Determination of Nutrient Fluxes and sediment oxygen demand at selected locations in Utah Lake

Prepared by

Mitch Hogsett & Ramesh Goel
Civil & Environmental Engineering
University of Utah

Table of Contents

Executive Summary

Sediments play an important role in controlling nutrient and dissolved oxygen dynamics in surface waters including lakes. Utah Lake is not an exception and has been designated to have excess phosphorus and total dissolved solids. Phosphorus is of particular concern because unlike nitrogen, most of the phosphorus entering a lake system remains there without making its way out through aerial pathways. Majority of the phosphorus staying in the lake system ends up in sediments in various forms depending upon sediment mineralogy. Various physical (i.e sediment disturbance), biological (bacteria mediated release) and chemical (i.e pH changes) can cause phosphorus in sediments to get into the overlying water column. This study was initiated to evaluate nitrogen and phosphorus fluxes with a particular emphasis on phosphorus, at 8 locations in Utah Lake. The study also included evaluating sediment mineralogy using X-ray diffraction technique. Sediment oxygen demand (SOD) was also determined simultaneously to evaluate dissolved oxygen sink in sediments. Furthermore, a detailed phosphorus fraction/speciation was also conducted in the top 1-2 cm sediments samples collected from the sampled locations. The effect of pH and DO changes on nutrient fluxes was investigated by changing these parameters in-situ.

Sediment phosphorus was primarily found bound to calcium and the Utah Lake mean sediment content was 0.09% or 900 mg P/kg dry sediment. XRD analysis showed that the majority of the dry sediment mass consisted of carbonate minerals. The surface sediments in Utah Lake proper consist of 70% water and are easily resuspended. 37% of the sediment %VS were associated with organic carbon compared to the general assumption of 50%. This was a result of the high carbonate and clay content in Utah Lake sediments. SOD was consistently -1 g DO/m²/d midlake, -1.5 g DO/m²/d near the shores, and -4.6 g DO/m²/d in the highly productive isolated Provo Bay. The water column consumed -1.1 to -6.7 g DO/m³/d and was the dominant contributor, not the sediments, to ambient DO dynamics in Utah Lake. Ammonia was released from the sediments at a fluxes ranging from

3

0.03-0.14 g/m^2/d in the lake proper with a much higher flux of 1.4 g/m^2/d in Provo Bay. Phosphorus was released from the sediments at four sites, but not at high enough fluxes to support ambient dissolved P concentrations, suggesting phosphorus loads from external sources such as WWTP discharges. The water column removed nutrients implying an active phytoplankton/heterotrophic community. This observation is also supported by the high WC oxygen demands. Lowering pH by roughly 1.5 units resulted in small releases of sediment P and this natural release would occur during winter conditions. Anoxic conditions resulted in additional ammonia fluxes at four of the sites while denitrification was not observed. In summary, this investigation suggests that Utah Lake sediments have sufficient sediment P but most of this is calcium bound. Sediments offer oxygen demand indicating that the sediments are active in terms of respiration and other biogeochemical activities.

Determination of Nutrient Fluxes and sediment oxygen demand at selected locations in Utah Lake

1.0 Introduction

Utah Lake, the largest freshwater lake in the State of Utah, is located in north-central Utah near the cities of Orem and Provo. Utah Lake has a surface area of roughly 380 km^2 (145 sq mile) and a storage capacity just shy of a million acre-feet (902,400 ac-ft). It is a shallow lake with an average depth of approximately 9-10 feet during normal reservoir operating conditions (Psomas, 2007). Utah Lake is the largest natural freshwater lake in the western United States in terms of surface area and has a maximum length and width of 24 and 13 miles, respectively.

A recently finished TMDL document for Utah Lake identified the amount of pollutants that the lake can handle from different sources without adversely affecting lake's water quality. More specifically, the lake was designated to have excess total phosphorus (TP) and total dissolved solids (TDS) on Utah's 2004 §303(d) list for exceedances of state criteria. Phosphorus is a key nutrient, especially in oligotrophic lakes (Ahlgren et al., 2006). Primary productivity depends upon P availability from various sources including those from release of P from particulate P, tributaries and P from surface sediments. Unlike nitrogen, phosphorus chemistry is complex. Phosphorus generally stays in the system except in cases where it flows out of the system with outflows (such as rivers and streams).

Internal loading is the mechanism by which sediment bound phosphorus is released into the water column through biogeochemical processes. Although still a subject of debate, a number of studies in the past have claimed P to be the limiting nutrient through laboratory controlled experiments (Bailey-Watts, 1978; and Bailey-Watts and Kirika,1993). Sediment bound P can have severe after effects when lake restoration efforts have been completed and external P loading has been reduced based on TMDL studies. P release can occur through pH driven sediment chemistry

changes and oxygen mediated bacterial P release. Furthermore, the knowledge of total phosphorus is not always sufficient to make management decision because, although bioavailable P is in the dissolved form, it only occupies a small fraction of TP in most of the cases. Also, depending upon sediment mineralogy and chemistry, P can exist in several other different forms, the fate of which depends upon in-situ pH values. Hence, apart from evaluating the release potential of P from sediments, special emphasis should be given to different chemical forms of P.

The first part of the study was designed to; (1) quantify phosphorus speciation/fractionation in sediments from selected locations, (2) evaluate the mineralogy of sediments using X-ray diffraction at selected locations and, (3) evaluate sediment and water column oxygen demand (SOD and WC) and nutrient dynamics associated with the sediments and water column at 3-locations in Utah Lake. In the second part of this study under an amendment, the scope was extended to; (4) evaluate sediment nutrient fluxes at five additional locations under varying pH and DO. The locations are provided in table 1 below.

Table 1: Utah Lake sediment sample information

Sample #	Location	Easting	Northing	Storet #
1	Provo Bay	441119.4	4449033.8	
2	Entrance to Provo Bay			4917770
3	1.3 miles W of Provo river outlet	435143.1	4454575	
4	SW Goshen Bay			4917600
5	Goshen Bay	425157.3	4437673.6	
6	0.5 miles W of Geneva Steel			4917320
7	0.5 miles W of Geneva Steel			4917310
8	Dry Creek, outlet of Utah Lake			
9	2 miles E of Saratoga Springs			4917520
10	1 mile E of Pelican Point			4917370
11	Site #3	425887.4	4447053.1	
12	Mid-lake, deep site			

Figure 1 provide a general overview of Utah Lake, the surrounding topography, municipalities, and sampling locations.

6
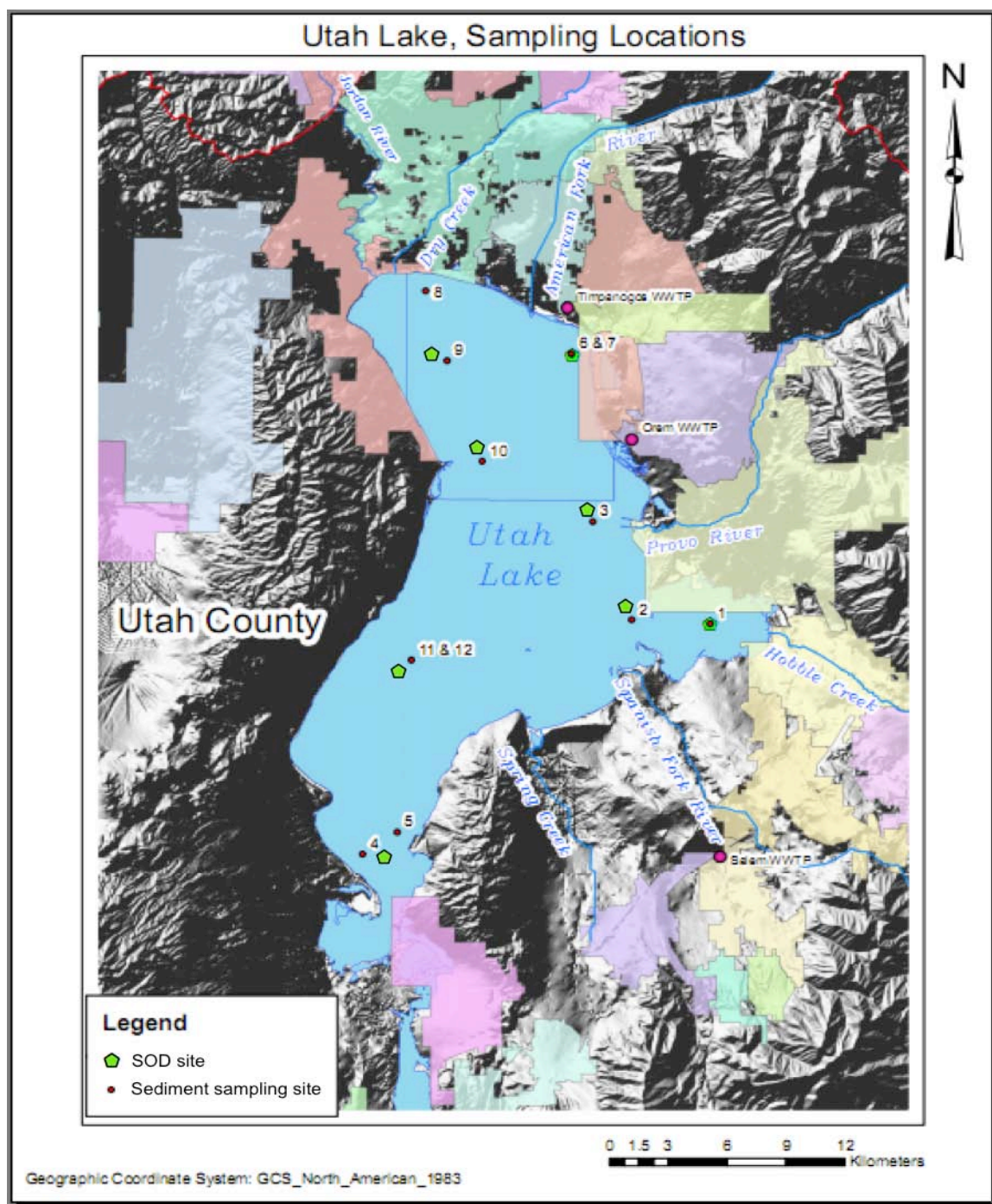
Figure 1: Utah Lake sampling locations

2.0 Methodology

2.1 Sediment Phosphorus-Speciation

Sediment core samples were collected using a gravity core by the Utah Division of Water Quality (DWQ) from 12 locations in Utah Lake. Table 2 shows details of sites and sampling days. The top 1-2 centimeters of sediment core samples were retained in a glass jar and stored on ice before returning to the lab and were stored at -4°C until further analysis.

Table 2: Utah Lake sediment sample information

Sample #	Location	Date	depth (cm)
1	Provo Bay	9/2/09	0-2
2	Entrance to Provo Bay	10/7/09	0-2
3	1.3 miles W of Provo river outlet	9/2/09	0-2
4	SW Goshen Bay	10/7/09	0-2
5	Goshen Bay	9/2/09	0-2
6	0.5 miles W of Geneva Steel	10/7/09	0-2
7	0.5 miles W of Geneva Steel	7/6/09	0-2
8	Dry Creek	6/12/08	3-6
9	2 miles E of Saratoga Springs	10/7/09	0-2
10	1 mile E of Pelican Point	10/7/09	0-2
11	Site #3	9/2/09	0-2
12	Mid-lake, deep site		2-4

The following sequential 5 steps of extraction were used to extract different forms of P from the lake sediments (Jensen and Thamdrup, 1993).

2.11. Extraction of loosely sorbed P: 1-g wet sediment was taken in a 50-mL polyethylene tube under oxygen free conditions. To this, 25-ml of 0.46 M Nitrogen purged NaCl solution was added under nitrogen atmosphere and the tube was closed by an air-tight screw cap. The centrifuge tube was shaken for 1 hour and centrifuged for 10 min at 3000 RPM. The supernatant was collected and another 25-ml aliquot of NaCl solution was added to wash the sample and the centrifugation

step was repeated. The supernatant was added to the previously collected supernatant and 1 ml 1 (M) H2SO4 was added to this supernatant in order to prevent co-precipitation of phosphate with Fe and Mn.

2.1.2. ***Extraction of Fe and Mn bound P***: To the sediment sample from the previous step, 25 ml BD-reagent (consisting of a pH 7.0 buffered solution of 0.11 M $Na_2S_2O_4$, 0.11 M $NaHCO_3$) was added under oxygen free environment to extract Fe and Mn bound P. After 1 hour of shaking at the room temperature, two BD washes and one 0.46 (M) NaCl wash were applied. To the recovered 100 mL supernatant, 8 ml of 1 (M) H2SO4 was added to prevent precipitation of Fe and Mn during the 1 hour aeration. The supernatant was stored until further analyzed.

2.1.3. Extraction of polyphosphates from clay minerals and aluminum oxides: This extraction was performed under aerobic conditions. To the sediment sample remaining after Fe bound P extraction, 0.1 M NaOH was added and placed on shaker for 18 hours. The sample was centrifuged and the supernatant was recovered in a fresh tube. Thereafter, one NaOH wash and one NaCl wash were applied and supernatants were recovered. The pH of the recovered supernatant was adjusted to 7 by adding 3 mL of 1 M H2SO4.

2.1.4. Extraction of Ca-bound P: To the sediments from the previous step after extraction of clay and aluminum bound P, 0.5 M HCl solution was used to extract calcium-bound phosphorus with 1 hour shaking. A NaCl wash was applied after the extraction.

2.15. Extraction of residual P: Sediment residue was dried at 105°C and ignited at 520°C. The sediment sample was subsequently boiled in 25 ml 1M HCl for 10 min.

2.1.6 Analysis of P: The extracted P from different steps, present as orthophsophorus, was measured using HACH method. Total P was calculated as the sum of all measured P forms.

2.2 X-Ray Diffraction (XRD)

Sediment samples utilized for phosphorus speciation were also used in the XRD analysis. Sediment samples were thoroughly mixed and a 5-gram subsample was dried at 104℃ before XRD analysis.

'Whole-rock and clay X-ray diffraction (XRD) analyses were preformed on each sample in the XRD using a Bruker D8 Advance X-ray diffractometer. Phase quantification was performed using the Reitveld technique and the program TOPAS, developed by Bruker Analytical X-ray Systems. The following operating conditions were utilized: Cu-K-α radiation at 40 kV and 40 mA, 0.02 º2θ and 0.75 º 2θ step sizes and an irradiation period lasting for 0.4 and 0.6 seconds per step, for clay and bulk samples respectively. The instrument was equipped with a 2-D detector which collected data over 2.6 mm (rather than at a point); a rotating sample stage; and an automated sample changer.

The samples were ground in a micronizing mill until fine enough to pass through a 325 mesh screen (particle size < 44 micrometers). One half of the sample was used for the whole rock analysis; the remaining sample for the clay fraction (<5 micrometer fraction).

The clay fraction was separated from the bulk sample using Stokes Law for particle sedimentation. The resulting slurry was applied to a glass slide and dried, after which, the samples were scanned. The samples were then allowed to interact with ethylene glycol vapors to induce swelling of smectite-bearing clays and scanned again using the same parameters. The air dried and glycolated patterns were then

compared to determine which, if any, smectite-bearing clays were present. Clay abundances were determined from the whole-rock X-ray diffraction scans.' An example graph produced during XRD analysis is provided in figure 2.
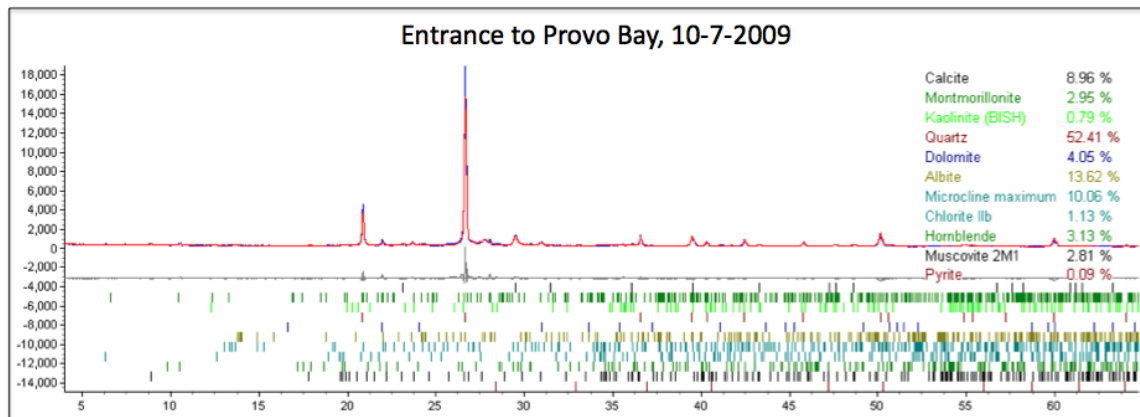
Figure 2: XRD graph from the top sediments near the entrance to Provo Bay

2.3 Sediment Oxygen Demand (SOD)

2.3.1 SOD measurements under ambient conditions: Sediment oxygen demand, SOD, chambers were installed at two locations in 2010, one location in 2011, and five locations in 2012 depending upon the availability of the motor boat from UDWQ. Sampling was conducted in the months of August and September to capture late summer conditions. The five installations in 2012 were a part of the amendment done in the spring of 2012. SOD sampling locations and dates are provided in Table 3. The 'sediment #' refers to the sampling locations shown in figure 1 of Utah Lake and detailed in Table 1.

SOD chambers were initially purged of all air in the plumbing and lowered to the bottom of Utah Lake via rope from a 'sampling barge' built for sampling in Utah Lake shown in figure 3(a) below. Depending on the depth, scuba or snorkeling gear was used to ensure a good seal, to install the data sonde, and to obtain water samples for nutrient analysis.

11

Table 3: SOD sampling sites and dates

sediment #	date	site
1	9/14/10	Provo Bay
2	8/3/12	Provo Bay entrance
3	8/2/12	outside marina
5	8/3/12	Goshen Bay
6	9/24/10	Geneva Steel
9	9/30/11	Utah Lk. Outlet
10	8/4/12	Pelican Point
12	8/4/12	Goshen Bay entrance

Submersible pumps running at 11 liters per minute cycled encapsulated lake water within the chambers to avoid stratification. The pumps were left on during the entire analysis to assure complete mixing within the chambers. A 12V deep cycle boat battery was stored on an inflatable float tube that was anchored near the chambers to provide power to the pumps (figure 3(b), below).

Figure 3: SOD chamber deployment 'barge' (a) and float tube used to carry the battery to power SOD chamber pumps (b)

Three SOD chambers were installed at each location of which two chambers (SOD 1 and SOD 2 and called testing chambers) measured DO consumption in the sediments and water column collectively and, one chamber (called control chamber or WC) just measured respiration in the water column only. SOD was measured for a total of 90-minutes with 45-mL water quality samples taken every 45 minutes to evaluate

dissolved nitrogen and phosphorus dynamics during ambient conditions. The fabrication and other details of SOD chambers is provided in Jordan River SOD reports submitted to UDWQ in the past and in our recent publication (Hogsett and Goel, 2013).

2.3.2 In situ pH and DO variations: After establishing baseline SOD rates and nutrient fluxes over a 90 minute time period, pH and DO were decreased using 4 (N) hydrochloric acid and sodium sulfite as an oxygen scavenger in the SOD 1 and SOD 2 testing chambers respectively. The pH was dropped roughly by 1.5 units to simulate seasonal pH drops recorded in the past by UDWQ regular monitoring. Figure 4 shows annual pH observations between the years of 1986-1995. The vertical red lines represent June summer values and the blue lines mark January winter observations. The reason the time period between 1986 and 1996 was chosen was due to the large number of observations made during this period by the Utah DWQ. The sinusoidal fluctuations in pH peaking in the summer and dropping in the winter are a result of lake inflows and primary production. It should also be noted that pH will also fluctuate over a diurnal cycle due to phytoplankton photosynthesis and respiration. It can be concluded from figure 4 that pH in general fluctuated between mid 8's to mid 7's mostly with couple of times hitting mid 6's values.
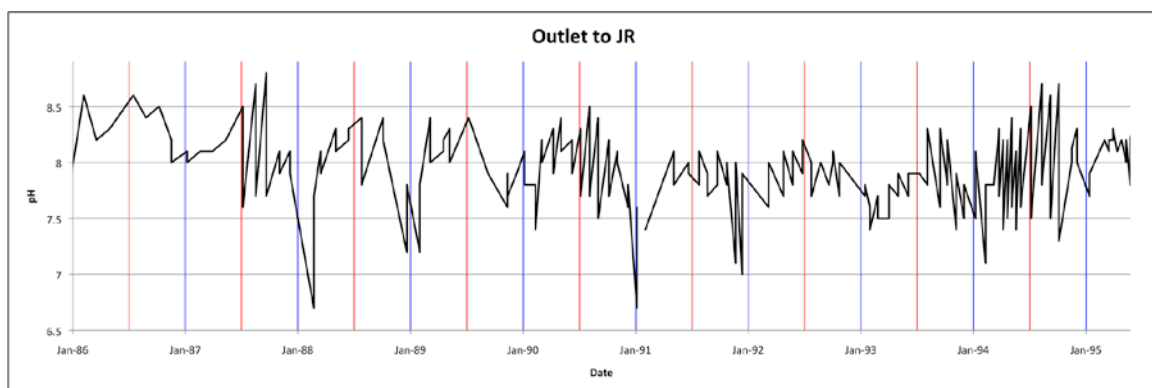

Figure 4: Annual Storet pH observations near the outlet of Utah Lake

13

How much acid was needed to be added to accomplish the exact drop in the pH in the chamber was predetermined by taking a core sample on site with lake water still sitting on the top of the core. Drop wise acid addition was done with gentle mixing. The amount of acid that was calculated based on the core sample experiment was normalized to the SOD chamber volume.

The effects of altering the pH in the chambers were measured 30 minutes after lowering chamber pH to estimate the initial abiotic release of nitrogen and phosphorus following an environmental change in the water column, such as the diurnal and annual pH swings.

SOD chamber DO concentrations were manipulated in the anoxic SOD 2 chamber by adding the oxygen scavenging sodium sulfite in predetermined concentrations to the chamber to achieve anoxic conditions.

$$Na_2SO_3 + \tfrac{1}{2}O_2 \rightarrow 2Na^+ + SO_4^{2-}$$
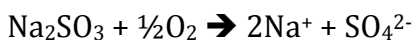
For example, assuming the DO in the SOD chamber needs to be dropped from 8.0 to 0 mg/L, then 2.4g of Na_2SO_3 salt needs to be introduced into the chamber. The salt was mixed into a slurry with 30mL of lake water in a syringe before it was injected into the SOD 2 chamber.

2.3.3 Sediment Core Collection, Total and Volatile solids and Total Organic Carbon quantification

Sediment cores collected during SOD sampling were acquired using an open barrel core while SCUBA diving or snorkeling. Sediment total solids (TS) and volatile solids (VS) were measured according to method 2540 G (APHA, 2005). Total organic carbon (TOC) of the bulk sediments was measured using a Shimadzu TOC-V with SSM-5000A solids sampling module. Inorganic carbon was initially removed from the sediment samples using a 5% HCl pretreatment before combustion at 900C.

3.0 Results and Discussion

3.1 P fractionation/speciation and XRD analysis

The results of the phosphorus speciation are provided in table 4. As described in the materials section, the P sequential extraction protocol has 5-steps. The P in the extracted samples was measured as dissolved P. Each row corresponding to each sample shows results of sequential extraction on each sample. The total P (TP) varied from a low of 282 mg P/kg of sediments for site 2 to a highest value of 1747 mg P/kg of sediments. This is the equivalent of 0.03% to 0.18% of the dry sediment mass being P. The mean percentage of sediment P for Utah Lake was 0.09%.

It is worth mentioning that, although the P concentrations are mentioned in the units of dry mass of sediments, wet sediments were used for P fractionation. Hence, the loosely bound P listed in table 4 comprised of sediment bound and pore water P.

Table 4: Utah Lake sediment phosphorus speciation

| Sediment Phosphorus (mg P/kg dry mass)							
Sample #	loosely bound P	Fe & Mn bound P	P from minerals and Al oxides	Ca bound P	residual P	total P (sum)	% Ca bound
1	253	439	148	778	150	1767	44
2	12	15	0	234	22	282	83
3	135	309	116	888	226	1674	53
4	0	63	332	319	0	715	45
5	81	157	83	692	120	1132	61
6	17	138	31	509	71	766	66
7	15	133	21	119	1	289	41
8	59	202	41	274	362	937	29
9	33	142	14	605	18	811	75
10	26	69	10	541	22	669	81
11	90	159	71	549	19	888	62
12	31	110	15	897	135	1188	76

Except couple of samples, most of samples in general contained low loosely bound P. The high value of 253 mg P/kg dry mass is a result of these sediments being located in the highly productive Provo Bay and is associated with sediment organic matter degradation.

Table 4b provides general comparisons for sediment TP concentrations. Roughly 930 mg p/kg dry mass were found in the sediment column of a Danish estuary known to experience periodic anoxia. Terrestrial soils range from 300-2000 mg P/kg dry mass depending on a variety of factors including organic content and historical P loadings (Kadlec and Wallace, 2009). Live macrophytes have TP consisting of organic P and are 0.15-0.24% P as dry mass. Utah Lake does have P enriched sediments but the majority of the TP is found in stable mineral forms, not as organic P.

Table 4b: Reference sediment TP

description	note	mg P/kg dry mass	
Danish estuary	TP using same extraction	930	(Jensen & Thamdrup, 1999)
live macrophytes	TP = organic P in this case	1500-2400	(Kadlaec & Wallace, 2009 pg. 352)
low P soils	TP	300-500	(Kadlaec & Wallace, 2009 pg. 354)
high P soils	TP	1000-2000	(Kadlaec & Wallace, 2009 pg. 354)

Utah lake sediments are known to be rich in carbonate related minerals and the majority of the sediment bound phosphorus was found associated with calcium. The XRD analysis performed on same samples and discussed later in this document also revealed the dominance of calcite mineral. Phosphorus can be precipitated from alkaline waters (pH 7-9) with roughly 300 mg/L $CaCO_3$ as an impurity in the calcium carbonate precipitate matrix or as a pure mineral such as hydroxyapatite as shown in the following chemical equation (Ferguson *et al.*, 1973):

$5Ca^{2+} + 3PO_4^{3-} + OH^- = Ca_5(PO_4)_3OH(s)$
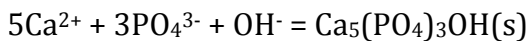
Since Utah Lake typically has pH values greater than 8, alkalinity between 200-300 mg/L $CaCO_3$, and a significant hydraulic retention time, the presence of high percentage of calcium P in all samples is not surprising. Other major forms were Fe, Mn and Aluminum bound phosphorus.

The distribution of different minerals in the top 1-2 cm lake sediments identified using XRD at various sites is provided in table 5.

Table 5: Utah Lake surface sediment mineral composition

| | Utah Lake surface sediment mineral composition (% mass) | | | | | | | | | | | | |
| | carbonates | | | clays | | | | silica oxides | feldspars | | other | | |
Sample #	calcite	aragonite	dolomite	illite	smectite	kaolinite	chlorite	quartz	K-feldspar	plagioclase	magnetite	pyrite	zeolite
1	54.0	0.6	2.2	3.3	4.7	2.1	1.9	17.9	7.4	5.0		1.0	
2	9.8		1.7	2.3	3.0	1.2	1.4	52.1	13.2	11.0			4.3
3	60.0	0.5	2.2	3.8	6.8	2.4	1.6	10.5	6.6	4.9		0.1	0.6
4	42.5		3.4	5.7	7.1	2.8	0.2	22.5	6.6	8.9		0.4	
5a	52.7	0.6	3.2	3.4	6.7	1.8	1.5	15.8	7.9	5.6			0.7
5b	51.0		2.7	4.1	4.3	3.4	4.7	16.7	7.1	5.8		0.2	
6	38.6		1.2	4.8	4.2	1.9	0.2	33.7	6.9	7.1	0.8	0.5	
7	49.0	0.5	1.7	4.1	3.6	2.5	1.1	20.5	9.1	6.6		1.0	0.5
8	63.4	0.5	2.4	4.6	5.0	2.7	2.1	9.1	6.0	4.3			
9	61.3	0.3	1.6	4.0	6.1	1.7	0.5	13.8	5.3	5.0		0.3	
10	27.3	4.7	1.8	3.0	3.3	2.0	0.1	38.8	6.8	10.2		0.4	1.7
11	66.9	0.4	2.0	4.1	6.2	2.4	1.7	7.2	5.4	3.2		0.1	0.5
12	61.3		2.3	5.4	5.8	2.0	2.1	9.5	6.0	4.9			0.6

The XRD analysis divided sediments primarily into 5 broad categories. Table 5 provides the mineral species identified and the associated % dry mass. Carbonate formed majority of the mass. The dominant mineral is calcite ($CaCO_3$) in samples

located in Utah Lake proper. Site 2 is located near the mouth of Provo Bay and is composed of sand, hence the low carbonate concentration and high concentrations of quartz (i.e. sand) and feldspars (cooled magma).

Table 6 provides the normalized % dry mass of each mineral group based on the total mass taken from table 5. The percentage of clay minerals was very consistent throughout the lake ranging from 11-17%. The exception was the sandy sediments (site 2) found near the outlet of Provo Bay. Additionally, large amounts of pyrite were visually observed in all samples but were not recognized in this XRD analysis. Apatite, a phosphate mineral group with the general formula $Ca_{10}(PO_4)6(OH, F, Cl, Br)_2$, was not observed in any of the samples, but this was expected since the detection limit for the XRD analysis was 0.1% and the maximum Ca bound P found in Table 4 (sites 3 and 4) was 0.09%. The XRD results are consistent with P fractionation in terms of calcium bound P and the presence of high percentages of calcite revealed through XRD analysis.

Table 6: Utah Lake Mineral Composition normalized over the total mass (% mass)

Sample #	1	2	3	4	5a	5b	6	7	8	9	10	11	12
Carbonate	57	12	63	46	57	54	40	51	66	63	34	69	64
Clay	12	8	15	16	13	17	11	11	14	12	8	14	15
Silica Oxide	18	52	10	23	16	17	34	21	9	14	39	7	10
Feldspar	12	24	12	15	12	12	14	16	10	10	17	9	11
Other	1	4	1	0	1	0	1	1	0	0	2	1	1

The P fractionation and XRD results show that most of the P in sediments of Utah lake are calcium bound. Based on the annual pH fluctuations in Utah lake (figure 4 above), it can also be concluded that the average pH of Utah Lake stays in basic range. since, calcium bound P is released in acidic pH range, it can also be concluded that most of the P in Utah Lake sediments is fixed and have less chances of released into the water column. However, it should also be noted that the P fractionation showed the presence of loosely bound, which can be released in the water column due to sediment disturbances associated with wind, boats and carp. In addition, other forms of P which can be released at high pH values are also present and have

the potential to cause eutrophication. The question whether Utah Lake is P limited or not is still open and should be evaluated by conducting long term controlled experiments.

3.2 Total and Volatile Solids in Sediments

3.2.1 TS and VS in surface sediments: During in-situ SOD experiments, surface sediment samples (0-2cm) were collected for total and volatile solids analysis. Table 7 provides percent total solids (%TS) and volatile solids (%VS) for all sites sampled for SOD. %VS can be directly used as a surrogate for organic matter present in the sediments. All sites had very fine sediments with a very high water content (i.e. low %TS). The %TS of 71% at the Provo Bay Entrance site is a result of the sediments being sand and much more consolidated. This result for Provo Bay entrance site also matches with XRD results in which case high percentage of silica oxide (table 6 above) and low total P (table 4 above) was measured at this site. SOD rates were higher in sediments that had higher %VS. It is assumed that sediment %VS is directly related to the water column oxygen demand in Utah Lake since the phytoplankton/BOD will eventually die/settle and contribute to %VS that will eventually decay in the sediments contributing to SOD.

Table 7: Surface Sediment %TS and %VS

site	%TS	%VS
Provo Bay	30	7.2
Provo Bay entrance	71	0.7
outside marina	28	5.5
Goshen Bay	34	5.5
Geneva Steel	30	5.9
Utah Lk. Outlet	33	5.2
Pelican Point	35	5.0
Goshen Bay entrance	33	4.8

Note: 0-2cm depth

3.2.2. TS and VS in sediment core samples: Sediment core samples (40~50 cm long) were collected from three sites to get information on deep sediments in Utah Lake. Deep sediments are often oxygen limited and undergo anaerobic/anoxic degradation rather than degradation in the presence of oxygen. However, gases such as methane can form in these deep anoxic sediments and eventually undergo oxidation at the interface of sediments and the water column.

Figure 5 shows %TS as dry sediments (y-axis) and depth (x-axis). The top 1-2cm of the sediment column at each location consisted of 30% TS, or 70% water by mass. The high water content provides the top 0-2 cm sediments the soft and muddy texture and make them susceptible to easily suspension in the water column. In general, the TS content in each sediment core sample increased with depth up to 30-cm and then become constant thereafter. This makes sense because with depth, sediment gets more compacted with less water content.
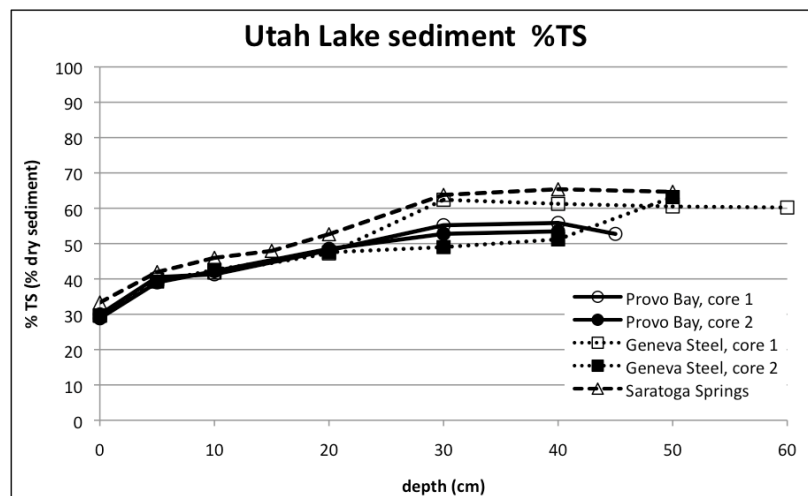
Figure 5: Utah Lake sediment column %TS

The sediment core samples were also analyzed for %VS. The depth integrated %VS data is shown in figure 6. Unlike TS, VS in general decreased with depth in all sediment core samples. As time passes, the old sediments (after undergoing aerobic degradation) get buried under new material such as the ones produced due to primary production and/or deposited from the water column due to sedimentation.

20

However, the process of organic degradation of organics in sediments continues albeit the mechanism slowly shifts from aerobic to anoxic metabolism due to oxygen diffusion limitations. %VS can be treated as surrogate for organic matter. Hence, when organic matter content decreases with depth, %VS also follows the same trend and this fact is reflected in figure 6. Among the sites, the Provo Bay core sample contained highest percentage of sediment VS.
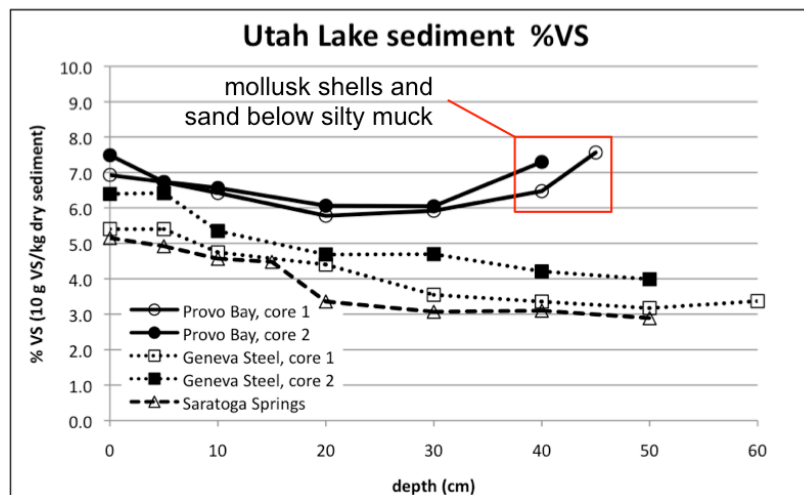

Figure 6: Utah Lake sediment column %VS

The %VS increase at 30cm in the Provo Bay sediment cores was due to a distinct organic enriched sandy layer with an abundance of mollusk shells. This sand layer is completely different than the fine silty muck layer covering the top 30 cm of the Provo Bay SOD sampling site. The interesting part is that the sediments in the isolated Provo Bay were historically sandy and this sand layer has been covered with silty muck. This 'excessive sedimentation' hypothesis is also supported by the observation that the entrance to Provo Bay site had sediments composed of sand, not silt or carbonate/clay.

Figure 7 below provides the total organic carbon (TOC) to %VS ratio for the Utah Lake sites (red squares). This figure also contains similar data from several locations in the Jordan River and Willard Spur for comparison purposes. The

general assumption when measuring %VS is that all burnable matter is organic and organic matter is composed of 50% carbon by mass. The sediments of Utah Lake have a high carbonate and clay content and, this results in additional mass losses when burning a %VS sample at 540°C associated with carbonate destruction and retained interstitial pore water losses. The TOC:VS relationship was 0.37 for the sites located in Utah Lake proper. This value can be used to estimate sediment organic carbon content when using %VS methods.
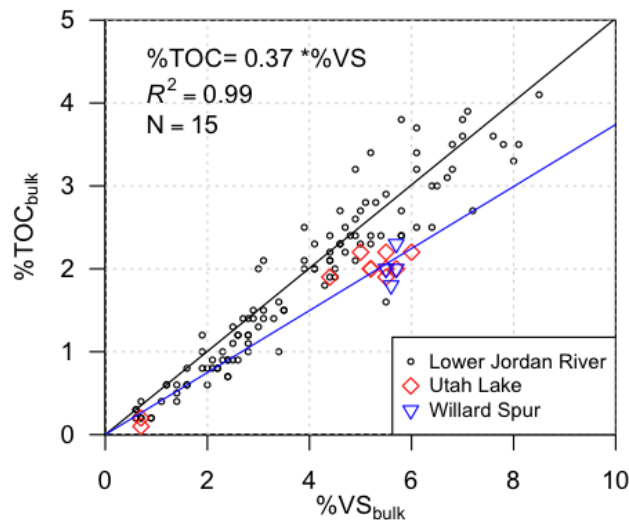
Figure 7: Sediment TOC:VS ratio for Utah Lake (red squares, Jordan River (black circles and Willard Spur (blue inverse triangles).

3.3 Sediment Oxygen Demand

3.3.1 SOD (Ambient conditions): Ambient conditions measured at all 8 SOD locations are provided in table 8. The elevated pH and ambient DO at the Provo Bay site are a result of primary production in the isolated bay receiving water from Hobble Creek, not the Provo River as the name would suggest. All sites visited during the afternoon hours had supersaturated ambient DO concentrations, even at the sites located in the center of the lake. The pH values were always greater than 8.5. Values greater than 8.6 were coupled with supersaturated ambient DO and

were associated with water column primary production. In general, the highest pH values were observed in the shallow sites where water column depths were 1 meter.

Table 8: Ambient conditions at time of SOD sampling

site	%DO sat.	pH	temp. (°C)	depth (m)
Provo Bay	165	9.6	17.1	1
Provo Bay entrance	129	9	23.5	1
outside marina	81	8.6	22.5	3
Goshen Bay	73	9	22	1
Geneva Steel	110	8.6	18.3	2
Utah Lk. Outlet	91	8.6	19.1	2.2
Pelican Point	114	8.9	23	3
Goshen Bay entrance	88	8.6	22.9	3

3.3.2: SOD Chamber consistency: Figure 8 provides the correlation between the SOD_1 and SOD_2 testing chambers. The SOD rates measured in the two chambers were consistent, demonstrating that the sediments were very homogeneous at all sites. The line in figure 8 represents a 1:1 relationship between the two SOD testing chambers.   Only six sampling events are shown in figure 8 due to probe malfunctions at two of the sites.
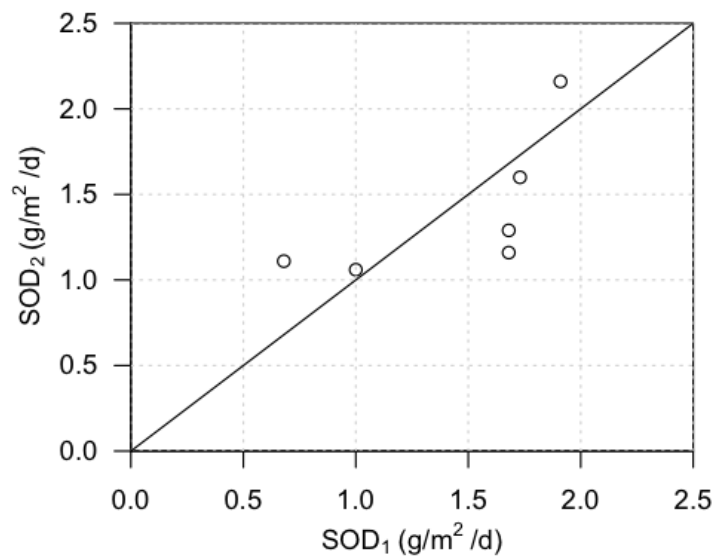
Figure 8: SOD chamber comparison

23

3.3.3: SOD Values under ambient conditions: Table 9 shows the two-chamber average SOD, water column oxygen demand (WC) and 'chamber calculated' nighttime ambient DO depletion rates. All results are presented as negative values since DO is being consumed. The SOD flux describes the amount of DO consumed at the two-dimensional sediment-water interface and the WC is presented as a volumetric rate to be comparable with BOD_5 measurements. The ambient columns in table 9 are presented as both an aerial DO flux and volumetric DO rate. Both of the ambient values were calculated by normalizing to depth and summing the SOD and WC fluxes/rates. The ambient aerial flux can be used to describe the sum of the DO dynamics occurring throughout the entire WC and sediment-water interface for mass balance equations. The ambient volumetric rate represents the DO dynamics from the perspective of the water column, which is useful because most WQ scientists use these parameters in terms of volumetric rates and concentrations. The ambient aerial flux and volumetric rates are equal when the depth of the WC is 1-meter. When the WC is deeper than 1m deep, the sediments become less influential to ambient DO concentrations in the productive Utah Lake.

Table 9: Observed SOD, WC and estimated ambient DO depletion rates

| site	SOD_{avg} $g/m^2/d$	WC $g/m^3/d$	ambient $g/m^2/d$	ambient $g/m^3/d$	depth m
Provo Bay	-4.61	-6.66	-11.3	-11.3	1
Provo Bay entrance	-1.42	-3.45	-4.9	-4.9	1
outside marina	-1.49	-2.28	-8.3	-2.8	3
Goshen Bay	-1.67	-3.4	-5.1	-5.1	1
Geneva Steel	-2.04	-1.9	-5.8	-2.9	2
Utah Lk. Outlet	-1.03	-1.28	-3.8	-1.7	2.2
Pelican Point	-1.06	-4.17	-13.6	-4.5	3
Goshen Bay entrance	-0.90	-1.11	-4.2	-1.4	3

The highly productive Provo Bay had the highest SOD and WC consumption flux/rate measured in Utah Lake. The WC oxygen demand was higher than SOD at all sites except at the Geneva Steel site where the WC rate was equal to the SOD flux. Since this site has a water column 2 meters deep, the WC rate becomes a greater DO consumer when normalized to an ambient aerial flux or rate. The sites located near the shores of Utah Lake (Provo Bay entrance, outside marina, Goshen Bay and Geneva Steel), all had SOD fluxes ranging from 1.4-2 $g/m^2/d$ and the deep water sites located off shore (Utah Lk. Outlet, Pelican Point and Goshen Bay entrance) had low SOD fluxes ranging from 0.9-1.06 $g/m^2/d$. In addition, these deepwater sites are located farther away from point and non-point nutrient sources compared to the near shore sites. The water column is more influencial to ambient oxygen dynamnics than the sediments in the productive Utah Lake.

3.3.4: SOD Values under DO and pH variations: Anoxic conditions were created inside testing chamber by adding an oxygen scavenger. Hence, no SOD was expected in the SOD chamber subjected to anoxic conditions. Furthermore no change in SOD values were observed in the SOD chamber which was subjected to pH lowering, demonstrating that small pH changes do not affect respiration and other DO consuming processes in sediments.

3.4 Nutrient Flux

3.4.1. Nutrient flux under ambient conditions (i.e no pH and DO changes): Figure 9 shows typical profiles obtained after plotting ammonia nitrogen concentrations obtained during chamber experiments at Provo Bay and Geneva Steel sites in 2010. The dashed lines represent SOD chambers and the solid line is the WC, or Control, chamber. The slopes of these lines were used to calculate nutrient fluxes. Similar graphs were obtained for other inorganic species and flux was calculated from the slope of the concentration lines.
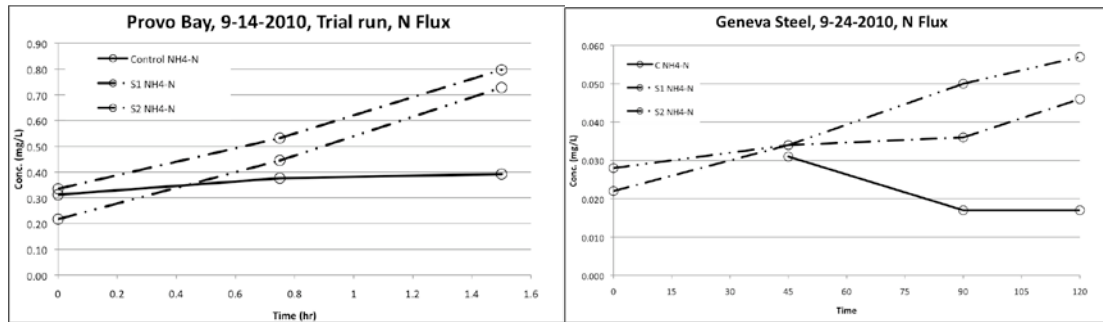
Figure 9: Ammonia-N fluxes measured in 2010

Table 10 provides the ambient dissolved nutrient concentrations at the time of sampling. Nitrite was not detected in all samples and ammonia and nitrate concentrations were relatively low, but measurable. The high ambient ammonia concentration in Provo Bay and lack of nitrate suggests organic matter decomposition. Non-purgeable dissolved organic carbon (NPDOC) was measured in 2012 and all sites consistently had concentrations between 5-6 mg-C/L. The high dissolved carbon:nitrogen (C:N) molar ratios (>10) suggest nitrogen limitation in terms of heterotrophic microbial activity. The low nitrogen:phosphorus (N:P) molar ratios (<10) also implies nitrogen limitation in terms of bioavailable nutrients for heterotrophic growth. The biologically favorable N:P ratio of 9.8 measured in Provo Bay supports the hypothesis that large amounts of decomposition and nutrient cycling are occurring in this shallow isolated bay.

Table 10: Initial ambient dissolved nutrient concentrations

site	ambient dissolved nutrient concentrations (mg/L)						
	NH_4-N	NO_3-N	TIN	PO_4-P	NPDOC	C:N ratio	N:P ratio
Provo Bay	0.31	0.00	0.31	0.07			9.8
Provo Bay entr.	0.02	0.05	0.07	0.04	6.1	102	3.9
Outside marina	0.02	0.05	0.07	0.05	6.3	106	3.1
Goshen Bay	0.02	0.05	0.07	0.00	6.3	105	
Geneva Steel	0.03	0.00	0.03	0.08			0.8
Ut LK outlet	0.02	0.06	0.08	0.04			4.5
Pelican Point	0.02	0.05	0.07	0.03	5.3	88	4.7
Goshen Bay entr.	0.02	0.06	0.08	0.03	5.1	74	5.9

note: nitrite concentrations were non-detectable at all sites

Table 11 provides average annual dissolved nutrient concentration measured at Storet sites located near SOD sampling locations. The low ambient nutrient concentrations encountered during SOD and nutrient flux sampling were representative typical historical conditions recorded in the Utah Lake.

Table 11: Storet average annual dissolved nutrient concentrations

	NH_4-N	#	NO_3-N	#	PO_4-P	#
Provo Bay Entrance	0.09	40	0.07	10	0.04	32
Geneva Steel	0.03	26	0.02	6	0.04	26

note: units = mg/L, Storet data, nitrite non-detect

Table 12 provides the fluxes of dissolved nitrogen and orthophosphate from the sediments. As mentioned before, nitrite was not detectable in the WQ samples, therefore the flux of nitrite was null. Nitrate fluxes from the sediments were negligible during dark conditions. The extremely high ammonia flux at the Provo bay site suggests organic matter decomposition, but the phosphorus flux was very low. The majority of the fluxes are positive, this means that the sediments are adding N and P to the water column during dark conditions. It should be noted that photosynthesis would consume the sediment released nutrients during daytime conditions.

Table 12: Averaged sediment nutrient fluxes

site	Sediment nutrient fluxes (g/m^2/d)				
	NH_4-N	NO_3-N	TIN	PO_4-P	NPDOC
Provo Bay	1.44	0.00	1.44	0.01	
Provo Bay entrance	0.10	0.01	0.10	0.39	-0.6
Outside marina	-0.03	0.02	-0.01	0.00	1.9
Goshen Bay	0.03	0.01	0.04	0.00	3.5
Geneva Steel	0.14	0.00	0.14	0.03	
Utah LK outlet	0.00	0.00	0.00	0.01	
Pelican Point	0.09	-0.01	0.09	0.00	1.2
Goshen Bay entrance	0.03	0.08	0.11	0.00	-0.3

note: nitrite concentrations were non-detectable at all sites

Table 13 provides the water column nutrient dynamics as a volumetric rate. The WC in Provo Bay acted as a large source of ammonia, but not dissolved phosphorus similar to the sediments. At all other sites the WC acted a sink for dissolved nitrogen and phosphorus (i.e. negative rates) and suggest that phytoplankton and/or other microbes are bio-assimilating nutrients within the WC during dark conditions. Similar to WC oxygen demand driving ambient DO dynamics in Utah Lake, the WC is also responsible for nearly all of the nutrient uptake. This is not surprising given the eutrophic nature of this well mixed turbid shallow lake.

Table 13: Nutrient flux associated with the water column

site	WC nutrient rates (g/m^3/d)				
	NH_4-N	NO_3-N	TIN	PO_4-P	NPDOC
Provo Bay	1.27	0.00	1.27	0.00	
Provo Bay entr.	-0.13	-0.01	-0.14	-0.29	2.4
Outside marina	-0.05	-0.05	-0.10	0.00	-10.8
Goshen Bay	0.06	-0.02	0.04	0.00	-10.7
Geneva Steel	-0.28	0.00	-0.28	-0.07	
Utah LK outlet	-0.09	0.01	-0.08	-0.01	
Pelican Point	-0.44	-0.01	-0.46	0.00	-6.4
Goshen Bay entrance	0.06	-0.35	-0.29	0.00	1.3

note: nitrite concentrations were non-detectable at all sites

3.4.2 Nutrient Fluxes under pH change: SOD measurements were first done under ambient conditions and then pH in one of the testing chambers was lowered by roughly 1.5 units to evaluate the effect of pH changes on nutrient fluxes. Figure 10 shows a typical pH profile in the testing chamber for all sampled sites before and after the pH manipulation. Two sites were samples in 2010, one in 2011 and five in 2012. As reflected in figure 10, the lowered pH in the chambers remained relatively stable with a slight increase over the testing period with the exception of the Goshen

Bay entrance site (red line) where chamber pH nearly rebounded to the original value over the 45-minute testing period. It is assumed that this was a result of the high sediment carbonate concentrations (>60% sediment dry weight) and associated buffering capacity.
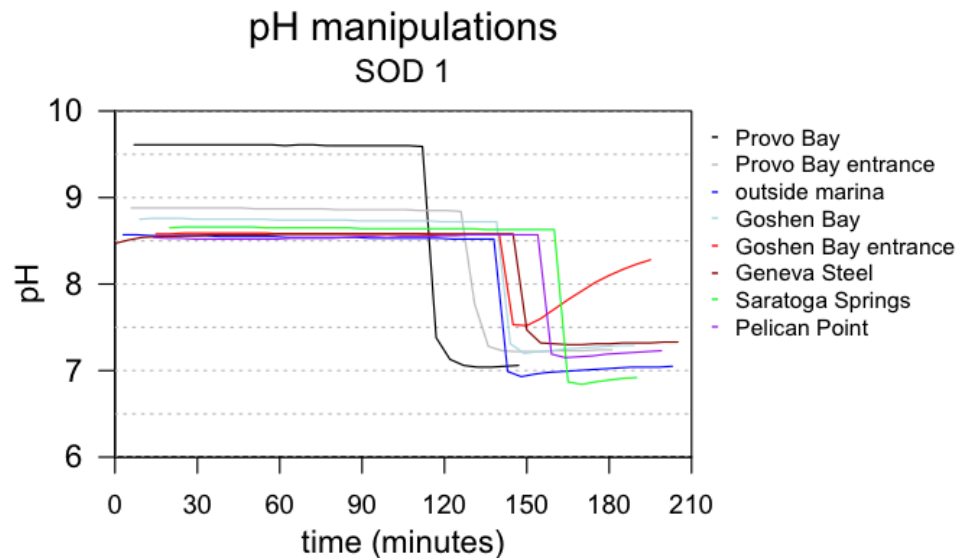
Figure 10: SOD chamber pH manipulations

Table 14 provides sediment nutrient releases from the eight sites following the lowering of chamber pH and mixing for 45 minutes to ensure all abiotic processes were complete. Lowering chamber pH to near neutral conditions did not affect the SOD fluxes and was assumed to affect only abiotic processes. Therefore the positive fluxes of ammonia and phosphorus from the sediments is expressed per unit change in pH, not per unit time. The units used in table 14 are non-traditional and represent the 'additional' sediment flux associated with decreasing the ambient pH 0.5 units. Although pH was dropped in larger increments than 0.5 units, additional fluxes associated with pH changes were normalized to 0.5 units for ease of comparison. The 'pH change' row in table 14 refers to the actual decrease in pH in the chambers and the 'pH drop' provides pH values measured in the chambers before and after manipulation. The positive fluxes measured may occur diurnally

29

due to pH fluctuations associated with photosynthesis and would occur seasonally as pH decreases during the winter months.

Table 14: Nutrient fluxes for pH manipulations

additional sediment flux associated with 0.5 unit pH drop (g/m^2/0.5 drop in pH)					
site	pH change	NH$_4$-N	NO$_3$-N	PO$_4$-P	ph drop
Provo Bay	2.6	0.25		0.15	9.6 to 7.0
Provo Bay entrance	1.7	0.02	0.00	0.01	8.9 to 7.2
Geneva Steel	1.3	0.04		0.10	8.6 to 7.3
Outside marina	1.6	0.17	0.00	0.00	8.6 to 7.0
Ut LK outlet	1.8	0.02	0.01	0.13	8.7 to 6.9
Pelican Point	1.3	0.03	0.01	0.03	8.5 to 7.2
Goshen Bay	1.4	0.01	-0.01	0.00	8.7 to 7.3
Goshen Bay entrance	1.1	0.01	0.01	0.00	8.6 to 7.5

The high release of 0.25 g NH4-N/m^2 per decrease in pH of 0.5 units at the Provo Bay site is most likely a result of loosely bound ionic exchanges in the organically enriched sediments. The addition of protons to decrease pH and relatively high ambient ammonia concentrations (0.31 mg/L, table 10) would be conducive to the release of sorbed ammonia in the highly productive Provo Bay sediments (Kadlac & Wallace, 2009, pg 274).

RH$^+$ + NH$_4^+$ + OH$^-$ $\longleftrightarrow$ RNH$_4^+$ + H$_2$O, where R = ligand

All other sites did not release significant amounts of ammonia from the sediments during pH reductions with the exception of the Outside Marina site. Nitrate fluxes were not influenced by the lowering of chamber pH. Ortho-phosphate was released from the sediments at the Provo Bay, Geneva Steel, Pelican Point and Utah Lake outlet sites during the pH lowering. The remainder of the sites did not release additional dissolved phosphorus following pH manipulations. Table 3 presented previously (sediment P speciation) shows that the majority of the sediment

phosphorus is Ca-bound, but the pH manipulations performed in the SOD chambers were not low enough to release this Ca-bound pool of phosphorus while simulating wintertime pH values in Utah Lake. However, the possibility of the release of calcium bound-P cannot be ruled out due to the lowering of pH.

3.4.3: Nutrient Fluxes under anoxic conditions: Dissolved Oxygen was removed in the SOD chamber to measure sediment nutrient fluxes under anoxic conditions. Table 13 provides the additional flux of nutrients from the sediments during anoxia. The values presented in table 15 are 'in addition' to the fluxes measured during ambient conditions (table 12, above). Negative flux implies transport from the water column to sediments.

Table 15: Additional nutrient flux during anoxic conditions

additional sediment flux associated with anoxia (g/m^2/d)			
site	NH$_4$-N	NO$_3$-N	PO$_4$-P
Provo Bay		0.00	0.31
Provo Bay entrance	0.03	0.01	0.00
Geneva Steel	0.07	0.00	-0.11
Utah LK outlet	0.13	-0.05	0.01
Pelican Point	0.11	0.01	0.03
Goshen Bay	-0.20	0.00	0.00
Goshen Bay entrance	-0.20	0.00	0.01

The sediments in the highly productive Provo Bay site did not release additional ammonia during anoxic conditions. Instead, the sediments removed ammonia from the water column faster during anoxic conditions than ammonia was released under aerobic conditions (table 15, above), which was not expected. The Provo Bay entrance, Geneva Steel, Utah Lk. Outlet and Pelican Point sites released more dissolved ammonia during anoxic conditions compared to aerobic conditions. Biological denitrification was not observed and may be a result of low ambient nitrate concentrations, lack of a bioavailable carbon source, or a low benthic

metabolism for denitrification in the nitrogen limited lake. Additional dissolved phosphorus was released from the sediments under anoxic conditions.

4.0 Conclusions

This is was one of very studies which evaluated SOD and nutrient fluxes under both ambient as well as varying pH and dissolved oxygen (DO) conditions. This applied research demonstrated that Utah Lake sediments have tendency to release phosphorus under changed pH and DO conditions. The key conclusions of this study are outlined below.

1. In terms of mineralogy, Utah Lake sediments are dominated by calcite mineral. The white murkiness occasionally seen in Utah Lake water could be due to the physical re-suspension of calcite rich sediments.
2. The total P (TP) varied from a low of 282 mg P/kg of sediments to a highest value of 1747 mg P/kg of sediments. Based on limited literature, it can be concluded that Utah Lake sediments are low to medium P loaded. The good news is that most of this sediment P is calcium bound and has very low potential of to be released in the water column based on the pH variation history of Utah Lake. Calcium bound P is released at low pH values.
3. In terms of total (TS) and volatile)VS) solids, all but Provo Bay entrance sites showed consistent results in which case TS averaged close to 30 % and VS averaged close to 5 %.
4. Long sediment core samples revealed that TS increased with depth whereas VS decreased with depth. VS can be used as surrogate for organic matter. Hence, it can be concluded that organic matter percentage decreased with depth.
5. All but Goshen Bay site showed SOD greater than 1.0 g/m^2/d.
6. The WC oxygen demand was higher than SOD at all sites except at the Geneva Steel site where the WC rate was equal to the SOD flux.
7. The pH variations did not affect SOD values.

32

8. Except at the Provo Bay Site, low nutrient fluxes were recorded at all other sites. In terms of concentrations, these were typical of those generally observed by UDWQ in their monitoring efforts.

9. Ammonia nitrogen release was observed at all sites due to pH drop during in-situ flux experiments. The release was highest at the Provo Bay Site. Measurable P releases were recorded at Provo Bay, Geneva Steel and Utah Lake Outlet sites

5.0 Acknowledgement

6.0 References

Ahlgren, J., Reitzel, K., Danielsson, R., Gogoll, A., and Rydin, E. 2006. Biogenic phosphorus in oligotrophic mountain lake sediments: Differences in composition measured with NMR spectroscopy. *Water Research*. 40:3705-3712.

APHA, AWWA, and WEF, 2005, <u>Standard Methods for the Examination of Water and Wastewater, 21st ed</u>. American Public Health Association, Washington, D.C.

Bailey-Watts, A.E. 1978. A nine-year study of the phytoplankton of the eutrophic and non-stratifying Loch Leven (Kinross, Scotland). *J. Ecol*. 6, 741–771.

Bailey-Watts, A.E., Kirika, A. 1993. Loch Leven NNR:Water Quality 1992–1994 with Special Reference to Nutrients and Phytoplankton, and an Assessment of Phosphorus Levels in the Loch Sediments. Interim Report to Scottish Natural Heritage. Institute of Freshwater Ecology, Edinburgh.

Ferguson, J., Jenkins, D. and Eastman, J. 1973. Calcium phosphate precipitation at slightly alkaline pH values. *Water Pollution Control Federation*. 45(4):620-631.

Jensen, H.S. and Thamdrup. 1993. Iron-bound phosphorus in marine sediments as measured by bicarbonate-dithionite extraction. *Hydrobiologia*. 253: 47-59.

Kadlec, H. and Wallace, S. 2009. <u>Treatment Wetlands, Second Edition</u>. Boca Raton, FL, Taylor and Francis Group.

Psomas. 2007. Utah Lake TMDL: Pollutant Loading Assessment & Designated BeneficialUse Impairment Assessment (Final Draft). Prepared for the Utah Division of Water Quality.