2002). Although under aerobic condition, higher DO levels could activate nitrifying bacteria, leading to high rates of biological ammonia oxidation and coupled nitrification–denitrification (Palmer et al., 2009). While under anaerobic conditions, ammonium release could be triggered due to anaerobic fermentation from nitrogen-rich sediments to the overlying water (Zhang et al., 2019). However, a sink of ammonium was still observed under anaerobic conditions, which could be caused by ammonia volatilization under alkaline conditions. Under increased pH, the un-ionized ammonia and toxicity were increased. The increased pH and toxicity may inhibit bacterial activities and cause more ammonia volatilization, which explains the high ammonium loss under high pH (Kadam & Boone, 1996; Venterea et al., 2015). Some other recent discovered pathways, such as ammonia-oxidation by archaea (He *et al.*, 2018), anammox (Yang et al., 2017) and dissimilatory nitrate reduction to ammonium (DNRA) (Nizzoli et al., 2010) have been discovered in lake sediment, resulting in ambient ammonium release or decrease. Similar to phosphorus release, the release of ammonium is also correlated with trophic status with higher ambient concentrations observed at Provo Bay (Herrmann et al., 2009). To have an estimated percentage ammonium loss from our study, Table 8 was listed at varying pH based on 20 °C ambient temperature. At the same temperature, the percentage of free ammonia increases along with pH increase. The highest percentage of free ammonium at pH =10 is 79.83%. From the Table 9 we can concur that the ammonium sink was higher in our study at some conditions (e.g., Provo_aerobic, pH =8.5) than the percentage of unionized form estimated in the Table 8.

This may indicate ammonium loss through other discussed pathways or continuous air stripping.

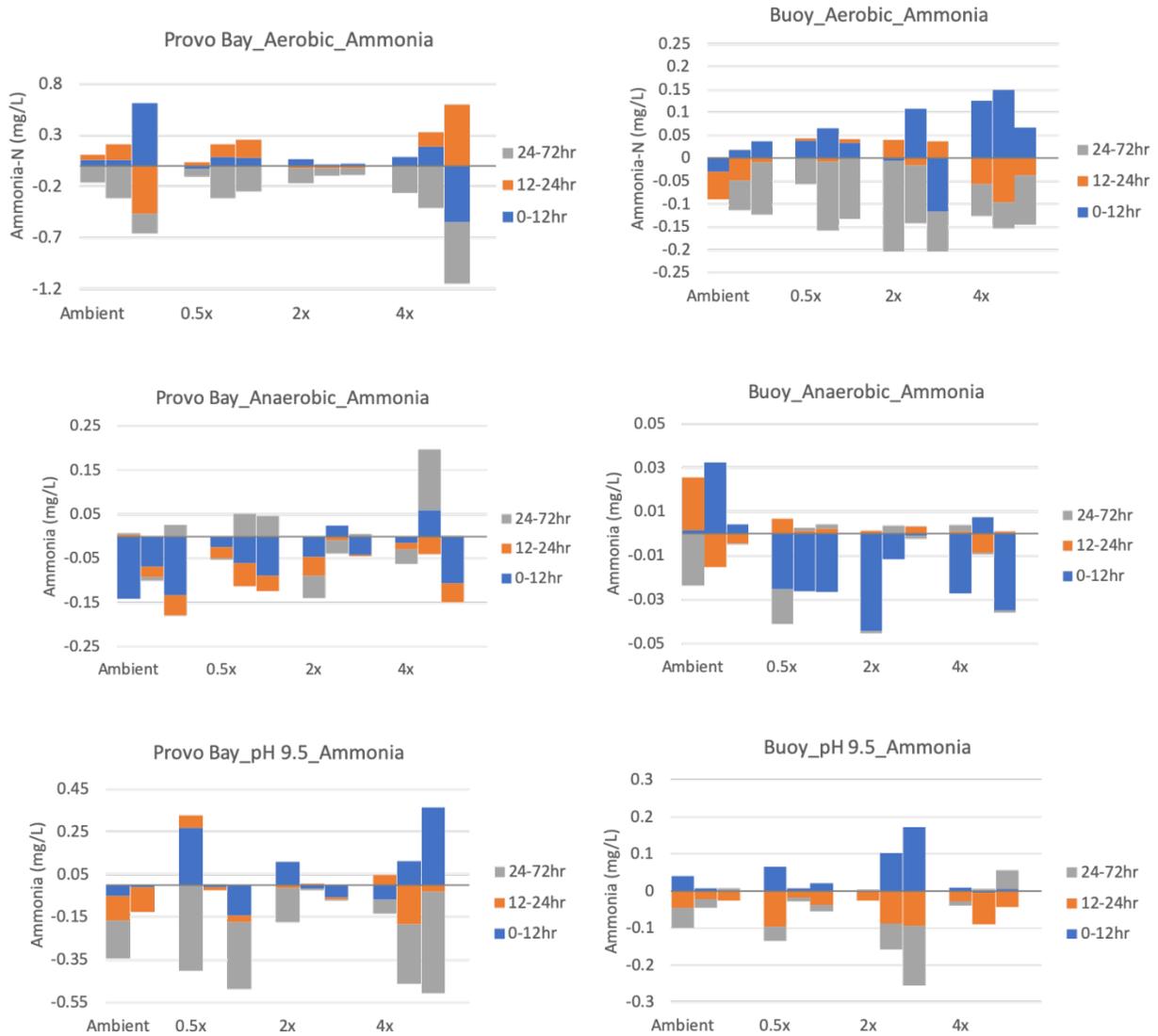


Figure 9. The changes of ammonium under different conditions.

Table 8. Percentages of free ammonia.

pH	8.0	8.4	8.8	9.2	9.6	10.0
Percent	3.81	9.04	19.98	38.55	61.17	79.83

Temperature was at 20 °C for percentage of unionized-ammonia (Emerson et al., 1975).

Table 9. Percentage of ammonium-N removed under different conditions.

Treatment	Ambient	0.5X	2X	4X
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Provo_ aerobic	97.092	96.525	96.174	97.441
Provo_ anaerobic	91.879	70.864	69.723	90.775
Buoy_ aerobic	73.795	88.013	81.248	47.144
Buoy_ anaerobic	-34.417	55.856	28.566	38.618
Provo_ high pH	90.932	80.671	69.375	90.062

5.0 Sediment oxygen demand

Sediment oxygen demand (SOD) is the rate at which dissolved oxygen is removed from the overlying water column in the bed sediments (Hatcher, 1986). The SOD can be a major factor of low dissolved oxygen concentrations and hypoxia conditions in lakes and streams (Doyle and Lynch, 2003). Several factors determining SOD values include temperature, water column dissolved oxygen concentrations, organic matter content, sediment grain size, flow rate, sediment disturbance and toxic substances, and measurement techniques (Medine et al., 1980; Krantzberg, 1994). SOD values were calculated for each site as the difference between experimental and control chambers (Hogsett & Goel, 2013). To have a standard comparison among different SOD values, SOD at different conditions were temperature corrected to 20 degrees Celsius using a standard Van't Hoff equation. As a result, the water column oxygen depletion rates were $-1.584 \text{ g/m}^3/\text{day}$ and $-0.432 \text{ g/m}^3/\text{day}$ for site Provo Bay and Buoy sites respectively. The SOD values were calculated as $-0.052 \text{ g/m}^2/\text{day}$ and $-2.965 \text{ g/m}^2/\text{day}$ for site Provo Bay and Buoy sites respectively. The SOD values were similar to the previous study, which reported SOD values in the range of -4.61 to $-0.90 \text{ g/m}^2/\text{day}$ from eight sites across the Utah Lake (Hogsett et al., 2019). In contrast to the result, the Provo Bay site was considered to have higher SOD than other open water area due to rich organic content. In calculating the SOD for the Provo Bay and buoy sites, we only considered the part of DO-time curve with graduate slope changes (Figure 10 and 11). Nevertheless, to verify the data, we re-visited Provo site and installed two testing chambers and one control chamber. However, none of the Sondes worked this time because they all were mistakenly switched off when we obtained those from UDWQ.

Table 10. SOD measurement by considering initial slope change.

Date	Chamber	pH	Temp (F)	Parameters (SOD or WC)	Corrected SOD (20°C)
Site: Provo Bay					

Oct 3 rd , 2019	Water (g/m ³ /day)	8.98	55.5	-1.584	
	Sediment (g/m ² /day)	8.98	55.5	-0.034	-0.052
Site: State Park site near DWQ buoy					
Oct 1 st , 2019	Water (g/m ³ /day)	8.42	58.7	-0.432	
	Sediment (g/m ² /day)	8.42	58.7	-2.018	-2.965

For example, the calculation of the SOD of Provo Bay:

According to the above figures, the SOD for each chamber can be calculated as follows: as shown in the Provo Bay, there is a sharp decrease in the working chamber. Not sure if it is because of the SONDE needs time to warm up and we initially kept this period time for calculations. However, if we only consider the slowly decrease part for each chamber, the slope will be as follows and the net SOD will become almost zero:

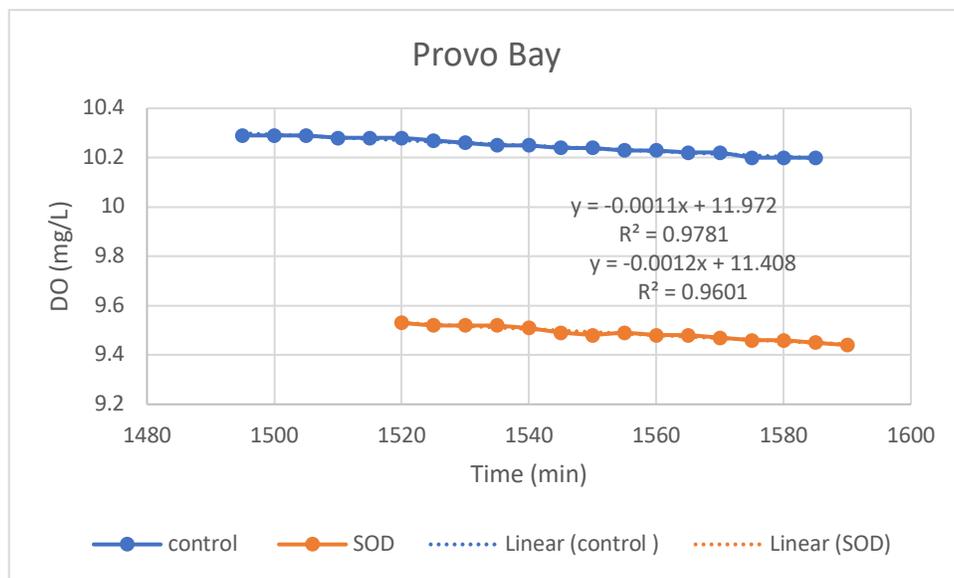


Figure 10. DO versus time for the Provo Bay site with gradual slope change.

The SOD for Buoy site:

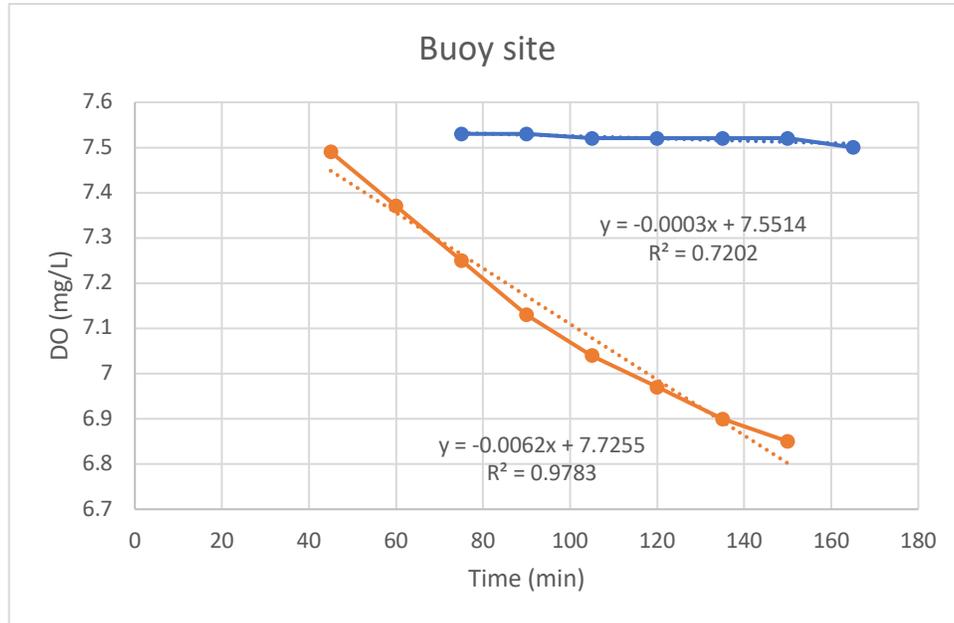


Figure 11. DO versus-time for the Buoy site with graduate slope change.

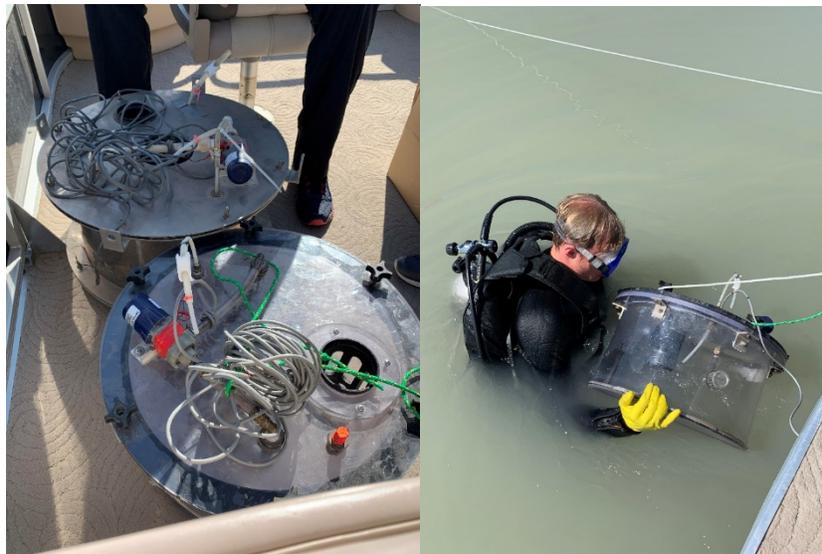


Figure 14. SOD chambers and installation in the field.

3.9 The dynamics of some major ions

In addition to the nutritional ions, other major ions in the lake water column playing important roles include Al^{3+} , Ca^{2+} and Mg^{2+} . The complex formed by aluminum (Al) and inorganic phosphate can present a significant portion of both dissolved and particulate Al pool under certain conditions. Briefly, the observations suggest that the Al-P complexation is pH-dependent and appears to predominate around pH= 6 (Dickson, 1980; Nalewajko and O’Mahony, 1988). The Al-P complex can be soluble or insoluble: two soluble forms are

$\text{AlH}_2\text{PO}_4^{+2}$ ($\log K \sim 3$) and AlHPO_4^+ ($\log K \sim 7$), and the insoluble form of AlPO_4 complex is more well-known. Moreover, inorganic phosphate can also adsorb onto the aluminum oxides and hydroxides, which has been extensively applied to both water treatment and lake management as a means of controlling excess dissolved P (Davis and Hem, 1989). As for the toxicity of Al to algae, it is most toxic under slight acidic conditions and the toxicity could be reduced by forming compound with organic matters, etc. in the lake (Gensemer & Playle, 1999).

Compared with Al, most alkaline lakes are more of a CaCO_3 system, such as Utah Lake. Ca-P complex can be formed at the surface sediment of the lake and eventually transformed to crystalline apatite (Stumm and Leckie 1971). The formation of complex, $\text{Ca}_3(\text{HCO}_3)_3\text{PO}_4$, in $\text{CaCO}_3\text{-H}_3\text{PO}_4\text{-H}_2\text{O}$ systems mostly takes two reacting compounds of CaCO_3 and H_3PO_4 into consideration. The solubility of complex was determined by the pH, alkalinity, and reacting compounds. It appeared that Ca-bound pool of phosphorus in sediment requires lower pH ($\text{pH} = 3$) to break down (Gao, 2012). Similar to calcium, magnesium is another ion that can form complex with phosphates in the lake sediment, such as compounds composed of calcium, magnesium and ammonium phosphates (e.g. struvite – $(\text{NH})_4\text{Mg}[\text{PO}_4] \times 6\text{H}_2\text{O}$).

4. Future perspectives

As the sediment responded significantly to different initial P concentrations, the effects of endogenous loading can be further clarified. The mineral compositions of surface sediment can be further studied to correlate with the P retention/release under different environmental conditions. Furthermore, field studies can be conducted to detect the anaerobic or aerobic conditions at different layers of sediment, as sediment responded quite differently to these situations. Temperature/seasons and algal bloom may also have effects on sediment nutrient release, which can be investigated more. In this regard, we make the following possible recommendations for future improvements and data gaps.

1. Conduct anaerobic experiments by purging with nitrogen gas with 5% CO_2 to maintain ambient pH in the water column.
2. Run experiments for longer than 72 hours to investigate long-term equilibrium.
3. It will be good to conduct other analysis such as XRD and XPS to reveal the mineralogy at the sediment-water column interface.
4. Future studies should include a complete mass balance approach for both nutrients, e.g. nitrogen and phosphorus in which case studying bacterial mineralization of P (from mineral phosphates to orthophosphate by bacterial enzymes) and bacteria mediated fate of N (e.g. fixation, denitrification) become important.
5. The sources and fate of organic P and its mineralization to SRP should be studied.

5. Conclusions

Distribution and transformation of nutrients in large shallow lakes has raised great concern as it may enhance internal nutrient loadings to the system. Being a natural alkaline lake, Utah Lake was previously reported to remove excess P by mineral precipitation. However, the incubation of sediment cores with varying initial P concentrations suggest that the lake may not remove all additional P when it is above a tolerant limit (2X and 4X of initial concentrations). Even 0.5X initial P concentrations observed increased ambient P concentrations with time as the sediment released P to reach equilibrium. Together with P, concentrations of other ions (e.g., ammonium and calcium) were also observed to change significantly. Additionally, the varying of physical parameters (e.g., DO and pH conditions) did affect the overall chemistry of the ecosystem, whereas the lake's strong buffer system can maintain a relatively stable state in natural conditions. Overall, the improvement of Utah Lake water quality may be delayed in response to decreased external loading and ambient concentrations. Results acquired from this study could help with explaining similar phenomenon in other freshwater lakes, as well as decision-making for environmental agencies.

6. Acknowledgement

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Appendix A- SOPs

Utah Lake Sediment–Water Nutrient Interactions Detailed Experimental and Quality Assurance Plans

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Graduate Students

**Submitted
August 8, 2019**

1.0 Project rationale and objectives

1.1 Rationale: The Utah Division of Water Quality (DWQ) recently initiated Phase 2 of the Utah Lake Water Quality Study (ULWQS) to evaluate the effect of excess nutrients on the lake's recreational, aquatic life, and agricultural designated uses and to develop site-specific nitrogen and phosphorus water quality criteria to protect these uses. Understanding the cycling of nutrients within Utah Lake will help describe the current state of the lake with respect to nutrients and ecology, and sediments are an important component of the nutrient cycling within the lake. Available reports and initial information on sediment oxygen demand (SOD) and nutrient release from sediments in Utah Lake provide some insight into sediment phosphorus characteristics and fluxes but stop short of converting bulk measurements into mobile or bioavailable fractions.

1.2 Study Objectives: The overall objective of this collaborative project is to; (1) understand the role of anoxia in nutrient release and sediment dynamics over a range of phosphorus concentrations, (2) understand the role of pH in water column–sediment interactions and nutrient releases and how does the equilibrium phosphorus concentration change over a range of water column pH and, (3) estimate the sediment oxygen demand and nutrient release from sediments under current conditions. Although nitrogen species will be measured during these experiments, the current RFA does not suggest calculating nitrogen fluxes or determining the fate of nitrogen species during these experiments. Four different tasks will complement these aforementioned objectives identified by the Science Panel in the recently released RFP.

3.0 Experimental Plan (SAPs)

Task 1. Develop sampling and analysis plan (SAP) (Drs. Goel and Carling and graduate students)

Sub task 1.1: Project kick off meeting: Pending approval and then contract signing of this project, we will immediately conduct an in-person meeting among us including the PI (Dr. Goel), the Co-PI (Dr. Carling) and potential graduate and undergraduate students. The purpose of this meeting will be to discuss project milestones, assign duties in terms of SOPs and QAPP writing. We will also discuss about the lab infrastructure in each key personnel's lab and the overall time frame of experiments. Minutes of the meeting will be recorded and stored electronically.

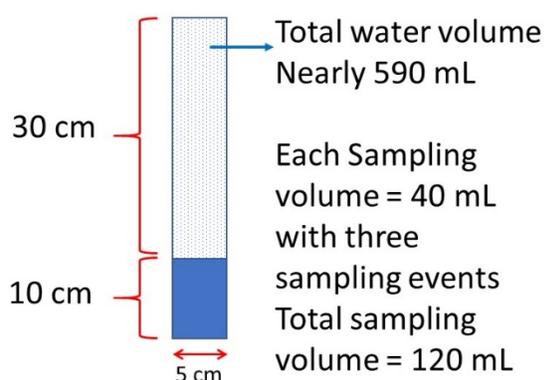
Sub task 1.2: Develop sampling and analysis plan (SAP): We will follow a similar strategy that we have followed for our EPA and current UDWQ funded projects. In summary, we plan to submit all necessary QAPP and SAP documents to the Science Panel before the beginning of any field work. We will access the available QAPP and SAP documents related to water quality sampling and sediment work available at the UDWQ website as reference material (<https://deq.utah.gov/water-quality/quality-assurance-and-quality-control-program-monitoring-water-quality>). **UDWQ's vision is that QAPP is meant to be an umbrella document outlining the minimum QA/QC requirements for environmental data collection.** As a team, we share DWQ's vision about QAPP and SAP importance and will adhere to these standards while coordinating with the Science Panel and UDWQ. In developing QAPP and SAP documents, we will coordinate with UDWQ through in person meetings and phone calls. After such meetings, a first draft of QAPP and SAP will be submitted to UDWQ for their input. Once the documents are finalized, they will be submitted to the Science Panel for their comments and approval. The format of SAP will follow the style suggested by the Science Panel in the sediment RFP document. We will also refer to SAP documents for common water quality parameters that are available at <https://deq.utah.gov/water-quality/quality-assurance-and-quality-control-program-monitoring-water-quality>. We expect to finish a first draft of SAPs and QAPP plans by August 8, 2019 to be shared with UDWQ and Science Panel members for their further comments. While preparing these documents, we will incorporate all the excellent comments provided by UDWQ and the Science Panel on the overall workplan and responses to our list of questions.

Final Deliverables of task 1: (I) Finalized milestones, (II) written QAPP and SOPs.

Task 2. Collect sediment cores from Utah Lake (Both labs)

Sub-task 2.1: Coordination with UDWQ and BYU for sediment core collection: This task will be jointly completed by Drs. Goel and Carling. Graduate students working directly on this project are also expected to help with sediment core collection. We will use a percussion corer to collect sediment cores from two sites specified in the project. We expect to collect our first set of cores on August 12th, 2019.

Sub-task 2.2: Collecting sediment cores: Sediment cores will be collected from one site in the middle of Provo Bay (DWQ monitoring site with UTM coordinates: 12T 440484 E 4448988 N) and one site in the open water of Utah Lake near the Utah Lake State Park water quality buoy. We will use the BYU pontoon boat to access sites. We will tow a smaller pontoon raft behind the boat that will be used as the drilling platform. The drilling platform will enable us to efficiently collect and extract cores, using a winch if necessary. We will use a percussion corer to collect sediment cores in plexiglass tubes that are 5 cm in diameter by 50 cm long. Each sediment core will be 10-20 cm long with at least 30 cm of overlying water. After collection, the cores will be placed upright in a cooler with ice. The cooler is designed with a rack to secure the cores. The samples will be kept cold and in the dark until returning to the lab. We will collect 12 cores per sampling day, with three sampling days to collect 36 cores at each site. The Co-PI Carling has successfully



collected dozens of similar cores with overlying water from multiple sites across Utah Lake using a percussion corer.

Figure 1: Sediment core with overlying lake water. Based on the given height and diameter of the core, the overlying water volume is calculated. With samples taken at 0, 12-, 24- and 72 hours, the total sampling volume is approximately 120 mL. The t=0 sample will be directly collected from separate container.

As suggested by the Science Panel members, we expect to collect approximately 10 cm (~4 inches) sediment core with 30 cm overlying lake water on the top thus enabling 1:3 sediment to water column ratio.

Table 1 provides details of cores and experiments. A total of 36 cores (39 if SOD conducted in the lab) will be collected per site. Our strategy is to sample the first site and finish all related experiments before sampling the second site. This strategy will allow us to avoid storing the sediment cores for an extended period of time. Nevertheless, we will make sure that both sites are sampled within a time span with no more than a $\pm 5^{\circ}\text{F}$ change in ambient water temperature difference over days of sampling. In the lab, the cores will be stored in the dark at 4°C walk-in refrigerator until further processing. If conducted ex-situ, sediment oxygen demand (SOD) experiments will be conducted immediately after returning to the lab.

Table 1: Details of cores that will be collected per site for two sites

Parameter/s and experiments	Rationale
Set 1: Sediment core P spiking in the water column under aerobic conditions, no spiking (control), 0.5, 2 and 4 times the ambient P concentration. (12 cores)	To determine the fate of dissolved P present in the overlying water column when the water column is in constant contact with sediments.

	Different concentration ranges reflect low, medium and high end of spiking.
Set 1 continuation: Sediment core P spiking in the water column under aerobic conditions, no spiking (control), 0.5, 2 and 4 times the ambient P concentration and then create anaerobic conditions after an equilibrium has been established under previous aerobic conditions. (Same 12 cores from ambient aerobic spiking experiments)	To determine the fate of dissolved P present in the overlying water column when the water column is in constant contact with sediments under oxygen free conditions. This experiment is a continuation from the previous set of experiments under aerobic conditions.
Set 2: Sediment core P spiking in the water column under aerobic conditions at a pH of 7.0, no spiking (control), 0.5, 2 and 4 times the ambient P concentration. (12 cores)	To determine the fate of dissolved P present in the overlying water column when the water column is in constant contact with sediments at neutral pH. Different concentration ranges reflect low, medium and high end of spiking.
Set 3: Sediment core P spiking in the water column under aerobic conditions at a pH of 9.5, no spiking (control), 0.5, 2 and 4 times the ambient P concentration. (12 cores)	To determine the fate of dissolved P present in the overlying water column when the water column is in constant contact with sediments at a slightly alkaline pH. Different concentration ranges reflect low, medium and high end of spiking.

The following table shows the sequences and potential dates for our sediment core collection. As recommended by some of the Science Panel members, this sampling strategy will allow us to quickly process the cores with limited storage time. Of course, this will require us to revisit the field sites multiple times but this will ensure maximum quality control.

Site 1: State Park site near DWQ buoy		
Date	# of cores	Experiment
August 12 th , 2019	12	Neutral pH
August 14 th , 2019	12	pH=9.5
August 16, 2019	12	Aerobic and anaerobic experiments
Site 2: Provo Bay		
Date	# of cores	Experiment
August 19 th , 2019	12	Neutral pH

August 21 st , 2019	12	pH=9.5
August 23 rd , 2019	12	Aerobic and anaerobic experiments

List of supplies for sub-task 2.2

1. Lake travel
 - a. BYU motor boat
 - b. Keys
 - c. Full tank of gas
 - d. Motor oil
 - e. Anchors
 - f. life jackets
2. Coring platform
 - a. Pontoon raft modified for coring; will be towed behind the motor boat
 - b. Pully mechanism and winch for extracting core from the lakebed (if necessary)
3. Sediment cores
 - a. Percussion corer
 - b. 4 extension poles
 - c. Handle
 - d. 40 plexiglass core sleeves
 - e. 40 core catchers
 - f. 80 caps
 - g. Tape measure for measuring core length and lake depth
 - h. Pole for measuring lake depth
 - i. Electrical tape
 - j. Aluminum foil
 - k. Cooler with ice, retrofitted to hold sediment cores upright
4. Water sampling
 - a. YSI Quattro multiparameter probe calibrated prior to each field day)
 - b. 16 wide mouth 1-gallon jugs (2 gallons of water per 12 cores)
 - c. Disposable gloves
 - d. Cooler with ice to hold water samples
 - e. Deionized water for rinsing
5. Miscellaneous
 - a. GPS
 - b. Field notebook with pencil
 - c. Sharpie
 - d. Lab tape
 - e. Paper towels
 - f. Wash cloths
6. Hand held camera to take field pictures
7. GPS device

Experimental steps for sub-task 2.2

1. Secure all equipment and sampling devices in the boat and drive to the sampling location. Anchor the motor boat and pontoon raft. Record GPS coordinates using a handheld GPS device.
2. Measure field parameters (temp, pH, conductivity, dissolved oxygen) at top and bottom of water column using YSI probe. Record measurements.
3. Collect 2 gallons of water (prior to sediment sampling, which would stir up the water column) and place in cooler.
4. Decontaminate the sampling apparatus and tools by rinsing with lake water. Perform decontamination process downstream of the boat.
5. Measure and record water depth to the nearest 10 cm with a pole and tape measure.
6. Assemble the core sampler and push it in the sediment to the depth required.
7. Pull out the corer out of the sediments. When the corer is relatively free from the surrounding sediment, pull the corer to the surface, detach the plexiglass tube containing the core, and cap the top and bottom of the core. Wrap electrical tape around the caps. Rinse the outside of the core with distilled water. Label core with a unique identifier using tape and Sharpie.
8. Wrap the core in aluminum foil and place it on the rack in a cooler.
9. Repeat steps 4 through 8 to collect more sediment cores, 12 cores per day.
10. Take photographs of water sampling and coring activities to document the field day.

Experimental quality control and assurance plan for core collection: The following quality controls will be exercised.

- (1) For each core collection exercise, a fresh set of plexiglass tubes will be used. Each tube will be thoroughly rinsed in autoclaved deionized water and air dried. A clean plastic core catcher and new lids will be used with each tube.
- (2) Upon collection, the sediment height is measured. Sediment height must be between 10-20 cm or the sediment is discarded. Further, if the core appears disturbed it is discarded.
- (3) Each core is given a unique identifier.
- (4) The core is immediately wrapped in aluminum foil, placed upright in a cooler, on ice and in the dark. The cooler contains a rack so the cores do not tip over during transport to the lab.

Deliverables of task 2: (1) A short report on field experiences for sediment core collection, (2) field pictures

Task 3. Perform sediment core experiments and laboratory analysis (All sub tasks under this task will be performed at the University of Utah).

Sub-task 3.1: Nutrient spike experiments under aerobic conditions: A set of 12 sediment cores will be used for this set of experiments. The cores with overlying Utah Lake water will be mounted on a PVC stand and wrapped in aluminum foil from the side. Two gallons of water is filtered using a vacuum filter and 0.45 μm filter paper, and filtered water is placed in separate 2 L bottles to adjust redox conditions and for phosphorus spiking. Ambient nutrient concentrations will be determined in the lake water samples. One strategy could be to use historical data collected by UDWQ for ambient nutrient concentrations and decide the spiking concentrations before the onset of sediment core collection. However, to ensure maximum accuracy, we would decide the spiking concentrations based on the measured ambient P concentration in lake water samples. Other water quality parameters such as temperature, pH, dissolved oxygen using a luminescent DO probe and turbidity will also be determined to ensure that they have not changed since the field measurements. After equilibrating at room temperature, the overlying water from nine out of twelve sediment cores will be taken out gently using a vacuum pump, leaving 1 cm of water above the sediment so it is not exposed directly to the atmosphere. Care will be taken as not to disturb sediments. Utah Lake water collected from the same site will be used to replace the overlying water after adjusting the total dissolved P (TDP) concentrations to 0.5X (by diluting with major ion water devoid of P), 2X and 4X the ambient P concentration using a 1000 mg-P/L KH_2PO_4 stock solution in three sets of sediment cores with each set consisted of triplicate cores. The unspiked set of sediment cores will serve as a control. The adjusted/spiked water is carefully added back to the sediment cores to limit disturbing the cores. To preserve water volume, time zero samples are collected from the 2 L bottles rather than from the cores. Immediately after adding water to sediment cores, a small aeration stone will be placed in each sediment core column at approximately 5-cm from the sediment-water interface. The aeration stones will be connected to an aquarium aeration pump which will be regulated by an electronic timer. The core columns are capped to prevent evaporation and contamination by lab dust; the air tubing will enter the column via a small hole in the cap.

Once spiked, all sediment columns will be kept un-agitated in the dark wrapped in aluminum foil. Additionally, to maintain mixed and aerobic conditions and to overcome diffusion limitations between sediment and the water column for nutrient fluxes, column water will be aerated every 2-h using the electronic timer. Care will be taken as not disturb the sediments during the aeration. Water samples for water quality analysis at 12-, 24-, and 72-h will be withdrawn from each column using a disposable 50-mL plastic pipette and, will be filtered (0.45 μm) and transferred to a 50-mL falcon tube for further analysis. Fluxes of phosphorus, ammonium, nitrite and nitrate will be calculated based on the concentrations measured and the internal cross-sectional area of each column. This sub-task will be performed at the University of Utah under the direction of Drs. Ramesh Goel and Greg Carling. Please note that the Dr. Carling's graduate student (Sheena Smithson) will also be helping with these experiments.

List of supply for sub-task 3.1

1. PVC racks to hold cores
2. Freshly collected Utah Lake water

- a. Vacuum filtration unit with pump
 - b. 0.45 μm filter paper (47 mm diameter)
 - c. 32 2-L bottles for transferring filtered water
3. Peristaltic pumps for removing overlying water from core columns
4. Chemicals for spiking/adjusting samples
 - a. Scientific grade KH_2PO_4 with 99.9. % purity
5. Tubing to carefully transfer filtered/spiked/adjusted water back into core columns
6. Major ion solution to match Utah Lake water for 0.5x P dilution
7. Core column measurements
 - a. Luminescent DO probe
 - b. Benchtop pH probe
 - c. Turbidity meter with cuvettes or turbidity probe
8. Core column aeration
 - a. Aeration stones (one stone per core; 72 total)
 - b. Aquarium pumps (one pump per two cores)
 - c. Tubing from pump to column (100 ft total)
9. Core column water samples
 - a. Syringes (1 per core)
 - b. Syringe filters (0.45 μm nylon)
 - c. 50 mL falcon tubes for sample collection
 - d. HNO_3 to acidify ICP-OES samples in separate vials from other non-acidified samples
10. Miscellaneous
 - a. Disposable gloves
 - b. Paper towels
 - c. Weighing balance
 - d. Tubes of different sizes
 - e. Disposable pipettes

- f. Analytical pipette and pipette tips of varying volumes.
- g. Milli Q grade water
- h. Electronic timers
- i. 1-L glass cylinders, Erlenmeyer flasks and volumetric flasks
- j. Extension cords

11. Lab analyses

- a. Ion chromatograph (IC) with auto sampler
 - i. IC tubes
 - ii. Eluents for IC
- b. ICP-OES with autosampler
 - i. ICP-OES tubes
- c. HACH spectrophotometer
 - i. Ammonium HACH kits
 - ii. Total dissolved N

Experimental steps for sub-task 3.1

1. Take out the sediment cores from cooler and let them equilibrate at room temperature for 30 minutes.
2. After 30 minutes, gently extract the overlying water using a peristaltic or vacuum pump without disturbing the underlying sediments from all 12 columns, leaving 1 cm of water so the sediment is not exposed to the air.
3. Suspend aeration stones approximately 5 cm from the interface of sediment and water column and connect them with aquarium pump which in turn will be connected with a timer. The timer to initiate aeration cycle at every 2-h. Do not start the aeration.
4. Filter 2 gallons of lake water that was collected separately at the time of sediment core collection using vacuum filter. Put filtered water into separate 2 L bottles. Measure the ambient nutrient concentrations in the filtered lake water.
5. Fill in the first set of three columns with Utah Lake to obtain 1:3 sediment to water ratio. This set will serve as a control. Start the aeration.
6. Take a known volume of Utah Lake water in a separate clean container and dilute it to 0.5 X times using major ion solution (devoid of P). Mix it well and take sample to measure different water quality parameters.

7. Add this diluted water to the next set of three columns to enable 1:3 sediment to water ratio. Start the aeration.
8. Likewise, take a known volume of filtered Lake water and spike with the stock solution of KH_2PO_4 to obtain 2X times the ambient P concentration. Add this P spiked Utah Lake water to the top of the next set of three columns to enable 2X times P concentration. Start the aeration.
9. Repeat step 9 with the only difference that the spiked concentration of KH_2PO_4 will be higher to obtain 4X times the ambient P concentration. Start the aeration.
10. Analyze water samples collected from step 6 through 10 at time zero and analyze for different water quality parameters.
11. Obtain water samples from a location at approximately 5 cm from the sediment water column interface in each column at 12-, 24-, and 72 hours. Analyze for different water quality parameters after filtering using syringe filter. Acidify sample for ICP-OES to 2% v/v HNO_3 .
12. Record all the data and lab observation in the lab book. Take pictures of set-ups.
13. Proceed to task 3.2 after 72 hours.

Experimental quality control and assurance plan for sub-task 3.1: The following quality controls will be exercised.

1. All aeration stones will be thoroughly washed in acid water to clean them. Aeration stones will be supplemented with 0.2 μm filter paper to avoid any aerosols entering the column.
2. All sediment columns will be covered with aluminum foil to avoid any light exposure of water column.
3. For each sampling period and for each column, separate and fresh disposable pipettes will be used and will be sacrificed after their usage.
4. Fresh autoclaved falcon tubes will be used for sample collection.
5. Personnel working on this task will be required to wear fresh gloves during the setting up of experiments and during each sampling event.
6. Samples needed to measure soluble constituents will be filtered immediately using a 0.45 μm nylon syringe filter.

Sub-task 3.2: Column experiments under anaerobic conditions: After the aerobic set of experiments have been completed, the sediment core columns used in aerobic experiments in sub-task 3.1 will be subjected to anaerobic conditions. The overlying water from the previous aerobic experiments will be replaced with fresh Utah Lake water. The aeration stones will be kept inside each column and will be connected with nitrogen cylinder. To create initial anaerobic

conditions, a predetermined volume of a stock solution of sodium sulfide containing trace amount of cobalt chloride will be added to each column and nitrogen gas will be purged to mix the added sodium sulfite solution. Thereafter, the nitrogen purging trend will follow the similar trend which was maintained for aeration in sub-task 3.1, e.,g nitrogen purging at every two hours to mix the water column and overcome the diffusional limitations. All columns will be covered air tight with a stopper as not allow the atmospheric oxygen to diffuse in the water column. A vent will be kept in the stopper to release nitrogen pressure during nitrogen purging. Care will be taken as not disturb sediments during nitrogen purging. Water samples for water quality analysis at 12-, 24-, and 72-h will be withdrawn from each column using a disposable 50-mL plastic pipette, filtered with a syringe filter, and transferred to a 50-mL falcon tube for further analysis. Dissolved oxygen will be routinely measured using a luminescent DO probe routinely and, especially during sampling times to ensure strict oxygen free conditions. Fluxes of phosphorus, ammonium, nitrite and nitrate will be calculated based on the concentrations measured and the internal cross sectional area of each column. This sub-task will be performed at the University of Utah under the direction of Drs. Ramesh Goel and Greg Carling. Please note that the Dr. Carling's graduate student (Sheena Smithson) will also be helping with these experiments.

List of supply for sub-task 3.2

1. PVC racks to hold cores
2. Freshly collected Utah Lake water
 - a. Vacuum filtration unit with pump
 - b. 0.45 μm filter paper (47 mm diameter)
 - c. 32 2-L bottles for transferring filtered water
3. Peristaltic pumps for removing overlying water from core columns
4. Chemicals for spiking/adjusting samples
 - a. Scientific grade KH_2PO_4 with 99.9. % purity
 - b. Scientific grade sodium sulfite with 99.9 % purity
 - c. Cobalt chloride with 99.9 % purity
5. Tubing to carefully transfer filtered/spiked/adjusted water back into core columns
6. Major ion solution to match Utah Lake water for 0.5x P dilution
7. Core column measurements
 - a. Luminescent DO probe
 - b. Benchtop pH probe

- c. Turbidity meter with cuvettes or turbidity probe
- 8. Core column aeration
 - a. Nitrogen cylinder fitted with regulator
 - b. Four way channel to distribute nitrogen gas.
 - c. Tubing from regulator to column
- 9. Core column water samples
 - a. Syringes (1 per core)
 - b. Syringe filters (0.45 μm nylon)
 - c. 50 mL falcon tubes for sample collection
 - d. HNO_3 to acidify ICP-OES samples in separate vials from other non-acidified samples
- 10. Miscellaneous
 - a. Disposable gloves
 - b. Paper towels
 - c. Weighing balance
 - d. Tubes of different sizes
 - e. Disposable pipettes
 - f. Analytical pipette and pipette tips of varying volumes.
 - g. Milli Q grade water
 - h. Electronic timers
 - i. 1-L glass cylinders, Erlenmeyer flasks and volumetric flasks
 - j. Extension cords
- 11. Lab analyses
 - a. Ion chromatograph (IC) with auto sampler
 - i. IC tubes
 - ii. Eluents for IC
 - b. ICP-OES with autosampler
 - i. ICP-OES tubes

- c. HACH spectrophotometer
 - i. Ammonium HACH kits
 - ii. Total dissolved N

Experimental steps for sub-task 3.2

1. Continuing from task 3.1, stop aeration and take out the overlying water using peristaltic or vacuum pump.
2. Disconnect aeration stone from aquarium pump and connect with Nitrogen cylinder.
3. In a separate container, add a predetermined volume of a stock solution of sodium sulfite supplemented with trace amount of cobalt chloride (catalyst).
4. Mix the water containing sodium sulfite and monitor drop in dissolved oxygen.
5. Spike water to 2x and 4x ambient phosphorus concentrations. Add synthetic lake water to make a 0.5x dilution.
6. Once the DO drops below instrument detection limit, obtain a homogenized water sample and analyze for proposed water quality parameters. This will constitute zero time sample.
7. Once the DO concentration falls below detection limit, fill in the sediment core columns with this oxygen free/spiked water simultaneously to the same height in sub-task 3.1.
8. Start nitrogen purging and close the top of each sediment core with an air tight stopper (having a small hole to release nitrogen pressure) to minimize air transfer from the atmosphere.
9. Monitor DO and pH periodically by opening the top stopper.
10. Collect water samples from a location at 5-cm from the bottom of the sediment in each column at 12-, 24-, and 72 hours. Acidify ICP-OES sample to 2% v/v HNO₃.
11. Analyze water samples for proposed water quality parameters.

Experimental quality control and assurance plan for sub-task 3.2: The following quality controls will be exercised.

1. All aeration stones will be thoroughly washed in acid water to clean them before using them again.
2. All sediment columns will be covered with aluminum foil to avoid any light exposure of water column.
3. For each sampling and for each column, separate and fresh disposable pipettes will be used and will be sacrificed after their usage.
4. Fresh autoclaved falcon tubes will be used for sample collection.

5. Personnel working on this task will be required to wear fresh gloves during the setting up of experiments and during each sampling event.
6. Scientific grade nitrogen will be used during experiments.
7. Samples needed to measure soluble constituents will be filtered immediately using a 0.45 μm nylon syringe filter.
8. All chemical used will be have more than 99 % purity.

Sub-task 3.3: P spiking column experiments under ambient conditions (neutral pH): These experiments will follow a similar strategy detailed in sub-task 3.1 under aerobic conditions except that the pH of the Utah Lake water will be gently adjusted to 7 by adding 0.5 N H_2SO_4 before spiking with P stock solution. All other experimental conditions and sampling strategy will be similar to aerobic experiments detailed in sub-task 3.1. Twelve cores will be used for this set of experiments with triplicate measurements under ambient, 0.5x, 2x, and 4x lake water P concentrations. This sub-task will also be performed at U of Utah under the direction of Drs. Greg Carling and Goel. All graduate students working on this project will participate in this experiment.

List of supply for sub-task 3.3

1. PVC racks to hold cores
2. Freshly collected Utah Lake water
 - a. Vacuum filtration unit with pump
 - b. 0.45 μm filter paper (47 mm diameter)
 - c. 32 2-L bottles for transferring filtered water
3. Peristaltic pumps for removing overlying water from core columns
4. Chemicals for spiking/adjusting samples
 - a. Scientific grade KH_2PO_4 with 99.9. % purity
 - b. 0.5 N H_2SO_4 for adjusting pH
5. Tubing to carefully transfer filtered/spiked/adjusted water back into core columns
6. Major ion solution to match Utah Lake water for 0.5x P dilution
7. Core column measurements
 - a. Luminescent DO probe
 - b. Benchtop pH probe
 - c. Turbidity meter with cuvettes or turbidity probe

8. Core column aeration
 - a. Aeration stones (one stone per core; 72 total)
 - b. Aquarium pumps (one pump per two cores)
 - c. Tubing from pump to column (100 ft total)
9. Core column water samples
 - a. Syringes (1 per core)
 - b. Syringe filters (0.45 μm nylon)
 - c. 50 mL falcon tubes for sample collection
 - d. HNO_3 to acidify ICP-OES samples in separate vials from other non-acidified samples
10. Miscellaneous
 - a. Disposable gloves
 - b. Paper towels
 - c. Weighing balance
 - d. Tubes of different sizes
 - e. Disposable pipettes
 - f. Analytical pipette and pipette tips of varying volumes.
 - g. Milli Q grade water
 - h. Electronic timers
 - i. 1-L glass cylinders, Erlenmeyer flasks and volumetric flasks
 - j. Extension cords
11. Lab analyses
 - a. Ion chromatograph (IC) with auto sampler
 - i. IC tubes
 - ii. Eluents for IC
 - b. ICP-OES with autosampler
 - i. ICP-OES tubes
 - c. HACH spectrophotometer

- i. Ammonium HACH kits
- ii. Total dissolved N

Experimental steps for sub-task 3.3

1. Take out the sediment cores from cooler and let them equilibrate at room temperature for 30 minutes.
2. After 30 minutes, gently extract the overlying water using a peristaltic or vacuum pump without disturbing the underlying sediments from all 12 columns, leaving 1 cm of water so the sediment is not exposed to the air.
3. Suspend aeration stones approximately 5 cm from the interface of sediment and water column and connect them with aquarium pump. Do not start the aeration.
4. Filter 2 gallons of lake water that was collected separately at the time of sediment core collection using vacuum filter. Put filtered water into separate 2 L bottles. Measure the ambient nutrient concentrations in the filtered lake water. Adjust all water to pH =7 with 0.5 N H₂SO₄.
5. Fill in the first set of three columns with Utah Lake to obtain 1:3 sediment to water ratio. This set will serve as a control. Start the aeration.
6. Take a known volume of Utah Lake water in a separate clean container and dilute it to 0.5 X times using major ion solution (devoid of P). Adjust solution to pH=7 if needed. Mix it well and take sample to measure different water quality parameters.
7. Add this diluted and pH-adjusted water to the next set of three columns to enable 1:3 sediment to water ratio. Start the aeration.
8. Likewise, take a known volume of filtered Lake water and spike with the stock solution of KH₂PO₄ to obtain 2X times the ambient P concentration. Add this P spiked Utah Lake water to the top of the next set of three columns to enable 2X times P concentration. Start the aeration.
9. Repeat step 9 with the only difference that the spiked concentration of KH₂PO₄ will be higher to obtain 4X times the ambient P concentration. Start the aeration.
10. Analyze water samples collected from step 5 through 9 at time zero and analyze for different water quality parameters.
11. Obtain water samples from a location at approximately 5 cm from the sediment water column interface in each column at 12-, 24-, and 72 hours. Analyze for different water quality parameters after filtering using syringe filter. Acidify sample for ICP-OES to 2% v/v HNO₃.
12. Record all the data and lab observation in the lab book. Take pictures of set-ups.

Experimental quality control and assurance plan for sub-task 3.3: The following quality controls will be exercised.

1. All aeration stones will be thoroughly washed in acid water to clean them before using them again.
2. All sediment columns will be covered with aluminum foil to avoid any light exposure of water column.
3. For each sampling and for each column, separate and fresh disposable pipettes will be used and will be sacrificed after their usage.
4. Fresh autoclaved falcon tubes will be used for sample collection.
5. Personnel working on this task will be required to wear fresh gloves during the setting up of experiments and during each sampling event.
6. Aeration stones will be supplemented with 0.2 μm filter paper to avoid any aerosols entering the column.
7. Samples needed to measure soluble constituents will be filtered immediately using a 0.45 μm nylon syringe filter.
8. Scientific grade nitrogen gas will be used.
9. All chemical used will be have more than 99 % purity.

Sub-task 3.4: P spiking column experiments under elevated pH condition (pH=9.5) (BYU): These experiments will follow a similar strategy and similar quality controls detailed in sub-task 3.3 under neutral pH conditions except that the pH of the overlying water column will be gently adjusted to 9.5 by adding 0.5 N NaOH. A small change will be employed in this set of experiments. Instead of adding the KH_2PO_4 stock solution into the Utah Lake water separately in a container, a predetermined volume (based on column overlying water volume) KH_2PO_4 will be added directly to the water column to accomplish 2X and 4X times the ambient P concentrations. All other experimental conditions and sampling strategy will be similar to neutral pH experiments detailed in sub-task 3.3. Twelve cores will be used for this set of experiments with triplicate measurements under ambient, 0.5x, 2x, and 4x lake water P concentrations.

Sub-task 3.5: Sediment oxygen demand determination (University of Utah): For shallow site with accessibility (for example Provo Bay), we will install SOD chamber in-situ using the methodology demonstrated by us in the past for the Utah Lake (Hogsett et al., 2019). For open water site, we will first try to go in the route of installing in-situ SOD chamber using a SCUBA diver. In case this does not work out, we will collect sediment cores in triplicate and determine SOD under laboratory scale controlled conditions. If conducted in the lab, care will be taken to inhibit any primary production by covering the sediment cores with dark cloth or aluminum foil.

For in-situ determination, automated data Sonde borrowed from UDWQ will be installed for continuous monitoring of DO. For lab scale SOD measurements, digital luminescent DO probe will be used in the sediment column. The sediment column during SOD determination in the lab will be gently agitated to enhance DO mass transfer but not to the extent to disturb sediments. The duration of experiments will be 180 minutes as opposed to 90 minutes. Please refer to our previous publication (Hogsett et al., 2019) for details. For in-situ SOD measurements, three SOD chambers will be installed as detailed in Hogsett and Goel, 2016. Two chambers will be open at the bottom (testing chambers) and will measure oxygen consumption in sediments and the overlying water column due to various activities. The third chamber (control chamber) will be closed at the bottom to measure oxygen consumption in the water column only. The duration of installation will be 3 hours from mid-morning to early afternoon.

The top section of each SOD chamber will consist of a lid that contains the pump, plumbing, water sampling tube, water quality probe connection, and attachments for ropes used to lift the SOD chamber out of the sediments and water. A submersible pump will be mounted on each chamber to internally circulate (if needed) the water inside the SOD chamber at a predetermined flow rate of 11 L/min. The Control SOD chamber will have a working volume of 44 liters and the Testing SOD chambers a working volume of 38 liters. This discrepancy in volumes is a result of the additional space provided in the Control chamber due to closed bottom which prohibits this control chamber to lose almost 1½" of vertical length into the sediments. The construction and design of these chambers is based on SOD chambers used by Georgia EPA.

In case we cannot deploy in-situ chambers for deep site, similar experiments will be conducted using sediment cores. In this case, oxygen consumption in the overlying water column due to activities in the sediments and water column will be measured directly in cores in triplicate after a specified period of time (e.g 180 minutes). A second set of triplicate PVC tubes containing Utah Lake water to the same water depth as in the sediment cores will measure oxygen consumption in the water column. However, in this document, we are including SAP for SOD assuming that we will be able to conduct SOD in-situ. In case this does not happen, we will submit a revised SAP for lab scale SOD protocol.

List of supply for sub-task 3.5

1. 2 SOD chambers with open bottom and one control chamber with closed bottom
2. Three data SONDES borrowed from the UDWQ
3. Submersible pumps
4. Portable small battery
5. One big battery to charge small batteries.

6. Electric cables
7. A laptop with SONDE software installed.
8. Disposable gloves
9. Paper towel
10. Scuba diving gear
11. Scuba diver
12. Motor boat (UDWQ)
13. DI water to rinse probe
14. Aeration stones to calibrate probes
15. A desktop computer to download data.

Experimental steps for sub-task 3.5

1. Calibrate data SONDEs in the lab by merging them in oxygen saturated water.
2. Check the air tightness of each SOD chamber in the lab.
3. Rinse all three SOD chambers thoroughly with DI water.
4. Load all equipment into the boat and drive to the site.
5. Locate approximate the same locations used in sub-tasks 2.2 to collect sediment cores using GPS device.
6. Scuba diver gets into water and examine locates relatively flat surface of sediments at the site to install chambers.
7. The control chamber will be first placed in the upstream of the boat approximately 10 meters from the boat by gently lowering it toe sediments and filling it with lake water slowly while lowering it.
8. The control chamber with closed bottom will be allowed to sit on the bottom and the data SONDE will be inserted into the SONDE holder mounted at the top of the chamber.
9. Likewise the two testing chambers will also be placed on the sediments in the similar fashion.
10. After placing the testing chamber, the chamber lid will be manually pressed to ensure water tightness and to avoid any hydraulic connection between the water inside and the chamber and the lake water.

11. Start internal submersible pumps mounted on each chamber to internally circulate water inside each chamber.
12. Activated data SONDE.
13. Monitor the submersible pumps in between for their operation.
14. Continue this experiments for 180 minutes.
15. Stope the submersible pumps after 3 hours and remove the data SONDES.
16. Download the data from each SONDE and check the accuracy of the data.
17. Gently take out the SOD chambers one by one from the water and place them on the boat.
18. Drive back to the shore.

Experimental quality control and assurance plan for sub-tasks 3.5: The following quality controls will be exercised.

1. Care will be taken as not to allow any air bubble either during in-situ chamber installation or during lab scale column experiments.
2. Data SONDE/ DO probes will be fully calibrated prior to their use.
3. The bottom rim of each chamber will be fully pushed into sediments for the sediment chambers to ensure no exchange of water between the chamber and outside water column.

Deliverables of task 3: (I) Raw data arranged electronically from all sets of experiments, (II) report on challenges and learning experience.

Sub-task 3.6: Statistical analysis: We will use the R package to conduct all the statistical analysis. We will use t-tests for more direct tests and comparison between data sets. Significance levels (p values) will be reported to levels of 0.05, and 0.01. For small sample sizes, we will also report p values between 0.05 and 0.10. Two-tailed Pearson correlation analysis will be used to determine the correlations between different parameters between different treatments. Principal component analysis will be used to evaluate interdependency of different parameters.

Task 4: Prepare technical report: We will use a three tier reporting strategy. First, we will present results at in-person meetings with UDWQ personnel and the Science Panel to inform about project progress and to seek input on future research direction. Secondly, we will submit a synopsis of preliminary analysis within two weeks from the date of experiments in the form of interim reports. Lastly, we will submit draft and final project reports containing all analyzed data, project rationale, future recommendations. The final project report will also contain raw data in the appendix.

Data analysis will focus on the following questions; **(1)** What is the equilibrium total dissolved phosphate concentration in the water column under all scenarios tested, **(2)** what is the internal P recycling from sediments to the water column based on P released from sediments expressed as flux (mg P/m²/hour) and loading (e.g., kg/day) and, **(3)** is there any anaerobic release and if yes, is it purely related to redox chemistry, primarily iron reduction or bacteria mediated or both. A detailed statistical analysis will be conducted (**see sub-task 3.6**) on different data sets to established correlations and interdependency. We will follow standard format for report preparation which we have been following for our EPA and UDWQ funded research projects.

[Deliverables of task 4: \(I\) Final report with all results analyzed and future recommendations.](#)

4.0 Approach for Science Panel Collaboration and Data Sharing

Our goal is to closely work with the Utah Lake Science Panel during the project period. We will accomplish this goal right from the beginning of the project. SAP and QAPP documents will be prepared in collaboration with the Science Panel by sharing the documents in the ULWQS Dropbox folder for their inputs and comments. Additionally, we will also attend Science Panel meetings as needed during the course of this project. Towards the middle of the project when we have finished field sediment core collection, we will request an Adobe Connect meeting with all Science Panel members to update them about the progress of the project and seek their inputs on pending lab work. **Please refer to each task for deliverables.**

The data management and data sharing are an integral part of this project and, the success of the scientific and engineering outcomes will depend upon a robust data sharing and data management plan. The new data generated by the project includes raw metadata from lab and literature review. The quality control and quality assurance plan for all the acquired data will be implemented according to US EPA established rules. Management of data will be accomplished on daily basis by maintaining proper lab notebooks and then managing the data electronically. Data will be made accessible to the Science Panel, UDWQ, other interested people, and the environmental community through presentations, interim reports, and peer reviewed publications. All the data including raw lab results, QA/QC results, final lab results, interpreted results, and any other associated data product will be shared with the Science Panel at the frequency stated in the RFP. We will also create a password protected online data repository to be shared with the Science Panel. All the collected data will be stored electronically with a weekly backup on an external hard drive. Proper statistical analyses will be conducted. Statistical analysis incorporating ANOVA and t-tests will be conducted to compare performance data between different experiments. The quality of sample measurements will be maintained by the daily use of standards and periodic analysis of blind standards. Our data dissemination plan will include presentations to local and national conferences, publishing in peer reviewed journals of international repute. No intellectual property is expected from this research.

5.0 SOPs and QAPP for water quality parameters

A. PROJECT/TASK ORGANIZATION

(a) Project team and responsibilities

Table 1 lists all personnel involved in the project.

Title	Name	Affiliation	Responsibilities	Contact
Project Manager	Dr. Ramesh Goel	University of Utah	Oversee and manage the whole project. He will also be responsible for project's QC plan	801-581-6110 (ram.goel@utah.edu)
Co-Project Manager	Dr. Greg Carling	BYU	Help with sediment core collection, analytical parameter quality controls and data analysis	greg.carling@byu.edu
Graduate student	Hanyan Li	University of Utah	Help with field and lab activities & data analysis	lihanyan7@gmail.com
Graduate student	TBD	University of Utah	Help with field and lab activities & data analysis	TBD
Graduate student	Sheena Smithson	BYU	Help with field and lab activities & data analysis	sheenamsmithson@gmail.com

(b) Quality assurance manager

The point of contact (Dr. Ramesh Goel) will be responsible for all quality control measures associated with the project activities, particularly with field and laboratory scale experiments and analytical measurements.

(c) Individual responsible for maintaining QA project plan

Dr. Ramesh Goel, project manager, and Dr. Greg Carling, CO-PI, will be responsible for maintaining the QA project plan. They will make sure that all project related activities are completed with milestones met and project reports are submitted as proposed.

(d) Parameters to be measured

The parameters include water quality and molecular microbiology. Table 3 lists these parameters and will be measured at all sites in impounded wetlands.

Table 3 lists different parameters which will be measured in different tasks.

Parameters-Tasks	Methodology	Parameters-Task	Methodology
3.1 -3.4- P spiking experiments		3.5- SOD measurement	

pH	pH probe	pH	Data Sonde*
Dissolved oxygen	Luminescent DO probe	Dissolved oxygen	Data Sonde*
Dissolved Orthophosphate	Ion chromatography	SOD	SOD chamber detailed earlier
Soluble reactive P only if ortho P is below detection limits	Molybdenum blue method These samples are analyzed in Dr. Aaunderud's lab at BYU		
Nitrate	Ion chromatography		
Nitrite	Ion chromatography		
Ammonium	Low range HACH Kit		
Turbidity	Turbidity probe or meter		
Alkalinity**	Titration		
Total dissolved P, major cations, and metals	ICP-OES		

*Will be borrowed from DWQ and will be conducted with DWQ staff.

**Alkalinity will only be measured at 0 and 72 hours.

(e) Standard operating procedures

For Dissolved NH₃-N, NO₃-N, NO₂-N, PO₄-P sample collection and analysis and, sediment sample collection, we will employ protocols provided at UDWQ's water quality website.

(f) Instrument detection limits

Table 4 shows IC detection limits and precision, accuracy and recovery.

Table 4: Analytical QC limits and reporting ranges

Parameter	Method	MRL* (mg/L)	Calibration range (mg/L)	Precision (%)	Accuracy (%)	Recovery (%)
NH ₃ -N	TNTplus 830, Method 10205 (HACH)	0.05	0.05-10	±10	±10	±10
NO ₃ -N	Ion Chromatograph	0.05	0.05-10	±10	±10	±10

NO ₂ -N	Ion Chromatograph	0.05	0.05-10	±10	±10	±10
PO ₄ -P	Ion Chromatograph	0.02	0.02-5	±10	±10	±10
Total dissolved P and trace metals	ICP-OES	0.005	.001-1	±10	±10	±10

(g) Resource and time constraints

The data produced from this project will be disseminated through peer reviewed conferences, peer reviewed publications and most importantly through status and final reports to UDWQ. The uncertainty associated with sample collection could be the significant source of errors. This uncertainty is mostly associated with spatial and temporal variations in constituent concentrations. The only way to minimize such variability is to sample frequently and at more locations. However, sometime this cannot be possible due to time and budgetary constraints. Uncertainty can also be introduced through sample handling, storage and laboratory analysis. In this project, we have designed a very practical and robust experimental plan with a solid quality assurance project plan to minimize the uncertainty associated with these sampling, handling and analysis for example. To ensure highest data accuracy, only assigned students will be doing field sampling and analysis and, everything will be recorded in the lab notebooks. This will eliminate data uncertainty that may come if sampling and analysis are done by different personnel at each sampling time. The project will sample 2-sites in Utah Lake. Hence, we expect the data generated to be very site specific. However, we also expect to generate a trend based on the produced data. Furthermore, even if the data generated will be site specific, conclusions drawn will lead us to apply some observations for other sites. These limitations will be reported in reports to UDWQ. The report will include future recommendations about how the uncertainties (if any) observed be minimized or overcomes in future.

(h) The responsibility of the project QA officer from QA in charge, training and method of training

The personnel working on this project will involve graduate students under the direct supervision of the project directors Drs. Ramesh Goel and Greg Carling. All personnel working on this project will receive prior training, both on laboratory as well as on field protocols such that the students working on the project can implement lab and field activities independent of the project Director. The training will include laboratory scale as well as field scale components. In the lab, students working on this project will be guided PI and the Co-PI during protocol development and testing. Personnel performing water sampling must be familiar with sampling techniques, safety procedures, proper handling, and record keeping. Samplers are responsible for attending refresher meetings held before the onset of each experiment to review procedures and techniques. Students will be trained well before the beginning of the sampling. For example, Ms. Hanyan Li is a senior PhD student and has been working on the Utal Lake water quality research

for the past 3 years. She is well trained in field sampling, collection of sediment and water samples. Students will be required to document everything related to the project in their laboratory/field notebook. For laboratory related analysis work, students will be trained to run the required analytical machines (such as IC machine) independently with known standards prepared in the lab.

Appendix B- Raw Data- This will be uploaded in Ubox – an online repository.

Appendix C: Field Pictures: These were provided to the UDWQ. However, these will be uploaded in Ubox – an online repository.