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Effects of eutrophication on birds in Three Bays of Great Salt Lake:

A comparative analysis with Utah DWR Waterbird Survey Data

Wayne Wurtsbaugh

LimnoVision
1342 E 1700 N
North Logan, Utah 84341
Wurtsbaugh@gmail.com

Bear River Bay (Willard Spur)

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Summary

Farmington Bay in Great Salt receives high nutrient loading from the surrounding metropolitan area, and this leads to very high algal production and hypereutrophic conditions (Figure A). The high phytoplankton abundance reduces light to deeper areas of the bay, likely reducing the production of periphyton and invertebrates in the deeper waters. Additionally, an anoxic deep brine layer intrudes into Farmington Bay, also reducing benthic invertebrates in this layer.

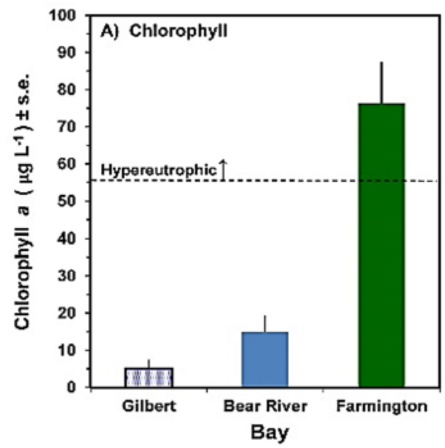


Figure A. Mean concentrations of chlorophyll *a*, a measure of phytoplankton abundance in three bays of Great Salt Lake. From Wurtsbaugh et al. (2012).

Bird densities are high in some areas of Farmington Bay, and this has led to the hypothesis that high nutrient loading and the resulting eutrophication are necessary to support the high bird densities (L. Meyers, personal communication). To test this hypothesis, the current study used the data from the 1997-2001 Utah Division of Wildlife Resources study (Paul and Manning 2008) to compare bird densities in Farmington Bay with the less eutrophic Bear River Bay, and with Ogden Bay that adjoins Gilbert Bay. The intensive 5-year DWR study surveyed birds at 10-day intervals in various habitat types (open water, shorelines and freshwater wetlands) from April-September. The survey was not designed to address how habitat characteristics influenced bird distribution, and no limnological data was collected during the survey. Consequently, the Waterbird Survey is an imperfect tool for addressing if eutrophication has influenced the distribution and abundance of birds. However, utilizing limnological data from other surveys before and after the Waterbird Survey allows some insights on the importance of eutrophication on the bird population.

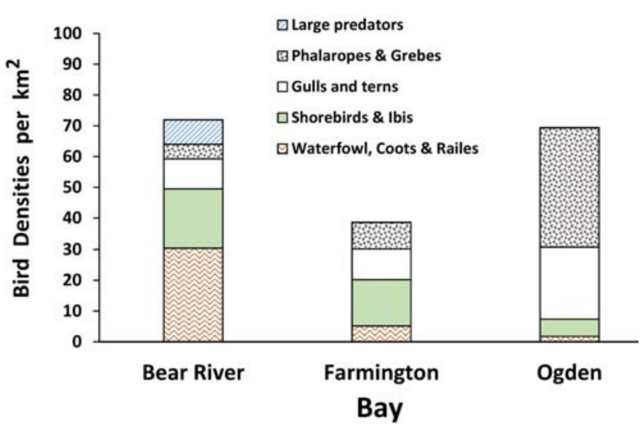


Figure B. Summary of bird densities in three bays of Great Salt Lake during the 1997-2001 Waterbird Survey (Paul and Manning 2008).

Overall bird densities were lowest in Farmington Bay (Figure B), suggesting that hypereutrophication is not necessary to support high bird densities. The lower overall densities in Farmington relative to Bear River Bay was due to much lower densities of waterfowl, coots and rails, particularly in the open water areas of the bay. Some available limnological data suggest that this could be due to low light penetration and hence the lower production of periphyton and benthic invertebrates in the deeper areas of Farmington Bay, and/or to the presence of the deep brine layer.

However, when individual habitat types in each bay were analyzed separately, the shoreline areas of Ogden Bay had the highest bird densities, with approximately equal densities of birds in Farmington and Bear River Bays (Fig. C). Farmington Bay's shoreline, however, had much higher densities of shorebirds (Avocets, Stilts, etc.) and lower densities of waterfowl than did Bear River Bay's shoreline. The high nutrient loading in Farmington Bay may shift primary production and the production of benthic invertebrates to these shallower waters, and thus provide higher prey densities for birds that forage along the shoreline.

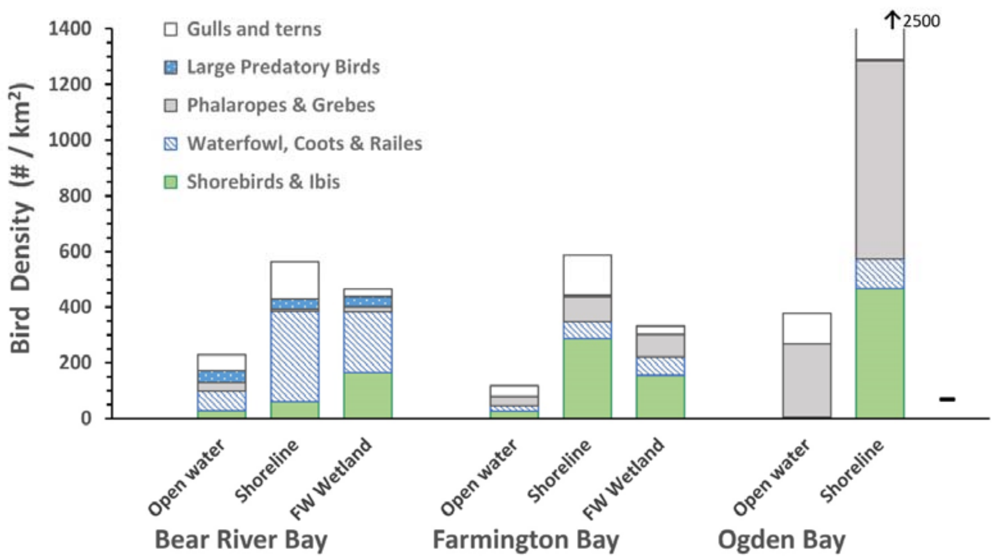


Figure C. Bird densities in three habitat types in the different bays on the eastern shore of Great Salt Lake. Data source: (Paul and Manning 2008).

Ongoing studies on the benthic invertebrates in Farmington and Bear River Bays, as well as additional analyses of the food webs in both bays will provide better insights into the distribution of birds around Great Salt Lake. An overriding problem influencing both Bear River and Farmington Bay is the desiccation of the lake resulting in greatly reduced amounts of habitat.

Introduction

Great Salt Lake is of worldwide importance for migratory birds and consequently is part of the *Western Hemispheric Shorebird Reserve Network (Whsrn 2017)*. Numerous surveys and publications have documented the importance of both Farmington Bay and Bear River Bay for hundreds of thousands of birds (e.g. Aldrich and Paul 2002; Paul and Manning 2008). Shorebirds are particularly abundant in Farmington Bay (Paul and Manning 2008) but Wurtsbaugh et al. (2012) found low numbers of birds in the open waters of the Bay, at least in the northern half where they surveyed.

Farmington Bay receives approximately 50% of its water inflow from secondary-treated wastewater plants (see Myers No date), and although nutrient inflows have not been carefully documented, estimated loading is very high (Wurtsbaugh et al. 2002) Limnological surveys in Farmington Bay have demonstrated that it is hypereutrophic with frequent loss of oxygen throughout the water column at night (Wurtsbaugh et al. 2012; Marden et al. 2015; Mcculley et al. 2015). Paleolimnological analyses have also demonstrated that Farmington Bay was less eutrophic prior to development of the Salt Lake Valley (Leavitt et al. 2012; Wurtsbaugh 2012). When salinities are between 1-5% massive blooms of toxic cyanobacteria (*Nodularia* sp.) occur in the bay (Fig. 1), with toxin concentrations well above those found to have caused bird mortalities in other systems (c.f. Matsunaga et al. 1999; Alonso-Andicoberry 2002; Wurtsbaugh et al. 2012).

Figure 1. Secchi depth measurement during a bloom of *Nodularia spumigena* in Farmington Bay on May 15, 2005.

The limnology of Bear River Bay has been studied less than Farmington Bay, but the limited analysis indicates that even though it is similarly shallow, it is far less eutrophic, with negligible concentrations of toxic cyanobacteria (Wurtsbaugh et al. 2012). The eastern portion of Bear River Bay, Willard Spur, was studied intensively from 2011-2013 to assess how nutrient releases from a new wastewater treatment plant might influence the food web (Ch2m Hill 2015). Experimental analyses done during this study suggested the increased nutrient loading caused earlier senescence of submerged aquatic macrophytes (Hoven et al. 2014), and indirectly influenced the production of food for birds.

The relatively similar morphological characteristics of Bear River Bay and Farmington Bay provide a good comparative opportunity to assess how eutrophication influences the bird populations in the two systems. A very large data set collected by the Utah Division of Wildlife Resources (DWR) is available to make this comparison (Paul and Manning 2008). For five years (1997-2001) researchers utilized overflights and shoreline surveys to identify and count birds throughout Farmington and Bear River Bays, as well as adjoining wetlands elsewhere (Fig. 7). The report of these surveys focused on individual species and total numbers, but bird densities per unit area were not summarized. Additionally, there was not an explicit effort to compare the densities in the two different bays. During the Waterbird Survey, limnological parameters were not measured, thus reducing the utility of the study to address the question of how eutrophication may influence the bird populations. However, some environmental data is available on the bays to help us understand the food web leading to the birds. The objective of my study was to summarize these reports focusing on the relative bird densities in Farmington and Bear River Bays in order to provide insights on how eutrophication influences bird densities.

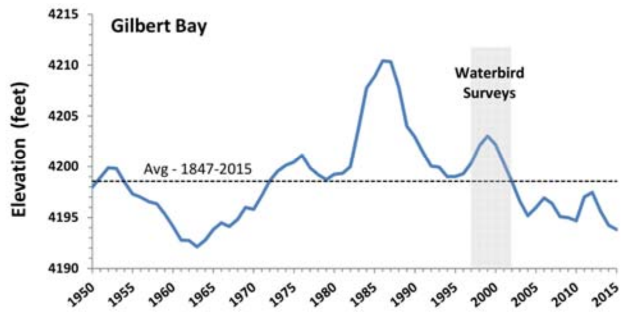


Figure 2. Changes in the elevation of Great Salt Lake (Gilbert Bay) from 1950-2015, showing the 1997-2001 period of the Waterbird Survey.

Study Area and Methods

The Great Salt Lake (GSL) is located in northwestern Utah, USA, at 41.1° N -112.5 W (Johnson et al. In Press). At a lake elevation of (4200 ft.), the total area of the lake is 4360 km^2 (1680 miles^2). At this elevation, Farmington Bay covers 312 km^2 (120 mi^2), and has a mean depth of only 1.1 m (3.5 ft.). Bear River Bay is approximately 2/3rds the area (212 mi^2; 82 mi^2) and is even shallower, with a mean depth of 0.6 m (2.0 ft.). Diked freshwater wetland along the periphery of the eastern and southern shores comprise 226 km^2 (87 mi^2) of the lake area.

Because it is a terminal lake, its elevation fluctuates greatly due to wet and dry cycles and and with water depletions for agriculture and other uses (Wurtsbaugh et al. 2017). The DWR Waterbird Surveys were done during a period when the lake was largely above it mean level of 1279.7 m (4198.6 ft; Fig. 2). Because they are shallow, the areas and depths of Farmington and Bear River Bays change markedly with changes in lake elevation.

Limnological characteristics—In many years, Farmington Bay has a deep brine layer (monimolimnion) below a depth of 0.9-1.0 m in the northern half of the bay (Fig. 3). This anoxic, hydrogen-sulfide rich layer forms because the dense saline waters from Gilbert Bay enter via the causeway bridge and underflow the fresher waters in Farmington Bay. Sedimenting algae decomposes in this layer, stripping the strata of oxygen. Although the zooplankton and benthic invertebrate prey of birds are only beginning to be studied in this layer, it is unlikely that any are there due to the anoxia and high concentrations of toxic hydrogen sulfide in this stratum.

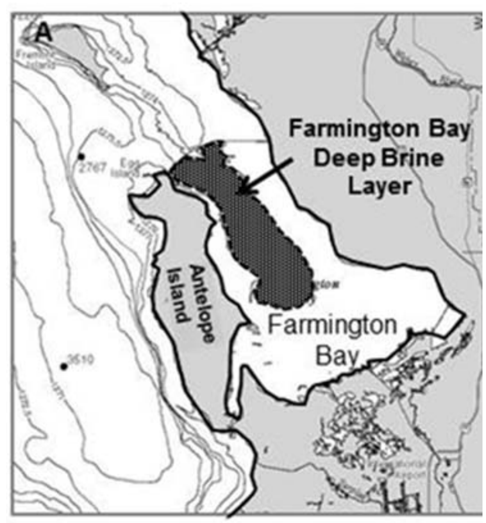


Figure 3. Position of the deep brine layer below depths of 1 m in the northern portion of Farmington Bay.

Salinity is one of the more important variables that will influence the abundance and distribution of the prey organisms of the birds. Salinity data was not collected as part of the Waterbird

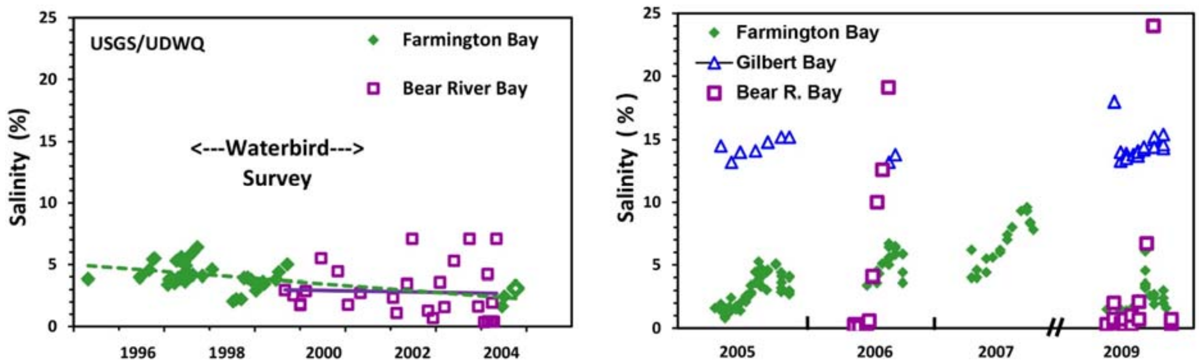


Figure 4. Left: Salinities at the outflow of Farmington and Bear River Bays into Gilbert Bay measured the USGS and Utah Division of Water Quality from 1995-2004 (www.waterqualitydata.us/portal). One point (open symbol) from Oct. 5, 2004 was taken from Marcarelli et al. (2005). Right: Surface water salinities in three bays of Great Salt Lake (2005-2009) from Wurtsbaugh et al. 2012. Salinities shown here are only for areas of Farmington and Bear River Bays that are distant from river inflows. Derived from Wurtsbaugh et al. 2012. Different salinity units available from the USGS and Utah DWQ were converted to % salinity using equations in Appendix 4.

Survey, but some data is available to help understand how this variable changes temporally and spatially. The salinity of water flowing out of Farmington Bay varied from 2-6%, during the survey (Fig. 4), but data are not available during 2000-2001. Salinities of water leaving Bear River Bay during the latter part of bird survey were similar to those in Farmington Bay, but variability was greater. Overall salinities for the 1995-2004 period shown in Fig. 4 (left) were lower in Bear River Bay than in Farmington Bay (2.4% vs. 3.6%). Wurtsbaugh et al. (2012) found that salinities in the northern part of Farmington Bay and the southwestern part of Bear River Bay were highly variable from 2005-2009. The variability is, in part, due to annual drought cycles, but also to the salinity gradient from the inflow areas to confluences with hypersaline Gilbert Bay (Fig. 5). Both bays are relatively fresh during spring runoff, but become saltier during the summer and fall as more Gilbert Bay water enters and mixes. These high salinities limit the establishment of submerged macrophytes in the saltier areas of both bays.

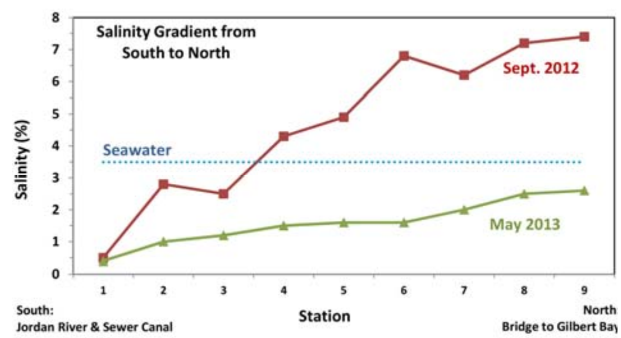


Figure 5. Salinity gradients in Farmington Bay from the south where freshwater enters, to the north where they bay joins Gilbert Bay though a bridge. Derived from (Mcculley 2014).

A very narrow deep brine layer was found in Bear River Bay, likely the result of seepage or discharges of brines from the adjoining Compass Mineral salt ponds. The wetlands in the Willard Spur area of Bear River Bay are largely fresh because a sill prevents saline water from intruding eastward. In 1999 when the lake rose to its highest level during the Waterbird Survey, researchers found that "*… many stands of emergent vegetation were inundated with lake water, and became salt burned*." This also occurred during the mid-

1980s (Fig. 2), when saline water covered all of the bay, including Willard Spur, killing macrophytes (Foote 1991).

As mentioned earlier, Farmington Bay is hypereutrophic with mean chlorophyll *a* levels over 70 µg/L, resulting in Secchi depth transparencies usually less than 0.25 m (10 inches). The low light penetration may limit the establishment of macrophytes in deeper water. Bear River Bay is also relatively productive, with mean chlorophyll levels near 15 µg/L (Fig. 6).

The blooms of the cyanobacteria, *Nodularia spumigena*, in Farmington Bay produce very high concentrations of the toxin nodularin (Fig. 6). Mean concentrations are well above those demonstrated to cause bird mortalities elsewhere, and concentrations as high as 663 µg/L have been documented. In comparison, mean concentrations (2014-2017) in Utah Lake were cyanotoxins are of concern are only 1.0 µg/L (Wurtsbaugh, unpublished data). However, an effort to determine if cyanotoxins are causing bird mortalities in Farmington Bay had limited success (Wurtsbaugh 2011).

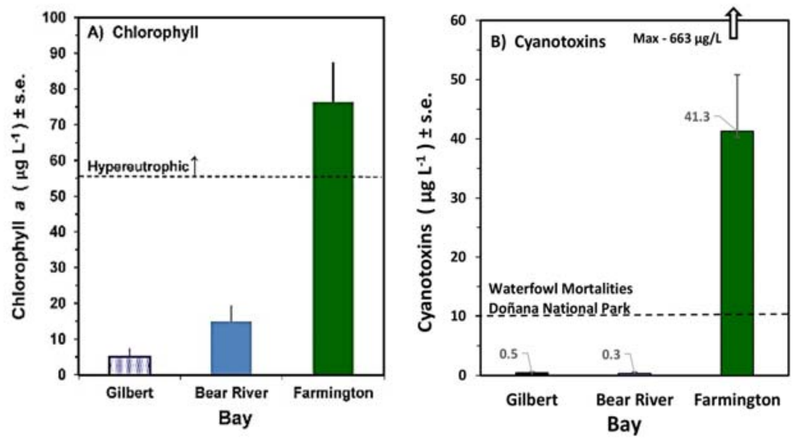


Figure 6. Left. Mean chlorophyll a concentrations in three bays of the lake during 2009. Chlorophyll provides a good index of overall phytoplankton biomass. The dotted line shows the criteria for excessive algal abundance. Right. Cyanotoxin (as microcystin LR equivalents) in the three bays. The dotted line shows the concentrations that have caused bird mortalities elsewhere. (From Wurtsbaugh et al. 2012).

Additional limnological information on Farmington Bay, and to a limited extent, Bear River Bay can be found in (Hayes 1971; Sorensen and Others 1988; Wurtsbaugh et al. 2002; Marcarelli and Wurtsbaugh 2003; Wurtsbaugh and Marcarelli 2004; Marcarelli et al. 2005; Wurtsbaugh and Marcarelli 2006; Gast et al. 2011; Wurtsbaugh and Epstein 2011; Mcculley 2014; Barnes and Wurtsbaugh 2015; Marden et al. 2015; Mcculley et al. 2015). There are also data collected by the Division of Water Quality in Willard Spur and the USGS that can be used to assess conditions there. (https://www.waterqualitydata.us/portal/).

Bird Data analysis—Mr. John Neill and Mr. John Luft of the Utah Division of Wildlife Resources (DWR) provided bird survey data on Bear River, Farmington and Ogden Bays collected in the 1997-2001 Waterbird Survey (Paul et al. 2002). The data included total count data/transect in each of the delineated areas in the bays for each of the five years the survey was done. During the survey DWR, personnel and volunteers counted and identified birds at up to 51 sites (Fig. 3) 17 times per year from April-September. A summary of the methods used by DWR to count the birds is provided in Appendix 1.

To compare data between the bays, the count numbers were normalized to the area (km^2) surveyed (Paul et al., Appendix 4). The DWR provided bird groupings by taxonomic category, but the present analysis regrouped birds into ecological categories based on their major habitat selection and diets (Table 1). This analysis focused on Farmington and Bear River Bays, but summary data on Ogden Bay is also shown to provide context.

Because the underlying reason from the study was the water quality in the bays, I only analyzed the bird density data in the open bays and the shorelines and wetlands contacting the open bays (Fig. 7; Appendix 2). That is, bird densities in areas in freshwater wetlands such as the Bear River Migratory Bird Refuge or the Farmington Bay Waterfowl Management Area were not utilized, because the effluents going into the two bays do not directly affect them. Only a single freshwater wetland in Farmington Bay was included (West Kaysville interior wetland; #17a; Fig. 7). The two freshwater wetlands in Bear River Bay were the much larger South Bear River area (#27) and Willard Spur area (#28). Counts of birds along the Antelope Island Causeway (#16) were not included in the analysis because the Waterbird Survey grouped birds on both the Ogden Bay and the Farmington Bay sides of the causeway.

During the different years of the DWR survey, the lake rose and fell, thus altering the areas of the different habitats. This did not influence the shoreline transect counts, because they were done as line and spot counts covering a swath 0.5 mile wide along the shoreline and into the shallow water. Arial surveys transects of the open waters and large wetlands of Bear River Bay were established in 1997 when the lake was near its lowest level of the survey (Fig. 2). As the lake rose, the open water area grew in area, but the length of the transects was not increased. Consequently, the total number of birds counted was likely underestimated during the high water years. I did not account for this change because bird <u>densities</u> were not influenced by transect length. This allowed comparisons to be made between the different bays without significant bias.

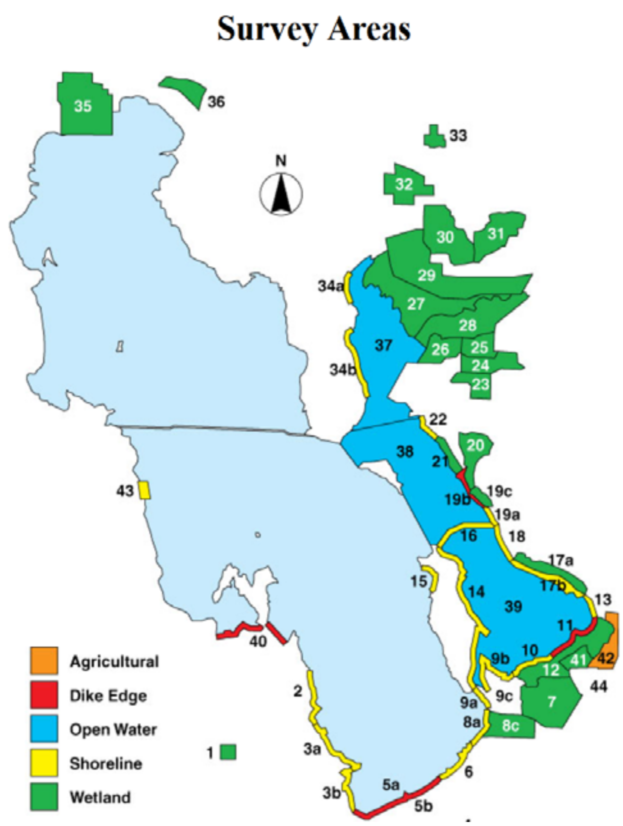


Figure 7. Map of habitat types and areas used in the Great Salt Lake Waterbird Survey(Paul and Manning 2008) . From: https://wildlife.utah.gov/gsl/waterbirdsurvey/areas.htm

Table 1. Ecological groupings and bird species analyzed in the study

Gulls and terns

BLTE	Black Tern	*Chlidonias niger*
BOGU	Bonaparte's Gull	*Larus philadelphia*
CAGU	California Gull	*Larus californicus*
CATE	Caspian Tern	*Sterna caspia*
FOTE	Forster's Tern	*Sterna forsteri*
FRGU	Franklin's Gull	*Larus pipixcan*
RBGU	Ring-billed Gull	*Larus delawarensis*

Phalaropes & Grebes

CLGR	Clark's Grebe	*Aechmophorus clarkii*
EAGR	Eared Grebe	*Podiceps nigricollis*
PBGR	Pied-billed Grebe	*Podilymbus podiceps*
WEGR	Western Grebe	*A. occidentalis*
WIPH	Wilson's Phalarope	*Phalaropus tricolor*
RPHA	Red-necked Phalarope	*Phalaropus lobatus*

Shorebirds & Ibis

WFIB	White-faced Ibis	*Plegadis chihi*
AMAV	American Avocet	*Recurvirostra americana*
BASA	Baird's Sandpiper	*Calidris bairdii*
BBPL	Black-bellied Plover	*Pluvialis squatarola*
BNST	Black-necked Stilt	*Himantopus mexicanus*
COSN	Common Snipe	*Gallinago gallinago*
GRYE	Greater Yellowlegs	*Tringa melanoleuca*
KILL	Killdeer	*Charadrius vociferus*
LBCU	Long-billed Curlew	*Numenius americanus*
LBDO	Long-billed Dowitcher	*Limnodromus scolopaceus*
LESA	Least Sandpiper	*Calidris minutilla*
LEYE	Lesser Yellowlegs	*Tringa flavipes*
MAGO	Marbled Godwit	*Limosa fedoa*
REKN	Red Knot	*Calidris canutus*
SAND	Sanderling	*Calidris alba*
SEPL	Semipalmated Plover	*Charadrius semipalmatus*
SESA	Semipalmated Sandpiper	*Calidrius pusilla*
SNPL	Snowy Plover	*Charadrius alexandrinus*
SPSA	Spotted Sandpiper	*Actitis macularia*
STLS	Stilt Sandpiper	*Calidris himantopus*
WESA	Western Sandpiper	*Calidris mauri*
WHIM	Whimbrel	*Numenius phaeopus*
WILL	Willet	*Catoptrophorus semipalmatus*

Large Predators: Pelicans, Cormorants, Herons, Egrets, Cranes

AWPE	American White Pelican	*Pelecanus erythrorhynchos*
DCCO	Double-crested Cormorant	*Phalacrocorax auritus*
BCNH	Black-crowned Night Heron	*Nycticorax nycticorax*
CAEG	Cattle Egret	*Bubulcus ibis*
GREG	Great Egret	*Casmerodius albus*
GTBH	Great Blue Heron	*Ardea herodias*
SNEG	Snowy Egret	*Egretta thula*
SACR	Sandhill Crane	*Grus canadensis*

Waterfowl, Coots & Railes

AGWT	Green-winged Teal	*Anas crecca*
AMWI	American Wigeon	*Anas americana*
BAGO	Barrow's Goldeneye	*Bucephala islandica*
BUFF	Bufflehead	*Bucephala albeola*
BWTE	Blue-winged Teal	*Anas discors*
CAGO	Canada Goose	*Branta canadensis*
CANV	Canvasback	*Aythya valisineria*
CITE	Cinnamon Teal	*Anas cyanoptera*
COGO	Common Goldeneye	*Bucephala clangula*
COME	Common Merganser	*Mergus merganser*
GADW	Gadwall	*Anas strepera*
GRSC	Greater Scaup	*Aythya marila*
LESC	Lesser Scaup	*Aythya affinis*
MALL	Mallard	*Anas platyrhynchos*
NOPI	Northern Pintail	*Anas acuta*
NSHO	Northern Shoveler	*Anas clypeata*
RBME	Red-breasted Merganser	*Mergus serrator*
REDH	Redhead	*Aythya americana*
RNDU	Ring-necked Duck	*Aythya collaris*
RUDU	Ruddy Duck	*Oxyura jamaicensis*
AMCO	American Coot	*Fulica americana*
SORA	Sora	*Porzana carolina*
VIRA	Virginia Rail	Rallus limicola

Results

A simple analysis of overall bird densities indicated that birds were almost twice as abundant in Bear River Bay as in Farmington Bay (Fig. 8). For this summary analysis, all of the birds counted in a given year were divided by the total area analyzed in each bay. This approach emphasizes birds that utilize the open waters of both bays and the extensive wetlands of Willard Spur (waterfowl, grebes, phalaropes), because the open water category dominated the total area surveyed. The analysis indicated that there was approximately a two-fold variation in bird densities over the five years of the study, but that the temporal changes in the two bays were relatively independent. For example, the lowest overall bird densities occurred in Bear River Bay in the year 2000, whereas this was the second highest year in Farmington Bay.

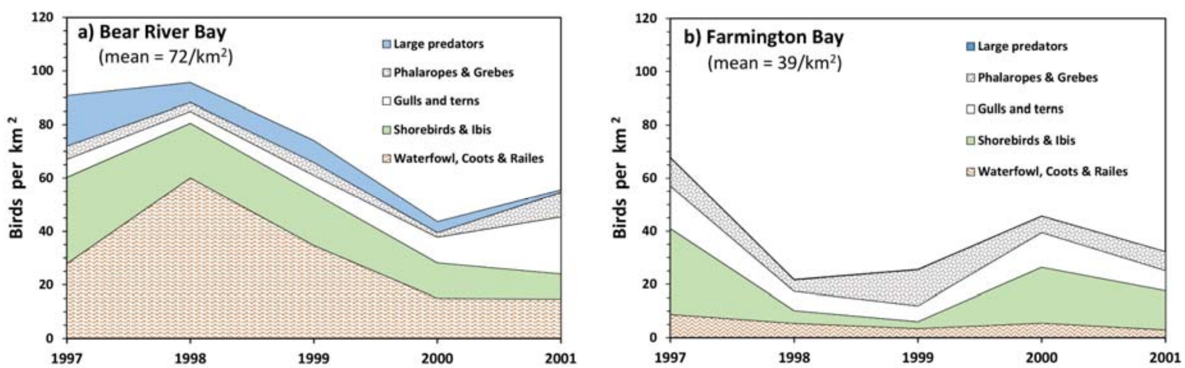


Figure 8. Summary of waterbird densities in Bear River Bay and Farmington Bay for the five years of the study. For this analysis, the total birds counted in all of the survey areas utilized (Appendix 2) was divided by the total area of all of the habitats (open water, shoreline, wetland) combined.

When bird densities were analyzed separately by habitat types, important differences emerged between the groups of birds utilizing each bay (Fig. 9; Appendix 5). In the open waters, Farmington Bay had the lowest density of all three bays. Overall densities were nearly two times higher in Bear River Bay than in Farmington Bay. This was primarily due to much higher densities of waterfowl and large predatory birds (primarily pelicans) in Bear River Bay, and high densities of phalaropes and grebes in Ogden Bay. Overall densities in the shoreline habitat were very similar between Farmington and Bear River Bays, but in Bear River, densities were dominated by waterfowl, whereas in Farmington Bay shorebirds were the dominate group. Ogden Bay had very high densities of shorebirds, phalaropes, grebes, gulls and terns that were associated with the shoreline habitat. Shorebird densities there were over twice those in Farmington Bay. In the freshwater wetland habitat, bird densities were somewhat higher in Bear River Bay than in Farmington, but again the types of birds were different, with Bear River dominated by a mix of shorebirds and waterfowl, whereas the freshwater wetland analyzed for Farmington Bay was dominated by shorebirds, ibis, with lower densities of waterfowl, phalaropes and grebes.

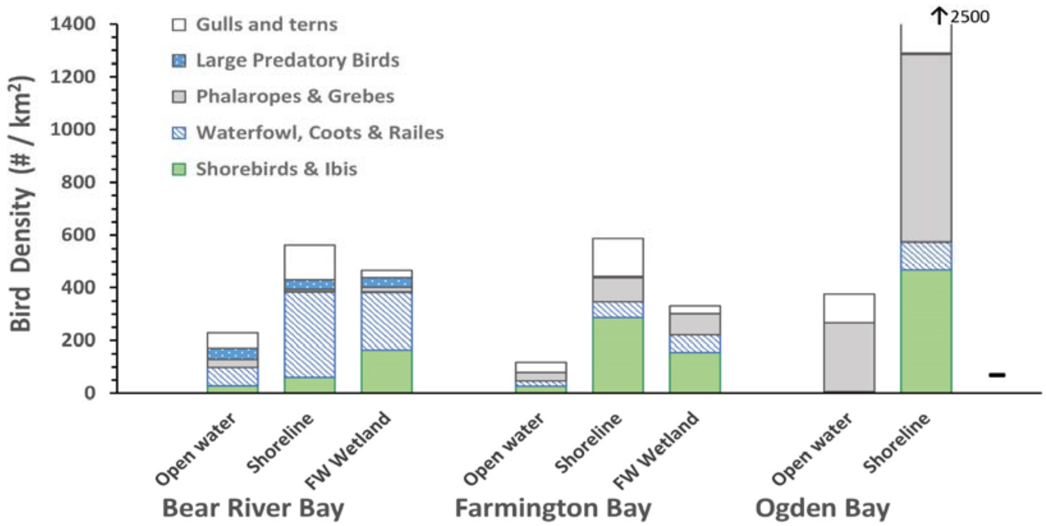
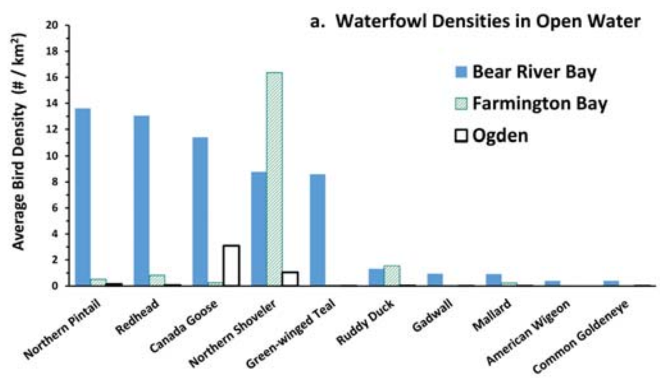


Figure 9. Mean bird densities in the open waters, shorelines and freshwater wetlands of the three bays during the 1997-2001 Waterbird Survey.

Figure 10 shows how different the three bays were with respect to particular species that utilize different habitats. In the open waters of the bays, several species of waterfowl were abundant in Bear River Bay, whereas Farmington Bay was dominated by Northern Shovelers, with relatively low densities of all other species except Ruddy Ducks. (Fig. 10a). Ogden Bay also had low densities of most species of waterfowl.

In contrast, shorebird densities in just the shoreline habitat were much higher in Ogden and Farmington Bays than in Bear River, particularly for American Avocet, Black-necked Stilts, Western Sandpipers and several other species (Figure 10b). Ogden Bay, however, had higher densities of many shorebird species than did Farmington Bay (Figs. 9, 10b).



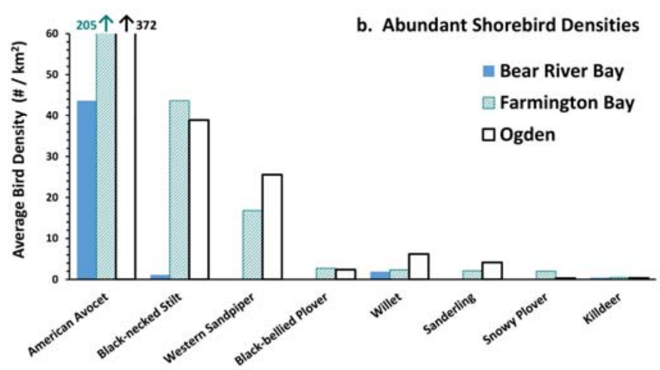


Figure 10a. Waterfowl densities in the open waters of Bear River Farmington and Ogden Bays measured during the Utah DWR waterbird survey**. Figure 10b**. Shorebird densities in just the shoreline habitat of the three bays during the 1997-2001 DWR survey.

Discussion

Limnological background—High nutrient loading to a system like Farmington Bay not only greatly increases phytoplankton abundance, but it also shifts the balance of primary production between the water column and the periphyton and macrophytes in the benthic (bottom) zone of the lake. In unproductive systems, particularly if they are shallow, over 50% of primary production occurs with the algae associated with the bottom (Vadeboncoeur et al. 2002; Vadeboncoeur et al. 2008; Brothers et al. 2016). With adequate light, the benthic algae out-compete the phytoplankton because they have "first-access" to the large store of nutrients in the sediments. In systems as shallow as Farmington and Bear River Bay one would expect over 80% of the primary production to be associated with the benthic zone if there is little eutrophication. However, with increased nutrient loading and growth of abundant phytoplankton, light penetration decreases and less and less periphyton and macrophytes can grow. The Secchi depths in Farmington Bay are typically < 0.25 m (10"). With this level of light penetration, good periphyton growth can only occur to about 0.5 m. Consequently, much of the northern end of the bay where it is deeper will have little benthic primary production, and periphyton growth will be slowed at even shallower depths.

Benthic production from periphyton supports different food webs than does pelagic production from phytoplankton. Fish are highly dependent on the production of the larger invertebrates that occur in the benthic zone, with only some juvenile fish and specialized planktivores dependent on the phytoplankton→zooplankton food web in the pelagic zone (Vadeboncoeur et al. 2002). Consequently, the hypereutrophication of Farmington Bay has likely forced periphyton growth, and the invertebrates dependent on this growth, to the shallower margins of the bay. It should be noted that both the Willard Spur area of Bear River Bay and the southern end of Farmington Bay contain fish (Moore and Wurtsbaugh 2012; Wurtsbaugh, personal observation)

The deep brine layer in Farmington Bay also contributes to a paucity of large benthic invertebrates in the deeper areas of the bay. In areas deeper than approximately 1 m, the dense brine from Gilbert Bay intrudes and produces a relatively stable layer that does not mix with the overlying water. Sedimenting algal material decomposes in the layer, stripping the oxygen from this stratum, and in turn allowing the reduction of abundant sulfate to hydrogen sulfide, the "rotten-egg" gas. Strong winds can disrupt this layer in Farmington Bay, and this is likely the reason for "lake stink" that sometimes plagues Salt Lake City and Davis County (Wurtsbaugh et al. 2012). Preliminary data indicate that densities of benthic invertebrates like chironomid midge larvae are very low in this layer (Fig. 12; Wurtsbaugh et al. 2015; Wurtsbaugh et al. 2018).

Food web and food abundance—The open water (Fig. 7) region of Farmington and Bear River Bays are probably the most directly comparable, as there is little aquatic vegetation, and salinity can be high enough in both bays to limit aquatic macrophytes (Fig. 4). As mentioned earlier, phytoplankton is far more abundant in Farmington Bay than in Bear River Bay. The high primary production in Farmington leads to high densities and biomasses of zooplankton. Wurtsbaugh et al. (2012) reported that zooplankton biomass was 5-10 higher in Farmington Bay from May-October than in the single year (2009) zooplankton were measured in Bear River Bay. Marden et al. (2015) also found high abundances of zooplankton in Farmington Bay, but his more recent data showed that populations crashed after early July, probably as the result of an increase in the insect predator, *Trichocorixa verticalis*. Although birds at Great Salt Lake feed on large zooplankton like brine shrimp and the corixids, they feed little on the smaller zooplankton such as *Daphnia, Moina* and copepods. Rather, most species feed on benthic invertebrates, corixids and brine shrimp (Wurtsbaugh 2009; Roberts 2013).

Benthic invertebrate densities in the lake have not been well documented, with the exception of the abundant brine fly larvae on the microbiolites of Gilbert Bay (Wurtsbaugh et al. 2011; Frank 2016). However, an experimental deployment of brine fly substrates demonstrated that brine flies were far less abundant in Farmington Bay than in Gilbert Bay (Fig. 11; Wurtsbaugh and Marcarelli 2006). Corixid adults, however, were abundant on these substrates. Frank (2016) found that invertebrate biomass was high in Farmington Bay, albeit lower than in Gilbert or Carrington Bay. In another study, a single survey of benthic invertebrates along the salinity and depth gradient in Farmington Bay showed that chironomid gnat larvae were very abundant at the south and mid-sections of the estuary, but dropped to very low densities in the north where salinities increased (Fig. 12; Wurtsbaugh et al. 2015). Invertebrates were nearly absent in the deep brine layer at the northern end of the bay. Frank (2016) also found a negative correlation between benthic invertebrates and depth in Farmington Bay. At the lake elevation during the DWR Waterbird survey, about 50% of Farmington Bay would have been underlain by a deep brine layer that intrudes from Gilbert Bay (Wurtsbaugh et al. 2012). This layer is anoxic and contains hydrogen sulfide making it inhospitable for benthic invertebrate prey. Indeed, preliminary analyses of an ongoing FFSL project indicate that prey densities are extremely low in the sediments beneath the deep brine layer (Fig. 7 in Wurtsbaugh et al. 2018).

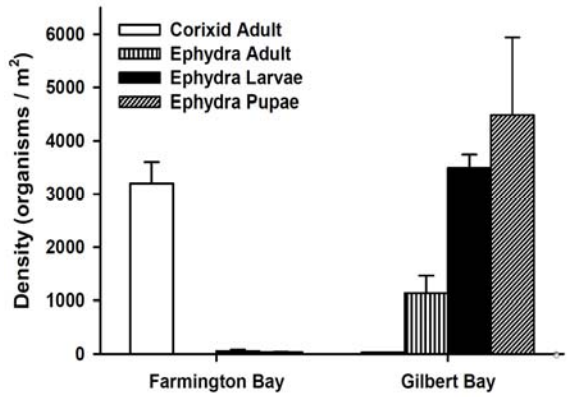


Fig. 11. Brine fly (*Ephydra* sp.) abundances on artificial substrates deployed in Farmington and Gilbert Bays. From Wurtsbaugh and Marcarelli (2006).

The very limited data on invertebrate abundances in Bear River Bay, and the complete lack of data for Ogden Bay makes it difficult to compare bird food availability amongst the bays. However, extensive benthic invertebrate analyses along salinity and inshore-offshore depth gradients are

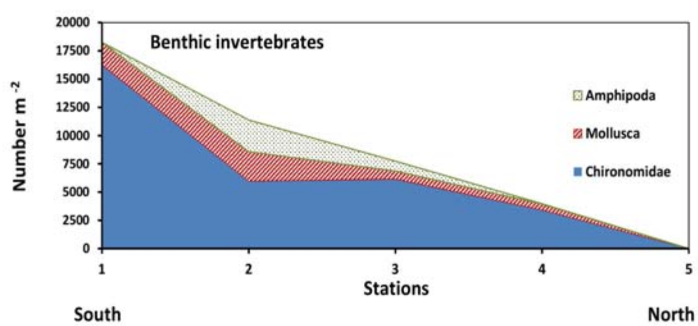


Figure 12. Abundances of benthic invertebrates along a S-N transect of Farmington Bay in October 2014. Sta. 1 is SE of the Sewer Canal and Sta. 5 is under the deep brine layer. From (Wurtsbaugh et al. 2015).

currently underway and will provide needed insights on how prey abundances differ between Farmington and Bear River Bays (Wurtsbaugh et al. 2018).

An unstudied potential source of food for shorebirds in all three bays is biofilm. Jardine et al. (2015) recently used isotopic techniques to show that biofilm (microbes, algae, muscilage) composed 20-50% of the diet of Western Sandpipers (*Calidris mauri*) during their migratory stopover at the Fraser River estuary (Canada). Biofilm is very abundant in Farmington Bay (personal observation), and thus a potential source of food for shorebirds. This food source would not be detectable in bird guts utilizing traditional microscopic techniques, so it is possible that it has gone unnoticed in the many diet studies that havbe been done.

Bird distribution and abundances—A direct comparison between the bays is complicated because of different salinity and hydrological characteristics. Although Farmington and Bear River Bays are estuaries with salinity gradients, Farmington sometimes has higher salt concentrations that may limit the establishment of submerged aquatic macrophytes, and consequently, only the southern, fresher end of Farmington Bay has submerged plants. However, during the Waterbird Survey when lake levels were higher, salinities of water leaving Farmington Bay appeared to be only slightly higher than water leaving the open water area of Bear River Bay. Like Farmington Bay, the open water area of Bear River Bay also lacks submerged aquatic macrophytes, at least in the southern parts I have visited in 2006, 2009 and 2017-18. In contrast, the entire Willard Spur region of Bear River Bay has extensive areas of this vegetation that attracts many species of birds.

During the Waterbird Survey overall bird densities were lower in Farmington Bay than in either Bear River or Ogden Bay, indicating that hypereutrophic conditions in Farmington are not likely responsible for the very high bird densities there. The lower densities in Farmington Bay were primarily due to lower densities in the expansive open waters of the bay. Wurtsbaugh et al. (2012) also reported lower bird densities in Farmington than in Gilbert Bay in the two years following the Waterbird Survey (Fig. 13). In this case, surveyed areas were in the open waters of each bay at similar depths. The survey are in Farmington Bay only included the northern half were the depth was > 0.5 m, and thus accessible to a jet-drive boat, and notably, it did not include the areas inhabited by shorebirds. Much of this portion of the bay was underlain by the anoxic deep brine layer, and thus unlikely to have contained many benthic invertebrate prey of the birds.

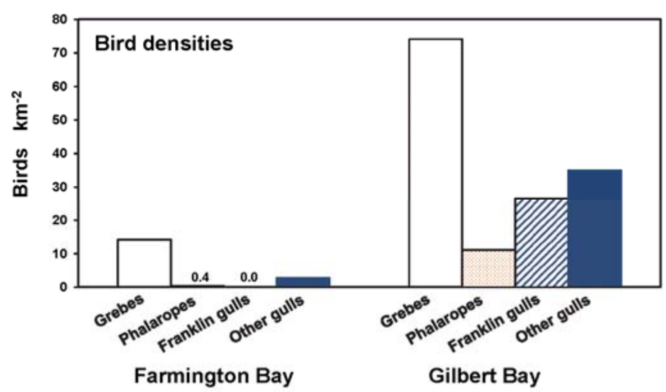


Figure 13. Bird densities estimated in the open water areas of Farmington Bay (northern half) and the western side of Gilbert Bay on five dates between March and December (2002-2003). From Wurtsbaugh et al. 2012.

In contrast to the observations during the Waterbird Survey and those shortly after by Wurtsbaugh et al. (2012), observations during 2017-2018 in the open waters of Farmington Bay have indicated relative high numbers of coots, phalaropes and earred grebes (Wurtsbaugh, personal observation). During these recent observations even the deepest parts of Farmington Bay were $\leq$1.0 m, and thus only a very limited deep brine layer was present in the northernmost, deep, area of the bay. The recent relatively high densities of birds in the open waters of Farmington Bay are consistent with high densities of phalaropes observed there by Frank (2016) during 2014-2015 when Great Salt Lake was near its all-time lowest recorded elevation. The apparent changes in bird densities in Farmington Bay could be the result of: (1) the considerable restriction of the deep brine layer when the bay is low; (2) low overall depth of the bay, making the production and accessibility of benthic invertebrates higher, or, (3) other unknown factors such as changes in toxic algae.

In contrast to the open waters, the shoreline habitat in Farmington Bay supported much higher densities of shorebirds than did the shoreline areas of Bear River Bay (Fig. 10b). This habitat is extensive in Farmington Bay, and American Avocets and other species are very abundant there. Eutrophication in Farmington Bay may support high periphyton growth and the production of invertebrates in the shallow shoreline areas ((Vadeboncoeur et al. 2008) The preliminary analysis of benthic invertebrate abundances in the shallow shoreline habitat where wading birds forage indicates that prey abundances are relatively similar in these areas of the Farmington and Bear River Bays (Wurtsbaugh et al. 2018). In nearly all sites of this study, midge larvae (Diptera) dominated the shallow shoreline community and these are suitable prey for many of the shorebirds and other birds that utilize the lake (Roberts 2013). Shorebirds, however, were considerably lower in Farmington Bay than in Ogden Bay, again suggesting that the hypereutrophic conditions of Farmington Bay are not necessary to support densities of shorebird in these shallow habitats. Since Ogden Bay is contiguous with Gilbert Bay its salinities are very high, but it also may be influenced by the nutrient-rich outfall from Farmington Bay. Limnological studies on the plankton and invertebrates in Ogden Bay are needed to help understand the high densities of birds that utilized that area. At the current low lake level, most of Ogden Bay is dry, however. Similarly, bird densities in Bear River Bay are currently strongly influenced by the desiccation of much of that ecosystem during the summer when river flows are diverted for agriculture.

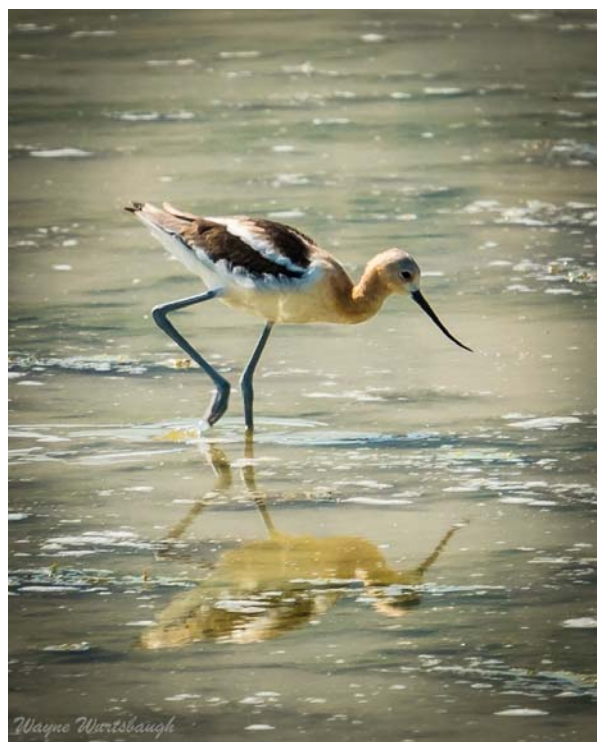


Figure 14. American Avocet foraging in the shallow water of Great Salt Lake.

The freshwater wetland areas Bear River Bay had only slightly higher densities of birds than did these wetlands in Farmington Bay. However, only a single, relatively small freshwater area of Farmington Bay was included in this analysis, so it is difficult to assess if there were any real differences.

Some questions raised during the current analysis are: (1) Why were shorebird densities so much lower along the shorelines of Bear River Bay than along those in Farmington Bay? (2) Is this due to higher periphyton growth and insect production in the shallow shoreline areas of Farmington than in Bear River Bay? (3) Why are waterfowl other than Northern Shovelers so much lower in all of the habitats of Farmington Bay than in Bear River Bay?

Additional analyses of the bird community data of Paul et al. (2002) and other studies, as well as more complete data on prey availability for birds in these bays will clarify why different bird species utilize some areas and ignore others. However, the present analysis does not confirm the hypothesis that the high nutrient loading and eutrophication in Farmington Bay is necessary to support the birds that utilize this bay.

Acknowledgements

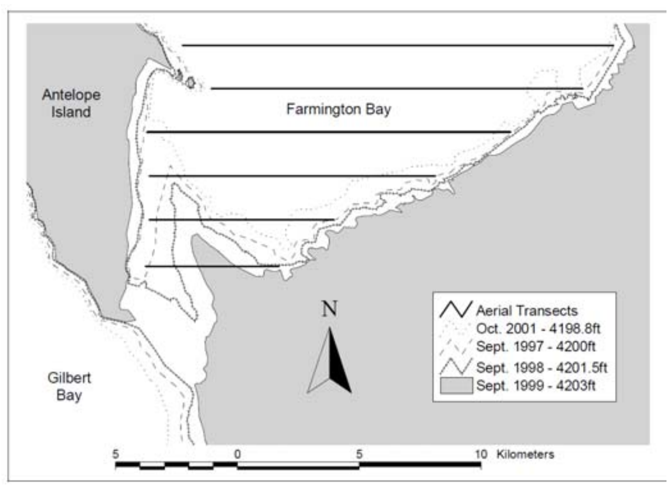
I thank Don Paul for organizing the original survey and for discussions of the DWR Waterbird Survey Report. I thank Mr. John Neill and Mr. John Luft of the Utah Division of Wildlife Resources for providing the raw data from the Waterbird Survey, and for useful discussions about the survey. The Utah Division of Forestry, Fire and State Lands provided funding for the project. I particularly want to thank Laura Vernon from the Division for her help in facilitating the project.

Appendix 1. Summary of the DWR survey methods used in the Waterbird Survey (Paul and Manning 2002):

"*Surveys were conducted every 10 days falling on or close to a designated target date. The first survey season in 1997 started in late June and continued until mid-September with nine survey periods. Seasons in 1998-2001 had 17 survey periods from April through September. Four survey techniques were used based upon the area type".*

"An important part of this ecosystem is the dynamic lake elevation, which during the study period ranged from 4199.3' to 4204.6' above sea level (ASL). During the study, the high lake elevation was in 1999. As a result, many stands of emergent vegetation were inundated with lake water, and became salt burned. As the lake receded to its lowest point during the study period in 2001, extensive mud bars void of vegetation were exposed. For five years researchers completed counts of waterbirds at GSL every ten days from April through September.

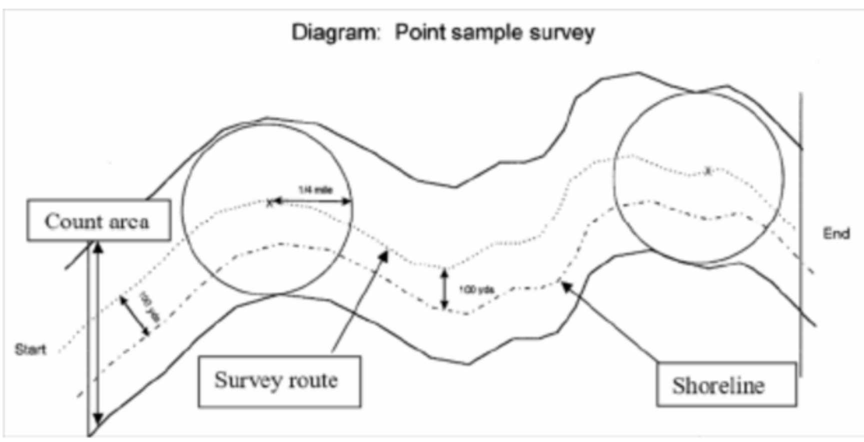
Aerial Survey (AR)—*Surveys were conducted from the air to count birds occupying open water in the large bays, …and in the Willard Spur area. Each body of water (Farmington, Ogden and Bear River bays and the Willard Spur) was broken into 0.25-mile wide transects spaced one mile apart….. In areas where shorelines were not surveyed (i.e., islands, remote areas, salt evaporation dikes), aerial surveys extended up to the shoreline. … To ensure plenty of light flights began around 7:30 am. According to the variety and abundance of waterbirds viewed below, speed of the plane varied but was typically in the range of 80-100 mph. Elevation varied, but the pilot and observers worked at maintaining an elevation of approximately 80-200 feet above the water surface. Two observers identified and counted waterbirds out to 0.125 miles on each side of the plane while noting observations on audiocassette recorders." "When GSL open water transects were developed in 1997, the GSL elevation was 4201.6' ASL (June 15, 1997). The transects for the open water in Farmington, Ogden, and Bear River bays were established so that the end points occurred one half mile off shoreline."* As the lake fluctuated in elevation and aerial extent, the transects were adjusted so that *"…counts were stopped short when the transect was within an estimated ½ mile of the shoreline."* See Fig. 15.



Append. **Figure 15.** Example of aerial transects flown in relation to the changing water expanse of Farmington Bay. From Paul & Manning (2002).

Total Count (TC)—*In total count areas, all waterbirds seen and heard in the accessible areas of the site were recorded. The number of observers varied based on the survey area demands. (e.g., numbers of birds, size of site). Often TC sites were not completely covered because of inaccessibility or the presence of dense, emergent vegetation that obstructed viewing.*

Walking Transect and Point Sample (TC w/ PS)—Surveys along the shoreline of the lake were comprised of a walking transect with at least one point sample (Fig. 16). Several shoreline areas were surveyed using all-terrain vehicles (ATV) due to their length. Survey routes began at a designated starting point and followed the contours of the shore 100 yards from the waterline (distance estimated by sight). All waterbirds observed within 0.25 mile on either side of the transect line were recorded. Upon reaching a point sample location, the observer began a 10-minute count of all birds within a 0.25-mile radius circular plot. Habitat and behavioral observations were also collected at point sample locations. All birds recorded along the transect, and within the point samples, were treated as a total count; point counts were recorded separately. All point sample locations were chosen in one of two random manners: numbers generated from a random numbers table determined the distance of random point count 11 locations from the designated starting point of the transect; ten percent of all drainage points on the south, east, and north shorelines of the lake were also selected randomly for a point count. Due to the dynamic nature of GSL shorelines, it was determined that point samples should always be centered 100 yards from the shoreline through time. The protocol required that a surveyor move at right angles from the permanently placed sample marker as necessitated by the fluctuating shoreline. At times under these conditions, the point sample marker may be isolated some distance from the shoreline on land, or be surrounded by water during high lake periods. Many of the shoreline areas in the South Arm and Farmington Bay were mapped with Global Positioning System (GPS) equipment."

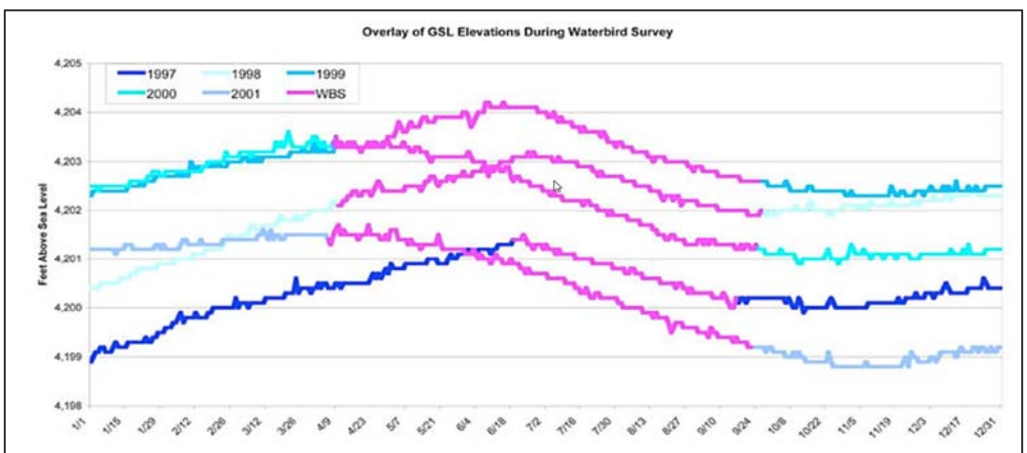


Append. **Figure 16**. Example of shoreline surveys and point samples used in the Waterbird Survey.

Appendix 2. Utah DWR survey areas (Paul et al. 2002) used in the present analysis. Counts along the Antelope Island automobile causeway were not utilized because Paul et al. (2002) grouped birds from both sides of the causeway, thus making it impossible to determine which bay they were from.

	Bear River Bay		**Farmington Bay**		**Ogden Bay**	
	Area #	Area (km^2)	Area #	Area (km^2)	Area #	Area (km^2)
Open Water	37	164.7	39	287.2	38	206.8
Subtotal area (km^2)		**164.7**		**287.2**		**206.8**
Shoreline	34A	4.3	10	7.9	21	8.114
	34B	10.6	11	5.2	22	3.894
			13	3.1	19A	3.004
			14	24.2	19B	3.942
			18	5.3		
			17B	13.3		
			9B	3.9		
Subtotal area (km^2)		**14.9**		**62.8**		**19.0**
Freshwater Wetland	27	82.7	17A	17.7		
	28	65.9				
Subtotal area (km^2)		**148.6**		**17.7**		
Total Area (km^2) for Bay		**328.2**		**367.7**		**225.8**

Appendix 3. Lake elevations (feet) during the 1997-2001 Utah DWR Waterbird Survey (WBS). Arial transects were established in 1997 when the lake was near the lowest elevation of the survey period. From: https://wildlife.utah.gov/gsl/waterbirdsurvey/elevations.htm



Great Salt Lake Elevation Fluctuations from 1997-2001

Appendix 4. Equations used to convert USGS and Utah DWQ salinity data to common units.

Equation		Source
% salinity	$= 132.404 * \mathrm{Ln}$ (Density, g/cm^3) $+ 0.7702$; $r^2 = 0.962$	W. Gwynn/C. Miller
% salinity	$= -0.000042*\mathrm{TDS}^2 + 0.095032*\mathrm{TDS} + 0.261212$; TDS = total dissolved solids (g/L); $r^2 = 0.999$	W. Gwynn/C. Miller
% salinity	$= 0.000038*(\mathrm{uS})^{1.064804}$; $r^2 = .982$, 100-100,000 uS	W. Wurtsbaugh

Appendix 5. Mean bird densities in different bays and habitat types measured during the 1997-2001 Great Salt Lake Waterbird Survey.

Species	Bear River Bay			Farmington Bay			Ogden Bay	
	Open water	Shoreline	Freshwater wetland	Open water	Shoreline	Freshwater wetland	Open water	Shoreline
Gulls and terns	9.485	22.464	4.629	6.446	24.237	4.842	18.242	205.129
Black Tern	0.006	0.000	0.417	0.015	0.479	0.023	0.001	0.068
California Gull	48.663	87.885	8.860	18.462	70.037	8.314	96.445	380.728
Caspian Tern	0.233	1.360	0.138	0.004	0.116	0.009	0.001	0.078
Forster's Tern	0.402	1.362	2.096	0.053	1.269	0.599	0.005	1.791
Franklin's Gull	5.973	30.630	15.488	18.746	63.609	19.408	11.977	741.908
Ring-billed Gull	1.636	13.550	0.774	1.397	9.910	0.702	1.022	106.204
Subtotal	**66.4**	**157.3**	**32.4**	**45.1**	**169.7**	**33.9**	**127.7**	**1435.9**
Pelicans, Cormorants, Herons, Egrets, Cranes	6.089	5.158	5.302	0.014	0.728	0.188	0.007	0.702
American White Pelican	41.368	34.365	33.865	0.074	2.448	0.209	0.027	3.130
Black-crowned Night Heron	0.025	0.033	0.131	0.000	0.403	0.221	0.000	0.133
Cattle Egret	0.000	0.065	0.071	0.000	0.134	0.177	0.000	0.031
Double-crested Cormorant	0.817	0.166	0.922	0.014	1.227	0.019	0.004	0.630
Great Blue Heron	0.112	0.494	0.397	0.006	0.240	0.116	0.008	0.338
Sandhill Crane	0.001	0.211	0.005	0.000	0.032	0.013	0.000	0.087
Snowy Egret	0.303	0.771	1.726	0.006	0.612	0.561	0.006	0.568
Subtotal	**48.7**	**41.3**	**42.4**	**0.1**	**5.8**	**1.5**	**0.1**	**5.6**
Phalaropes & Grebes	5.174	1.405	2.911	5.460	14.902	13.313	43.531	118.291
Clark's Grebe	0.000	0.174	0.000	0.000	0.028	0.000	0.000	0.000
Eared Grebe	7.547	6.380	6.704	22.479	24.276	9.562	227.299	59.294
Pied-billed Grebe	0.000	0.010	0.009	0.000	0.012	0.000	0.000	2.141
Red-necked Phalarope	0.359	0.017	0.004	0.500	5.719	1.197	0.598	6.599
Western Grebe	4.953	1.478	2.312	0.018	0.175	0.000	0.046	0.025
Wilson's Phalarope	18.187	0.373	8.439	9.765	59.201	69.116	33.244	641.690
Subtotal	**36.2**	**9.8**	**20.4**	**38.2**	**104.3**	**93.2**	**304.7**	**828.0**
Shorebirds & Ibis	1.641	3.552	9.665	1.557	16.906	9.118	0.084	27.492
American Avocet	13.429	43.652	57.957	23.709	204.961	72.869	1.257	372.132
Baird's Sandpiper	0.000	0.000	0.013	0.000	0.190	0.000	0.000	0.226
Black-bellied Plover	0.010	0.000	0.025	0.005	2.704	0.172	0.000	2.379
Black-necked Stilt	5.270	1.113	14.383	2.604	43.643	52.056	0.083	38.898
Greater Yellowlegs	0.000	0.064	0.032	0.000	0.266	0.001	0.000	0.071
Killdeer	0.000	0.425	0.013	0.000	0.472	0.002	0.000	0.332
Least Sandpiper	0.000	0.000	0.000	0.000	0.169	0.000	0.000	0.485
Lesser Yellowlegs	0.000	0.001	0.000	0.000	0.027	0.022	0.000	0.078
Long-billed Curlew	0.001	1.118	0.000	0.000	0.049	0.002	0.001	0.192
Long-billed Dowitcher	5.212	0.002	21.235	0.000	0.461	6.238	0.000	3.160
Marbled Godwit	0.316	0.070	19.186	0.006	0.167	0.048	0.007	0.744
Sanderling	0.002	0.000	0.000	0.000	2.101	0.000	0.000	4.137
Snowy Plover	0.000	0.035	0.000	0.000	2.002	0.000	0.000	0.293
Spotted Sandpiper	0.000	0.007	0.001	0.000	0.013	0.001	0.000	0.019
Western Sandpiper	0.000	0.014	17.929	0.000	16.800	1.320	0.000	25.563
White-faced Ibis	3.649	11.984	33.457	0.147	11.032	21.651	0.078	12.473
Willet	0.006	1.897	0.081	0.001	2.342	0.620	0.002	6.175
Subtotal	**29.5**	**63.9**	**174.0**	**28.0**	**304.3**	**164.1**	**1.5**	**494.8**
Waterfowl, Coots & Railes	4.389	20.258	13.668	1.241	3.753	4.142	0.279	6.696
American Coot	10.481	33.775	35.155	0.020	7.220	14.142	0.006	2.662
American Wigeon	0.392	48.257	1.481	0.018	0.213	0.051	0.000	1.105
Blue-winged Teal	0.000	0.035	0.020	0.000	0.063	0.013	0.000	0.271
Bufflehead	0.007	0.005	0.091	0.000	0.024	0.016	0.000	0.007
Canada Goose	11.381	55.884	2.151	0.249	3.975	2.616	3.094	10.178
Canvasback	0.013	0.016	0.304	0.000	0.005	0.006	0.000	0.018
Cinnamon Teal	0.144	2.210	5.983	0.003	0.669	2.897	0.002	2.959
Common Goldeneye	0.392	0.052	0.015	0.002	0.004	0.000	0.002	0.006
Gadwall	0.936	13.869	26.702	0.041	2.373	0.642	0.008	2.798
Green-winged Teal	8.595	75.806	61.229	0.049	4.810	1.783	0.000	21.930
Lesser Scaup	0.231	0.636	0.263	0.019	0.233	0.052	0.054	0.783
Mallard	0.913	4.976	23.561	0.229	2.258	6.972	0.000	2.224
Northern Pintail	13.606	19.146	30.752	0.511	1.254	1.953	0.148	9.069
Northern Shoveler	8.775	52.242	25.099	16.358	35.631	32.107	1.051	50.400
Readhead	13.043	10.729	3.683	0.817	0.713	1.906	0.070	2.163
Ruddy Duck	1.311	6.490	2.205	1.540	0.601	1.107	0.029	0.572
Subtotal	**74.6**	**344.4**	**232.4**	**21.1**	**63.8**	**70.4**	**4.7**	**113.8**
Grand Total	**255.5**	**616.7**	**501.5**	**132.6**	**647.9**	**363.1**	**438.7**	**2878.3**

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