Report to the Utah Division of Water Quality

Biotic and chemical changes along the salinity gradient in Farmington Bay, Great Salt Lake, Utah

Utah State University
Watershed Sciences Aquatic Practicum Class Report

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Contents

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Executive Summary

Farmington Bay in the Great Salt Lake is a 310 km^2 (120 mi^2) shallow bay that receives municipal and industrial wastes from over 1.5 million people, and is thus one of the most polluted water bodies in Utah. On October 2, 2014 the USU Watershed Science Aquatic Practicum class conducted a transect analysis of limnological conditions at five stations along a 28-km (17.4 mi) north-south gradient of Farmington Bay. Additional experiments and analyses were subsequently done in the laboratory to help understand factors controlling plankton and benthic invertebrates in the bay. Due to drought, the depth in the bay ranged from only 0.2 m (7") in the south, to 0.8 m (34") in the north, and interchange of water with hypersaline Gilbert Bay was minimal. Consequently, the salinity gradient in Farmington Bay ranged from 0.3% in the south where river and secondary-treated wastewater deliver fresh water, to 1.0% in the north near the Antelope Island Causeway (**Fig. 1**). The deep-brine layer (monimolimnion) that normally underlies the northern half of the bay was absent and there was minimal vertical stratification in the water column.

Total phosphorus concentrations were greater than 320 µg/L at all stations but peaked at concentrations >1000 µg/L at two stations "downstream" of the input from the Salt Lake Sewage Canal (Northwest Oil Drain). The abundance of phytoplankton, as measured by chlorophyll levels, was <40 µg/L in the southern and mid-portions of the bay, but increased to 100 µg/L in the north where toxic, nitrogen-fixing cyanobacteria (blue-green algae) were dominant. However, periphytic algae attached to the bottom were very abundant at the shallow southern stations.

Zooplankton were dominated by cladocera (*Daphnia, Moina* and cyclopoid copepods) and increased to over 175/L, and >1000 µg/L in the northern part of the bay (**Fig. 1**). A predatory insect of zooplankton, *Trichocorixa verticalis*, increased to over 1/L in the north. Laboratory

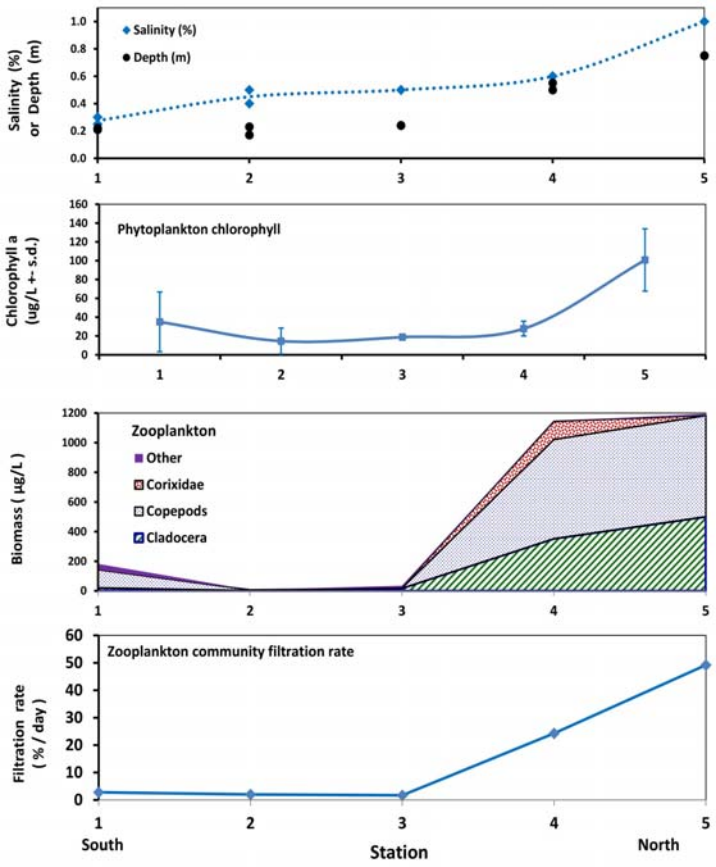

Figure 1. Changes in salinity, chlorophyll, zooplankton composition and zooplankton grazing rate on phytoplankton along the south (Sta. 1) to north (Sta. 5) axis of Farmington Bay.

experiments demonstrated that the cladoceran zooplankton (*Daphnia* and *Moina*) were effective grazers and where they were abundant at the northern stations could graze approximately 50%/day of the phytoplankton (both green algae and cyanobacteria) (**Fig. 1**).

Predation experiments with the corixids indicated they could remove 20% of the cladocerans each day at the northern stations (**Fig. 2**). The marked increase in the northern portion of the bay was due to large increases in corixid densities.

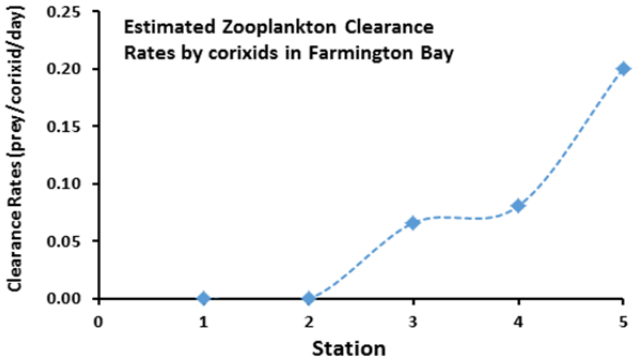

Figure 2. Estimated predation rates (as clearance rate—fraction of water cleared per day) of corixids on cladoceran zooplankton in Farmington Bay on 2 October 2014.

Benthic invertebrate analyses indicated that chironomids (gnat larvae) dominated the community and they were very abundant in the southern and mid-portion of the bay, but absent in the north (**Fig.** 3A). Snails (Mollusca) and scuds (Amphipoda) were also abundant at the shallow stations in the southern area where periphyton was abundant. Mean biomass of invertebrates in the bay (16.9 g dry weight/m^2) was among the highest reported in a freshwater lake, but invertebrates were nearly absent in the northern area where the deep brine layer normally is located.

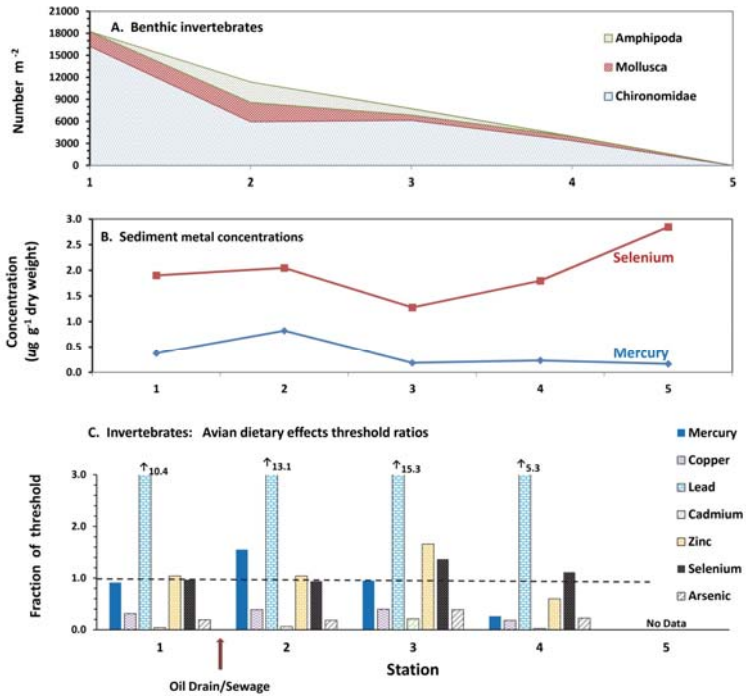

Figure 3. Benthic invertebrate densities (A), concentrations of two metals in the sediments (B), and metal concentrations in the invertebrates expressed as a fraction of the dietary thresholds for birds (C) at five stations in Farmington Bay. No invertebrates were available for metal analysis at Station 5.

Analyses of concentrations of 31 metals in the sediments indicated that most metals were highest at Stations 2 and 3, downstream of the Northwest Oil Drain/Sewage Canal (**Fig. 3B**). However, the metalloids, selenium and arsenic, were generally highest in the north where the salt wedge from Gilbert Bay enters. At one or more stations metal concentrations in the Chironomid larvae exceeded dietary thresholds recommended for birds (Fig. 3C). This was particularly true for lead.

Birds were abundant in the bay during our October sampling, with mean densities of 2800/km^2 along the transect. American coots and phalaropes were dominant in the northern part of the bay, whereas American avocets and ducks were dominant in the south. If this pattern is normal, our analyses indicate that species utilizing the south have higher exposures to most heavy metals, whereas those in the north are exposed to higher levels of cyanobacterial toxins and metalloids. Understanding the spatial context of contaminants and distribution of the birds is thus critical for understanding potential risks for avian species in Farmington Bay.

Chapter 1

Background Limnological Conditions In Farmington Bay

Wayne Wurtsbaugh

The southeast portion of the Great Salt Lake is called Farmington Bay. At mid- to low-water conditions the bay is largely isolated from the larger lake by Antelope Island, and an automobile causeway leading to the Island. The bay is situated close to greater metropolitan Salt Lake City with over 1.5 million people, and the domestic wastewater and industrial discharges of the city contribute approximately half of the water inflow to the lake (Meyers and Houston 2006). The nutrient loading from these discharges promotes large blooms of toxic cyanobacteria and other algae and the bay is hypereutrophic (Wurtsbaugh et al. 2012; Marden et al. 2015). Frequent nighttime anoxia throughout the water column and hydrogen sulfide released from a deep brine layer in the bay contributes to "lake stink" that influences the metropolitan area. Additionally, industrial discharges from the city via the Northwest Oil Drain/Sewage Canal reach the southern end of Farmington Bay, and metal concentrations in this area are high (Waddell et al. 2009). Large populations of wading birds, waterfowl and other species feed and nest around the parameter of the bay. Given the pollution problems in the bay, there are concerns that these species could be affected by the metals and the toxic cyanobacteria. Consequently, there has been considerable research in recent years to understand the contaminant issues, and to better describe the complex ecological processes that occur along the salt gradient in the bay.

As part of this effort, the Utah State University Aquatic Ecology Practicum course (WATS 4510) studied the bay in October 2014. Samples were taken at five stations along the north-south salinity gradient, and additional analyses and experiments were done in laboratories at the university. Students in the class focused on the zooplankton and on the benthic vertebrates, both of which have received relatively little attention in previous studies. This report is a compilation of the reports presented in the class.

This chapter briefly presents some background limnological information that was collected during the study.

Figure 1. Farmington Bay and the five stations sampled on 2 October, 2014.

Methods

Samples were collected on 2 October, 2014. Airboats provided by the Utah Division of Water Quality (DWQ) and the Utah Department of Wildlife Resources (DWR) were utilized to access the stations because many were located in shallow water. Because of a prolonged drought influencing the lake, Stations 1-2 had depths of only slightly greater than 0.2 m, whereas the deepest station near the causeway bridge was only 0.75 m. An additional effect of the drought was to reduce the intrusion of a salt wedge from Gilbert Bay, so that the waters in Farmington Bay had much lower salinities than in recent years.

Prior to the sampling the weather was warm with precipitation, followed by a cool and clear day immediately preceding our sampling effort. On the day of sampling it was clear, with air temperatures ranging from 14^{o}C in the morning to 18^{o}C in the afternoon. Winds were initially near 6 km/hr. when we sampled Station 5 in the northern part of the bay, but soon calmed to around 1 km/hr.

The initial intent was to sample five equally-spaced stations along the central longitudinal axis of the lake. However, the water was too shallow in the south-central area to stop the airboats, so the distance between Stations 2 and 3 was longer than between other stations (**Fig. 1**). At each station we sampled at two locations separated by approximately 100 m. These replicates helped describe small-scale and sampling variability at each station. When the water was deeper than 0.3 m, we measured several parameters near the surface (0.2 m), and 10 cm from the bottom with a YSI Model 58 sensor. At shallower stations we sampled only near the surface (0.1 or 0.2 m depth).

Parameters measured as part of the background limnological information included:

Parameter	**Method**
Temperature	YSI Model 58
Oxygen	YSI Model 58 with membrane sensor
Specific Conductivity	YSI Model 58
Salinity	Refractometer
pH	pH paper
Chlorophyll *a* concentration (algal biomass indicator)	Water filtered on 1µm filter; fluorometric measurement w/ Turner 10AU fluorometer
Phycocyanin pigment (from cyanobacteria)	In vivo measurement with Turner 10AU fluorometer
Secchi depth transparency	30-cm black and white disk
Total phosphorus	0.2 m sample; acid persulfate digestion followed by acid-molybdate colorimetric analysis

Birds were quantified along the axis of the bay by the DWR boat driver, Mr. John Neill, an experienced birder. He counted and identified those on the left side of the airboat out to a distance of 200 m as we cruised between stations. The number counted was then converted to densities utilizing the distance

between stations (GPS coordinates and Google Earth measurements) and the assumed 0.2 km width of the observed transect.

Additional methods are given in each of the student's chapters.

Table 1. Physical-chemical parameters at the five stations sampled in Farmington Bay.

Station	Replicate	Coordinates		Station depth (m)	Secchi depth (m)	Temperature (C)	Dissolved Oxygen (mg/L)	Specific conductivity (mS/cm)	Salinity (%)	pH*
1	A	40.9408	-112.0030	0.22	> 0.22	17.7	8.5	2.11	0.3	6.8
1	B	40.9396	-112.0015	0.21	>0.21	20.1	11.5	2.45	0.3	6.8
2	A	40.9131	-112.0512	0.17	>0.17	19.4	10.6	2.87	0.4	7.0
2	B	40.9139	-112.0518	0.23	0.2	17.7	8.5	4.20	0.5	6.5
3	A	40.9873	-112.1375	0.24	>0.21	14.3	14.8	3.17	0.5	8.0
3	B	40.9870	-112.1390	0.24	>0.24	15.3	14.2	2.91	0.5	8.0
4	A	41.0827	-112.1554	0.50	>0.5	12.9	8.0	3.35	0.6	7.0
4	B	41.0289	-112.1568	0.55	>0.5	13.0	8.5	3.34	0.6	7.0
5	A	41.0639	-112.2277	0.75	0.4	12.4	6.3	5.03	1.0	7.0
5	B	41.0645	-112.2266	0.75	0.4	12.3	6.7	5.30	1.0	7.0

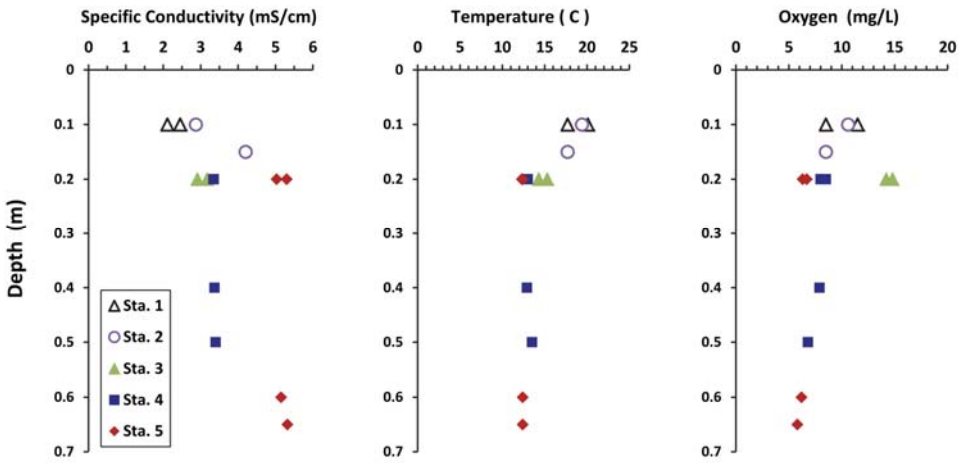

Figure 2. Vertical profiles of specific conductivity, temperature and oxygen levels at the five stations. At Stations 1-3 measurements were only made near the surface because of the shallow water.

Results

Water column depths ranged from near 0.2 m at Stations 1-3, but increased to near 0.8 m by Station 5 (Table 1). At Stations 1-4 Secchi depths were greater than the depth of the station, and thus they could

not be measured. At Station 5 the Secchi depth (0.4 m) was about one half of the total depth. Salinities ranged from 0.3% at Station 1 to 1.0% at Station 5. Temperatures ranged from 12°C to 20°C, but the differences were likely due to the northernmost station being sampled early in the morning, whereas Station 1 in the south was not sampled until mid-afternoon. Additional parameters are shown in Table1. There was minimal vertical stratification at Stations 4 and 5 where it was deep enough to measure profiles (**Fig. 2**). For example, mean oxygen levels at Station 5 were 6.5 mg/L at the surface and 6.0 mg/L near the bottom. Total phosphorus concentrations were over 320 µg/L at all the stations in the bay (**Fig. 3**). Concentrations were greater than 1000 µg/L at Stations 2 and 3, which were immediately "downstream" from the discharge of the Sewer Canal. Total phosphorus concentrations decreased markedly at Stations 4 and 5, probably reflecting uptake by the benthic periphyton and sedimentary losses.

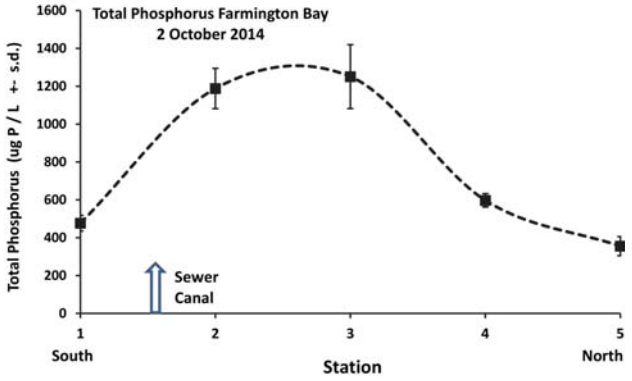

Figure 3. Total phosphorus concentrations in samples from 0.1-0.2 m depth at five stations in Farmington Bay.

Mean chlorophyll *a* levels in Farmington Bay were less than 40 ug/L at Stations 1-4, but increased to over 100 µg/L at Station 5 near the causeway (**Fig. 4**). Phycocyanin concentrations, a measure of cyanobacteria densities, were moderate and followed a nearly identical pattern to that displayed by chlorophyll.

Different bird species had different distribution patterns along the central axis of Farmington Bay (**Fig. 5**). Phalaropes (primarily *Phalaropus lobatus*) were very abundant in the northern part of the bay between Stations 3 and 5. Ducks (primarily Northern Shovelers, *Anas clypeata*) were most abundant at the southern end of the bay. American coots (*Fulica americana*) were also very abundant throughout most of the bay. American avocets (*Recurvirostra americana*) were only seen in the shallow

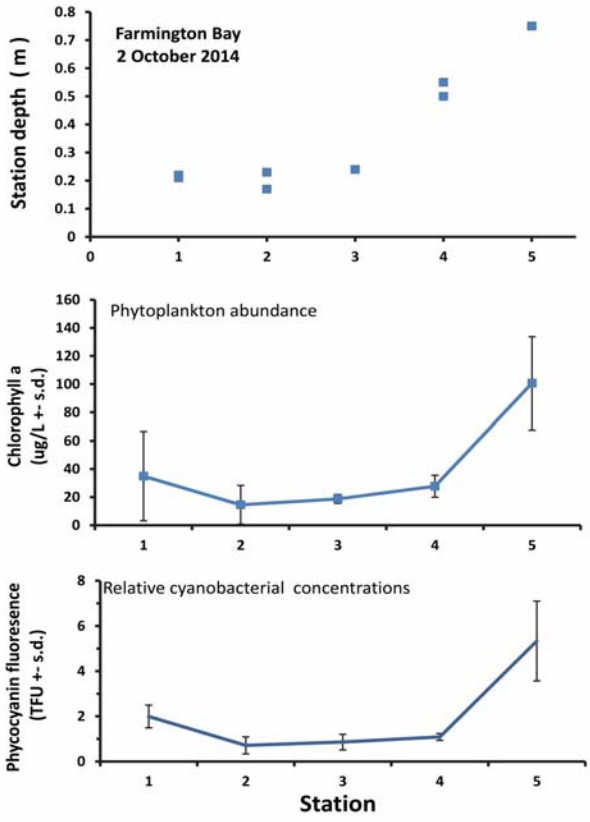

Figure 4. Changes in depth, chlorophyll concentrations and relative phycocyanin (cyanobacteria) levels in the surface waters (0.15-0.20 m) at the five stations in Farmington Bay on 2 October 2014.

waters between Stations 1 and 3. Gulls (primarily California gulls) were not abundant in the bay (**Fig. 4**). Other species observed in low numbers were white pelicans (3) and eared grebes (11).

Although densities of individual species varied greatly along the transect, the overall density was fairly constant between 2,500 and 3,000 birds per square kilometer (**Fig. 6**).

Discussion

On the sampling date, Farmington Bay had only a minimal salinity gradient from the south to the north. This was likely a consequence of the very low level of Gilbert Bay which minimized the movement of salt wedge into Farmington Bay through the bridge opening in the causeway. The flow fresh water from the Jordan River and the waste water treatment plants kept the entire bay at a salinity of ≤1%. Additionally, without a salt wedge intruding into the bay, there was not deep brine layer present. In previous years the salinity of Farmington Bay has reached 9% and an anoxic deep brine layer with high levels of toxic hydrogen sulfide has usually underlain much of the northern part of the bay (Wurtsbaugh et al. 2012). Consequently, densities of zooplankton and benthic invertebrates reported in the subsequent chapters may not be characteristic of the bay at higher water levels.

The high nutrient loading from the wastewater treatment plants and from non-point sources throughout the watershed cause the bay to be highly productive. At Stations 1-4 the chlorophyll levels of phytoplankton indicated mesotrophic or eutrophic conditions, whereas the 100 µg/L concentration at Station 5 indicates a hypereutrophic condition there. The high productivity has been documented previously by several investigators (See Wurtsbaugh et al. 2012; Marden et al. 2015).

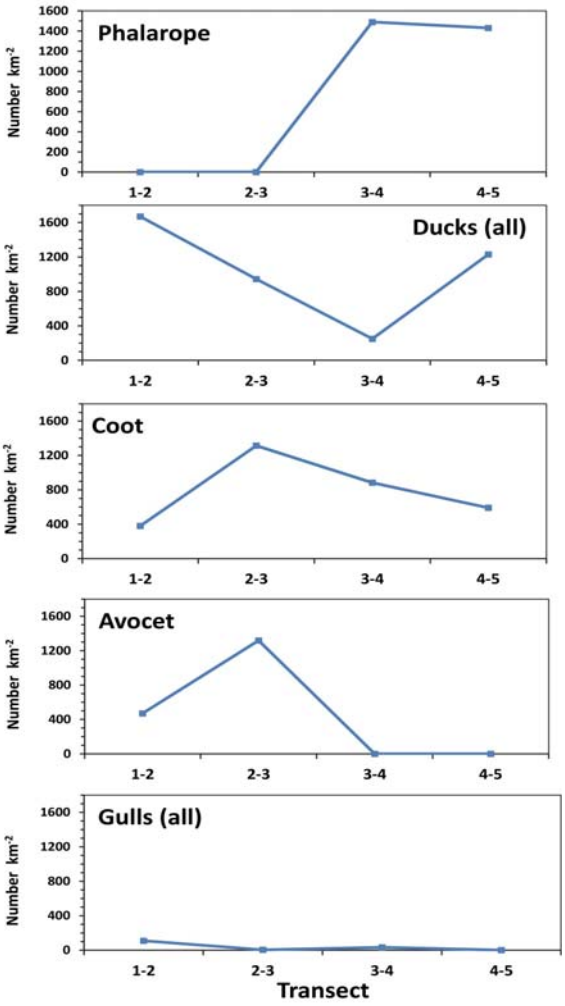

Figure 5. Densities of five different bird taxa estimated along transects between the five stations in Farmington Bay on 2 October 2014.

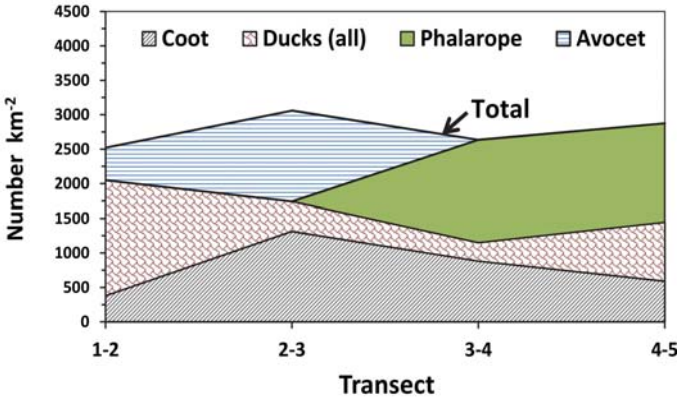

Figure 6. Summary of the abundances of the four main bird species observed between the stations sampled along the transect in Farmington Bay on 2 October 2014. Bird counts by John Neill.

However, the chlorophyll levels measured in the phytoplankton do not fully capture the amount of primary productivity available to grazers, as there was also a considerable amount of periphyton in the shallow reaches in the southern and mid-portion of the bay (**Fig. 7**). At these shallow stations Secchi depths were greater than the total depth, so high amounts of light reached the bottom and this, combined with high nutrient levels, fueled the growth of the periphyton. At Stations 1-2 there were floating mats of periphyton, but these were not included in our estimate of phytoplankton chlorophyll. At Stations 3 surface mats were not present, but there were attached algae on the compact sediments. Future work needs to include the periphyton as part of the sampling design, as it can be a substantial portion of the productivity of shallow aquatic systems.

Figure 7. Floating mats of periphyton near Station 2 in Farmington Bay. Station 2 is near the discharge point of the Sewage Canal and Northwest Oil Drain. Airboat is visible in the distance.

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Chapter 2

Great Salt Lake Zooplankton Grazing Rates on Algae and Cyanobacteria in Farmington Bay

Jonathan Hudson

Abstract

On 2-Oct-2014 the USU WATS 4510 class sampled five stations in Farmington Bay of the Great Salt Lake along a salinity gradient to characterize the zooplankton composition densities and biomass. Crustacean zooplankton densities at the southern and central part of the bay were generally low, although cyclopoid and harpacticoid densities were high at the southern-most station (40 and 12 L^{-1}, respectively). At the two northernmost stations the cyclopoid copepods, and the cladocerans *Daphnia* sp. and *Moina* sp. were very abundant, with combined densities over 150 L^{-1}.

Dominant zooplankton from three stations were used to measure grazing rates on the phytoplankton and cyanobacteria. The experiments were done in strained lake water with three levels of grazers in 50-ml beakers for 6 hr. The changes in chlorophyll was used as an index of grazing on the algae, and changes in the pigment phycocyanin was used as a measure of grazing on the dominant cyanobacteria, *Nodularia spumigena*. For Stations 3 and 5, grazing by *Daphnia* and *Moina* was measured and harpacticoid copepods were used for Station 1. Grazing rates of *Daphnia* and *Moina* were modest (ca. 0.25 ml $individual^{-1}$ day^{-1}), and the harpacticoid copepods did not appear to filter phytoplankton at all. Phycocyanin reduction was not detected in the harpacticoid and *Moina* treatments, but *Daphnia* filtered the cyanobacteria at rates comparable to the other phytoplankton. Because of the high zooplankton densities in the northern two stations, estimated community filtration rates were 24 and 49% of the water column per day, respectively. These results suggest that when the zooplankton are abundant, they impart a significant mortality rate on the phytoplankton, and help restrain the algal blooms.

Introduction

The Great Salt Lake has been an area of study in the last three decades and a rising concern of water quality issues including heavy metals (i.e. mercury and selenium), and nutrient loading. Nutrient loading in one of the lake's bays (Farmington) has led to eutrophication or in some cases hyper-eutrophication in past years (Wurtsbaugh, 2005). During algal blooms high densities of *Nodularia*, a toxic genus of cyanobacteria, have been reported (Wurtsbaugh, 2004). Along with high algal blooms reported in 2004 (Wurtsbaugh, 2004) *Artemia* and other zooplankton were abundant during certain seasons and they may improve water clarity by grazing the phytoplankton.

Although *Artemia*, a phytoplankton grazer, can have high impacts on algal populations and dominate seasonally, it would be beneficial to know the impact and abundance of other grazing taxa in Farmington Bay that are present when *Artemia* are not. Also, Farmington Bay normally has a salinity gradient (Wurtsbaugh, 2004, 2005) that may affect zooplankton distribution.

To help understand how zooplankton might influence the phytoplankton populations in Farmington Bay, we sampled them at five stations along the salinity gradient. Additionally, a controlled lab experiment looking at grazing effects of dominate zooplankton species found along the salinity gradient was done to determine whether the dominate taxa reduced algal concentrations.

There are two main concerns that need to be addressed when looking at grazing by zooplankton. Rigler (1961) highlighted previous studies that suggested there is a constant filtration rate that is proportional to the density of food particles until a certain concentration of food is reached. Rigler hypothesized that the filtering organism is limited by its own ability to ingest, or digest food. This is important to consider when looking at grazing rates as it applies to algal levels in a controlled experiment. If algal levels are high, the zooplankton may become satiated, and reduce their grazing rate. Likewise, if there are too little algae the zooplankton may eliminate all the algae before the end of the experiment making it impossible to calculate the grazing rate. Consequently, having the correct amount of algae is important for a successful experiment.

Methods

Field—Stations were selected to spatially represent Farmington Bay and capture the salinity gradient (see Chapter 1). Two replicates separated by 100 m were taken at each station to get a better estimate of the mean and an estimate of the variance. Temperature, dissolved and specific conductivity were collected at each replicate station with an YSI model 55 meter 0.2 meters under the surface. At the three deeper stations measurements were also taken 0.1 meters from the bottom but there was no significant difference with surface values. Salinity was measured at each station using a portable refractometer. Chlorophyll samples were also collected at each station by submerging a 1 liter container in approximately 0.2 meters under the surface and then placed in a cooler.

Zooplankton for identification and enumeration were collected using a vertical tow net with a diameter of 30 cm and mesh size of 153 µm. At each station the net was lowered until it was 10 cm off the lake bottom and then retrieved vertically at approximately 1 m sec^{-1}. The contents were then transferred to pre-labeled containers and preserved in ~2% Lugol's solution and stored in a cooler. Live zooplankton samples for the lab experiment were taken using the same methods at Stations 1, 3 and 5 and stored in a cooler. Water for the lab experiment was collected at the same stations as the live zooplankton and was filtered through a 64-µm screen to remove the macro-zooplankton. At Utah State University campus the live samples were placed in 19-liter holding buckets and aerated.

Laboratory methods—Each sample was sub-sampled using a Hensen-Stempel pipette to provide at least 100 organisms to count (Lind, 1974). Identification and enumeration were done at the same time using the same subsample and the J.G. and P.R. Needham (1962) key for crustaceans. The zooplankton samples were counted at 30x magnification in circular counting chambers. Average lengths were obtained by measuring 10 random organisms from each group under a dissecting microscope at 30x and recording micrometer units which were then converted into millimeters. Average lengths were then used to estimate the biomass of each taxa using the equations of Benke et al. (1999) for corixidae, and Watkins et al. (2011) for other zooplankton.

Initial chlorophyll and phycocyanin algal pigment levels were measured using a fluorometer. For the chlorophyll analyses, 10 ml of water from each station was filtered through a 1-µm A/E glass fiber filter then frozen to lyse the phytoplankton and help in the extraction process. Then the filters were placed into 10 ml of 95% ethanol to extract the chlorophyll. The extracted chlorophyll was measured using the non-acidification method of Welschmeyer (1994) on a Turner 10AU fluorometer, and the phycocyanin was quantified *in vivo* using an optical kit provided by Turner.

Grazing experiment—For this experiment I used the dominate taxa present at Stations 1 (harpacticoid copepods), and at 3 and 5 (the cladocera, *Daphnia* and *Moina*). The experiment was set up with three densities of each species with a control, low and high grazing pressure. The control group had no zooplankton while the low and high levels had densities targeted to graze 30 and 75 % of the water, respectively, with three replications at each level for each species. Vials were individually labeled, then randomly assigned a treatment level. Table 1 shows the densities of each treatment level.

Table 1. Treatment densities (number/L) for the laboratory experiment (multiply by 0.05 to get the number in each 50-ml beaker).

Taxa	Control	Low	High
Daphnia sp.	0	40	100
Moina sp.	0	160	400
Harpacticoid copepods	0	500	1160

Fifty milliliters of strained water collected the day before was used as the grazing medium for the experiment. Each species was placed in the water from the station they were taken from (i.e. *Daphnia* was placed in water from Station 5 from where they were collected). Individuals were taken from their

holding buckets using a glass tube and counted into a 100-ml Erlenmeyer flask. The experiment then ran in the dark for 6 hr. The temperature in the room started at 15.3° C (time 1200) and ended at 17.5° C (time 1802). At the end of the experiment 10 ml of water from each flask was extracted for chlorophyll analysis and filtered using the methods described above. Approximately 20 ml of water was used for the phycocyanin using the methods described above.

Filtration rates were calculated as:

$$\frac{\ln(\text{pre}) - \ln(\text{post})}{\text{density} * \text{time}}$$

Where "pre" and "post" represent the initial and final chlorophyll *a* or phycocyanin concentrations in each beaker.

This gave us the total amount of chlorophyll that was grazed by the zooplankton as our response variable. The resulting data was then analyzed with linear regression using the R statistical package. Using these variables gives us a fraction of water filtered per individual as the slope coefficient.

Results

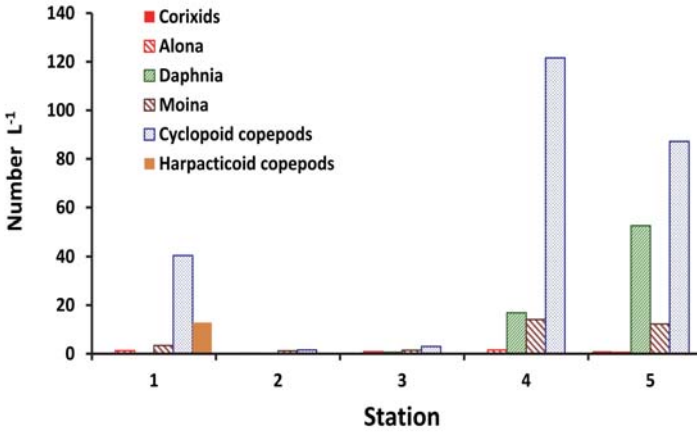

Figure 1. Densities of different zooplankton taxa at five stations in Farmington Bay.

Composition—Zooplankton taxonomic compositions and total biomass differed between stations especially between Stations 1, 2, 3 and 4, 5 (**Fig. 1; Table 2**). The composition at Station 1 was dominated by copepods consisting of harpacticoid and cyclopoid copepods (67 ind. L^{-1}) with few cladocera consisting of *Alona, Daphnia, Moina* and *Bosmina* (4 individuals L^{-1}). Ostracoda and two unidentified zooplankton made up the rest of the composition and were classified as other (17 individuals L^{-1}). At Stations 2 and 3 we saw similar compositions but with much lower densities (all groups were < 8 individuals L^{-1}). At Station 3 corixidae were present in low densities (0.2 individuals L^{-1}). At Station 4, *Daphnia* (17 individuals L^{-1}) and *Moina* (14 individuals L^{-1}) dominated the cladocera with a few *Alona* (1.6 individuals L^{-1}). Copepods were all cyclopoids (121 individuals L^{-1}) and nauplii with no harpacticoids present. Also at Station 4 we saw corixidae in greater numbers (0.4 individual L^{-1}). Station 5 was similar to Station 4 except we saw even higher densities of *Daphnia* (53 individuals L^{-1}) and corixidae (1.1 individuals L^{-1}).

Invertebrate biomasses at Stations 1-3 were all less than 200 µg/L, whereas at Stations 4 and 5 biomass was greater than 1000 µg/L (**Fig. 2**). Biomass was dominated by copepods at Station 1, cladocera at Stations 2 and 3, whereas copepods and cladocera were co-dominate in biomass at Stations 4 and 5. Also, where we saw an increase in crustacean biomass at Stations 4 and 5, corixidae appeared.

Table 2. Densities of zooplankton at the five stations in Farmington Bay. Mean ± standard deviations of the samples of two replicates at each station.

	Corixids		Cladocera								Copepods				Ostracoda	
			Alona		Bosmina		Daphnia		Moina		Cyclopoid copepods		Harpacticoid copepods			
Station	#/L	s.d	#/L	s.d	#/L	s.d	#/L	s.d	#/L	s.d	#/L	s.d	#/L	s.d	#/L	s.d
1	0.00	0.00	1.30	1.50	0.04	0.06	0.00	0.00	3.38	1.89	40.46	38.42	12.87	19.57	11.13	15.40
2	0.00	0.00	0.25	0.18	0.00	0.00	0.06	0.08	1.21	1.55	1.56	1.70	0.11	0.16	0.23	0.01
3	0.18	0.25	0.84	0.68	0.00	0.00	0.64	0.70	1.45	0.35	2.98	1.92	0.00	0.00	6.25	1.37
4	0.43	0.39	1.57	1.78	0.00	0.00	16.87	21.18	14.08	14.12	121.57	116.32	0.00	0.00	3.18	0.50
5	1.07	0.28	0.59	0.83	0.00	0.00	52.72	7.17	12.27	12.68	87.17	31.86	0.00	0.00	2.95	4.17
Grand Total	0.34	0.46	0.91	0.99	0.01	0.02	14.06	22.74	6.48	8.65	50.75	65.26	3.53	10.61	4.75	6.62

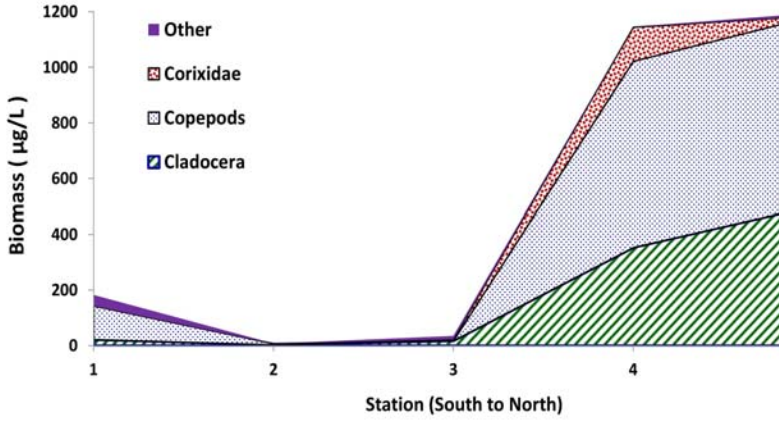

Figure 2. Biomasses of different zooplankton taxa at five stations in Farmington Bay.

Experimental Measurements of Grazing Rates —The treatments with *Daphnia* and *Moina* significantly decreased chlorophyll *a* ($p < 0.05$), whereas the harpacticoid copepods did not reduce algal concentrations ($p > 0.05$), and actually showed increasing post chlorophyll levels after the 6-hr grazing trial (**Fig. 3**). No significant slopes ($p > 0.05$) were found for phycocyanin concentrations for *Daphnia*, *Moina* or copepod treatments. However, at $\sigma = 0.10$ we saw a significant slope for *Daphnia*. Again we saw an increase in phycocyanin levels leading to positive slopes suggesting that phycocyanin levels

actually increased (see **Fig. 4**). Actual chlorophyll levels in each treatment after the 6 hours of grazing are shown in Appendix I.

Coefficients on the regression slope were used to estimate individual filtration rates for each treatment species. Filtration rates were much lower than expected (<1% ind^{-1}, planned for 15% ind^{-1}). As will be discussed later, this may be due to the organism's ability digest food compared to the maximum filtration rate at which the organism can filter (Rigler, 1961). Table 2 shows the filtration rates I acquired from our linear regression slopes which were converted into percent per individual per day.

Filtration (clearance) rates for *Daphnia* and *Moina* feeding on phytoplankton (Chl. *a*) were relatively similar, near 0.5% of the water filtered per individual per day. The filtration rate of Daphnia on cyanobacteria (as indicated by the pigment phycocyanin) was also similar, but the variance of this estimate was high. As mentioned, the experiment with harpactocoid copepods didn't show any significant reduction in chlorophyll or phycocyanin, suggesting immeasurable filtration rates for this taxa.

Table 2. Clearance rates for *Daphnia*, *Moina* and harpacticoid shown in percent of the water column cleared per day, per individual. Total individual clearance rates are shown on the bottom row. Error terms are standard deviations. Rates for harpacticoid copepods and Moina grazing on cyanobacteria (phycocyanin) were not significant.

Taxa	Chlorophyll	Phycocyanin
Daphnia sp.	0.51 ± *0.18*	0.45 ± *0.52*
Moina sp.	0.57 ± *0.20*	—
Harpacticoid copepods	—	—

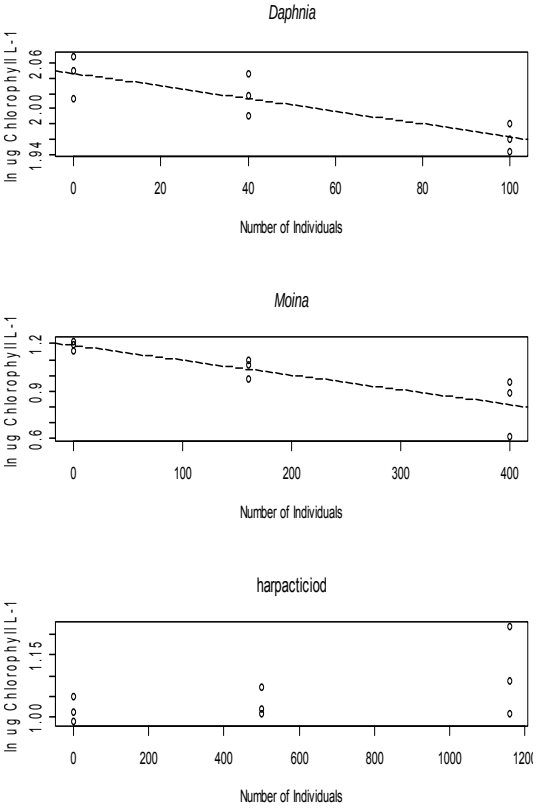

Figure 3. Regressions of post-chlorophyll concentrations (µg L^{-1}) for *Daphnia, Moina* and harpactocoid copepods as a function of densities of grazing animals. Significant slopes at 0.05 for *Daphnia* (p-value: 0.0033) and *Moina* (p-value: 0.0032) suggest that both *Daphnia* and *Moina* can effectively graze algae. There was no significant trend for harpacticoids (p-value: 0.1218) suggesting that they do not have a significant grazing impact on algae.

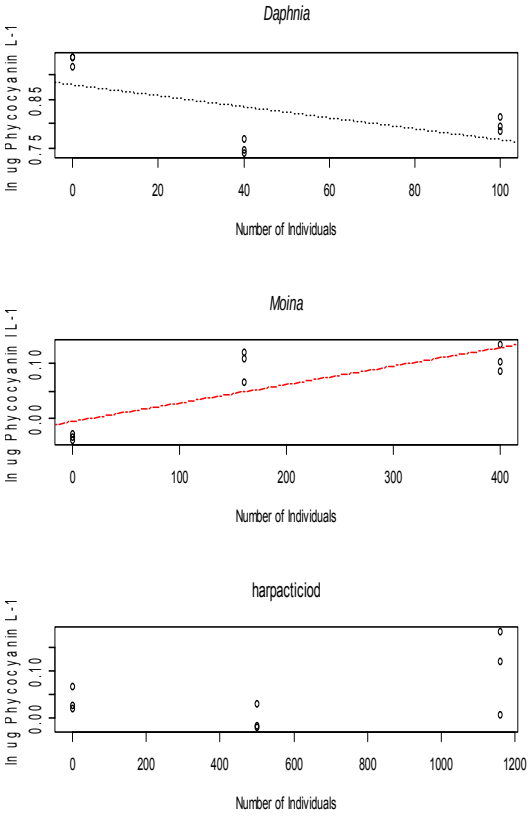

Figure 4. Figure 3 shows regression of post phycocyanin in µg liter-1 for *Daphnia, Moina* and harpacticoid treatments. None of the treatments showed a significant negative slopes at σ = 0.05 that would suggest grazing, but at σ =0.10 *Daphnia* is significant. This suggests that *Moina* and harpacticoids do not have a significant effect on cyanobacteria by grazing whereas daphnia may be able to graze cyanobacteria. Also, noted is the significant increasing trend for *Moina* that suggests there is an increased amount of phycocyanin post treatment.

Community filtration rates were estimated using the densities for *Daphnia, Moina* and harpacticoids measured from the field sampling then multiplying them by the calculated grazing rate for each taxon. Table 4 shows these community rates given in percent of the water column cleared per day. At Stations 1-3 where zooplankton densities were relatively low, estimated community filtration rates were less than 3% per day. However, at Stations 4 and 5 the higher densities of grazers increased the community filtration rates to 24% and 49%/day, respectively. Only Daphnia showed a marginally significant grazing rate on cyanobacteria (phycocyanin pigment indicator), and this resulted in estimated filtration rates by this population of 17% and 53%, respectively, at Stations 4 and 5.

Table 3. Estimated daily percent of water column filtered using chlorophyll (all algae) and phycocyanin (cyanobacteria) filtration rates calculated in the laboratory, and densities of each taxa measured from field samples. Rates are shown for each taxa and a community estimate for all species combined. For example, we estimate that the zooplankton community at Stations 4 and 5 filtered 24% and 49%, respectively of the chlorophyll *a*.

Taxa	Station 1	Station 2	Station 3	Station 4	Station 5
			Chlorophyll		
Daphnia sp.	0	0.1	0.5	12.6	39.0
Moina sp.	2.8	1.9	1.2	11.7	10.2
Harpacticoid copepod	0	0	0	0	0
Community Total	**2.8**	**2.0**	**1.7**	**24.3**	**49.2**
			Phycocyanin		
Daphnia sp.	0	0.1	0.6	17.2	53

Discussion

The composition and density of zooplankton in Farmington Bay changed greatly at the different stations but the factors causing these changes are difficult to determine given the limited scope of our study. We can only speculate given observations in the field. Salinity changed from 1% at the north end down to 0.3% on the south end suggesting salinity may be influencing zooplankton survival and/or population growth rates. Also, factors such as water current changed from deeper to shallower going north to south with a stronger current on the southern end. At Station 2 we recorded a velocity of 0.2 m/s across the shallow bay. These velocities may have swept zooplankton out of the southern zone as the reproductive replacement rate could have slower than the loss rate due to advection northward. Unfortunately, we only measured the water velocity at a single replicate at one station, so the exact advection rate is unknown. Nevertheless, it is possible that the low densities at the southern end were partially due to the water currents in the bay at the time we sampled.

The filtering rates of the zooplankton were low compared to potential rates. Lampert (1987), for example, reports filtering rates of Daphnia near the size of ours (mean = 1.1 mm) near 1 ml individual^{-1} hr^{-1}. At this rate, a single Daphnia could have cleared 6 ml, or 12% of the 50 ml in the experimental

flasks in the 6 hr. experiment. However, we found much lower rates of only 0.5% day^{-1}. The low filtering rates seen in our experiment may have been caused by satiation due to the availability of high phytoplankton concentrations. Rigler (1960) showed that feeding rates, the amount of phytoplankton cleared from the water, were equal to particle concentrations at or below a certain threshold and didn't change at concentrations above this threshold. Rigler also found that filtration rate was not constant over time when food concentrations were above the threshold.

Since Farmington Bay was meso- to hypereutrophic at the time of sampling, with chlorophyll levels at the stations used in the experiment ranging from 12-120 µg/L, the zooplankton may not have filtered at maximum capacity for the full duration of the experiment. This may explain the low filtration rates that I encountered, making our estimated filtration rates relevant only for similar chlorophyll levels. This also would affect the outcome of my regression models by not finding a significant filtration rate when one may have existed. We say this because at the initial chlorophyll levels in the experiment (highest: 124 µg L^{-1}, lowest: 12 µg L^{-1}) the zooplankton may not have been able to make a significant impact on the algae in the 6 hours of the experiment given their grazing rates at those levels.

Despite the low individual filtration rates of the zooplankton, the community filtration rates were still moderately high in the northern two stations (24-49% day^{-1}) due to extremely high zooplankton densities there. These rates mean that vulnerable phytoplankton taxa would suffer a 24-49% mortality rate due to the zooplankton grazing. The cyanobacteria (dominated by *Nodularia spumigena*) also appear to be vulnerable to grazing, at least by *Daphnia*, as phycocyanin decreased in treatments with this grazer. However, more work is need to verify this, as the regression coefficient for the decrease in pigment concentration was only significant at $p = 0.10$. Additional work is also needed to test the filtration rates of the harpactocoid copepods (and cyclopoids) because the experiment suggested that increasing copepod densities in the experiments actually increased the amount of phytoplankton in the flasks. This may have been an artifact due to a carry-over of high-algae water when we were adding the copepods. Since so many copepods were used, a considerable amount of water was transferred to the beakers. In future experiments, the zooplankton need to be suspended in water with identical chlorophyll levels to that that will be used in the experiment, so that any carry-over of water will not change the initial conditions.

Our finding that *Daphnia* may be able to graze *Nodularia* (as measured by the reduction in phycocyanin pigments) is supported by a study done by Tillmanns et. al. (2008) where he showed that not only did 21 out of 29 zooplankton species tested ingest a diet containing cyanobacteria, but showed they had positive growth rates on that diet. Tillmanns et al. (2008) also showed that the filamentous form of cyanobacteria was more easily grazed than the single celled forms. Farmington Bay at times has high concentrations of *Nodularia*, a filamentous cyanobacterium containing phycocyanins. When present, *Daphnia* may help reduce the populations of this toxic species.

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Appendix I. Final mean chlorophyll levels in treatments with different grazing zooplankton taxa at three different densities.

	Density (#/L)	Final Chlorophyll (ug/L)	Relative Phycocyanin (TFU)
Copepods	0	10.4	1.09
	500	10.8	1.00
	1160	13.0	1.29
Daphnia	0	110.6	8.49
	40	104.2	5.65
	100	91.4	6.30
Moina	0	15.4	0.92
	160	11.2	1.26
	400	6.9	1.29

Chapter 3

Effects of the invertebrate predator, *Trichocorixa verticalis* on zooplankton in Farmington Bay, Great Salt Lake (Utah)

Chantel Rasmussen

Summary

On October 2, 2014 we sampled zooplankton and corixid abundance at five stations at Farmington Bay of the Great Salt Lake. Zooplankton from each station were identified and measured. Microcosms representing conditions at Stations 1, 3, and 5 were created in the laboratory to measure *Trichocorixa verticalis* (water boatmen) predation on zooplankton. For these stations the dominate zooplankton taxa, *Daphnia* sp. (2 sizes) and *Moina* sp., were identified to use in the laboratory experiment. In the experiment 0-10 corixids/liter were used to understand how different densities of corixid affect zooplankton. The prey (zooplankton) and predators (corixid) were placed in beakers and left for 24 h. Predation rate estimates for Station 1 were inconclusive. In the Station 3 treatments, we estimate that corixids killed 24% of the *Moina*/day, but only 10%/day of the *Daphnia*. In the Station 5 experiment, small *Daphnia* were consumed at a much higher rate (26%/day) than large *Daphnia* (14%/day). When the rates measured in the laboratory experiments were applied to the density of corixids measured in the field, we estimate that corixids could eat 15-25% of cladocera per day. This experiment shows that corixids are capable and do prey on zooplankton other than *Artemia*. Corixids in Farmington Bay are predators that significantly impact the density and diversity of zooplankton. By removing the grazing zooplankton, corixids may allow larger populations of phytoplankton to flourish and promote eutrophication in Farmington Bay.

Introduction

When studying food webs in aquatic ecosystems most people think of fish as the top predator. But what happens when the area of interest has few to no fish? In the situation of Farmington Bay of the Great Salt Lake, the top predators are believed to be invertebrates and migratory birds. In this project I focused on the effect and role a specific invertebrate, the backswimmer, *Trichocorixa verticalis*, on the zooplankton population. The presence of a top predator can affect the biomass of organisms in lower trophic levels. Predation ultimately has a cascading effect down throughout the food chain (Dodds 2002), producing a trophic cascade effect. As stated in Horrocks (2004), it is extremely important to understand corixid predation and prey selection because of the impact invertebrate predation has on the food web of the Great Salt Lake. This information could be used when making management decisions (Dodds 2002).

In 2003 there were six zooplankton taxa identified in Farmington Bay (Wurtsbaugh 1992). Of those six, the dominate species were; brine shrimp (*Artemia franciscana*), harpacticoid copepods (*Cletocamptus albuquerquensis*), *Bosmina* sp., and corixids (*Trichocorixa verticalis)*. In Farmington Bay *Artemia* densities were variable seasonally. In the months of April and May densities were high but declined sharply just after June. It seems as if the brine shrimp can establish high densities but populations are not stable. Conversely, densities of the invertebrate predators (corixids) rose during late June. Corixids had high densities throughout the summer, even after the brine shrimp and most other crustacean prey were no longer present in Farmington Bay. As pointed out in Wurtsbaugh (1992), the stress conditions of Farmington Bay could be one reason that the brine shrimp and crustacean zooplankton may not have survived. Another possibility is that corixid predation reduced their abundance. Horrocks (2004) studied corixid predation on brine shrimp and found that corixids feed on brine shrimp abundance. However, if brine shrimp are at extremely low densities, how is it possible for the corixids to survive? This question brings me to my hypothesis that corixids, *Trichocorixa verticalis,* prey upon other species of zooplankton when brine shrimp are at low densities.

Corixids are described as oval shaped, streamline, fully aquatic species ranging from 1-5 mm long. These hemipterans have dark bodies, large compound eyes, short antennae, and legs modified for deep diving, fast swimming and eating. The small forelegs are evolved for feeding and stridulating, the middle for clinging, and the hind legs provide locomotion. The thorax provides a protective shield for the air sack. Corixids spend most of their time on the bottom, only coming to the surface to renew their air storage. The water-boatmen's wings provide them with an easy form of dispersal allowing them to use all available habitats (Scudder, 1976). They are omnivorous, feeding on both plant and animal matter.

Most corixidae species are found in freshwaters but some taxa have been found in saline environments in high abundances. It is only recently that researchers have focused on corixids in saline areas. Scudder (1976) explains that there are 12 genera of water-boatmen living in environments of over 3% salinity. Hammer (1986) describes the salinity range of *Trichocorixa verticalis* as 3-9%. However, Hayes (1986) found low densities in Farmington Bay above salinities of 6%. Because of their tolerance to hypersalinity, these taxa of corixids have become invasive species in three different continents; Africa,

Europe, and Australia (Van De Meutter 2010). This salinity niche explains why corixids thrive in the Great Salt Lake area, especially Farmington Bay.

It is possible that corixids could play an important role in the ecosystem of Farmington Bay, as the salinity is often in their preferred range. Understanding which species corixids prey upon could help us understand the important role each individual plays in the Great Salt Lake area. Understanding their abundance and possible importance in the trophic cascade will help us understand eutrophication in Farmington Bay.

Methods

Study Area and Sites— The Great Salt Lake is divided into four distinct bays; Farmington, Gilbert, Bear River and Gunnison. For this project I focused on the Farmington Bay area. Farmington Bay is bordered by heavenly populated areas. Inflows from the south are affected by direct municipal treatment plant discharges and the inflow of the Sewer Canal. These discharges have high levels of nutrients and the canal previously discharged heavy metals into Farmington Bay (Wurtsbaugh 2012). High nutrient levels are also introduced by non-point sources. The high nutrient loading causes Farmington Bay to be hypereutrophic (Wurtsbaugh et al. 2012). Much of the fresh water is brought in from the south and flows to the north where it meets Gilbert Bay. Reverse flows from this hypersaline bay of the Great Salt Lake results in a salinity gradient along the north-south axis of Farmington Bay. The salinity gradient is subject to seasonal changes. For example during spring runoff salinity levels in 2004 were 4% compared to 10% in the fall (Wurtsbaugh2004). However, salinities were much lower during my study (see Chapter 1).

Figure 1. Google Earth image showing the geographic location of each of the five sampling sites at Farmington Bay of the Great Salt Lake.

Five stations in Farmington Bay were selected along a transect (**Fig. 1**). Doing this placed the stations along the deepest area of the bay. Station 1 was on the shallow, south side of the bay, closest to the sewer canal and the waste water plants. Station 5 was located closest to the causeway and was the furthest point to the north. Background limnological conditions at the five stations are described in Chapter 1.

Field Sampling—At each of the Stations two replicate samples were taken using a vertical tow of a 30-cm diameter zooplankton net with a 153-µM mesh size. This mesh should have collected nearly all crustacean zooplankton, but most rotifers would have passed through. Each sample was placed in a plastic cup, preserved in 3-4% formalin, and labeled with station information. These samples were kept in a dark room at 20°C until removed for classification. At Stations 1, 3, and 5 Farmington Bay water was

taken for my laboratory experiment. Additional vertical or horizontal zooplankton tows were taken at these three sites to collect corixidae and other zooplankton for the laboratory experiment.

To determine the dominate zooplankton taxa, each sample from a study station was examined under a microscope. A subsample of known volume was taken from each sample cup using a Hensen-Stempel pipette to obtain at least 200 individuals. The subsample was placed into a counting chamber and the individual zooplankton were counted and measured with an ocular micrometer at a magnification of 25-30X. Biomasses were estimated with length-weight equations (see Chapter 1).

Laboratory Experiment—In the laboratory, the Farmington Bay water was filtered using an 80-µ mesh to remove crustacean prey species. The corixids from each station were then removed, placed in a single aerated bucket containing filtered water, and held at 20°C. To standardize hunger levels, as suggested in Simonis (2013), predators were starved for 24 h prior to the start of the experiment. Then, 200 ml of filtered Farmington Bay water was placed into each of six beakers for each of the three study sites (18 total). Each beaker received water from the corresponding locations at Farmington Bay. At each of the three sites there were two control beakers that had no predators, two beakers with one corixid per beaker (i.e. density = 5/L), and two beakers with two corixids per beaker (10/L). The prey species were removed from the aerated buckets with a small glass tube, identified and placed into their respective beakers. For the station 1 treatments a random selection of 40 copepods was placed in each beaker. The beakers representing Station 3 each received 20 *Daphnia* sp. and 20 *Moina* sp. Finally, the beakers representing Station 5 received 20 large *Daphnia*, and 20 small *Daphnia*. The average size of each prey taxa is shown in Table 1. The corixids were then removed from the bucket using the same small glass tube and placed into the beakers. The beakers were then left alone for 24 hours in lighting of 150 µE m^{-2} sec^{-1} and a 12:12 light-dark. After 24 hours the corixids were removed from all of the beakers and preserved in 3-4% formalin. The zooplankton in each of the beakers was filtered on 80-µM mesh, identified and counted.

Table 1. Sizes of zooplankton used in the experiments.

Experiment Station	Species	Average Length (mm)
1	Harpacticoid copepods	0.59
1	Cyclopoid copepods	0.63
3	*Daphnia*	1.22
3	*Moina*	0.48
5	Large *Daphnia*	1.73
5	Small *Daphnia*	0.62

Data Analysis—To understand the effects of corixid on the zooplankton, clearance rates were calculated for each of the experiment treatments. As shown in Hambright (2001) by calculating the clearance rate you can understand how many zooplanktons in the water column are being consumed. The final number of individual prey in each beaker was plotted on a graph with predator density as the independent variable. Clearance rates were determined by fitting the data to a log-linear regression. When the data is fit with a power regression, the negative of the slope will show the clearance rate (fraction of water cleared per predator per day). A slope of 0 indicates that no predation has occurred (Hambright, 2001).

The actual predation rate in the field at each of the five stations in Farmington Bay was calculated as:

C = d * e

Where: C = estimates the portion of the water in the lake that is being cleared
d = Corixid density (#/L)
e = average clearance rate obtained from experiment

Results

***Prey densities along the transect*—**In collaboration with Jon Hudson, fellow student, we found that the zooplankton taxonomic composition and total biomass differed between stations (**Figs. 2, 3**). The lowest biomasses, <200 µg/L were found at Stations 1-3. These biomasses contrast with those at Stations 4 and 5 that were >1000 µg/L. Station 1 was dominated by harpacticoid and cyclopoid copepods with a few *Alona, Daphnia, Moina, and Bosmina* (**Fig. 3a, b**). We also found Ostracoda and two unidentified zooplankton. At Station 2 and 3 we saw similar compositions to that at Station 1, only with lower densities. Station 3 had no harpacticoids and very few *Daphnia*. At Station 4 we found an increase in biomass and the dominate taxa shifted. The zooplankton at Station 4 consisted of mostly adult and copepodid copepods and copepod nauplii. We also found some *Daphnia, Alona,* and *Moina.* Station 5 was similar to Station 4 but with increased numbers of *Daphnia* (**Fig. 3a**).

Corixid densities in Farmington Bay increased from the south to the north. No corixids were found at Stations 1 and 2 (**Fig. 3c**), and at Station 3 and 4, mean densities were only 0.35 and 0.43/liter, respectively. At Station 5

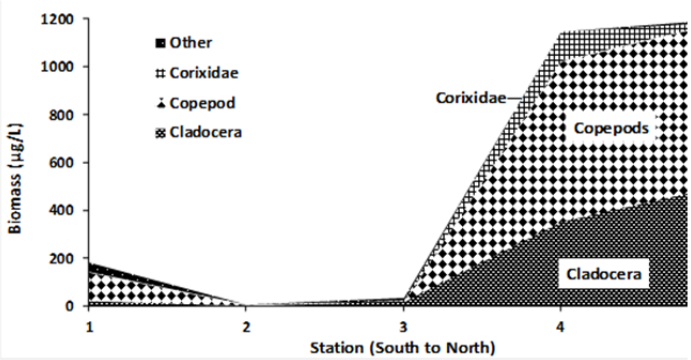

Figure 2. Zooplankton biomass estimates for Farmington Bay of the Great Salt Lake. Species have been grouped together in; corixidae, copepod, cladocera, and unknown. A dramatic increase is seen at Stations 4 and 5.

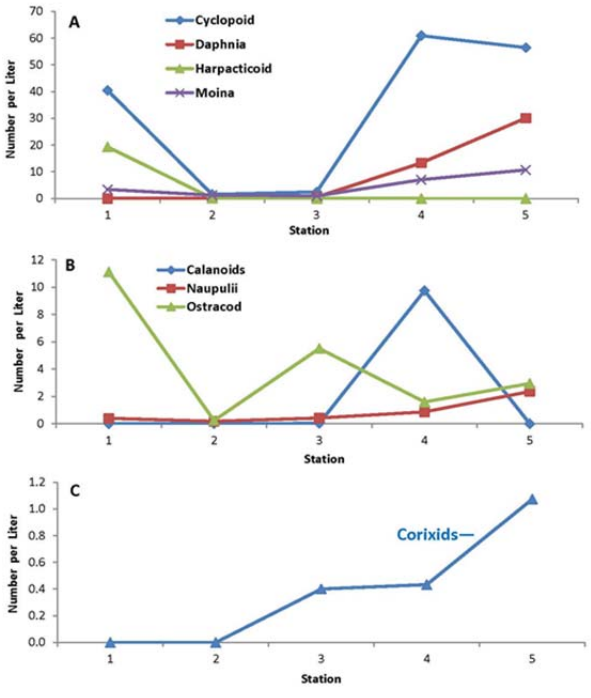

Figure 3. Densities of zooplankton at five stations in Farmington Bay on 2 October, 2014

mean densities increased to 1.07/liter.

***Predation experiment*—**In the Station 1 experiment the predation rates were negligible: there seemed to be no relationship between predator numbers and consumption rates (Appendix 1). This could be due to a number of things: initial number counts were not accurate, corixids in the experiment were sick or small or the corixids might have had a harder time capturing and handling the copepods that were used as prey in this experiment. To correctly understand the relationship between corixids and copepods further experimentation is needed.

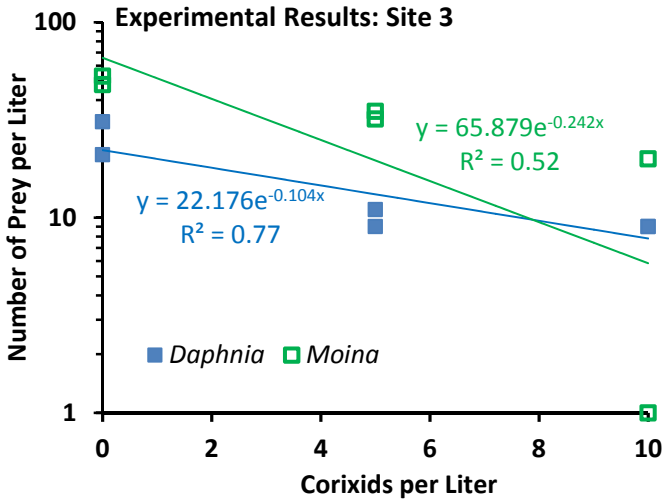

Figure 4. Final densities of *Daphnia* and *Moina* in the Station 3 experiment. The solid blue boxes represent *Daphnia* and the boxes outlined in green represent *Moina*. The exponents in the equations represents the clearance rates.

In water from Station 3 increasing corixids distinctly reduced prey densities in the beakers (**Fig. 4**). In water from Station 3 *Moina* were consumed at a higher rate than were *Daphnia*. In water from Station 5, small *Daphnia* were consumed at a much higher rate than were large *Daphnia* (**Fig. 5**).

When the sizes of prey used in the experiments were regressed against clearance rates, there was a suggestion that small cladocerans were eaten faster than large prey (**Fig. 6**), but because of the small sample size this result was not significant (p = 0.17).

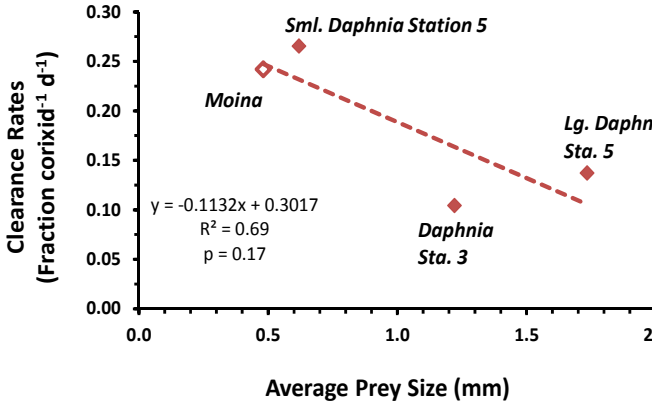

Figure 6. The relationship between prey size (mm) and clearance rates by the predator *Trichocorixa verticalis* in laboratory experiments. Smaller prey were consumed at a higher rate than the larger individuals, but the regression was not significant.

***Laboratory experiment & estimated predation rates in the bay*—**Estimated clearance rates varied considerably among species of prey (Table 2). At Station 3 clearance rates were 24% corixid^{-1} day^{-1} for *Moina* and 10%/day for *Daphnia*. At Station 5 the clearance rates were of 14% corixid^{-1} day^{-1} for large *Daphnia* 26% for the small *Daphnia* (**Fig.** 7).

The experimentally-determined rates and the natural densities of corixids in Farmington Bay were used to estimate predation rates in Farmington Bay (**Fig. 7**). The average of these clearance rates (18.7% corixid^{-1} day^{-1}) from the experiment Station 3 and 5, were used to understand the rate at which the corixid could remove cladocerans from the water in Farmington Bay. At Stations 1 and 2 there were no

corixids so the clearance rate would have been zero. At Station 3, mean corixid density was 0.4 L^{-1} resulting in a field estimate of 7.5% day^{-1}. At Stations 4 and 5 I estimated respective clearance rates of 8% and 20% day^{-1}. However, the estimated predation rate on small *Daphnia* at Station 5 was 28% day^{-1}.

Table 2. Experimental estimates of clearance rates of *Trichocorixa verticalis* feeding on different species of prey from Farmington Bay.

Station	Prey	Mean prey Size (mm)	Clearance Rates (% day^{-1} $corixid^{-1}$)
3	*Daphnia*	1.22	10%
3	*Moina*	0.48	24%
5	Big *Daphnia*	1.73	14%
5	Small *Daphnia*	0.62	26%

Discussion

The experiment showed that corixids should have an effect on the abundance of zooplankton in Farmington Bay. Horrocks (2004) reached a similar conclusion when studying corixid predation on brine shrimp. Between the clearance rates calculated in this experiment and those done by Horrocks (2004), the predation rates suggest that corixid have a significant impact on the waters at Farmington Bay. Also, my clearance rate estimates suggest that smaller prey are consumed at a faster rate than large prey (**Fig. 6**). However, harpacticoid and cyclopoid copepods used in the Station 1 experiment had respective mean lengths of only 0.59 and 0.63 mm, and they were not eaten in significant numbers, suggesting that prey size is not the only factor regulating consumption.

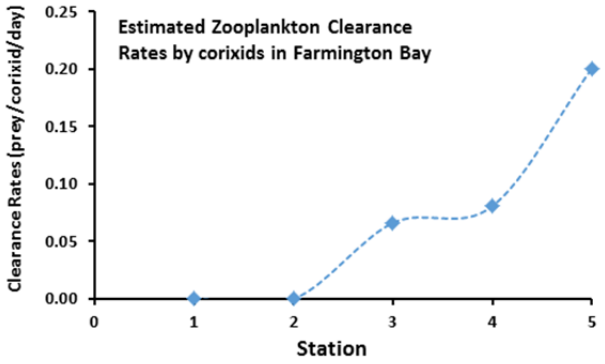

Figure 7. Estimated zooplankton clearance rates (fraction of water cleared per day) due to corixid predation in Farmington Bay on 2 October 2014. Note that at Stations 3-5 have the highest density of corixids and therefore the highest clearance rates. Compare to corixid density graph, Figure 5.

At high densities the corixids could significantly impact the zooplankton population. Wurtsbaugh (unpublished data) found mean densities of 0.79 corixids L^{-1} at northern stations in Farmington Bay during from May-October, 2005-2006, with densities as high as 5 L^{-1}. Utilizing these densities and the estimated clearance rate obtained for cladocerans in my experiment, predation rates would be from 15% (mean) to 94% day^{-1} (max). Consequently, the actual predation rates are highly dependent on the densities of corixids in different areas of the lake.

This experiment demonstrated that corixid are capable of preying on cladoceran zooplankton when brine shrimp are not abundant. It is important to understand what influence the corixids have on

Farmington Bay because it may be important in the structuring of the food web in the Great Salt Lake (Wurtsbaugh, 1992).

In conclusion, corixids in Farmington Bay are predators that significantly impact the density and diversity of zooplankton at each respective site and could be considered when making management decisions to improve the water quality of the bay (Dodds 2002).

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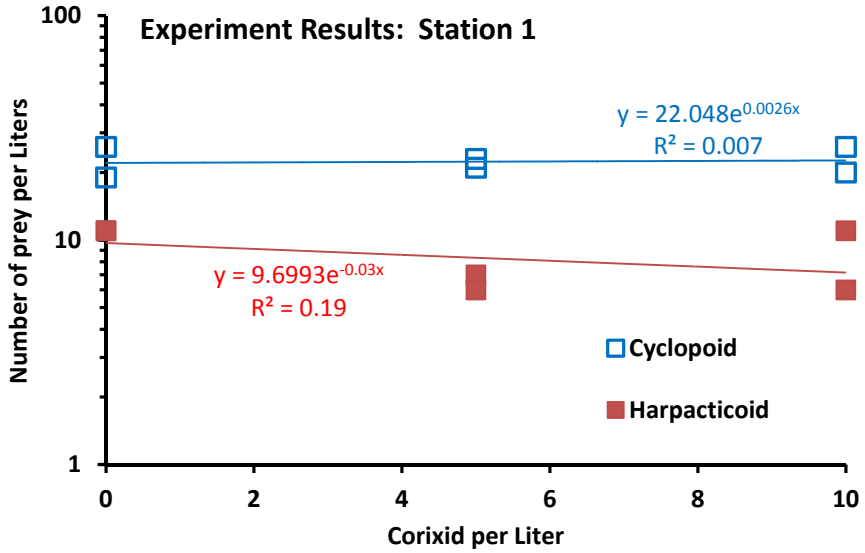

Appendix 1. Copepod prey densities at three densities of corixid predators using Station 1 prey. Corixid predation had no significant effect on the copepods in this experiment.

Chapter 4

Benthic Macroinvertebrates in Farmington Bay, Utah and Possible Factors that Affect their Population Densities

Clayton Winter and Wayne Wurtsbaugh

Abstract

Farmington Bay is located on the southeast side of the Great Salt Lake and its main water in flow is the Jordan River and other river systems. Very little has been done to study the current populations of benthic invertebrates in the bay with the most recent preliminary sampling from 2010. Consequently, on 2 October 2014, we sampled at five stations (**Fig. 1**) along the north-south axis of the bay to determine the species composition and biomass of the invertebrates. Due to the low water level in the bay salinities at all stations were $\leq$ 1%The invertebrates from twenty Eckman Dredge samples were analyzed to Order and a few to genus and species. The dominant macroinvertebrates were the Chironomids that represented over 80% of individuals at four out of the five stations. Densities of chironomids declined from the southern-most stations to the north. Station 1 had most of the individuals (35,000 m^{-2}) and diversity. At station 5 near the causeway bridge the lowest density of invertebrates were found (90 m^{-2}). This data provides a foundation for possible future studies to be conducted on Farmington Bay's benthic macroinvertebrate populations.

Introduction

Farmington Bay is located the Great Salt Lake Valley. The bay is on the southeast corner of the Great Salt Lake. The purpose of the study was to identify and quantify the different populations of benthic macroinvertebrates within Farmington Bay. Farmington Bay is mostly famous for the awful smell it produces when wind events occur and also for its waterfowl hunting. Like most urban water environments, human pollution plays a big role in the habitat and its overall health. The bay provides an area of refuge for birds, and is believed to produce large quantities of food for migratory birds throughout most of the year until it freezes during the winter months. However, studies have been done on the benthic invertebrates in the bay (Miller et. al

Figure 1. Station locations sampled in Farmington Bay. Two replicates were taken at each station, separated by 100 meters.

2010, Marcarelli and Wurtsbaugh 2003, Wurtsbaugh and Marcarelli 2006). Consequently, it is important to study the community of benthic macroinvertebrates because of their potential importance for the bird community. Additionally, the composition of the invertebrates may be useful as a bioindicator to determine the degree of water pollution of the bay (Miller, et al. 2010).

Figure 2. Eckman dredge sampler used in collecting benthic macroinvertabrates.

Salinity is likely a dominant factor determining the abundances and species in the bay, as salinities can range from near fresh water to 9%. The freshest water occurs in the south where the Jordan River discharges. The saltiest water is in the north where intrusions of hypersaline Gilbert Bay water occur. Consequently, Farmington Bay is similar to a coastal estuary. Wolf et al. (2009) categorized the salinity tolerance of benthic macroinvertebrates in coastal waters in Germany. Their study provided large amount of information about the different benthic families and their salinity tolerances and water chemistry tolerances. Chironomids, the dominant taxa in Farmington Bay (Miller 2010) can survive in some drought stricken environments and many taxa can tolerate poor water quality (Pinder et al.1986).

The primary questions in my study were: (1) what taxa were present; (2) how did the taxonomic composition change throughout the bay and what densities were present. These factors were addressed relative to changes in habitat characteristics of depth, Secchi depth, salinity, and pH.

Study Area and Methods

Located in the Great Salt Lake Valley, the Farmington Bay study area consisted of five stations ranging from near the inflow of the Jordan River to the causeway near the Antelope Island Marina (**Fig**. 1) Two replicates that were ~100 m apart were sampled.

Figure 3. Placing the sample into a screen bucket to be washed.

Airboats were obtained from the Utah Division of Natural Resources and the Utah Water Quality Agency which allowed us to reach the shallow sites. The samples were collected on October 2nd, 2014.

An Ekman dredge sampler (**Fig. 2, 3**) was used to collect the samples. The dimensions of the Ekman dredge was 15 x 15 cm wide, and 15 cm for a height,

but only ~5 cm deep of benthic material was collected. Once the dredge was closed it is hauled to the surface and the sediments were sieved in a bucket with 500 micrometer mesh. At each of the replicate stations two dredges were collected to make sure enough benthic invertebrates were collected for my study as well as to provide invertebrates for a metal study done by another student (see Chapter 4). The invertebrate samples were preserved with 95% ethanol. The jar was filled halfway with the sample and the other half with ethanol. At each station fellow students collected data on the water depth, chlorophyll *a* concentrations, Secchi depth, salinity (refractometer), and a vertical profile of temperature, oxygen and conductivity were taken.

The benthic invertebrate samples were processed using standard protocols of the National Aquatic Monitoring Center (Miller et al. 2010) and the US Geological Survey. The samples were sieved again through a 500 micrometer sieve and the sorting of individuals from organic and inorganic material began. The sieve was placed in a wash bucket to float the contents of the sample. Because of low expected invertebrate densities, the entire dredge sample was analyzed Most samples took 4-5 hours to process, but samples from Stations 1A and 1B took ~10 h due to the amount of periphyton in them. The samples were dominated by Chironomidae: we donated 50 Chironomids from each station for a metal concentrations study but did include the numbers in our data set. During the sorting process a dissection microscope was used at a power of 10X. The dominant Chironomid taxa were counted and measured with an ocular micrometer at 10X power. With the help of a colleague, Matt Schroer, we were able to classify some of the chironomids to tribe and genus. For this, chironomids were mounted in resin on a microscope slide, and the characteristics of the head capsules were analyzed using a compound microscope at 100X for most of the identifications. Length measurements of the chironomids were converted to dry weight assuming that their shape conformed to a cylinder with a diameter of 20% of the length and a specific gravity of 1.05 (Wetzel and Likens 1991) and a dry:wet ratio of 0.10 (Dermott and Paterson 1974).

Figure 4. Types of substrate at each station. Sta. 1 sediments at far left.

Results

The physical and chemical characteristics of the bay changed from the south to the north (**Fig. 4, 5**). Depth varied from approximately 0.21 m in the south (Station 1) to 0.75 m in the north near the causeway. Salinities were lower than expected, varying from a mean of 0.3% in the south to 1.0% in the north. There was a change in type of substrate and a decline in periphyton from Station 1 to Station 5. Station 1 had more algal growth compared to station three and five. Water temperatures ranged from 12-19°C, but this range was likely the result of sampling Station 5 at 10:00 in the morning and working southward to Station 1 which was not sampled until 14:30. Oxygen levels were high and supersaturated at some stations, likely as the result of the periphyton growth. pHs, measured with pH paper, varied from 6.8 to 8.0. These, and other characteristics are shown in Appendix 1, as well as in Chapter 1.

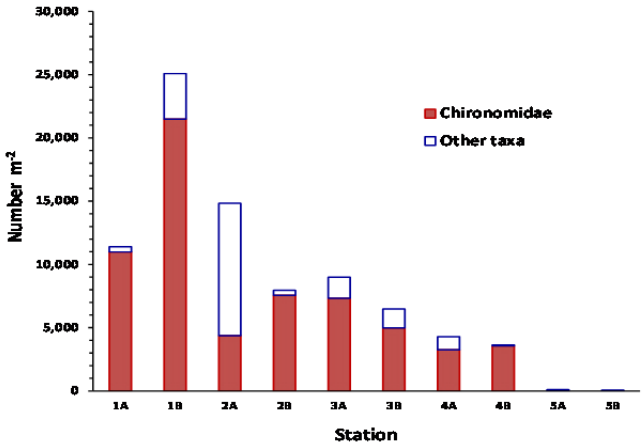

Figure 6. Total density of invertebrates along the north to south gradient in Farmington Bay. Two replicates, separated by 100 m, we collected at each station. The top of each histogram shows the total density.

There was a decline in the densities of invertebrates from Station 1 to Station 5 (**Fig. 6**). Mean densities of all invertebrates were near 18,000 m^2 at Station 1, but declined to only 86 m^2 at Station 5. Chironomids dominated the fauna at nearly all of the sites sampled, except at Station 5 (**Fig. 7**). Gastropods were moderately abundant at stations 1-4, and especially at station 2A where they represented about 25% of the organisms. The scud, *Gammarus* sp., was also abundant at Station 2A. Station 5 was dominated by Ephyridae, albeit at low densities.

At Stations 1-4 Chironomidae (midges) dominated the benthic fauna (Table 1). Two sub-families of midges, Tanypodinae and particularly Chironominae, dominated at most stations.

The biomass of dominate chironomids is shown in **Fig. 8**. Mean biomasses of midge larvae ranged from 43 g m^{-2} at Station 1, to 0 mg m^{-2} at Station 5, with a mean of 16.9 g m^{-2}.

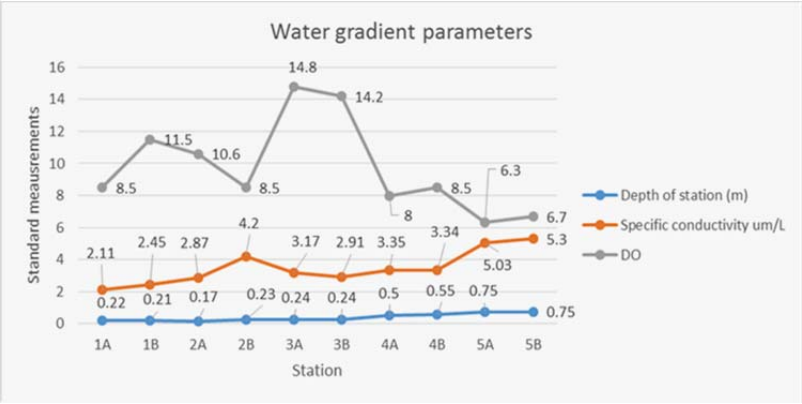

Figure 5. Physical-chemical changes in limnological parameters at the five stations.

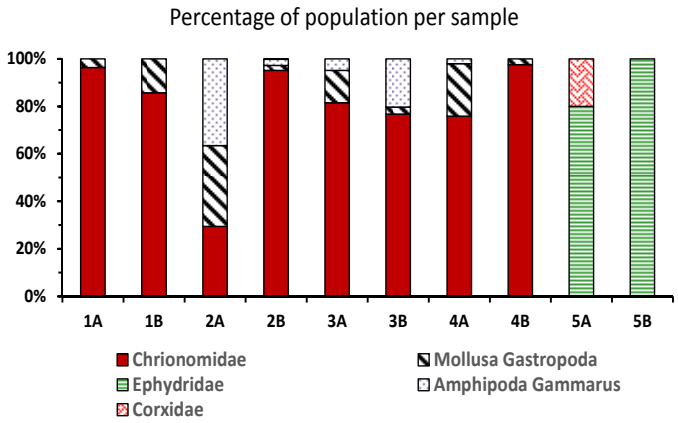

Figure 7. Percentage composition of the benthic invertebrates at each site sampled along the transect.

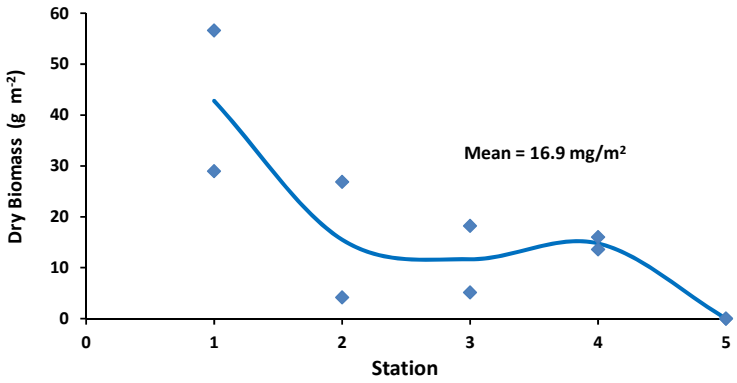

Figure 8. Biomasses of Chironomidae (midges) at five stations in Farmington Bay on 2 October 2014.

Table 1. Densities of benthic organisms at the five stations in Farmington Bay.

				Density (#/m2)							
Station	Latitude	Longitude	Salinity (%)	Chironomidae: Orthocladiinae	Chironomidae: Chironominae	Chironomidae: Tanypodinae	Chironomidae Total	Mollusa Gastropoda	Ephydridae	Amphipoda (Gammarus)	Corxidae
1A	40.9408	-112.0030	0.3	65	5,711	5,216	10,991	409	0	0	0
1B	40.9396	-112.0015	0.3	0	5,409	16,078	21,487	3,599	0	0	0
2A	40.9131	-112.0512	0.4	0	1,315	3,060	4,375	5,043	0	5,409	0
2B	40.9139	-112.0518	0.5	1,616	2,866	3,082	7,565	172	0	194	22
3A	40.9873	-112.1375	0.5	1,207	6,034	86	7,328	1,228	0	431	0
3B	40.9870	-112.1390	0.5	776	4,181	22	4,978	194	0	1,315	0
4A	41.0827	-112.1554	0.6	0	3,254	0	3,254	948	0	86	0
4B	41.0289	-112.1568	0.6	43	2,845	668	3,556	86	0	0	0
5A	41.0639	-112.2277	1.0	0	0	0	0	0	86	0	22
5B	41.0645	-112.2266	1.0	0	0	0	0	0	65	0	0

Discussion

Our study demonstrated that Chironomid larvae were very abundant at most stations in Farmington Bay, and snails and Gammarus were also abundant at some sites. The biomass of the chironomids can be compared with the biomass of benthic invertebrates studied throughout the world (**Fig. 9**). The biomass we found in the bay was among the very highest reported from any lake in the world. This was expected given the low salinity at the time of the sampling, and the extremely high primary productivity of the bay (Wurtsbaugh et al. 2012). Additionally, sites 1-3 were very shallow (< 0.25 m) and light

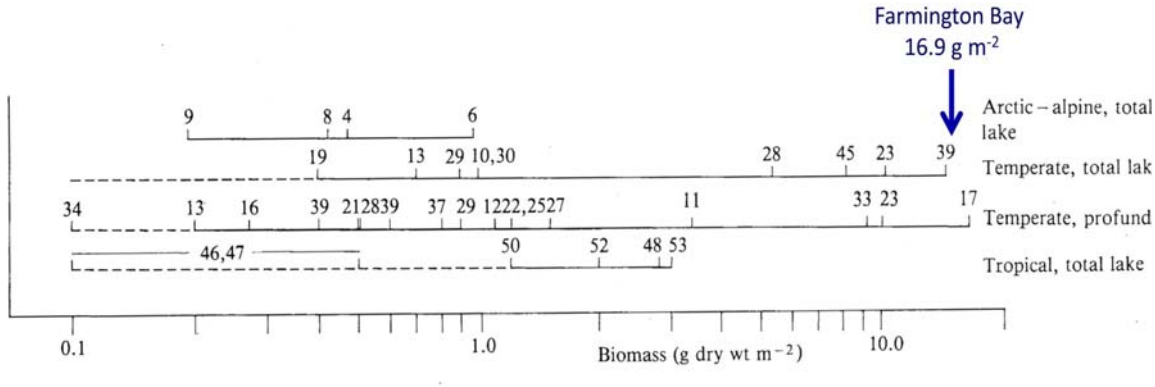

Figure 9. Comparison of the benthic invertebrate biomass of lakes of the world (Morgan 1980) and the mean biomass of Chironomid larvae found in Farmington Bay, Utah (2 October 2014). Each number above the horizontal axes represents a separate lake. The value for Farmington Bay only includes the dominant Chironomid taxa, and would be slightly higher if other taxa had been measured.

penetrated to the bottom and thus could support abundant production of periphyton to help sustain the benthic grazers.

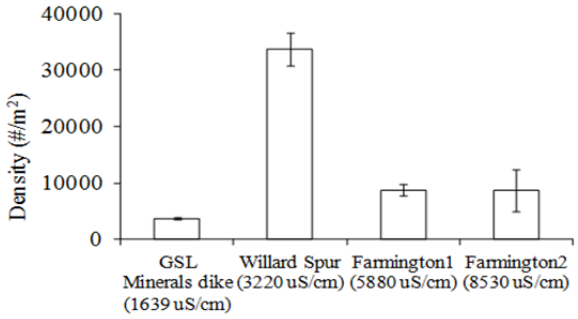

Figure 10. Densities of benthic invertebrates in Farmington and Bear River Bays (GSL Minerals dike and Willard Spur) in June-July 2010. Data from Scott Miller (2010).

The results of our study can also be compared with the benthic invertebrates found during a preliminary study of Farmington Bay in June-July, 2010 (**Fig. 10**; Miller, 2010). At that time, salinities (conductivities) in Farmington Bay were somewhat higher than when we sampled, but densities were similar to what we found at Stations 1-4. Similar to our study, Miller also found that Chironomids represented 84-97% of the invertebrates at the two sites sampled in Farmington Bay. Our short study, combined with his, indicates that chironomids are abundant and likely provide one of the abundant sources of food for the shorebirds that utilize the bay. Our single sample taken in early October provides only a snapshot of the potential dynamics of benthic invertebrates in the bay. Many chironomids are univoltine or bivoltine, but some can be multivoltine, especially among the subfamily Orthocladiinae, with continuous recruitment for much of the year (Pinder at el. 1986). Consequently, the diversity and the densities of chironomidae and other organisms could be considerably different in the spring and summer. Salinities also likely changed over the course of the year and at different sites, and this would likely change the abundances and species composition. Future studies will need to address the seasonal dynamics of the benthic invertebrates in the bay.

Salinities in Farmington Bay can be as high as 9% in the surface water, and even higher in the deep brine layer, and this would limit what benthic invertebrates could tolerate conditions in the bay (Wurtsbaugh et al. 2012). Most dipterans such as the chironomids that were so abundant cannot tolerate salinities as high as even 0.5%, but a few can tolerate salinities of 1% (Wolf et al. 2009). Because of the drought and low water levels in Farmington Bay when we sampled, exchanges with the high-salinity water of Gilbert Bay were not occurring, and consequently, salinities throughout the water column were $\leq$ 0.6% at Stations 1-4, and thus supportive of the chironomids. When salinities in Farmington Bay were 4-9% in 2005, an analysis of artificial substrates deployed in the bay indicated that chironomids were entirely absent (Wurtsbaugh and Marcarelli 2006). The benthic community then was 97.6% *Trichocorixa verticalis* (corixids), 1.6% *Ephydra hians*, and 0.8% *E. cinerea*. In contrast at similar depths in Gilbert Bay the community composition on the substrates was 99.1% E. cinerea. Similarly, when salinities were 8-9% in Farmington Bay in 2002, a limited sampling indicated that only *Ephydra* sp. were present (Marcarelli and Wurtsbaugh 2003).

The very low density of invertebrates at Station 5 where the salinity was 1% is puzzling. Some chironomids tolerate this salinity, as well as other euryhaline species such as brine flies. Nevertheless, densities of brine flies (*Ephydra* sp.) were less than 90/m^2. In contrast, Wurtsbaugh and Marcarelli (2006) found densities of *Ephydra hians* around 3200/m^2 on artificial substrates in Farmington Bay when

salinities were higher. The light penetration at Station 5 was relatively low in 2014 so that periphyton production may have been minimal, but the high production of phytoplankton in the water column should have provided an abundant rain of organic material to the bottom that could have provided food for benthic invertebrates.

However, Station 5, and indeed, much of the northern part of Farmington Bay is frequently underlain by a deep brine layer caused by a salt wedge of dense water intruding from Gilbert Bay. Because of the high biological productivity of the overlying water, the deep brine layer is anoxic and contains high concentrations of hydrogen sulfide (Wurtsbaugh and Marcarelli 2004). It is possible that the very low densities of benthic invertebrates we found at Station 5 was due to periodic intrusion (internal wave) of a salt wedge through the bridge in the Antelope Island Causeway. However, when we sampled, this was not present, as salinity and oxygen conditions were relatively uniform from the surface to the bottom. It is also possible that the 1% salinity we found at Station 5 was sufficiently high to preclude Chironomids from inhabiting that part of the bay. Additional work is needed to document invertebrate abundances at more normal salinities in the bay, and particularly when the deep brine layer is present.

Future researchers on the benthic invertebrate community will have to consider appropriate sampling equipment. Although we successfully used an Eckman dredge to sample the substrates and organisms, a considerable portion of the bay had very hard-pack sediments that were difficult to penetrate with the light Eckman dredge. In the shallowest waters we were able to push the dredge through the hard layer to get our sample, but had the water been deeper, this would not have been possible. Additionally, biostromes are present in the bay on the eastern edge of Antelope Island, and these cannot be quantitatively sampled with an Eckman dredge (Marcarelli and Wurtsbaugh 2003). Consequently, a variety of sampling devices may be needed to effectively sample this important component of the biota in Farmington Bay. Despite the limitations of our short-term study, we hope that our work will help to pave the way for future projects to further the knowledge of Farmington bay.

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Appendix 1. Station locations, salinities and other limnological characteristics at the five stations sampled in Farmington Bay, 2 October, 2014.

Station	Depth (m)	Latitude	Longitude	Salinity (%)	Temperature (C)	Oxygen (mg/L)	Secchi Depth (m)	Specific Conductivity (mS/cm)	pH (paper)	Characteristics
1	0.22	40.9402	-112.0023	0.28	18.9	10.0	> 0.2	2.28	6.75	Fine sediment with some periphyton growth; some oil smell
2	0.20	40.9135	-112.0515	0.45	18.6	9.6	>0.2	3.54	6.75	Fine sediment with some periphyton growth; strong smell of oil; ; water velocity ~ 0.2 m/sec (Rep A)
3	0.24	40.9872	-112.1382	0.50	14.8	14.5	>0.2	3.04	8.00	Hardpack sediment with sand below
4	0.53	41.0558	-112.1561	0.60	13	8.3	0.43	3.35	7.00	Higher turbidity
5	0.75	41.0642	-112.2272	1.00	12.4	6.5	0.41	5.17	7.00	Detrital material & excess spent casings from organisms

Chapter 5

Metal Concentrations in Benthic Invertebrates in Farmington Bay (Great Salt Lake) With Respect to Sediments

Carson Richards

Summary

Surficial sediments and invertebrate samples were collected in Farmington Bay of the Great Salt Lake in October, 2014 and analyzed for metal concentrations. Five sites across Farmington Bay were sampled with two replicates at each. Sediment concentrations where compared to Threshold Effect Concentration and Probable Effects concentrations established for fresh water. All priority metals (As, Cd, Se, Cu, Pb, Hg, Zn) had concentrations that exceeded the Threshold Effect Concentration in at least one station across the bay for both sediments. However, when compared to the Probable Effects Concentrations only one metal, selenium, exceeded the limit. Mercury, and particularly lead concentrations in the invertebrates, exceeded dietary thresholds for birds at one or more stations. Boron, iron, potassium, magnesium, manganese, strontium, and chromium all showed a significant correlation between concentrations in the sediments and in the benthic invertebrates. These results indicate that birds that feed upon invertebrates in Farmington Bay may be at some risk from the elevated metal concentrations there.

Introduction

Farmington Bay is the south eastern bay of the Great Salt Lake. It is separated from the Great Salt Lake by a causeway at the north end and Antelope Island in the west. High density urban areas are present to the east of Farmington Bay along the Wasatch front. Concentrations of some metals in Farmington Bay have been found to be above acceptable water quality criteria promulgated *for fresh waters* (Wurtsbaugh et al. 2012). The Great Salt Lake and Farmington Bay receive industrial, urban, mining and agricultural inputs from a 37,500 km^2 watershed which includes over 1.7 million people (Naftz et al. 2008). The majority of these inputs enter from the south east corner of the bay where there is a sewage/oil drain canal inflow (**Fig. 1**). The EPA has classified this canal as a superfund cleanup site due to metals contamination (The Forrester Group, 2001). The Jordan River, as well as treated sewage releases, also add to the inflow of Farmington Bay. There

Figure 1: Shows the oil drain at the south end of Farmington Bay. In the back ground you can see the metropolitan area and the refineries. Photo courtesy of Wayne Wurtsbaugh.

are outflows from Farmington Bay through culverts and a bridge at the north end of the bay, which spill into Gilbert Bay and the rest of the Great Salt Lake. Besides inputs from the oil drain, atmospheric deposition from metal smelting in the Salt Lake Valley is also an important contributor to the high metal concentrations (Wurtsbaugh et al. 2012).

Farmington Bay is very important for migratory birds in the pacific flyway. Birds passing through need a place to rest, feed and nest along the Great Salt Lake (Paton, 1995). Roberts (2013) summarized waterfowl and other bird diets in the Great Salt Lake. He found that most birds that utilized the Great Salt Lake relied heavily on benthic aquatic invertebrates as a food source. He also suggested that if invertebrate populations were reduced it would directly affect avian populations. It's also possible that if there are high concentrations of metals in the invertebrates these could be transferred to the birds which could be detrimental to their populations.

Because of potentially high metal concentrations in Farmington Bay I analyzed seven priority metals in the surficial sediments and the invertebrates that were highlighted by Waddell et al. (2009) and Wurtsbaugh et al. (2012). The priority metals analyzed were arsenic, cadmium, selenium, copper, lead, mercury, and zinc. In recent years selenium and mercury have received particular attention by researchers and managers interested in the Great Salt Lake. Data on other metals are presented in an appendix.

The primary hypothesis of this study was that there are no changes in metal concentrations from the north to the south end of the bay. My secondary hypothesis was that there are no correlations between metal concentrations in the sediments and in the benthic invertebrates.

Figure 2: Farmington Bay and showing all five sampling locations. Stations 5 being the northern most stations, closest to the rest of the Great Salt Lake.

Study Area and Methods

Study Area—We sampled five stations across the Farmington Bay from north to south (**Fig. 2**). We started with the northern most station near the causeway by Antelope Island and continued south across the bay. Sampling was by airboat due to low water levels, and lasted from mid-morning to late afternoon. Due to the low water level, there was very little salinity gradient across the bay: salinities ranges from 1% at Station 5 to 0.25% at Station 1. Weather was mostly sunny with some cloud cover. Water temps ranged from 15.3℃ in the morning to 17.5℃ when we finished. There was a large distance between Station 2 and 3, approximately 11 Km, due to the low water, and the danger of the air boats being stranded if they stopped in that area. Water depths ranged from 0.75 m at Station 5 and 0.17 m at Station 2. Table 1 shows site locations as well as other variables that changed across the bay.

Field Sampling—Sampling took place on October 2nd, 2014. At each station there were two replicates, which were separated by 100 m. At each replicate I took one sediment sample and one invertebrate sample. Once anchored at the station, preventing drift, I first took my invertebrate's sample using a 6" x 6" Ekman dredge. We used a 500-µm sieve to concentrate the invertebrates and remove sediments. We then transferred the invertebrates into jars and filled them with 95% ethanol for preservation. Then samples were labeled and stored in coolers for transportation to the lab. Sediment samples were taken concurrently with the invertebrate samples using a gravity Wildco gravity corer (**Fig. 3**). Once dropped over the side of the boat the device uses its own weight and gravity to penetrate into the sediments. It was then pulled up, plugged with a cork and sediments were forced to the top of the tube with a push rod. I then sampled the top 1 cm, assuming that that layer was all that would influence the benthic invertebrate community. The sample was stored in a plastic baggy.

Figure 3: Capping the bottom of the gravity coring device with a stopper on Farmington Bay. Photo courtesy of Wayne Wurtsbaugh.

Sediments were not homogenous across the bay. The sediments at Station 3 had a hard crust with softer sandy sediments below. Stations 1 and 2 had a distinct oil/ tar smell. There is a possibility this was coming from the nearby oil drain that comes into Farmington Bay near Station 2 (**Fig. 1**). The rest of the samples were silty, and Station 5 contained a lot of organic matter (Table 1).

Station	Replicate	GPS		Time	Temp	DO	% Salinity	Depth	PH	Substrate
1	A	40.94075	-112.003	1430	17.7	8.5	0.3	0.22	6.75	Silty
1	B	40.93956	-112.002	1450	20.1	11.5	0.25	0.21	6.75	Silty
2	A	40.91309	-112.051	1325	19.4	10.6	0.4	0.17	7	Silty
2	B	40.9139	-112.052	1351	17.7	8.5	0.5	0.23	6.5	Silty
3	A	40.98734	-112.137	1158	14.3	14.8	0.5	0.24	8	Hard crust, sandy
3	B	40.98703	-112.139	1245	15.3	14.2	0.5	0.24	8	Hard crust, sandy
4	A	41.08265	-112.155	1104	12.9	8	0.6	0.5	7	Silty, smelt like oil /
4	B	41.02885	-112.157	1130	13	8.5	0.6	0.55	7	Silty, smelt like oil /
5	A	41.06393	-112.228	924	12.4	6.3	1	0.75	7	Silty, smelt like oil /
5	B	41.06445	-112.227	1013	12.3	6.7	1	0.75	7	Silty, smelt like oil /

Table 1: Shows site locations as well as other variables that changed across the bay.

Laboratory Analyses—Processing of the sediments began on October 3rd, 2014. Sediments were oven dried at 70°C for approximately 72 hours. Once a constant weight was achieved, I ground the sediments in a mortar and pestle, to a consistent particle size. A 1 g subsample was sent to the Utah Veterinary Diagnostic Laboratory, Logan, Utah for metals analysis. There the nitric-acid leachable mineral concentrations in each sample were quantified using inductively coupled plasma mass spectroscopy (ICP-MS). One gram samples were digested in 10 ml trace mineral grade nitric acid in screw-cap Teflon tubes on a heat block at 90°C for 4 hours. The digests were diluted 1:20 with 18.2 MOhm ultrapure

water to provide a 5% nitric acid matrix prior to analysis. This resulted in a matrix match to the standards and quality control samples. Samples that had higher mineral content than the high standard were diluted 1:10 in 5% nitric acid and reanalyzed. Standard curves for all metals, except mercury, consisted of five concentrations between 10 and 2500 μg l^{-1}. The standard curve for mercury consisted of three concentrations from 2.5 to 10 μg l^{-1}. A quality control (QC) test sample was analyzed every fifth samples to validate analytical accuracy. The QC 11 sample had to be +/- 5% of the known mineral specifications to pass. If any samples failed the QC test they were then re-analyzed (Wurtsbaugh, 2012). The IPC-MS analysis provided data for many potentially toxic metals that are shown in table 1A of the Appendix. However, as mentioned previously, only the seven priority metals were analyzed in detail for this report.

The invertebrate samples were sorted in the National Aquatic Monitoring Center, Utah State University, by classmate Clayton Winters (Chapter 3). Chironomids were most abundant across the sites so they were used for my analysis. No chironomids were found at Station 5, so no data on the metal content of invertebrate was available there. Approximately 50 chironomids from each site were used in my analysis: they ranged from 7 to 15 mm in length and comprised primarily of the families Orthocladiinae, Chironominae, and Tanypodinae (see C. Winters in this report). Lab processing took place on October 8th, 2014. Invertebrates were cleaned with 18 Mohm deionized water then oven dried to constant weight at 70°C from October 8th until the 9th, approximately 27 hours. I then ground them up to a constant size using a mortar and pestle. A 1 gram subsample of the ground up invertebrates was then transferred into plastic, acid-washed plastic scintillation vials and sent off to the Veterinary Diagnostic Laboratory for analysis. The same process previously described above was used to analyze for metals.

Data analysis—For a statistical analysis of each metal, I used paired t-tests to determine if invertebrate concentrations differed from metal concentrations in the sediments. I also created graphs to show if there were correlations between the sediment and invertebrate concentrations. P values less than 0.05 were considered significant.

Lastly I compared the individual metal concentrations in the sediments to the Threshold Effect Concentrations (TEC) and the Probable Effect Concentrations (PEC) established for fresh water sediments (MacDonald et al. 2000). These allowed me to estimate how toxic each individual metal concentration might be to the organisms in Farmington Bay. To better compare the Threshold Effect Concentrations of all the priority metals to each other, I calculated the field concentrations as a ratio of the Threshold Effects Concentration and the Probable Effect Concentration using these formula:

$$TEC\ Ratio = \frac{Field\ Concentration}{Established\ TEC} \qquad PEC\ Ratio = \frac{Field\ Concentration}{Established\ PEC}$$

These ratios allowed me to more easily compare the metals at different sites on a similar scale. One can then identify which metals surpasses the threshold and at which sites.

I also compared the metal concentrations in the benthic invertebrates to dietary threshold effects that have been suggested as possibly causing harm to birds that would ingest them (Waddell et al. 2009). Again, the metal concentrations in the invertebrates were expressed as a ratio of the dietary thresholds.

Results

Sediment–invertebrate correlations and spatial patterns—Surprisingly, statistical correlations between metal concentrations in the sediments and in the invertebrates were not significant for any of the priority metals ($p > 0.05$). The correlation for arsenic was nearly significant with a p-value of .055. I did go beyond the priority metals to see if there were significant correlations between sediment and invertebrate concentrations. Seven other metals did show significance at the < 0.05 level: boron, iron, potassium, manganese, aluminum, strontium, and chromium (Table 1A, Appendix).

The overall patterns in metal concentrations between invertebrates and the sediments were scattered. I used paired t-test analysis to see if metals in the sediments were significantly different from the concentrations of metals in the invertebrates. The t-test only showed one of the priority metals, arsenic, to show a significant difference between concentrations in the sediments and in the invertebrates ($p < 0.000$; **Fig. 4**). Though many were not significant, there were a few trends. The first was sediments having higher concentrations than the invertebrates at all sites, as with cobalt (**Fig. 5a**). Opposite of that were a few metals that had higher concentrations in the invertebrates than in the sediments (e.g. selenium; **Fig. 5b**). Most common and most surprising were the graphs that had higher concentrations in the sediments than the invertebrates at Stations 1, 2, and 4 with Station 3 having higher concentrations in the invertebrates than the sediments (**Fig. 5c**).

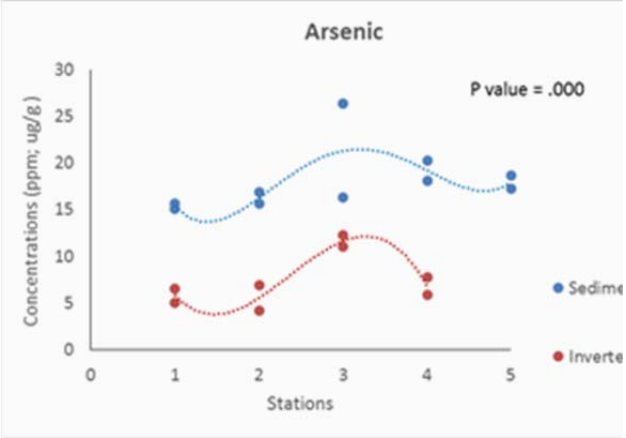

Figure 4. Arsenic concentrations in the sediments at five stations in Farmington Bay. It also show the t-test analysis p-value with a 95% confidence interval.

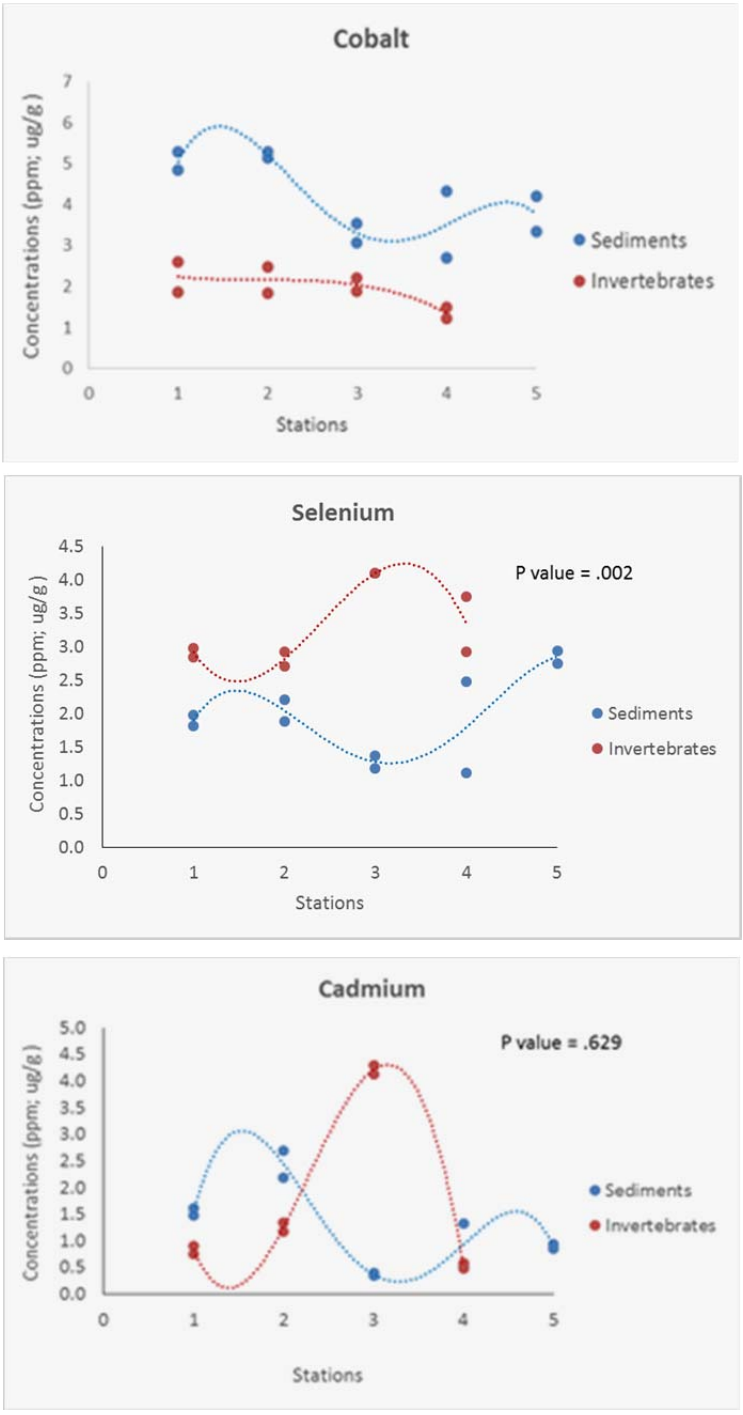

Figure 5. Cobalt (a), selenium (b) and cadmium (c) concentrations in sediments and invertebrates at 4-5 stations in Farmington Bay. Not the much higher concentrations of cadmium in the invertebrates at Station 3.

Threshold and Probable Effects Concentrations

Sediments—Analyses of the surficial sediments across Farmington Bay showed that all priority metals were present in high concentrations. When the sediment samples were compared to the Threshold Effects Concentrations established for fresh water, all priority metals exceeded the limit at one or more stations across the transect (**Fig. 6**). At Stations 1 and 2, the two stations closest to the sewage / oil drain, every priority metal exceeded its Threshold Effect Concentration. In particular, mercury's concentrations at Station 1 was 0.38 ppm, it then doubled at Station two at 0.82 ppm and then decreased across the transect ending at 0.17 ppm. Copper and lead, along with most other metals, showed similar results, starting fairly high and increasing at Station 2, then decreasing across the rest of the transect (**Fig. 6**).

Concentrations of the priority metals in relation to the Probable Effects Concentrations indicated that none of these contaminants exceeded this level in the sediments (**Fig. 6**, below). However, the same general pattern shown by the TEC was present, with the highest ratios for mercury, copper, lead, cadmium and zinc at Station 2.

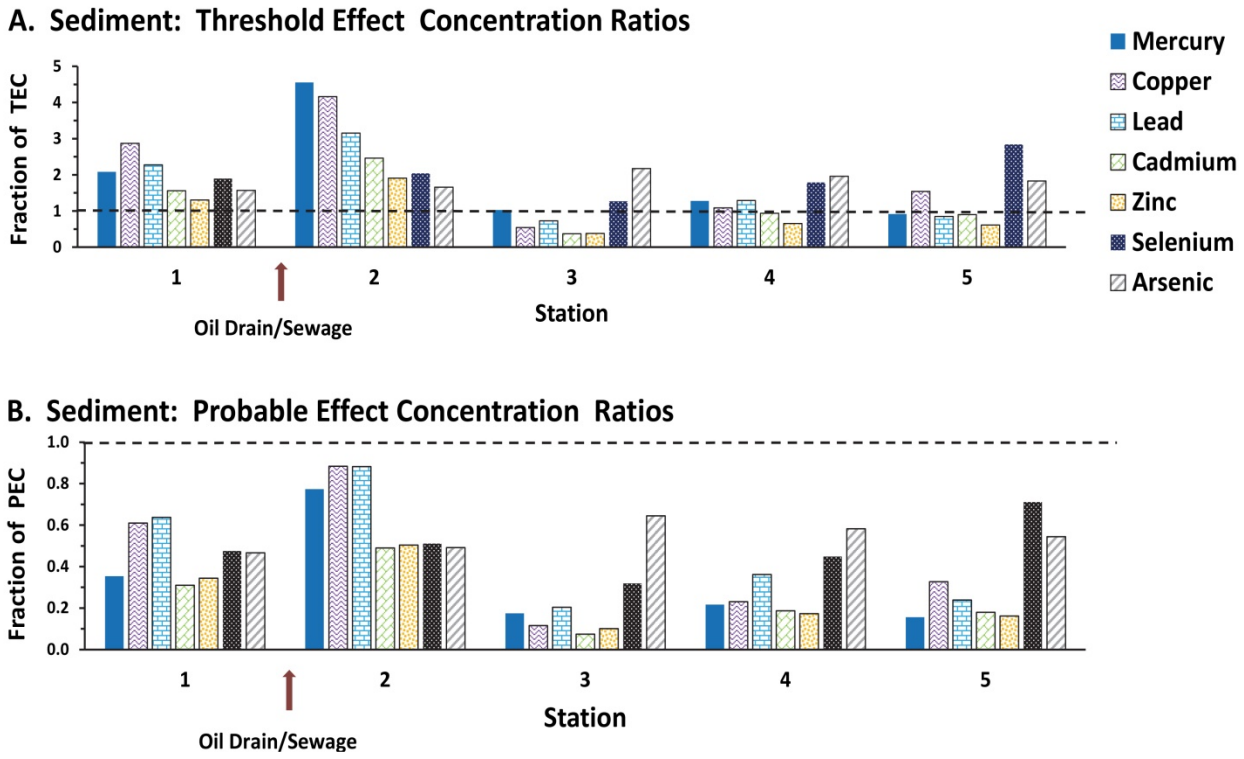

Figure 6. Levels of priority metals and metalloids in the sediments of Farmington Bay at the five stations expressed as a fraction of the Threshold Effects Concentrations (A), and the Probable Effects Concentrations (B). Note that the metals had the highest ratios at Station 2, whereas the metalloids (Se, As) had fairly constant ratios across the bay. Dotted lines show Threshold Effects Concentrations and Probable Effects Concentrations.

***Invertebrates*—**The invertebrate metal ratios had a different pattern than the sediment concentrations (**Fig. 7**). The invertebrate concentrations relative to the dietary thresholds for birds were fairly high at Station 1 and 2, but peaked at Station 3 and then decreased markedly at Station 4. In contrast, the metal concentrations in the sediments peaked at Station 2.

A 2-way analysis of variance of the sediments and invertebrate metal concentrations was done using SYSTAT 8.0 (SYSTAT 1992) that highlighted this difference (Appendix Table 2A). The significant p values ($p \leq 0.02$) indicated that metal concentrations were not homogeneous in the bay, and the significant interaction terms indicated that not all metals behaved spatially in a similar fashion. This was true of both the analysis of the sediments, and for the invertebrates.

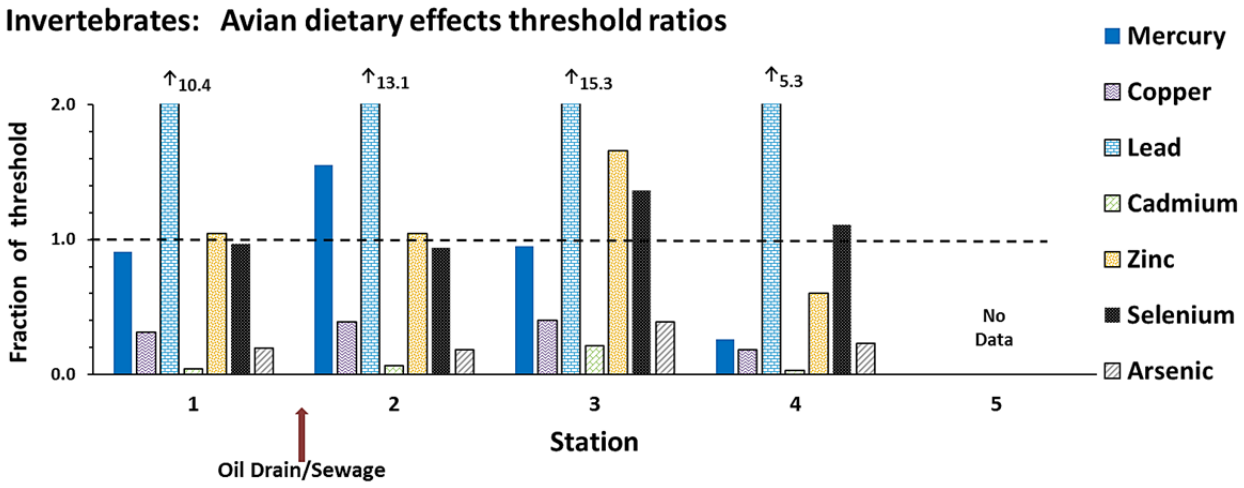

Figure 7. Levels of priority metals and metalloids in the benthic invertebrates (Chironomid larvae) of Farmington Bay at the five stations expressed as a fraction of the avian dietary threshold effects suggested by Waddell et al. (2009) for Farmington Bay. Note that many of the metals in the invertebrates had the highest ratios at Station 3. No chironomids were found at Station 5, so metals data in them is not available. The dotted line shows that dietary threshold ratio above which effects might be evident in birds that would consume the invertebrates.

The different spatial pattern in the sediments and in the invertebrates can also be seen by analyzing the mean concentrations of all of the priority metals (**Fig. 8**). This figure emphasizes how metal concentrations were highest in the invertebrates at Station 3, but low in the sediments at that station. This analysis, however, blends the concentration patterns of all of the metals (and metalloids), and these did not always show the same patterns (see above).

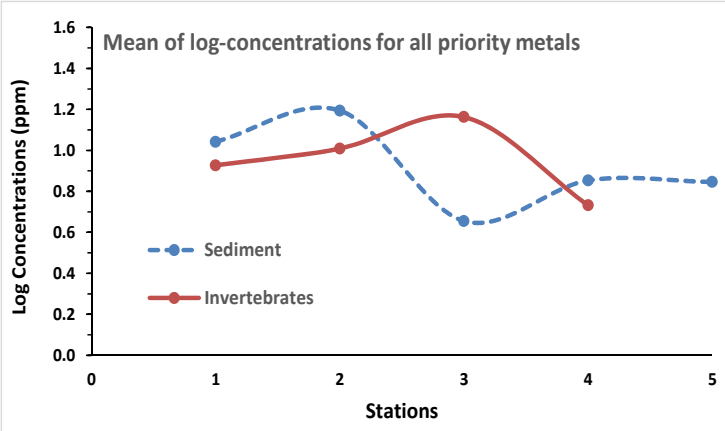

Figure 8. Changes in the mean log concentrations of all seven priority metals in the sediments and in the invertebrates at the stations in Farmington Bay.

Discussion:

Although this study only found one metal, selenium, to reach the Probable Effect Concentration for invertebrates, there is still reason to be concerned about contaminants in Farmington Bay. Many other metals such as; mercury, arsenic, cadmium, copper, lead, and zinc were found at levels above Threshold Effects Concentrations and therefore at levels of concern. These findings are consistent with Waddell et al. (2009), Wurtsbaugh et al's (2012) and McCulley et al's (2015) findings of moderately high metal concentrations in Farmington Bay.

My hypothesis that metal concentrations were equal across the bay was refuted. Rather, mercury, lead, copper, zinc and cadmium concentrations were all higher at the south end of the bay, particularly near the outflow of the Sewage Canal. The finding of higher concentrations at the south end of the bay is consistent with the results of Wurtsbaugh et al. (2012), McCulley et al. (2015) and particularly Sorensen and others (1988) who found high concentrations of metals in the sediments near the outfall of the Sewage Canal/Oil Drain, but lower concentrations further north.

In contrast to concentrations of most metals, the metalloids, selenium and arsenic, changed little across the bay, or were slightly higher near the north. The more even concentration may be a combination of loading from the Sewage Canal, as well as intrusions of Gilbert Bay water that has high levels of both selenium and arsenic (Sturm, 1980; Adams et al. 2015).

With regard to my other hypothesis, I found few correlations between concentrations in the sediments and concentrations in the invertebrates of the priority metals I analyzed. My findings also support Farag et al. (1998) who studied metal concentrations throughout a riverine system in northern Idaho. They found the metal concentrations to be higher in the sediments than the invertebrates which is similar than what I found in Farmington Bay. I am uncertain as to why some of the invertebrate concentrations were higher than the sediment concentrations at Station 3. This could possibly be due to flow moving the invertebrates or maybe it could have something to do with the sediments in Station three, since they did have a hard crust. It also could be attributed to our methods of analysis. We took the metal concentrations from the sediments rather than from the organic matter which would be the food base for the invertebrates. If we had separated out detrital material and periphyton, which are more

available to the benthic invertebrates, then maybe we would have seen different patterns. The sediment samples we analyzed appeared to be composed primarily of inorganic materials, not the food of the Chironomid larvae.

I think it is also important to look at what effect these high metal concentrations have on the benthic invertebrate population. Beasley and Kneale (1999), conducted a study on first order streams in the United Kingdom and found that increased heavy metal along with other pollution caused by urbanization decreased invertebrate populations by 50%. Canfield et al. (1994) studied invertebrates in the Upper Clark River, Montana which had been polluted with 400 metric tons of ore deposits. Their results showed that with high concentrations of heavy metals in the sediments, the pollution-tolerant Chironomidae were present 90% of the time. Clements (1994) studied invertebrates in the Upper Arkansas River Basin, Colorado. They found that zinc concentrations were upward of 0.05 µg/g in the water at some polluted sites, which is low compared to our average zinc concentrations of 117 µg/g that we found in the sediments. They compared healthy reference sites to sites affected with high metal pollution. Their findings show that healthy sites were composed of pollution-sensitive Ephemeroptera, where the polluted sites were composed of pollution-tolerant Chironomidae. Although all of these studies concentrated more on the effects that the metal concentrations had on the biota and not the metal concentrations themselves, they did show that pollution and heavy metals can severely reduce invertebrate populations and produce pollution-tolerant invertebrate populations similar to that found in Farmington Bay.

The metal concentrations in Farmington Bay may influence the large population of shorebirds and migratory waterfowl that utilize the area. Wurtsbaugh (in this report) reported thousands of ducks, coots, avocets and phalaropes utilizing the bay. The ducks, coots and avocets were particularly concentrated in the southern end of the bay where most metals had the highest concentrations in the sediments and/or invertebrates. Some species of birds using the Great Salt Lake rely heavily on invertebrates (Roberts, 2013).

A study by Ohlendorf (1986) also is relevant to Farmington Bay. They studied birds that preyed upon invertebrates from wetlands Joaquin Valley of California which had high concentrations of selenium. The offspring's of these birds had high rates of deformity. The deformities included missing or abnormal eyes, beaks, wings, legs and feet. Brain, heart, liver and skeletal anomalies were also found. If selenium were to increase more in Farmington Bay problems such as those found in Joaquin Valley of California might occur. Selenium isn't the only problem in Farmington Bay, mercury concentrations were also high in my study. Boening (2000) found that birds fed inorganic mercury showed a reduction in food intake equaling poor growth. Increased enzyme production, decreased cardiovascular function, blood parameter changes, immune response, kidney function and structure, as well as behavioral changes were also found. Burger and Gochfeld (1997) conducted a study where they looked at feathers from fledgling birds exposed to concentrations of mercury. They found these birds to have lower hatchability, lower embryo and chick survival, and lower chick weight. These cases show the effects that elevated amounts of selenium and mercury can have on avian populations. In the case of Farmington Bay it is important to make sure metal concentrations do not increase any more causing problems for not only the invertebrate populations but also the local bird populations.

Farmington Bay would greatly benefit from future research looking at the effects that the heavy metals have on the local bird populations. Hopefully in the future, inputs of pollution and heavy metals will

decrease. Wurtsbaugh (2012) demonstrated that metal concentrations in the sediments of Gilbert Bay, but metals at the south end of Farmington Bay appeared to be stable or increasing (metalloids), but the temporal scale of change in that study was unclear. Chadwick et al. (1986) was able to show that years after mining inputs polluted the Silver Bow Creek of Montana, the stream was able to recover to near pre-mining populations. This shows that if metal pollutants decrease in Farmington Bay, the benthic invertebrate populations could show positive effects. This in turn would help the ever so important avian populations on Farmington Bay.

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Appendices

Table 1A: Shows the analysis of regression p-values for the relationship of concentrations of metals in the sediments and in the invertebrates at stations 1-4 (n = 8).

Regression Analysis P-values	
Boron	0.009
Iron	0.010
Potassium	0.018
Maganese	0.028
Aluminium	0.022
Strontium	0.009
Chromium	0.002

Table 2A: Results of the 2-way analysis of variance for both the sediments and the invertebrates. The significant p values indicate that metal concentrations were not homogeneous in the bay, and the significant interaction terms indicates that not all metals behaved spatially in a similar fashion.

Sediments Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
STATION	13.855	4	3.464	23.459	0.000
METAL$	311.314	6	51.886	351.395	0.000
STATION*METAL$	7.663	24	0.319	2.162	0.018
Error	5.168	35	0.148		

Invertebrate Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
STATION	7.079	3	2.360	74.510	0.000
METAL$	257.457	6	42.909	1354.919	0.000
STATION*METAL$	5.011	18	0.278	8.790	0.000
Error	0.887	28	0.032		

Appendix. Concentrations of metals in the sediments and invertebrates of five stations in Farmington Bay on October 2nd, 2014. Note that insufficient invertebrates were available for metals analysis at Station 5.

			Raw Concentrations (ppm; ug/g, dry weight)														
Treatment	Station	Replicate	Silver	Aluminium	Arsenic	Boron	Barium	Beryllium	Calcium	Cadmium	Cobalt	Chromium	Copper	Iron	Mercury	Potassium	Lithium
Sediments	1	A	0.9	5566	15.7	45	193	0.50	143035	1.61	5.29	18.6	96.8	9217.9	0.39	2583	52
Sediments	1	B	0.75	5047	15.1	47	186	0.39	131823	1.48	4.84	17.1	84.8	8414.71	0.36	2588	46
Sediments	2	A	2.75	4447	15.6	40	227	0.61	150537	2.70	5.28	35.3	139.8	8728.23	0.92	2179	44
Sediments	2	B	2.13	4269	16.8	50	204	0.47	163358	2.18	5.15	28.7	123.5	8415.66	0.72	2236	48
Sediments	3	A	<0.01	1515	16.3	96	260	0.16	261771	0.34	3.07	3.1	11.4	3663.79	0.15	937	43
Sediments	3	B	0.02	1391	26.3	119	236	0.16	276379	0.40	3.53	3.3	23.0	3438.26	0.22	845	38
Sediments	4	A	0.09	3597	20.3	98	270	0.27	190858	1.32	4.32	9.6	56.0	6225.96	0.38	2193	54
Sediments	4	B	<0.01	1516	18.1	102	280	0.12	266635	0.54	2.69	2.9	12.8	3527.66	0.08	898	36
Sediments	5	A	<0.01	5199	18.7	118	134	0.47	85527	0.93	4.21	9.7	50.2	8067.04	0.21	6831	78
Sediments	5	B	<0.01	4070	17.2	127	109	0.36	71728	0.86	3.33	7.7	47.4	6840.87	0.12	8816	83
Invertebrates	1	A	0.63	2283	6.6	28	109	0.21	75594	0.90	2.61	8.9	55.9	4265.79	0.38	907	22
Invertebrates	1	B	0.84	1646	5.1	28	82	0.15	58275	0.75	1.87	6.8	69.5	3478.62	0.35	861	16
Invertebrates	2	A	1.57	1335	4.2	17	86	0.17	45993	1.18	1.84	13.0	67.9	2931.26	0.46	635	12
Invertebrates	2	B	1.21	2128	6.9	30	113	0.22	81050	1.35	2.49	13.9	87.9	4385.6	0.78	976	21
Invertebrates	3	A	0.64	1223	11.0	88	130	0.18	77209	4.29	2.2	7.2	100.3	2487.77	0.44	494	22
Invertebrates	3	B	0.37	992	12.3	66	123	0.15	126592	4.13	1.89	5.2	59.0	2275.27	0.32	425	29
Invertebrates	4	A	0.22	1070	7.8	53	84	0.14	99337	0.58	1.5	4.4	38.0	2477.73	0.12	509	17
Invertebrates	4	B	0.33	940	5.9	51	72	0.10	77875	0.49	1.22	3.8	35.5	2080.28	0.09	477	17

			Raw Concentrations (ppm; ug/g, dry weight)														
Treatment	Station	Replicate	Magnesium	Maganese	Molybdenum	Sodium	Nickel	Phosphorus	Lead	Antimony	Selenium	Silicon	Tin	Strontium	Thallium	Vanadium	Zinc
Sediments	1	A	29894	484	0.93	2894	12.66	2023	87.55	0.06	1.82	230	1.31	1115	0.31	18.8	166
Sediments	1	B	28778	460	1.13	3890	11.25	2057	75.6	0.05	1.98	194	1.33	1000	0.26	17.6	150
Sediments	2	A	24204	387	1.81	3121	13.08	2163	121	0.06	2.21	184	3.43	1342	0.48	14.5	249
Sediments	2	B	26813	411	1.23	4213	11.38	1946	104.9	0.06	1.88	175	2.64	1598	0.41	15.6	213
Sediments	3	A	26237	250	5.11	4714	5.05	379	16.33	0.05	1.18	209	0.20	2941	0.49	12.7	35
Sediments	3	B	26339	227	8.24	3945	5.25	693	35.96	0.04	1.37	179	0.35	3145	0.37	14.8	57
Sediments	4	A	28697	287	9.48	8080	9.42	1218	67.67	0.06	2.48	205	0.56	2172	0.47	16.8	114
Sediments	4	B	22227	156	9.61	5248	5.32	385	24.88	0.05	1.11	175	0.15	3056	0.68	13.3	45
Sediments	5	A	32304	352	6.21	63934	11.13	1311	32.96	0.03	2.94	142	0.75	507	0.47	12.5	79
Sediments	5	B	32323	274	6.81	98980	8.95	1324	28.1	0.04	2.75	133	0.72	474	0.37	10.9	69
Invertebrates	1	A	14594	269	0.62	447	6.12	6677	58.8	0.10	2.84	299	1.42	529	0.11	11.0	197
Invertebrates	1	B	11823	208	0.66	538	4.58	8410	45.64	0.10	2.98	309	1.03	387	0.08	11.6	174
Invertebrates	2	A	8647	146	2.55	628	5.29	8195	56.86	0.16	2.71	238	3.06	346	0.15	7.3	179
Invertebrates	2	B	13437	222	4.18	633	6.40	7652	73.77	0.20	2.92	227	2.92	590	0.18	8.8	192
Invertebrates	3	A	14065	184	7.69	596	7.35	7406	89.58	0.29	4.10	313	2.28	873	0.06	8.7	326
Invertebrates	3	B	15394	179	3.65	1034	4.54	8762	63.61	0.22	4.09	304	0.77	1319	0.12	8.3	264
Invertebrates	4	A	13474	122	2.14	1256	3.47	7198	25.84	0.13	3.75	216	0.46	1113	0.09	7.2	113
Invertebrates	4	B	11562	100	1.95	1169	3.48	7246	27.05	0.14	2.92	192	0.53	887	0.07	5.6	101