Ecosystem Assessment of Mercury in the Great Salt Lake, Utah 2008

Utah Department of Environmental Quality

Division of Water Quality

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Synopsis of the 2008 Great Salt Lake Mercury Ecosystem Assessment

Introduction

The Great Salt Lake (GSL) and its adjacent wetlands is a necessary oasis to approximately 7.5 million birds that visit the lake annually. The lake lies within the Pacific Flyway and is a key mid-point stopover as well as an over-wintering destination providing nutritional energy for migration, breeding, nesting habitat and resting areas for avian wildlife. The avian community feeds on the aquatic organisms specialized to highly saline conditions that include brine shrimp (*Artemia fransicana*), brine fly (*Ephydra*), and numerous algal species in the open waters. In the adjacent wetlands, they feed on vegetation and fresh water macroinvertebrates.

In 2003, water column measurements conducted by the United States Geological Survey (USGS) reported elevated methyl mercury (MeHg) concentrations exceeding 33 nanograms per liter (ng/L), some of the highest recorded levels in the United States (Naftz et al., 2008). Waterfowl breast muscle tissue was then analyzed for total mercury (THg) because of the potential for MeHg, a more toxic organic form of Hg, to accumulate in the GSL food chain, from algae, plants, and macroinvertebrates to waterfowl and local hunters. Testing from three of the ten waterfowl species in 2005 and 2006, showed mean THg concentrations in the waterfowl breast muscle tissue above the United States Environmental

Protection Agency (USEPA) screening value of 0.3 parts per million (ppm) THg (USEPA, 2000a). In response, the Utah Department of Health (2005; 2006) issued the first United States waterfowl consumption advisory for the 3 species of waterfowl (Cinnamon Teal, Northern Shoveler and Common Goldeneye). Vest et al. (2008) reported the highest concentrations of THg ever recorded in North America in wintering waterfowl. These elevated Hg concentrations were the impetus for additional investigations into possible toxic exposures to the biota of the GSL and to people who hunt waterfowl.

Through funding provided by a USEPA Regional Geographic Initiative Grant and a one time state appropriation from the Utah legislature, a comprehensive effort to compile data for Hg concentrations in the GSL ecosystem began in 2008. The objective of this assessment was to provide baseline information on the timing and extent of Hg concentrations in the GSL ecosystem including the water column, sediments, waterfowl and the waterfowl food chain biota, both lake-wide and in the adjacent wetlands, and to compare these concentrations to known literary benchmarks for toxicity to avian wildlife and their food chain.

To accomplish this, a project team was assembled in 2008. Table 1 provides a list of the researchers involved, their affiliation, role in the assessment and the corresponding chapter in this report.

Table 1 Project team including the researchers, organization, role and corresponding chapter

RESEARCHER	ORGANIZATION	ROLE IN THE PROJECT	CHAPTER IN THIS REPORT
Dave Naftz	U.S. Geological Survey	Water column and sediment in the open water and wetlands	Chapter 1: Mercury Distribution in Sediment and Water Samples Collected from Great Salt Lake, Utah, and Surrounding Wetland Areas
Jim Van Leeuwen, John Neill, Phil Brown, Jaimi Butler and John Luft	Utah Department of Natural Resources/Utah Division of Wildlife Resources/Great Salt Lake Ecosystem Program	Brine shrimp, Northern Shovelers and Cinnamon Teal	Chapter 2: Assessment of Total Mercury Concentrations in Great Salt Lake Brine Shrimp (*Artemia franciscana*) Chapter 3: Mercury Concentrations in Cinnamon Teal (*Anas cyanoptera*) and Northern Shoveler (*Anas clypeata*) at Great Salt Lake, Utah
Christine Cline	U.S. Fish and Wildlife Service	Northern Shovelers and Cinnamon Teal	Chapter 3 Mercury Concentrations in Cinnamon Teal (*Anas cyanoptera*) and Northern Shoveler (*Anas clypeata*) at Great Salt Lake, Utah
Wayne Wurtsbaugh and Caleb Izdepski	Utah State University	Brine fly and periphyton	Chapter 4 Biostrome Communities and Mercury and Selenium Bioaccumulation in the Great Salt Lake,Utah
Jodi Gardberg, Amy Dickey and John Whitehead	Utah Department of Environmental Quality/ Division of Water Quality	Project management	
Sandie Spence, Jim Berkeley and Cynthia Rodriguez	U.S. Environmental Protection Agency with assistance from U.S. Fish and Wildlife Service	Compilation of literary benchmarks and grant oversight	

This synopsis provides a general overview of 2008 Hg concentrations in the GSL open waters and wetlands by presenting conceptual models of the ecosystems. These models contain the exposure pathways with the overall mean Hg concentrations found in this assessment compared to the benchmarks of Hg toxicity chosen from published literature. Each chapter herein contains in-depth results of 2008 Hg concentrations in the Great Salt Lake open waters and wetlands. The remainder of this section summarizes study results by providing an abstract from each report chapter.

Chapter 1: Mercury Distribution in Sediment and Water Samples Collected from Great Salt Lake, Utah, and Surrounding Wetland Areas

Abstract: To better understand the distribution and biogeochemical cycling of Hg, water and sediment samples were collected from throughout the south arm of GSL and the surrounding wetland areas. Modeled annual total Hg (THg) load from six riverine input sources to GSL was 6 kilograms (kg) and the combined annual wet and dry atmospheric deposition of Hg to GSL was about 30 kg. Salt-corrected concentrations of THg in 58 sediment samples collected beneath the south arm of GSL did not exceed the Washington Marine Sediment Quality Standard of 410 nanograms per gram (ng/g) (dry weight); however, the ratio of methylmercury (MeHg) to THg (in weight percent) in near-surface sediment samples were elevated compared to worldwide baselines. Water samples collected from 5 monitoring sites in the south arm of GSL and 1 site in Farmington Bay were analyzed for THg and MeHg. Four out of the six monitoring sites contained THg concentrations below the U.S. Environmental Protection Agency (USEPA) aquatic life standard for fresh water; however, THg concentration in water samples from the other two monitoring sites (3510 and 2565) consistently exceeded the USEPA aquatic life standard for fresh water; however, most of the samples from these sites were below the aquatic life standard for saline water. With the exception of two water samples collected from

the Farmington Bay monitoring site, all of the water samples collected from the open-water areas of GSL exceeded the uncontaminated baseline concentration for MeHg. Water from four wetland areas surrounding GSL was monitored for THg and MeHg concentrations during 2008. Water samples collected from the Bear River Bird Refuge and Ambassador Duck Club contained low levels of THg and MeHg; however, water samples collected from Howard Slough and the Turpin Unit consistently contained elevated levels of THg and MeHg. The THg concentration in sediment samples collected from 4 out of the 5 wetland areas surrounding GSL did not exceed the Washington Marine Sediment Quality Standard; however, the sediment quality standard was exceeded in sediment samples collected from the Farmington Bay Waterfowl Management Area. The proportion of MeHg in sediment samples collected from the Farmington Bay Waterfowl Management Area and Turpin Unit was found to be elevated relative to sediment samples collected from other parts of the world. The abundant organic matter and nutrients associated with the sewage dominated outfall from the Salt Lake City sewage canal could be a contributor to the high proportion of MeHg in the sediment samples collected from the wetland areas. As a result of a planned fish poisoning event, tissue samples from 17 dead carp were analyzed for THg. The THg concentration in the fish tissue samples were below the USEPA mercury screening limit for protection of human health and below the level of concern for protection of fish-eating mammals.

Chapter 2 Assessment of Total Mercury Concentrations in Great Salt Lake Brine Shrimp (*Artemia franciscana*)

Abstract: Naturally occurring brine shrimp (*Artemia fransicana*) through all its life stages (cysts, nauplii, and adults) were sampled from June to December, 2008 to characterize the life stage, seasonal and spatial total mercury (THg) concentrations collected from the open waters of Gilbert Bay, Great Salt Lake. There was a substantial increase in THg concentrations from cysts/nauplii to adults lake-wide. However, THg concentrations in GSL brine shrimp cysts from the streaks, cysts/nauplii and adult shrimp were all below 0.1 ppm (ww), the lowest observed adverse effect level as a fresh weight dietary item for Mallards (Heinz, 1979). When compared to Ever's dietary risk ranges (Evers et al., 2004),

the cysts from streaks and the cysts/nauplii taken from selected sites pose little risk as a dietary item for avian wildlife. Adult brine shrimp may pose a moderate dietary risk. No difference in median THg concentrations in adult brine shrimp or cysts/nauplii were detected over the sites sampled. For adult brine shrimp, a significant difference in THg concentrations was detected over the season. Further analysis showed that the difference occurred in July when median THg concentrations decreased. No differences across months were detected in cysts/nauplii. Additional investigation to more accurately characterize any potential risks to waterfowl or shorebirds at Gilbert Bay from Hg is recommended.

Chapter 3 Mercury Concentrations in Cinnamon Teal (*Anas cyanoptera*) and Northern Shoveler (*Anas clypeata*) at Great Salt Lake, Utah

Abstract: Over seven million waterbirds utilize Great Salt Lake (GSL), Utah and its associated wetlands during some portion of their biannual migration. High concentrations of mercury (Hg) had been detected in the water column and wintering waterfowl; subsequently, the first ever consumption advisory for waterfowl in the United States was issued for GSL. To better understand Hg concentrations in waterfowl, egg, liver and breast muscle tissues from 2 species in 2008 were evaluated for mercury: Northern Shoveler (*Anas clypeata*), a wintering waterfowl that feed in the hypersaline open waters of GSL, and Cinnamon Teal (*Anas cyanoptera*), a summer breeding population that nest in the GSL fresh water wetlands. As a percentage of total mercury (THg), Cinnamon Teal eggs contained 94.4 ± 9.80% methyl mercury (MeHg), with a mean MeHg concentration of 0.177 ± 0.150 parts per million (ppm) wet weight (ww) and a range from 0.048 – 0.715 ppm ww. All eggs except two outliers sampled from Ogden Bay wetlands had MeHg concentrations levels less than the lowest observed adverse effect limit (LOAEL) of 0.5 ppm ww. Mean MeHg liver concentrations in Cinnamon Teal were 0.205 ± 0.080 ppm ww at Bear River Bay wetlands, 0.497 ± 0.368 ppm ww at Ogden Bay wetlands, and 0.452 ± 0.699 ppm ww at Farmington Bay wetlands. The mean Cinnamon Teal MeHg liver concentrations at all bays were below the LOAEL of 0.89 ppm ww for reproductive impacts. Mean Cinnamon Teal THg breast muscle tissue concentrations were 0.336 ± 0.405 ppm ww for summer adults, exceeding the

U.S. Environmental Protection Agency screening value of 0.3 ppm ww and 0.154 ± 0.132 ppm ww for autumn adults that did not exceed the screening level. The overall sample mean of 0.163 THg in the adult breast muscle tissue did not exceed the EPA screening level. While mean Cinnamon Teal egg and liver Hg concentrations were below levels of concern, a trend towards elevated levels of liver Hg concentrations were found in autumn-collected birds at Ogden Bay wetlands. It was not determined whether these birds arrived on the lake with that exposure or if they were exposed to Hg via the GSL open-water food chain, or in the wetlands. As a percentage of THg, Northern Shoveler livers contained 60.755% ± 16.794 MeHg with a mean of 0.662 ± 0.607 ppm ww and range from 0.124 to 2.873 ppm ww. Mean MeHg liver concentrations in Northern Shoveler were 0.861 ± 0.651 ppm ww at Bear River Bay wetlands, 0.730 ± 0.672 ppm ww at Ogden Bay wetlands, and 0.439 ± 0.456 ppm ww at Farmington Bay wetlands. The mean MeHg liver concentrations at all bays were below the LOAEL of 0.89 ppm ww for reproductive impacts. Mean THg breast muscle tissue concentrations in Northern Shoveler were 0.24 ppm ww at Bear River Bay, 0.20 ppm ww at Ogden Bay and 0.18 ppm ww at Farmington Bay. The mean THg at each location and the overall sample mean of 0.163 ppm ww in the adult breast muscle tissue did not exceed the EPA screening level.

Chapter 4 Biostrome Communities and Mercury and Selenium Bioaccumulation in the Great Salt Lake, Utah

Abstract: The main basin of the Great Salt Lake has a salinity near 15% and is critical habitat for over 200 species of migratory birds. The diet of many of these birds is dependent on the food web of carbonaceous biostromes (stromatolites) that grow profusely at depths <4 m and cover approximately 260 km^2 of the lake's littoral zone. These reef-like structures are nearly the only solid substrate in the lake and they are consequently the dominant area where periphyton and benthic invertebrates grow. We investigated this community at three sites in the lake to understand its importance for production processes that support the bird assemblage and to assess whether they are an important vector for bioconcentration of the high mercury levels that have been documented in the lake. The periphyton community growing on (and building) the biostromes was

>99% colonial cyanobacteria (*Aphanothece* sp.). Periphyton chlorophyll levels averaged 900 mg m^{-2} or about nine times that of the lake's phytoplankton. Lake-wide estimates of chlorophyll suggest that production on the biostromes rivals that of the phytoplankton. Biostromes are the principal habitat for brine fly (*Ephydra gracilis*) larvae that are fed upon by many birds utilizing the lake. Using a pumped-bucket sampler, brine fly larval densities on the biostromes were found to increase from 7,000 m^{-2} in June to 20,000 m^{-2} in December. Pupation and adult emergence halted in October and larvae of various instars overwintered. Most larvae grew into 3rd instars before emergence began in the spring. Mean total dissolved and dissolved methylmercury concentrations in water over the biostromes were 5.0 and 1.2 ηg L^{-1}. Total mercury concentrations in the periphyton, fly larvae, pupae, and adults were, respectively, 152, 189, 379 and 659 ηg g^{-1}dry weight, suggesting that bioconcentration is only moderate in the short food web and through fly developmental stages. However, Common Goldeneye ducks (*Bucephala clangula*) that feed primarily on brine fly larvae at the Great Salt Lake had concentrations near 8000 ηg Hg g^{-1} dry weight in muscle tissue and 50800 ηg g dry $weight^{-1}$ in their livers (Vest et al., 2008). Selenium concentrations in periphyton, brine fly larvae and goldeneye liver tissue were high (1,700, 1,200 and 24,000 ηg g^{-1}, respectively) and Hg:Se molar ratios were <1.0 in all tissues tested, suggesting that the high concentration of mercury in the ducks may be detoxified by combining with selenium. Measurements of methyl mercury in waterfowl tissue are needed to confirm this finding.

Conceptual Models for Hg in Great Salt Lake, Utah

Constructing the Conceptual Site Models

Conceptual models were constructed that summarize and illustrate the ecological receptors and exposure routes of Hg concentrations for four distinct habitats: GSL Open Waters/Gilbert Bay (Figure 1), Bear River Bay (Figure 2), Ogden Bay (Figure 3) and Farmington Bay (Figure 4) wetlands. Ecological receptors are those entities that are exposed to a contaminant and exposure to Hg can be

direct (via the water column and/or sediment) or dietary (by ingestion). The ecological receptors (e.g., brine shrimp and brine flies in different life stages and waterfowl) are in boxes and the potential exposure pathways are represented by arrows. Each receptor box shows the 2008 mean Hg concentration (in white text) compared to the literary benchmark (in yellow text). The mean Hg concentration is based from samples collected over all seasons and locations in 2008. For more in-depth statistical analysis of Hg concentrations between locations and throughout the season, please refer to Chapters 1 though 4. For those boxes that are empty, either there was no data taken in 2008 for that receptor or there is no known benchmark with which to compare it to. Future efforts should focus on filling these data gaps.

Establishing Ecological Threat Benchmarks

The USEPA and U.S. Fish and Wildlife Service (USFWS) did an extensive literature review to identify potential benchmarks for Hg impairment in avian species. Hg benchmarks were needed for liver concentrations in birds, dietary items for birds, water, and sediment. Caution should be used when comparing the measured concentrations to the literary benchmarks. While the following benchmarks provide useful comparisons, their precise applicability to the GSL has yet to be determined.

Evers et al. (2004) undertook extensive studies with Common Loons (*Gavia immer)* in the northeastern United States to determine Hg benchmarks and risk ranges for this species. Evers proposed risk ranges from low to extra high for

dietary exposures, egg concentrations, blood concentrations, and feather concentrations. Of these indicators, the dietary risk ranges were chosen for comparison in this assessment and are reported in MeHg parts per million (ppm) wet weight (ww).

Evers (2004) Dietary Exposure Risk Ranges:

- Low Risk in Diet < 0.05 MeHg ppm ww
- Moderate Risk in Diet 0.05 – 0.15 MeHg ppm ww
- High Risk in Diet 0.15 – 0.3 MeHg ppm ww
- Extra High Risk in Diet >0.3 MeHg ppm ww

For several reasons, these risk levels may be conservative when applied to GSL biota. For instance, Evers defines the upper limit of the low risk range as equivalent to a no observed adverse effect level (NOAEL). Also, the Common Loon does not inhabit the GSL, nor do fish which represent the dietary items used by Evers (2004). However, to our knowledge the Ever's database is the most comprehensive source of Hg toxicity studies available, which makes the benchmarks useful.

For Hg concentrations in avian livers, USEPA and USFWS applied a similar concept of risk ranges to the available literature benchmarks to establish low, moderate, high, and extra high concentrations for Hg in avian livers.

Risk Ranges for Avian Livers:

- Low risk in livers < 0.89 MeHg ppm ww – Below lowest observed adverse effect level (LOAEL) for Mallard reproductive impacts (Heinz, 1979)

- Medium risk in livers 0.89 – 2 MeHg ppm ww – From LOEL to threshold for sublethal effects noted by several authors including Fimreite (1971), Heinz (1979), and Scheuhammer (1987)
- High Risk in livers 2 to 6 MeHg ppm ww – From sublethal effects threshold to the threshold for major toxic effects suggest by Zillioux et al. (1993) and Spalding et al. (1994).
- Extra High Risk > 6 MeHg ppm ww – Includes concentrations above which long term survival significantly impacted.

For water column THg concentrations, the USEPA aquatic life criteria of 25 ng/L for salt water was applied to open water samples and 12 ng/L for fresh water for the wetland samples. For sediment, the Washington Marine Sediment Quality Standard of 410 ng/g dry weight (dw) (State of Washington, 1995) was chosen.

Results for Open Waters (Gilbert Bay) of Great Salt Lake

The conceptual site model constructed for the open waters (Gilbert Bay) of the GSL is shown in Figure 1.

Figure 1. Conceptual model of the open waters of Great Salt Lake. Mean Hg concentrations as reported in this study are listed in white and compared to literary benchmarks listed in yellow

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An extremely high mean THg concentration (46.6 ng/L) was measured in the deep brine layer similar to the high concentrations previously reported by USGS in 2003 (33 ng/L; Naftz et al., 2008). However, the mean concentration of THg in the shallow brine layer of 5.31 ng/L is well below the USEPA aquatic life criteria of 25 ng/L. The deep brine layer exists in Carrington and Gilbert bays of GSL and its extent is dependant on the salinity driven density differences between these bays and the hypersaline Gunnison Bay. The deep brine layer is characterized by salinity approaching saturation, anoxic conditions, and high rates of sulfate reduction that is suspected to increase Hg methylation rates. The deep brine and shallow brine layers remain separate except during storms and wind events when mixing of the layers occurs. When the layers mix, the MeHg from the deep brine layer can become available to the biota in the biologically active shallow layer. The mean THg for sediment of 182 nanograms /gram (ng/g) dw was well below the Washington State Marine MeHg Sediment Standard of 410 ng/g dw.

THg concentrations increase with life stage of both brine flies (larvae to pupae to adults) and brine shrimp (cysts to nauplii to adults). No increase in concentration

was observed from periphyton to brine fly larvae but no benchmark in the literature was found to compare it to. Missing from this assessment is both phytoplankton (algae) data that brine shrimp feed upon and a benchmark with which to compare it to. Further study would include this data and further review of the literature.

According to Ever's risk ranges, the risk posed by brine fly as a dietary item for avian wildlife increases from a low risk from the larvae to high risk from adult brine flies. This can have significance for those species that feed primarily on brine flies. Vest et al. (2008) reported that during the late winter of 2004 and 2005, 100% of the female Common Goldeneyes contained elevated concentrations of Hg (> 1.0 ppm ww, medium risk), and 5% contained harmful amounts of Hg (30.0 ppm ww, extra high risk). He indicated that this could be attributed to their diet that consists primarily of brine fly larvae. More information on Hg concentrations in species that feed primarily on brine flies is warranted.

According to Ever's risk ranges, brine shrimp cysts and nauplii pose a low risk as a dietary item to avian wildlife and adult brine shrimp pose a moderate risk. Vest et al. (2008) reported the dietary composition of Northern Shovelers as primarily brine shrimp and brine shrimp cysts and mean THg liver concentrations as 1.79, 3.86 and 3.84 ppm ww in November, December and February, respectively. According to the Ever's risk ranges, these concentrations correspond to a moderate to high risk to avian wildlife. Conversely, in this assessment, the mean

MeHg liver concentration for Northern Shovelers was 0.662 MeHg ppm ww, below the lowest observed effect level (LOEL) for reproductive impact in Mallards (Heinz, 1979) and much lower than previously observed by Vest et al. (2008). Further information is needed to discern whether this difference can be attributed to the time or locations of collection, analytical procedures, and/or exposure to the GSL as opposed to elsewhere in the migratory pathway.

In regards to human heath, the mean THg in Northern Shoveler breast muscle tissue from this assessment was 0.207 ppm ww, which is lower than the USEPA health screening value of 0.3 ppm. (USEPA, 2000a). In addition, the mean THg concentration in breast muscle tissue at each location was below the EPA screening value (0.24 ppm ww at Bear River Bay, 0.20 ppm ww at Ogden Bay and 0.18 ppm ww at Farmington Bay). These observed concentrations are also lower than the mean THg concentration of 0.383 ppm ww observed at Farmington Bay that was the basis for the consumption advisory in 2005 (Utah Department of Health, 2005; 2006). Brine shrimp cysts that are harvested from the GSL and used as feed for aquaculture (primarily fish and shrimp) destined for human consumption had a mean THg concentration of 0.0071 ppm ww, well below the industry THg standard for commercial aquaculture of 0.30 ppm ww. Together, these data suggest that in 2008, Hg within the open water of the Great Salt Lake posed little threat to human health; however, the discrepancy with previous observations needs to be evaluated to determine the year-to-year variation in human health risk.

Results for the Adjacent Wetlands to Great Salt Lake

Conceptual models were composed for wetlands adjacent to Bear River Bay (Figure 2), Ogden Bay (Figure 3) and Farmington Bay (Figure 4) of the GSL.

Figure 2. Conceptual model of the Bear River Bay wetlands adjacent to the Great Salt Lake. Mean Hg concentrations as reported in this study are listed in white and compared to literary benchmarks listed in yellow

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Figure 3. Conceptual model of the Ogden Bay wetlands adjacent to the Great Salt Lake. Mean Hg concentrations as reported in this study are listed in white and compared to literary benchmarks listed in yellow

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Figure 4. Conceptual model of the Farmington Bay wetlands adjacent to the Great Salt Lake. Mean Hg concentrations as reported in this study are listed in white and compared to literary benchmarks listed in yellow

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At all wetland locations the water column mean THg concentrations (Bear River Bay: 2.93 ng/L, Farmington Bay; 7.43 and 4.26 ng/L and Ogden Bay; 7.04 ng/L) were below the USEPA aquatic life criteria of 12 ng/L for fresh water. However, Naftz (Chapter 1) observed a strong diurnal pattern in THg concentrations with consistently decreasing concentrations during daylight periods and increasing

concentrations during non-daylight periods. He warned that daytime monitoring of selected wetlands surrounding GSL may significantly underestimate the THg content in the water column.

At all but 1 wetland location the sediment mean THg (Bear River Bay: 17.38 ng/g, Farmington Bay: 57.6ng/g – Turpin Unit and 79.0 ng/g – Ambassador Duck Club and Ogden Bay: 141.0 ng/g) was below the Washington State Marine Hg Sediment Standard of 410 ng/g dw. The 1 location that the mean exceeded the sediment standard was at the Oil drain outfall (838 ng/g) that drains into Farmington Bay, GSL.

At all wetland locations in 2008, the mean MeHg concentration in Cinnamon Teal livers (Bear River Bay: 0.205 ppm ww, Farmington Bay; 0.452 ppm ww and Ogden Bay; 0.497 ppm ww) were below the LOAEL (< 0.89 ppm ww) for reproductive impact (Heinz, 1979). At all wetland locations, the mean MeHg concentration in Cinnamon Teal eggs (Bear River Bay: 0.133 ppm ww, Farmington Bay; 0.135 ppm ww and Ogden Bay; 0.246 ppm ww) were less than the LOAEL of 0.5 ppm ww in mallard eggs (Heinz, 1979; Evers et al., 2004). However, two out of the 10 eggs sampled at Ogden Bay wetlands exceeded the benchmark for reproduction.

In regards to human heath, the mean THg in Cinnamon Teal breast muscle tissue from this assessment was 0.163 ppm ww, which is lower than the USEPA

health screening value of 0.3 ppm. (USEPA, 2000a). In addition, the mean THg concentration in breast muscle tissue at each location was below the EPA screening value (0.09 ppm ww at Bear River Bay, 0.18 ppm ww at Ogden Bay and 0.20 ppm ww at Farmington Bay).

Missing data from this assessment include phytoplankton, vegetation and macroinvertebrates as dietary items for wetland birds. Future collection efforts should include these organisms to fill these data gaps.

Conclusions

The conceptual models were designed to give an ecosystem overview of Hg concentrations in the open waters and adjacent wetlands of GSL. In-depth analysis of water column, sediment, brine shrimp, brine fly, Northern Shoveler and Cinnamon Teal Hg concentrations sampled at different locations and at different times throughout the season of 2008 are provided in the individual chapters. Based on this 2008 assessment, key findings include

- The mean THg water concentration in the deep brine layer is extremely high. However, the mean concentration of THg in the shallow brine layer is well below the USEPA aquatic life criteria. When mixing of the layers occurs during storm and wind events, MeHg from the deep brine layer can become available to the biota in the biologically active shallow layer.

- The mean THg in sediments at all locations except one at the Oil Drain outfall to Farmington Bay were below the Washington State Marine Sediment Standard.
- The mean THg breast muscle tissue concentrations in the two waterfowl species (Cinnamon Teal and Northern Shoveler) were below the USEPA screening value of 0.3 ppm used to calculate consumption advisories.
- The mean MeHg concentrations in liver tissue for both Northern Shoveler and Cinnamon Teal were below the LOAEL for reproductive impact.
- At all wetland locations, the mean MeHg concentration in Cinnamon Teal eggs were less than the LOAEL of 0.5 ppm ww for reproductive effects.
- The mean THg concentrations increase with life stage for both brine flies (larvae to pupae to adults) and brine shrimp (cysts to nauplii to adults).
- THg concentrations in wetlands vary diurnally which needs to be considered when using water concentrations as a surrogate for estimating exposure.

Further study is needed including:

- Research on Hg in the parts of the GSL food chain (e.g., phytoplankton in the open waters and vegetation and macroinvertebrates in the wetlands) that weren't part of this or other assessments.
- More information on those avian species that feed primarily on brine flies or on brine shrimp.
- More information on whether avian species are exposed to Hg at the GSL or elsewhere.

- A laboratory round robin to confirm and compare results from previous studies to this assessment.
- Research on the relationship between selenium and mercury in avian species.

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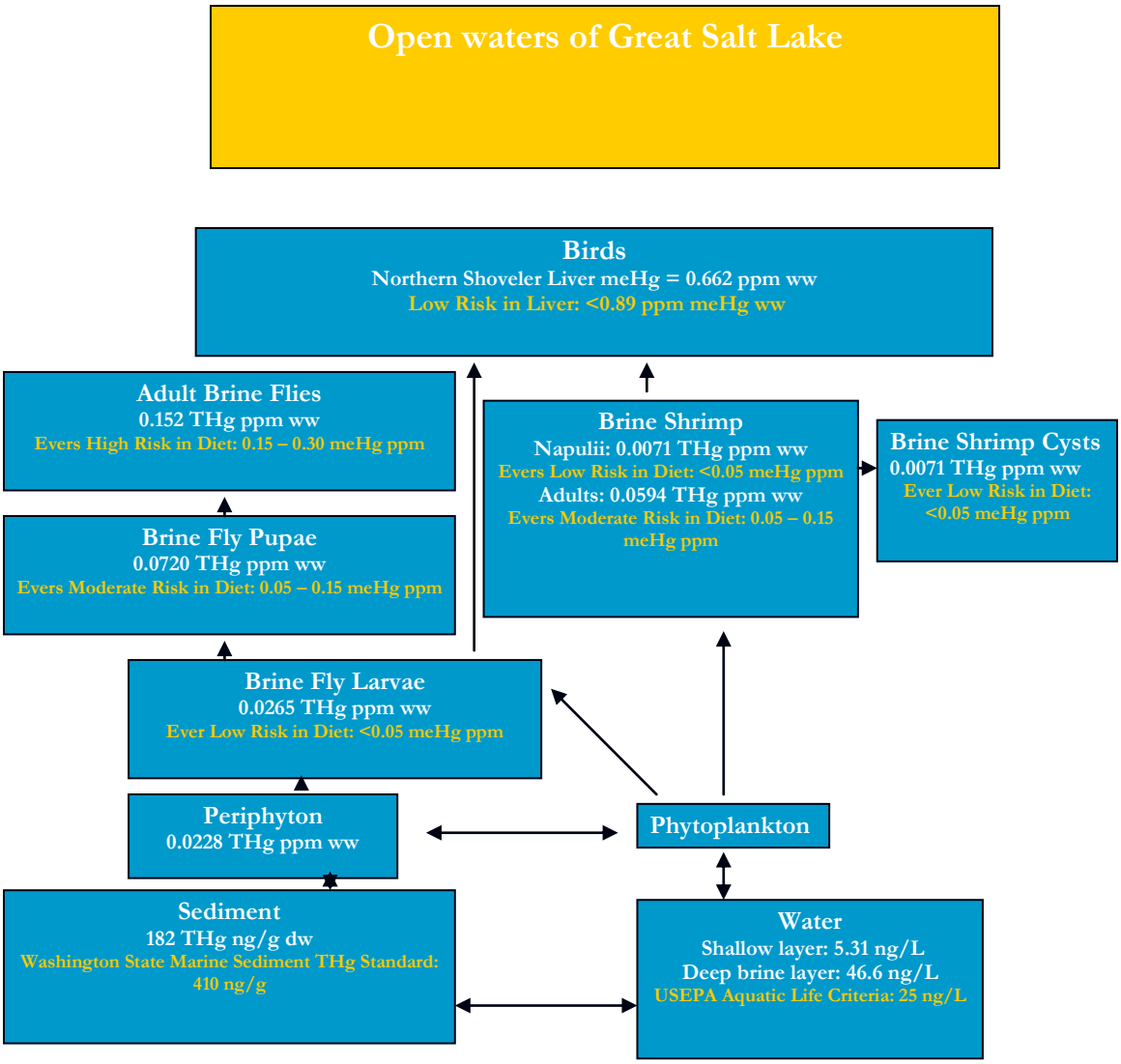

Figure 1. Conceptual model of the open waters of Great Salt Lake. Mean Hg concentrations as reported in this study are listed in white and compared to literary benchmarks listed in yellow

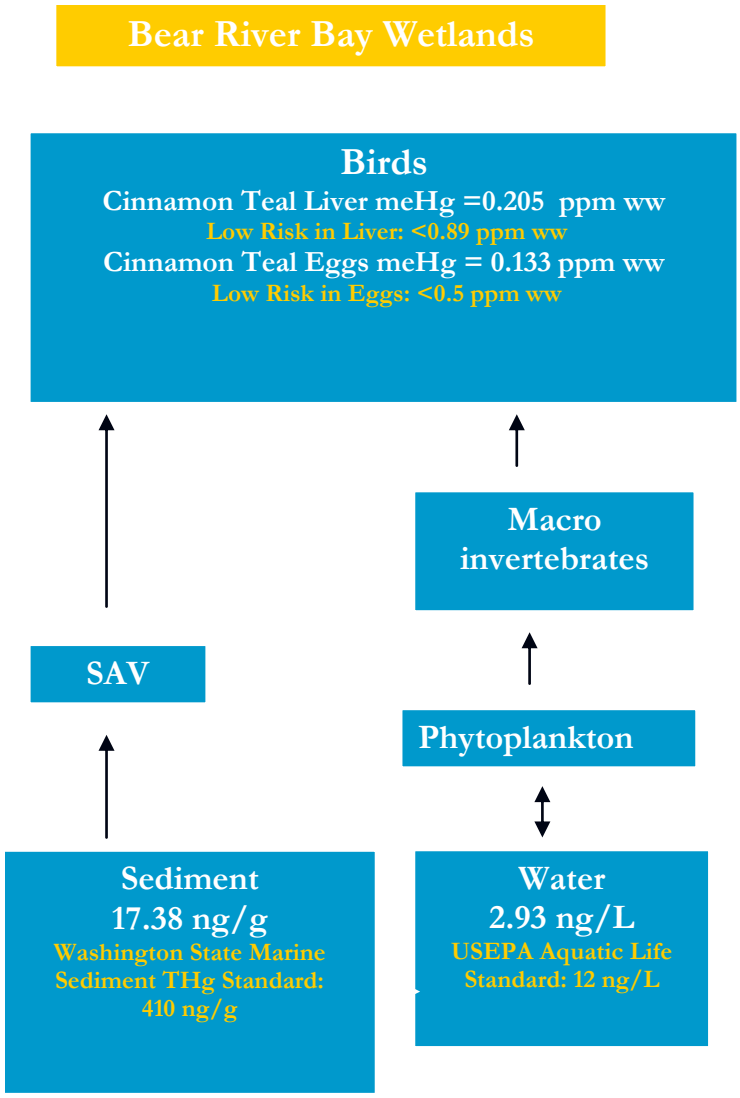

Figure 2. Conceptual model of the Bear River Bay wetlands adjacent to the Great Salt Lake. Mean Hg concentrations as reported in this study are listed in white and compared to literary benchmarks listed in yellow

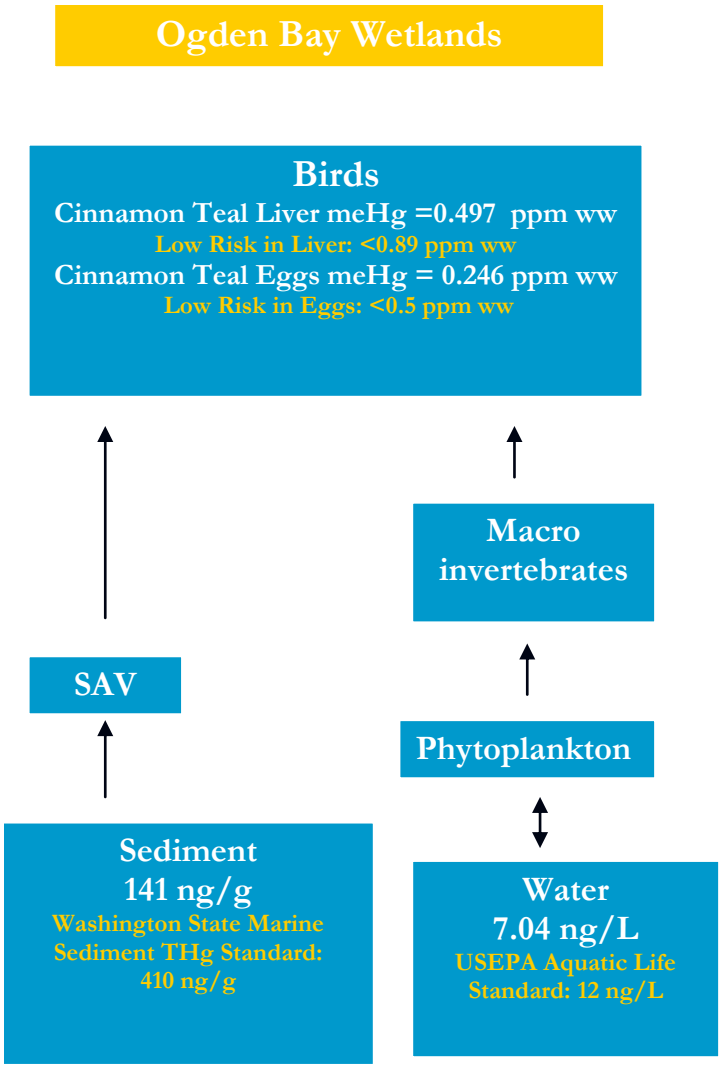

Figure 3. Conceptual model of the Ogden Bay wetlands adjacent to the Great Salt Lake. Mean Hg concentrations as reported in this study are listed in white and compared to literary benchmarks listed in yellow

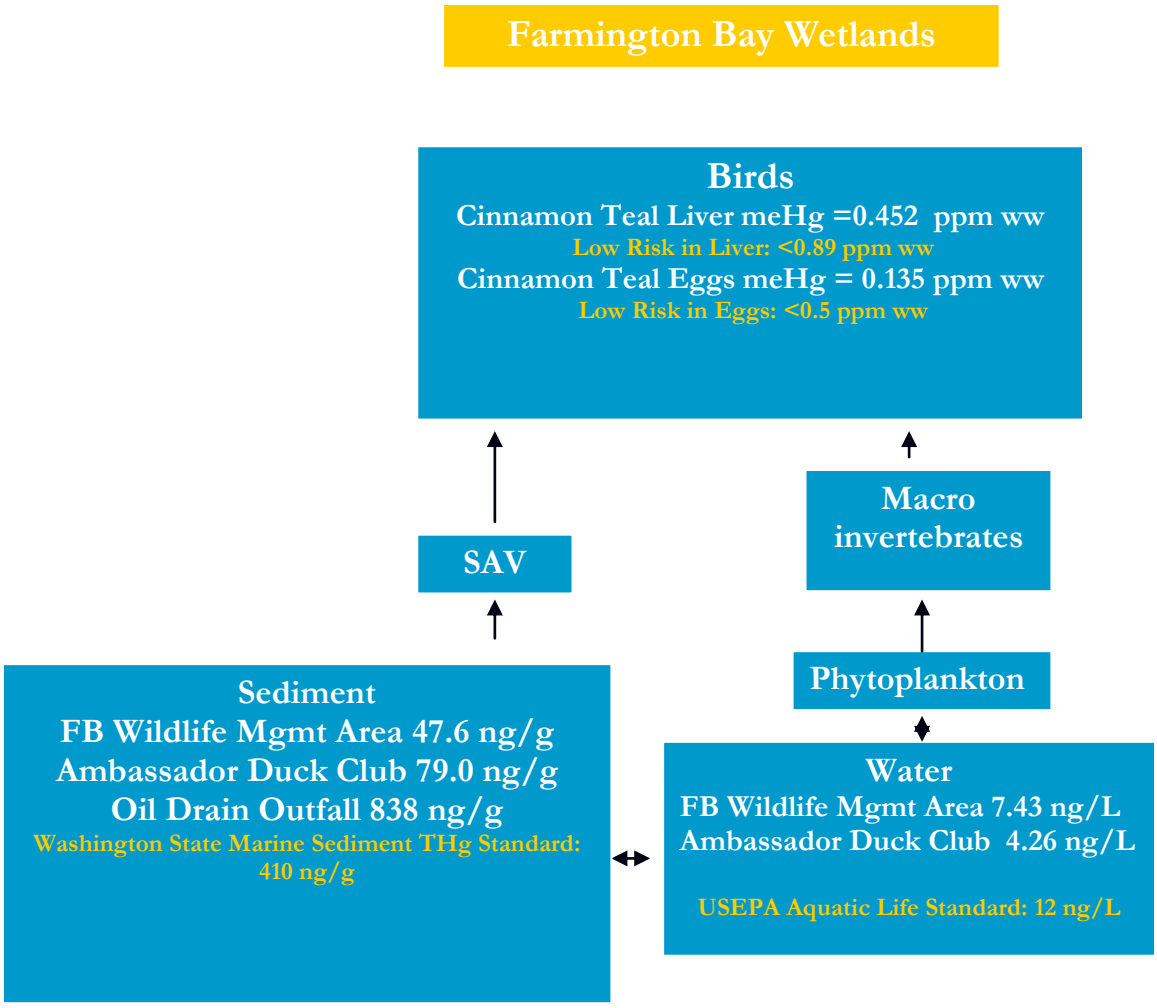

Figure 4. Conceptual model of the Farmington Bay wetlands adjacent to the Great Salt Lake. Mean Hg concentrations as reported in this study are listed in white and compared to literary benchmarks listed in yellow

Chapter 1. Mercury Distribution in Sediment and Water Samples Collected from Great Salt Lake, Utah, and Surrounding Wetland Areas

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Abstract

Despite the hemispheric importance of the Great Salt Lake (GSL) ecosystem, little is known about the input and biogeochemical cycling of mercury (Hg) in the open water and surrounding wetlands. To better understand the distribution and biogeochemical cycling of Hg, water and sediment samples were collected from throughout the south arm of GSL and the surrounding wetland areas. Modeled annual total Hg (THg) load from six riverine input sources to GSL was 6 kilograms (kg) and the combined annual wet and dry atmospheric deposition of Hg to GSL was about 30 kg. Salt-corrected concentrations of THg in 58 sediment samples collected beneath the south arm of GSL did not exceed the Washington Marine Sediment Quality Standard of 410 nanograms per gram (ng/g) (dry weight); however, the ratio of methylmercury (MeHg) to THg (in weight percent) in near-surface sediment samples were elevated compared to worldwide baselines. Water samples collected from 5 monitoring sites in the south arm of GSL and 1 site in Farmington Bay were analyzed for THg and MeHg. Four out of the six monitoring sites contained THg concentrations below the U.S. Environmental Protection Agency (USEPA) aquatic life standard for fresh water;

however, THg concentration in water samples from the other two monitoring sites (3510 and 2565) consistently exceeded the USEPA aquatic life standard for fresh water; however, most of the samples from these sites were below the aquatic life standard for saline water. With the exception of two water samples collected from the Farmington Bay monitoring site, all of the water samples collected from the open-water areas of GSL exceeded the uncontaminated baseline concentration for MeHg.

Water from four wetland areas surrounding GSL were monitored for THg and MeHg concentrations during 2008. Water samples collected from the Bear River Bird Refuge and Ambassador Duck Club contained low levels of THg and MeHg; however, water samples collected from Howard Slough and the Turpin Unit consistently contained elevated levels of THg and MeHg. The THg concentration in sediment samples collected from 4 out of the 5 wetland areas surrounding GSL did not exceed the Washington Marine Sediment Quality Standard; however, the sediment quality standard was exceeded in sediment samples collected from the Farmington Bay Waterfowl Management Area. The proportion of MeHg in sediment samples collected from the Farmington Bay Waterfowl Management Area and Turpin Unit was found to be elevated relative to sediment samples collected from other parts of the world. The abundant organic matter and nutrients associated with the sewage dominated outfall from the Salt Lake City sewage canal could be a contributor to the high proportion of MeHg in the sediment samples collected from the wetland areas. As a result of a planned fish

poisoning event, tissue samples from 17 dead carp were analyzed for THg. The THg concentration in the fish tissue samples were below the USEPA mercury screening limit for protection of human health and below the level of concern for protection of fish-eating mammals.

Introduction

Mercury (Hg) contamination is now of global concern and effects many water bodies that have no obvious source(s) (Brigham and others, 2003). Methylmercury (MeHg), the organic form of Hg, is highly toxic to the nervous system and can adversely affect sensitive segments of the population, particularly children and women of childbearing age. Mercury is currently the leading cause of impairment in estuaries and lakes in the continental United States and has resulted in fish consumption advisories covering > 4 million hectares of lakes and 644,000 km of streams within the United States (USEPA, 2002).

During reconnaissance-phase sampling in 2003, the USGS and the State of Utah found elevated levels of Hg in water samples from Great Salt Lake (GSL) (Naftz and others, 2008). Great Salt Lake is a terminal lake with a surface area that can exceed 5,100-km^2 (fig. 1a). Combined with the 1,920 km^2 of perimeter wetlands, the GSL ecosystem is recognized as a vital waterfowl habitat of hemispheric importance (Aldrich and Paul, 2002). The GSL ecosystem receives industrial, urban, mining, and agricultural discharge from a 37,500-km^2 watershed that includes more than 2.1 million people in northern Utah. The unique combination

of saline waters and freshwater wetlands of the GSL ecosystem comprise one of the most important breeding and staging areas for colonial waterbirds, waterfowl, and shorebirds in western North America. Because of the continental and hemispheric importance of GSL to several migratory and breeding waterbirds, it has been designated a site of Hemispheric Importance in the Western Hemisphere Shorebird Reserve Network (Aldrich and Paul 2002).

Figure 1a. Locations where water, sediment, and fish-tissue samples were collected and analyzed for total mercury and (or) methylmercury, Great Salt Lake, Utah.

Figure 1b. Water and sediment sampling locations near Bear River Bird Refuge, Utah.

Figure 1c. Water and sediment sampling locations near Howard Slough, Utah.

Figure 1d. Water, sediment, and fish tissue sampling locations near Farmington Bay Waterfowl Management Area and Turpin Unit, Utah. Fish tissue sampling location is identified by the triangle symbol.

Figure 1e. Water and sediment sampling locations near Ambassador Duck Club, Utah.

Despite the ecological importance of the GSL ecosystem, little is known about the input and biogeochemical cycling of Hg, in the open water and surrounding wetlands. Recent biogeochemical assessments by federal and state agencies have found elevated levels of MeHg in water and biota associated with the GSL ecosystem (Naftz et al. 2008; Darnall and Miles, 2009; Naftz et al. 2009; Vest et al. 2008). Water samples from GSL have been found to contain elevated concentrations of MeHg exceeding 30 ng/L (Naftz et al. 2008) and total Hg concentration in eared grebe livers were found to increase by almost threefold during the fall molting period on GSL (Darnall and Miles, 2009). Vest et al. (2008) found Hg concentrations in liver samples collected from three duck species (common goldeneye, northern shoveler, and green-winged teal) overwintering in the GSL ecosystem were among or exceeded the highest values reported in the published literature.

Elevated Hg concentrations in waterfowl resulted in the first health advisory in the United States limiting human consumption of three duck species harvested from the GSL ecosystem (Utah Department of Health, 2006). The wetlands surrounding GSL likely play a key role in the generation of MeHg. Previous studies (Olson and Cooper, 1976; Branfireun et al. 1996; Driscoll et al. 1998) have indicated that wetlands are important zones of MeHg production and that wetland reclamation activities could increase MeHg export to downstream water bodies (Marvin-DiPasquale et al. 2003).

As a result of the elevated levels of Hg found in the GSL ecosystem and the hemispheric importance of this system to migratory waterfowl, the Utah Department of Environmental Quality/Water Quality Division (UDEQ/DWQ) determined that more detailed sampling of water and sediments from GSL and the surrounding wetlands were needed to better understand the distribution and biogeochemical cycling of Hg. The USGS was tasked with collecting and analyzing additional water and sediment samples in the open water and surrounding wetlands of GSL. Specific objectives of this work were to determine: (1) variations in THg and MeHg concentration in water and sediment-core samples collected from the south arm of GSL; (2) annual loading of THg to GSL from riverine inputs; and (3) variations in THg and MeHg concentration in water and near-surface sediments from wetland areas.

Methodology

Sample collection

Because of potential contamination issues associated with the collection of Hg samples, special sample collection techniques were applied. For unfiltered Hg samples, pre-cleaned Teflon tubing was used to pump water samples from various depths into pre-cleaned and double bagged Teflon bottles provided by the USGS Hg Research Laboratory in Middleton, Wisconsin. Filtered water samples were passed through a 0.45 μm pore size, pre-cleaned capsule filters provided by the USGS Hg Research Laboratory. After collection, water samples were acidified to pH <2.0 with ultra-pure, 50% HCl, also provided by the USGS Hg Research Laboratory. All water samples were processed inside a fully-enclosed processing chamber to prevent the introduction of airborne contamination. After collection and acidification, water samples were double bagged and stored in the dark and on ice prior to analysis.

Dissolved organic carbon (DOC) samples were filtered through a glass-fiber filter into 125-ml amber glass bottles that had been baked at 450 deg. C. The DOC samples were acidified to a pH < 2.0 using 1 ml of 4.5 N H_2SO_4 and chilled at 4 deg. C until analysis.

With the exception of site 3510 (fig. 1a), a gravity coring device was used to collect all sediment cores. The 6.7-cm diameter gravity coring device was lowered slowly through the water column until it was about 1 m above the lake

bottom, at which point it was released to free-fall into the sediment. Within 6 hours of collection, the sediment cores were sectioned into 1-cm increments by personnel wearing powder-free latex gloves and placed into wide-mouthed, plastic containers. The core at site 3510 was collected using a box coring device. Surface sediment samples from perimeter wetland areas were collected from either a canoe or by wading and placed into wide-mouthed plastic containers, as well. All sediment samples were then chilled on ice prior to freeze drying.

Field measurements

Field parameters (pH, water temperature, specific conductance, and dissolved oxygen) were measured at inflow and lake sites using an In-Situ Troll 9500 multiparameter water-quality monitor. Specific conductance, dissolved oxygen, and pH probes were calibrated on a daily basis, prior to taking measurements. Temperature probe calibration was verified on an annual basis with a NIST certified thermometer.

Stream discharge at the Goggin Drain, Weber River, and Lee Creek gages (fig. 1a) was measured using standard USGS methods (Buchanan and Somers, 1968; 1969; Carter and Davidian, 1968) which apply a continuous record of water stage calibrated to periodic measurements of streamflow. Due to the low channel gradients and wind influence on inflow rates at the Bear River, Farmington Bay, and Kennecott Utah Copper Corporation (KUCC) gage sites (fig. 1a), normal stage-to-discharge relationships did not exist. Instead, hydroacoustic

instrumentation in combination with velocity index methods (Simpson, 2001) was used to accurately gage streamflow at those sites.

Analytical

All Hg analyses were performed at the USGS Hg Research Laboratory in Middleton, Wisconsin. Total Hg concentration in water was determined using cold vapor atomic fluorescence spectrometry (CVAFS) (Olson and DeWild 1999). The MeHg concentration in water was determined using distillation/ethylation/gas-phase separation with CVAFS detection (DeWild et al. 2002). Primary standards for total Hg were obtained commercially and certified against a NIST standard reference material. No reference materials are currently available for MeHg. Standards for MeHg were prepared in the laboratory. Known reference samples were analyzed at the beginning of each analytical run, after every 10 samples and at the end of each run. Method blanks were prepared by adding $SnCl_2$ to 125 ml of Hg-free water and purging for 20 minutes to ensure removal of any residual Hg. Method blanks were run periodically during each sample run and used to calculate the daily detection limit (DDL). The accepted value for the DDL is < 0.04 ng/l. Matrix spikes were analyzed during each run or every 10 samples. Percent recovery of matrix spikes had to fall between 90% and 110% for the sample run to be accepted. The analytical precision was ± 0.02 ng/L for both the total Hg and MeHg methods (DeWild et al. 2002).

DOC was determined at the USGS National Water Quality Laboratory in Lakewood, Colorado, using UV-promoted persulfate oxidation and infrared spectrometry (Brenton and Arnett 1993).

Prior to analysis of THg in sediments, freeze-dried samples were digested and oxidized in a Teflon digestion bomb with aqua regia at room temperature overnight to convert all Hg to Hg^{2+}. The digested samples were then diluted to volume with 5 percent bromine monochloride (BrCl). After dilution, the samples were pre-reduced with hydroxylamine hydrochloride ($NH_2OH*HCl$) to remove any free halogens, then reduced with stannous chloride ($SnCl_2$) to convert Hg^{2+} to gaseous mercury (Hg_0). The Hg_0 was then analyzed using CVAFS according to the method described in Olund and others (2004).

Prior to analysis of MeHg in sediments, the freeze-dried samples were extracted according to the methods outlined in DeWild and others, (2004) using a combination of potassium bromide, copper sulfate, and methylene chloride. After extraction, the samples were ethylated using sodium tetraethyl borate. After ethylation, the samples were purged with nitrogen gas and the ethylated Hg was collected on sample traps containing Carbotrap. The ethylated Hg species were then thermally desorbed from the sample traps and analyzed using CVAFS according to the methods outlined in DeWild and others (2004).

After freeze drying, tissue samples were extracted for THg using dilute nitric acid according to the methods described in Hammerschmidt and Fitzgerald (2006). The extracted tissue samples were analyzed for THg using CVAFS at the USGS Mercury Research Laboratory in Middleton, Wisconsin, according to USEPA Method 7470A (SW-846) (USEPA, 1994).

Data archival

Discharge and water-quality data, as well as the associated metadata, collected during this project are archived in the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2010) and can be accessed through an interactive map interface (NWIS Mapper) at: http://wdr.water.usgs.gov/nwisgmap/index.html or by site name or number (NWISWeb) at: http://waterdata.usgs.gov/ut/nwis/qw/. Table 1 contains a list of the site names and numbers sampled during this study.

Table 1. Field ID and corresponding U.S. Geological Survey NWISWeb site name and number of sampling locations where mercury data were collected from 2003 through 2008.

Results and Discussion

Mercury inputs

Riverine

The USGS loading software, LOADEST (Runkel and others, 2004), was used to estimate the mass loading of whole water THg at six inflow sites to GSL (Bear River outflow, Weber River outflow, Farmington Bay outflow, Goggin Drain outflow, Lee Creek outflow, and KUCC outflow) (fig. 1a*). The automated model selection in LOADEST was used to select the best regression model from a set of nine predefined models. Under the automated selection option, adjusted maximum likelihood estimation (AMLE) (Cohn, 1988; Cohn and others, 1992), is used to determine model coefficients and estimates of log load. The predefined model with the lowest value of the Akaike Information Criterion (AIC) statistic was then used for final load estimation (Judge and others, 1988).

Table 1. Field ID and corresponding U.S. Geological Survey NWISWeb site name and number of sampling locations where mercury data were collected from 2003 through 2010.

Field ID	Site Name	Site Number
Bear River Refuge inflow	(B- 9- 2)19aba Bear River Wetland Unit5C Inflow	413033112062501
Bear River Refuge mid-pond	(B- 8- 2)17cac Bear River Wetland Unit5C Middle	412540112053401
Bear River pond outlet	(B- 8- 2)17cdc Bear River Wetland Unit5C Outflow	412522112053901
Causeway Breach	GSL BREACH AT LAKESIDE, UT	10010020
West Culvert	GSL WEST CULVERT	411325112400701
East Culvert	GSL EAST CULVERT	411318112334001
Bear River outflow	BEAR RIVER BAY OUTFLOW	411403112200801

Field ID	Site Name	Site Number
	AT GSL MINERALS CORP BRIDGE	
Weber River outflow	N FK WEBER RIV NR WEST WARREN, UT	411316112132201
GSL 2267	GSL 2267, 1 MI NW OF FREMONT ISLAND	411116112244401
Ogden Bay	Ogden Bay, 5MI N, 2MI W of Farmington Bay marina	410809112163001
DD-I core site	GSL DD-I core site	411024112330901
GSL 2565	GSL 2565, NW OF HAT ISLAND	410644112382601
DD-C core site	GSL DD-C core site	410413112220601
GSL 2767	GSL 2767, 4 MI W OF N TIP OF ANTELOPE ISLAND	410422112200001
Farm. Bay outflow	GSL FARMINGTON BAY OUTFLOW AT CAUSEWAY BRIDGE	410401112134801
Farmington Bay	Farmington Bay, 1.4MI E, 3.5MI S of FB marina	410224112095101
DD-L core site	GSL DD-L core site	410036112261501
GSL 3510	GSL 3510, 6 MI WEST OF ANTELOPE ISLAND	405356112205601
DD-Q core site	GSL DD-Q core site	404933112175001
DD-R core site	GSL DD-R core site	404840112123701
Goggin Drain outflow	GOGGIN DRAIN NEAR MAGNA UTAH	10172630
Lee Creek outflow	LEE CREEK NEAR MAGNA, UT	10172640
KUCC outflow	KENNECOTT DRAIN NEAR MAGNA, UT	10172650
Howard Slough inlet	(B- 5- 3)26ddd Howard Slough Inlet	410803112092701
Howard Slough mid-pond	(B- 5- 3)35bdd Howard Slough (mid-pond)	410732112092601
Howard Slough outlet	(B- 5- 3)35cbc Howard Slough Outlet	410724112093901
Legacy Parkway pond	(B-2-1)12bbc FB WETLANDS POND NR LEGACY PKW	405544111542901
Turpin Unit inflow	TURPIN UNIT INFLOW NEAR FARMINGTON BAY WETLANDS	405440111554101
Turpin Unit mid-pond	TURPIN UNIT MIDDLE NEAR FARMINGTON BAY WETLANDS	405542111564101
Turpin Unit outflow	TURPIN UNIT OUTFLOW NEAR FARMINGTON BAY WETLANDS	405545111565301
SC 1	FARMINGTON BAY SEWER OUTLET SC 01	405500112023001
SC 2	FARMINGTON BAY SEWER OUTLET SC 2	405443112025001
SC 3	FARMINGTON BAY SEWER OUTLET SC 3	405427112030401
SC 4	FARMINGTON BAY SEWER OUTLET SC 04	405505112014001
SC 5	FARMINGTON BAY SEWER OUTLET SC 05	405448112015901
SC 6	FARMINGTON BAY SEWER OUTLET SC 6	405430112022001
SC 7	FARMINGTON BAY SEWER	405412112023901

Field ID	Site Name	Site Number
	OUTLET SC 07	
SC 8	FARMINGTON BAY SEWER OUTLET SC 08	405451112011401
SC 9	FARMINGTON BAY SEWER OUTLET SC 09	405436112013101
SC 10	FARMINGTON BAY SEWER OUTLET SC 10	405426112020101
Ambassador Duck Club inflow	(B- 1- 2)12bac Amb. Duck Club Pond Inlet	405020112011001
Ambassador Duck Club mid-pond	(B- 1- 2)11aad Amb. Duck Club Pond at Center Pos	405018112013101
Ambassador Duck Club outflow	(B- 1- 2) 1ccc Amb. Duck Club Pond Outlet	405033112012501

Detailed results on the mass loading of THg for each inflow source can be found in Naftz and others (2008). Total estimated THg load to GSL during a one-year time period from April 2007 through March 2008 was 6 kg (fig. 2). Almost 50% of the annual THg load was contributed by outflow from Farmington Bay outflow (2.8 kg). The second major contributor of Hg_t to GSL was from the Bear River outflow (36%). Minor THg loads (< 18%) were contributed by the four remaining streamflow sites.

Figure 2. Distribution of THg loads contributed to Great Salt Lake from each inflow site during April 1, 2007 to March 31, 2008. KUCC is the abbreviation for Kennecott Utah Copper Corporation.

Atmospheric

Atmospheric deposition can be one of the major sources of Hg to aquatic environments (Krabbenhoft and Rickert, 1995); therefore, determination of the relative proportions of riverine versus direct atmospheric Hg inputs to the lake surface of GSL will be important for understanding Hg cycling in the lake and developing future remediation strategies. Atmospheric Hg deposition can be from both dry and wet deposition directly to the surface of GSL. The surface area of GSL used in the atmospheric deposition calculations was calculated for the highest mean monthly lake elevation recorded at both the south (1279.4 m) and north arm (1279.2 m) of GSL during the spring of 2007. Based on lake area tables developed for GSL by Baskin (2005, 2006), a maximum lake surface area

of 3.2 x 10^9 m^2 was available (not including Farmington or Bear River Bays) during the study period for atmospheric Hg deposition.

Measurements and associated modeling of dry deposition of reactive gaseous mercury (RGM) to the surface of GSL was conducted over a one year period (2006–2007) by Peterson and Gustin (2008). Annual dry deposition of Hg modeled by Peterson and Gustin (2008) was 4.4 $\mu g/m^2$. Using the cumulative surface area of GSL during the spring of 2007 of 3.2 x 10^9 m^2, approximately 14 kg of Hg would be deposited to the lake surface during 2006–2007.

Wet deposition of Hg to the surface of GSL was estimated using data collected at the Mercury Deposition Network (MDN) site located near GSL (Latitude: 40^o 42' 42.48"; Longitude: 111^o 57' 39.23"; Elevation: 1297 m) (fig. 3). This MDN site has been operating since May 2007. Annual wet deposition of Hg during 2008 at this site was 5.0 $\mu g/m^2$ (National Atmospheric Deposition Program, 2010). Combining the cumulative surface area of GSL during the spring of 2007 of 3.2 x 10^9 m^2 with the estimated annual wet deposition value, approximately 16 kg of Hg would be deposited to GSL via wet deposition processes.

Figure 3. Total mercury in wet deposition at the monitoring site near Great Salt Lake, Utah (circled) and the western United States (National Atmospheric Deposition Program, 2010). Deposition is in micrograms per square meter ($\mu g/m^2$).

Comparison of annual cumulative atmospheric (30 kg) versus riverine (6 kg) deposition of THg to GSL indicates that atmospheric deposition processes are the major input source to GSL by about 5:1. Additional atmospheric and riverine Hg data are needed to further confirm and refine these annual deposition amounts.

The combined annual atmospheric and riverine input rates of Hg were compared to longer-term Hg input rates estimated from dated sediment records in GSL (Naftz and others, 2010). Recent (1980 to 2007) sediment accumulation rates of THg in the six cores (DD-I, DD-C, DD-L, GSL 3510, DD-Q, and DD-R; shown in fig. 1a) ranged from about 30 to > 140 $\mu g/m^2/yr$, with median of 50 $\mu g/m^2/yr$ for all 6 cores during the past 30 years (fig. 4). This recent THg sediment accumulation is much larger than the measured atmospheric + riverine Hg deposition of 11.8 $\mu g/m^2/yr$ for GSL (Naftz and others, 2010). The large difference may be a result of underestimating the amount of Hg deposited to GSL via dry deposition by Peterson and Gustin (2008). More detailed measurements of dry deposition of

Hg to GSL are currently (2010) underway by researchers at the University of Utah (Kevin Perry, Univ. of Utah, oral commun., May 2010).

Figure 4. Comparison of mass accumulation rates (MAR) of mercury in sediment cores (box plot) to annual measured riverine/atmospheric inputs during 2007/2008 (dashed line) to Great Salt Lake, Utah.

Gilbert Bay

Sediment cores

Sediment cores were collected from six locations in Gilbert Bay, within the south arm of GSL (DD-I, DD-C, DD-L, GSL 3510, DD-Q, and DD-R) (fig. 1a). The top 10 cm of each core was sectioned into 1-cm slices and analyzed for THg and MeHg. Due to the high salinity of GSL, the THg and MeHg concentration from each sediment sample were corrected for salt content using the method described in Oliver and others (2009).

Figure 5 compares the salt-corrected THg for samples from each of the coring sites to the Washington Marine Sediment Quality Standard of 410 ng/g (dry weight) (State of Washington, 1995). The Washington sediment standard was used because Utah does not have a standard for Hg. All of the sediment samples collected from GSL were below the sediment quality standard (fig. 5). Relative to the six coring sites, site 3510 contained the highest median and mean THg concentration; however, both the median and mean values were < 300 ng/g.

Figure 5. Box plots of salt-corrected, total mercury concentration in sediment samples collected from six coring sites in the south arm of Great Salt Lake, Utah, compared to marine sediment quality standard adopted by the State of Washington.

The ratio of MeHg to THg, expressed in weight percent, was determined for the sediment core samples collected from GSL (fig. 6) and compared to the average ratios found in most sediment samples (1.0 to 1.5 percent) as compiled by Ulrich and others (2001). In general, at least one sample from each sediment core exceeded the ratio typical of most sediment samples (fig. 6). The highest MeHg to THg was generally associated with the uppermost sediment sample. Previous research at Salmon Falls Creek Reservoir in southwestern Idaho found that Hg methylation was enhanced at the sediment/water interface, where there is low oxygen, and abundant organic matter and plant nutrients (Gray and Hines, 2009). This same set of circumstances is likely responsible for the high proportion of MeHg in sediment samples from the sediment/water interface in GSL.

Figure 6. Methylmercury-to-total-mercury ratios in weight percent for sediment samples collected from Gilbert Bay, Great Salt Lake, Utah, compared to ratios typically found in sediments (Ulrich and others, 2001).

Water

Unfiltered water samples were collected from five monitoring sites in the south arm of GSL (2565, 3510, 2267, 2767, Ogden Bay) and one monitoring site in Farmington Bay (fig. 1a). Water samples were collected from 2005 through 2008 and were analyzed for THg and MeHg by the USGS Mercury Research Laboratory in Middleton, Wisconsin.

The THg concentration in water samples from the open water of GSL were compared to the USEPA aquatic life standard of 12 ng/L for fresh water and 25 ng/L for salt water (Administration, 2010). The THg in water samples from monitoring sites 2767, 2267, and Ogden Bay, were all below the USEPA aquatic life standard for both fresh and salt water and only one sample from the Farmington Bay monitoring site exceeded the fresh water standard (fig. 7). In contrast, THg concentration in water samples from monitoring sites 3510 and 2565 consistently exceeded the USEPA aquatic life standard for fresh water. The median concentration of THg at site 2565 was 22 ng/L, significantly above the aquatic life standard for fresh water but below the standard for salt water of 25

ng/L. Water samples with elevated THg concentration were collected in deeper parts of the water column, generally below 6.0 m in depth.

Figure 7. Box plots of total mercury concentration in water samples collected from five monitoring sites in the south arm of Great Salt Lake and one monitoring site in Farmington (Farm.) Bay, Utah, compared to the USEPA aquatic life standards for total mercury [N, number of samples].

Currently (2010) there is not an established aquatic life standard for the concentration of MeHg in water; therefore, MeHg concentration in water samples was compared to an “uncontaminated worldwide baseline” concentration of 0.3 ng/L developed from MeHg data compiled by Gray and Hines (2009). With the exception of two water samples collected from the Farmington Bay monitoring site, all of the water samples collected from the open-water areas of GSL exceeded the uncontaminated baseline concentration for MeHg (fig. 8). The elevated levels of MeHg in the water samples from the open-water areas of GSL are consistent with the high proportion of MeHg in shallow (0 to 1 cm depth) bottom sediments collected below the GSL water column (fig. 6) and likely reflect geochemical conditions supportive of Hg methylation, as discussed in a previous section of the report.

Figure 8. Box plots of methylmercury concentration in water samples collected from five monitoring sites in the south arm of Great Salt Lake and one monitoring site in Farmington (Farm.) Bay, Utah, compared to the worldwide uncontaminated baseline value for methylmercury compiled by Gray and Hines (2009) [N, number of samples].

Previous work done by Naftz and others (2008) found that a persistent and widespread anoxic layer in the south arm of GSL, referred to as the deep brine layer (DBL), may be responsible for the elevated levels of MeHg found in GSL. The DBL has high rates of sulfate reduction, likely increasing the Hg methylation capacity of GSL. Hydroacoustic and sediment-trap evidence indicate that turbulence introduced by internal waves generated during sustained wind events can temporarily mix the elevated MeHg concentrations in the DBL with the more biologically active sections of the water column in the lake (Naftz and others, 2008).

Ongoing (2010-11) research has installed a LakeESP (PME, Inc., 2010) on the south arm of GSL (fig. 9). The LakeESP monitors water temperature, pH, conductivity, PAR, and depth, as well as current velocity and direction at multiple depths in the water column using a SonTek Argonaut-XR. Meteorology sensors collect wind speed/ direction, humidity, air temperature, barometric pressure,

liquid precipitation, and net long and short wave radiation. Data are scanned once a minute and stored to the LakeESP's internal memory card. Data are then telemetered every hour to PME's server and the USGS receives the data via FTP. A strong wind event that occurred on June 16, 2010, illustrates how data collected from the LakeESP platform can be utilized to better understand and simulate the turbulent mixing process in the water column and the potential transport of MeHg from the DBL to the upper water column of GSL (fig. 10).

Figure 9. Deployment of LakeESP (PME, Inc., 2010) in the south arm of Great Salt Lake, Utah during May 2010.

Figure 10. Changes in surface wind speed and water temperature with depth below lake surface during June 16-17, 2010 at the LakeESP station (PME, Inc., 2010), Great Salt Lake,

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Perimeter wetland water samples

Unfiltered water samples were collected from selected water bodies at Bear River Bird Refuge (fig. 1b), Howard Slough (fig. 1c), Turpin Unit (fig. 1d), and Ambassador Duck Club (fig. 1e). Water samples were collected from May through October, 2008, and analyzed for THg and MeHg by the USGS Mercury Research Laboratory in Middleton, Wisconsin.

The THg concentration in water samples were compared to both the USEPA drinking water and aquatic life standards for fresh and salt water for each of the wetland areas. There is no established standard for the concentration of MeHg in water; therefore, MeHg concentration in water samples was compared to MeHg and THg data compiled and produced by Gray and Hines (2009) for each of the four wetland areas surrounding GSL. Comparisons included uncontaminated global baselines (Gill and Bruland, 1990; Leermakers and others, 1996; Lyons and others, 1999; Gray and others, 2000; Gray and others, 2004; Seiler and others, 2004; Loseto and others, 2004; Gray and others, 2005), as well as Salmon Falls Creek Reservoir, a water body in south-central Idaho with elevated levels of Hg in fish tissue first documented in 2001 (Gray and Hines, 2009).

All water samples collected from the Bear River Bird Refuge were below the fresh and salt water USEPA aquatic life standard for THg (fig. 11). Only one of the samples collected from the mid-pond site contained a MeHg concentration exceeding the worldwide uncontaminated baseline.

Figure 11. Total mercury versus methylmercury concentrations for whole water samples collected from Bear River Bird Refuge, Utah, compared to water data collected from Salmon Falls Creek Reservoir, Idaho (Gray and Hines, 2009); Antarctica lakes (Lyons and others, 1999); Canada arctic lakes (Loseto and others, 2004); Narraguinnep Reservoir, Colorado (Gray and others, 2005); Nevada lakes (Seiler and others, 2004); and uncontaminated worldwide

baselines (Gill and Bruland,1990; Leermakers and others, 1996; Gray and others, 2000; Gray and others, 2004; Loseto and others, 2004). The USEPA drinking water standard for Hg of 2000 ng/L (USEPA, 2003) and the USEPA aquatic life standard for Hg in fresh water (12 ng/L) and salt water (25 ng/L) (Administration, 2010) are also shown for reference. Graph modified from Gray and Hines (2009).

Water samples collected from Howard Slough were higher in both THg and MeHg concentrations compared to water samples from the Bear River Bird Refuge (fig. 12). Two of the Howard Slough water samples exceeded the USEPA aquatic life standard for THg in fresh water and one of the Howard Slough water samples exceeded the salt water aquatic life standard. All but two of the water samples from Howard Slough exceeded or equaled the worldwide uncontaminated baselines for both THg and MeHg (fig. 12). Seven of the water samples contained MeHg concentrations similar to water samples collected from SFCR, Idaho, a water body with elevated Hg levels in fish tissue.

Figure 12. Total mercury versus methylmercury concentrations for whole water samples collected from Howard Slough, Utah, compared to water data collected from Salmon Falls Creek Reservoir, Idaho (Gray and Hines, 2009); Antarctica lakes (Lyons and others, 1999); Canada arctic lakes (Loseto and others, 2004); Narraguinnep Reservoir, Colorado (Gray and others, 2005); Nevada lakes (Seiler

and others, 2004); and uncontaminated worldwide baselines (Gill and Bruland,1990; Leermakers and others, 1996; Gray and others, 2000; Gray and others, 2004; Loseto and others, 2004). The USEPA drinking water standard for Hg of 2000 ng/L (USEPA, 2003) and the USEPA aquatic life standard for Hg in fresh water (12 ng/L) and salt water (25 ng/L) (Administration, 2010) are also shown for reference. Graph modified from Gray and Hines (2009).

A detailed sampling program was conducted at the Howard Slough wetland site during July 2008 to determine how MeHg concentration in water exiting the wetland complex could change over a 24-hour cycle. Dissolved (< 0.45 μm) MeHg showed a strong diurnal variation with consistently decreasing concentrations during daylight periods and increasing concentrations during non-daylight periods. The proportion of MeHg relative to THg in the water column consistently decreased with increasing sunlight duration, indicative of photodegradation. During the field experiment, measured MeHg photodegradation rates ranged from 0.02 to 0.06 ng L^{-1} hr^{-1}. Study results indicated that daytime monitoring of selected wetlands surrounding GSL may significantly underestimate the MeHg content in the water column. Wetland managers should consider practices that maximize the photodegradation of MeHg during daylight periods. Additional details on these study results can be found in Naftz and others (in review).

Only one of the water samples collected from the Turpin Unit contained THg and MeHg concentrations within the limits of uncontaminated baselines (fig. 13). All of the inflow samples to the Turpin Unit exceeded the USEPA aquatic life standard for THg in fresh water. Eight of the nine water samples collected from the Turpin Unit had elevated concentrations of MeHg similar to water samples collected from SFCR, Idaho, a water body with elevated Hg levels in fish tissue. Based on the water data collected from the Turpin Unit, it is likely that biota utilizing this site could accumulate elevated levels of Hg.

Figure 13. Total mercury versus methylmercury concentrations for whole water samples collected from Turpin Unit, Utah, compared to water data collected from Salmon Falls Creek Reservoir, Idaho (Gray and Hines, 2009); Antarctica lakes (Lyons and others, 1999); Canada arctic lakes (Loseto and others, 2004); Narraguinnep Reservoir, Colorado (Gray and others, 2005); Nevada lakes (Seiler and others, 2004); and uncontaminated worldwide baselines (Gill and Bruland,1990; Leermakers and others, 1996; Gray and others, 2000; Gray and others, 2004; Loseto and others, 2004). The USEPA drinking water standard for Hg of 2000 ng/L (USEPA, 2003) and the USEPA aquatic life standard for Hg in fresh water (12 ng/L) and salt water (25 ng/L) (Administration, 2010) are also shown for reference. Graph modified from Gray and Hines (2009).

Although the THg concentration in water samples collected from the Ambassador Duck Club are slightly elevated relative to worldwide uncontaminated baselines, all the samples were below the USEPA aquatic life standard for fresh water (fig. 14). The MeHg concentration in water samples was low and plotted within the range expected for water from uncontaminated areas. Based on the water samples collected from the Ambassador Duck Club, biota utilizing this site should not accumulate elevated levels of Hg.

Figure 14. Total mercury versus methylmercury concentrations for whole water samples collected from the Ambassador Duck Club, Utah, compared to water data collected from Salmon Falls Creek Reservoir, Idaho (Gray and Hines, 2009); Antarctica lakes (Lyons and others, 1999); Canada arctic lakes (Loseto and others, 2004); Narraguinnep Reservoir, Colorado (Gray and others, 2005); Nevada lakes (Seiler and others, 2004); and uncontaminated worldwide baselines (Gill and Bruland,1990; Leermakers and others, 1996; Gray and others, 2000; Gray and others, 2004; Loseto and others, 2004). The USEPA drinking water standard for Hg of 2000 ng/L (USEPA, 2003) and the USEPA aquatic life standard for Hg in fresh water (12 ng/L) and salt water (25 ng/L) (Administration, 2010) are also shown for reference. Graph modified from Gray and Hines (2009).

A previous USGS national-scale study found a positive and statistically significant ($p < 0.001$) correlation between DOC and unfiltered MeHg concentrations in water samples (Scudder and others, 2009). The DOC and MeHg concentrations from 46 water samples collected from the four wetland areas surrounding GSL were compared (fig. 15). A weak, but positive correlation ($R^2 = 0.185$, $p < 0.002$) was found between DOC and MeHg in the wetland water samples. This correlation suggests that elevated concentrations of DOC in wetland water bodies may be influencing the methylation of inorganic forms of Hg

and subsequent bioaccumulation, similar to results found in other areas of the United States.

Figure 15. Best fit line comparing dissolved organic carbon to methylmercury concentration in water samples collected from wetlands surrounding Great Salt Lake, Utah, during 2008.

Perimeter wetland sediment samples

The top 5 cm of bottom material sediments from five wetland sites (Bear River Bird Refuge, Howard Slough, Farmington Bay Waterfowl Management Area, Turpin Unit, and Ambassador Duck Club) were sampled and analyzed for THg (figs. 1b thru 1e). The concentration of THg was compared to the Washington Marine Sediment Quality Standard of 410 ng/g (dry weight) (State of Washington, 1995). With the exception of samples collected from the Farmington Bay Waterfowl Management Area, all the THg concentrations were below the sediment quality standard (fig. 16). Out of the 10 sediment samples collected from the Farmington Bay Waterfowl Management Area, 7 contained THg concentrations above the marine sediment quality standard, with the highest concentration exceeding 1,900 ng/L (fig. 16). The location of the samples exceeding the marine sediment quality standard are shown in Figure 17 and are all in the proximity of where the Salt Lake City sewage canal discharges to Farmington Bay.

Figure 16. Box plots of total mercury concentration in sediment samples collected from five wetland sites surrounding Great Salt Lake, Utah, compared to marine sediment quality standard adopted by the State of Washington.

Figure 17. Sediment sampling locations in Farmington Bay Waterfowl Management Area in the vicinity of the outflow from the Salt Lake City sewage canal. Sites labeled in red exceed the marine sediment quality standard for mercury (State of Washington, 1995) during the sampling program conducted in 2008.

The THg concentrations in sediment samples from the 10 locations in Farmington Bay Waterfowl Management Area were compared with sediment samples that were collected at the same locations and analyzed for THg in 2000 by the U.S. Fish and Wildlife Service (Waddell and others, 2009) (fig. 18). In general, the sediment samples collected during 2008 had lower THg concentration than samples collected during 2000. The highest THg concentration found in samples collected during 2000 exceeded 6,000 ng/g (fig. 18). Comparison of the 2000 and 2008 data sets indicate a decrease in particulate-bound THg concentration in recent outfall from the Salt Lake City sewage canal; however, it is likely that the higher THg concentrations observed

in the samples collected during 2000 are still present at deeper horizons in the sediment record.

Figure 18. Comparison of total mercury concentration in sediment samples collected from the same sites in Farmington Bay Waterfowl Management Area in 2000 (Waddell and others, 2009) and 2008 (this study).

In order to gain further insight into potential sediment toxicity, the ratio of MeHg to THg was determined in the sediment samples collected in 2008 from the Farmington Bay Waterfowl Management Area (fig. 19). The ratio, expressed in weight percent, was compared to the average ratios found in most sediment samples (1.0 to 1.5 percent) as compiled by Ulrich and others (2001). Six of the ten sediment samples exceeded the THg-to-MeHg ratio typical of most sediment samples (fig. 19). The highest MeHg to THg was found in sample SC-06, containing 9 percent MeHg (fig. 19). The abundant organic matter and nutrients associated with the sewage dominated outfall from the Salt Lake City sewage canal is a likely contributor to the high proportion of MeHg in the sediment samples collected from Farmington Bay Waterfowl Management area. The other four wetland areas surrounding GSL contained THg-to-MeHg ratios more typical of sediment samples collected from other areas (fig. 20). All the sediment samples collected from the Ambassador Duck Club and Howard Slough sites were at or below the ratio typical of most sediments (Ulrich and others, 2001).

Three sediment samples collected from the Turpin Unit exceeded the THg-to-MeHg ratio typical of most sediment samples. Elevated ratios in the sediment samples collected from the Turpin Unit are consistent with the elevated MeHg concentrations found in water samples collected from this area (fig. 13). The samples collected from the Turpin Unit are in close proximity (~ 4 km) to the elevated THg and MeHg concentrations in sediment samples collected from the Farmington Bay Waterfowl Management Area and may reflect a common source(s) of elevated Hg in the watershed.

Figure 19. Methylmercury-to-total-mercury ratios in weight percent for sediment samples collected from Farmington Bay Waterfowl Management Area, Utah, compared to ratios typically found in sediments (Ulrich and others, 2001).

Figure 20. Methylmercury-to-total-mercury ratios in weight percent for sediment samples collected from four wetland areas surrounding Great Salt Lake, Utah, compared to ratios typically found in sediments (Ulrich and others, 2001).

Perimeter wetland fish tissue samples

Carp populations in the wetlands surrounding GSL are periodically managed by applying rotenone to selected water bodies during ice-covered conditions (fig.

21). The dead carp that wash up on the shoreline provide a food source to the over wintering golden eagle population residing in the perimeter wetlands. Because of the elevated THg concentrations found in bottom sediments from the Farmington Bay Waterfowl Management Area and Turpin Unit, tissue samples from dead carp were collected during a rotenone poisoning event in January 2010.

Figure 21. Utah Department of Natural Resources employee applying rotenone to an ice-covered pond in Farmington Bay Waterfowl Management Area, Utah, during January 2010.

Seventeen dead carp were collected from wetland shoreline areas within 1 day of a poisoning event during January 2010 (fig. 22). The whole carp samples were placed in plastic bags and kept chilled during transport to the USGS laboratory for processing. Within 24-hours of sample collection, a skinless filet tissue sample was taken behind the dorsal fin of each fish and analyzed for THg (dry weight) and percent moisture at the USGS Mercury Research Laboratory according to the procedures described in the laboratory methods section in the report.

Figure 22. Total mercury concentration in skinless filets of common carp samples collected from a pond in Farmington Bay Waterfowl Management Area, Utah, during January 2010 compared to level of concern for protection of fish-eating mammals (Yeardley and others, 1998; Peterson and others, 2007) and human health (USEPA, 2001; 2009).

After conversion from dry weight to wet weight concentration, the THg in the 17 fish tissue samples ranged from 0.003 to 0.030 mg/kg, and were all below the USEPA mercury screening limit of 0.3 mg/kg (wet weight) for protection of human health (USEPA, 2001; 2009). The fish tissue data were also below the 0.1 mg/kg (wet weight) level of concern for protection of fish-eating mammals (Yeardley and others, 1998; Peterson and others, 2007). Fish length was compared to THg concentration (dry weight) in the 17 filet samples (fig. 23). For fish lengths > 65 cm, there was an increasing THg concentration with increasing organism length.

Figure 23. Comparison between total mercury concentration in skinless filets of common carp samples to fish length. Fish tissue samples collected from a pond in Farmington Bay Waterfowl Management Area, Utah, during January 2010.

Conclusions

During reconnaissance-level sampling in 2003, the USGS and the State of Utah found elevated levels of THg and MeHg in water samples collected from GSL. As a result of elevated Hg levels resulting in biota, the first health advisory in the United States limiting human consumption of three duck species was issued by the State of Utah. Despite the hemispheric importance of the GSL ecosystem, little is known about the input and biogeochemical cycling of Hg in the open water and surrounding wetlands. To better understand the distribution and biogeochemical cycling of Hg, water and sediment samples were collected from throughout the south arm of GSL and the surrounding wetland areas.

Modeled annual THg load from six riverine input sources to GSL was 6 kg. Almost 50% (2.8 kg) of the annual THg load was from the Farmington Bay outflow to GSL. The combined annual wet and dry atmospheric deposition of Hg to GSL was about 30 kg, exceeding riverine input by a ratio of about five to one. Sediment-core data collected from the lake suggest that dry deposition of Hg measured and modeled by Peterson and Gustin (2008) may be underestimating the actual dry deposition by about an order of magnitude.

Salt-corrected concentrations of THg in 58 sediment samples collected beneath the south arm of GSL did not exceed the Washington Marine Sediment Quality Standard of 410 ng/g (dry weight). The ratio of MeHg to THg (in weight percent) in near-surface sediment samples exceeded the ratio typical of sediment samples collected from other parts of the world (1.0 to 1.5 percent). It is likely

that Hg methylation is enhanced at the sediment/water interface in GSL, where there is low oxygen, and abundant organic matter and plant nutrients.

Water samples collected from 5 monitoring sites in the south arm of GSL and 1 site in Farmington Bay were compared to the USEPA aquatic life standards for THg of 12 ng/L in fresh water and 25 ng/L in salt water and the uncontaminated worldwide baseline concentration of 0.3 ng/L developed from MeHg data compiled by Gray and Hines (2009). With the exception of one sample collected from Farmington Bay, the THg in 4 out of the 6 monitoring sites were below the USEPA aquatic life standard for fresh water. The THg concentration in water samples from the other two monitoring sites (3510 and 2565) consistently exceeded the USEPA aquatic life standard for fresh water; however, most of the water samples from these sites were below the aquatic life standard for salt water. Levels of MeHg were found to be elevated, as well. With the exception of two water samples collected from the Farmington Bay monitoring site, all of the water samples collected from the open-water areas of GSL exceeded the uncontaminated baseline concentration for MeHg.

Water from four wetland areas surrounding GSL were monitored for THg and MeHg concentrations during 2008. Each of the wetland areas had unique THg and MeHg concentration signatures. Water samples collected from the Bear River Bird Refuge and Ambassador Duck Club contained low levels of THg and MeHg. In contrast, water samples collected from Howard Slough and the Turpin

Unit consistently exceeded USEPA aquatic life criteria for THg in fresh water and the worldwide uncontaminated baseline concentration for MeHg. A positive correlation was found between DOC and MeHg in the water samples collected from the four wetland sites, indicating that elevated concentrations of DOC in wetland water bodies surrounding GSL may be influencing the methylation of inorganic forms of Hg.

The concentration of THg in sediment samples collected from 4 out of the 5 wetland areas surrounding GSL did not exceed the Washington Marine Sediment Quality Standard of 410 ng/g (dry weight). Elevated concentrations of THg were found in sediment samples collected from the Farmington Bay Waterfowl Management Area, with 7 out of the 10 samples exceeding the marine sediment quality standard. The ratio of MeHg to THg (in weight percent) in the majority of sediment samples collected from the Farmington Bay Waterfowl Management Area consistently exceeded the ratio typical of sediment samples collected from other parts of the world (1.0 to 1.5 percent). Three sediment samples collected from the Turpin Unit, in close proximity to the Farmington Bay Waterfowl Management Area, also exceeded the THg-to-MeHg ratio typical of most sediment samples. The abundant organic matter and nutrients associated with the sewage dominated outfall from the Salt Lake City sewage canal could be a contributor to the high proportion of MeHg in the sediment samples collected from the Farmington Bay Waterfowl Management area and the Turpin Unit.

During a rotenone poisoning event in January 2010, tissue samples from 17 dead carp were collected from a small pond in close proximity (~ 3 km) to the Turpin Unit water and sediment monitoring sites and analyzed for THg. The THg concentration in the fish tissue samples ranged from 0.003 to 0.030 mg/kg (wet weight), and were all well below the USEPA mercury screening limit of 0.3 mg/kg (wet weight) for protection of human health and below the 0.1 mg/kg (wet weight) level of concern for protection of fish-eating mammals.

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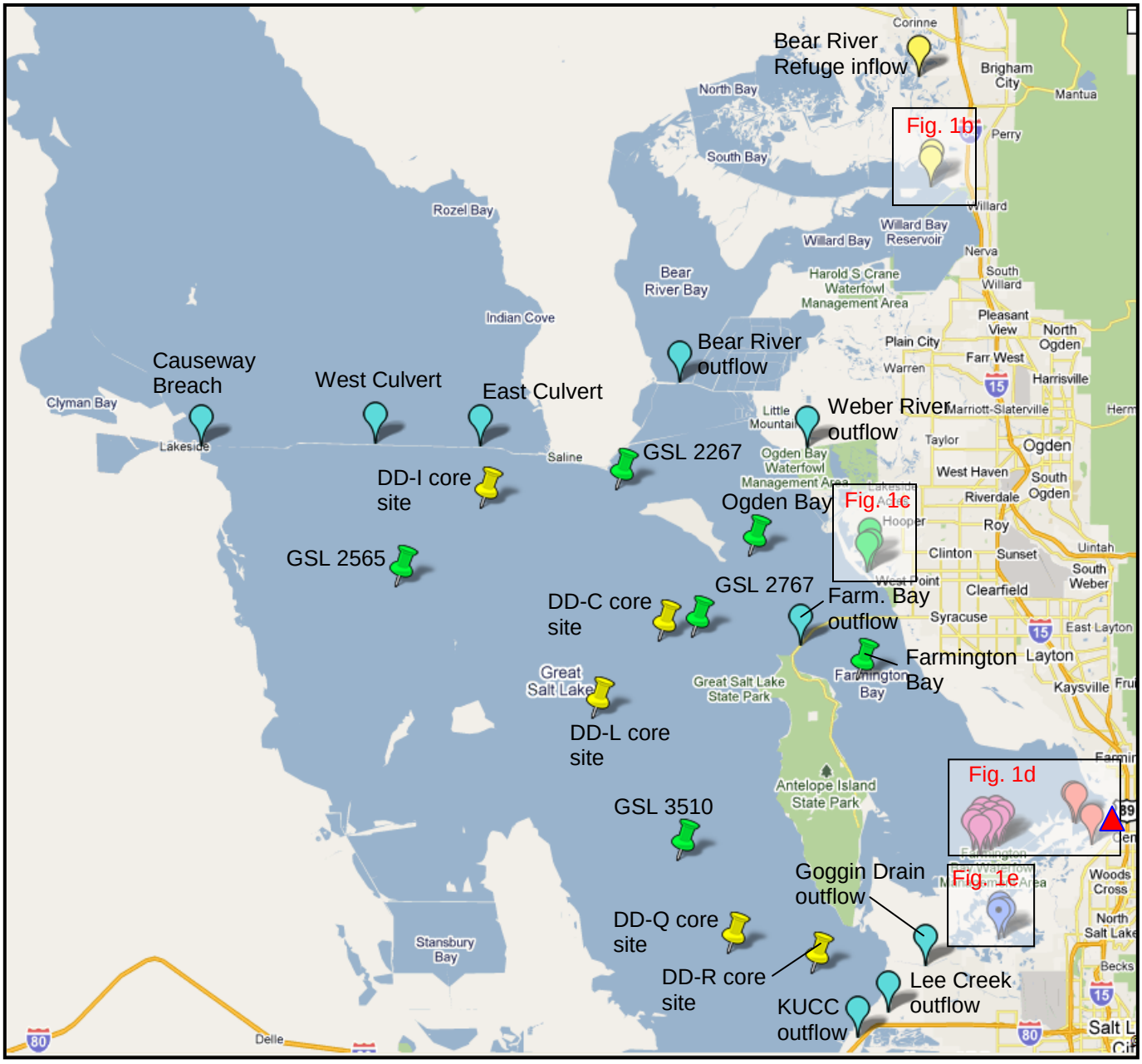

Explanation

- Bear River Waterfowl Management area water and sediment sample sites
- Riverine inflow sample sites to Great Salt Lake
- Howard Slough water and sediment sample sites
- Turpin Unit water and sediment sample sites
- Ambassador Duck Club water and sediment sample sites
- Sewer Canal sediment sample sites
- Great Salt Lake open-water sample sites
- Great Salt Lake sediment core sample sites
- Fish tissue sample site

Figure 1a. Locations where water, sediment, and fish-tissue samples were collected and analyzed for total mercury and (or) methylmercury, Great Salt Lake, Utah.

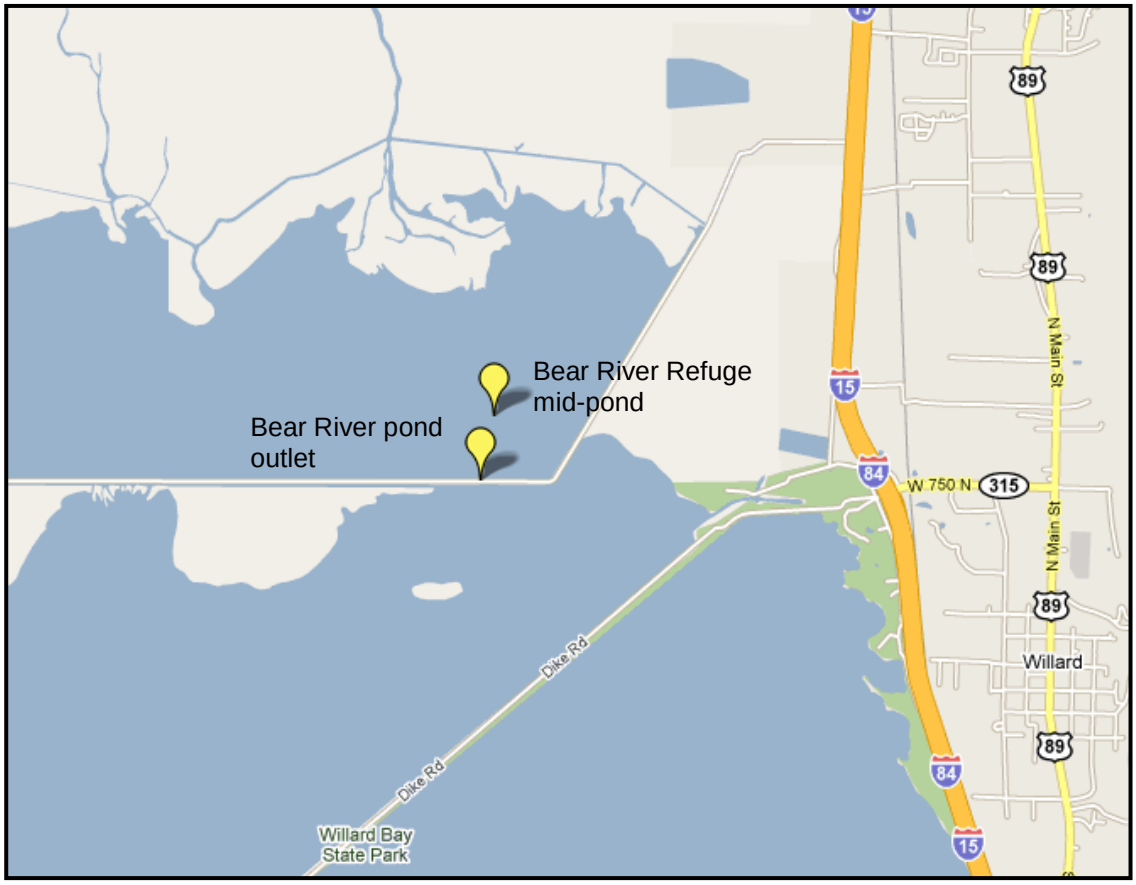

Figure 1b. Water and sediment sampling locations near Bear River Bird Refuge, Utah.

Figure 1c. Water and sediment sampling locations near Howard Slough, Utah.

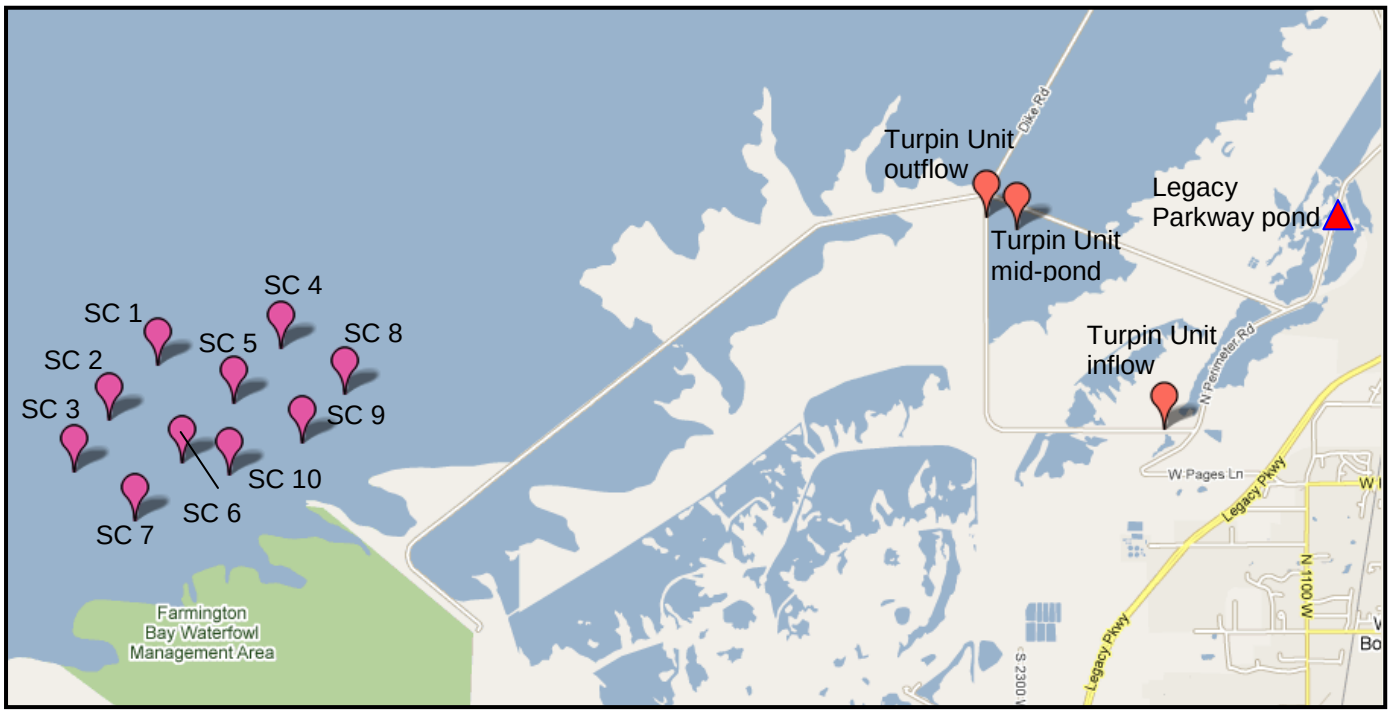

Figure 1d. Water, sediment, and fish tissue sampling locations near Farmington Bay Waterfowl Management Area and Turpin Unit, Utah. Fish tissue sampling location is identified by the triangle symbol.

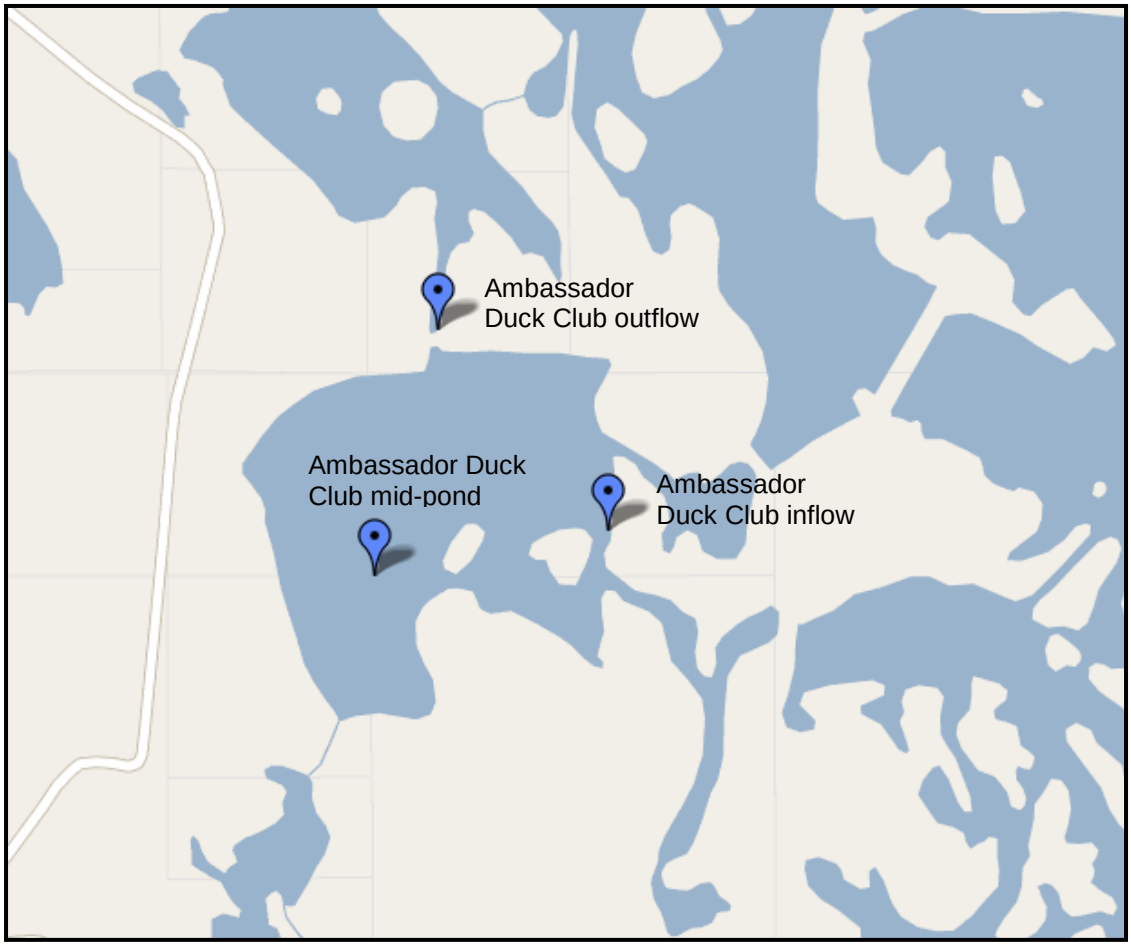

Figure 1e. Water and sediment sampling locations near Ambassador Duck Club, Utah.

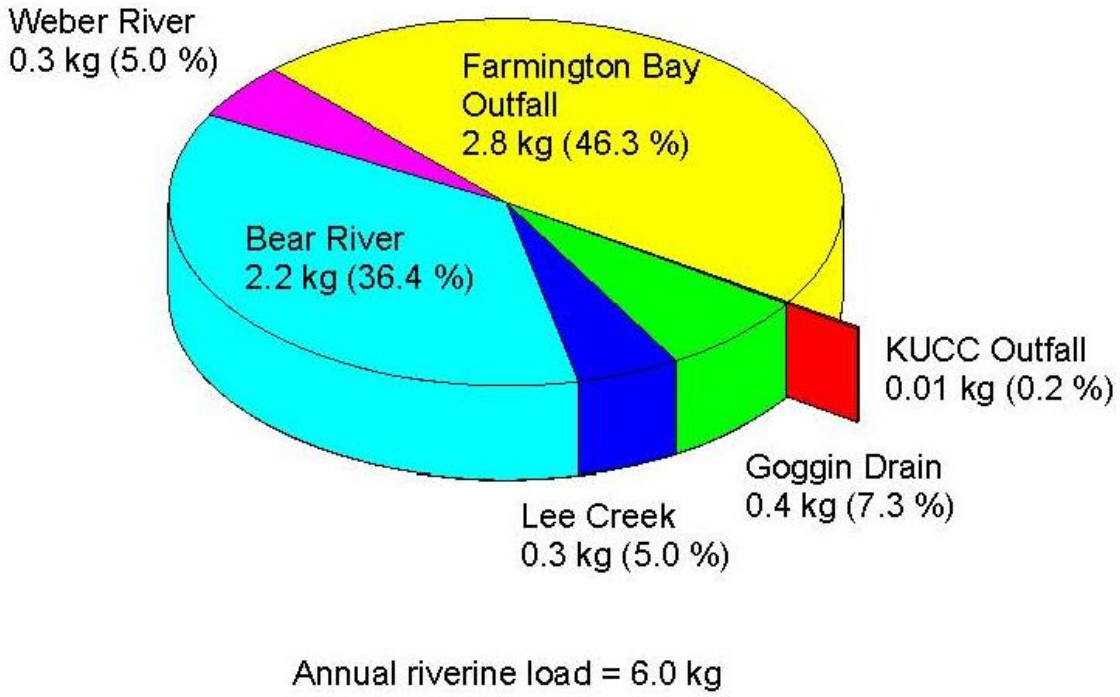

Figure 2. Distribution of Hg_{total} loads contributed to Great Salt Lake from each inflow site during April 1, 2007 to March 31, 2008. KUCC is the abbreviation for Kennecott Utah Copper Corporation.

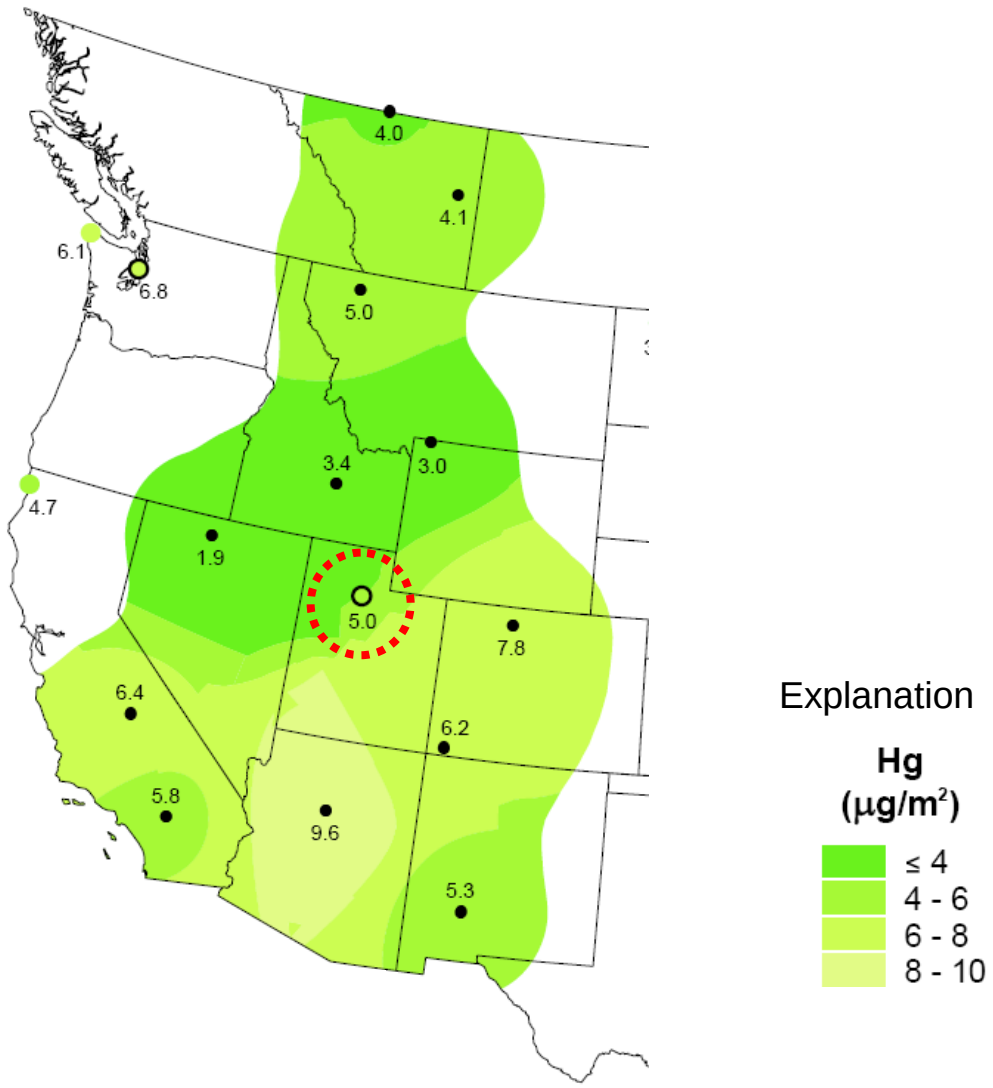

Figure 3. Total mercury in wet deposition at the monitoring site near Great Salt Lake, Utah (circled) and the western United States (National Atmospheric Deposition Program, 2010). Deposition is in micrograms per square meter ($\mu g/m^2$).

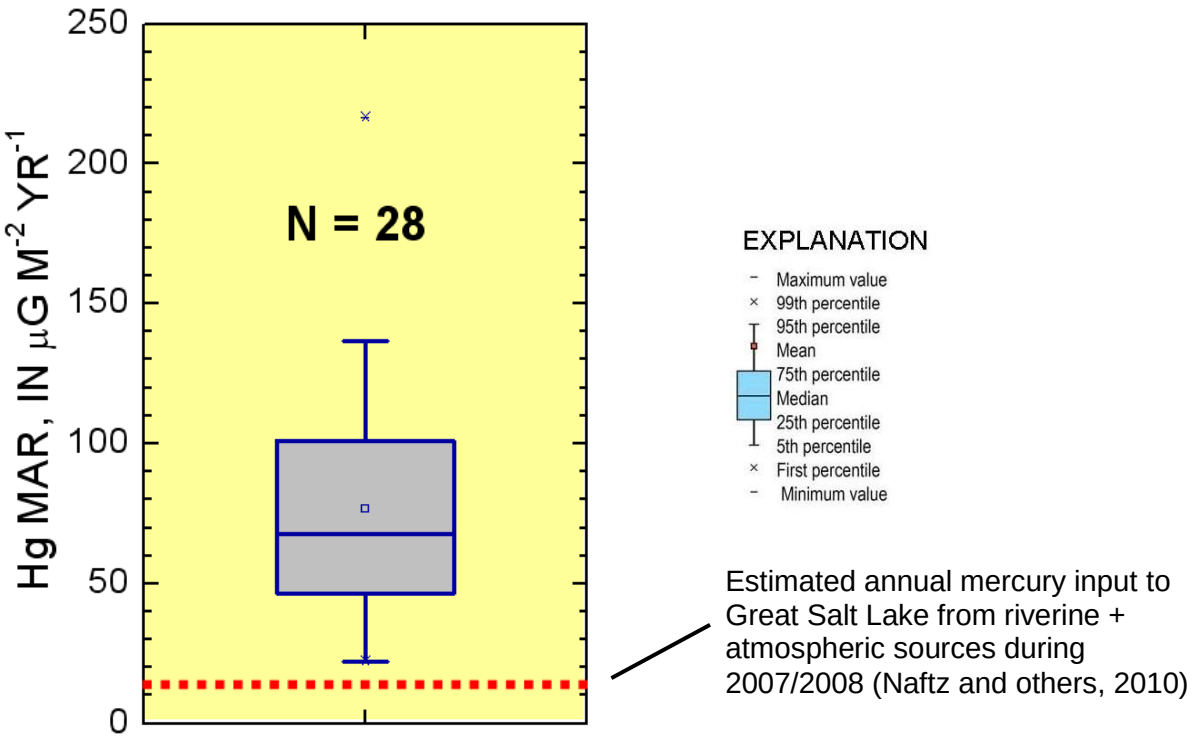

Figure 4. Comparison of mass accumulation rates (MAR) of mercury in sediment cores (box plot) to annual measured riverine/atmospheric inputs during 2007/2008 (dashed line) to Great Salt Lake, Utah.

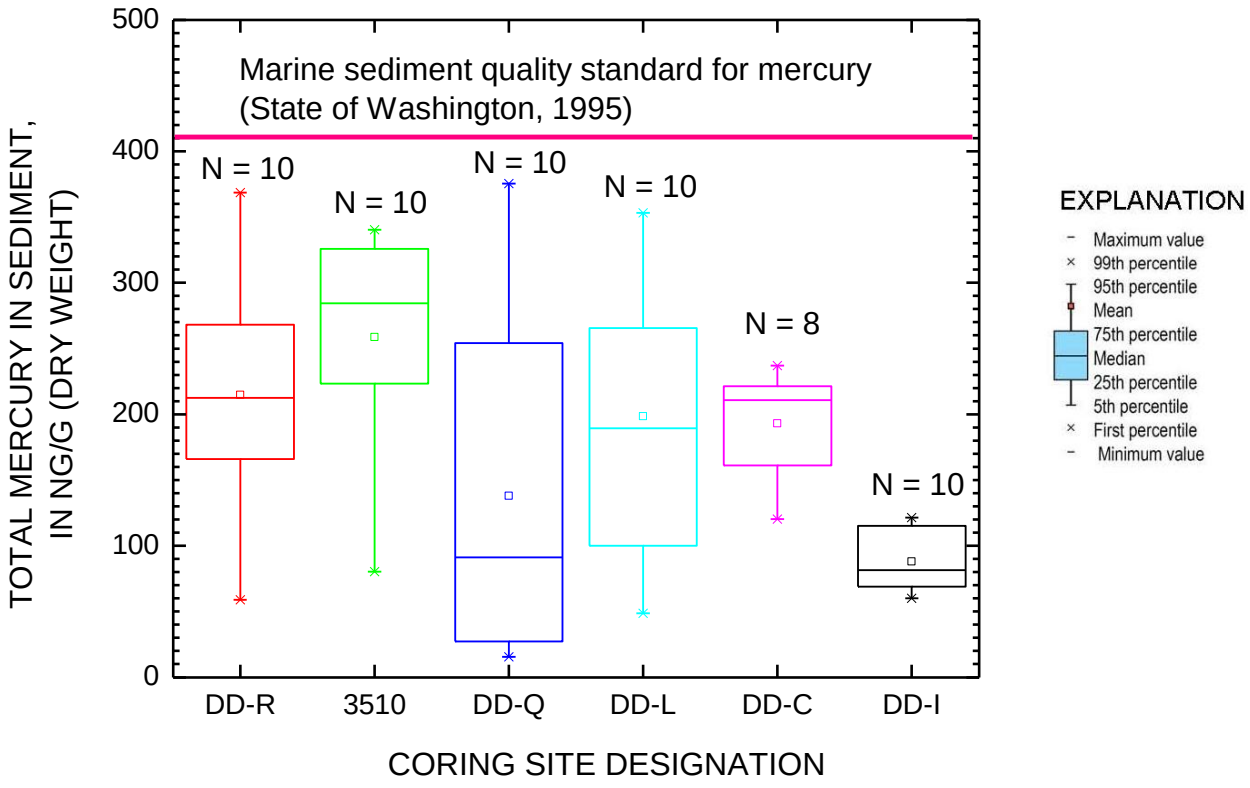

Figure 5. Box plots of salt-corrected, total mercury concentration in sediment samples collected from six coring sites in the south arm of Great Salt Lake, Utah, compared to marine sediment quality standard adopted by the State of Washington.

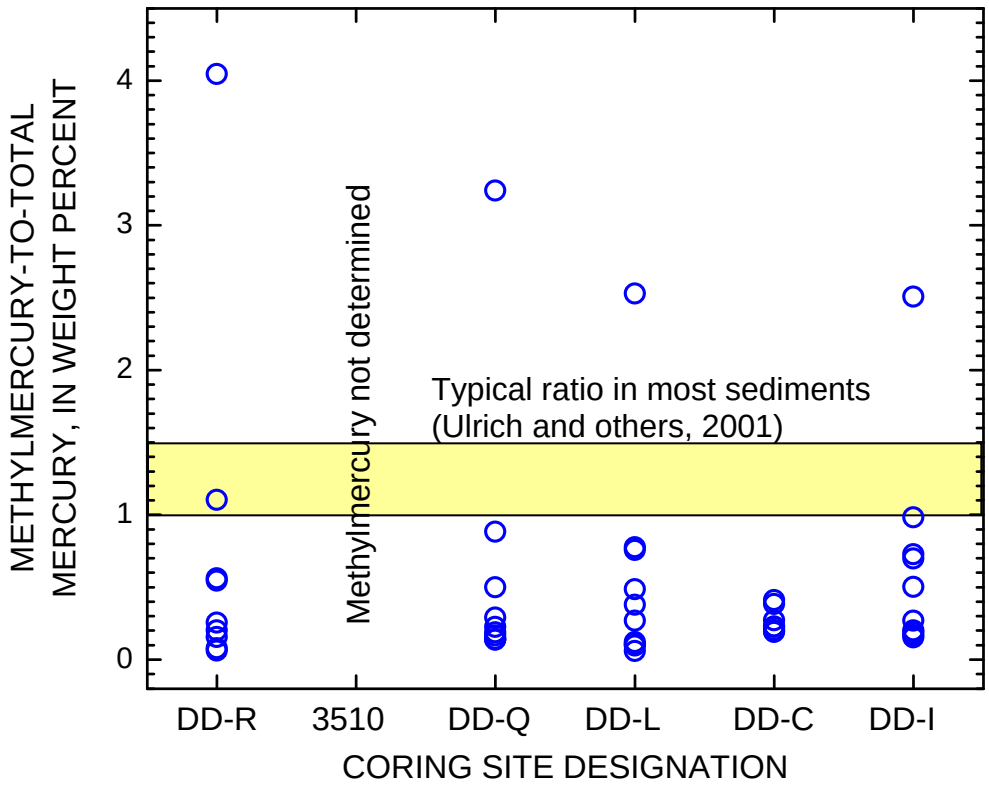

Figure 6. Methylmercury-to-total-mercury ratios in weight percent for sediment samples collected from Gilbert Bay, Great Salt Lake, Utah, compared to ratios typically found in sediments (Ulrich and others, 2001).

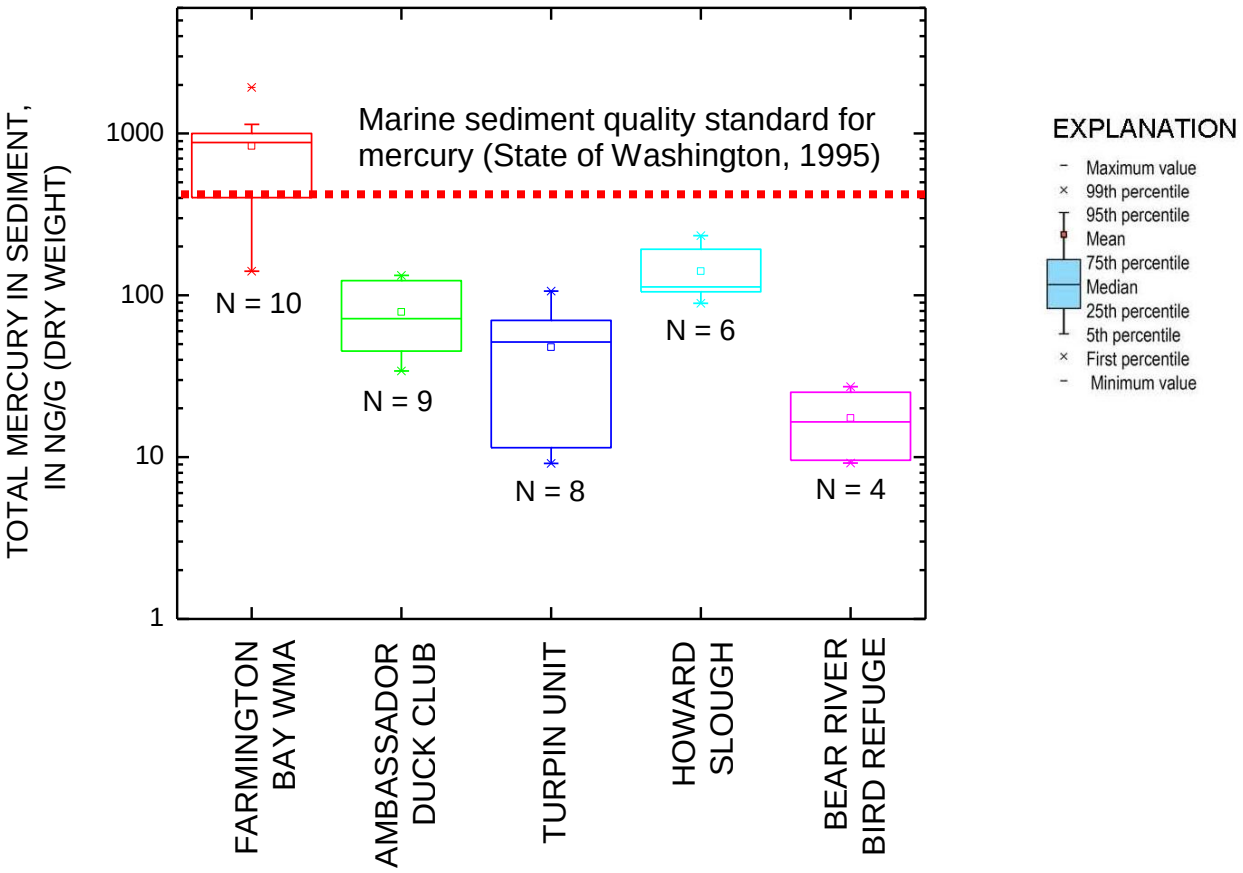

Figure 16. Box plots of total mercury concentration in sediment samples collected from five wetland sites surrounding Great Salt Lake, Utah, compared to marine sediment quality standard adopted by the State of Washington.

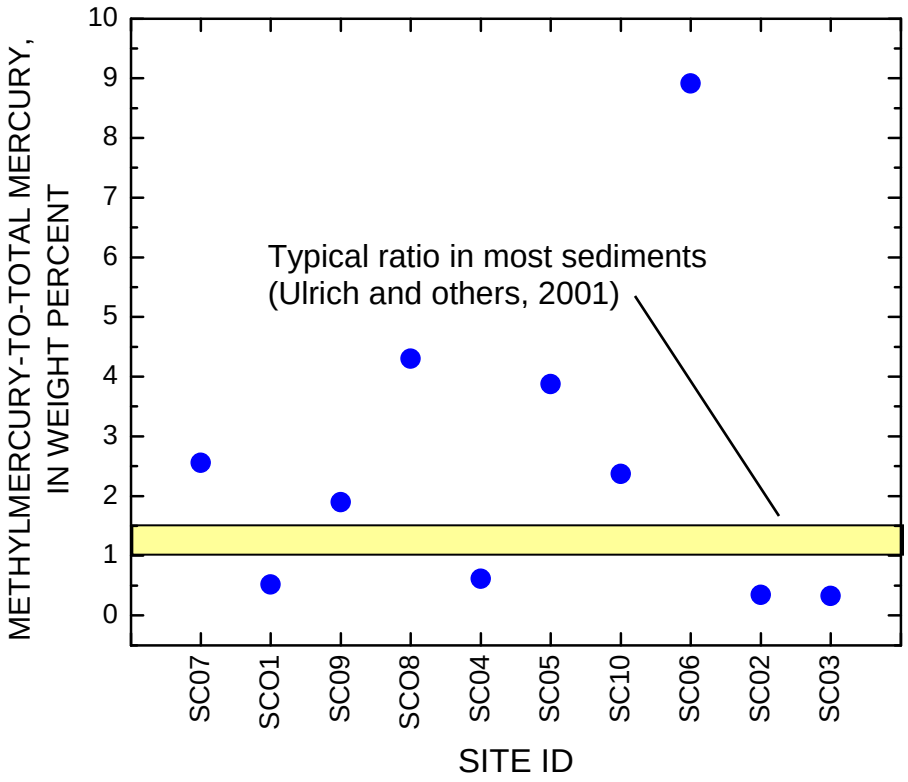

Figure 19. Methylmercury-to-total-mercury ratios in weight percent for sediment samples collected from Farmington Bay Waterfowl Management Area, Utah, compared to ratios typically found in sediments (Ulrich and others, 2001).

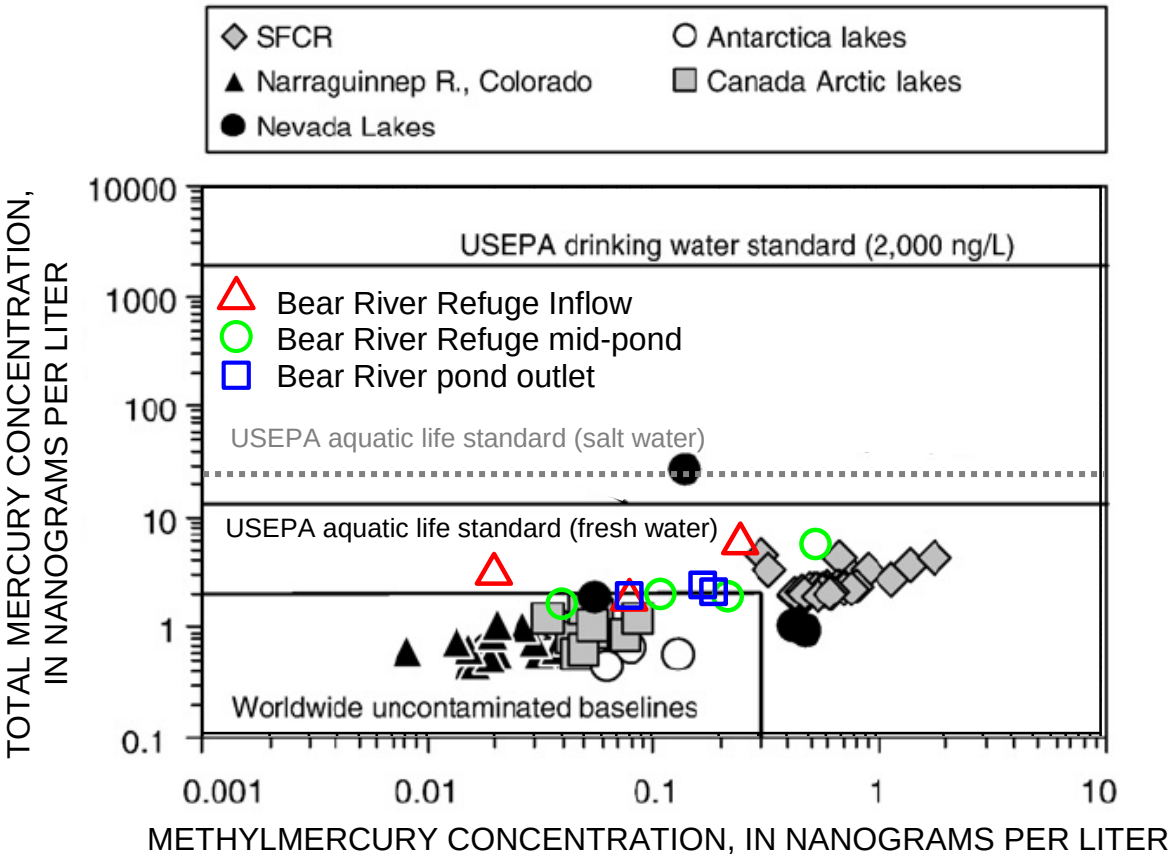

Figure 11. Total mercury versus methylmercury concentrations for whole water samples collected from Bear River Bird Refuge, Utah, compared to water data collected from Salmon Falls Creek Reservoir, Idaho (Gray and Hines, 2009); Antarctica lakes (Lyons and others, 1999); Canada arctic lakes (Loseto and others, 2004); Narraguinnep Reservoir, Colorado (Gray and others, 2005); Nevada lakes (Seiler and others, 2004); and uncontaminated worldwide baselines (Gill and Bruland,1990; Leermakers and others, 1996; Gray and others, 2000; Gray and others, 2004; Loseto and others, 2004). The USEPA drinking water standard for Hg of 2000 ng/L (USEPA, 2003) and the USEPA aquatic life standard for Hg in fresh water (12 ng/L) and salt water (25 ng/L) (Administration, 2010) are also shown for reference. Graph modified from Gray and Hines (2009).

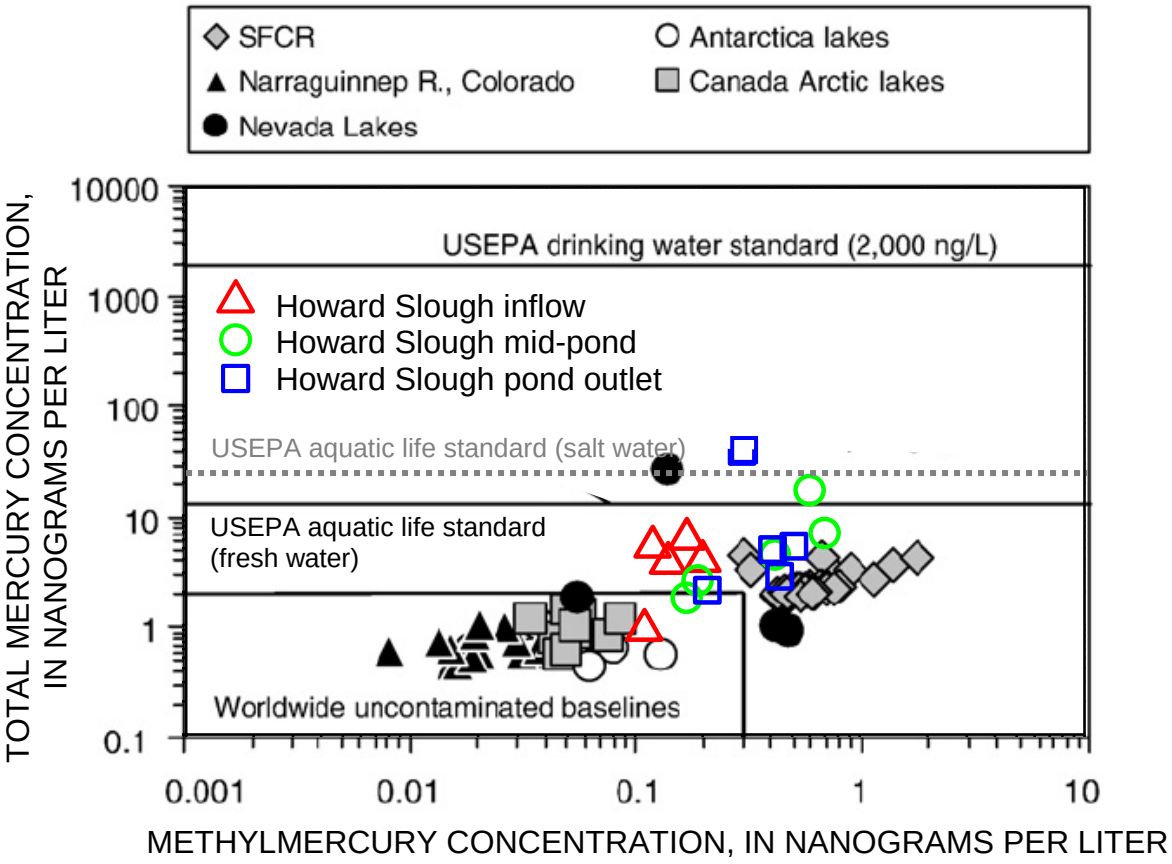

Figure 12. Total mercury versus methylmercury concentrations for whole water samples collected from Howard Slough, Utah, compared to water data collected from Salmon Falls Creek Reservoir, Idaho (Gray and Hines, 2009); Antarctica lakes (Lyons and others, 1999); Canada arctic lakes (Loseto and others, 2004); Narraguinnep Reservoir, Colorado (Gray and others, 2005); Nevada lakes (Seiler and others, 2004); and uncontaminated worldwide baselines (Gill and Bruland,1990; Leermakers and others, 1996; Gray and others, 2000; Gray and others, 2004; Loseto and others, 2004). The USEPA drinking water standard for Hg of 2000 ng/L (USEPA, 2003) and the USEPA aquatic life standard for Hg in fresh water (12 ng/L) and salt water (25 ng/L) (Administration, 2010) are also shown for reference. Graph modified from Gray and Hines (2009).

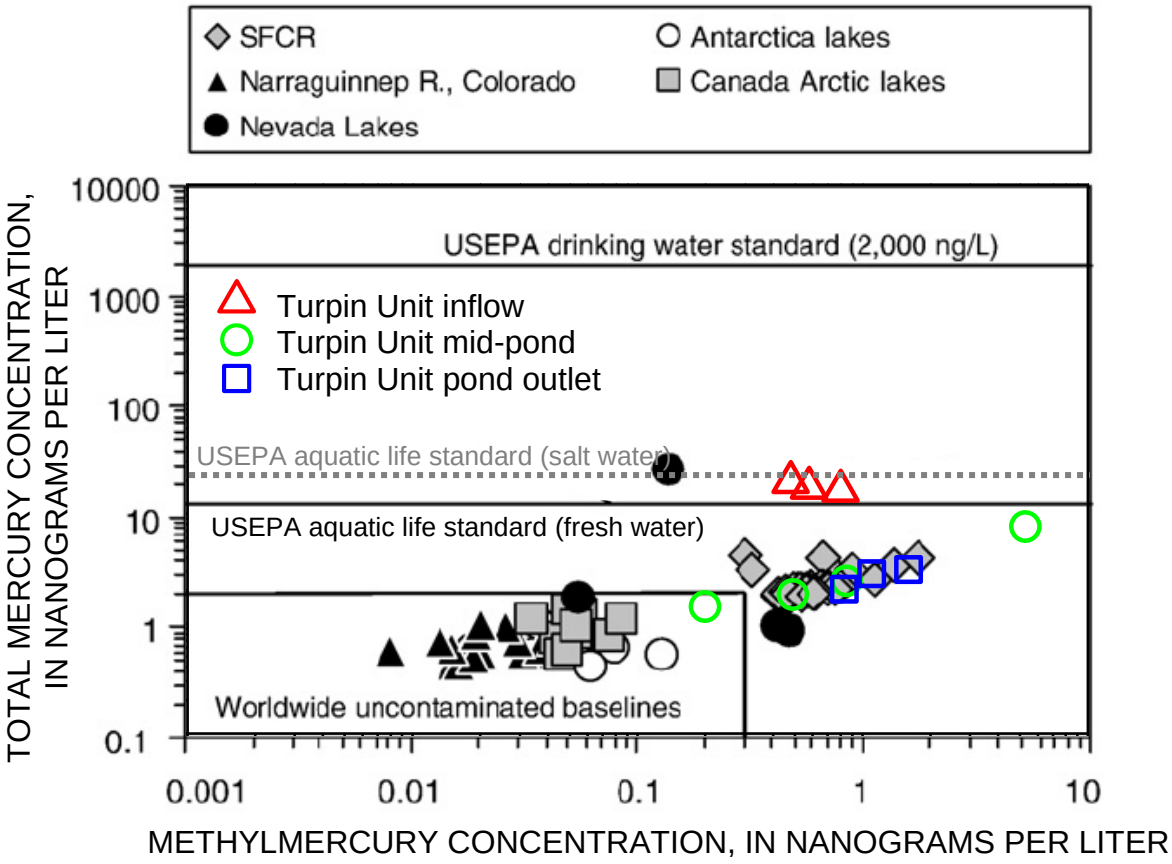

Figure 13. Total mercury versus methylmercury concentrations for whole water samples collected from Turpin Unit, Utah, compared to water data collected from Salmon Falls Creek Reservoir, Idaho (Gray and Hines, 2009); Antarctica lakes (Lyons and others, 1999); Canada arctic lakes (Loseto and others, 2004); Narraguinnep Reservoir, Colorado (Gray and others, 2005); Nevada lakes (Seiler and others, 2004); and uncontaminated worldwide baselines (Gill and Bruland,1990; Leermakers and others, 1996; Gray and others, 2000; Gray and others, 2004; Loseto and others, 2004). The USEPA drinking water standard for Hg of 2000 ng/L (USEPA, 2003) and the USEPA aquatic life standard for Hg in fresh water (12 ng/L) and salt water (25 ng/L) (Administration, 2010) are also shown for reference. Graph modified from Gray and Hines (2009).

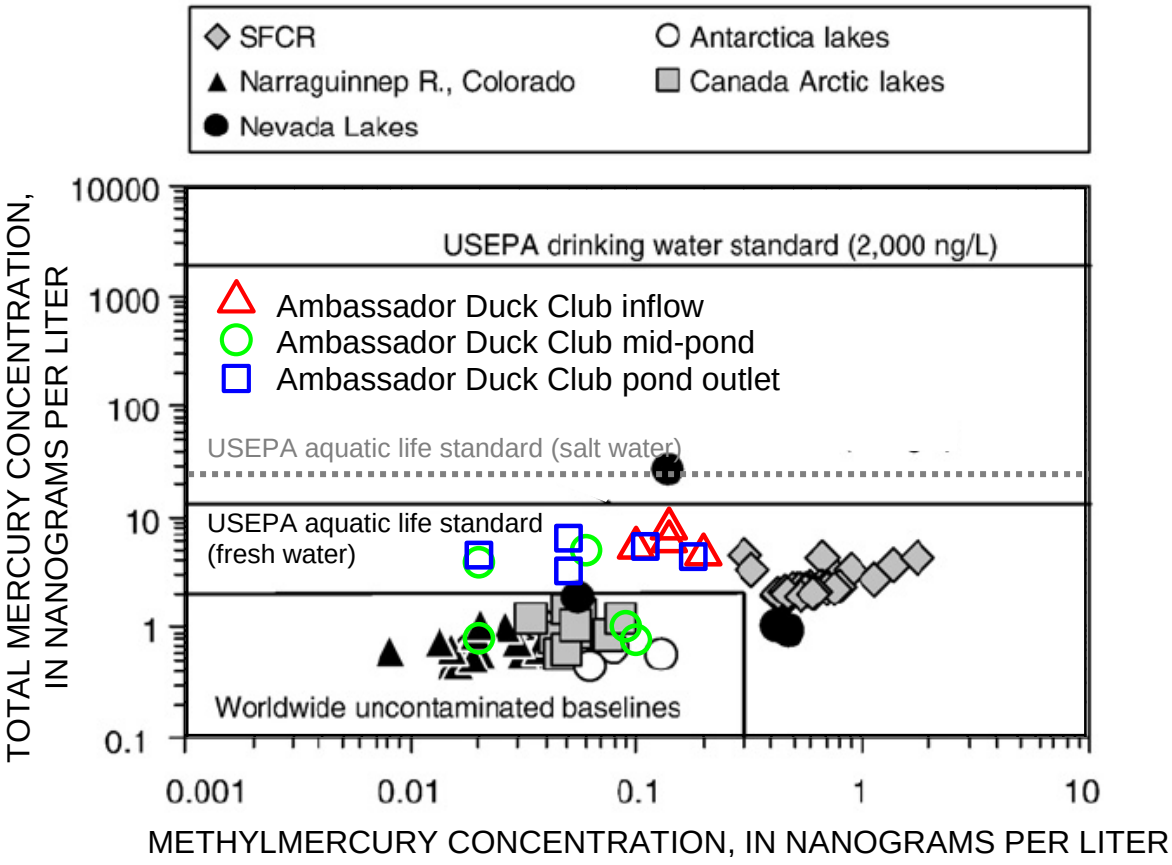

Figure 14. Total mercury versus methylmercury concentrations for whole water samples collected from the Ambassador Duck Club, Utah, compared to water data collected from Salmon Falls Creek Reservoir, Idaho (Gray and Hines, 2009); Antarctica lakes (Lyons and others, 1999); Canada arctic lakes (Loseto and others, 2004); Narraguinnep Reservoir, Colorado (Gray and others, 2005); Nevada lakes (Seiler and others, 2004); and uncontaminated worldwide baselines (Gill and Bruland,1990; Leermakers and others, 1996; Gray and others, 2000; Gray and others, 2004; Loseto and others, 2004). The USEPA drinking water standard for Hg of 2000 ng/L (USEPA, 2003) and the USEPA aquatic life standard for Hg in fresh water (12 ng/L) and salt water (25 ng/L) (Administration, 2010) are also shown for reference. Graph modified from Gray and Hines (2009).

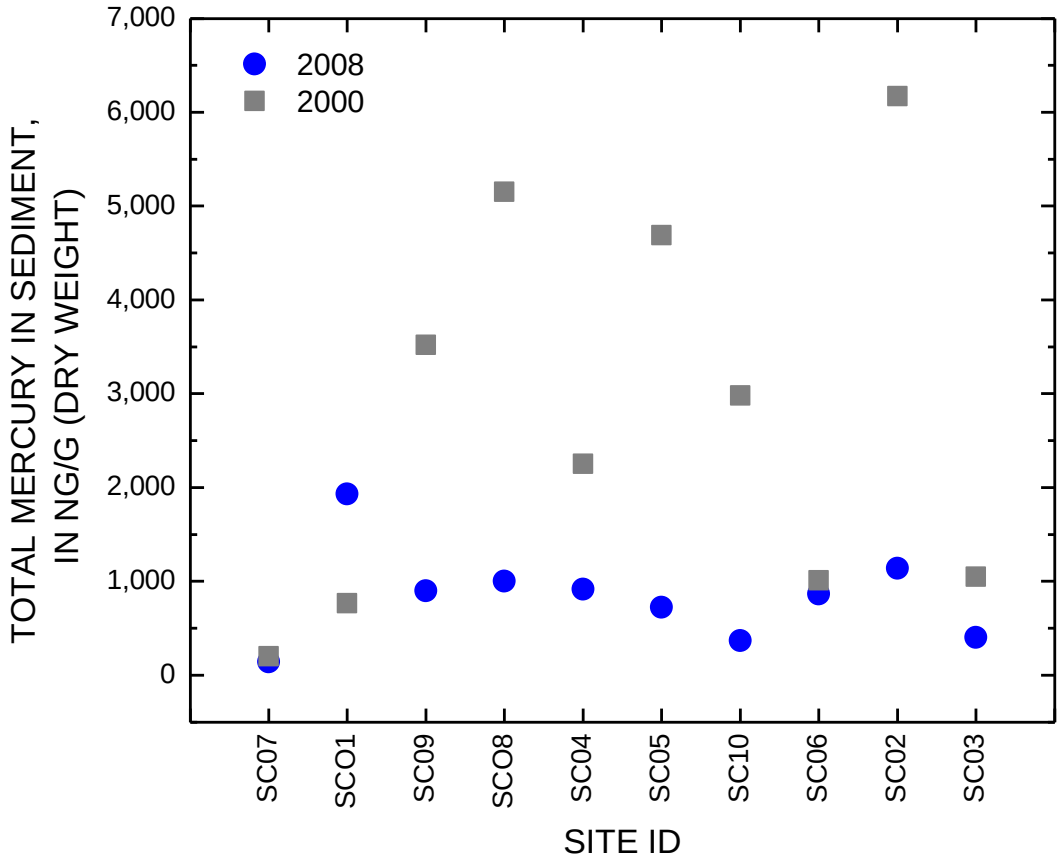

Figure 18. Comparison of total mercury concentration in sediment samples collected from the same sites in Farmington Bay Waterfowl Management Area in 2000 (Waddell and others, 2009) and 2008 (this study).

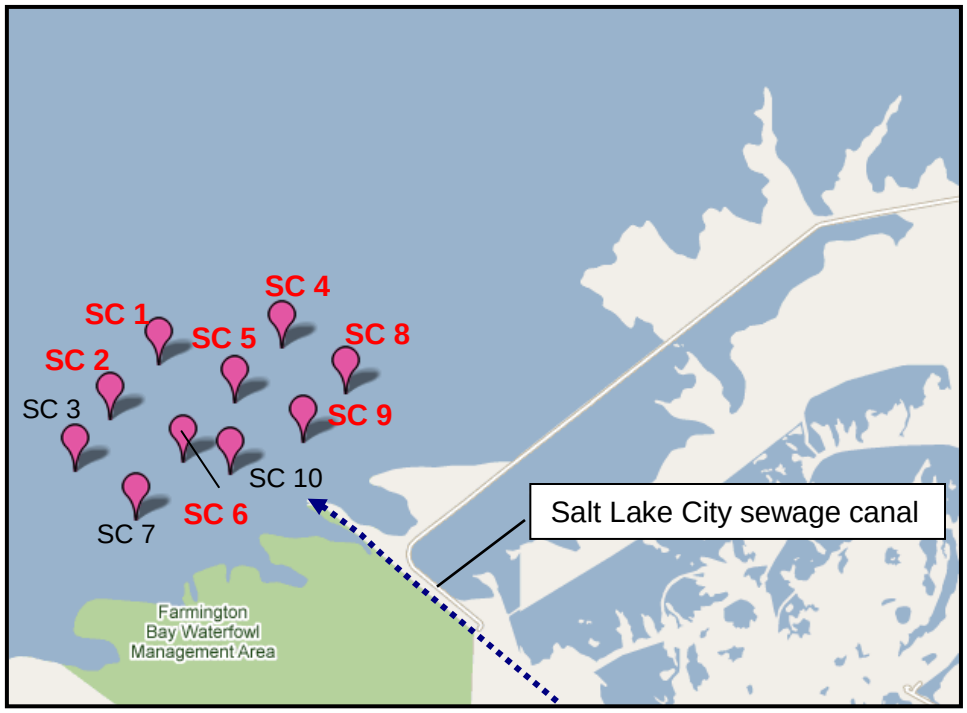

Figure 17. Sediment sampling locations in Farmington Bay Waterfowl Management Area in the vicinity of the outflow from the Salt Lake City sewage canal. Sites labeled in red exceed the marine sediment quality standard for mercury (State of Washington, 1995) during the sampling program conducted in 2008.

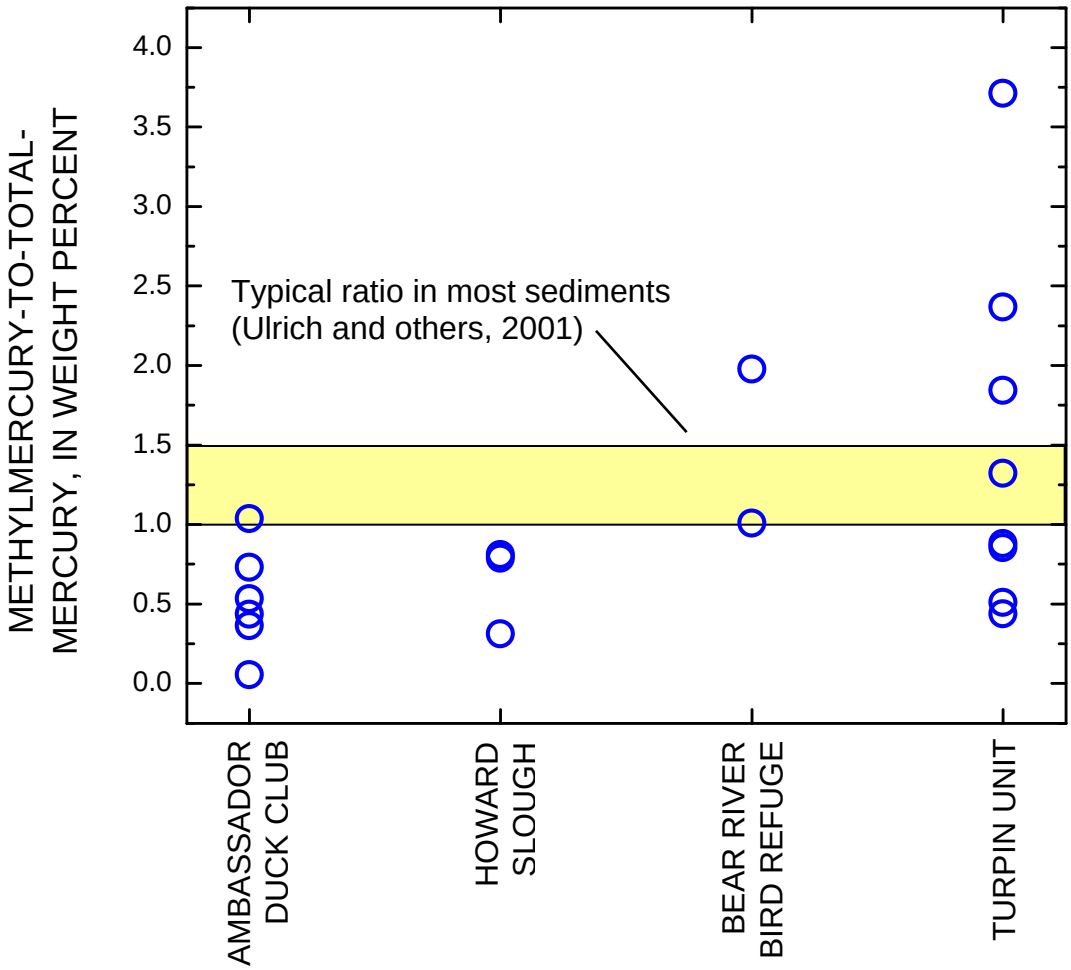

Figure 20. Methylmercury-to-total-mercury ratios in weight percent for sediment samples collected from four wetland areas surrounding Great Salt Lake, Utah, compared to ratios typically found in sediments (Ulrich and others, 2001).

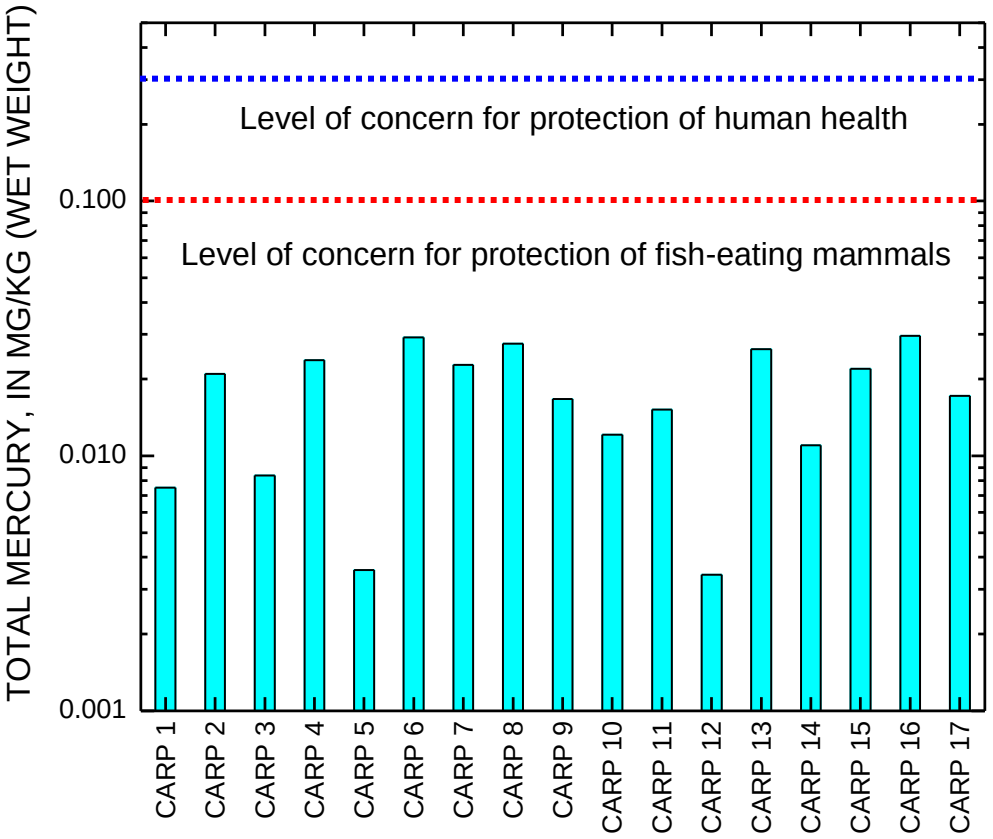

Figure 22. Total mercury concentration in skinless filets of common carp samples collected from a pond in Farmington Bay Waterfowl Management Area, Utah, during January 2010 compared to level of concern for protection of fish-eating mammals (Yeardley and others, 1998; Peterson and others, 2007) and human health (USEPA, 2001; 2009).

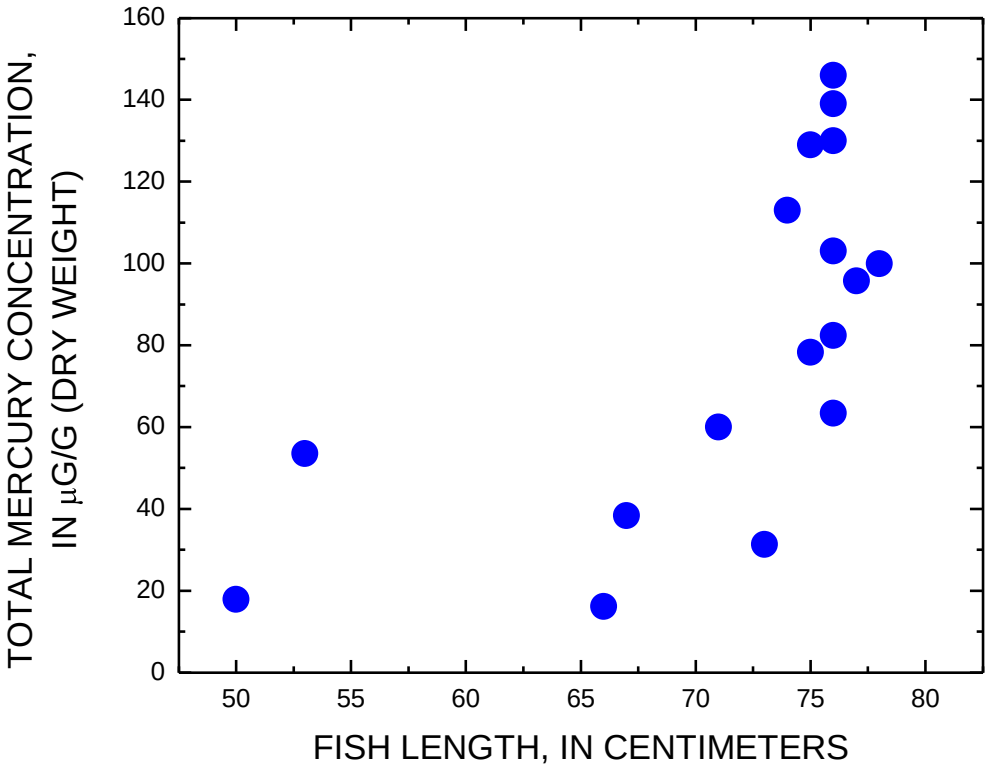

Figure 23. Comparison between total mercury concentration in skinless filets of common carp samples to fish length. Fish tissue samples collected from a pond in Farmington Bay Waterfowl Management Area, Utah, during January 2010.

Figure 21. Utah Department of Natural Resources employee applying rotenone to an ice-covered pond in Farmington Bay Waterfowl Management Area, Utah, during January 2010.

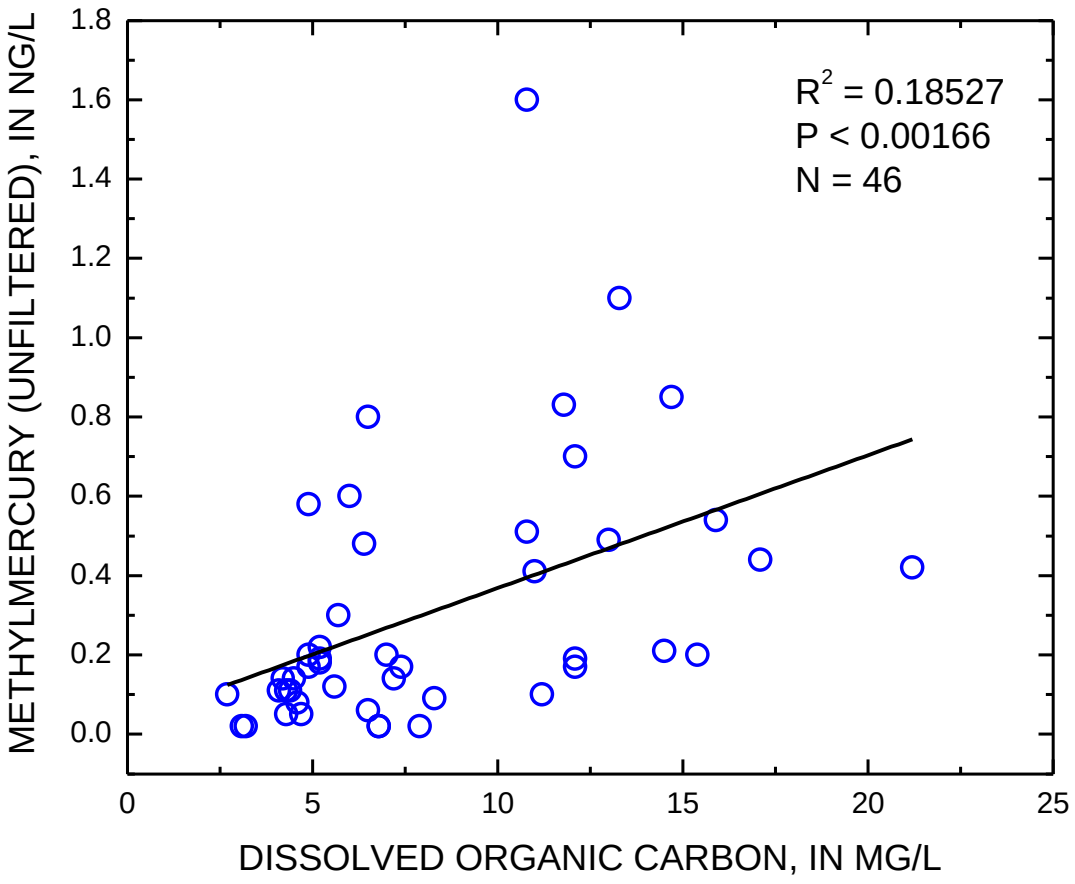

Figure 15. Best fit line comparing dissolved organic carbon to methylmercury concentration in water samples collected from wetlands surrounding Great Salt Lake, Utah, during 2008.

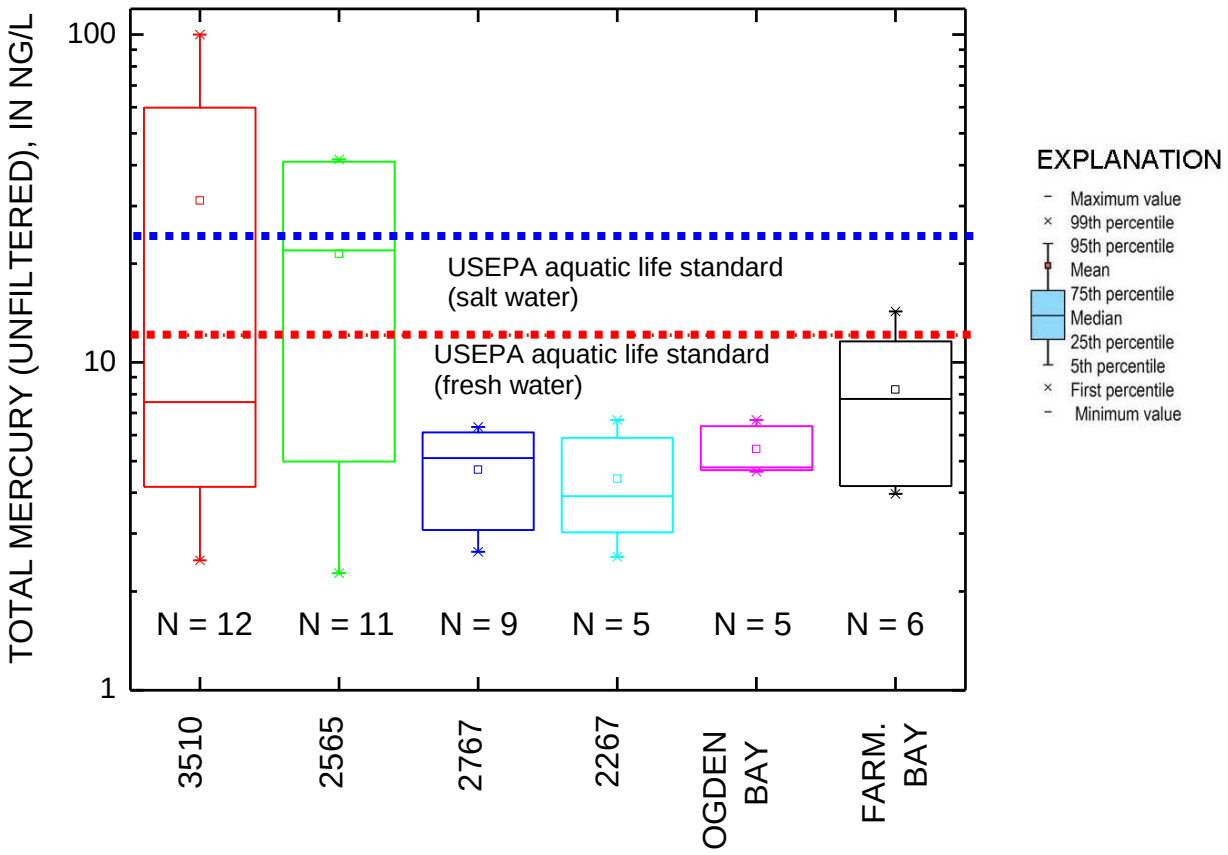

Figure 7. Box plots of total mercury concentration in water samples collected from five monitoring sites in the south arm of Great Salt Lake and one monitoring site in Farmington (Farm.) Bay, Utah, compared to the USEPA aquatic life standards for total mercury [N, number of samples].

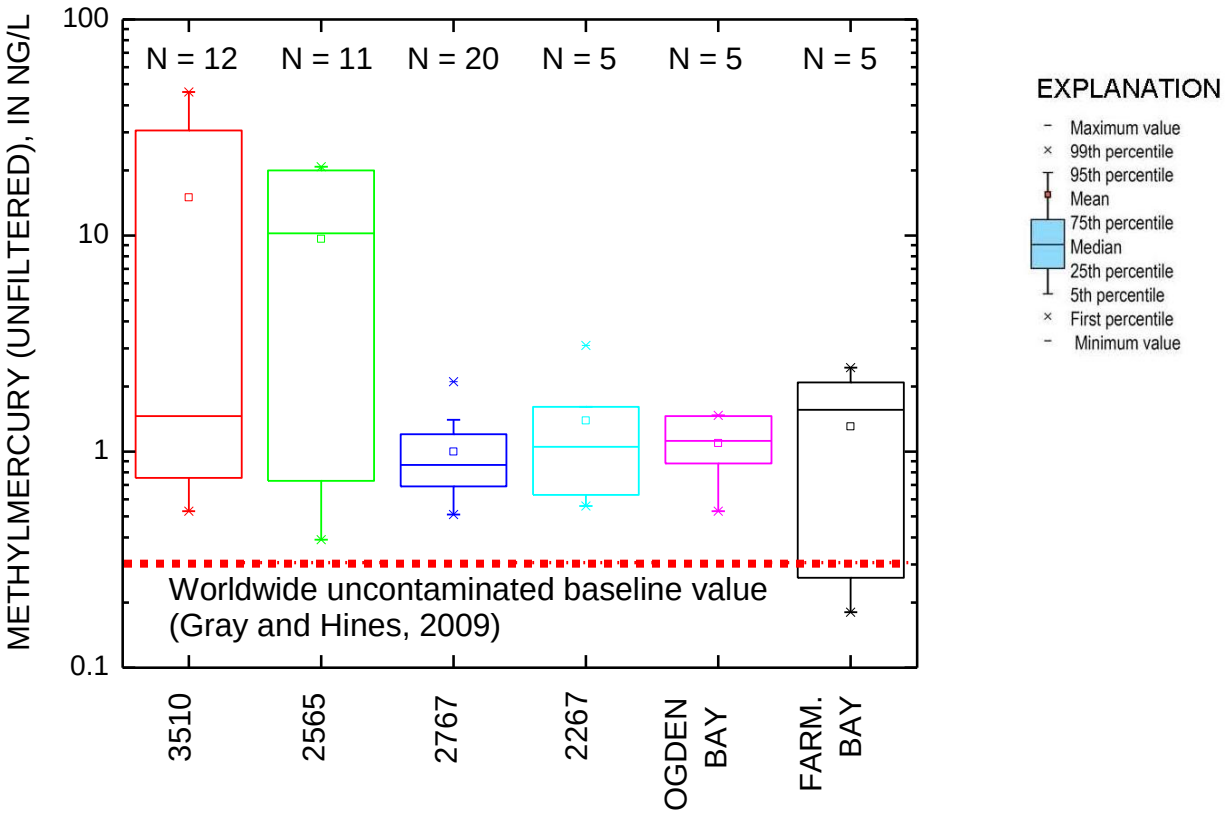

Figure 8. Box plots of methylmercury concentration in water samples collected from five monitoring sites in the south arm of Great Salt Lake and one monitoring site in Farmington (Farm.) Bay, Utah, compared to the worldwide uncontaminated baseline value for methylmercury compiled by Gray and Hines (2009) [N, number of samples].

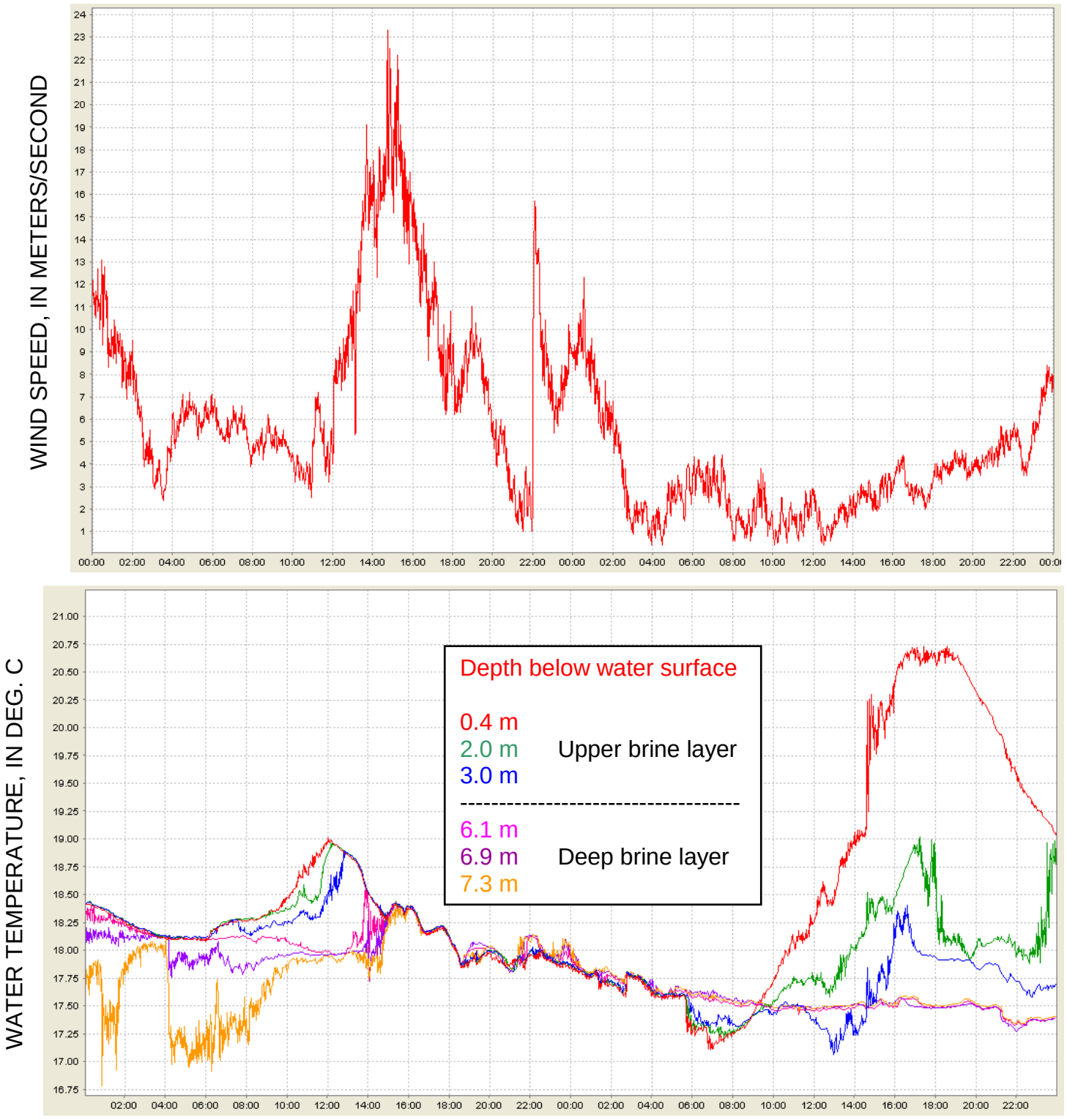

Figure 10. Changes in surface wind speed and water temperature with depth below lake surface during June 16-17, 2010 at the LakeESP station (PME, Inc., 2010), Great Salt Lake,

Figure 9. Deployment of LakeESP (PME, Inc., 2010) in the south arm of Great Salt Lake, Utah during May 2010.

Chapter 2. Assessment of Total Mercury Concentrations in Great Salt Lake Artemia (Artemia franciscana)

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Abstract

Naturally occurring brine shrimp (*Artemia fransicana*) through all its life stages (cysts, nauplii, and adults) were sampled from June to December, 2008 to characterize the life stage, seasonal and spatial total mercury (THg) concentrations collected from the open waters of Gilbert Bay, Great Salt Lake. There was a substantial increase in THg concentrations from cysts/nauplii to adults lake-wide. However, THg concentrations in GSL brine shrimp cysts from the streaks, cysts/nauplii and adult shrimp were all below 0.1 ppm (ww), the lowest observed adverse effect level as a fresh weight dietary item for Mallards (Heinz, 1979). When compared to Ever's dietary risk ranges (Evers et al, 2004), the cysts from streaks and the cysts/nauplii taken from selected sites pose little risk as a dietary item for avian wildlife. Adult Brine shrimp may pose a moderate dietary risk. No difference in median THg concentrations in adult brine shrimp or cysts/nauplii were detected over the sites sampled. For adult brine shrimp, a significant difference in THg concentrations was detected over the season. Further analysis showed that the difference occurred in July when median THg concentrations decreased. No differences across months were detected in cysts/nauplii. Additional investigation to more accurately characterize any potential risks to waterfowl or shorebirds at Gilbert Bay from Hg is recommended.

Introduction

The Great Salt Lake (GSL) and its adjacent wetlands are a necessary oasis to approximately 7.5 million birds that visit the lake annually (UDWR website). The lake lies within the Pacific Flyway and is a key mid-point stopover as well as an over-wintering destination providing nutritional energy for migration, breeding, nesting habitat and resting areas for waterfowl and shorebirds. The avian community feed on the aquatic organisms specialized to highly saline conditions that include brine shrimp (*Artemia fransicana*), brine fly, corixid and numerous algal species.

Recent water column investigations conducted by the US Geological Survey (USGS) reported elevated methyl mercury (MeHg) concentrations exceeding 33 nanograms per liter (ng/L) some of the highest recorded levels in the United States (Naftz et al. 2008). The potential of toxic MeHg from the water column bioaccumulated in the food chain led to investigations of mercury (Hg) concentrations in the waterfowl in 2005. Those studies resulted in the first US waterfowl consumption advisory for 3 species of GSL waterfowl. Average THg concentrations in the waterfowl breast muscle tissue had exceeded the EPA aquatic tissue standard of 0.3 ppm MeHg (UDWR, 2006). In 2008, Vest et al. reported the highest concentrations of THg ever recorded in North America in wintering waterfowl (Vest et al., 2008). These elevated THg concentrations created concern over the lakes' health and its possible toxic effects to the biota.

A lake wide Great Salt Lake Mercury ecosystem assessment commenced in the spring of 2008 to measure Hg concentrations in the water column, sediment, biota and wetlands. As part of this assessment, THg concentrations were measured in brine shrimp from the open waters of Gilbert Bay, GSL to characterize life stage (cysts, nauplii, juveniles and adults), seasonal, and spatial THg concentrations.

Methodology

Study Sites

Samples were collected at six long-term sites that were chosen to be representative of different chemical (e.g. salinities) and hydrologic characteristics (Figure 1) in Gilbert Bay, GSL. Table 1 contains a list of the sites, location, average depth of water and the presence or absence of the anoxic deep brine layer that underlies a shallower and less dense layer in some parts of the lake *i.e.*, a chemocline. The deep brine layer contains the geochemical conditions supportive of mercury methylation (Naftz, 2010). The deep brine layer in Gilbert Bay, GSL is at a depth of approximately 6.5 m below the surface of water.

Table 1 Brine Shrimp sample sites including site name, location, USGS station ID, average depth and the presence or absence of the deep brine layer

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Figure 1 Site locations of brine shrimp sampling in Gilbert Bay, Great Salt Lake

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Sample Collection

Brine shrimp samples were collected at all sites from June 15th through December 10th, 2008. The samples were collected monthly except during the months of September, October, November, and December when samples were collected bi-monthly. Brine shrimp were collected using one of two 3 meter x 0.50 m x 152 micrometer (µm) mesh plankton nets, one net for shallow sites (< 6m) and the other for deep sites (> 6m). This was done to limit potential cross contamination of brine shrimp in the upper water column from brine shrimp in the deep brine layer. Depths were determined at each site using a weighted measuring tape. A single vertical plankton net haul was conducted at each of the six sites monthly (or bi-monthly). The plankton net was then rinsed from the net and dolphin cup using filtered (153 µm mesh) natural lake water contained in an 11.36 L herbicide sprayer. The sample was then placed into a 1L polyurethane sample jar. All samples were placed into an iced cooler for transport. Additional cysts were collected randomly from large surface aggregates ("streaks") when present during the mercury sampling runs. Surface cysts were collected with a 0.25 m x 1 m x 153 um mesh plankton net. To acquire cyst samples, the plankton net was drawn across the streak, rinsed with filtered lake water, placed into a labeled sample jar and placed in an iced cooler for transport. The locations of the streaks were documented using latitudinal and longitudinal coordinates.

Sample Processing

Following the field collection, samples were brought to the laboratory for exterior decontamination and preparation for processing. All the samples were processed within 24 hours of collection. All utensils were pre and post rinsed using a 5% HCL solution follow by a DI water rinse. Each sample was fractionated using a successive stacked/coupled series of 5.08cm dia. x 10.16 cm long PVC tubes (Carol D. Carson and Kelly C. Rakow 2005). At the end of each tube, mesh was adhered via silicone calking. Mesh sizes were 750µm, 500µm and 118µm respectively. The purpose of this was to fractionate life stages into adults (750 µm), juveniles (500µm) and cysts/nauplii (118µm). Once each sample was placed into sieve tubes, samples were then rinsed thoroughly with a 17% saline DI water/sea-salt solution followed by 0% saline DI water. Fractionation tubes were then separated and the sample back-flushed into Buchner funnel apparatus, then pump (*Gast* model#DOA-P104-AA) filtered through Whatman 90mm #1 qualitative filter paper to rid the sample of excess moisture. Once filtered, the fractionated sample was checked for non-brine shrimp material such as brine fly larva/casings, plant material or foreign debris. If other material were observed, they were removed via Teflon coated forceps and or spatula. Each sample was then placed into separate pre-weighed and post weighed sterile square 30ml nalgene bottles, bar-coded, and logged with the site number, date and life stage. Samples were then frozen and shipped overnight to the USGS Wisconsin Research Water Center, in Middleton Wisconsin for THg analysis.

Analytical

All mercury analyses were performed at the USGS Wisconsin Mercury Research Laboratory in Middleton, Wisconsin. All values were reported on a dry weight basis.

Statistical

Descriptive statistics were generated for the THg concentration of adult brine shrimp and cysts/nauplii by location and month. Potential seasonal and spatial differences in THg concentrations in brine shrimp adults and cysts/nauplii were investigated using the non parametric Kruskal Wallace test. Significance levels were set at 0.05 (alpha). Where results were found to be statistically significant, Tukey's multiple comparison test was applied. Seasonality was defined by grouping all samples collected lake-wide by the month sampled. Monthly brine shrimp cyst samples collected from the streaks were described using descriptive statistics.

Data Archival

All Brine Shrimp data and associated metadata are archived in the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2010) and can be accessed through an interactive map interface (NWIS Mapper) at: http://wdr.water.usgs.gov/nwisgmap/index.html or by site name or station ID (NWISWeb) at: http://waterdata.usgs.gov/ut/nwis/qw/. Table 1 contains a list of the site names and USGS station ID's sampled for this study.

Results and Discussion

A total of 116 samples (60 adult brine shrimp, 56 cysts and nauplii and 26 cysts from streaks) were evaluated for THg concentrations lake-wide, by location and month, by life stage and compared to avian dietary benchmarks (Heinz, 1979, Evers 2004). Table 2 lists the summary statistics by site for both adult brine shrimp and cysts/nauplii. Table 3 lists summary statistics by month over all sites for both adult brine shrimp and cysts/nauplii. Table 4 lists summary statistics for the cyst that were collected from the streaks. Figures 2 and 3 are simple box plots of THg concentrations in brine shrimp adults and cyst/nauplii by location. Figures 4 and 5 are simple box plots of THg concentrations in brine shrimp adults and cyst/nauplii by month.

Table 2 Descriptive statistics of adult brine shrimp and cyts/nauplii by location

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Table 3 Descriptive statistics of adult brine shrimp and cyts/nauplii by month

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Table 4 Descriptive statistics of brine shrimp cysts collected from the streaks by month

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Figure 2 Simple box plot of THg concentrations in cyst/nauplii by location

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Figure 3 Simple box plot of THg concentrations in adult brine shrimp by location

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Figure 4 Simple box plot of THg concentrations in cyst/nauplii by month over all locations.

Figure 5 Simple box plot of THg concentrations in adult brine shrimp by month over all locations.

To compare the THg concentrations in brine shrimp cysts/nauplii and adults to the dietary benchmarks, a conversion of dry weight (as reported by the USGS Wisconsin laboratory) to wet weight was performed. The dry weight measurement was multiplied by (1- percent moisture/100). A 90% moisture content was used based on the average percent moisture of 68 Adult brine shrimp samples reported by the USFWS for the GSL (2009).

Lake wide summary

The mean THg concentration ± the standard deviation in adult brine shrimp for all samples (n=60) was 0.0594 ± 0.0015 ppm ww with a range of 0.0192 ppm to 0.0976 ppm . The mean THg concentration ± the standard deviation in cysts/nauplii for all samples (n=56) was 0.0071 ± 0.0029 ppm ww with a range of

0.0017 ppm to 0.0162 ppm . The mean THg concentration ± the standard deviation for cysts from streaks (n=26) was 0.0071 ± 0.0029 ppm ww with a range of 0.0017 ppm to 0.0162 ppm. THg was detected in all samples (Figure 6).

Figure 6 Average THg concentrations in brine shrimp cysts collected from the streaks by month, 2008

Location

Statistical analysis of the median THg concentrations for adult brine shrimp and cysts/nauplii across sampling sites in Gilbert Bay, GSL indicated that there was no significant difference (Adults: p=0.668, Cysts/nauplii: p=0.264) between sites

Seasonality

A significant difference (p=0.0011) in median THg concentrations in adult brine shrimp over the season (monthly from June to December), 2008 was detected. The Tukey multiple comparison test showed that the difference occurred in July where the mean THg concentration decreased. After July, the concentration increased in August leveling out the rest of the season. Analysis of median THg concentrations for cysts/nauplii indicated that there was no significant difference over the season (p=0.680).

Dietary Benchmarks for Avian Wildlife

THg concentrations in GSL brine shrimp cysts from the streaks, cysts/nauplii and adult shrimp were all below 0.1 ppm (ww), the lowest observed adverse effect

level as a fresh weight dietary item for Mallards (Heinz, 1979). Evers et al. (2004) undertook extensive research with Common Loons, a piscivorous species, in the northeastern United States to determine mercury benchmarks and risk ranges for this species. Evers proposed dietary exposures risk ranges as:

- Low Risk in Diet < 0.05 MeHg ppm (ww)
- Moderate Risk in Diet 0.05 – 0.15 MeHg ppm (ww)
- High Risk in Diet 0.15 – 0.3 MeHg[1] ppm (ww)
- Extra High Risk in Diet >0.3 MeHg[1] ppm (ww)

Evers defines the upper limit of the low risk range as equivalent to a no observed adverse effect level (NOAEL). The Common Loon does not inhabit Gilbert Bay, nor do fish which represent the dietary items used by Evers (2004). Uncertainties exist regarding applying Evers (2004) benchmarks to the GSL but Ever's database was the most comprehensive found. Assuming that the majority of THg in brine shrimp is MeHg, the range of THg concentrations in adult brine shrimp sampled (lake wide) falls within the moderate risk range while cysts/nauplii and the cysts collected from the streaks are low risk dietary items to avian wildlife.

The USFWS assessment of contaminants in Great Salt Lake (USFWS, 2009) reported an average THg concentration in adult brine shrimp as 0.047 ppm ww in 1996, 0.029 ppm ww in 1999, 0.01 ppm ww in 2000 and 0.10 ppm ww in 2006 (personal communication, USFWS-Nathan Darnall). For years 1996 through 2000, these average concentrations are lower than those observed during this

2008 study. However, in 2006 the reported USFWS average THg concentration of 0.1 ppm ww in 2006 indicates that adult brine shrimp would be a moderate to high risk dietary item. Whether this difference can be attributed to the year sampled, methodology, or the laboratory analysis needs to be determined through further study.

Life Stages

To assess whether mercury was increasing from the early (cysts/nauplii) to late life stages (adult brine shrimp), the average percent increase relative to cysts nauplii concentrations resulted in an average 750% increase over all locations. While this appears to be a substantial increase in the concentration of Hg over the life stage of a brine shrimp, in the context of toxicity to avian wildlife, all 116 samples were below 0.1 ppm ww avian dietary benchmark (Heinz, 1979).

Deep Brine Layer Influence

The deep brine layer that flows from Gunnison Bay into Gilbert Bay was sampled in 2003 by the USGS and contained the highest levels of methyl mercury recorded (Naftz, 2008). The deep brine layer is anoxic and has the reducing conditions suitable to methylation. It was hypothesized that brine shrimp sampled from locations with a deep brine layer present (Sites DWR3 and 3510) would have higher THg concentrations than at other locations. However, the results do not support an increase in THg concentrations collected from these

sites. The mean THg concentrations for adult brine shrimp at Site 3510 (0.0607 ± 0.0140 ppm) and Site DWR3 (0.0548 ± 0.0204) were comparable to the mean THg concentrations at the other sites as was the cysts/nauplii mean THg concentration at Site 3510 (0.0054 ± 0.0033 ppm) and Site DWR3 (0.0071 ± 0.0036).

Conclusions

Naturally occurring brine shrimp (*Artemia fransicana*) through all its life stages (cysts, nauplii, and adults) were sampled from June to December, 2008 to characterize the life stage, seasonal and spatial THg concentrations collected from the open waters of Gilbert Bay, Great Salt Lake. There was a substantial increase in THg concentrations from cysts/nauplii to adults lake-wide. However, THg concentrations in GSL brine shrimp cysts from the streaks, cysts/nauplii and adult shrimp were all below 0.1 ppm (ww), the lowest observed adverse effect level as a fresh weight dietary item for Mallards (Heinz, 1979). When compared to Ever's risk ranges (Evers et al, 2004), the cysts from streaks and the cysts/nauplii taken from selected sites pose little risk as a dietary item for avian wildlife. Adult Brine shrimp may pose a moderate dietary risk. No difference in median THg concentrations in adult brine shrimp or cysts/nauplii were detected over the sites sampled. For adult brine shrimp, a significant difference in THg was detected over the season. Further analysis showed that the difference occurred in July when THg concentrations decreased. No differences across months were detected in cysts/nauplii. Additional investigation to more

accurately characterize any potential risks to waterfowl at Gilbert Bay from Hg is recommended.

Acknowledgements

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Table 2 Brine Shrimp Sample Sites including site name, location, USGS station ID, average depth and the presence or absence of the deep brine layer

SITE NAME	SITE LOCATION	USGS STATION ID	AVERAGE DEPTH OF WATER DURING 2008 (METERS)	PRESENCE OF DEEP BRINE LAYER
Site 2267	1 mile NW of Freemont Island - 4.5 miles southwest of the Bear River Bay inflow	411116112244401	3.6	no
Site 2767	4 miles W of North tip of Antelope Island - near Farmington and Ogden Bay inflows	410422112200001	1.6	no
Site 2935	W of Carrington Island - South part of Carrington Bay	410130112403601	4.3	no
Site DWR 3	North part of Carrington Bay – 12.8 km NNW of Hat Island	410955112402201	7.8	yes
Site 3510	Gilbert Bay – 6 miles W of Antelope Island	405356112205601	7.6	Yes, yet dilute and intermittent
Site 4069	South Gilbert Bay – 8 miles W of Saltair Marina	404607112193801	4.3	no

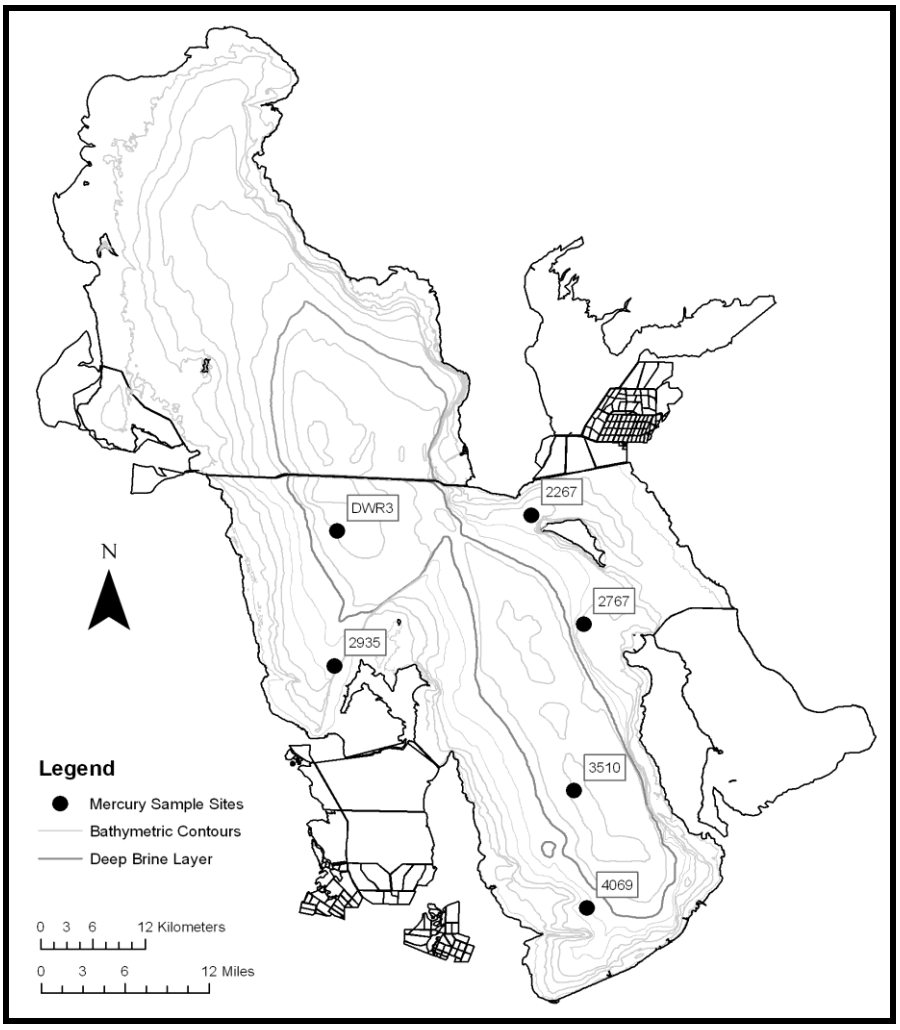

Figure 1 Site locations of brine shrimp sampling in Gilbert Bay, Great Salt Lake

Table 3 Descriptive statistics of Adult brine shrimp and Cyts/nauplii by location

SITE	LIFE STAGE	SAMPLE COUNT	MEAN ± SD THg ppm ww	GEOMEAN THg ppm ww	RANGE THg ppm ww
2267	Adult Cysts/Nauplii	10 8	0.0583 ± 0.0048 0.0084 ± 0.0033	0.0582 0.0080	0.0528 - 0.0694 0.0059 - 0.0162
2767	Adult Cysts/Nauplii	10 9	0.0598 ± 0.0139 0.0067 ± 0.0012	0.0577 0.0066	0.0252 - 0.0767 0.0047 - 0.0079
2935	Adult Cysts/Nauplii	10 10	0.0634 ± 0.0189 0.0069 ± 0.0015	0.0607 0.0068	0.0319 - 0.0976 0.0042 - 0.0100
DWR 3	Adult Cysts/Nauplii	10 10	0.0548 ± 0.0204 0.0071 ± 0.0036	0.0505 0.0062	0.0192 - 0.0863 0.0018 - 0.0144
3510	Adult Cysts/Nauplii	10 10	0.0607 ± 0.0139 0.0054 ± 0.0033	0.0586 0.0047	0.0269 - 0.0740 0.0017 - 0.0126
4069	Adult Cysts/Nauplii	10 9	0.0592 ± 0.0139 0.0082 ± 0.0032	0.0572 0.0078	0.0275 - 0.0724 0.0050 - 0.0156

Table 4 Descriptive statistics of Adult brine shrimp and Cyts/nauplii by month

MONTH	LIFE STAGE	SAMPLE COUNT	MEAN ± SD THg ppm ww	GEOMEAN THg ppm ww	RANGE THg ppm ww
June	Adult Cysts/Nauplii	6 3	0.0567 ± 0.0160 0.0047 ± 0.0032	0.0543 0.0040	0.0291 - 0.0731 0.0018 - 0.0082
July	Adult Cysts/Nauplii	6 6	0.0384 ± 0.0201 0.0085 ± 0.0042	0.0346 0.0078	0.0192 - 0.0723 0.0038 - 0.0162
August	Adult Cysts/Nauplii	6 6	0.0639 ± 0.0076 0.0070 ± 0.0022	0.0635 0.0067	0.0563 - 0.0767 0.0036 - 0.0095
September	Adult Cysts/Nauplii	12 12	0.0616 ± 0.0176 0.0077 ± 0.0037	0.0590 0.0068	0.0252 - 0.0976 0.0017- 0.0156
October	Adult Cysts/Nauplii	12 12	0.0673 ± 0.0085 0.0069 ± 0.0019	0.0669 0.0066	0.0561- 0.0863 0.0028 - 0.0100
November	Adult Cysts/Nauplii	12 12	0.0571 ± 0.0094 0.0065 ± 0.0014	0.0563 0.0063	0.0383 - 0.0679 0.0040 - 0.0087
December	Adult Cysts/Nauplii	6 5	0.0626 ± 0.0086 0.0072 ± 0.0042	0.0621 0.0065	0.0543 - 0.0733 0.0037- 0.0144

Table 5 Descriptive statistics of brine shrimp cysts collected from the streaks by month

MONTH	SAMPLE COUNT	MEAN ± SD THg ppm ww	GEOMEAN THg ppm ww	RANGE THg ppm ww
June	3	0.0087 ± 0.0037	0.0082	0.0052-0.0126
July	2	0.0061 ± 0.0001	0.0061	0.0060-0.0061
August	2	0.0091 ± 0.0001	0.0091	0.0090-0.0091
September	7	0.0118 ± 0.0015	0.0117	0.0093-0.0142
October	9	0.0092 ± 0.0007	0.0092	0.0084-0.0105
November	1			0.0108

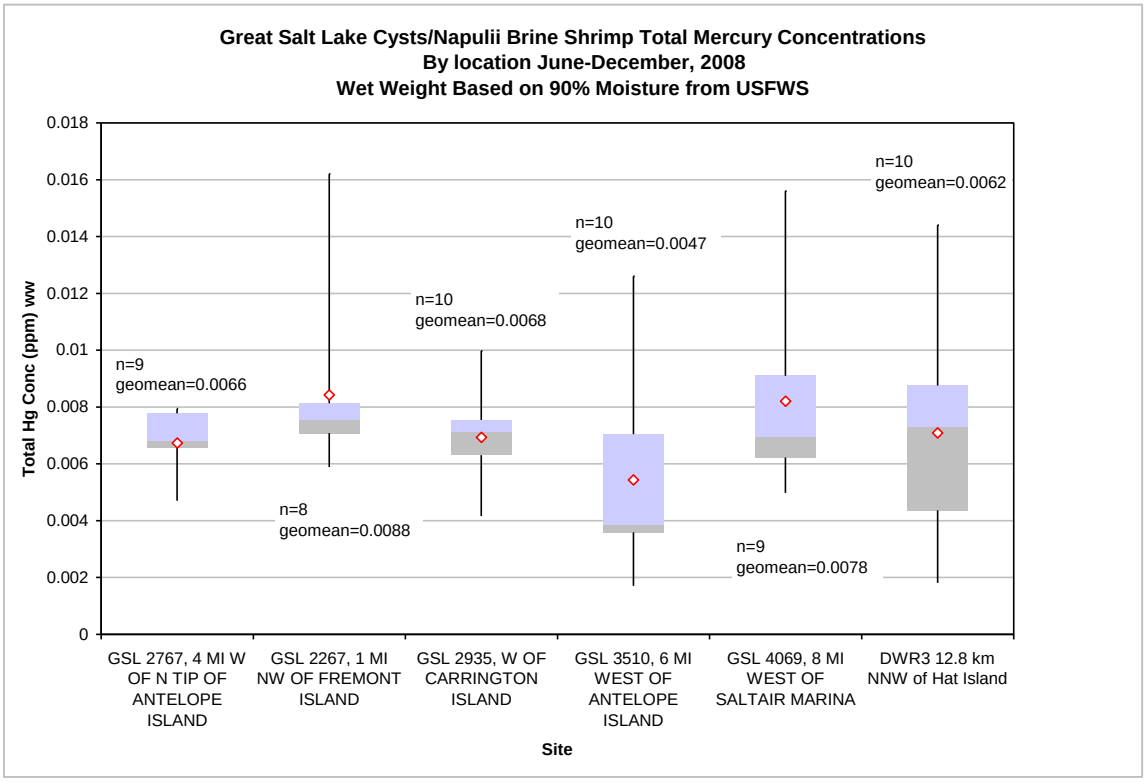

Figure 2 Simple box plot of THg concentrations in cyst/nauplii by location. The median is the line between the blue and gray portions. The blue portion is the upper quartile and the gray portion is the lower quartile. The upper line extends to the highest data point and the lower line to the sample minimum. The diamonds represent the average of the data set. The number of samples (n) and the geometric mean (geomean) are also provided. The geometric mean is a measure of central tendency and dampens the effects of outliers.

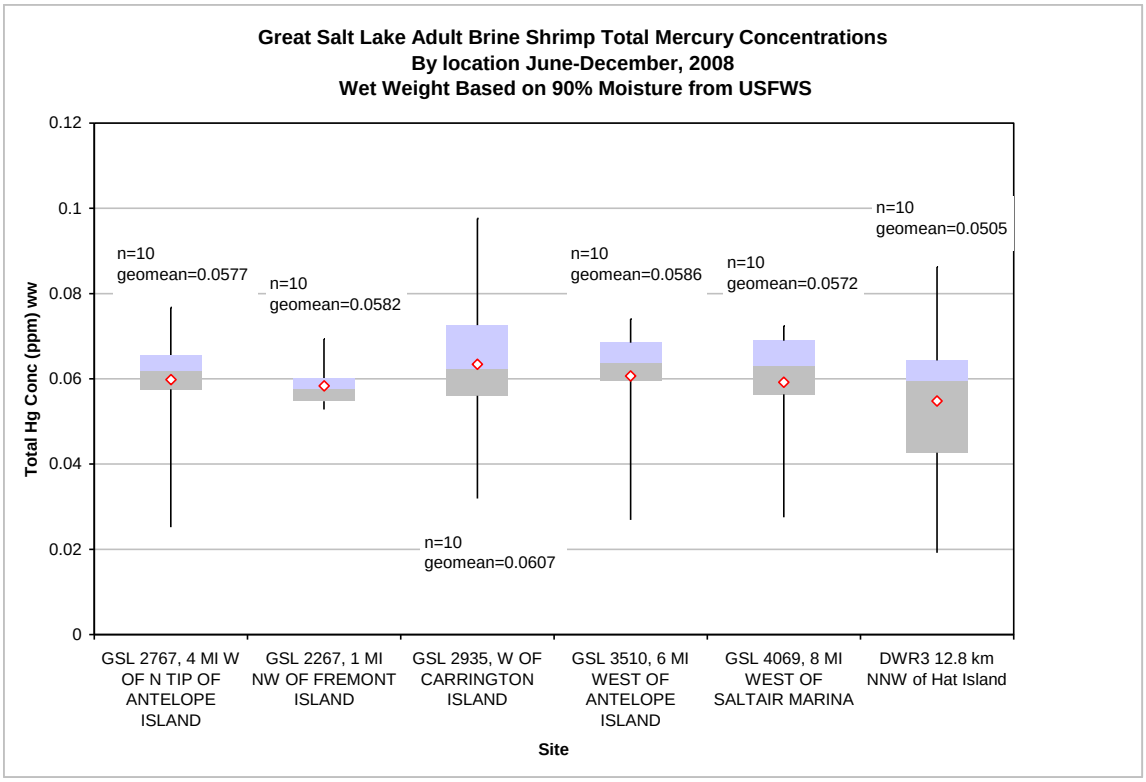

Figure 3 Simple box plot of THg concentrations in adult brine shrimp by location. The median is the line between the blue and gray portions. The blue portion is the upper quartile and the gray portion is the lower quartile. The upper line extends to the highest data point and the lower line to the sample minimum. The diamonds represent the average of the data set. The number of samples (n) and the geometric mean (geomean) are also provided. The geometric mean is a measure of central tendency and dampens the effects of outliers.

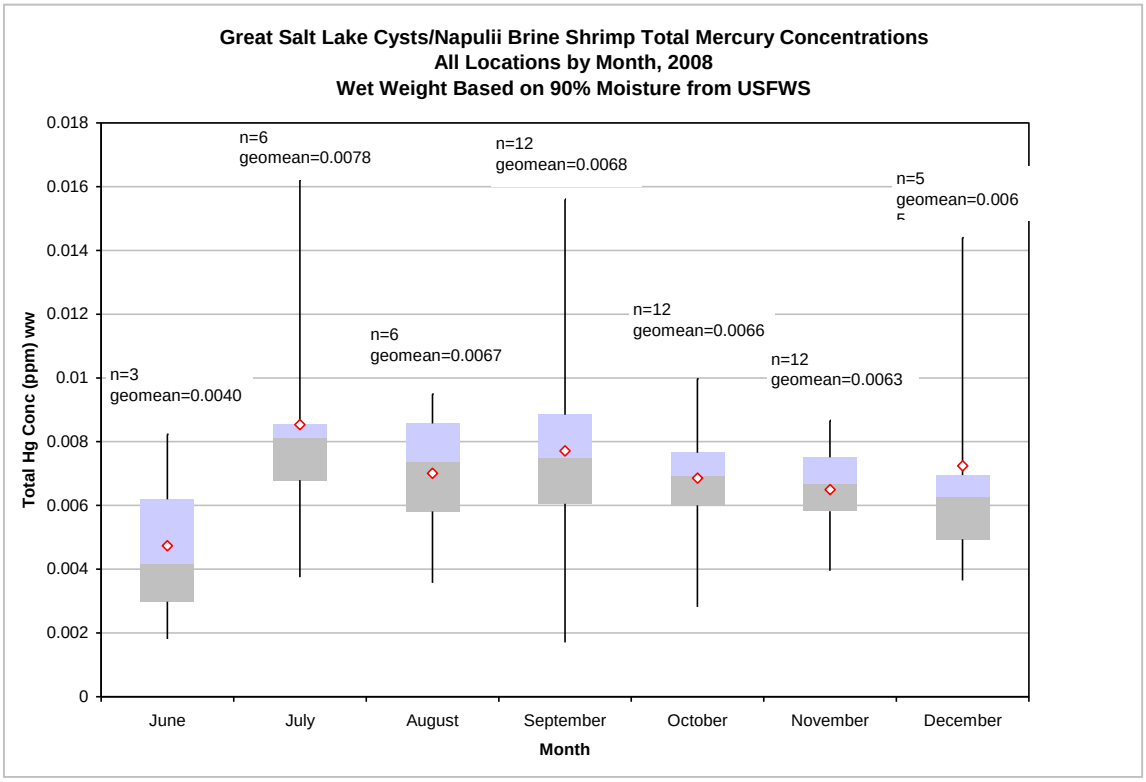

Figure 4 Simple box plot of THg concentrations in cyst/nauplii by month over all locations. The median is the line between the blue and gray portions. The blue portion is the upper quartile and the gray portion is the lower quartile. The upper line extends to the highest data point and the lower line to the sample minimum. The diamonds represent the average of the data set. The number of samples (n) and the geometric mean (geomean) are also provided. The geometric mean is a measure of central tendency and dampens the effects of outliers.

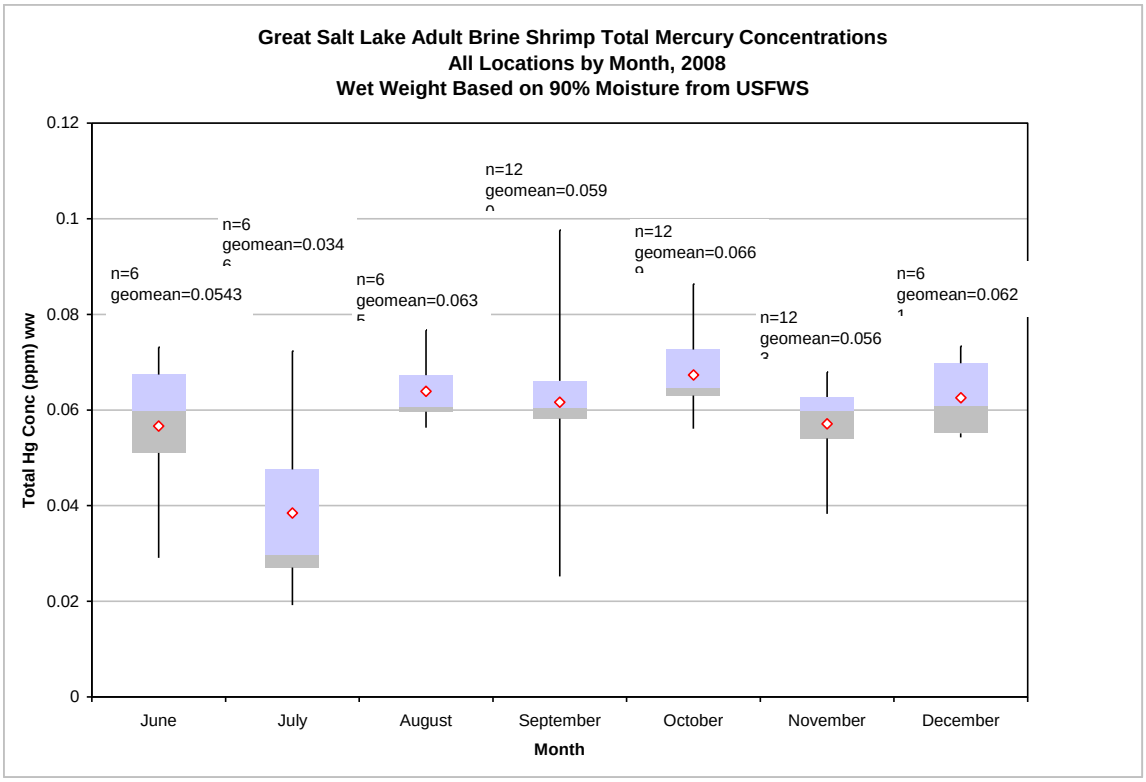

Figure 5 Simple box plot of THg concentrations in adult brine shrimp by month over all locations. The median is the line between the blue and gray portions. The blue portion is the upper quartile and the gray portion is the lower quartile. The upper line extends to the highest data point and the lower line to the sample minimum. The diamonds represent the average of the data set. The number of samples (n) and the geometric mean (geomean) are also provided. The geometric mean is a measure of central tendency and dampens the effects of outliers.

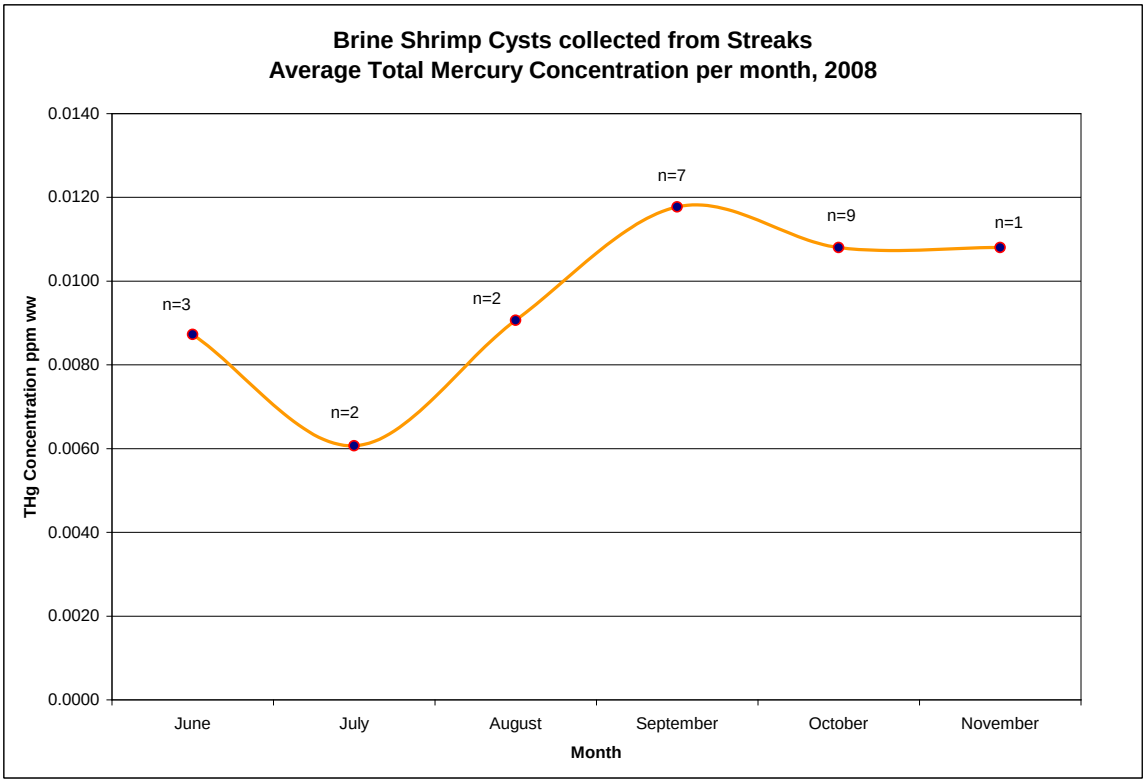

Figure 6 Average THg concentrations in brine shrimp cyst collected from the streaks by month, 2008

Chapter 3. Mercury Concentrations in Cinnamon Teal (*Anas cyanoptera*) and Northern Shoveler (*Anas clypeata*) at Great Salt Lake, Utah

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Abstract

Over seven million waterbirds utilize Great Salt Lake (GSL), Utah and its associated wetlands during some portion of their biannual migration. High concentrations of mercury (Hg) had been detected in the water column and wintering waterfowl; subsequently, the first ever consumption advisory for waterfowl in the United States was issued for GSL. To better understand Hg concentrations in waterfowl, egg, liver and breast muscle tissues from 2 species in 2008 were evaluated for mercury: Northern Shoveler (*Anas clypeata*), a wintering waterfowl that feed in the hypersaline open waters of GSL, and Cinnamon Teal (*Anas cyanoptera*), a summer breeding population that nest in the GSL fresh water wetlands. As a percentage of total mercury (THg), Cinnamon Teal eggs contained 94.4 ± 9.80% methyl mercury (MeHg), with a mean MeHg concentration of 0.177 ± 0.150 parts per million (ppm) wet weight (ww) and a range from 0.048 – 0.715 ppm ww. All eggs except two outliers sampled from Ogden Bay wetlands had MeHg concentrations levels less than the lowest observed adverse effect limit (LOAEL) of 0.5 ppm ww. Mean MeHg liver concentrations in Cinnamon Teal were 0.205 ± 0.080 ppm ww at Bear River Bay wetlands, 0.497 ± 0.368 ppm ww at Ogden Bay wetlands, and 0.452 ± 0.699 ppm ww at Farmington Bay wetlands. The mean Cinnamon Teal MeHg liver concentrations at all bays were below the LOAEL of 0.89 ppm ww for reproductive impacts. Mean Cinnamon Teal THg breast muscle tissue concentrations were 0.336 ± 0.405 ppm ww for summer adults, exceeding the U.S. Environmental Protection Agency screening value of 0.3 ppm ww and 0.154 ± 0.132 ppm ww for autumn adults that did not exceed the screening level. The

overall sample mean of 0.163 THg in the adult breast muscle tissue did not exceed the EPA screening level. While mean Cinnamon Teal egg and liver Hg concentrations were below levels of concern, a trend towards elevated levels of liver Hg concentrations were found in autumn-collected birds at Ogden Bay wetlands. It was not determined whether these birds arrived on the lake with that exposure or if they were exposed to Hg via the GSL open-water food chain, or in the wetlands. As a percentage of THg, Northern Shoveler livers contained 60.755% ± 16.794 MeHg with a mean of 0.662 ± 0.607 ppm ww and range from 0.124 to 2.873 ppm ww. Mean MeHg liver concentrations in Northern Shoveler were 0.861 ± 0.651 ppm ww at Bear River Bay wetlands, 0.730 ± 0.672 ppm ww at Ogden Bay wetlands, and 0.439 ± 0.456 ppm ww at Farmington Bay wetlands. The mean MeHg liver concentrations at all bays were below the LOAEL of 0.89 ppm ww for reproductive impacts. Mean THg breast muscle tissue concentrations in Northern Shoveler were 0.24 ppm ww at Bear River Bay, 0.20 ppm ww at Ogden Bay and 0.18 ppm ww at Farmington Bay. The mean THg at each location and the overall sample mean of 0.163 ppm ww in the adult breast muscle tissue did not exceed the EPA screening level.

Introduction

Over seven million waterbirds utilize Great Salt Lake (GSL), Utah and its associated wetlands during some portion of their biannual migration. In particular, three to five million waterfowl representing 35 species find the necessary habitat for migrating, breeding, molting, and wintering (Aldrich and Paul 2002). Testing of GSL water in 2003 by the U.S. Geological Survey (USGS) identified record methyl mercury (MeHg) concentrations of >30 nanograms per liter (ng/L) for any tested waterbody (Naftz et al. 2008). As

defined by the British Columbia Ministry of Environment (2001), these concentrations well exceed their 2 ng/L standard for total mercury (THg) when MeHg constitutes 5% of the total.

The potential of the more toxic organic form of mercury (Hg) to accumulate rapidly in the GSL food chain, from algae, plants, and macroinvertebrates to waterfowl and local hunters, led researchers to test Hg levels in the muscle tissue of waterfowl. Testing from three of the ten waterfowl species showed Hg concentrations above the U.S. Environmental Protection Agency's health standard of 0.3 parts per million (ppm) wet weight (ww), leading to the Utah Department of Health, Division of Wildlife Resources and Division of Water Quality to issue the nation's first ever human health advisory for the consumption of waterfowl including Cinnamon Teal (*Anas cyanoptera*), Northern Shoveler (*A. clypeata*), and Common Goldeneye (*Bucephala clangula*) (Utah Department of Health 2005; 2006).

We intend to identify and narrow the spatial and temporal extent of Hg within two of the three species of waterfowl that tested high for Hg. GSL provides a nationally important area for nesting Cinnamon Teals with estimates over 40,000 breeding adults. Although Cinnamon Teals are a large component of the summer breeding population, they are amongst the first species to leave in the fall (late September, early October). For wintering waterfowl species, Northern Shovelers constitute a large proportion that feed on abundant GSL food

resources, especially, when cold winter temperatures freeze freshwater marshes and force waterfowl to the high salinity, unfrozen portions of GSL (Aldrich and Paul 2002). Peak migratory populations of Northern Shovelers can exceed 160,000 (Paul and Manning 2002). Cinnamon Teals and Northern Shovelers, two key species of the GSL food chain with consumption advisories, congregate in freshwater and saline wetlands that are more readily accessible to local hunters in the fall, while Common Goldeneyes frequent the pelagic portions of the GSL not as easily accessed and collected.

Our objectives were three-fold. First, identify Hg concentrations for Cinnamon Teals throughout various stages of their life cycle (spring adults, eggs, summer juveniles, and autumn adults). Second identify Hg concentration for Northern Shovelers during the winter months. And third, identify spatial differences in Hg exposure for these two species within each of the three bays (Bear River, Ogden, and Farmington) on the eastern side of GSL.

Methodology

Study Sites

As with most waterbirds found at Great Salt Lake, waterfowl tend to concentrate in three geographically and hydrologically separate areas on the east side of the lake. From north to south they are Bear River Bay, Ogden Bay, and Farmington Bay (Figure 1). Each bay is supplied by one of three major tributaries (Bear

River, Weber River, and Jordan River, respectively) with extensive freshwater marshes and associate brackish and saline habitats. Collections of Cinnamon Teals and Northern Shovelers focused on these three areas.

Figure 1. Locations at Great Salt Lake, Utah, where egg, juvenile, and adult life stages of Cinnamon Teal and Northern Shoveler were collected for mercury analysis.

Sample Collection

Cinnamon Teals (CITE) were collected from the GSL in the freshwater marshes of Bear River Bay (BR), Ogden Bay (OB), and Farmington Bay (FB) starting in May 2008 with the arrival of migrants and ending in early October with their departure (Figure 1). From each bay, we collected arriving spring migrants (early May), eggs (late May-early July), juveniles (late July-late August), and autumn adults (late September-early October). Cinnamon Teal eggs were collected in appropriate habitat, typically salt grass (*Distichlis spicata*) meadows with nearby water or vegetated areas alongside constructed dikes. Nests were located by observing locations where CITE hens would flush from their nests. We used one of three methods for flushing females: 1) walking through vegetation holding a chain between two people, and dragging the chain elevated above ground through the vegetation, being careful not to damage potential nests; 2) driving

along dikes with a long, horizontal pole attached perpendicularly to the vehicle with several tethers for aluminum cans clanging through the vegetation; or 3) using trained dogs. Spring and autumn adults along with juvenile CITEs, one from each brood were identified by behavior, flightlessness, and feather characteristics, and collected in freshwater wetlands near nesting areas.

Northern Shovelers (NSHO) were collected in the saline and freshwater areas of Bear River, Ogden, and Farmington bays from mid-October through the end of December (Figure 1). We grouped the samples into early and late time periods with November 16th marking the beginning of the late period.

All ducks were collected with a shotgun using steel shot by ambush or lured by decoys with the exception of three juvenile CITE collected from airboats, using nets and spotlights on a moonless night.

Eggs were labeled in the field by writing on the shells in pencil and were transported to the processing laboratory at ambient temperature. Eggs were generally processed immediately upon return from the field but when this was not possible they were refrigerated after collection and processed within 24 hours. Birds were labeled with date and collection location (GPS coordinates), placed in plastic bags, and frozen at the earliest opportunity.

Sample Processing

Eggs were weighed, measured, and floated in a graduated cylinder filled with distilled, deionized water to determine volume by specific gravity. Eggs were opened at the large end (containing the air sac) using chemically-cleaned, stainless steel scissors and forceps. After carefully breaking away the shell and removing the membrane overlying the air sac, egg contents were emptied into a tared, chemically clean glass jar, examined for developmental stage and possible malformations, weighed to obtain content weight, and then frozen at -20° C prior to analysis.

Ducks (both CITE and NSHO) were necropsied in December 2008 and January 2009. Birds were removed from the freezer and placed in refrigerators (4° C) to thaw for 24-48 hours prior to necropsy. Birds were weighed and morphometric measurements taken, then breast muscle and liver tissues were collected for chemical analysis using stainless steel dissecting tools that were washed with Alconox® and rinsed with deionized water after each use. CITE were aged (juvenile vs. adult) by looking for the bursa of Fabricius, which is an internal immune function, glandular organ attached to the digestive tract near the cloaca that is present in birds until about six months of age. Livers were divided into right- and left-lobes and placed separately into labeled Whirl-pak® polyethylene bags. The right breast muscles (pectoralis and supracoracoideus) were dissected from the sternum and rib cage and sectioned into roughly six equal parts. To minimize variance due to differential vascularization of a different

muscle region, we subsectioned each part and placed into a Whirl-pak® bag to make a total sample mass of approximately five grams (J. Vest, pers. comm.). Samples were then re-frozen and stored at -20° C prior to analysis.

Analytical

Samples of CITE right-lobe liver, breast muscle, and egg; and NSHO right-lobe liver were shipped on dry ice via overnight air to the USGS Mercury Research Laboratory in Middleton, Wisconsin for analysis. Northern Shoveler breast muscle samples were analyzed at the U.S. Environmental Protection Agency (USEPA) Region 8 Laboratory in Denver, CO.

All tissue samples were prepared and analyzed for Hg extraction and quantitation by freeze-drying until completely dry, then homogenizing using a glass mortar. Muscle and liver tissues were further homogenized using a high-speed stainless steel ball mill. Samples were then transferred to glass serum vials and dry weight determined. Aliquots for THg analysis were analyzed by direct combustion using a Nippon model MA-2999 mercury analyzer according to USEPA Method 7473 (U.S. Environmental Protection Agency 2007). Aliquots for MeHg were first extracted with dilute nitric acid, and then analyzed by ethylation, purge and trap, and cold vapor atomic fluorescence spectrometry. Results were reported in nanograms/gram (ng/g, or parts per billion) dry weight. The USGS lab also reported percent moisture, which was used to calculate wet weight concentrations.

The USEPA lab prepared and analyzed NSHO muscle tissue samples following USEPA Method 7473 (U.S. Environmental Protection Agency 2007) by the process of thermal decomposition, amalgamation, and atomic absorption spectrophotometry using a DMA 80 automatic mercury analyzer (Milestone, Inc. Shelton, CT) and reported in milligrams per kilogram (mg/kg, or parts per million) wet weight. Unless otherwise noted, all data are reported in parts per million wet weight (ppm ww) and the mean plus or minus the standard deviation (±SD).

Data Archival

THg and MeHg data for all CITE and NSHO samples are archived within the USGS National Water Information System (NWIS) with the exception of the NSHO muscle samples analyzed by the USEPA (U.S. Geological Survey 2010). Table 1 lists all NWIS site numbers and names with the species collected. Access the data using an interactive map (NWIS Mapper) of surface-water and other sites at http://wdr.water.usgs.gov/nwisgmap/index.html or searching field/lab samples by site number or name (NWISWeb) at http://waterdata.usgs.gov/ut/nwis/qw/.

Statistical Analysis

Data were analyzed with NCSS Version 2001 (Number Cruncher Statistical Systems, Kaysville, Utah) including descriptive statistics (mean, geometric mean,

standard deviation and standard error) analyses of data distribution, and statistical comparisons between sample groups. Data were tested for normality, and if normally distributed were evaluated using parametric GLM ANOVA for variance between grouping variables (sites, seasons and/or age groups, as appropriate). Two-way means comparisons were performed with uneven sample-size t-tests, and multiple comparisons of means were performed using the Tukey-Kramer multiple comparison test. Where data were non-normally distributed, variance was evaluated with non-parametric Kruskal-Wallace one-way ANOVA on ranks, and means were compared with non-parametric Kruskal-Wallace multiple comparisons z-value test. Because of generally small sample sizes and the objective of screening for potential impacts (i.e., incorrectly rejecting the null hypothesis is preferable to incorrectly accepting it), differences were evaluated at $\alpha = 0.10$. For CITE muscle and liver data, data were compared between sites and between spring (May 1 – May 30), summer (June 1 – August 30), and autumn (September 1 – October 31) seasons. NSHO data were compared between sites and between early autumn (October 1 – November 15) and late autumn/early winter (November 16 – December 31) seasons.

Table 1. U.S. Geological Survey National Water Information System site numbers and site names where Cinnamon Teal (CITE) and Northern Shoveler (NSHO) were collected at Great Salt Lake, Utah in 2008.

Results and Discussion

Cinnamon Teal

Thirty CITE eggs (68.9 ± 1.12% moisture), ten each from Bear River (BR), Farmington Bay (FB), and Ogden Bay (OB), had a mean THg concentration of 0.187 ± 0.156 ppm ww with a range from 0.052 to 0.784 ppm ww (Table 2). As a percentage of THg, eggs contained 94.4 ± 9.80% MeHg, with a mean concentration of 0.177 ± 0.150 ppm ww and a range from 0.048 – 0.715 ppm ww. Mean THg at each of the three wetlands ranged from 0.142 ± 0.032 ppm ww at BR to 0.267 ± 0.249 ppm ww at OB; mean MeHg ranged from 0.133 ± 0.031 to 0.246 ± 0.239 ppm ww at BR and OB, respectively. Although the highest mean concentrations of both THg and MeHg were observed at Ogden Bay (Figure 2), there was no significant difference in THg, MeHg, percent moisture or percent MeHg among eggs from the three bays when tested with a non-parametric ANOVA (p = 0.369). Egg THg concentrations were normally distributed at Farmington and Bear River bays but were not at Ogden Bay, where two eggs with the highest observed concentrations of THg were outliers to the data distribution (0.784 and 0.678 ppm ww). All other eggs except these two outliers had THg concentrations levels less than the lowest observed adverse effect limit (LOAEL) of 0.5 ppm ww in mallard eggs (Heinz 1979; Evers et al. 2004).

Table 2. Summary of total (THg) and methyl (MeHg) mercury concentration data for various time periods, age classes, and tissues of Cinnamon Teal (CITE) and

Northern Shoveler (NSHO) collected in 2008. ppm ww = parts per million wet weight, SD = standard deviation.

Figure 2. Simple box plots of methyl mercury concentrations in Cinnamon Teal eggs collected in 2008 from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean.

Mean CITE liver THg concentrations were 0.273 ± 0.099 ppm ww (n=11) at BR, 0.577 ± 0.400 ppm ww (n=12) at OB, and 0.615 ± 0.945 ppm ww (n=27) at FB. Both THg and MeHg concentrations were normally distributed at BR and OB but were not at FB, primarily driven by two birds collected in the spring at FB with 4.86 and 2.10 ppm ww THg. These were the highest liver mercury concentrations observed during the study. Mean MeHg concentrations were 0.205 ± 0.080 ppm ww at BR, 0.497 ± 0.368 ppm ww at OB, and 0.452 ± 0.699 ppm ww at FB (Figure 3). The mean concentrations at all bays were below the LOAEL of 0.89 ppm ww for reproductive impacts in mallards (Heinz 1979). Mean MeHg was higher at OB because it had the highest mean percent MeHg (83% at OB, 75% at BR and 77% at FB). BR had the lowest mean liver THg and MeHg concentrations and the lowest percent MeHg.

Location was a significant source of variability (α=0.10) in CITE liver THg concentrations across all seasons (n = 50, p = 0.086). Mean liver THg concentrations at OB and BR were significantly different according to the non-parametric Kruskal-Wallace multiple comparisons z-value test (Z = 2.15, with significance at Z >1.96). At FB, the only area where all three seasons could be evaluated, season did not contribute to variability in THg or MeHg in CITE livers. In birds collected during the Autumn (actual collection dates ranging from Sept. 27 – Oct. 17), location was a significant source of variability in THg (p = 0.063), with mean THg concentrations being significantly different between BR and OB however caution should be taken with this comparison because only two birds were collected at BR during this period. At OB, mean THg and MeHg liver concentrations were both significantly higher in the autumn (0.694 ± 0.389 ppm ww THg, 0.608 ± 0.359 ppm ww MeHg) compared to the summer (0.226 ± 0.168 ppm ww THg, 0.164 ± 0.093 ppm ww MeHg), with the non-parametric Kruskal-Wallace ANOVA significant at p = 0.077 (Figure 4). Again, caution should be taken with these comparisons because of small and uneven sample sizes.

Figure 3. Simple box plots of methyl mercury concentrations in Cinnamon Teal livers collected in 2008 from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean

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Figure 4. Simple box plots of methyl mercury concentrations in Cinnamon Teal livers collected during the summer months (May – August) versus the autumn (September-October) 2008 at each bay, Great Salt Lake, Utah. BR = Bear River Bay, OB = Ogden Bay and FB=Farmington bay, n = number of samples, geomean = geometric mean

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THg concentrations in CITE breast muscle tissue ranged from 0.014 ppm ww (in an autumn bird from Farmington Bay) to 1.36 ppm ww (in a spring adult from Farmington Bay; Table 2) with a mean THg concentration of 0.163 $\pm$ 0.207 ppm ww. Mean THg breast muscle concentrations were 0.09 ± 0.040 ppm ww at BR, 0.177 ± 0.260 ppm ww at OB, and 0.198 ± 0.152 ppm ww at FB (Figure 5). Four CITE from FB had muscle THg concentrations > 0.3 ppm ww (three spring birds and one autumn). One bird from Ogden Bay exceeded 0.3 ppm ww. There was no effect of location on muscle THg concentrations for all samples collectively, but there were significant seasonal effects at FB where spring mean concentrations were greater than in the summer or autumn and during the autumn OB concentrations were greater than BR concentrations (Figure 5). Concentrations of both MeHg and THg in CITE liver tissue were highly correlated with THg concentration in breast muscle tissue from the same birds (R^2 = 0.974 and 0.935, respectively; Figure 6). The slope was significant for both regressions ($p < 0.0001$).

Figure 5. Simple box plots of methyl mercury concentrations in Cinnamon Teal breast muscle tissue collected in 2008 from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean -

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Figure 6. Correlation of total mercury concentrations in Cinnamon Teal breast muscle with liver tissue collected from the same bird at Great Salt Lake, Utah.

Mercury concentrations in CITE from GSL wetlands in 2008 were generally lower than those observed in previous studies. While mean Hg concentrations in Cinnamon Teal eggs were generally below levels of concern, individual eggs exceeded levels of concern for reproduction, particularly at OB. OB, which contains two State-owned waterfowl management areas, is closest to the railroad causeway that separates the north and south arms of GSL (Figure 1). THg concentrations in autumn CITE breast muscle tissue from GSL wetlands in 2008 were generally lower than the comparable mean THg concentrations observed in previous studies by the Utah Department of Health (2005; 2006) in 2004 and 2005 (0.475 ppm ww, n = 2; 0.370 ppm ww, n = 33; respectively). Mean liver and breast muscle THg concentrations were also generally below levels of

concern; however, we observed elevated levels in individual birds and a trend towards elevated levels in autumn-collected birds at OB. Individual birds collected in the spring at FB had liver Hg concentrations associated with reproductive impairment; but, we cannot determine if these birds arrived on the lake with that exposure, if they were exposed to Hg via the GSL open-water food chain, or if they were exposed to more localized, known Hg sources within the Farmington Bay wetlands (U.S. Fish and Wildlife Service 2009).

The dense brine in the hypersaline north arm is the hypothesized source of the "deep brine layer" in the south arm that supports increased Hg methylation in GSL (Naftz et al. 2008). Elevated Hg concentrations in tissues of GSL birds may be more strongly associated with exposure to the saline, open-water component of the GSL ecosystem via consumption of brine shrimp and brine flies, the dominant food source in GSL. These macroinvertebrates, in turn, consume photosynthetic plankton with accumulated MeHg, which is present in high concentrations in the water column. Our results tend to confirm this hypothesis. We sampled CITE that were most likely feeding in shallow or ponded emergent wetlands while nesting in the summer rather than the open-water of GSL (J. Luft, pers. comm.). Thus it may be that CITE are minimally exposed to Hg "fixed" by the GSL food-chain while they are nesting and raising young. However, as they begin to move into the open lake in the later summer and autumn to feed on littoral brine shrimp and brine fly populations, the likelihood and magnitude of Hg exposure in CITE may increase. This may be what is responsible for the

elevated Hg as seen in CITE collected during the hunting season (Vest et al. 2009).

The issue of whether the GSL is “impaired” by Hg (as defined by the Clean Water Act) is important to management of the lake. Our results indicate that more investigation is needed, particularly in the late summer and autumn, and also at OB. Also, avian species that may be more exposed to Hg, either in the open waters of the GSL or localized sources should be further evaluated. Finally, the very high correlation between liver and breast muscle Hg concentrations may allow muscle tissue data (previously collected to assess human health risks from consumption of hunted waterfowl) to be used to estimate health and reproductive risks to GSL birds.

Northern Shoveler

A total of 48 Northern Shovelers (NSHO) were analyzed for mercury concentrations from Bear River Bay (BR), Ogden Bay (OB) and Farmington Bay (FB) in the GSL. Twenty-one of these birds were collected in the early time period (mid-October through November 15th) and the remainder in the late time period (November 16th through December). For all samples combined, liver THg concentrations ranged from 0.168 ppm ww (early period at FB) to 6.841 ppm ww (late period at OB) with a mean of 1.132 ± 1.122 ppm ww. MeHg concentrations in NSHO livers ranged from 0.124 to 2.873 ppm ww with a mean of 0.662 ± 0.607 ppm ww. Percent MeHg of THg in NSHO liver tissues (60.755% ± 16.794)

was lower than that found in Cinnamon Teal livers (78.201% ± 15.232), and the NSHO percentage decreased between the early and late time periods from 66.827% to 56.032%.

Mean NSHO liver THg concentrations were 1.295 ± 0.686 ppm ww (n=15) at BR, 1.444 ± 1.704 ppm ww (n=15) at OB, and 0.736 ± 0.651 ppm ww (n=18) at FB. Mean MeHg concentrations were 0.861 ± 0.651 ppm ww at BR, 0.730 ± 0.672 ppm ww at OB, and 0.439 ± 0.456 ppm ww at FB (Figure 7). The mean MeHg liver concentrations at all bays were below the LOAEL of 0.89 ppm ww for reproductive impacts in mallards (Heinz 1979). A significant difference (p=0.009) in median MeHg concentrations in NSHO livers among the three bays was detected. The Tukey multiple comparison test showed that the difference occurred between BR and FB where the mean MeHg concentration at FB was much lower. Analysis of median liver MeHg concentrations indicated that there was no significant difference between those NSHO collected early in the season as opposed to later collections (p=0.779; Figure 8).

Figure 7. Simple box plots of methyl mercury concentrations in Northern Shoveler livers collected from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean.

Figure 8. Simple box plots of methyl mercury concentrations in Northern Shoveler livers collected lakewide from mid-October to mid-November (early) and mid-November to the end of December (late), 2008. n = number of samples, geomean = geometric mean.

THg concentrations in NSHO breast muscle tissue ranged from 0.047 ppm ww (early period from FB) to 1.240 ppm ww (late period from FB; Table 2) with a mean concentration of 0.207 ± 0.205 ppm ww. From these tissue samples, four NSHO from BR, one from FB and four from OB had muscle THg concentrations > 0.3 ppm ww (2 early period and 7 late period), the USEPA screening value for THg in breast muscle tissue (U.S. Environmental Protection Agency 2000). Mean NSHO breast muscle THg concentrations in ppm ww were 0.240 ± 0.170 (n=15) at BR, 0.203 ± 0.142 (n=15) at OB, and 0.182 ± 0.271 (n=18) at FB (Figure 9). This overall mean and the mean THg concentration from FB is lower than the comparable mean concentration of 0.383 ppm ww (n=30) observed for NSHO collected in FB that, in part, was the basis for the waterfowl consumption advisory established in 2005 (Utah Department of Health 2006). There was neither a significant difference in breast muscle THg concentrations at the three locations sampled nor was there a difference between waterfowl in the early and late time periods.

Figure 9. Simple box plots of total mercury concentrations in Northern Shoveler breast muscle tissue collected from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean.

Acknowledgements

The long and challenging hours of sample collection were made possible with assistance from John Luft, Tom Aldrich; Rich Hansen, Farmington Bay Waterfowl Management Area (WMA) manager, and his assistant, Jason Jones; Val Bachman, Ogden Bay WMA manager, and his assistant, Dave Rich; Bridget Olson, Mitch Newman, David Brodstein, Greg Hansen, and the hunters who donated birds. John Isenhart, Josh Vest, Scott Edler, Phil Brown, Jim Van Leeuwen, Elizabeth Bankhead, Breanna Bartosz, Megan Dalton, Amy Dickey, Justin Feld, Cristina Juran, and Sean Mathis helped out with the necropsies. Project management and funding for lab analysis of tissue samples came from the Utah Department of Environmental Quality/Division of Water Quality and the USEPA.

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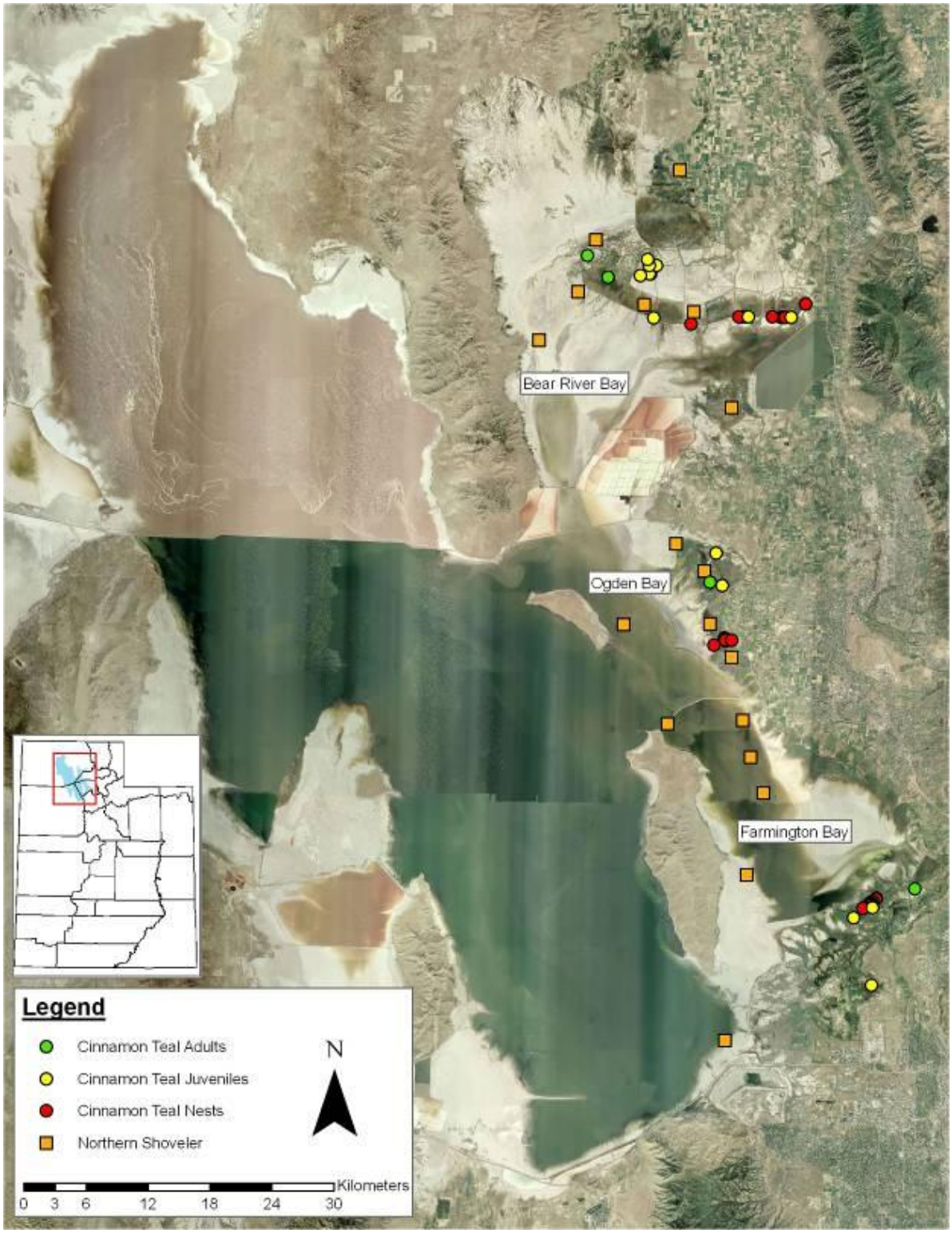

Figure 1. Locations at Great Salt Lake, Utah, where egg, juvenile, and adult life stages of Cinnamon Teal and Northern Shoveler were collected for mercury analysis.

Site Number	Site Name	Species
410732112092601	(B- 5- 3)35bdd Howard Slough (mid-pond)	CITE/NSHO
412540112053401	(B- 8- 2)17cac Bear River Wetland Unit5C Middle	CITE
405445111594001	N. Turpin unit dike by Farmington Bay, Wetlands	CITE
411202112112501	Ogden Bay/Ogden Bay WMA Unit 1	CITE/NSHO
412358112230901	Bear River Bay/Open Water (2.0 km ENE of Boothe Valley Hill on Promontory Pt.)	NSHO
412536112122301	Bear River Bay/BRMBR Unit 4B	NSHO
412634112202801	Bear River Bay/BRMBR Unit 9	NSHO
412916112191801	Bear River Bay/BRMBR Unit 1	NSHO
412555112155101	Bear River Bay/BRMBR Unit 3D	NSHO
413259112133001	Bear River Bay/Tri-State Duck Club	NSHO
412036112094001	Bear River Bay/Harold Crane WMA	NSHO
410910112165901	Ogden Bay/Open Water (12.4 km N of Buffalo Pt. on Antelope Is.)	NSHO
411326112132401	Ogden Bay/Ogden Bay WMA Pintail Flats	NSHO
410916112105901	Ogden Bay/Ogden Bay WMA Unit 3	NSHO
405610112081301	Farmington Bay-Seagull Point/Open Water	NSHO
404728112093401	Gilbert Bay-Lee Creek/Open Water	NSHO
410400112134901	Antelope Island Causeway Breach (westernmost)	NSHO
410219112080301	Farmington Bay/Open Water (5.7 km S of Antelope Is. Causeway Gatehouse)	NSHO
410028112070701	Farmington Bay/Open Water (9.0 km S of Antelope Is. Causeway Gatehouse)	NSHO
410415112083601	Farmington Bay/Open Water (2.8 km SW of Antelope Is. Causeway Gatehouse)	NSHO

Table 1. U.S. Geological Survey National Water Information System site numbers and site names where Cinnamon Teals (CITE) and Northern Shovelers (NSHO) were collected at Great Salt Lake, Utah in 2008.

Species	Time Period	Age Class	Tissue	Sample Count	THg ppm ww		MeHg ppm ww		Percent Moisture	
					Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
CITE	Spring	Egg	Egg	30	0.187 ± 0.156	0.052 – 0.784	0.177 ± 0.15	0.048 – 0.715	68.872 ± 1.121	66.56 – 71.38
CITE	Spring	Adult	Liver	9	1.145 ± 1.517	0.179 – 4.862	0.825 ± 1.121	0.167 – 3.704	70.616 ± 5.277	58.2 – 77.504
CITE	Spring	Adult	Muscle	9	0.336 ± 0.405	0.042 – 1.36	NA	NA	73.45 ± 0.682	72.331 – 74.321
CITE	Summer	Juvenile	Liver	21	0.289 ± 0.211	0.071 – 1.014	0.236 ± 0.193	0.066 – 0.941	72.995 ± 3.313	68.421 – 83.964
CITE	Summer	Juvenile	Muscle	21	0.097 ± 0.071	0.019 – 0.342	NA	NA	79.094 ± 3.408	71.909 – 86.46
CITE	Autumn	Adult	Liver	20	0.508 ± 0.33	0.059 – 1.296	0.403 ± 0.315	0.047 – 1.111	69.024 ± 5.437	48.712 – 76.888
CITE	Autumn	Adult	Muscle	20	0.154 ± 0.132	0.014 – 0.5	NA	NA	73.831 ± 1.415	71.868 – 77.851
NSHO	Early Winter	Adult	Liver	21	0.819 ± 0.489	0.168 – 2.098	0.543 ± 0.353	0.124 – 1.524	71.159 ± 1.5	68.93 – 73.87
NSHO	Early Winter	Adult	Muscle	21	0.167 ± 0.095	0.047 – 0.36	NA	NA	NA	NA
NSHO	Late Winter	Adult	Liver	27	1.375 ± 1.397	0.254 – 6.841	0.754 ± 0.742	0.147 – 2.873	71.015 ± 1.661	68.61 – 76.34
NSHO	Late Winter	Adult	Muscle	27	0.238 ± 0.258	0.052 – 1.240	NA	NA	NA	NA

Table 2. Summary of total (THg) and methyl (MeHg) mercury concentration data for various time periods, age classes, and tissues of Cinnamon Teal (CITE) and Northern Shoveler (NSHO) collected in 2008. ppm ww = parts per million wet weight, SD = standard deviation.

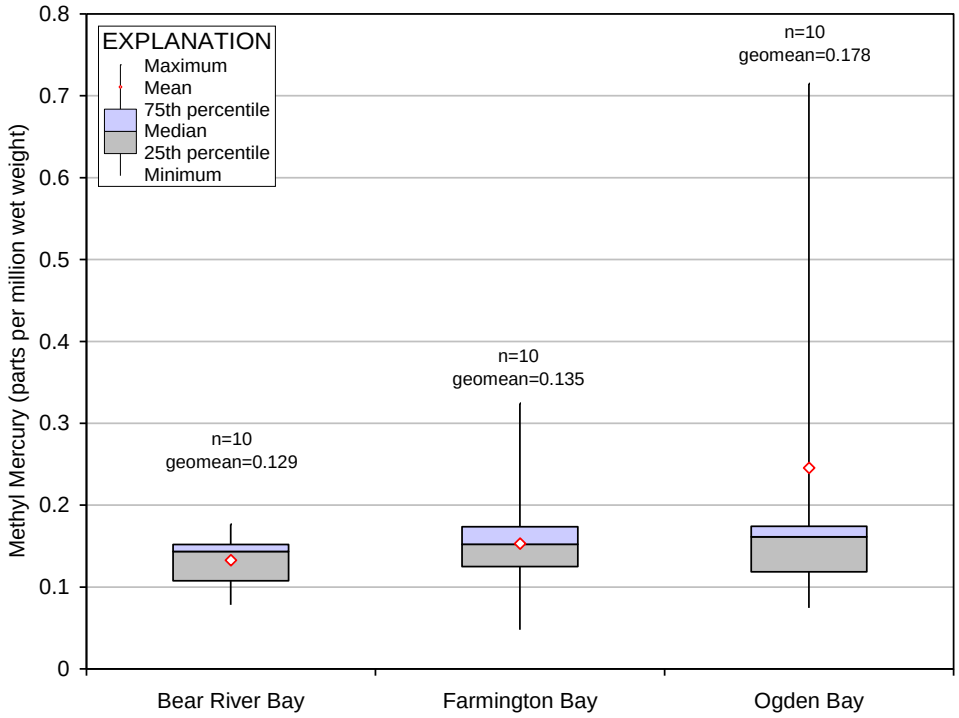

Figure 2. Simple box plots of methyl mercury concentrations in Cinnamon Teal eggs collected in 2008 from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean.

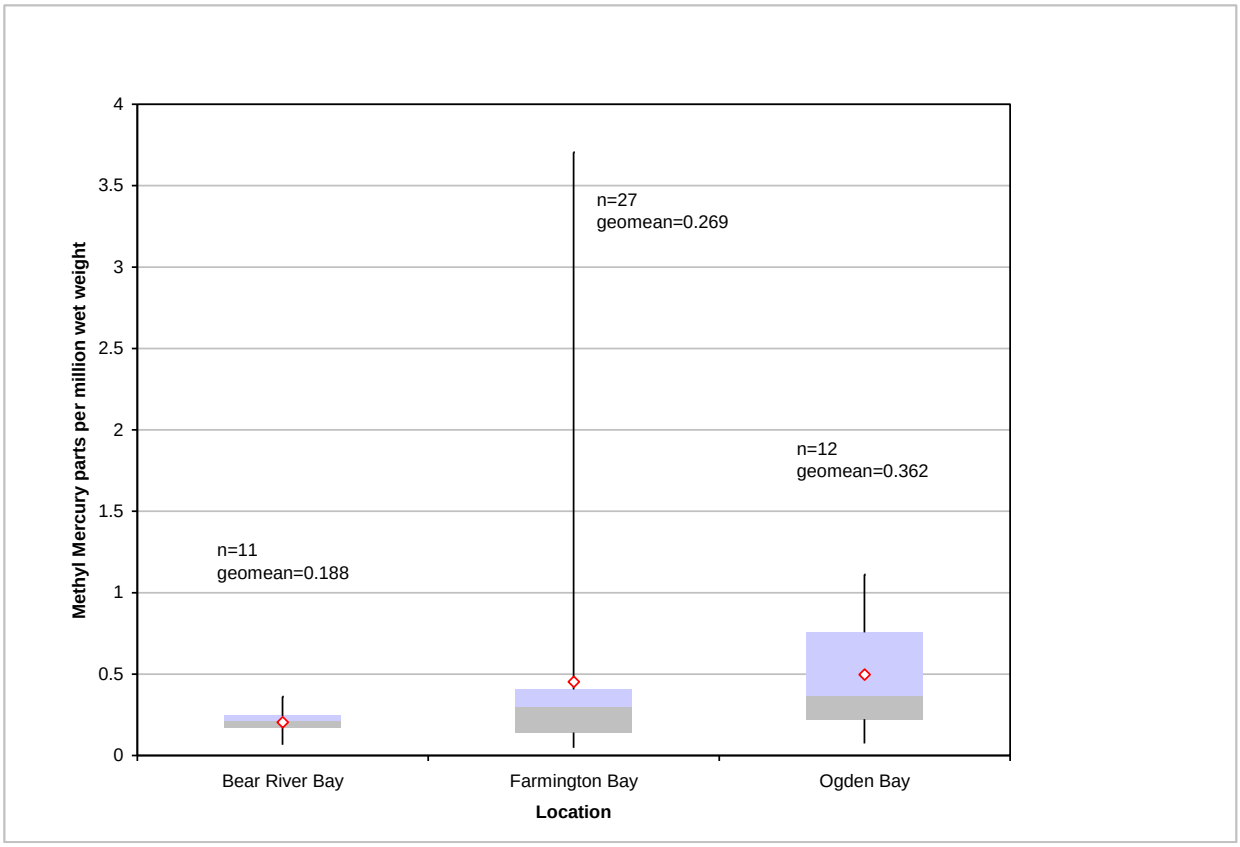

Figure 3. Simple box plots of methyl mercury concentrations in Cinnamon Teal livers collected in 2008 from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean

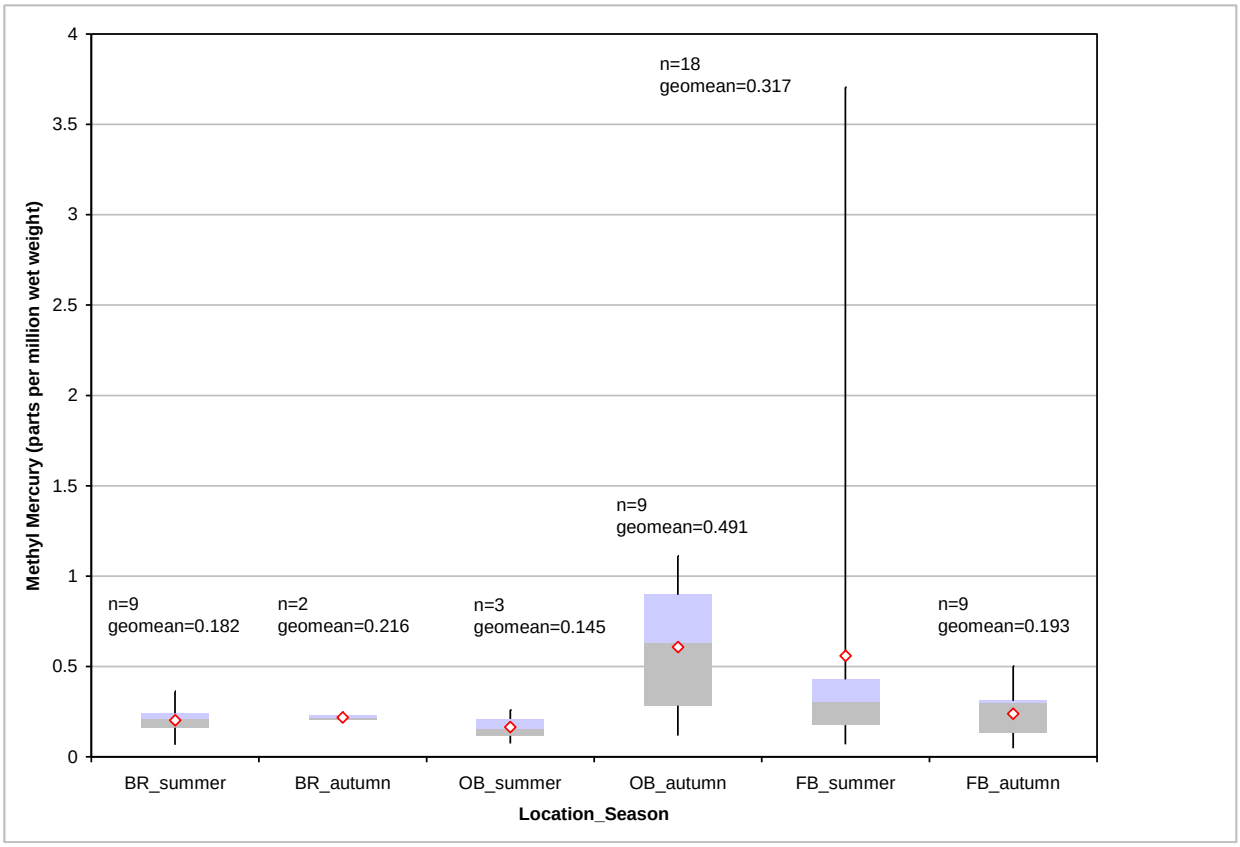

Figure 4 Simple box plots of methyl mercury concentrations in Cinnamon Teal livers collected during the summer months (May – August) versus the autumn (September-October) 2008 at each bay, Great Salt Lake, Utah. BR = Bear River Bay, OB = Ogden Bay and FB=Farmington bay, n = number of samples, geomean = geometric mean

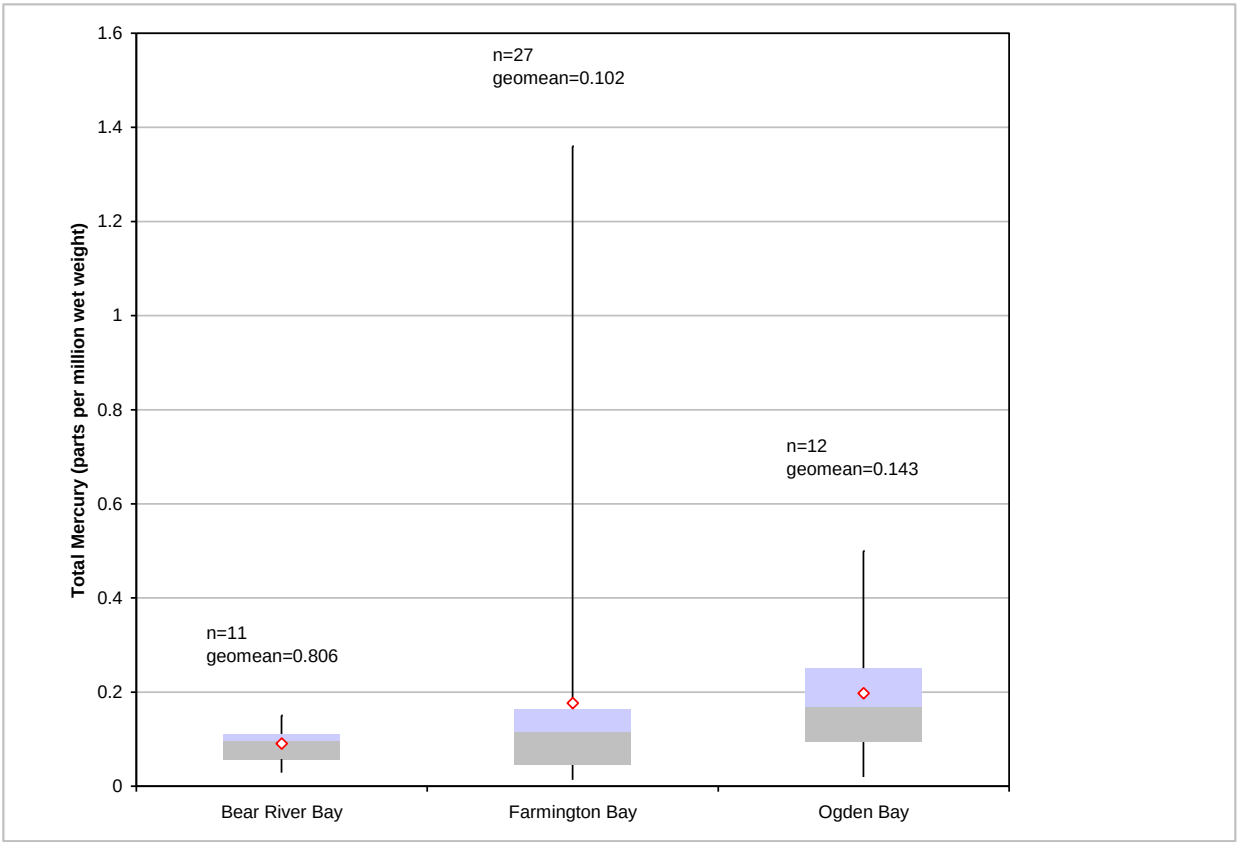

Figure 5. Simple box plots of methyl mercury concentrations in Cinnamon Teal breast muscle tissue collected in 2008 from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean

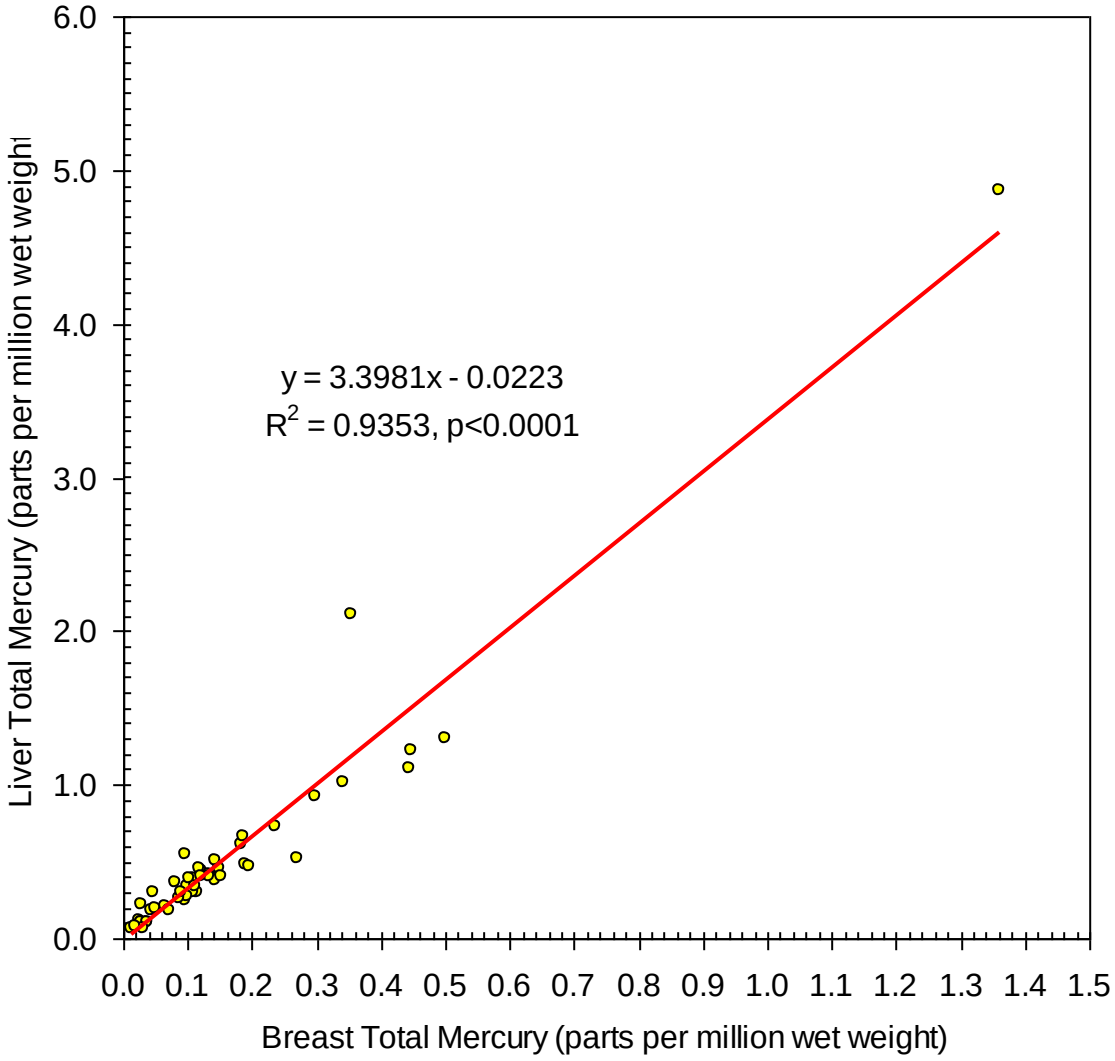

Figure 6. Correlation of total mercury concentrations in Cinnamon Teal breast muscle with liver tissue collected from the same bird at Great Salt Lake, Utah.

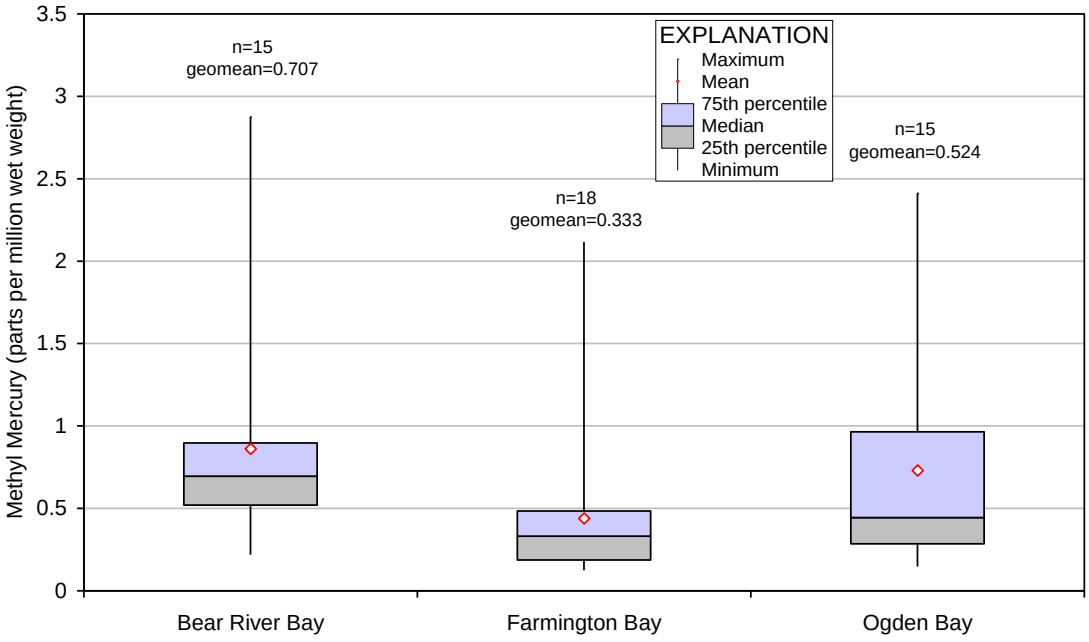

Figure 7. Simple box plots of methyl mercury concentrations in Northern Shoveler livers collected from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean.

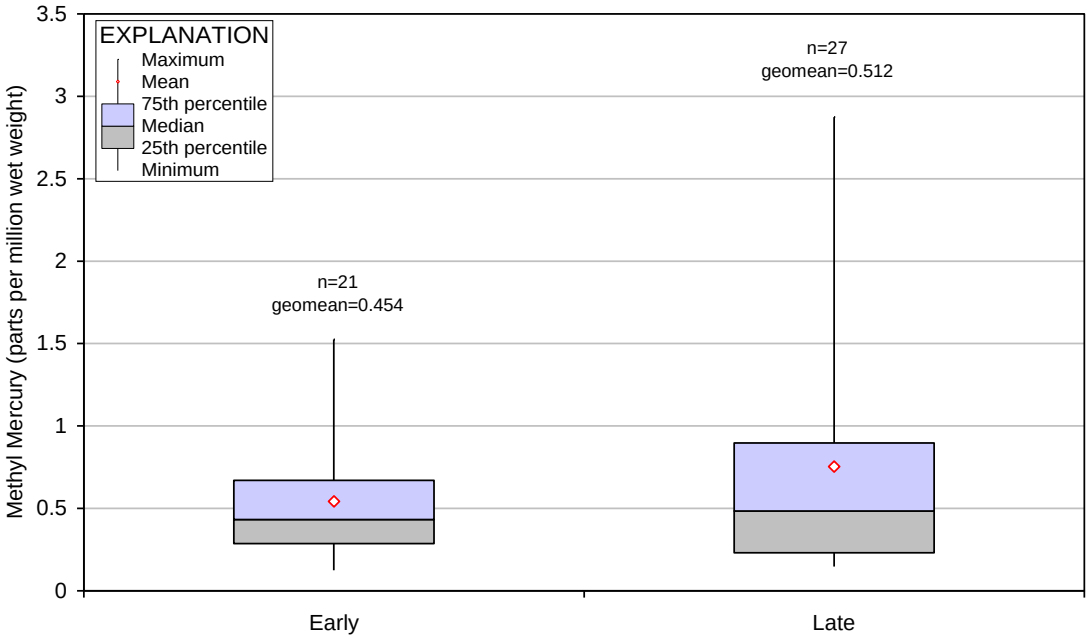

Figure 8. Simple box plots of methyl mercury concentrations in Northern Shoveler livers collected lakewide from mid-October to mid-November (early) and mid-November to the end of December (late), 2008. n = number of samples, geomean = geometric mean.

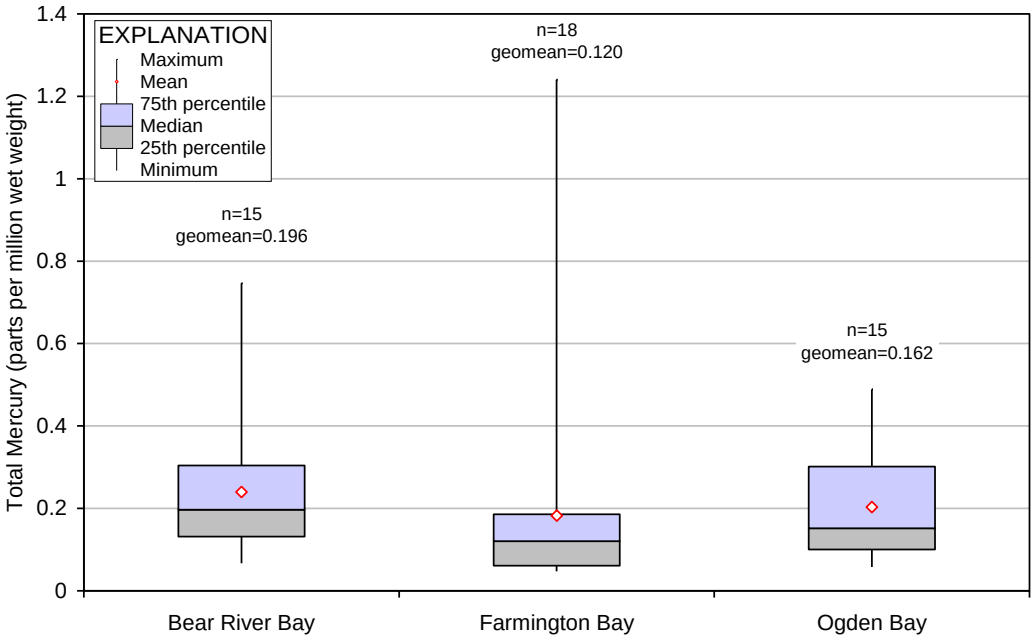

Figure 9. Simple box plots of total mercury concentrations in Northern Shoveler breast muscle tissue collected from three locations at Great Salt Lake, Utah. n = number of samples, geomean = geometric mean.

Chapter 4. Biostrome communities and mercury and selenium bioaccumulation in the Great Salt Lake (Utah, USA)

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Abstract

The main basin of the Great Salt Lake has a salinity near 15% and is critical habitat for over 200 species of migratory birds. The diet of many of these birds is dependent on the food web of carbonaceous biostromes (stromatolites) that grow profusely at depths <4 m and cover approximately 260 km^2 of the lake's littoral zone. These reef-like structures are nearly the only solid substrate in the lake and they are consequently the dominant area where periphyton and benthic invertebrates grow. We investigated this community at three sites in the lake to understand its importance for production processes that support the bird assemblage and to assess whether they are an important vector for bioconcentration of the high mercury levels that have been documented in the lake. The periphyton community growing on (and building) the biostromes was >99% colonial cyanobacteria (*Aphanothece* sp.). Periphyton chlorophyll levels averaged 900 mg m^{-2} or about nine times that of the lake's phytoplankton. Lake-wide estimates of chlorophyll suggest that production on the biostromes rivals that of the phytoplankton. Biostromes are the principal habitat for brine fly (*Ephydra gracilis*) larvae that are fed upon by many birds utilizing the lake. Using a pumped-bucket sampler, brine fly larval densities on the biostromes were found

to increase from 7000 m^{-2} in June to 20,000 m^{-2} in December. Pupation and adult emergence halted in October and larvae of various instars overwintered. Most larvae grew into 3rd instars before emergence began in the spring. Mean total dissolved and dissolved methyl mercury concentrations in water over the biostromes were 5.0 and 1.2 ηg L^{-1}. Total mercury concentrations in the periphyton, fly larvae, pupae, and adults were, respectively, 152, 189, 379 and 659 ηg g^{-1}dry weight, suggesting that bioconcentration is only moderate in the short food web and through fly developmental stages. However, Common Goldeneye ducks (*Bucephala clangula*) that feed primarily on brine fly larvae at the Great Salt Lake had concentrations near 8000 ηg Hg g^{-1} dry weight in muscle tissue and 50800 ηg g dry $weight^{-1}$ in their livers (J. Vest et al. 2008). Selenium concentrations in periphyton, brine fly larvae and Goldeneye liver tissue were high (1700, 1200 and 24000 ηg g^{-1}, respectively) and Hg:Se molar ratios were <1.0 in all tissues tested, suggesting that the high concentration of mercury in the ducks may be detoxified by combining with selenium. Measurements of methyl mercury in waterfowl tissue are needed to confirm this finding.

Introduction

The Great Salt Lake, the largest saline lake in North America, is extremely important for migrant birds that forage in its productive waters and along its margins (Aldrich and Paul, 2002). Salinities above 12% in most parts of the lake exclude predacious fish, so that the invertebrates produced in the system can be

channeled to the birds. The lake's pelagic zone produces abundant brine shrimp (*Artemia franciscana*; hereafter *Artemia*) but the only other abundant macroinvertebrate in the lake tolerant of high salinity is the brine fly (*Ephydra gracilis*; formerly *E. cinerea*). The brine fly larvae feed primarily on periphyton growing on, and forming the abundant biostromes covering much of the shallow littoral area of the lake (Eardley, 1938); (Collins, 1980). Although considerable work has been done on the lake's pelagic food web composed of phytoplankton and *Artemia* (e.g. (Stephens and Birdsey, 2002; Wurtsbaugh, 1992; Wurtsbaugh and Gliwicz, 2001), very little is known about the benthic food web in the lake. In the better-studied food webs of saline Mono Lake and Aber Lake the ecology of brine flies and biostromes are better understood (Herbst, 1988; Herbst, 1990; Herbst and Bradley, 1993), and the brine flies (*E. hians*) in those locations are important prey for several bird species.

Biostromes have had an important influence on the geological history of the earth and modern biostrome communities elsewhere are being studied to help understand both geological processes and modern food web dynamics (e.g. Dinger et al., 2006; Dupraz and Visscher, 2005; Elser et al., 2005; Vasconcelos et al., 2006) studied the population ecology of brine flies associated with biostromes in the Great Salt Lake during the summer, but provided little information on the biostromes themselves, nor about the seasonality of the brine flies. Wurtsbaugh (2009) recently provided some preliminary information on the biostrome food web. However, the ecology of these structures is poorly

understood, not only in the Great Salt Lake, but elsewhere. The biostromes food web in the Great Salt Lake is particularly important because it provides abundant brine flies that help fuel the enormous migratory bird populations utilizing the lake (Wurtsbaugh, 2009).

The biostrome food web is important not only as a food resource, but because it may also contribute to high mercury levels observed in some bird species that utilize the lake. The Great Salt Lake was recently found to have some of the highest mercury levels documented in the United States (Naftz et al., 2008), and in 2005 the State of Utah placed three waterfowl species on a consumption advisory list because of their high mercury levels (Scholl and Ball, 2005). The species with the highest mercury concentration, the Common Goldeneye duck (*Bucephala clangula*), has a diet consisting of 70% brine fly larvae when it is at the lake (Vest et al., 2008; J. Vest, personal communication). Formation of toxic methyl mercury usually occurs in benthic environments (King et al., 2000) and thus could potentially be associated with the biostromes. Additionally, methylation is strongly associated with sulfate-reducing bacteria in anoxic zones and sulfate levels are extremely high in the Great Salt Lake, thus facilitating methylation (Brandt et al., 2001). However, the expected high primary production by periphyton on biostromes would provide an oxic environment, at least during the day, so strong methylation in this environment would not be expected. Because of the high mercury levels in Common Goldeneye, and the

unique ecology of biostromes, we were consequently interested in understanding the bioconcentration of mercury in the biostrome food web.

The Great Salt Lake and its biota also have high concentrations of selenium (Conover and Vest, 2009a; Conover and Vest, 2009b; Oliver et al., 2009; Vest et al., 2008; Wurtsbaugh, 2009). Because selenium can counteract the toxic effects of mercury (Khan and Wang, 2009) a final objective of our study was to relate the mercury and selenium levels in the biostrome communities to determine if there might be some antagonistic interactions between the two contaminants.

Methods

Study sites

The Great Salt Lake (Fig. 1) is a 5200 km^2 closed-basin system in Utah, USA (41.04 N, 112.28 W) bordered on its eastern and southeastern shores by the Salt Lake City metropolitan area. The lake has been impacted by industrial and municipal discharges, as well as by transportation causeways that divide the system into four large bays. Gunnison Bay (2520 km^2), located in the northwest of the lake, has salt concentrations over 27%. The biostromes in Gunnison Bay are nearly unstudied. Preliminary observations indicate that they do not have any periphyton associated with them, but there are pink and bright-green microorganisms in different layers, probably representing Archaea and sulfur-reducing microbes. Farmington Bay (260 km^2) in the SE, and Bear River Bay in

the NE are both shallow with mean depths < 1 m and highly variable salinities. We studied Gilbert Bay (2400 km^2), in the central portion of the lake. This bay is separated from Gunnison Bay by a railway causeway. Gilbert Bay typically has surface salinities ranging between 11% and 18%, but salinities have ranged from 6% to 27% over the past 160 years (USGS, 2010. http://ut.water.usgs.gov/greatsaltlake/ Accessed Nov. 2010). Gilbert Bay supports a large population of *Artemia*. The lake elevation during the study was 1278.6 m (USGS, 2010. http://ut.water.usgs.gov/greatsaltlake/ Accessed Nov. 2010). At this elevation, the respective mean and maximum depths of Gilbert Bay are 4.9 and 9.4 m (Baskin, 2005). The bay is meromictic due to flow of saturated brines from Gunnison Bay through culverts in the railway causeway into the deeper strata of Gilbert Bay (Loving et al., 2002) creating a deep-brine layer (monimolimnion) below approximately 6.7 m. The upper 6.7 m of Gilbert Bay is well-mixed and oxic. The deep-brine layer is anoxic with substantial hydrogen sulfide, and consequently has no macroinvertebrates. Gilbert Bay has high nutrient levels and is mesotrophic (Stephens and Gillespie, 1976); (Wurtsbaugh, 1988). With the exception of meromixis due to the railway causeway, Gilbert Bay is the most natural remaining part of the Great Salt Lake with populations of brine shrimp, brine flies and actively growing biostromes. Biostromes occur along the perimeter of much of the Great Salt Lake (Fig. 1), and at the water surface elevation at the time of the study, occurred at depths from 0 to approximately 3.9 m where there was sufficient light for photosynthesis. Eardley (1938) provided a detailed map of the benthic structure of the Great Salt

Lake, although no methods were provided on how this information was collected. The deep brine layer now underlies approximately 44% of Gilbert Bay. In the remaining sediments covered by the oxygenated mixed layer biostromes, oolitic sand and mud represent 23%, 62%, and 15% of the substrate, respectively (Table 1). Recent work suggests that biostromes may be more extensive than what Eardly suggested (R. Baskin, personal communication). Some of these are laminated and thus can be considered stromatolites, but the composition of few of them has been documented, so we use the more general term "biostrome" here. In Gilbert Bay we have encountered nearly pure cultures of *Aphanothece* sp. in the biostromes. (Halley, 1976) also described the biostromes as being composed of coccoid cyanobacteria characteristic of *Aphanothece* sp. when the salinity was ca. 16%, and (Carozzi, 1962) described them as being formed by *A. packardii* when the salinity was near 27%. Collins (1980), however, reported primarily diatoms on the biostromes when the lake had a salinity of 13%. The small 1.4-µm diameter *Aphanothece* cells are embedded in a mucilaginous matrix that is partially calcified. The growing cyanobacteria and likely other microbes change the chemistry of the water, causing carbonates to precipitate and the biostromes to grow (Dupraz and Visscher, 2005). The brine fly *Ephydra gracilis* is the dominant invertebrate on the biostromes, but *Ephydra hians* have also been reported in the lake.

Samples were collected at three locations in 2008 during five periods: 30 May–3 June (hereafter called the June samples); 16–18 July; 2–7 Sept; 20–22 Oct, and;

1–4 Dec. At each location we collected on shallow (0.9-1.6 m) and deep (2.1-3.9 m) biostromes, that were within 1-km of each other. Station 1 was in the SE part of Gilbert Bay (40.805° N, -112.185° W) 5 km north of a large mine (Kennecott Utah Copper) discharge canal and 3 km west of the Goggin Drain that discharges some Jordan River water into Gilbert Bay. Biostromes in the shallow stations here were dome-shaped, approximately 1-m in diameter and 0.2-0.3 m high, but they often grew together forming irregular fields 10-100 m across. Some of the biostromes at the deep location were columns approximately 0.5–m in diameter and 0.7–1.5 m tall. Station 2 (41.145° N, -112.335° W) was adjacent to the SW margin of Fremont Island and biostromes here were similar in configuration to the domed types at Station 1. Station 2 is close to the discharge from polluted Farmington Bay that receives treated sewage and industrial influents from Salt Lake City and Davis County (Fig. 1). Station 2 is also near the inflow of the lake's primary river via Bear River Bay. Station 3 (40.925° N, -112.495° W) was on the NE side of Stansbury Island, more than 28 km from any of the major freshwater inflows. It is the closest site to the US Magnesium Corporation of America atmospheric emissions, 20 km to the west. The biostromes here formed a continuous hard plate, perhaps 0.4 thick, except at parts of the deep collection sites where there were some interspersed areas of sand below them. Halley (1976) and Pedone and Folk (1996) provide additional description of macro- and micro-structure of the biostromes in the Great Salt Lake.

Water, biostrome collections, chlorophyll and organic matter

Duplicate dissolved mercury samples were first collected at the deep site at each station to avoid disturbing the sediments. A SCUBA diver collected water from 2-5 cm above the sediment surface using pre-cleaned Teflon tubing which was pumped to the surface using a peristaltic pump and a pre-cleaned (Olson and DeWild) quartz-fiber filter cartridge. The whole system was flushed with site-specific water at each location. Water was then pumped directly into double bagged, pre-cleaned Teflon® containers and the samples were fixed with Omnitrace® HCL. Replicates were taken at least 5 m apart from each other.

Profiles of water temperature were collected at each site with a YSI Model 85 sensor (Yellow Springs Instruments). There was little stratification and here we report values measured at 0.2 m. Air temperatures were derived from a station at the Salt lake City International Airport located near the SE margin of Farmington Bay. Secchi depth transparencies were measured with a 20-cm black and white disk. Salinities of surface water were measured with a refractometer.

At each station duplicate samples for organic matter, chlorophyll, and total mercury content of live biostromes were collected by SCUBA divers who pried off pieces with a rinsed stainless steel abalone iron. These portions were carefully harvested to prevent turbulent loss of organic matter and care was taken to

sample through the total thickness of the organic surface layer. Samples were sealed in zip-loc bags underwater and immediately placed on ice at the surface.

In the laboratory, biostrome portions were split four ways and the two-dimensional surface areas were determined by photographing each piece along with a ruler and utilizing a computer program to calculate the area. A chlorophyll *a* subsample was frozen and subsequently placed in 30 ml of 95% ethanol, and extracted in the dark for at least 24 hours. The chlorophyll solution was then diluted with ethanol and concentrations measured in a Turner 10_AU fluorometer with the non-acidification method (Welshmeyer 1994). Blanks and standards were analyzed at the beginning of each run. In the second sample, organic matter as ash free dry mass (AFDM) was determined by oven drying a subsample at 70°C to constant weight, and then ashing it at 450°C for 4-5 hours and reweighing. For mercury analysis of the organic material in the biostromes a third subsample from each deep (3m) site was treated with 1 N Omnitrace® HCl to remove carbonates. This required several hours and the replacement of the acid until all bubbling of CO_2 stopped. Although this treatment should have removed all carbonates, non-carbonate inorganic materials may have remained. The acid-treated fraction was then stored in acid-cleaned polyethylene vials for subsequent total mercury analysis. The total mercury of the whole biostrome was determined from the fourth subsample obtained from the deep sites. This biostrome was rinsed with de-ionized water and frozen. On one occasion we subsampled carbonate material several centimeters below the growth zone of the

cyanobacteria so that the mercury content of the carbonate alone could be measured.

Brine fly collection and analyses

Duplicate larval and pupal brine fly samples were collected at each depth at all sites. The larvae and pupae were sampled on the biostromes by a SCUBA diver using a pump sampler similar to that of (Voshell et al., 1992). The 0.053 m^2 sampler consisted of an inverted high density polyethylene carboy with the bottom cut off (Wurtsbaugh and Horne, 1983). A port was cut in the side and a rubber glove attached to it so that a diver could agitate the substrate within the sampler. A flexible foam strip on the bottom of the carboy helped seal it against the irregular surfaces of the biostromes. Two, 2.3 kg lead weights were attached to the lower part of the bucket to increase stability and to keep the unit on the substrate. To function effectively, the sampler had to be placed on a relatively level substrate. This precluded sampling on the sides of the columnar–shaped biostromes at the deep location of Station 1. Once the sampler was positioned, the diver jerked the attached pump hose so that the operators in the boat could begin bringing water to the surface with a hand-powered bilge pump (Guzzler Model Vacuum Pump, U.S. Plastics Corp.). The diver then began scouring the substrate with a scrub brush. For each sample, 95 L of water was pumped directly through a 500–µm sieve on deck. This mesh may have allowed some 1st instar larvae to pass through. An analysis done by fitting an exponential decline model to brine fly larvae captured by filling five different sets of four successive

buckets indicated that a 95–L pumped sample captured 97% of the larvae. Brine fly samples were transferred into acid-cleaned 500 ml polyethylene jars, and stored on ice for transport. Brine flies from deep samples remained chilled and were enumerated within 48 h. The duplicate larvae and pupae subsamples (~150 mg) from the deep sites were then frozen for mercury analysis. Samples from the shallow site were fixed with 95% ethanol. These larvae were subsequently measured with a dissecting scope with an ocular micrometer so that length-frequency distributions could be constructed.

At each station a single sample of adult brine flies were collected with a sweep net on the shore nearest the shallow dive site. In the laboratory the flies were rinsed with freshly-deionized water to remove salts, frozen, dried at 70°C, and subsequently analyzed for total mercury content.

Mercury analyses

All mercury analyses were performed at the US Geological Survey Wisconsin District Mercury Research Laboratory in Middleton, Wisconsin. Total Hg (THg) in filtered-water samples was determined using cold vapor atomic fluorescence spectrometry (CVAFS) (Olson and DeWild). The methyl mercury (MeHg) in the water samples was determined using distillation/ethylation/gas-phase separation with CVAFS detection (DeWild et al., 2002). Primary standards for THg were obtained commercially and certified against a NIST standard reference material. No reference materials were available for MeHg. Standards for MeHg were

prepared in the laboratory. Known reference samples were analyzed at the beginning of each analytical run, after every 10 samples and at the end of each run. Method blanks were prepared by adding $SnCl_2$ to 125 ml of Hg-free water and purging for 20 min to ensure removal of any residual Hg. Method blanks were run periodically during each sample run and used to calculate the daily detection limit (DDL). The accepted value for the DDL is < 0.04 ηg L^{-1}. Matrix spikes were analyzed during each run or every 10 samples. Percent recovery of matrix spikes had to fall between 90% and 110% for the sample run to be accepted. Three field replicates and two process blanks were collected and analyzed for THg and MeHg. Field replicate results were in close agreement, with replicates ranging from 3.0% to 5.5% for THg and 2.7% to 15.9% of the routine sample value for MeHg. Process blanks had low THg (0.08 and 0.10 ηg L^{-1}) and MeHg (<0.04 ηg L^{-1}) concentrations.

The THg in biostrome and brine fly samples was extracted and analyzed according to the methods outlined in (Olund et al., 2004). Each sample was extracted by room-temperature acid digestion and oxidation with aqua regia. The samples were then brought up to volume with a 5% BrCl solution to ensure complete oxidation and then heated at 50°C in an oven overnight. Samples were then analyzed for THg with an automated flow injection system incorporating a cold vapor atomic fluorescence spectrometer. Solid standards from the National Research Council Canada were used (BEST-1 for sediments; TORT-2 or LUTS-1 brine flies). A method detection limit of 0.3 ηg of Hg per digestion bomb was

established using multiple analyses of a solid-phase environmental sample. All values are reported on a dry weight basis for the tissues and sediments.

Selenium analyses

Results from the mercury analyses were compared from similar collections made in 2006-2007 to measure selenium bioaccumulation in the Great Salt Lake biostrome food web (Wurtsbaugh, 2009). That study used nearly identical methods to those described above. However, samples were collected only at two stations: Station 1 (as for the Hg study), and a station on the NW end of Antelope Island (Fig. 1). Samples were collected in June and September, 2006, with a small additional set collected in April 2007. Immature brine flies were also collected on mud and sand substrates with a dredge, but few individuals were encountered. The tissue and water samples were analyzed for total selenium by hydride generation–atomic absorption spectrometry with acid-digested samples. The detection limits for selenium in the tissues and water were 0.1 and 0.05 μg Se g^{-1}, respectively.

Length-weight and Dry to wet weight conversions

A length-weight relationship for larvae was established by sorting out groups of similar-sized individuals ranging from 2.0 to 10.5 mm, drying them to constant weight and weighing. The length-weight relationship established was;

$$mg = 0.0318 * mm^{1.718} \qquad r^2 = 0.913$$

Mercury concentrations from our study were measured and expressed in units of dry weight, but because wet weights are commonly used for promulgating standards we used ratios of dry weight:wet weight to convert values. Periphyton was assumed to be 8% dry weight (Sladecek and Sladeckova, 1963). We analyzed dry:wet ratios from a single sample of brine fly larvae collected in October 2010 and obtained a mean of 28% ± 14% s.d., but with a range of 4-95%. Due to the lack of values for pupae and adults and the very high range, we instead used values from Herbst (1986) for larvae (14%) and adults (23%) of *E. hians* and assumed intermediate values for pupae (19%). The assumed dry:wet ratio for goldeneye duck breast and liver tissue was 25% (J. Vest, personal communication). This value was used to convert his mercury data measured in wet weight, to dry weight equivalents. Because of the high variability in determining wet weights of small invertebrates, the mercury values expressed in wet weight units are only approximate.

Statistical analyses

Statistical analyses were done in SYSTAT version 8.0 (SPSS, Inc.). Statistical outliers identified by SYSTAT were not used in the analyses. In most cases missing values or incomplete factorial designs (e.g. no pupae or adult brine flies during two sampling periods) precluded to repeated measure analyses of

variances, so some statistical power was lost, and significant differences are consequently conservative.

Results

Environmental conditions, chlorophyll levels and ash-free dry mass

Water temperatures in March were ca. 8°C, increased to 19°C by our first sampling in June, and rose to a maximum of 27°C in July (Fig. 2). By December water temperatures had cooled to near 7°C. Minimum air temperatures that would influence the survival of adult brine flies were exceptionally warm in the spring of 2008, but reached normal temperatures near 14°C by late May, and climbed to 21°C in July. By October nighttime temperatures declined to near zero and were negative by December. Secchi disk transparencies varied substantially with the wax and wane of *Artemia* grazers. In the early spring before brine shrimp were abundant transparencies were < 0.4 m. The transparency rose to 3.8 m in July and declined to 0.7 m in December when *Artemia* disappeared from the water column and phytoplankton bloomed (see Wurtsbaugh and Gliwicz (2001) for a description of plankton cycles). Salinities in Gilbert Bay were 14.5% during June when the lake was receiving maximum freshwater discharges during spring runoff. The salinity increased to 16.6% by October and declined to 16.1% when winter precipitation began.

Chlorophyll concentrations in the biostrome periphyton were high. Mean levels ± s.e. from September-December were 893 ± 48 mg m^{-2}. A 3-way analysis of variance (n = 36) indicated that there were no significant differences in

concentrations between stations (p = 0.91), sampling period (p = 0.39) and depth (p = 0.07). A comparison of chlorophyll in the periphyton and in the phytoplankton showed that the biostrome production is very important in the overall economy of the lake (Fig. 3). Although biostromes cover only 18% of the area covered by phytoplankton (Fig. 3A), the concentration of chlorophyll in them was eight times higher than the integrated concentration of phytoplankton chlorophyll (Fig. 3B). The product of the areas times the concentrations provides a measure of the total amount of chlorophyll in each of these compartments, and this calculation indicates that biostrome chlorophyll was somewhat more abundant than that of the phytoplankton (Fig. 3C).

The amount of organic material in the biostromes averaged 158 ± 6.1 mg cm^{-2}. A 3-way analysis of variance (n = 54) of samples collected from June-December indicated that there were no significant differences between stations (p = 0.13), sampling period (p = 0.79) and depth (p = 0.59). The mean composition of biostrome material for the September sample was 11% organic material, 84% carbonates and 5% inorganic residual left after the combustion and acidification steps.

Brine fly abundance and biomass

Brine flies were very abundant on the biostromes and they were the only benthic invertebrate encountered, other than occasional *Artemia that* more likely were in the water column and captured in our bucket sampler. Densities of brine fly

larvae were not significantly different at the different stations ($p = 0.58$), or at different depths ($p = 0.26$), but densities did vary seasonally ($p = 0.003$). Larvae were less abundant in the June and July samples, with mean densities between 8000 and 10000 m^{-2} (Fig. 4). By September samples densities had climbed to over 18000 m^{-2}, and they remained near those levels through early December. Variability was high, and individual sample densities ranged from 2500 to 59000 m^{-2}. Mean overall brine fly larval density during the study was 16300 m^{-2}.

Brine fly pupae were considerably less abundant than the larvae (Fig. 4). The pupae densities were not significantly different at different stations ($p = 0.49$) or depths ($p = 0.09$), but densities were significantly different seasonally ($p = 0.000$). Densities were highest in June and July, with means near 1500 m^{-2}. By September densities declined by half and by October and December pupae were negligible or absent. These very low densities coincided with nighttime minimum temperatures near 0°C or lower. Although we did not quantitatively sample adult flies at the shoreline, they were very abundant from June through September, but by October it was impossible to sample enough for mercury analyses.

Brine fly larval size distributions varied markedly over the sampling period (Fig. 5). Larvae were largest in June, with a single mode centered at 8 mm, and there were no larvae less than 4 mm. By July, however, a new cohort with small larval instars was most abundant, with new modes at 3 and 5 mm, but with a mode remaining at 8 mm. By September the smallest instars were rare, and the most

abundant size class was 4-5 mm long. In December the population was dominated by intermediate size classes.

Brine fly biomass on the biostromes was estimated utilizing the densities, size structure and the length-weight relationship we established. The mean dry weight of the June group of large larvae was 1.4 mg, but the mixed cohorts latter in the year had mean weights near 0.7-0.8 mg (Fig. 6). Although larval densities were low in June, the high mean weight resulted in a high biomass near 13 g dry weight m^{-2}. Biomass declined in July, then increased latter in the fall with increases in the densities of larvae. Mean larval biomass on the biostromes from June-December was 14.0 g dry weight m^{-2}.

Mercury concentrations

Dissolved mercury concentrations over the biostromes in the Great Salt Lake were moderately high (Fig. 7). Total dissolved mercury averaged 5.0 ηg L^{-1} (25 pM) and methyl mercury constituted 25% of the total (1.2 ηg L^{-1}; 6.0 pM). Dissolved mercury concentrations at the different stations were not significantly different ($p = 0.252$), but those from different sampling periods were ($p < 0.000$). In July total (2.6 ηg L^{-1}) and methyl mercury (0.65 ηg L^{-1}) were significantly lower ($p < 0.044$; Bonforroni-adjusted pair wise comparison) than during the other sampling periods.

Mercury concentrations varied substantially between the fractions of the biostromes analyzed. A 3-way ANOVA followed by a post-hoc Bonforroni comparison test indicated that the mercury content in carbonates, intact biostromes, and the acid-treated periphyton material were all significantly different ($p < 0.000$), with respective mean concentrations of 22, 69 and 152 ηg g^{-1} dry weight. Estimated periphyton concentrations based on the assumed dry:wet ratio was 12 ηg g^{-1} wet weight. Because we assumed that brine fly larvae fed only on the periphyton, we did a separate 2-way ANOVA on this food component to determine if there were significant spatial or temporal differences. Periphyton at Station 2 (Fremont Island) had significantly higher mercury levels than the other two stations (Fig. 8; $p <0.000$), with a mean concentration of 222 ηg g dry $weight^{-1}$. Total mercury concentrations of the periphyton in July (65 ηg L^{-1}) were also significantly lower than the other months ($p < 0.032$; June data was not available, however).

Mercury concentrations in the brine flies increased progressively through different growth stages. A paired t-test of small (4.6 ± 1.5 mm s.d.) and large brine fly larvae (8.5 ± 1.6 mm s.d.) indicated that the large larvae had significantly ($p = 0.02$) higher concentrations (208 ηg g^{-1} dry weight) than the small larvae (179 ηg g^{-1}). Overall mean mercury concentrations during the study based on dry weights were 189 ηg g^{-1} in the larvae, 379 ηg g^{-1} in the pupae, and 659 ηg g^{-1} in the brine fly adults. Respective estimates based on wet weights were 26, 72 and 152 ηg g^{-1}. A 2-way analysis of mercury concentrations in the three brine fly

life stages followed by post-hoc tests indicated that these differences were all significant ($p < 0.002$). There was also a significant difference among stations ($p = 0.030$). In contrast to the periphyton data, mercury concentrations in the brine flies were significantly higher at Station 3 (Stansbury Island) than at the other two stations that did not differ from each other. Values for all of the analyzed mercury samples are given in Appendices 1-4.

Discussion

Ecological importance of biostromes

Although stromatolites and other biostromes have been studied extensively from a geological perspective with regards to the earth's evolutionary changes (Grotzinger and Knoll, 1999), their importance in modern systems is only beginning to be appreciated (e.g. Elser et al. (2006); Paerl et al. (2001); Dinger et al. (2006); Vasconcelos et al. (2006)). Our study demonstrated that the widespread biostromes in the Great Salt Lake contribute significantly to the biological productivity and are important in delivering high levels of mercury in the lake into higher trophic levels.

Although primary production has not been measured on the lake's biostromes, their high chlorophyll levels and large areal extent suggest that their productivity could rival that of phytoplankton in the water column. Even though benthic productivity in lakes has not been studied as extensively as that in the pelagic

zone, it can often contribute more than 50% of overall productivity, especially in shallow systems (Vadeboncoeur et al., 2008) such as the Great Salt Lake. Water transparencies in the Great Salt Lake during the summer growing period are usually 2-4 m (Wurtsbaugh and Gliwicz, 2001); Fig. 2), thus allowing sufficient light for photosynthesis to depths of 4-8 m (2 to 3 Secchi depths; (Kalff, 2001)). When *Artemia* disappear from the water column in winter, grazing is greatly reduced, and phytoplankton proliferates. Water transparencies then decrease to <0.5 m (Wurtsbaugh and Gliwicz, 2001), which would reduce the active growth of biostromes to a depth of 1–1.5 m. The periphyton in the biostromes are thus dependent on active grazing by *Artemia* to allow sufficient light to reach a sufficient part of the lake bottom. The lower depth limit of biostromes (ca. 3.9 m in during our study) might be limited by light penetration, but the availability of carbonate-rich groundwater inflows could also be a contributing factor (Lopez-Garcia et al., 2005; Moore and Burne, 1994). The total depth of the Great Salt Lake varies appreciably with climatic cycles (6 m over the last 140 years), so that the depths where we encountered biostromes are not necessarily reflective of the water depths at which they grew most actively.

The actively growing biostromes in the Great Salt Lake that have an abundant population of grazing invertebrates is interesting from a paleoecological perspective because it has been argued that the profuse biostromes formed during the Precambrian period 500 millions years ago did so because metazoan grazers were absent. The biomass of grazing brine fly larvae on the biostromes

in the Great Salt Lake is among the highest reported for benthic invertebrates in lakes (LeCren and Lowe-McConnel, 1980), yet the biostromes were healthy. This suggests that an absence of grazers is not critical for the maintenance of biostromes, as has been suggested by others (Grotzinger, 1990; Moore and Burne, 1994; Pratt, 1982).

Brine fly population ecology

Brine fly densities and biomass (14 g m^{-2}) on biostromes in the Great Salt Lake, and the overall biomass rivals that of *Artemia* in the water column. In the mercury study we only measured brine flies on the biostromes, because a limited study by (Wurtsbaugh, 2009) reported low densities on both sand and mud substrates. Collins (1980) also found low brine fly pupal densities on sand, but nearly equivalent densities on biostromes and mud substrates, but he did not count larvae on different substrates. Extrapolating our mean brine fly larval densities to biostromes throughout the entire lake yields an estimate of 38 tons of flies (dry weight). If Collins' estimate for brine flies on mud is scaled to the entire lake and added to the biostrome value, we estimate that approximately 62 tons of brine fly larvae are present in the Great Salt Lake. This is 84% of the biomass of *Artemia* in the lake based on calculations by (Wurtsbaugh, 1992). These estimates are based on only single years of data for both species, and on poorly-documented areas of the different substrates (Collins, 1980; Eardley, 1938), but the calculation nevertheless suggests near parity in the biomass contribution of these two species of invertebrates in the ecosystem.

The annual life cycle of *Ephydra gracilis* appears to be similar to that of the better-studied alkali fly *Ephydra hians* (Herbst, 1988). The length-frequency distributions of brine flies in the Great Salt Lake suggest that there are several cohorts present throughout the year. Pupation and reproduction by adults largely ceased by October when air and water temperatures fell. Herbst (1988) found that pupae could not survive at temperatures of 5°C, and it seems unlikely that adults could thrive when air temperatures drop below zero. The larval population on the biostromes entered the winter with a diverse size structure (Fig. 5), but in the late spring most of the larvae were large and likely third instars. This suggests that there was slow growth over the winter and more likely in the early spring, with the majority of individuals reaching the third instar by spring, pupating, and starting a new generation. However, the size-frequency distribution in July showed that there were multiple instars present, so clearly reproduction in the spring was not synchronous. Herbst (1988) found a similar situation for the alkali flies in Mono Lake. Collins (1980) suggested that brine flies grow from egg to pupae in 3-4 weeks and spend 2-3 weeks as pupae, and this is similar to growth rates found by Herbst for the alkali fly. This suggests that there could be up to three generations from May–September in the Great Salt Lake. The increasing number of larvae on the biostromes from June through October supports this hypothesis. Unfortunately, we did not sample early in the spring, and our six-week sampling interval was inadequate to clearly resolve detailed population cycles. Consequently, additional year-around analyses will be necessary to better understand the life cycle of the Great Salt Lake brine flies.

Mercury in the biostrome food web

Mercury concentrations measured in the water and in the biostrome biota were moderately high (Fig. 7, 8). The total mean mercury concentration in the water (5 ηg L^{-1}) was below the US EPA aquatic life standards of 12 ηg L^{-1} for fresh waters and 25 ηg L^{-1} for salt water (Administration, 2010), but the mean methyl mercury level of 1.2 ηg L^{-1} was four times the uncontaminated worldwide baseline of 0.3 ηg L^{-1} (Gray and Hines, 2009). Mercury concentrations in brine flies were relatively similar to those of *Artemia* in the lake. Mean concentrations of THg in *Artemia* measured during a parallel study in 2008 (Utah Division of Wildlife Resources, unpublished data) were 59 ηg g^{-1} wet weight, approximately double that estimated for brine fly larvae (26 ηg g^{-1} wet weight) and somewhat lower than concentrations in brine fly pupae (70 ηg g^{-1} wet weight) or adults (152 ηg g^{-1} wet weight). Mean total mercury concentrations in the larvae were only 25% of the lowest observed adverse effect limit (100 ηg g^{-1} MeHg) for prey of birds proposed by (Chan et al., 2003). Large brine fly larvae that are more likely to be eaten by birds had somewhat higher concentrations, but were still below the suggested dietary threshold, even if all of the mercury in them is assumed to be MeHg (see below). Pupae do not appear to be a major dietary item of birds at the Great Salt Lake, but adult flies, with the highest concentration of total mercury 152 ηg g^{-1} wet weight, are commonly eaten by many birds (see below) and do exceed the suggested bird threshold if the mercury in them is primarily methylated.

The reason for the progressively increasing concentration of mercury in the different stages of brine fly is most likely due to lipid loss in the pupae and adults. In a related species (*Ephydra hians*) caloric content decreased from 12.4 to 11.2 to 7.2 calories per individual in larvae, pupae and adults, respectively (Herbst, 1986). This is likely due to metabolism of calorie-rich lipids by the older stages, with an associated concentration of mercury in the remaining tissue.

The significantly higher concentrations of mercury in brine flies collected at Stansbury Island (Station 1) were not expected. (Naftz et al., 2009) found that 50% of the fluvial input of mercury to Gilbert Bay entered on the east side of the lake from Farmington Bay, and Sorensen et al. (1988) found mercury concentrations as high as 1500 ηg g^{-1} in the sediments at the south end of Farmington Bay. We consequently expected high concentrations at the station closest to the Farmington Bay discharge to Gilbert Bay (Fremont Island), or at the SE end of Gilbert Bay near the mining discharge of Kennecott Copper Corporation. The higher concentrations we found in the brine flies at the Stansbury Island site are consistent, however, with higher levels of mercury found in water, brine shrimp and eared grebes (*Podiceps nigicollis; (Gray and Hines, 2009)*) at (or near) this site relative to sites on the east side of the lake (Conover and Vest, 2009a). Grebes in the Great Salt Lake eat *Artemia*, as well as brine fly larvae (Gafney 2008; Conover and Vest 2009b). The reason for the high concentration of mercury in the brine flies and grebes at the Stansbury site is unclear. One hypothesis is that brine fly larvae at this site, being more distant

from sources of nutrients, have slower growth rates, and consequently are able to concentrate more mercury than brine flies growing faster (i.e. “growth dilution”; (Pickhardt et al., 2002) in areas where nutrients enter Gilbert Bay (near Fremont Island and the southeast side of Gilbert Bay). Alternatively, there may be natural sources of mercury in this region. There was a discrepancy in our data in that the highest mercury concentrations in biostrome periphyton were found at Station 2 (Fremont Island), whereas the highest concentrations in the brine flies were at Station 3. A possible explanation for this is that our periphyton analyses were biased because that tissue included a small portion of inorganic material that was not removed by the acid treatment. Additional analyses of the spatial distribution of mercury in the biota around the Great Salt Lake are warranted, especially since many birds concentrate in Bear River and Farmington Bays where pollutant sources are potentially much higher.

Biomagnification of mercury and selenium in the Great Salt Lake food web

Although the diets of birds that forage in the Great Salt Lake have not been studied in detail, it is clear that different species utilize invertebrates from three different food webs: (1) the periphyton-brine web on the biostromes; (2) the pelagic food web leading to *Artemia*, and; (3) a playa-based food web with freshwater sheet flow and diverse freshwater invertebrates (Fig. 9). American avocets, eared grebes, and particularly goldeneye ducks rely heavily on larvae and adult brine flies. The biomagnification factors leading to goldeneye ducks were: water→periphyton, 30000; periphyton→brine fly larvae, 1.2;

larvae→goldeneye duck breast tissue, 43X or 269X for liver tissue (based on dry weight Hg concentrations). The high biomagnification of mercury from the water to periphyton was not unexpected (Pickhardt and Fisher, 2007). Additionally, it is likely that some of the mercury taken up by periphyton was derived from pelagic seston particles and *Artemia* fecal matter that settled onto the biostrome surfaces, decomposed on the benthic surface, and enriched the interstitial water of the biostrome, rather than by direct uptake from overlying water. The biomagnification from periphyton into brine fly larvae was quite small (1.2X), whereas the increase from the larvae into the goldeneye duck breast tissue was moderately high (43X). The increase from brine fly larvae to goldeneye liver tissue was very high (269X). The high THg in goldeneye livers (50800 ηg g^{-1} dry tissue) may be due to the fact that inorganic Hg can bind to proteins and selenium in the liver (Bridges and Zalups, 2005; Khan and Wang, 2009) but not in muscle tissue, thus resulting in elevated concentrations of non-toxic inorganic mercury in the liver of birds (Scheuhammer et al., 1998).

This process may be facilitated by the relative high selenium concentrations in the Great Salt Lake water and biota (Fig. 10). Selenium levels in the lake are relatively high as a result of selenacious soils in the region, mining activities that release some of the selenium, and the natural characteristic of the lake to concentrate salts. Selenium concentrations were far higher than the mercury levels in the same media: 397 ηg Se L^{-1} in the water, and 1200-1800 ηg Se g^{-1} dry weight in the periphyton and brine fly tissues (Fig. 10). Some have argued

that *molar* ratios of total Hg:Se that are less than 1 indicate that mercury is not present in toxic quantities (e.g. Berry and Ralston (2008). These ratios in the water, periphyton, brine flies and goldeneye duck livers from the Great Salt Lake are all less than 1.0 (Fig. 11). Selenium may also counteract the neurotoxicity of mercury and increase non-toxic mercury content in the brain (Whanger, 2001). Although the molar ratios of Hg:Se are suggestive that selenium may be counteracting mercury toxicity in the Great Salt Lake, analyses of MeHg in invertebrate and bird tissues are needed because all forms of selenium are not antagonistic to mercury toxicity (Yang et al., 2008).

High mercury levels in the Great Salt Lake

Although mercury levels in the water and biota of the Great Salt Lake are high, the source of the high levels is not understood. One possibility is that there is natural weathering of cinnabar deposits and concentration in an evaporative saline lake. The Oquirrh Mountains which abut the Great Salt Lake have known cinnabar deposits south of the lake. Although there isn't currently a surface water connection to this area, in prehistoric times Lake Bonneville reached this area and well beyond. High atmospheric deposition into the lake has been suggested as the source of the high mercury levels (Naftz et al., 2008; Naftz et al., 2009) as there are upwind atmospheric sources of Hg associated with gold processing facilities in north-eastern Nevada. Additionally, the concentrated Cl^- and Br^- halogens of the lake might facilitate atmospheric deposition to the lake surface (Mason and Gill, 2005). However, (Peterson and Gustin, 2008) found

relatively normal levels (4.4 μg m^{-2} yr^{-1}) of dry atmospheric Hg deposition to the lake so this possibility is still not resolved. Preliminary estimates of wet deposition are higher (5.5 μg m^{-2} yr^{-1} ; (Naftz et al., 2009) than those for dry deposition, and riverine input adds 1.7 μg m^{-2} yr^{-1}, for a total of 11.6 μg m^{-2} yr^{-1}, levels that are relatively high (EPA, 2007). Analysis of mercury concentrations in a single sediment core described by Naftz et al. (2009) shows a slightly decreasing trend in mercury concentrations and deposition rates from 1905 to 2006, although these trends were not significant ($p = 0.11$ for both). Nevertheless, it suggests that mercury contamination has not increased over the last century.

An alternative hypothesis for the high mercury levels in the lake is that mercury emissions and discharges related to the gold and silver mining over the past 150 years have left a legacy of contaminated sediments that continually mobilize mercury into the food web. Using gold and silver mining records (Ege, 2005) and an emission factor estimate of 0.75 kg Hg kg^{-1} Au or Ag (Lacerda and Salomons, 1998), 20 million kg of mercury would have been utilized for gold and silver processing in Utah during the last 150 years. If this amount is annualized and theoretically spread over the entire State of Utah, the legacy mining deposition would be 60 times higher than the current atmospheric deposition rates. Nearly all of this mining activity (and presumably mercury releases) have been within 75 km of the Great Salt Lake, and 70% are in the Oquirrh Mountains on the southern edge of the lake, so it is possible that annualized legacy deposition and

runoff to the lake has been 2-3 orders of magnitude higher than the current atmospheric deposition. Consequently, it is likely that large amounts of mercury have entered the lake in previous decades. Additional coring analyses (D. Naftz, personal communication; W. Wurtsbaugh) and atmospheric deposition studies (D. Naftz) are underway that may help resolve the competing hypotheses for the current high mercury levels in the lake.

Whatever the source of the mercury, there are several mechanisms that facilitate its retention and methylation so that large amounts concentrate in the biota. Causeway construction separating Gilbert Bay from the more saline Gunnison Bay allows a deep brine layer (monimolimnion) to form below 6.7 m in Gilbert Bay, and the organic matter from the productive lake decomposes in this layer making it anoxic with reducing conditions. Although the Great Salt Lake is primarily a sodium chloride system like the sea, 7% of its salt is sulfate, and consequently sulfate reduction is extremely high in the monimolimnion and in anoxic sediments (Brandt et al., 2001) around the rest of the lake. Since mercury methylation is often coupled to sulfate reduction (King et al., 2000) the high methyl mercury concentrations, especially in the monimolimnion (10-40 ng L-1Naftz et al., 2008), are understandable. The lake also has exceedingly high concentrations of dissolved organic matter (DOM>40 mg C L-1; Leenheer et al., 2004), and this helps maintain mercury in solution, as well as affecting the production and bioaccumulation of MeHg (Ravichandran, 2004). Photolytic degradation of methyl mercury to non-toxic forms is also enhanced by humic

DOM and inhibited by chlorides (Zhang and Hsu-Kim, 2010). However, because both chlorides and DOM and are very high in the Great Salt Lake, and because the DOM is highly bleached (Aiken and Wurtsbaugh, unpublished data), it is difficult to predict how these competing ligands would interact to influence demethylation, Detailed work will be necessary to unravel the complex chemistry and biotic interactions in this unusual lake.

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Table 1. Morphometric characteristics of Gilbert Bay of Great Salt Lake at a lake elevation of 1280.2 m (4200 ft), which is near the mean historical elevation. The data exclude areas of the southern salt ponds and Farmington Bay. Gilbert Bay's area is derived from Baskin (2005). The areas of biostromes, oolitic sand and mud were derived from the proportional areas shown in the map of Collins (1980), with an adjustment to a lake level of 1280.2 m. At that lake elevation the lake's mean depth is 5.55 m.

Region	Area of Sediments (km^2)	Volume ($m^3 \times 10^9$)
Gilbert Bay (total)	2057	11.42
Biostromes	261	
Oolitic sand	712	
Mud	172	

Figures

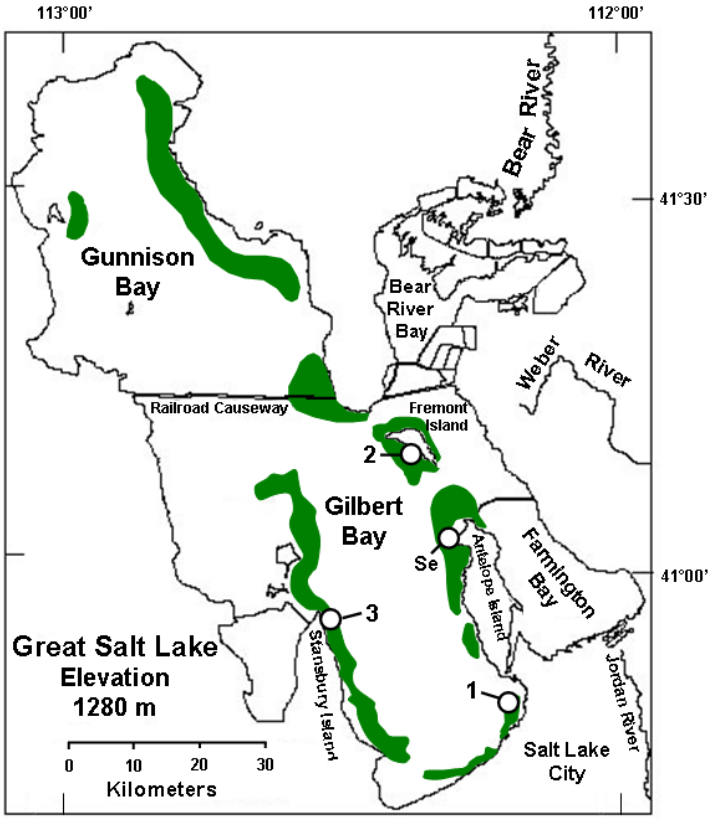

Fig. 1. Sampling stations in Gilbert Bay, Great Salt Lake, and the approximate distribution of biostromes (after Collins, 1980; Eardley, 1938). Stations used for mercury sampling were: Sta. 1 – SE Gilbert Bay; Sta. 2 – Fremont Island; Sta. 3 – Stansbury Island. Biostromes at Station 1 were also sampled in 2007 for selenium (Se), as was a station at the northern tip of Antelope Island (Se). Dark shading indicates areas of biostromes.

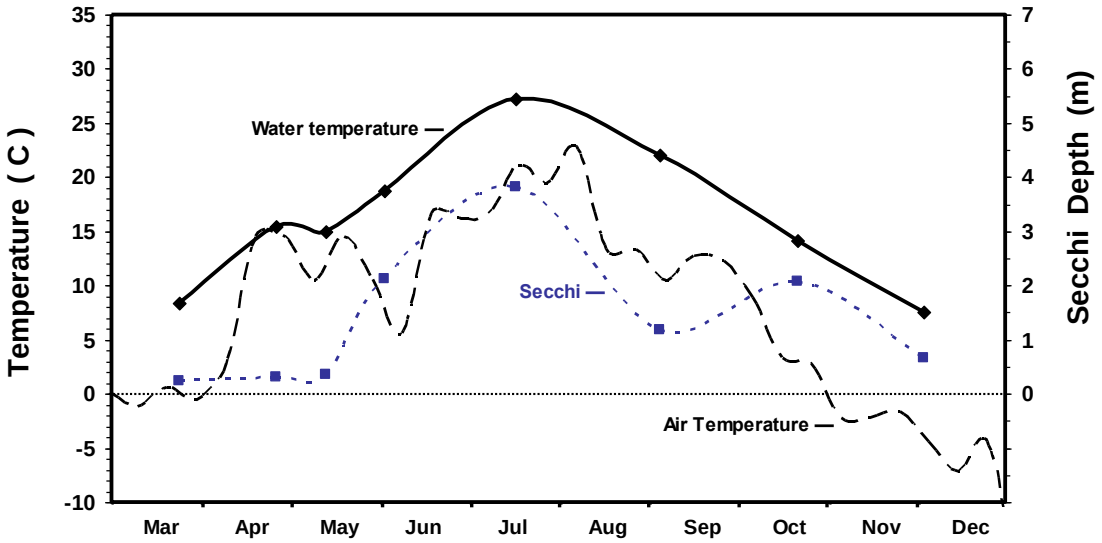

Fig. 2. Minimum nightly air temperatures, and mean water temperature and Secchi depth transparencies in Gilbert Bay, Great Salt Lake, in 2008. Data for March-May were taken by the Utah Division of Wildlife Resources at a mid-lake station.

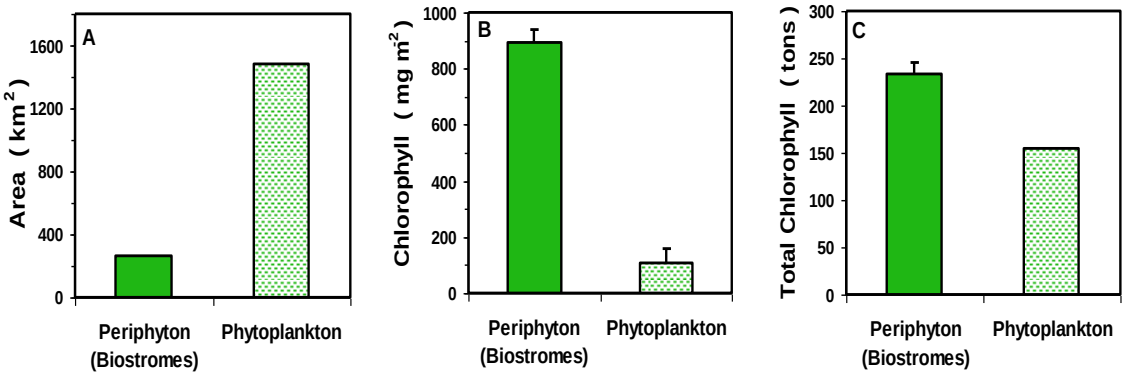

Fig. 3. Comparison of the relative abundance of chlorophyll in the periphyton on biostromes and in the phytoplankton of Gilbert Bay (Great Salt Lake). A. Lake area occupied by biostrome periphyton and that of the phytoplankton. B. Chlorophyll levels on the biostromes and the integrated phytoplankton chlorophyll (0–6.7 m). C. Total chlorophyll (tons) in the Great Salt Lake in the biostromes and phytoplankton. The amount of phytoplankton chlorophyll in Gilbert Bay was based on unpublished values of W.A. Wurtsbaugh collected from 2002-2009 (n = 234; mean 16 mg m^{-3}), and an estimated mixed-layer volume of 9.7 10^9 m^3.

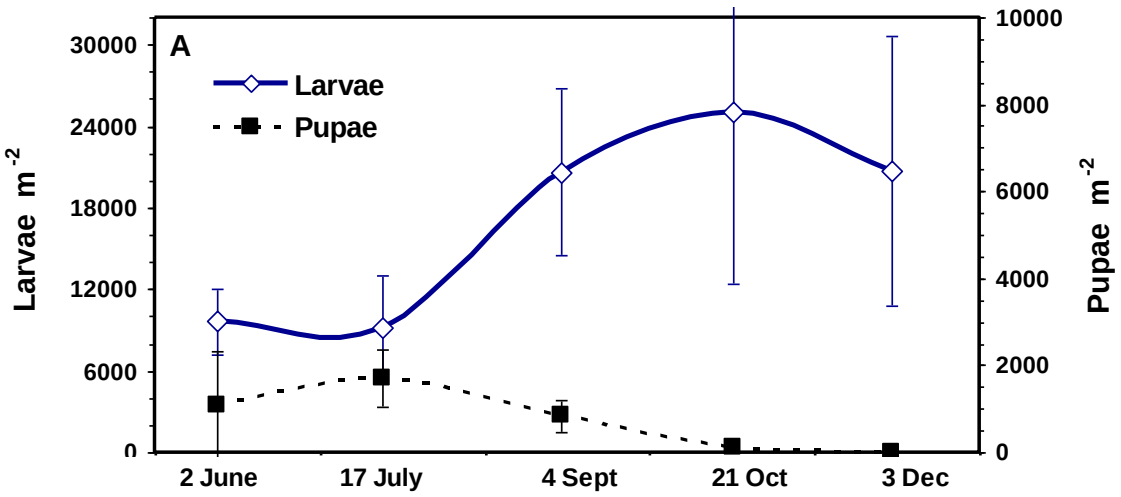

Fig. 4. Mean ± s.e. of brine fly larvae and pupae (right axis) densities at the three biostrome study sites in 2008. Sample dates shown are the median dates of a sampling interval which lasted 2-4 days. Note different scales used for the larvae and pupae.

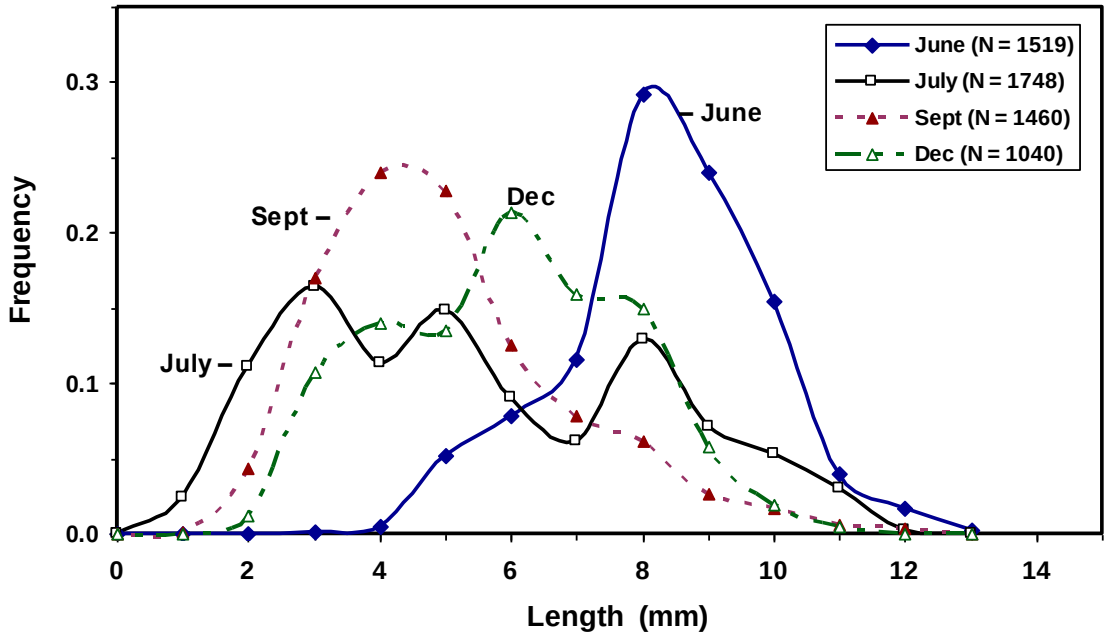

Fig. 5. Size-frequency polygons of larval brine flies on biostromes in the Great Salt Lake during four periods in 2008. The midpoints of the sampling intervals were: 2 June; 17 July; 4 Sept; 21 Oct; 3 Dec.

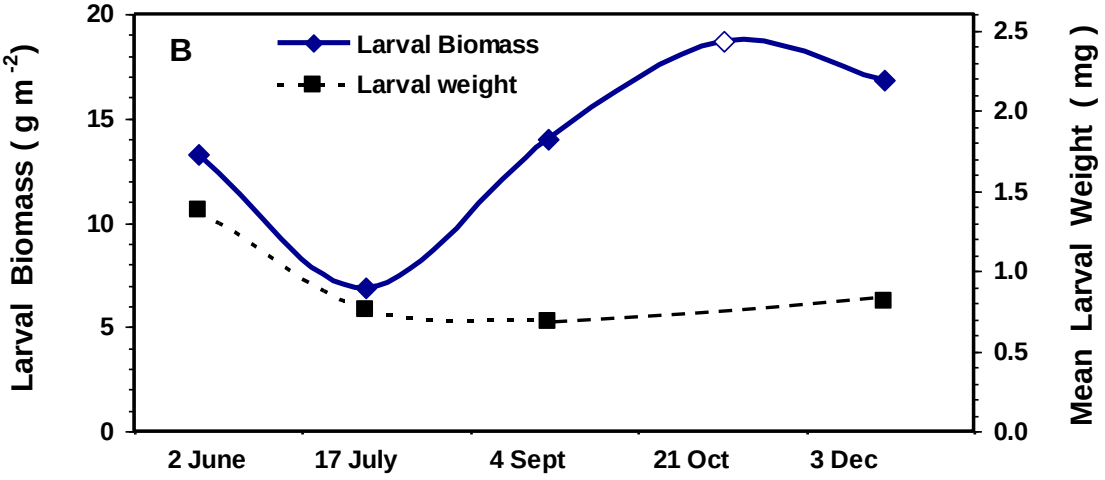

Fig. 6. Mean dry weights of brine fly larvae (right axis), and the biomass (left axis) of larvae on biostromes in the Great Salt Lake. Larval lengths and weights were not estimated in October, so the mean of September and December weights were utilized to estimate larval biomass at that time (open symbol).

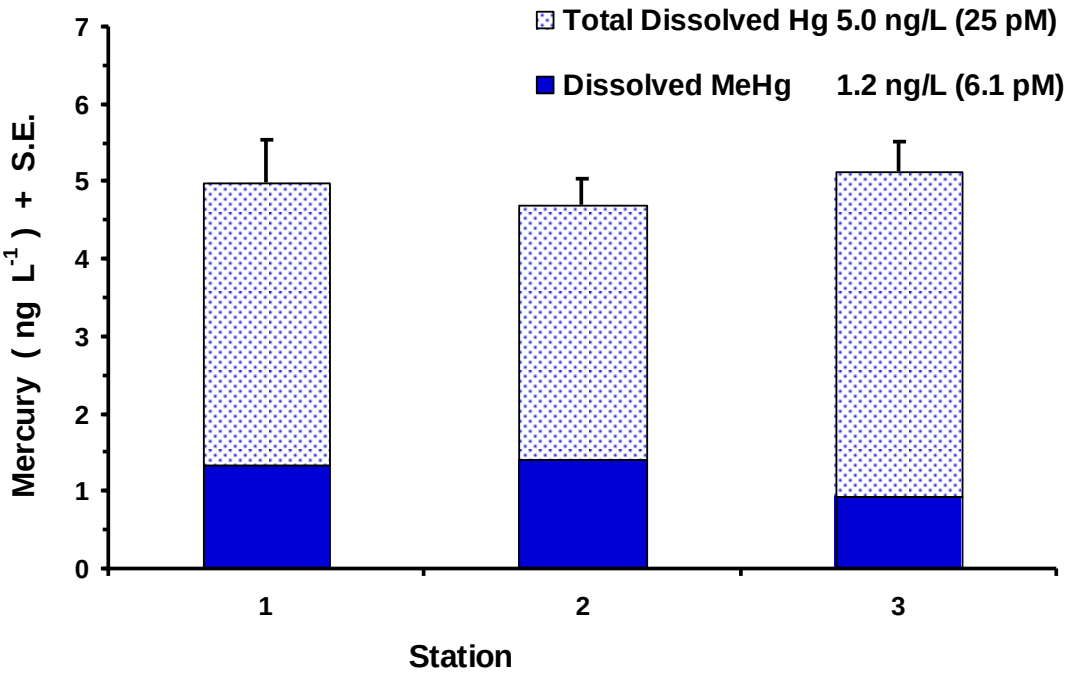

Fig. 7. Dissolved mercury concentrations above biostromes at the three sampling stations in the Great Salt Lake. Methyl mercury accounted for 25% of the total.

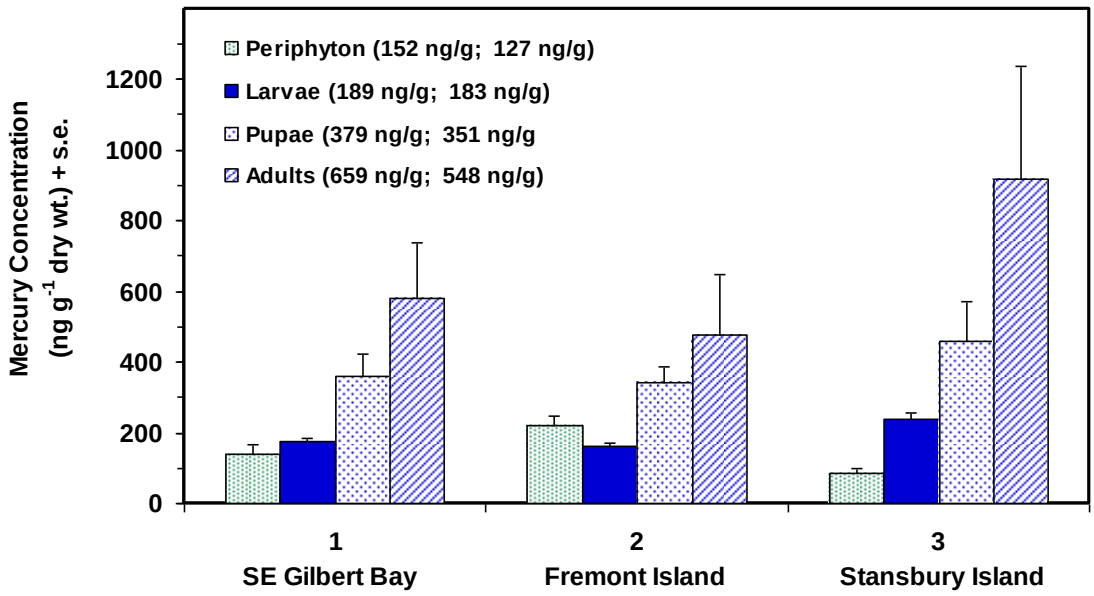

Fig. 8. Mean total mercury concentrations in periphyton and brine fly larvae, pupae and adults associated with biostromes at three stations in the Great Salt Lake. The periphyton values shown here were from samples that were acidified to remove carbonates. Overall arithmetic (left) and geometric mean (right) mercury concentrations are shown in the inset.

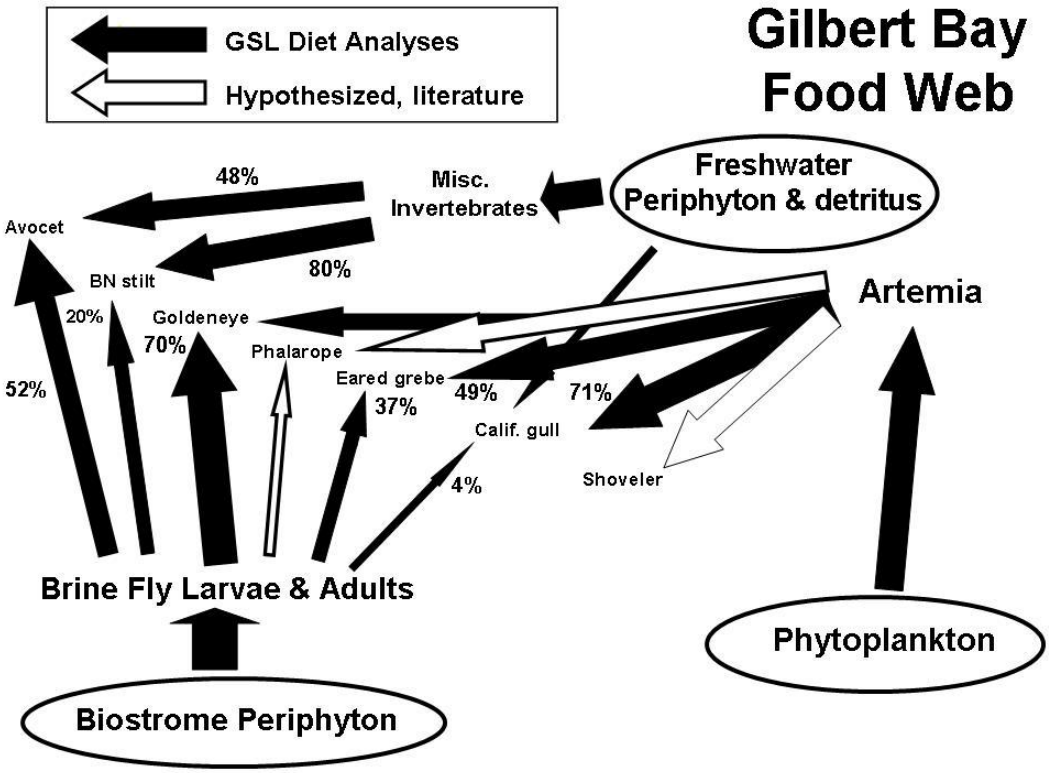

Fig. 9. Food web resources of dominant birds that utilize the Great Salt Lake. Open arrows are hypothesized pathways based on studies in other saline lakes and ponds. The Freshwater Periphyton and Detritus pathway occurs on the mud flats of Gilbert and Farmington Bays. Species codes and samples sizes: Avocets–American avocets (12); BN stilt–Black-necked stilt (4); Goldeneye–common goldeneye ducks (120); Calif. gull–California gull (53); Grebe–Eared grebe (94); Shoveler–northern shoveler duck; Phalarope–Wilson's and red-necked phalaropes. Data from Conover and Vest (2009a), Conover and Vest (2009b), Cavitt (2007), Vest et al. (2008), Gafney (2009).

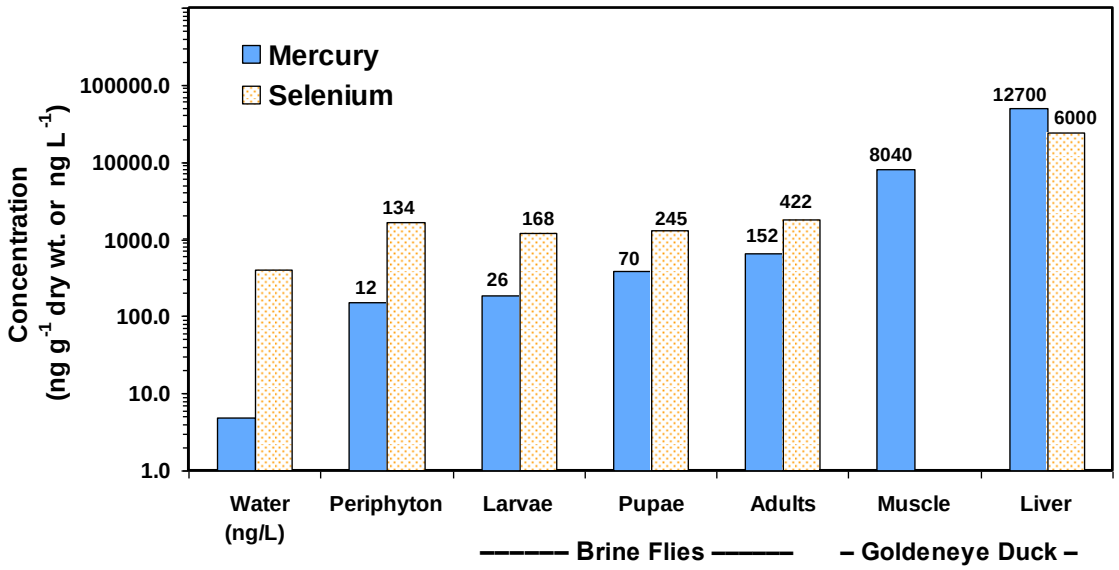

Fig. 10. Concentrations of total mercury and selenium and in the food web associated with biostromes in the Great Salt Lake. Water concentrations are in ηg L^{-1} while histograms for the other components are ηg g^{-1} dry weight. Values shown above the bars are estimated concentrations on a wet-weight basis based on assumed dry:wet weight ratios of: periphyton–0.08; larvae–0.14; pupae–0.19; adults–0.23; duck muscle and liver–0.25. Selenium concentrations for the water, periphyton and brine flies were derived from Wurtsbaugh (2009). Mercury concentrations for duck breast muscle are from 2005 samples collected by the Utah Division of Water Quality, and mercury and selenium concentrations in duck livers are from Vest et al. (2008).

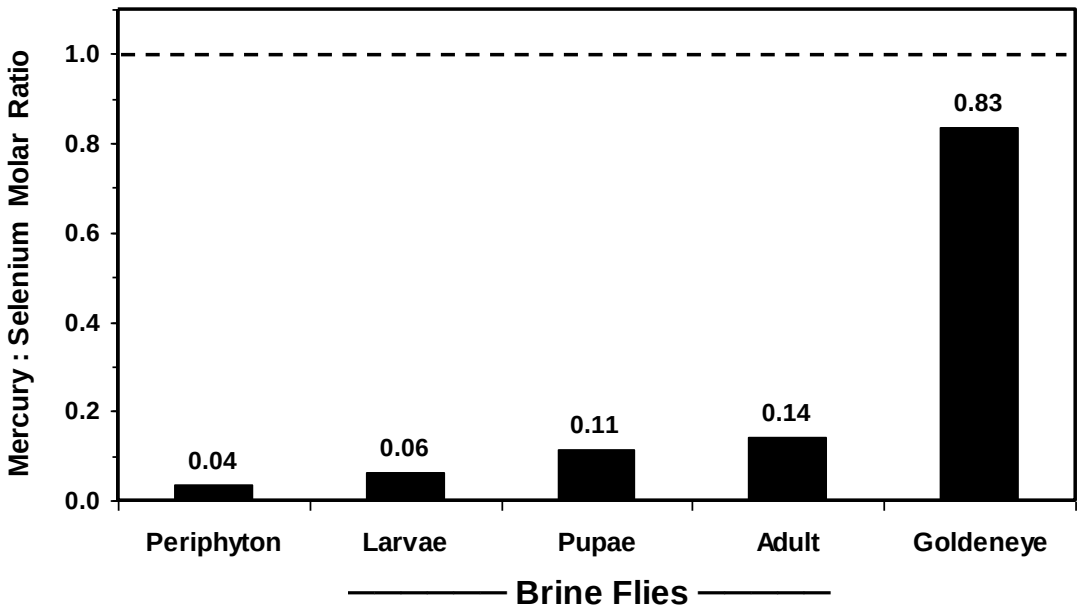

Fig. 11. Molar ratios of mercury to selenium in the food web components associated with biostromes in the Great Salt Lake. The dashed line shows the 1:1 ratio below which mercury is hypothesized to be non-toxic.

Appendix 1. Collection locations, dates and total mercury concentrations for brine flies. Values in italics were identified by SYSTAT as statistical outliers and/or were from inadequate sample sizes and were not used in the analyses.

Brine Flies										
Station	**Collection Date**	**Period**	**Time**	**Depth (m)**	**REP.**	**Stage**	**Size Class**	**USGS Sample ID**	**Concentration (ng Total Hg / g dry wt)**	**Notes**
USU1	30-May-08	1_June		Air	1	Adults		MSC499F	272	
USU2	2-Jun-08	1_June		Air	1	Adults		MSC500F	141	
USU3	3-Jun-08	1_June		Air	1	Adults		MSC501F	401	
USU1	18-Jul-08	2_July	1315	Air	1	Adults		MSC504F	711	
USU2	16-Jul-08	2_July	1215	Air	1	Adults		MSC503F	672	
USU3	17-Jul-08	2_July	1220	Air	1	Adults		MSC502F	1500	
USU1	2-Sep-08	3_Sept	1445	Air	1	Adults		MSC526F	762	
USU2	7-Sep-08	3_Sept	1700	Air	1	Adults		MSC704G	618	
USU3	7-Sep-08	3_Sept	1200	Air	1	Adults		MSC705G	852	
USU1	20-Oct-08	4_Oct	1645	Air	1	Adults		MSC759G	*136*	Small Sample size (NUIA)
USU1	30-May-08	1_June		2.8	1	Larvae		MSC483F	161	
USU2	2-Jun-08	1_June		2.8	1	Larvae		MSC482F	131	
USU3	3-Jun-08	1_June		3.9	1	Larvae		MSC484F	133	
USU1	18-Jul-08	2_July	1245	2.5	1	Larvae		MSC509F	126	
USU2	16-Jul-08	2_July	1138	2.5	1	Larvae		MSC507F	167	
USU3	17-Jul-08	2_July	1145	2.7	1	Larvae		MSC505F	233	
USU1	2-Sep-08	3_Sept	1255	3.0	1	Larvae		MSC725G	180	
USU1	2-Sep-08	3_Sept	1255	3.0	2	Larvae		MSC726G	166	
USU2	7-Sep-08	3_Sept	1545	2.4	2	Larvae		MSC723G	132	
USU2	7-Sep-08	3_Sept	1545	2.4	1	Larvae		MSC724G	116	
USU3	7-Sep-08	3_Sept	1335	2.6	1	Larvae		MSC727G	226	
USU3	7-Sep-08	3_Sept	1335	2.6	2	Larvae		MSC728G	205	
USU1	20-Oct-08	4_Oct	1500	1.0	1	Larvae	Lg	MSC746G	170	
USU1	20-Oct-08	4_Oct	1500	1.0	1	Larvae	Sml	MSC745G	129	
USU1	20-Oct-08	4_Oct	1330	3.0	1	Larvae	Lg	MSC757G	164	
USU1	20-Oct-08	4_Oct	1330	3.0	1	Larvae	Sml	MSC756G	157	
USU2	22-Oct-08	4_Oct	1150	1.2	1	Larvae	Lg	MSC749G	169	
USU2	22-Oct-08	4_Oct	1150	1.2	1	Larvae	Sml	MSC748G	133	
USU2	22-Oct-08	4_Oct	1435	2.1	1	Larvae	Lg	MSC755G	160	
USU2	22-Oct-08	4_Oct	1435	2.1	1	Larvae	Sml	MSC754G	175	
USU3	22-Oct-08	4_Oct	1530	1.0	1	Larvae	Lg	MSC743G	218	
USU3	22-Oct-08	4_Oct	1530	1.0	1	Larvae	Sml	MSC742G	186	
USU3	22-Oct-08	4_Oct	1700	2.8	1	Larvae	Lg	MSC752G	341	
USU3	22-Oct-08	4_Oct	1700	2.8	1	Larvae	Sml	MSC751G	259	
USU1	1-Dec-08	5_Dec	1430	3.0	1	Larvae	Lg	MSC054H	215	
USU1	1-Dec-08	5_Dec	1430	3.0	1	Larvae	Sml	MSC052H	192	
USU1	1-Dec-08	5_Dec	1435	3.0	2	Larvae	Lg	MSC053H	230	
USU1	1-Dec-08	5_Dec	1435	3.0	2	Larvae	Sml	MSC056H	198	
USU2	4-Dec-08	5_Dec	1130	3.0	1	Larvae		MSC055H	206	
USU2	4-Dec-08	5_Dec	1135	3.0	2	Larvae		MSC058H	209	
USU3	3-Dec-08	5_Dec	1235	3.0	2	Larvae		MSC057H	286	
USU3	3-Dec-08	5_Dec	1230	3.0	1	Larvae		MSC059H	287	
USU1	30-May-08	1_June		2.8	1	Pupae		MSC486F	142	
USU3	3-Jun-08	1_June		3.9	1	Pupae		MSC485F	210	
USU1	18-Jul-08	2_July	1245	2.5	1	Pupae		MSC510F	384	
USU2	16-Jul-08	2_July	1138	2.5	1	Pupae		MSC508F	402	
USU3	17-Jul-08	2_July	1145	2.7	1	Pupae		MSC506F	528	
USU1	2-Sep-08	3_Sept	1255	3.0	2	Pupae		MSC718G	475	
USU1	2-Sep-08	3_Sept	1255	3.0	1	Pupae		MSC722G	469	
USU2	7-Sep-08	3_Sept	1545	2.4	1	Pupae		MSC719G	397	
USU2	7-Sep-08	3_Sept	1545	2.4	2	Pupae		MSC721G	365	
USU3	7-Sep-08	3_Sept	1335	2.6	1	Pupae		MSC720G	641	
USU1	20-Oct-08	4_Oct	1500	1.0	1	Pupae		MSC747G	*96*	Small Sample size (NUIA)
USU1	20-Oct-08	4_Oct	1330	3.0	1	Pupae		MSC758G	329	
USU2	22-Oct-08	4_Oct	1150	1.2	1	Pupae		MSC750G	211	
USU3	22-Oct-08	4_Oct	1530	1.0	1	Pupae		MSC744G	*33*	Small Sample size (NUIA)
USU3	22-Oct-08	4_Oct	1700	2.8	1	Pupae		MSC753G	Lost	

Appendix 2. Collection locations, dates and total mercury concentrations for biostrome components. "Carbonate" refers to biostrome material below the zone of microbial growth. "Periphyton" is biostrome material that was treated with HCl to remove carbonates. "Sediment" refers to intact, untreated biostromes. Values in italics were identified by SYSTAT as statistical outliers and/or were from inadequate sample sizes and were not used in the analyses.

Sediments									
Station	Collection Date	Period	Time	Depth (m)	REP	Sediment fraction	USGS Sample ID	Concentration (ng Total Hg / g dry wt)	Notes
USU1	20-Oct-08	4_Oct	NA	3.0		CARBONATE	MSC760G	9.5	
USU1	20-Oct-08	4_Oct	NA	3.0		CARBONATE	MSC761G	6.0	
USU1	20-Oct-08	4_Oct	NA	3.0		CARBONATE	MSC762G	22.8	
USU2	22-Oct-08	4_Oct	NA	3.0		CARBONATE	MSC763G	10.0	
USU2	22-Oct-08	4_Oct	NA	3.0		CARBONATE	MSC764G	16.5	
USU2	22-Oct-08	4_Oct	NA	3.0		CARBONATE	MSC765G	21.3	
USU3	22-Oct-08	4_Oct	NA	2.8		CARBONATE	MSC766G	17.8	
USU3	22-Oct-08	4_Oct	NA	2.8		CARBONATE	MSC767G	45.6	
USU3	22-Oct-08	4_Oct	NA	2.8		CARBONATE	MSC768G	44.8	
USU1	18-Jul-08	2_July	1230	2.5	1	PERIPHYTON	MSC511F	59.0	
USU1	18-Jul-08	2_July	1230	2.5	2	PERIPHYTON	MSC512F	46.0	
USU2	16-Jul-08	2_July	1115	2.5	1	PERIPHYTON	MSC513F	125.0	
USU2	16-Jul-08	2_July	1115	2.5	2	PERIPHYTON	MSC514F	81.0	
USU3	17-Jul-08	2_July	1130	2.7	1	PERIPHYTON	MSC515F	38.0	
USU3	17-Jul-08	2_July	1130	2.7	2	PERIPHYTON	MSC516F	39.0	
USU1	2-Sep-08	3_Sept	1255	3.0	1	PERIPHYTON	MSC708G	186.7	
USU1	2-Sep-08	3_Sept	1300	3.0	2	PERIPHYTON	MSC709G	301.9	
USU2	7-Sep-08	3_Sept	1530	2.4	1	PERIPHYTON	MSC710G	212.8	
USU2	7-Sep-08	3_Sept	1530	2.4	2	PERIPHYTON	MSC711G	205.5	
USU3	7-Sep-08	3_Sept	1320	2.6	1	PERIPHYTON	MSC706G	123.8	
USU3	7-Sep-08	3_Sept	1320	2.6	2	PERIPHYTON	MSC707G	95.7	
USU1	20-Oct-08	4_Oct	1315	3.0	1	PERIPHYTON	MSC729G	138.8	
USU1	20-Oct-08	4_Oct	1320	3.0	2	PERIPHYTON	MSC730G	60.3	
USU2	22-Oct-08	4_Oct	1420	2.1	1	PERIPHYTON	MSC731G	294.7	
USU2	22-Oct-08	4_Oct	1425	2.1	2	PERIPHYTON	MSC732G	219.7	
USU3	22-Oct-08	4_Oct	1650	2.8	1	PERIPHYTON	MSC733G	88.1	
USU3	22-Oct-08	4_Oct	1655	2.8	2	PERIPHYTON	MSC734G	108.5	
USU1	30-May-08	1_June		2.8	1	SEDIMENT	MSC495F	43.0	
USU1	30-May-08	1_June		2.8	2	SEDIMENT	MSC497F	33.0	
USU2	2-Jun-08	1_June		2.8	1	SEDIMENT	MSC487F	197.0	
USU2	2-Jun-08	1_June		2.8	2	SEDIMENT	MSC493F	140.0	
USU3	3-Jun-08	1_June		3.9	2	SEDIMENT	MSC489F	138.0	
USU3	3-Jun-08	1_June		3.9	1	SEDIMENT	MSC491F	86.0	
USU1	18-Jul-08	2_July	1230	2.5	1	SEDIMENT	MSC517F	39.0	
USU1	18-Jul-08	2_July	1230	2.5	2	SEDIMENT	MSC521F	32.0	
USU2	16-Jul-08	2_July	1115	2.5	2	SEDIMENT	MSC518F	40.0	
USU2	16-Jul-08	2_July	1115	2.5	1	SEDIMENT	MSC520F	71.0	
USU3	17-Jul-08	2_July	1130	2.7	2	SEDIMENT	MSC519F	39.0	
USU3	17-Jul-08	2_July	1130	2.7	1	SEDIMENT	MSC522F	39.0	
USU1	2-Sep-08	3_Sept	1300	3.0	2	SEDIMENT	MSC713G	36.3	
USU1	2-Sep-08	3_Sept	1255	3.0	1	SEDIMENT	MSC717G	54.8	
USU2	7-Sep-08	3_Sept	1530	2.4	1	SEDIMENT	MSC712G	51.7	
USU2	7-Sep-08	3_Sept	1530	2.4	2	SEDIMENT	MSC715G	46.1	
USU3	7-Sep-08	3_Sept	1320	2.6	2	SEDIMENT	MSC714G	35.4	
USU3	7-Sep-08	3_Sept	1320	2.6	1	SEDIMENT	MSC716G	36.2	
USU1	20-Oct-08	4_Oct	1315	3.0	1	SEDIMENT	MSC736G	68.0	
USU1	20-Oct-08	4_Oct	1320	3.0	2	SEDIMENT	MSC737G	49.0	
USU2	22-Oct-08	4_Oct	1420	2.1	1	SEDIMENT	MSC738G	157.2	
USU2	22-Oct-08	4_Oct	1425	2.1	2	SEDIMENT	MSC739G	101.3	
USU3	22-Oct-08	4_Oct	1655	2.8	2	SEDIMENT	MSC741G	34.9	
USU3	22-Oct-08	4_Oct	1650	2.8	1	SEDIMENT	MSC740G	45.0	
USU1	1-Dec-08	5_Dec	1440	3.0	1	SEDIMENT	MSC060H	171.0	Replacement for MSC773G
USU1	1-Dec-08	5_Dec	1445	3.0	2	SEDIMENT	MSC061H	144.0	Replacement for MSC772G
USU1	1-Dec-08	5_Dec	1445	3.0	2	SEDIMENT	MSC772G	Lost	
USU1	1-Dec-08	5_Dec	1440	3.0	1	SEDIMENT	MSC773G	Lost	
USU1	1-Dec-08	5_Dec	1445	3.0	2	SEDIMENT	MSC776G	44.0	
USU1	1-Dec-08	5_Dec	1440	3.0	1	SEDIMENT	MSC779G	38.0	
USU2	4-Dec-08	5_Dec	1140	3.0	1	SEDIMENT	MSC062H	289.0	Replacement for MSC771G
USU2	4-Dec-08	5_Dec	1145	3.0	2	SEDIMENT	MSC063H	290.0	
USU2	4-Dec-08	5_Dec	1145	3.0	2	SEDIMENT	MSC770G	283.0	
USU2	4-Dec-08	5_Dec	1140	3.0	1	SEDIMENT	MSC771G	Lost	
USU2	4-Dec-08	5_Dec	1145	3.0	2	SEDIMENT	MSC775G	74.0	

Appendix 3. Collection locations, dates and filtered total mercury and methyl mercury concentrations for water samples used in the biostrome analyses.

Water									
Station	Collection Date	Period	Time	Depth (m)	REP	Fraction	USGS Sample ID	Concentration (ng / L)	Notes
USU2	7-Sep-08	3_Sept	1520	2.4	2	Filt Methyl Hg	MLO311AVN	0.69	
USU3	7-Sep-08	3_Sept	1300	3.0	1	Filt Methyl Hg	MLO287AVV	0.72	
USU3	7-Sep-08	3_Sept	1315	3.0	2	Filt Methyl Hg	MLO317AVV	0.73	
USU1	20-Oct-08	4_Oct	1315	3.0	1	Filt Methyl Hg	NVD295AWU	2.30	
USU1	20-Oct-08	4_Oct	1320	3.0	2	Filt Methyl Hg	LMZ205AWG	1.80	
USU2	22-Oct-08	4_Oct	1420	2.1	1	Filt Methyl Hg	LMZ216AWU	1.80	
USU2	22-Oct-08	4_Oct	1425	2.1	2	Filt Methyl Hg	JFD310AWU	0.91	
USU3	22-Oct-08	4_Oct	1530	2.8	1	Filt Methyl Hg	WIM359AWU	0.61	
USU3	22-Oct-08	4_Oct	1535	2.8	2	Filt Methyl Hg	WIM276AWU	0.83	
USU1	1-Dec-08	5_Dec	1415	3.0	1	Filt Methyl Hg	JFD321AXL	0.88	
USU1	1-Dec-08	5_Dec	1420	3.0	2	Filt Methyl Hg	WIM213AXM	1.30	
USU2	4-Dec-08	5_Dec	1115	3.0	1	Filt Methyl Hg	WIM391AXM	1.10	
USU2	4-Dec-08	5_Dec	1120	3.0	2	Filt Methyl Hg	WIM178AXL	2.10	
USU3	3-Dec-08	5_Dec	1220	3.0	1	Filt Methyl Hg	WIM223AXM	1.70	
USU3	3-Dec-08	5_Dec	1225	3.0	2	Filt Methyl Hg	JFD307AXL	1.10	
USU1	30-May-08	1_June		2.8	1	Filt Total Hg	MEB090AUU	4.55	
USU1	30-May-08	1_June		2.8	2	Filt Total Hg	MEB083AUU	4.40	
USU3	3-Jun-08	1_June		3.9	1	Filt Total Hg	MIP153AUU	6.24	
USU3	3-Jun-08	1_June		3.9	2	Filt Total Hg	DPK087AUU	5.93	
USU1	18-Jul-08	2_July	1215	2.5	1	Filt Total Hg	WIT050AVU	2.44	
USU1	18-Jul-08	2_July	1225	2.5	2	Filt Total Hg	WIT248AVU	2.69	
USU2	16-Jul-08	2_July	1040	2.5	1	Filt Total Hg	WIT376AVU	2.77	
USU3	17-Jul-08	2_July	1100	2.7	1	Filt Total Hg	WIT137AVU	2.72	
USU1	2-Sep-08	3_Sept	1330	3.0	1	Filt Total Hg	WIT213AWO	5.59	
USU1	2-Sep-08	3_Sept	1330	3.0	2	Filt Total Hg	WIT203AVX	5.62	
USU2	7-Sep-08	3_Sept	1515	2.4	1	Filt Total Hg	DPK012AVK	5.01	
USU2	7-Sep-08	3_Sept	1520	2.4	2	Filt Total Hg	WIT302AWF	4.91	
USU3	7-Sep-08	3_Sept	1300	3.0	1	Filt Total Hg	WIT392AWO	5.36	
USU3	7-Sep-08	3_Sept	1315	3.0	2	Filt Total Hg	MEB090AVX	5.11	
USU1	20-Oct-08	4_Oct	1315	3.0	1	Filt Total Hg	WIT289AWD	8.74	
USU1	20-Oct-08	4_Oct	1320	3.0	2	Filt Total Hg	WIT184AWK	5.52	
USU2	22-Oct-08	4_Oct	1420	2.1	1	Filt Total Hg	MIP049AXH	4.85	
USU2	22-Oct-08	4_Oct	1425	2.1	2	Filt Total Hg	NVD510AXH	4.78	
USU3	22-Oct-08	4_Oct	1530	2.8	1	Filt Total Hg	WIT411AWL	4.27	
USU3	22-Oct-08	4_Oct	1535	2.8	2	Filt Total Hg	WIT372AVO	4.34	
USU1	1-Dec-08	5_Dec	1415	3.0	1	Filt Total Hg	DPK047AXP	5.04	
USU1	1-Dec-08	5_Dec	1420	3.0	2	Filt Total Hg	MLO127AXN	5.25	
USU2	4-Dec-08	5_Dec	1115	3.0	1	Filt Total Hg	WIT137AXT	5.31	
USU2	4-Dec-08	5_Dec	1120	3.0	2	Filt Total Hg	WIT060AXT	5.28	
USU3	3-Dec-08	5_Dec	1220	3.0	1	Filt Total Hg	MLO106AXN	6.43	
USU3	3-Dec-08	5_Dec	1225	3.0	2	Filt Total Hg	MLO164AXN	5.77	

Appendix 4. Mercury concentrations collected by the Utah State University group to support the pelagic brine shrimp and seston sampling of the Utah Division of Wildlife Resources.

Open-Water Stations Only Sampled for Water Concentrations (ng Hg / L)

Station	Collection Date	Period	Time	Depth (m)	REP	Fraction	USGS Sample ID	Concentration	Notes
GSL 2767	2-Jun-08	1_June		2.8	1	Filt Methyl Hg	WIM347ASJ	0.61	
GSL 2767	2-Jun-08	1_June		2.0	1	Filt Methyl Hg	MEB026AUS	3.63	
GSL 3381	3-Jun-08	1_June		2.0	1	Filt Methyl Hg	WIT101AUS	1.00	
GSL3510	30-May-08	1_June		2.0	1	Filt Methyl Hg	NVD264ARX	0.49	
GSL 2767	16-Jul-08	2_July	1430	2.0	1	Filt Methyl Hg	WIM410AVS	0.74	
GSL 3381	17-Jul-08	2_July	1010	2.0	1	Filt Methyl Hg	WIM366AVS	0.72	
GSL 4069	18-Jul-08	2_July	1350	2.0	1	Filt Methyl Hg	DIS266AVS	0.60	
GSL 2767	7-Sep-08	3_Sept	1415	2.0	1	Filt Methyl Hg	WIM037AVI	0.56	
GSL 3381	7-Sep-08	3_Sept	1135	2.0	1	Filt Methyl Hg	JFD316AVF	1.10	
GSL 4069	2-Sep-08	3_Sept	1040	2.0	1	Filt Methyl Hg	MEB032AVN	0.99	
GSL 2767	22-Oct-08	4_Oct	1830	1.5	1	Filt Methyl Hg	DIS264AWU	0.87	
GSL 3381	22-Oct-08	4_Oct	1800	2.0	1	Filt Methyl Hg	WIM319AWU	1.00	
GSL 4069	20-Oct-08	4_Oct	1614	2.0	1	Filt Methyl Hg	WIM226AWU	0.95	
GSL 2767	4-Dec-08	5_Dec	1230	2.0	1	Filt Methyl Hg	MLO335AXM	0.69	
GSL 3381	3-Dec-08	5_Dec	1430	2.0	1	Filt Methyl Hg	WIM311AXT	1.30	
GSL 4069	1-Dec-08	5_Dec	1545	2.0	1	Filt Methyl Hg	WIM371AXM	0.70	
GSL 2767	2-Jun-08	1_June		2.0	1	Filt Total Hg	WIT303AUU	3.68	
GSL 3510	30-May-08	1_June		2.0	1	Filt Total Hg	JFD529AUT	3.92	
GSL 2767	16-Jul-08	2_July	1430	2.0	1	Filt Total Hg	NVD559AVU	2.75	
GSL 3381	17-Jul-08	2_July	1010	2.0	1	Filt Total Hg	WIT016AVU	2.66	
GSL 4069	18-Jul-08	2_July	1350	2.0	1	Filt Total Hg	WIT014AVU	2.52	
GSL 2767	7-Sep-08	3_Sept	1415	2.0	1	Filt Total Hg	WIT391AWO	4.74	
GSL 3381	7-Sep-08	3_Sept	1135	2.0	1	Filt Total Hg	MLO091AWO	5.25	
GSL 4069	2-Sep-08	3_Sept	1040	2.0	1	Filt Total Hg	DPK068AWO	4.81	
GSL 2767	22-Oct-08	4_Oct	1830	1.5	1	Filt Total Hg	WIT429AWL	4.76	
GSL 3381	22-Oct-08	4_Oct	1800	2.0	1	Filt Total Hg	WIT409AWL	4.47	
GSL 4069	20-Oct-08	4_Oct	1614	2.0	1	Filt Total Hg	WIT136AXH	4.54	
GSL 2767	4-Dec-08	5_Dec	1230	2.0	1	Filt Total Hg	WIT179AXN	5.19	
GSL 3381	3-Dec-08	5_Dec	1430	2.0	1	Filt Total Hg	NVD506AXN	5.29	
GSL 4069	1-Dec-08	5_Dec	1545	2.0	1	Filt Total Hg	GLA546AXP	4.86	
GSL 2767	2-Jun-08	1_June		2.0	1	Tot Methyl Hg	W1M326ASG	1.20	
GSL 3381	3-Jun-08	1_June		2.0	1	Tot Methyl Hg	MEB060ATG	1.20	
GSL 2767	16-Jul-08	2_July	1430	2.0	1	Tot Methyl Hg	WIM157AVS	*7.10*	Outlier (NUIA; Stud. Resid. = 3.29)
GSL 3381	17-Jul-08	2_July	1010	2.0	1	Tot Methyl Hg	WIM140AVU	0.74	
GSL 4069	18-Jul-08	2_July	1350	2.0	1	Tot Methyl Hg	WIM180AVS	0.70	
GSL 2767	2-Sep-08	3_Sept	1040	2.0	1	Tot Methyl Hg	MLO320AVV	0.93	
GSL 3381	7-Sep-08	3_Sept	1415	2.0	1	Tot Methyl Hg	DPK150AVS	2.10	
GSL 4069	7-Sep-08	3_Sept	1135	2.0	1	Tot Methyl Hg	DPK162AVG	0.94	
GSL 2767	22-Oct-08	4_Oct	1830	1.5	1	Tot Methyl Hg	WIM414AWU	1.10	
GSL 3381	22-Oct-08	4_Oct	1800	2.0	1	Tot Methyl Hg	WIM183AWU	1.20	
GSL 4069	20-Oct-08	4_Oct	1614	2.0	1	Tot Methyl Hg	WIM219AWU	0.98	
GSL 2767	4-Dec-08	5_Dec	1230	2.0	1	Tot Methyl Hg	WIM196AXL	1.40	
GSL 3381	3-Dec-08	5_Dec	1430	2.0	1	Tot Methyl Hg	WIM085AXL	1.30	
GSL 4069	1-Dec-08	5_Dec	1545	2.0	1	Tot Methyl Hg	WIM056AXN	1.00	
GSL 2767	2-Jun-08	1_June		2.0	1	Total Hg	MLO090AUP	3.74	
GSL 3381	3-Jun-08	1_June		2.0	1	Total Hg	ML0122ATG	4.12	
GSL 2767	16-Jul-08	2_July	1430	2.0	1	Total Hg	WIT045AVU	*13.40*	Outlier (NUIA; Stud. Resid. = 5.70)
GSL 3381	17-Jul-08	2_July	1010	2.0	1	Total Hg	WIT269AVU	5.27	
GSL 4069	18-Jul-08	2_July	1350	2.0	1	Total Hg	WIT197AVI	Lost	
GSL 2767	7-Sep-08	3_Sept	1415	2.0	1	Total Hg	MTW209AWO	5.05	
GSL 3381	7-Sep-08	3_Sept	1135	2.0	1	Total Hg	MLO101AWD	5.69	
GSL 4069	2-Sep-08	3_Sept	1040	2.0	1	Total Hg	MLO122AVX	5.51	
GSL 2767	22-Oct-08	4_Oct	1830	1.5	1	Total Hg	WCC165AXH	6.35	
GSL 3381	22-Oct-08	4_Oct	1800	2.0	1	Total Hg	NVD542AWK	6.71	
GSL 4069	20-Oct-08	4_Oct	1614	2.0	1	Total Hg	NVD536AWK	4.73	
GSL 2767	4-Dec-08	5_Dec	1230	2.0	1	Total Hg	WIT315AXS	6.11	
GSL 3381	3-Dec-08	5_Dec	1430	2.0	1	Total Hg	MEB085AXP	6.57	
GSL 4069	1-Dec-08	5_Dec	1545	2.0	1	Total Hg	WIT133AXT	5.48	