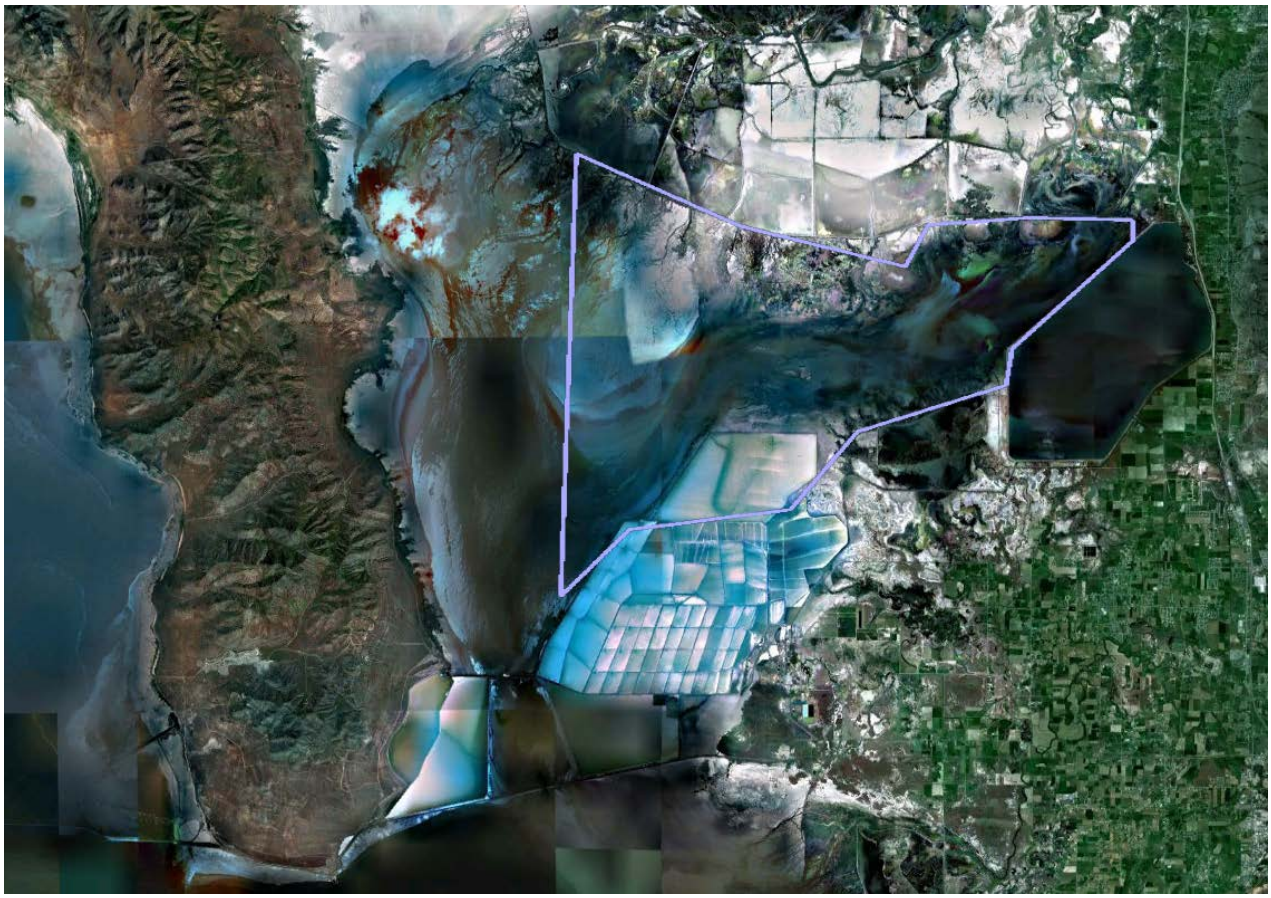


Assessment of wetland vegetation in the Willard Spur, Great Salt Lake, UT:

A literature review

Prepared by Rebekah Downard, Kimberly A. Sims, A. Lexine Long, and Karin M. Kettenring

Ecology Center and Department of Watershed Sciences, Utah State University

For the Utah Division of Water Quality

Cite as: R. Downard, K.A. Sims, A.L. Long, and K.M. Kettenring. 2013. Assessment of wetland vegetation in the Willard Spur, Great Salt Lake, UT: A literature review. Final report to the Utah Division of Water Quality. 42pp.

Introduction

The purpose of this literature review is to provide background information on the habitat and vegetation of Willard Spur, Great Salt Lake, UT, to address the question: *What water quality standards are fully protective of the beneficial uses of Willard Spur as they relate to the proposed publically owned treatment works (POTW) discharge?*

To that end, we address the following questions:

1. What species of emergent and submerged aquatic vegetation are of interest in terms of habitat and impacts from nutrients in Willard Spur? What water depths/conditions are characteristic of their preferred habitat? What work has been done in the past to study this relationship in the Willard Spur area (including Bear River Migratory Bird Refuge, Harold Crane Wildlife Management Area, and Bear River Bay)?
2. What factors might affect plant species and vegetation cover in wetland habitats similar to Willard Spur, e.g., water level, salinity, nutrients?
3. What invasive plant species are of concern in the Willard Spur area? What are the possible effects of invasive plant species upon habitat values and use by wildlife in Willard Spur?
4. What do the existing data describe in terms of the distribution of existing vegetation, including percent cover of emergent vegetation, submerged aquatic vegetation, invasive species, phytoplankton, and biomass of algae in Willard Spur?
5. What datasets or maps are available that document the habitat and/or vegetation of Willard Spur in past years?
6. What does the literature reveal regarding the effects of nutrients on the distribution, abundance, and reproduction of invasive plant species found in the Willard Spur area?

The Willard Spur is a unique wetland environment within the unusual system of the Great Salt Lake, and the area has not been studied extensively. To address questions about vegetation and habitat we must first describe the unique geographic, ecological, and hydrological context of the Willard Spur, especially in relation to the larger GSL ecosystem. After a brief overview of the Willard Spur, we will discuss the important habitat species (Q1), the way they interact with the environment of the Willard Spur (Q2), invasive species of concern (Q3), the information we currently have to describe the vegetation and algal communities of the Willard Spur (Q4), older vegetation data sets (Q5), and potential future distributions of invasive species (Q6). Where appropriate, we use information from other regions of the GSL where research has been underway for several years to determine bird use of different habitat types and the water quality dynamics driving changes to habitat. Where region-specific research is not available, we rely on the larger wetland ecology literature to address our six questions.

Context

Geographic context. Great Salt Lake (GSL) is the world's fourth largest terminal lake, and consists of four large bays that vary in salinity (see Figure 1; UDWQ 2009). Because of its relatively shallow depth, fluctuations in basin precipitation have significant impacts on water levels and salinities. These fluctuating water levels and salinities drive the distribution and abundance of vegetation and other aquatic species. The GSL receives an average of 2.9 million acre-feet of water and 2.2 million tons of salt annually. The majority of inflow comes from the Bear River drainage (39%), followed by direct precipitation (31%), Weber River drainage (13%),

Jordan River drainage (9%), minor side streams (5%), and groundwater (3%) (Arnow and Stephens 1990). GSL wetlands are mainly associated with the deltas of major tributaries (Figure 1). Eighty five percent of the State of Utah's population lives in the Wasatch Front region east of the GSL, and that population is predicted to increase by 50% in 20 years, growth that will require significant water development (Baskin et al. 2002). Several researchers have pointed to decreased water inputs due to upstream diversions and climate change as the biggest threat to the larger GSL ecosystem (Bedford 2009, Belovsky et al. 2011).

Before construction of the east-to-west railroad causeway in 1959, the GSL was considered relatively well mixed, but the causeway essentially cut the GSL in half and permanently altered the flow of water and dissolved solids. Flow restriction has resulted in overall higher dissolved solids in Gunnison Bay, although lake water levels can alter net north-south flow (Loving et al. 2000). The large influx of freshwater from the Bear River drainage results in some of the lowest salinity levels (1-22%) in the Bear River Bay and therefore greater plant, macroinvertebrate, and fish species diversity than other bays within the lake (Moore 2011). The Willard Spur (Figure 2), a channel linking Bear River drainage areas in the north and east, to the Bear River Bay to the west, consists mainly of open water, with an estimated volume of 11.7 million cubic meters when the Lake is at an elevation of 1,280.6m (4,202 feet) (von Stackelberg 2010). The Spur is bounded by several man-made structures, including the southern dikes of Bear River Migratory Bird Refuge (BRMBR), Harold Crane Wildlife Management Area (HCWMA), and Willard Bay Reservoir, as well as evaporative ponds of GSL Minerals (see Figure 1, Manning and Paul 2003).

Ecological context. GSL is an oasis in a largely desert region that hosts millions of migratory birds from the Central and Pacific Flyways every year (Bedford 2009). Willard Spur is a unique area of ecological importance within GSL due to the abundance of habitat that it provides to migratory birds that make use of the waterway and shorelines (Manning and Paul 2003). The unimpounded marsh and open water bay of the Willard Spur are some of the least known aspects of the GSL ecosystem, but provide important breeding, foraging, and resting habitat for birds (SWCA 2012). According to Aldrich and Paul (2002), the avian community at Willard Spur "is exceptionally complex. With its species richness, diversity, and overall abundance, this area continually provides one of the most magnificent displays of bird life on the lake. Although the smallest region on the Lake, it makes an exceptional contribution to the lake's avian population." The birds that utilize these habitats represent significant portions of North American populations of each species. Large freshwater inputs from the Bear River also result in higher levels of fish, macroinvertebrate, and vegetation diversity relative to other parts of the GSL (Aldrich and Paul 2002).

Changes in input of freshwater and lake elevation result in fluctuating water depths, salinity, and ultimately different vegetation communities that provide important habitat for migratory birds (Keddy et al. 2009). There are four basic types of wetlands present in the Willard Spur region: open water wetlands dominated by submerged aquatic vegetation (SAV), emergent marshes dominated by herbaceous plant species, hemi-marsh composed of both submerged and emergent wetland types, and playas composed of halophytic (salt-tolerant) vegetation (Aldrich and Paul 2002). Open water wetlands contain SAV that are a critical food source for waterfowl; emergent wetlands and hemi-marsh provide large seeds for migratory bird feeding and cover for nesting and molting; wading birds utilize the warm, temporarily flooded

habitat of playa wetlands to forage for invertebrates (Cowardin et al. 1979, Aldrich and Paul 2002).

Hydrologic and nutrient context. Hydrology is an important factor controlling wetland structure and function, and is highly dynamic in arid regions due to differences in the timing of precipitation and stream flow. The Bear River watershed is the dominant supply of freshwater to Willard Spur. The Bear River receives most precipitation as snow at higher elevations during the winter months while releasing a large pulse of stored water during spring runoff. The valleys, like that in which the GSL is located, receive much less precipitation that is more evenly distributed throughout the year (Baskin et al. 2002). Bear River flow rates can range from 6,520 to 2,020 cubic feet per second (cfs) during peak spring runoff in wet and dry years, respectively, before dropping to 552 cfs or less later in the summer (UGSG 2013). The volume of the water in Willard Spur, and GSL more generally, responds to these changes with relatively small changes in elevation (fluctuating between 1,278 and 1,283 meters (4,191 – 4,212 ft) above sea level), but large changes in surface area, due to the gentle slopes of the lake bed (GSL Planning Team 2013). Bear River Bay in particular fluctuates in area more than other bays of the lake (Manning and Paul 2003). Extensive areas of wetland adjacent to GSL have been impounded prevent these large fluctuations in wetland water level. Willard Spur, however, remains unimpounded. As such, there are substantial differences in flooded wetland area that occur both seasonally and between high and low water years. These fluctuations impact the cycling of nutrients in ways that are currently difficult to predict, but likely involve dilution of nutrients, changes in the connectivity of the Willard Spur aquatic system to sources of nutrients and other larger bodies of water, and the varied effects of salinity on the fate and rate of cycled nutrients (GSL Planning Team 2013).

Nitrogen and phosphorous, in various forms, are the main elements of interest when discussing nutrient enrichment in wetlands, since these elements are considered to be most likely limiting to plant growth (Reddy and DeLaune 2008, Schlesinger and Bernhardt 2013). When nitrogen enters a wetland it may be incorporated into plant tissues, sorbed to soil organic matter, or ammonified or denitrified by bacteria in saturated soils. Nitrogen may also be exported from a wetland by gaseous losses (N_2 or N_2O, associated with denitrification), or by surface water transport to other aquatic systems or aquifers. In contrast, phosphorus can be taken up by plants, sequestered in litter and organic soils, bound to clay soil particles, or exported via surface water transport (Mitsch and Gosselink 2007); but there are no other significant pathways for phosphorus to be removed from an ecosystem in a closed hydrologic basin.

Little research has been done on the nutrient dynamics in the Willard Spur. Extrapolating from research on nutrient dynamics in the hyper-saline portions of the GSL or freshwater and brackish wetland systems elsewhere in the country is difficult because the Spur has a unique ecological community present along a dynamic hydrologic and salinity gradient. Applying knowledge from other regions of the U.S. is also complicated by fluctuating water levels that change the salinity of the Spur from month to month and disrupt the hydrologic connectivity between sources of freshwater and nutrients, Willard Spur, and GSL (CH2M Hill 2013). The major sources of nutrients to Willard Spur are from BRMBR, Willard Bay Reservoir, HCWMA outfalls, and the Perry POTW; the relative nutrient contribution of each of these varies over the course of the year (CH2M 2013). Annual precipitation fluctuations, and the resulting inflows from each water source, play a major role in determining the nutrient load that eventually reaches

Willard Spur. When the lake elevation is below 1,278 m (4,164 ft), a common event during dry years, Bear River Bay is no longer connected to the main body of the lake and much of the Willard Spur is dewatered (GSL Planning 2013).

GSL, like many terminal lakes, is hyper-eutrophic, having accumulated nutrients over many centuries (Belovsky et al. 2011). Under these conditions nutrient loads from the watershed represent only a small proportion of total nutrient pools. For these types of systems, there is a need to better understand the relative importance of nutrient inputs (as loads) versus internal cycling on nutrient availability, and need to be studied on decadal scales (Belovsky et al. 2011). In the open water hyper-saline system (including Gilbert Bay), increased nitrogen inputs lead to increased phytoplankton production, which favors increased brine shrimp production and supports large bird populations (Roberts 2013). This process is mediated by salinity, as nitrogen can also be sequestered in brine layers and may be released during periods of low water and extremely high salinity (Belovsky et al. 2011). Much less is known about how nutrients affect the wetland plant communities in the freshwater and brackish parts of GSL, including Willard Spur. Recent research in freshwater and brackish bays of GSL indicate that increased nutrients can cause excessive algal production that is detrimental to SAV growth and lead to anoxia and toxic algal blooms (Hoven and Miller 2009, GSL Planning Team 2013). In addition, emergent vegetation is threatened by invasive plant species, such as *Phragmites australis*. *Phragmites*' spread may be enhanced by nutrients because it is more effective at utilizing nutrients than many native species, thus increased nutrients shift the competitive advantage in favor of *Phragmites* (Farnsworth and Meyerson 2003, Minchinton and Bertness 2003).

Policy context. The Clean Water Act requires states to develop numeric water quality standards for the amount of nitrogen and phosphorous a particular water body can receive before its designated beneficial uses are impaired (Mitsch and Gosselink 2007, Nadeau and Leibowitz 2003, EPA 2008). The State of Utah is currently developing water quality standards for GSL that are specific to the dynamic nature of nutrient cycling, transport, and storage as mediated by changing salinity levels (USGS 1985, CH2M Hill 2010). Site-specific standards are necessary for GSL because it has a greater capacity for nutrient absorption due to the dynamics of brine shrimp populations (Bioeconomics, Inc. 2012, UDWQ 2012). Currently there are no numeric nutrient criteria for wastewater treatment discharge specific to the GSL, but there are narrative criteria for the Bear River Bay to protect "infrequent primary and secondary contact recreation, waterfowl, shorebirds, and other water-oriented wildlife including their necessary food chain" (GSL Planning Team 2013). An increased understanding of the vegetation of the Willard Spur utilized by wildlife and the impacts to that vegetation due to changes in water quality would enable managers and policy makers to better predict the effects of future threats on the Willard Spur's ecosystems.

Here we present a literature review on Willard Spur wetland vegetation, including invasive plants, and their relationship to abiotic factors with a focus on nutrients.

Responses to Questions 1-6

1. What species of emergent and submerged aquatic vegetation are of interest in terms of habitat and impacts from nutrients in Willard Spur? What water depths/conditions are characteristic of their preferred habitat? What work has been done in the past to study

this relationship in the Willard Spur area (including BRMBR, HCWMA, and Bear River Bay)?

Historical and current management plans indicate a handful of plant species are important for migratory bird habitat in GSL wetlands. Studies of bird diets have found that plants commonly make up nearly 50% of waterfowl diets in the early summer and more than 90% by the late summer and fall, shifting as plants and their seeds grow through the season (Cox and Kadlec 1995, Wilson et al. 2011). Shorebirds rely less on plant material in their diet, with seeds constituting just 15% of shorebird diets (Cavitt 2006). Plant species tend to be limited to specific wetland types based on salinity and water regime and will be discussed below in order of decreasing depth and permanence of water. The 2004 management plan for BRMBR (which includes the northern-most portion of the Willard Spur) provides the most specific recommendations for water depth management practices to maintain desirable habitat species (Olson et al. 2004).

Open Water/Submerged Wetlands. Open water wetlands dominated by SAV are used extensively by waterfowl, which include ducks, swans, and geese. Key SAV species in open water wetlands include *Stuckenia pectinata* (sago pondweed), *Stuckenia filiformis* (fine leaf pondweed), *Ruppia maritima* (widgeon grass) and *Zannichellia palustris* (horned pondweed) (Christiansen and Low 1970, Cox and Kadlec 1995, Hoven 2010). The tubers and seeds of submerged species provide food for waterfowl and shorebirds and provide structural support for macro-invertebrate communities utilized by multiple bird guilds (Dennison et al. 1993). According to Olson et al. (2004), water levels of deep submerged communities should be maintained at 46 - 91 cm to attract larger waterfowl. Shallow submergent wetlands that are used by ducks and other smaller waterfowl should be flooded to a depth of 10 - 46 cm. Older research conducted in the impounded northern portion of Bear River Bay found that greatest SAV production rates were found in areas flooded to 46 cm, with lower production at higher depths and significantly less production at lower water depths (Robel 1962). SAV are found in freshwater and brackish wetlands, and of submerged species, *Stuckenia pectinata* has the highest salinity tolerance (Kantrud 1990). See Table 1 for a condensed list of important habitat plant species and associated water level and salinity thresholds. The timing of flooding is also critical in determining plant communities. Submerged wetlands are characterized by more permanent flooding regimes (Cowardin et al. 1979). However, a recent survey of the lowest parts of the Bear River Bay near GSL Minerals found that SAV growth is likely supported through low water years by ample seed banks (Hoven 2011).

Emergent wetlands. Emergent wetlands are dominated by herbaceous vegetation (grasses and grass-like species) growing up through standing water. These wetlands provide both food in the form of seeds and cover for nesting, brooding, and molting habitat for waterfowl (Aldrich and Paul 2002). Key emergent species include *Schoenoplectus maritimus* (alkali bulrush), *Schoenoplectus acutus* (hard stem bulrush), *Schoenoplectus americanus* (Olney's three square bulrush), and *Distichlis spicata* (salt grass) (Table 1) (Christiansen and Low 1970, Cox and Kadlec 1995, Aldrich and Paul 2002, Olson et al. 2004, CH2M Hill 2005). Less desirable but common plant species include *Typha* species (cattail) and *Phragmites australis* (common reed); these will be discussed in Questions 3 and 6. Older studies on the GSL also include *Hordeum jubatum* (foxtail barley), *Juncus arcticus* (arctic rush), *Salix* spp. (willows), *Eleocharis palustris* (common spikerush), *Xanthium strumarium* (cocklebur), *Atriplex* spp. (saltbush),

Asclepias speciosa (showy milkweed), and *Polypogon monspeliensis* (rabbit foot grass) as species that showed up consistently in emergent vegetation surveys (Williams and Marshall 1937, 1938, Chura 1962). Deep emergent marshes with water depths between 30 and 60 cm tend to be dominated by *Schoenoplectus acutus* and shallow emergent marshes with water levels between 5 and 20 cm are characterized by *Schoenoplectus maritimus* (Olson et al. 2004). However, older work conducted by Robel (1962) on private land in the Bear River Bay found that increasing water depths beyond 40 cm increased the vigor of *Schoenoplectus maritimus*. Emergent wetlands can have a number of different water regimes, from temporarily flooded to permanently flooded (Cowardin et al. 1979). Research on salinity and plant growth has found that salinity tolerances vary by species. Table 1 lists these tolerances, which vary by study, but generally *Phragmites* is the least tolerant emergent species, followed by *Typha* spp. *Schoenoplectus acutus* is tolerant of moderate salinities and *Schoenoplectus maritimus* is the most salt-tolerant emergent species (Kadlec 1982, Christiansen and Low 1970, CH2M Hill 2005). Early work to determine the best salinity levels for important habitat species was conducted at Ogden Bay WMA, south of Willard Spur in the 1960s and found that draining wetlands was a good idea when conductivity exceeded 10 mmhos/cm in order to promote the healthiest emergent vegetation conditions (Christiansen and Low 1970).

Hemi-marsh. Hemi-marsh habitats are a mix of open water and emergent wetlands (composed of the species listed above) and harbor the greatest diversity of bird communities around the GSL (Aldrich and Paul 2002). The structure of vegetation, with regard to distance to water, height, and density, is important for birds when considering habitat use, particularly in hemi-marsh wetlands. For breeding, waterfowl require protected nesting areas and access to open water for food. At Ogden Bay Waterfowl Management Area (OBWMA), south of the Willard Spur, median distance from nest to open water was 4.6m (Dey 1964). *Typha* spp. serve as nesting habitat for some waterfowl and muskrats often open up dense stands to create more breeding areas for waterfowl. Canada geese in particular favor the elevation provided by muskrat houses made from *Typha* spp. fragments as well as the ample food in surrounding open water (Smith 1955). Typical vegetation cover and type of nesting platform chosen by Canada geese were *Schoenoplectus maritimus* vegetation mats and *Typha* spp. muskrat houses (Dey 1964). Hemi-marsh water levels held to a depth of 20-30 cm should provide good nesting habitat, plant food, and structure for invertebrates that support multiple bird guilds (Olson et al. 2004). *Schoenoplectus maritimus*, *S. americanus*, and *Ruppia maritima* are commonly located in regions of moderate salinity, while *S. acutus* and *Stuckenia pectinata* are found in regions with the freshest water (no number provided, Aldrich and Paul 2002). According to work done by Cox and Kadlec (1995) in the Bear River Bay, water with salinity lower than 2.8 mmhos/cm had the most productive stands of emergent and submerged vegetation, while high salinity sites around 27.9 mmhos/cm had low vegetation, and areas with salinity >27.9 mmhos/cm did not have standing vegetation.

Playa. Nesting habitat for shorebirds differs from that of waterfowl. As such, shorebirds are most likely to feed and nest in playa or mudflat habitats. Playa communities are dominated by *Salicornia rubra* (red swampfire), *Sarcocornia utahensis* (Utah swampfire), *Suaeda calceoliformis* (Pursh seepweed) and *Suaeda moquinii* (Mojave seablite) (Christiansen and Low 1970, Cox and Kadlec 1995, Aldrich and Paul 2002, Olson et al. 2004, CH2M Hill 2005, Hoven 2010) (Table 1). Shorebirds, such as the long-billed curlew, avocets, and stilts tend to nest near small patches of vegetation close to bare ground (Paton and Dalton 1994, Aldrich and Paul 2002).

A study conducted at Harold Crane WMA found that long-billed curlews selected nesting vegetation <10 cm tall and preferred *Salicornia rubra, Bassia hyssopifolia* (fivehorn smotherweed), *Suaeda calceoliformis*, *Distichlis spicata*, and *Chenopodium album* (lambs quarter) (Paton and Dalton 2004). Playas or mudflats usually only have surface water during the spring months and at very shallow levels, 0-5 cm (Cowardin et al. 1979, Olson et al. 2004). Species with the highest salinity tolerances include *Sarcocornia utahensis*, *Salicornia rubra*, *Distichlis spicata*, and *Suaeda* spp. (Kadlec 1982).

Appendix A contains comprehensive plant lists from vegetation surveys conducted in 1934, a 2006 survey of BRMBR, and the USDA-NRCS Ecological Site Descriptions completed in 2005.

Water chemistry characteristics of preferred habitat. No research to date has been done on the ideal nutrient conditions for important habitat species in the Willard Spur. In many studies outside the GSL, *Stuckenia pectinata* has displayed tolerance to eutrophic waters much better than other submerged species (Kantrud 1990). A recent study on wetland biota and water quality in Farmington Bay in the southern part of GSL and Public Shooting Grounds WMA to the north of Willard Spur, may provide a relevant comparison between communities at baseline and nutrient enriched sites. In this study, the sites with the most nutrient enrichment, including two near the outfalls of wastewater treatment plants, had lower native species richness, but this was also true of sites with the lowest levels of nutrients. Eutrophic sites were dominated by *Alopecurus aequalis* (short awn foxtail), *Phalaris arundinacea* (reed canary grass), *Phragmites australis*, *Salicornia rubra*, *Schoenoplectus maritimus*, *Schoenoplectus acutus*, *Schoenoplectus americanus*, *Atriplex micrantha* (two-scale saltbush), *Bidens cernua* (nodding beggars tick), *Polygonum lapathifolium* (curlytop knotweed), *Typha domingensis* (southern cattail), *Typha latifolia* (broad-leaved cattail), *Rumex crispus* (curly dock), and *Lemna minor* (lesser duckweed). Several of these species are considered undesirable or provide little habitat value to wildlife species. Oligotrophic and reference sites were dominated by *Distichlis spicata*, *Hordeum jubatum*, *Schoenoplectus americanus*, *Schoenoplectus maritimus*, and *Typha latifolia* (CH2M Hill 2006). This research was done primarily in impounded wetlands, thus the water regime conditions and subsequent salinity may not be relevant to Willard Spur wetlands. Many relationships between water quality parameters and plant communities were non-linear or unclear, pointing to the need for careful sampling and multiple years of research (CH2M Hill 2006).

Extreme hydrologic fluctuations and wildlife habitat. The effects of fluctuating water levels on waterfowl habitat are well-documented. Fluctuating water levels can be detrimental to waterfowl food plants and nesting habitat as rapidly rising water levels can flood out nests and falling water levels can stress vegetation (Wolf 1955, Christiansen and Low 1970, Foote 1989, Manning and Paul 2003). Both waterfowl and shorebirds avoid nesting near fluctuating water levels (Aldrich and Paul 2002), and flooding in particular has been linked to shorebird nest failure (Cavitt 2006). Because of the dynamic hydrology and low gradient bottom of the lake, during periods of low water, expansive mudflats are exposed that provide important sources of macroinvertebrates for birds (Wolheim and Lovvorn 1995, Manning and Paul 2003, Belovsky et al. 2011,). These periods of low water also have the effect of promoting more vigorous stands of existing plant communities by slowing natural wetland succession in emergent communities, a process by which the abundance of plant communities change according to shifting

environmental conditions like hydroperiod and salinity (van der Valk 1981). However, periods of low water longer than one growing season may provide opportunities for the establishment of undesirable species (e.g., *Typha* spp. and *Tamarix* spp.) (Christiansen and Low 1970).

Foote (1989) looked specifically at the four years preceding and following the major GSL flood of the mid-1980s and found that flood-displaced waterfowl did not return to nearby suitable habitat to nest following the water's recession. This same flood has also been interpreted as a positive event because it converted old, unproductive emergent communities to more productive states (Aldrich and Paul 2002). A study conducted from 1997 to 2001, a period of time where the entire GSL fluctuated by 1.6 m, considered a representative water pattern of the Lake, found that duck use was higher in flood years and low during dry years as areas of emergent vegetation that had been salt burned emerged. During this same study period, shorebird and colonial nesting bird use was high in the expanding, exposed, un-vegetated mud bars as GSL receded (Manning and Paul 2003). The Spur itself faces more dramatic hydrologic fluctuations than the main GSL, as illustrated by the 1.2 meter decrease from 2011-2012 (CH2M HILL 2013), which suggests Willard Spur may be more suitable for nesting ducks in wet years and shorebirds and colonial nesting birds in dry years (see Manning and Paul (2003) for descriptions of common nesting bird species).

2. What factors might affect plant species and vegetation cover in wetland habitats similar to Willard Spur, e.g., water level, salinity, nutrients?

There are many factors that interact in complex ways to affect vegetation in habitats similar to Willard Spur. Abiotic factors including water depth and flood duration, salinity, and nutrients can be quite dynamic within and between years due to changes in factors such as stream flow from snow pack, weather events, and wind mixing that determine where a given habitat type occurs (SWCA 2012). Here we synthesize the most relevant literature relating these abiotic factors to wetland vegetation.

Water flow. Water depth and velocity of water have a direct effect on all of the abiotic factors listed above in addition to their direct effects on wetland vegetation. The presence of vegetation (both emergent plants and SAV) significantly slows water velocity within wetlands and enhances litter and sediment accumulation (Clarke 2002), an important factor in areas with wastewater discharge. Willard Spur is considered to be a sheet flow wetland, characterized by water moving very slowly across a level landscape surface (Kindscher et al. 2004). Current understanding of effluent flow paths in the Spur indicate that a discharge pipe sends effluent across private wetlands before reaching the Spur; along this path vegetation may decrease the velocity of water and take up some nutrients before they reach the open water of the Spur (Nepf 1999, CH2M HILL 2013). Water flow in and out of GSL wetlands has a significant effect on salinity as decreased inputs and subsequent drying causes salts to rise from deeper sediments to the soil surface (Kadlec 1982). Research by Christiansen and Low (1970) recommends maintaining consistent flows into and out of wetlands or drawing down wetlands when inputs decrease in order to maintain low enough salinity to promote healthy vegetation. More recent work to define and assess the health of GSL wetlands has suggested that unimpounded wetlands, like those in the Willard Spur, should be receiving freshwater inflows during a critical period from April through July to maintain a healthy plant community and associated wetland functions (SWCA 2012).

Related to water velocity is the impact of wave action on vegetation; generally wave action is detrimental to SAV in shallow (<1 meter deep) water because it can uproot vegetation (Kantrud 1990); however, wind mixing is an important aspect in mixing between waters with different salinities and nutrient levels within GSL (Belovsky et al. 2011).

Fluctuating water levels. Fluctuating water levels can have mixed effects on plant species abundance, depending upon previous water table depth, duration of flooding or drying, and resulting soil salinity (Nelson 1955). Alternating flooding and drying can bring salts to the surface of sediment, affecting the establishment of certain types of plants on exposed soil surfaces (especially *Typha* spp. and *Schoenoplectus acutus*), while deep continuous flooding pushes salts deeper into sediments (Kadlec 1982). However, salty, shallowly flooded mud flats can harbor productive invertebrate communities that provide an excellent food source for shorebirds (see Question 1). Fluctuating water levels will also affect wetland seed banks and therefore, future vegetation establishment. Seed banks collected from five vegetation types (*Typha* spp., *Schoenoplectus acutus, Schoenoplectus maritimus, Distichlis spicata,* and *Phragmites australis*) and an open water site at Ogden Bay WMA were subjected to flood and drawdown conditions treatments (Smith and Kadlec 1983). Germination was most successful in the moist treatments (no surface water) rather than permanently submerged treatments (4 cm), suggesting an important role for fluctuating water levels in maintaining wetland communities (Smith and Kadlec 1983). Another study conducted at Ogden Bay WMA provides a thorough record of wetland succession following flooding of a formerly dry area (Nelson 1955). This study found that emergent species require periodically very shallow water (<10 cm) or exposed sediments to germinate (Nelson 1955). However, rapidly declining water levels are a concern for spread of invasive *Typha* spp. and *Phragmites australis*. Nelson (1955) documents 100 acres being taken over by *Typha* spp. in a single season when mudflats were exposed, which allowed for seedling establishment because the water table was such that salinity levels did not inhibit germination. This suggests that there is a threshold for both rate of water level fluctuations and subsequent salinity levels.

At the other extreme, stabilized water levels can also have negative impacts on vegetation. Following the impoundment of many GSL freshwater marshes, diverse vegetative communities were converted to monotypic stands of *Typha* and other undesirable species (Aldrich and Paul 2002). Periodic flooding by hyper-saline waters is considered one option for preventing the dominance of invasive species (SWCA 2012). The effects of flooding depend on the plant group and salinity of the water. Submerged species establish best in permanently flooded water regimes, less than 2.5 m deep, but *Stuckenia pectinata* (a key food species) can tolerate "significant" water level fluctuations (up to 1 meter depending on water quality) (Kantrud 1990).

Salinity. Water depth, water chemistry, and salinity have complex interactions such that predicting changes in salinity with changes in water levels can be challenging (Langrein 1961, Hahl and Langford 1964, Kadlec 1986). The Bear River Bay/Willard Spur area has a unique salinity level compared to the rest of the lake partly due to compartmentalization from the causeway (Flowers 1934, Waddell and Bolke 1973, Loving et al. 2000) but there is a highly variable salinity gradient, documented from 0.78 to 15 mmhos/cm during 2011 – 2012, due to fresh water inflow from the Bear River and seasonal evaporation rates (SWCA 2012, Hooker and Ostermiller 2013). The boundaries and composition of plant communities are limited by salinity and water depth tolerances. Plant species diversity tends to be higher in fresh and brackish

waters than in more saline parts of the GSL (Anderson 2010). With regard to biomass, common GSL wetland species tend to grow best in fresher water (<3 mmhos/cm), which also means that the freshest regions of the lake (near inputs) also have the most aggressive plant species present (Christiansen and Low 1970, Aldrich and Paul 2002). Growth of *Typha* spp. and *Schoenoplectus acutus* is noticeably diminished at conductance higher than 6 mmhos/cm, which is common during the summer months (Christiansen and Low 1970). Increased salinity (>1.9 mmhos/cm) and/or drought may result in decreased cover of *Typha* spp., which may be viewed positively or negatively by managers depending on the nativity of the *Typha* lineage affected (Anderson 1977). *Typha* spp. tend to replace *Schoenoplectus maritimus* only when soil salinity has decreased sufficiently (<2.6 mmhos/cm) while *Stuckenia pectinata* may be replaced by *Chara* spp. (algae) under elevated salinity (>1.3 mmhos/cm) (Kadlec 1982). *Phragmites* seeds and seedlings are inhibited with salinities approximately greater than 15.6 and 7.8 mmhos/cm, respectively (Chambers et al. 2003). Increased salinity can also cause decreases in phytoplankton and invertebrate populations (Roberts 2013). Changes to the salinity of the Willard Spur occur naturally due to fluctuations in freshwater input and rates of evapotranspiration; however, salinity could increase over the long-term due to upstream water allocations of the Bear River (UDWRe 2000, Aldrich and Paul 2002).

Nutrients. Nutrient levels and other water quality components can also significantly affect wetland vegetation. The principals of wetland ecology suggest that the highly productive nature of wetland vegetation can more effectively assimilate higher levels of nitrogen and phosphorous than other aquatic ecosystems, which is why wetlands are used in some waste water treatment plants. However, there is a limit to the amount of nutrients wetlands can assimilate and excess nutrients have been linked to reductions in species richness, increased algal production that suppresses macrophyte production, and hypoxic water conditions in large wetland complexes from the Great Lakes, Chesapeake Bay, and Everglades (Keddy 2010). Research on wetlands and eutrophication in other regions suggests that nutrients alter competitive outcomes between plants (e.g., Templer et al. 1998, Ehrenfeld 2003, Perry et al. 2004, Hovick et al. 2011). In particular, invasive *Phragmites australis* is a high nutrient specialist and can outgrow and out-compete more desirable native species under high nutrient conditions (Mozder and Zieman 2010) (see Question 3 below for more discussion on this point). In open water wetlands, SAV obtain nutrients primarily from sediments, and phosphorous in particular can be transferred from sediment to water or vice versa by SAV due to photosynthesis, plant senescence, and wind mixing, thus impacting the amount of phosphorous available to the ecosystem (Carignan and Klaff 1980, Anderson and Mitsch 2005, Myers et al. 2006). Thus it is important to understand the phenology of wetland vegetation in this region to better understand vegetation influences on nutrient cycling.

As discussed earlier, GSL wetlands have unique biogeochemical properties related to nutrient enrichment, hydroperiods, brine shrimp, and salinity, warranting site-specific research of the impacts of nutrients on this ecosystem (GSL Planning Team 2013). Initial research done by CH2M Hill (2005) found GSL wetland sites that were high in nutrients and had low salinities were dominated by *Phragmites australis*, *Typha latifolia*, and *Schoenoplectus maritimus*, while nutrient-poor and saline sites were dominated by *Distichlis spicata* and *Schoenoplectus americanus*. These results again point to the need to investigate the interactions between nutrients and salinity. Research on the nutrient cycling processes within impounded Farmington Bay wetlands has been conducted focused primarily on SAV (see CH2M Hill 2005, 2009, Miller

and Hoven 2007, Hoven 2010, Miller et al. 2011). These studies found that relationships between nutrients and plant communities are non-linear, compounded by salinity, and likely interacting with metal and micro-nutrient concentrations.

Water depth. In addition to the impacts of fluctuating water levels on plant establishment outlined above, water depth can also affect water temperature and sediment/water column mixing, which can alter plant community composition. Decreased water levels can increase mixing between sediments and the water column (often due to wind), ultimately affecting water chemistry by changing the oxygen concentration in sediments and causing sediments to release or absorb phosphorous (Kadlec 1994, Myers et al. 2006). Higher flood levels (1m above normal) in impounded wetlands can increase mortality in emergent vegetation, which leads to higher levels of interstitial nitrogen and phosphorous (Kadlec 1986). Water depth can also affect daily temperature fluctuations and plant activity, thereby altering nutrient processing, although seasonal changes in solar radiation and plant phenology tend to be most important for a plant's rate of nutrient processing (Kadlec 1999, Kadlec and Reddy 2001).

3. What invasive plant species are of concern in the Willard Spur area? What are the possible effects of invasive plant species upon habitat values and use by wildlife in Willard Spur?

A full vegetation survey needs to be conducted to determine the presence and abundance of invasive species in the Willard Spur, but local research and management reports identify several potential species of concern around GSL including: *Lepidium latifolium* (perennial pepperweed), *Lythrum salicaria* (purple loosestrife), *Rumex crispus*, *Myriophyllum spicatum* (Eurasian watermilfoil), *Phragmites australis*, *Potamogeton crispus* (curly-leaf pondweed), *Tamarix* spp. (salt cedar), *Typha* × *glauca* (hybrid cattail) (CH2M HILL 2006, UDWR 2009, USDA, NRCS 2012). Invasive species often form monotypic stands that change nesting habitat structure and displace native species, which can alter the ecosystem functions wetlands perform, including nutrient cycling (Zedler and Kercher 2004). Below we discuss two of the most common invasive species and briefly mention other species of concern. See Question 6 for discussion of the factors driving invasions.

Phragmites australis. Following major GSL flooding in the 1980s, *Phragmites australis* (hereafter *Phragmites*) was one of the first species to colonize un-vegetated areas of the Lake (Aldrich and Paul 2002, Kulmatiski et al. 2011, Kettenring 2012, Kettenring et al. 2012). Currently the invasive lineage of *Phragmites* is the most widespread invasive vegetation around Willard Spur and has been identified as one of the most serious stresses to GSL health (SWCA 2012). The invasive lineage of *Phragmites* is a concern for waterfowl habitat because it creates tall (2-4 meters), dense to "impenetrable" monocultures that displace desirable native wetland vegetation, fragments marshes, and reduces the quality of the habitat and ecosystem services provided by wetlands (Silliman and Bertness 2004, Kettenring et al. 2012). In the Bear River Bay, *Phragmites* has been crowding out native grass and bulrush species that waterfowl feed on, but *Phragmites* continues to be used for nesting by secretive marsh wrens and as cover for flightless birds during molting (Olson 2007). In the Great Lakes region, *Phragmites* has been found to provide suitable habitat for many species of land birds, although it provides limited habitat for summer nesting bird species (Meyer et al. 2010). Numerous reports (including Anderson 2010, SWCA 2012) anecdotally cite the negative effects of *Phragmites* on waterfowl

breeding habitat in the GSL area, but more research needs to be done to quantify the habitat impact of *Phragmites* around the GSL (Kettenring et al. 2012).

Typha spp. The impact of *Typha* spp. (*Typha latifolia*, *Typha x glauca*, and *Typha domingensis*) invasion on habitat is similar to that of *Phragmites*. *Typha* × *glauca*, which is a hybrid between *Typha latifolia* (native broadleaf cattail) and *Typha angustifolia* (non-native narrowleaf cattail), is the most aggressive of the *Typha* species. *Typha x glauca* expands rapidly in disturbed watersheds to crowd out native species (Smith 1967, Sharitz et al. 1980, Waters and Shay 1990, Kuehn et al. 1999, Larkin et al. 2012a) although the extent to which it is a pervasive problem in GSL wetlands is unknown. In low densities, *Typha* spp. can be used for nesting habitat by smaller marsh birds or geese (Smith 1955, Dey 1964), but establishment of monotypic stands of *Typha* spp. (regardless of their nativity) can crowd out plant food sources for waterfowl and affect nesting habitat (Sojda and Solberg 1993, Woo and Zedler 2002, Larkin et al. 2012b). In addition to forming monotypic stands that can only be utilized by a small number of wildlife species for nesting habitat, *Typha latifolia* and *Typha domingensis* have traditionally been viewed by biologists around the GSL as poor food species and thus other plant species have been favored in their places (Christiansen and Low 1970, Aldrich and Paul 2002).

Other invasive species. *Tamarix* spp., a shrub, is of concern primarily near streams and ditches where it displaces native species, lowers water tables, and enhances fire risk (UDWR 2009). *Lythrum salicaria*, an emergent forb, decreases habitat values because it restricts production of native species through pollinator competition, out-competes other species for resources via prolific seed production and vegetative reproduction, and complicates management actions by restricting water flow where it has established (Zedler and Kercher 2004, Galatowitsch et al. 1999). Once established, this inferior waterfowl food is very difficult to eradicate (UDWR 2009). *Lythrum salicaria* is not known to be widespread in the Willard Spur, but has historically been present along the Weber River. A recent report suggests that *Myriophyllum spicatum*, a submerged aquatic species, became established in waterfowl management areas of the GSL (UDWR 2009), although given that there is a native species of the same genus, there are some concerns about correct identification. This poor food source for waterfowl forms dense mats that exclude valuable food sources and is also problematic in that it disrupts waterways and clogs water management structures (UDWR 2009).

4. What do the existing data describe in terms of the distribution of existing vegetation, including percent cover for emergent vegetation, submerged aquatic vegetation, invasive species, phytoplankton, and biomass of algae in Willard Spur?

The distribution of different wetland types, cover of invasive species, and algal communities are determined by water depth, flood duration, and water chemistry; as these parameters change between seasons and years, the distribution of communities of interest also changes. According to a recent report by SWCA (2012), the unimpounded marshes of GSL (including Willard Spur) are composed of five habitat types that differ in their water regime and dominant vegetation: wet meadow, tall and short emergent marshes, hemi-marsh, and wetlands dominated by SAV. Older reports provide some information on the distribution of emergent and freshwater communities. According to BRMBR's long-term habitat management plan (Olson et al. 2004), the north-eastern portion of Willard Spur encompassed in Refuge Unit 6 is 74% shallow to deep submerged marsh dominated by SAV. The western portion of the unit is 26%

shallow emergent marsh. The north-central and north-eastern portion of the Spur in BRMBR Units 7 and 8 is primarily hemi-marsh.

Two recent mapping efforts (2007 and 2011) describe broad patterns of vegetation distribution in the Willard Spur. A 2007 project by Ducks Unlimited mapped the vegetation around the GSL wetlands using a combination of field methods and digitized polygons based on interpretation of 2006 1-m NAIP aerial imagery. Mapping unit size varied, depending on the site. Mapping units range from 1 m to 45,130 km (Ducks Unlimited 2007). Table 2 lists wetland vegetation in Willard Spur based on this dataset and Figure 3 contains a vegetation map of the area.

In 2011 (May 12, 13, 25; June 10, 15, 17), high resolution multispectral imagery was collected using Utah State University's high resolution multispectral digital imagery system (Long et al. 2012). Images were acquired at 1-m resolution, with imagery in four bands: red, green, blue, and near-infrared. This dataset is the most comprehensive mapping effort of *Phragmites* and native emergent vegetation around the GSL to date. The area flown for data collection included all major wetland areas around the eastern third of the GSL (Figure 4). Following image acquisition, imagery was orthorectified, mosaicked, and calibrated using ERDAS Imagine software. Imagery was ground truthed following orthorectification to acquire sample points to use as training pixels for the vegetation classification. Vegetation was classified into nine groups of major vegetation to determine the distribution of wetland plant species of interest. These vegetation classes are: *Phragmites*, *Typha* spp., *Distichlis spicata*, *Salicornia* spp., *Schoenoplectus acutus*, playa wetlands, native emergent wetland, upland, and open water. The native emergent class consists of both wet meadows and emergent species such as *Schoenoplectus maritimus* and *Schoenoplectus americanus* (*Schoenoplectus americanus* "complex", Flora of North America Association 2008). See Table 3 for areas of vegetation around the Willard Spur based on the 2011 classified imagery. In particular, note that there are >1000 acres of *Phragmites australis* present in the Willard Spur (2% of the area). The classified vegetation for the entire GSL can be found here: http://maps.gis.usu.edu/gslw/index.html. In addition, high resolution digital elevation data was collected in 2011 using LiDAR (Light Detection And Ranging) flights for Utah Geologic Survey (http://gis.utah.gov/data/elevation-terrain-data/2011-lidar/). This digital elevation data could be used to look at wetland basin morphology in the Willard Spur.

No data exist describing the distribution of phytoplankton or algal biomass specific to the Willard Spur. Appendix B contains a list of phytoplankton species from Farmington Bay and Gilbert Bay. Research in these other regions of the Lake indicate that eutrophication, salinity, and grazing by brine shrimp drive the species diversity and biomass of phytoplankton (Wurtsbaugh & Marcarelli 2004a, 2004b, 2004c, Marcarelli et al. 2006, Belovsky et al. 2011). Wurtsbaugh and Marcarelli (2004c) found 28 species of phytoplankton in Farmington and Gilbert Bays; while species were generally found in both bays, biomass was four times higher in Farmington Bay. Belovsky et al. (2011) found more than 60 species of phytoplankton in their study of Gilbert Bay, but did not provide a species list. In both studies, biomass and dominant species shifted through the season according to temperature, salinity, and brine-shrimp grazing and levels of production were associated with nitrogen levels in the water column, where more nitrogen led to increased phytoplankton production.

5. What datasets or maps are available that document the habitat and/or vegetation of Willard Spur in past years? We will identify researchers and the date of work, summarize available information and methods used, and identify tasks needed to process data as required to compare datasets.

There are few historical datasets that describe the vegetation in the Willard Spur in particular; however, the historical account of Flowers (1934) contains a list of species present in Willard Spur (Table 4) as well as water content, pH, and soil salinity during June 1929. In the Bear River Bay area, Williams and Marshall (1937, 1938) list vegetation used by ducks and geese for nesting in the BRMBR and include hand-drawn vegetation zones and maps of sites. These historical vegetation accounts can be used as a baseline with which to compare more recent vegetation data (see Appendix A for species lists from BRMBR (2006) and the NRCS Ecological Site Descriptions from the Willard Spur (2005)).

Historical mapping data for Willard Spur can most likely be extracted from any number of National Agricultural Imagery Program (NAIP) datasets. By comparing the 2004 data to aerial photography from 1977, Kulmatiski *et al*. (2010) estimated the percent cover of *Phragmites* along the eastern shore of the GSL increased from 20.4% to 56.4%; this area surveyed included at least part of the Willard Spur (see Figure 2 in Kulmatiski et al. 2010). However, this imagery was at 30m, so fine scale changes of *Phragmites* cover would not be detectible. Below we summarize other available datasets taken of areas in the vicinity of (but not necessarily including) Willard Spur that might be of interest in the context of this project.

2010 BRMBR Multispectral Imagery: In May 2010, multispectral imagery was obtained around the Bear River Migratory Bird Refuge and this was compared to 1992 imagery from the same area. This work was conducted by an undergraduate researcher at Utah State University (USU, Melina Santos Vanderlinder in collaboration with Drs. David Rosenberg, Christopher Neale, and Karin Kettenring, and Ph.D. student Omar Alminagorta), and was presented at the 2012 National Conference on Undergraduate Research. The abstract can be seen here: https://ncurdb.cur.org/ncur/archive/Display_NCUR.aspx?id=60337 . The majority of this dataset is outside of the Willard Spur area.

2007 Ducks Unlimited GSL Vegetation Mapping Project: In 2007 Ducks Unlimited mapped wetland vegetation around the GSL using both aerial imagery and field survey methods. The data is available as a GIS shapefile, and a brief report is available on their website. http://www.ducks.org/utah/utah-projects/ut-great-salt-lake-wetlands-assessment-project.

2006 Farmington Bay: In 2006, 1-m multispectral imagery was collected in Farmington Bay by Frontier Corp. for Dr. Christopher Neale at USU. This imagery does not cover the Willard Spur area. There is no report for this data set.

2003 Brigham City Wetland Multispectral Imagery: In May 2003, 1-m multispectral imagery was collected in Brigham City around a wetland mitigation complex by Frontier Corp. for Dr. Christopher Neale at USU. This imagery was used to classify wetland types (upland, open water, bare soil, mudflat/playa, emergent wet meadow, and emergent marsh). However, this imagery does not cover the Willard Spur area.

2000 Farmington Bay IKONOS Imagery: In 2000, USU acquired IKONOS multispectral imagery at 4m resolution that was collected on July 13, 2000. This imagery, along with 30-m

LANDSAT imagery and ground control points, was used to classify vegetation around the Farmington Bay area into 17 classes. The study area for this project is outside of the Willard Spur area. The report is available here: http://www.gis.usu.edu/ArcWebpage/inside_table/projects_2000.html

1992 Great Salt Lake imagery: Multi-spectral airborne video imagery was collected by Dr. Christopher Neale's lab at USU in areas around the Great Salt Lake in May 1992, and only the area covering the Bear River Migratory Bird refuge has been processed. Processing and classification of the imagery for Willard Spur would require a significant amount of work, but could be done if the resources were available.

Changes in Phragmites distribution between 2007 and 2011: For this report, a very basic change analysis was performed in ArcGIS to determine the change in *Phragmites* distribution using the 2011 1-m multispectral imagery data set (Figure 5), and the 2007 *Phragmites* mapping data from Ducks Unlimited (Figure 3). The 2007 Ducks Unlimited mapping project had 12 different vegetation classes (Table 2) and the 2011 USU 1-m dataset has nine different vegetation classes. The vegetation classes were fairly different between the two datasets, so we only compared the *Phragmites* distribution (as opposed to other vegetation classes) between the two years. The 2007 Ducks Unlimited data had two classes comprised of *Phragmites*. The *Phragmites* 1 class consisted of any area of vegetation where the density of *Phragmites* was greater than 75%. The *Phragmites* 2 class consisted of any area of vegetation where the density of *Phragmites* was between 50 and 75%. Because of the way the vegetation classes were structured, any areas that contained under 50% *Phragmites* density were not captured in the 2007 data. We clipped the 2007 Ducks Unlimited data and 2011 USU 1-m data down to the extent of the Willard Spur boundary (Figures 6 and 7). We then counted the number of 2011 1-m raster cells that fell within the 2007 Ducks Unlimited *Phragmites* polygons, and then calculated the percentage of that polygon that was occupied by *Phragmites* to determine which 2007 *Phragmites* classes the current data would correspond to. Of the 16 polygons of Ducks Unlimited *Phragmites* 2 class, only three of the polygons would remain in the *Phragmites* 2 class (69.96 acres). The remainder of the polygons fell beneath the 50% threshold. All of the 2007 Ducks Unlimited *Phragmites* 1 polygons fell below the 50% threshold in 2011, meaning they would not be in either of the Ducks Unlimited *Phragmites* 1 or *Phragmites* 2 classes. There was also 117.32 acres of *Phragmites* in the 2011 USU dataset that fell outside of the 2007 mapped *Phragmites* polygons. The total area of *Phragmites* in Willard Spur from the 2011 data set was 1,264 acres. Overall the analysis showed a potential increase in extent of the *Phragmites* distribution around Willard Spur, but a decrease in density of *Phragmites*. However, due to the high resolution of the 2011 data, a larger extent of *Phragmites* distribution was captured, and it is difficult to determine if the larger extent is due to actual expansion of *Phragmites*, or the higher resolution of the 2011 data. Due to the 2007 mapping methods, data would only capture areas of *Phragmites* where the *Phragmites* density was greater than 50%. This means areas with a lower density of *Phragmites* were not mapped in 2007.

6. What does the literature reveal regarding the effects of nutrients on the distribution, abundance, and reproduction of invasive plant species found in the Willard Spur area?

Growth of photosynthetic organisms in aquatic ecosystems is often limited by nitrogen (N) and/or phosphorous (P) (Elser et al. 2007). Higher nutrient levels in wetlands, which are often a landscape sink for nutrients, sediments, and water, can promote high levels of production

and species diversity up to a point (Mitsch and Gosselink 2007). Across a diversity of temperate wetlands types, once threshold levels of nitrogen and phosphorous have been crossed, wetland species diversity can decline. However, wetlands exist along a gradient of nutrient conditions, so nutrient impact thresholds are likely to be system-specific. Given the enormous impact of humans on global nitrogen cycling, research efforts should focus on plant and soil N:P ratios as well as community and individual species-level effects to better understand nutrient dynamics in particular wetlands including anthropogenic impacts (Galloway et al. 2008, Gruber and Galloway 2008, Bedford et al. 1999). The relationship between increased nutrients and plant diversity is particularly complicated in the Willard Spur due to the hyper-eutrophic state of the GSL itself, highly dynamic hydrology, and the interactive effects of salinity, hydrology, and nutrients on organisms. Many invasive species, including *Typha* spp. and *Phragmites*, benefit from increased nutrients (Rickey and Anderson 2004, Zedler and Kercher 2004, Larkin et al. 2012a). Once established, nutrient enrichment can lead to further suppression of native species by invasive species such as *Typha* spp. due to increased invasive productivity which may block even more light for native plants (Hovick et al. 2011). In the GSL, the distribution of invasive species reflects a number of environmental drivers such as nutrient levels, salinity levels, hydrologic conditions including water levels fluctuations, and disturbance regimes, but the relative importance of these factors for particular species is unknown (CH2M Hill 2005). Below is a summary of the effect of nutrients on the most common invasive species in the Willard Spur area.

***Phragmites australis*.** *Phragmites* has relatively high nitrogen and phosphorous resorption efficiency (49%) as well as higher overall nitrogen levels than other emergent macrophytes (Lawniczak 2011). This suggests that from an ecological standpoint, *Phragmites* is well suited for absorbing nutrients from nutrient rich sediments. In both coastal and inland marsh studies, invasive *Phragmites* performs better under elevated nutrient levels than native *Phragmites* or other native emergent plants by growing taller, producing more biomass, and tolerating deeper water; all these factors promote *Phragmites* expansion (Galatowitsch et al. 1999, Minchinton and Bertness 2003, Rickey and Anderson 2004, Saltonstall and Stevenson 2007, Mozdzer et al. 2010). At the landscape scale, *Phragmites* is known to be associated with anthropogenic development and the associated elevated nutrient levels, especially nitrogen, that accompany this development (Bertness et al. 2002, Silliman and Bertness 2004, King et al. 2007). Work underway in the Kettenring lab by MS student Lexine Long is looking at what factors best explain the current distribution of invasive *Phragmites* using species distribution modeling; results will be forthcoming.

In comparing invasive and native *Phragmites* from northern Utah, Kulmatiski et al. (2010) found that although invasive *Phragmites* was taller and produced more biomass than native *Phragmites* plants, these differences were not related to nutrient enrichment (both nitrogen and phosphorous); however nutrient levels in this experiment were much lower than previous studies, which suggests that these results may not be directly relevant to field conditions. Invasive *Phragmites* can increase sexual reproduction (more florets and inflorescences produced) in areas with elevated nutrients (Kettenring et al. 2011); given that invasive *Phragmites* spreads predominantly by seeds in the Great Salt Lake (Kettenring and Mock 2012), findings from these nutrient enrichment experiments and landscape level analyses suggest that *Phragmites* will proliferate via sexual reproduction at elevated nutrient levels.

***Typha* spp.** The expansion of *Typha* species has been linked to both nutrient and hydrologic dynamics. The mechanism of expansion differs by lineage (Anderson and Mitsch 2005). The *Typha x glauca* hybrid acquires nitrogen better than native wetland species and holds onto it over multiple generations, contributing to a shift from native wetland vegetation to *Typha* × *glauca* (Galatowitsch et al. 1999, Woo and Zedler 2002). It is then very difficult for other species to come into areas with established populations of *Typha* × *glauca* because of the amount of plant litter produced. High levels of litter contributed more to the success of *Typha* × *glauca* than its superior capacity to acquire nitrogen (Larkin et al. 2012a, Larkin et al. 2012b). In experimental manipulations, *Typha domingensis* was found to increase growth by as much as 45% with elevated nutrients and by almost 60% with increased water depth (Newman et al. 1996). *T. angustifolia* grows best under eutrophic conditions, with hypertrophic conditions resulting in changes in biomass allocation in favor of shoots instead of roots (Steinbachová-Vojtíšková *et al*. 2006).

***Lythrum salicaria*.** Although *Lythrum salicaria* is considered a problematic invasive plant in GSL wetlands, the impacts of increased nutrients on this plant are likely to be less important than impacts on *Phragmites* or *Typha* spp. Fertilization studies found that increased nitrogen did not enhance the ability of *Lythrum salicaria* to suppress other species, relative to *Typha latifolia* and suggested *Lythrum salicaria* suppresses colonization via below-ground competition rather than light reduction (Hovick et al. 2011).

Myriophyllum spicatum. *Myriophyllum spicatum* can tolerate a wide range of temperatures and environmental conditions but it forms dense mats under high nutrient conditions (UDWR 2009). *Myriophyllum spicatum* accelerates nutrient cycling by releasing large amounts sediment nutrients, especially phosphorous, into the water during the decay process (Donaldson and Johnson 1999). *Myriophyllum spicatum* appears to obtain nutrients from below the top 5 cm of sediment so nutrient loading at the soil surface or just below would likely result in its increased growth (Carignan 1985).

***Tamarix* spp.** The GSL plant species list in Flowers (1934) did not mention *Tamarix* spp. However, 20 years later, Nelson (1955) noted it as common in Ogden Bay (as summarized in Christensen 1962). As of 2007, *Tamarix* accounts for less than one percent of the vegetative cover at Willard Spur (7 acres) (Table 2). This species tends to come in when natural river flows have been disturbed, usually through dam releases and irrigation (Tomaso 1998). When high and low water levels no longer correspond to seasonal fluctuations, *Tamarix* is able to establish due to reduced recruitment and growth of native species (Birken and Cooper 2006). To simulate wastewater discharge, a threshold experiment tested acceptable levels of nitrogen for *Tamarix* and two native riparian species (cottonwood and willow); *Tamarix* responded to increased nitrogen by growing taller and it outperformed the native riparian species only at the highest nutrient concentrations (nitrogen 556 mmol m^{-3}, phosphorous 323 $mmolm^{-3}$) (Marler et al. 2001).

Research needs

There are a number of different topics that require additional information to more fully address the questions posed above. We describe them in more detail here.

Development of assessment criteria for the Willard Spur. Over the last decade in particular, there has been significant interest in developing methods for defining and assessing the health of GSL wetlands. There are a number of studies that address how to assess potential water quality impacts of POTWs discharges that can serve as useful guidelines for implementing a similar assessment plan for the Willard Spur. Because these studies focus on areas of the Lake with different water chemistry and hydrology, care should be taken in adapting results to the sheet-flow wetlands of the Willard Spur. Research on nutrient enrichment in the open water portions of the Bay were conducted by Wurtsbaugh & Marcarelli (2004a, 2004b, 2004c, 2005, 2006), Belovsky (2005, 2011) and CH2M HILL (2005, 2006). Myers and Houston (2006), Myers and Miller (2006), and Myers et al. (2006) present data on sheet-flow wetlands in Farmington Bay. Assessment of impounded Farmington Bay wetlands has been presented in Miller and Hoven (2007), Schulle (2008), Goel and Myers (2009), Hoven (2010), and Miller et al. (2011). These studies provide a starting point in developing monitoring techniques in the Willard Spur; however application of Farmington Bay research to Willard Spur should be done with care as the research was done in a watershed dominated by urban rather than agricultural stressors and primarily in impounded wetlands.

Relationships between wetland vegetation, particularly invasive species, and elevated nutrients. Further vegetation studies should look at the effects of nutrients on both the overall Willard Spur ecosystem and particular plant species of interest. Decreased cover of native plant habitat-forming species in the Willard Spur could be detrimental to migratory birds and ultimately reduce the ability of the wetlands to effectively perform biogeochemical cycling functions. Therefore, it is important to identify threshold nutrient levels past which invasive species of particular concern (e.g., *Phragmites australis* and *Typha* spp.) might spread rapidly and negatively affect the valuable wildlife habitat of the Willard Spur.

Consequences of plant invasions to habitat quality. A study similar to the Meyer et al. (2010) Great Lakes study needs to be conducted in the GSL to quantify the effect of *Phragmites australis* stands on migratory birds. Although there is anecdotal evidence indicating that *Phragmites* can degrade wildlife habitat, there is little quantitative data documenting its impact on migratory bird populations (Kettenring et al. 2012). Furthermore, given the varied patch size and density of *Phragmites* in GSL wetlands, it would be important to know where thresholds exist (if they do) of *Phragmites* patch size and density where substantially more harm to migratory birds might occur.

Change in Phragmites cover over time. Future remote sensing imagery at similar resolution to the 2011 data (1-m) could be classified into the same groups as the 2011 data and used to look at change in *Phragmites* cover over time in the Willard Spur. Such data would enable managers to assess whether it continues to expand, and if so, at what rate, or if management efforts are leading to a decline in its cover over time.

Literature cited

AGRC (2001) Wetlands (SGID93 Water). Accessed March 2012. ftp://ftp.agrc.utah.gov/SGID93_Vector/NAD83/MetadataHTML/SGID93_WATER_Wetlands.html

Aldrich TW, Paul DS (2002) Avian ecology of the Great Salt Lake. In Gwynn JW (ed) Great Salt Lake: An overview of change. Department of Natural Resources, Salt Lake City, UT. http://ugspub.nr.utah.gov/publications/dnr/GSL2002.pdf.

Amsberry L, Baker MA, Ewanchuk PJ, Bertness MD (2000) Clonal integration and the expansion of *Phragmites australis*. Ecological Applications 10: 1110-1118. http://www.esajournals.org/doi/pdf/10.1890/1051-0761%282000%29010%5B1110%3ACIATEO%5D2.0.CO%3B2.

Anderson CJ, Mitsch WJ (2005) Effect of pulsing on macrophyte productivity and nutrient uptake: a wetland mesocosm experiment. American Midland Naturalist 154: 305–319. http://dx.doi.org/10.1674/0003-0031(2005)154[0305:EOPOMP]2.0.CO;2.

Anderson CM (1977) Cattail decline at Farmington Bay Waterfowl Management Area. Western North American Naturalist 37: 24–34.

Anderson NM (2010) Patterns of change: documenting habitat, bird and human use in Bear River Bay, particularly the Great Salt Lake Minerals proposed expansion area. http://www.ourlakeourresponsibility.org/wp-content/uploads/2011/01/Anderson_Bear_River_Bay.pdf.

Arnow T, Stephens DW (1990) Hydrologic characteristics of the Great Salt Lake, Utah, 1847-1986. United States Geological Survey Water Supply Paper 2332. http://pubs.er.usgs.gov/publication/wsp2332.

Baskin RL, Kidd MW, Thiros SA, Giddings EM, Hadley HK, Stephens DW, Gerner SJ (2002) Water-Quality Assessment of the Great Salt Lake Basins, Utah, Idaho, and Wyoming-Environmental Setting and Study Design. United States Geological Survey Water-Resources Investigation 02/4115. http://pubs.usgs.gov/wri/wri024115/pdf/wri024115.pdf.

Bedford BL, Walbridge MR, Aldous A (1999) Patterns in nutrient availability and plant diversity of temperate North American wetlands. Ecology 80: 2151–2169. http://www.esajournals.org/doi/abs/10.1890/0012-9658(1999)080%5B2151:PINAAP%5D2.0.CO%3B2

Bedford D (2009) The Great Salt Lake America's Aral Sea? Environment 51: 8–21. http://www.tandfonline.com/doi/pdf/10.3200/ENVT.51.5.8-21.

Belovsky GE (2005) Farmington Bay Report – Corixid predation on brine shrimp. http://cdsewer.org/GSLRes/2005_Farmington_Bay_Brine_Shrimp_Predation_Report_Belovsky_ND.pdf

Belovsky GE, Stephens D, Perschon C, Birdsey P, Paul D, Naftz D, Baskin R, Larson C, Mellison C, Luft J, Mosley R, Mahon H, Van Leeuwen J, Allen DV (2011) The Great Salt Lake Ecosystem (Utah, USA): long term data and a structural equation approach. Ecosphere 2: 1–40. http://www.esajournals.org/doi/pdf/10.1890/ES10-00091.1

Bertness MD, Ewanchuk PJ, Silliman BR (2002) Anthropogenic modification of New England salt marsh landscapes. Proceedings of the National Academy of Sciences 99: 1395–1398. http://www.pnas.org/content/99/3/1395.short

Bioeconomics, Inc (2012) Economic significance of the Great Salt Lake to the State of Utah. Report for Great Salt Lake Advisory Council. http://www.gslcouncil.utah.gov/docs/2012/Jan/GSL_FINAL_REPORT-1-26-12.PDF.

Birken AS, Cooper DJ (2006) Processes of *Tamarix* invasion and floodplain development along the lower Green River, Utah. Ecological Applications 16: 1103–1120. http://www.esajournals.org/doi/abs/10.1890/1051-0761(2006)016%5B1103:POTIAF%5D2.0.CO%3B2.

Carignan R (1985) Nutrient dynamics in a littoral sediment colonized by the submersed macrophyte *Myriophyllum spicatum*. Canadian Journal of Fisheries and Aquatic Sciences 42: 1303–1311. http://www.nrcresearchpress.com/doi/pdf/10.1139/f85-162

Carpenter SR, Lodge DM (1986) Effects of submersed macrophytes on ecosystem processes. Aquatic Botany 26: 341–370. http://www.sciencedirect.com/science/article/pii/0304377086900318

Cavitt JF (2006) Productivity and foraging ecology of two co-existing shorebirds breeding at Great Salt Lake, Utah 2005 - 2006. http://cdsewer.org/GSLRes/2006_Productivity_and_Foraging_Ecology_2005_-_2006_-_Weber.pdf

Chambers RM, Osgood DT, Bart DJ, Montalto F (2003) *Phragmites australis* invasion and expansion in tidal wetlands: Interactions among salinity, sulfide, and hydrology. Estuaries 26: 398-406. http://link.springer.com/article/10.1007/BF02823716

CH2M HILL (2005) Statistical analysis of 2004 data on wetland plants and invertebrates in Farmington Bay, Great Salt Lake, Utah. Final Technical Memorandum. http://www.cdsewer.org/GSLRes/2005_Analysis_of_Wetland_Data_Technical_Memorandum_-_CH2M_Hill.pdf.pdf

CH2M HILL (2006) Analyses of 2005 data on wetland biota and water quality in Farmington Bay, Great Salt Lake, Utah. Final Technical Memorandum. http://www.cdsewer.org/GSLRes/2006_Analysis_of_2005_Wetland_Data_Technical_Memorandum_-_CH2M_Hill.pdf

CH2M HILL (2010) Statewide nutrient removal cost impact study. Final Report for the Utah Division of Water Quality.

http://www.waterquality.utah.gov/POTWnutrient/report/StatewideNutrientRemovalCostImpactStudyRptFINAL.pdf

CH2M HILL (2013) Development of water quality standards for Willard Spur: hydrology and nutrient loads 2011-2012. Presentation to Willard Spur Science Panel January 28, 2013. http://www.willardspur.utah.gov/documents/SP01-2829-13/Hydrology_Loads.pdf

Christensen EM (1962) The rate of naturalization of *Tamarix* in Utah. American Midland Naturalist 68: 51–57. http://www.jstor.org/stable/2422635

Christiansen JE, Low JB (1970) Water requirements of waterfowl marshlands in northern Utah. Utah Division of Fish and Game, Salt Lake City, UT.

Chura N (1962) Food availability and selective utilization by juvenile mallards (*Anas Platyrhynchos Platyrhynchos* L.) on the Bear River Migratory Bird Refuge, Utah. All Graduate Theses and Dissertations Paper 326. http://digitalcommons.usu.edu/etd/326/

Clarke SJ (2002) Vegetation growth in rivers: influences upon sediment and nutrient dynamics. Progress in Physical Geography 26: 159–172. http://ppg.sagepub.com/content/26/2/159.short

Cowardin LM, Carter V, Golet FC, LaRoe ET (1979) Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service. http://www.fws.gov/wetlands/Documents/Classification-of-Wetlands-and-Deepwater-Habitats-of-the-United-States.pdf

Cox R, Kadlec J (1995) Dynamics of potential waterfowl foods in great salt lake marshes during summer. Wetlands 15: 1–8. http://link.springer.com/article/10.1007/BF03160674

Dennison WC, Orth RJ, Moore KA, Stevenson JC, Carter V, Kollar S, Bergstrom PW, Batiuk RA (1993) Assessing water quality with submersed aquatic vegetation. BioScience 43: 86–94. http://www.jstor.org/stable/1311969

Dey NH (1964) Canada Goose production and population stability, Ogden Bay Waterfowl Management Area, Utah. Master's Thesis, Utah State University. http://digitalcommons.usu.edu/etd/1939/.

Donaldson S, Johnson W (1999) Cooperative Extension Fact Sheet Eurasian Watermilfoil. http://www.unce.unr.edu/publications/files/nr/2002/FS0209.pdf

Ducks Unlimited (2007) UT Great Salt Lake wetlands assessment project. http://www.ducks.org/utah/utah-projects/ut-great-salt-lake-wetlands-assessment-project.

Ehrenfeld JG (2003) Effects of exotic plant invasions on soil nutrient cycling processes. Ecosystems 6: 503-523. http://link.springer.com/article/10.1007/s10021-002-0151-3.

Elser JJ, Bracken MES, Cleland EE, Gruner DS, Stanley HW, Hillebrand H, Ngai JT, Seabloom EW, Shurain JB, Smith JE (2007) Global analysis of nitrogen and phosphorus limitation

of primary producers in freshwater, marine and terrestrial ecosystems. Ecology Letters 10: 1135–1142. http://onlinelibrary.wiley.com/doi/10.1111/j.1461-0248.2007.01113.x/full

EPA (2006) Guidance on systematic planning using the data quality objective process. http://www.epa.gov/quality/qs-docs/g4-final.pdf.

EPA (2008) Clean Water Act jurisdiction following the U.S . Supreme Court's decision in Rapanos V. United States & Carabell V. United States. http://water.epa.gov/lawsregs/guidance/wetlands/upload/2008_12_3_wetlands_CWA_Jurisdiction_Following_Rapanos120208.pdf

Farnsworth E, Meyerson L (2003) Comparative ecophysiology of four wetland plant species along a continuum of invasiveness. Wetlands 23: 750–762. http://link.springer.com/article/10.1672/0277-5212(2003)023%5B0750:CEOFWP%5D2.0.CO%3B2

Flora of North America Association. 2008. *Schoenoplectus pungens*. http://www.efloras.org/florataxon.aspx?flora_id=1&taxon_id=242357940.

Flowers S (1934) Vegetation of the Great Salt Lake Region. Botanical Gazette 95: 353–418. http://www.jstor.org/stable/2471414

Foote AL (1989) Response of nesting waterfowl to flooding in Great Salt Lake wetlands. Western North American Naturalist 49: 614–617.

Galatowitsch S, Anderson N, Ascher P. (1999) Invasiveness in wetland plants in temperate North America. Wetlands 19: 733–755. http://link.springer.com/article/10.1007/BF03161781

Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA (2008) Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320: 889-892. http://www.sciencemag.org/content/320/5878/889.short

Gruber N, Galloway JN (2008) An Earth-system perspective of the global nitrogen cycle. Nature 451: 293-296. http://www.nature.com/nature/journal/v451/n7176/full/nature06592.html

Goel R, Myers L (2009) Evaluation of cyanotoxins in the Farmington Bay, Great Salt Lake, Utah. http://cdsewer.org/GSLRes/2009_CYANOBACTERIA_PROJECT_REPORT.pdf

Great Salt Lake Planning Team. (2013). Final Great Salt Lake comprehensive management plan. http://www.ffsl.utah.gov/sovlands/greatsaltlake/2010Plan/OnlineGSL-CMPandROD-March2013.pdf

Hahl DC, Langford RH (1964) Dissolved mineral inflow to great salt lake and chemical characteristics of the salt lake brine. Water Resources Bulletin 3 – Part II. http://ugspub.nr.utah.gov/publications/water_resources_bulletins/WRB-3part2.pdf

Hooker TD, Ostermiller J (2013) Willard Spur 2011-12 monitoring data and analyses. Utah Division of Water Quality. Willard Spur Science Panel Meeting January 2013. http://www.willardspur.utah.gov/documents/SP01-2829-13/WaterChemistry.pdf.

Hoven HM (2010) The 2009 report on SAV condition in Farmington Bay and other impounded wetlands of Great Salt Lake. http://www.cdsewer.org/GSLRes/2009_Report_on_SAV_Condition_in_Farmington_Bay_and_other_Impounded_Wetlands_of_Great_Salt_Lake.pdf

Hoven HM (2011) Evidence of sustained submerged aquatic vegetation (SAV) growth in Bear River Bay, Great Salt Lake, Utah.

Hoven HM, Miller TG (2009) Developing vegetation metrics for the assessment of beneficial uses of impounded wetlands surrounding Great Salt Lake, Utah, USA. Natural Resources and Environmental Issues 15: 11. http://digitalcommons.usu.edu/nrei/vol15/iss1/11

Hovick SM, Bunker DE, Peterson CJ, Carson WP (2011) Purple loosestrife suppresses plant species colonization far more than broad-leaved cattail: experimental evidence with plant community implications. Journal of Ecology 99: 225–234. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2745.2010.01754.x/full

Jasmer GE (2000) Wetland water depths used by selected wildlife species and groups. Biology Technical Note No. 66. U. S. Department of Agriculture Natural Resources Conservation Service.

Kadlec JA (1982) Mechanisms affecting salinity of Great Salt Lake marshes. American Midland Naturalist 107: 82-94. http://www.jstor.org/stable/2425190

Kadlec JA (1986) Effects of flooding on dissolved and suspended nutrients in small diked marshes. Canadian Journal of Fisheries and Aquatic Sciences 43: 1999–2008. http://www.nrcresearchpress.com/doi/pdf/10.1139/f86-245

Kadlec RH (1994) Detention and mixing in free water wetlands. Ecological Engineering 3: 345–380. http://www.sciencedirect.com/science/article/pii/0925857494000077

Kadlec RH (1999) Chemical, physical and biological cycles in treatment wetlands. Water Science & Technology 40: 37–44. http://www.sciencedirect.com/science/article/pii/S0273122399004175

Kadlec RH, Reddy KR (2001) Temperature effects in treatment wetlands. Water Environment Research 73: 543–557. http://www.jstor.org/stable/25045537

Kantrud HA (1990) Sago pondweed (*Potamogeton pectinatus* L.): a literature review. U.S. Geological Survey Resource Publication 176. http://pubs.er.usgs.gov/publication/2000134

Keddy PA (2010) Wetland ecology: principles and conservation. 2nd Edition. Cambridge, New York.

Keddy PA, Fraser LH, Solomeshch AI, Junk WJ, Campbell DR, Arroyo MTK, Alho CJR (2009) Wet and wonderful: the world's largest wetlands are conservation priorities. Bioscience 59: 39–51. http://www.jstor.org/stable/10.1525/bio.2009.59.1.8

Kettenring KM. (2012) Management of *Phragmites* in the Great Salt Lake watershed. Final report to Utah Department of Natural Resources, Division of Forestry, Fire & State Lands. http://www.ffsl.utah.gov/sovlands/greatsaltlake/techteam/RFP/2012/FinalReports/KettenringEtAlFinalReport_14July2012-dnd.pdf

Kettenring KM, De Blois S, Hauber DP (2012) Moving from a regional to a continental perspective of *Phragmites australis* invasion in North America. AoB Plants 2012: pls040–pls040. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3676263/

Kettenring KM, McCormick MK, Baron HM, Whigham DF (2011) Mechanisms of *Phragmites australis* invasion: feedbacks among genetic diversity, nutrients, and sexual reproduction. Journal of Applied Ecology 48: 1305–1313. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2745.2010.01712.x/full

Kettenring KM, Mock KE (2012) Genetic diversity, reproductive mode, and dispersal differ between the cryptic invader, *Phragmites australis*, and its native conspecific. Biological Invasions 14: 2489–2504. http://link.springer.com/article/10.1007/s10530-012-0246-5#page-1

Kindscher K, Aschenbach T, Ashworth SM (2004) Wetland vegetation response to the restoration of sheet flow at Cheyenne Bottoms, Kansas. Restoration Ecology 12: 368–375. http://onlinelibrary.wiley.com/doi/10.1111/j.1061-2971.2004.00293.x/abstract.

King RS, Deluca WV, Whigham DF, Marra PP (2007) Threshold effects of coastal urbanization on *Phragmites australis* (common reed) abundance and foliar nitrogen in Chesapeake Bay. Estuaries and Coasts 30: 469–481. http://www.springerlink.com/index/81141463044219Q6.pdf.

Kuehn MM, Minor JE, White BN (1999) An examination of hybridization between the cattail species *Typha latifolia* and *Typha angustifolia* using random amplified polymorphic DNA and chloroplast DNA markers. Molecular Ecology 8: 1981–1990. http://onlinelibrary.wiley.com/doi/10.1046/j.1365-294x.1999.00792.x/abstract.

Kulmatiski A, Beard KH, Meyerson LA, Gibson JR, Mock KE (2010) Nonnative *Phragmites australis* invasion into Utah wetlands. Western North American Naturalist 70: 541–552.

Langrein WB (1961) Salinity and hydrology of closed lakes. US Geological Survey Professional Paper 412. http://pubs.usgs.gov/pp/0412/report.pdf.

Larkin D, Freyman M, Lishawa S, Geddes P, Tuchman N (2012) Mechanisms of dominance by the invasive hybrid cattail *Typha* × *glauca*. Biological Invasions 14: 65–77. http://www.springerlink.com.dist.lib.usu.edu/content/8h7730l4p7883707/abstract/.

Larkin DJ, Lishawa SC, Tuchman NC (2012) Appropriation of nitrogen by the invasive cattail *Typha* × *glauca*. Aquatic Botany 100: 62–66. http://www.sciencedirect.com/science/article/pii/S0304377012000368.

Lawniczak AE (2011) Nitrogen, phosphorus, and potassium resorption efficiency and proficiency of four emergent macrophytes from nutrient-rich wetlands. Polish Journal of Environmental Studies 20: 1227–1234. http://www.pjoes.com/pdf/20.5/Pol.J.Environ.Stud.Vol.20.No.5.1227-1234.pdf.

Long AL, Neale CMU, Kettenring KM (2012) Determining the current extent of *Phragmites australis* in Great Salt Lake wetlands using multi-spectral remote sensing techniques. Final report to the Utah Department of Natural Resources, Division of Forestry, Fire & State Lands. http://www.cnr.usu.edu/files/uploads/faculty/Kettenring/Kettenring%20et%20al.%20Final%20Report_14%20July%202012.pdf.

Loving BL, Miller CW, Waddell KM (2000) Water and salt balance of Great Salt Lake, Utah, and simulation of water and salt movement through the causeway, 1987-98. U.S. Dept. of the Interior, U.S. Geological Survey WRI – 2000 – 4221. http://pubs.er.usgs.gov/publication/wri004221.

Manning AE, Paul DS (2003) Migratory waterbird use of the Great Salt Lake ecosystem. Great Basin Birds 6: 5-17. http://www.gbbo.org/gbbarticles/2003%20-%20Manning%20-%20Migratory%20waterbird%20use%20of%20the%20Great%20Salt%20Lake%20ecosystem.pdf.

Marcarelli AM, Wurtsbaugh WA, Griset O (2006) Salinity controls phytoplankton response to nutrient enrichment in the Great Salt Lake, Utah, USA. Canadian Journal of Fisheries & Aquatic Sciences 63: 2236–2248. http://www.nrcresearchpress.com/doi/pdf/10.1139/f06-113.

Marler RJ, Stromberg JC, Patten DT (2001) Growth response of *Populus fremontii*, *Salix gooddingii*, and *Tamarix ramosissima* seedlings under different nitrogen and phosphorus concentrations. Journal of Arid Environments 49: 133–146. http://www.sciencedirect.com/science/article/pii/S0140196301908389.

Meyer SW, Badzinski SS, Petrie SA, Ankney CD (2010) Seasonal abundance and species richness of birds in common reed habitats in Lake Erie. Journal of Wildlife Management 74: 1559–1567. http://onlinelibrary.wiley.com/doi/10.1111/j.1937-2817.2010.tb01284.x/abstract.

Miller TG, Hoven HM (2007) Ecological and beneficial use assessment of Farmington Bay wetlands: assessment and site-specific nutrient criteria methods development, Phase I. Progress report to EPA, Region VIII. http://www.deq.utah.gov/workgroups/gsl_wqsc/docs/2007/May/Farmington_Bay_Wetlands_Progress_Report_May_2007.pdf.

Miller TG, Richards D, Hoven HM, Johnson WP, Hogset M, Carling GT (2011) macroinvertebrate communities in great salt lake impounded wetlands, their relationship to water and sediment chemistry and to plant communities and proposed modifications to the MMI. Report to Jordan River/Farmington Bay Water Quality Council.

Minchinton TE, Bertness MD (2003) Disturbance-mediated competition and the spread of *Phragmites australis* in a coastal marsh. Ecological Applications 13: 1400–1416. http://www.esajournals.org/doi/abs/10.1890/02-5136.

Mitsch W , Gosselink JG (2007) Wetlands. 4th Ed. Wiley, New York.

Moore H (2011) Fish Diversity of Willard Spur, Great Salt Lake: aquatic ecology practicum (WATS 4510) class report. http://www.cnr.usu.edu/files/uploads/faculty/WATS_Faculty/Wurtsbaugh/Willard_Spur_Fish_USU_2011_Moore.pdf.

Mozdzer TJ, Zieman JC (2010) Ecophysiological differences between genetic lineages facilitate the invasion of non-native *Phragmites australis* in North American Atlantic coast wetlands. Journal of Ecology 98: 451-458. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2745.2009.01625.x/full.

Mozdzer TJ, Zieman JC, McGlathery KJ (2010) Nitrogen uptake by native and invasive temperate coastal macrophytes: importance of dissolved organic nitrogen. Estuaries and Coasts 33: 784–797. http://www.springerlink.com/index/v309v336p2271631.pdf.

Myers L, Houston J (2006) Great Salt Lake - Farmington Bay: an evaluation of phosphorus loading. http://cdsewer.org/GSLRes/2006_Farmington_Bay_Phosphorus_Mass_Balance_Report_2005_Data_-_CDSD.pdf.

Myers L, Houston J, Williams C (2006) Great Salt Lake, Farmington Bay sediment phosphorus study. http://cdsewer.org/GSLRes/2006_Great_Salt_Lake_Farmington_Bay_Sediment_Phosphorus_Study_2005_Data_-_CDSD.pdf.

Myers L, Miller TG (2006) Farmington Bay open water outstanding issues. http://cdsewer.org/GSLRes/2006_Farmington_Bay_Open_Water_and_Wetlands_Research_Needs_-_10-2006.pdf.

Nadeau T, Leibowitz S (2003) Isolated wetlands: an introduction to the special issue. Wetlands 23: 471–474. http://www.springerlink.com.dist.lib.usu.edu/content/p1364g720g129jh6/abstract/.

Nelson NF (1955) Factors in the development and restoration of waterfowl habitat at Ogden Bay Refuge, Weber County, Utah. Utah State Department of Fish and Game, Salt Lake City. http://www.cnr.usu.edu/quinney/htm/collections/theses-dissertations/publication=12236.

Newman S, Grace JB, Koebel JW (1996) Effects of nutrients and hydroperiod on *Typha*, *Cladium*, and *Eleocharis*: Implications for Everglades restoration. Ecological Applications 6: 774-783. http://www.jstor.org/discover/10.2307/2269482?uid=3739928&uid=2129&uid=2&uid=70&uid=4&uid=3739256&sid=21101402207283.

Nepf HM (1999) Drag, turbulence, and diffusion in flow through emergent vegetation. Water Resources Research 35: 479–489. http://onlinelibrary.wiley.com/doi/10.1029/1998WR900069/pdf.

Olson BE (2007) *Phragmites* control plan: U.S. Fish and Wildlife Service. http://www.fws.gov/bearriver/Phragmites_Control_Plan.pdf.

Olson BE, Lindsey K, Hirshboeck V (2004) Habitat management plan Bear River Migratory Bird Refuge. U.S. Dept. of the Interior Fish and Wildlife Service.

Paton PWC, Dalton J (1994) Breeding ecology of long-billed curlews at Great Salt Lake, Utah. Western North American Naturalist 54: 79–85.

Perry LG, Galatowitsch SM, Rosen CJ (2004) Competitive control of invasive vegetation: a native wetland sedge suppresses *Phalaris arundinacea* in carbon enriched soil. Journal of Applied Ecology 41: 151-162.

Reddy KR, DeLaune RD (2008) Biogeochemistry of wetlands: science and application. Francis and Taylor, Boca Raton, FL.

Rickey MA, Anderson RC (2004) Effects of nitrogen addition on the invasive grass *Phragmites australis* and a native competitor *Spartina pectinata*. Journal of Applied Ecology 41: 888–896. http://onlinelibrary.wiley.com/doi/10.1111/j.0021-8901.2004.00948.x/abstract.

Robel RJ (1962) Changes in submerged vegetation following a change in water level. Journal of Wildlife Management 26: 221-224.

Roberts A (2013) Avian diets in a saline ecosystem: Great Salt Lake, Utah, USA. Human-Wildlife Interactions 7: 158–168. http://www.berrymaninstitute.org/journal/spring2013/HWI_7.1_pp158-168_small.pdf.

Saltonstall K, Stevenson J (2007) The effect of nutrients on seedling growth of native and introduced *Phragmites australis*. Aquatic Botany 86: 331–336. http://www.sciencedirect.com/science/article/pii/S0304377006001951.

Schlesinger WH (2013) Biogeochemistry: an analysis of global change. 3rd Edition. Academic Press, Waltham, MA.

Schulle MEP (2008) Synoptic study of phosphorus concentrations in Farmington Bay. Master's Thesis, The University of Utah. http://cdsewer.org/GSLRes/Farmington_Bay_Phosphorus_Synoptic_Study_-_2008.pdf.

Sharitz RR, Wineriter SA, Smith MH, Liu EH (1980) Comparison of isozymes among *Typha* species in the Eastern United States. American Journal of Botany 67: 1297–1303. http://www.jstor.org/stable/2442132.

Silliman BR, Bertness MD (2004) Shoreline development drives invasion of *Phragmites australis* and the loss of plant diversity on New England salt marshes. Conservation Biology 18: 1424–1434. http://onlinelibrary.wiley.com/doi/10.1111/j.1523-1739.2004.00112.x/full.

Smith LM, Kadlec JA (1983) Seed banks and their role during drawdown of a North American marsh. Journal of Applied Ecology 20: 673–684. http://www.jstor.org/stable/2403534.

Smith RI (1955) The breeding territory and its relationship to waterfowl productivity at Ogden Bay Bird Refuge. Master's Thesis, Utah State Agricultural College.

Smith SG (1967) Experimental and natural hybrids in North American *Typha* (*Typhaceae*). American Midland Naturalist 78: 257–287. http://www.jstor.org/stable/2485231.

Sojda RS, Solberg KL (1993) Waterfowl Management Handbook, Section 13.4.13. Management and control of cattails. http://digitalcorpora.org/corp/nps/files/govdocs1/183/183401.pdf.

Steinbachová-Vojtíšková L, Tylová E, Soukup A, Novická H, Votrubová O, Lipavská H, Čížková H (2006) Influence of nutrient supply on growth, carbohydrate, and nitrogen metabolic relations in *Typha angustifolia*. Environmental and Experimental Botany 57: 246–257. http://www.sciencedirect.com/science/article/pii/S0098847205000924

SWCA (2012) Definition and assessment of Great Salt Lake health. Salt Lake City, Utah. Prepared for Great Salt Lake Advisory Council. http://link.springer.com/content/pdf/10.1007%2FBF03161444.

Templer P, Findlay S, Wigand C (1998) Sediment chemistry associated with native and non-native emergent macrophytes of a Hudson River marsh ecosystem. Wetlands 18: 70–78. http://link.springer.com/content/pdf/10.1007%2FBF03161444.

Tomaso JMD (1998) Impact, biology, and ecology of salt cedar (*Tamarix* spp.) in the Southwestern United States. Weed Technology 12: 326–336. http://www.jstor.org/stable/3988397.

UDWQ (2009) Development of an assessment framework for impounded wetlands of Great Salt Lake. Great Salt Lake Water Quality Studies. http://www.deq.utah.gov/Issues/gslwetlands/docs/FinalReport122209.pdf.

UDWQ (2012) A Great Salt Lake water strategy. http://www.waterquality.utah.gov/greatsaltlake/documents/GreatSaltLakeWaterQualityStrategy040912_v8_line_items.pdf.

UDWR (2009) Utah aquatic invasive species management plan. http://wildlife.utah.gov/mussels/plan.php

UDWRe (2004) Bear River Basin: Planning for the future. http://www.water.utah.gov/planning/SWP/bear/bearRiver-1A.pdf.

USDA, NRCS (2012) The PLANTS Database (http://plants.usda.gov, 8 October 2012), http://www.plants.usda.gov/java/noxiousDriver

USDA, NRCS (2013) Web Soil Survey. (accessed 01 October 2013), http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

USGS (1985) National water summary 1984; hydrologic events, selected water quality trends, and ground water resources. WSP – 2275. http://pubs.er.usgs.gov/publication/wsp2275.

USGS (2013) USGS 10126000 Bear River near Corinne, UT. National Water Information System. http://waterdata.usgs.gov/usa/nwis/uv?site_no=10126000.

van der Valk AG (1981) Succession in wetlands: a Gleasonian approach. Ecology, 62: 688-696. http://www.jstor.org/stable/1937737

von Stackelberg N (2010) Estimated nutrient levels in Willard Spur with Perry-Willard POTW. Technical Memorandum. http://www.willardspur.utah.gov/documents/willard_spur_TM1_final(2).pdf

Waddell KM, Bolke EL (1973) The effects of restricted circulation on the salt balance of Great Salt Lake, Utah. Water Resources Bulletin 18. http://ugspub.nr.utah.gov/publications/water_resources_bulletins/WRB-18.pdf

Waters I, Shay JM (1990) A field study of the morphometric response of *Typha glauca* shoots to a water depth gradient. Canadian Journal of Botany 68: 2339–2343. http://www.nrcresearchpress.com.dist.lib.usu.edu/doi/abs/10.1139/b90-298#.UPmPcmcu1GM

Williams CS, Marshall WH (1937) Goose nesting studies on Bear River Migratory Waterfowl Refuge. The Journal of Wildlife Management 1: 77–86. http://www.jstor.org/stable/3795764

Williams CS, Marshall WH (1938) Duck nesting studies, Bear River Migratory Bird Refuge, Utah, 1937. The Journal of Wildlife Management 2: 29–48. http://www.jstor.org/stable/3796165

Wilson N, Cavitt J, Linford M (2011) Dietary Analysis and physical condition of waterfowl at Great Salt Lake. Avian Ecology Laboratory, Department of Zoology, Weber State University.

Wolf K (1955) Some effects of fluctuating and falling water levels on waterfowl production. The Journal of Wildlife Management 19: 13–23. http://www.jstor.org/stable/3797548

Wollheim WM, Lovvorn JR (1995) Salinity effects on macroinvertebrate assemblages and waterbird food webs in shallow lakes of the Wyoming High Plains. Hydrobiologia 310: 207–233. http://link.springer.com/article/10.1007/BF00006832.

Woo I, Zedler JB (2002) Can nutrients alone shift a sedge meadow towards dominance by the invasive *Typha x glauca?* Wetlands 22: 509–521. http://www.springerlink.com/index/er1q0674603pm534.pdf.

Wurtsbaugh W, Marcarelli A (2004a) Hydrogen sulfide in Farmington Bay and the Great Salt Lake: a potential odor-causing agent. Report to Davis Sewer Improvement District. http://cdsewer.org/GSLRes/2004_H2S_in_Farmington_Bay_Report_2003_Data_-_USU.pdf.

Wurtsbaugh W, Marcarelli A (2004b) Analysis of phytoplankton nutrient limitation in Farmington Bay and the Great Salt Lake. Report to Central Davis Sewer Improvement District. http://cdsewer.org/GSLRes/2004_Phytoplankton_Nutrient_Limitation_Report_2003_Data_-_USU.pdf.

Wurtsbaugh W, Marcarelli A (2004c) Phytoplankton and zooplankton in Farmington Bay and the Great Salt Lake, Utah. Report to Central Davis Sewer Improvement District. http://cdsewer.org/GSLRes/2004_Phytoplankton_and_Zooplankton_Report_2003_Data_-_USU.pdf.

Wurtsbaugh W, Marcarelli A (2005) Continuing analysis of phytoplankton nutrient limitation in Farmington Bay and the Great Salt Lake. Report to Central Davis Sewer Improvement District. http://cdsewer.org/GSLRes/2005_Continuing_Phytoplankton_Nutrient_Limitation_Report_2004_Data_-_USU.pdf.

Wurtsbaugh W, Marcarelli A (2006) Eutrophication in Farmington Bay, Great Salt Lake, Utah, 2005 annual report. Report to Central Davis Sewer District. http://cdsewer.org/GSLRes/2006_Eutrophication_in_Farmington_Bay_Report_2005_Data_-_USU.pdf.

Zedler JB, Kercher S (2004) Causes and consequences of invasive plants in wetlands: opportunities, opportunists, and outcomes. Critical Reviews in Plant Sciences 23: 431–452. http://www.tandfonline.com/doi/abs/10.1080/07352680490514673#.UlJ702mkrGE.

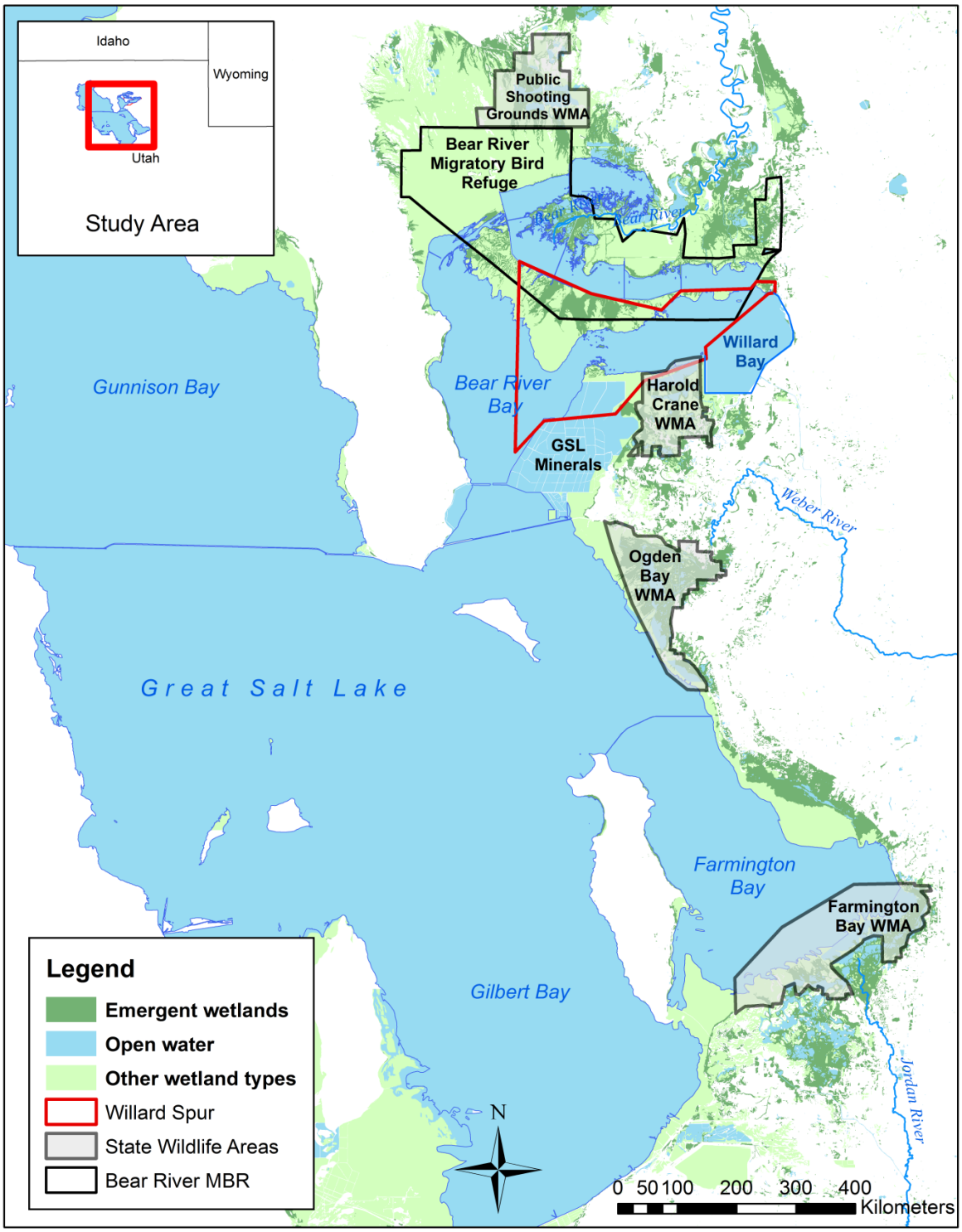


Figure 1. The Great Salt Lake wetlands and management areas. Wetland extent according to the National Wetland Inventory (AGRC 2001)

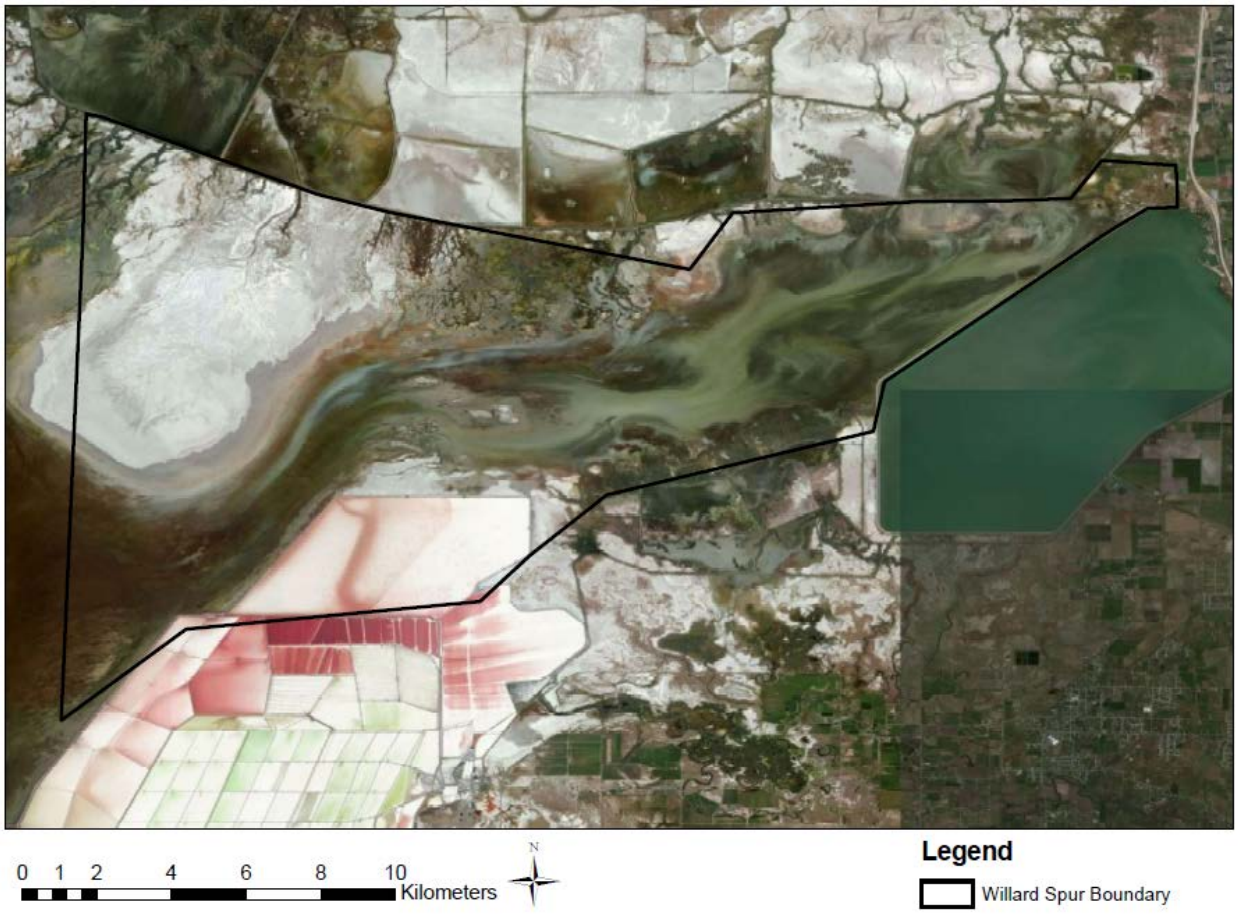


Figure 2. Willard Spur area (outlined in black) of Great Salt Lake.

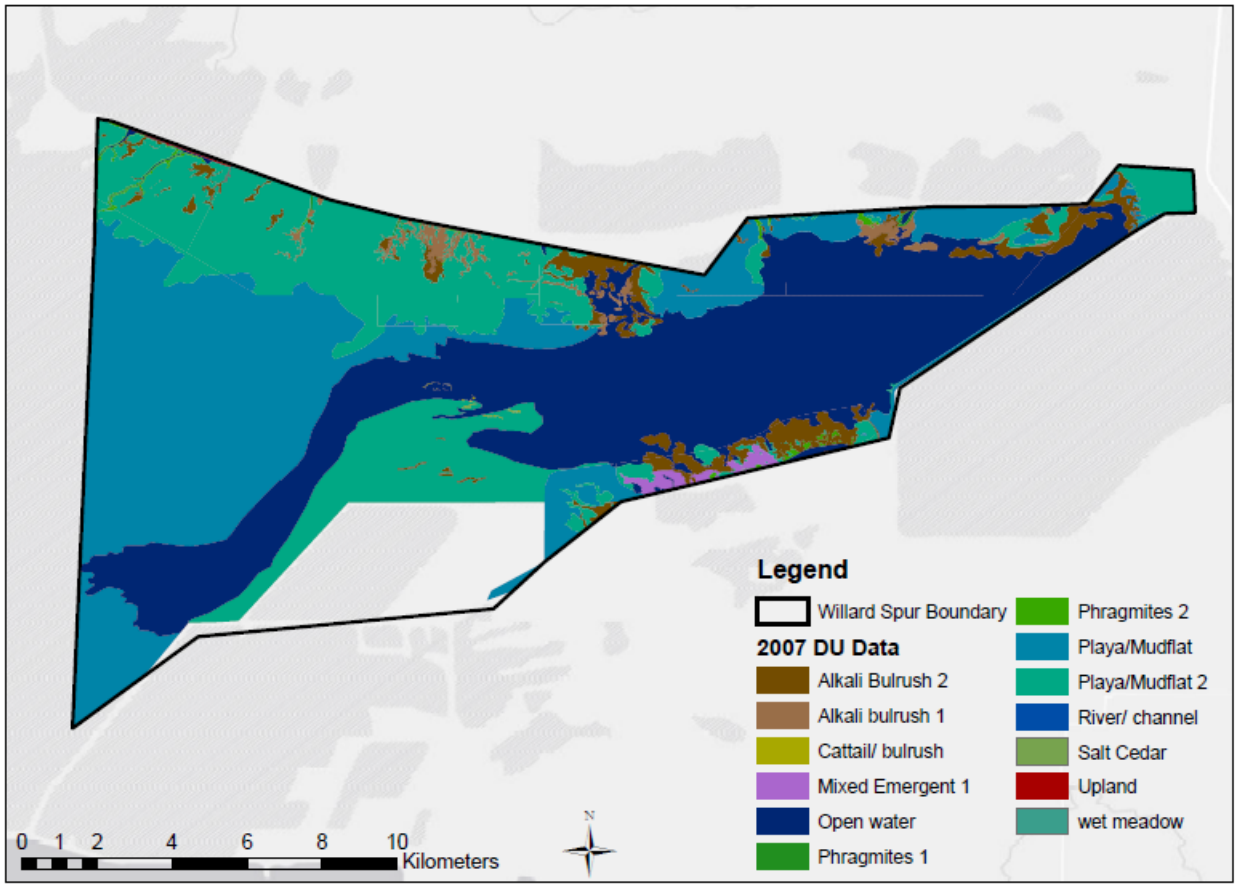


Figure 3. Classified wetland vegetation of the Willard Spur from the 2007 Ducks Unlimited mapping efforts.

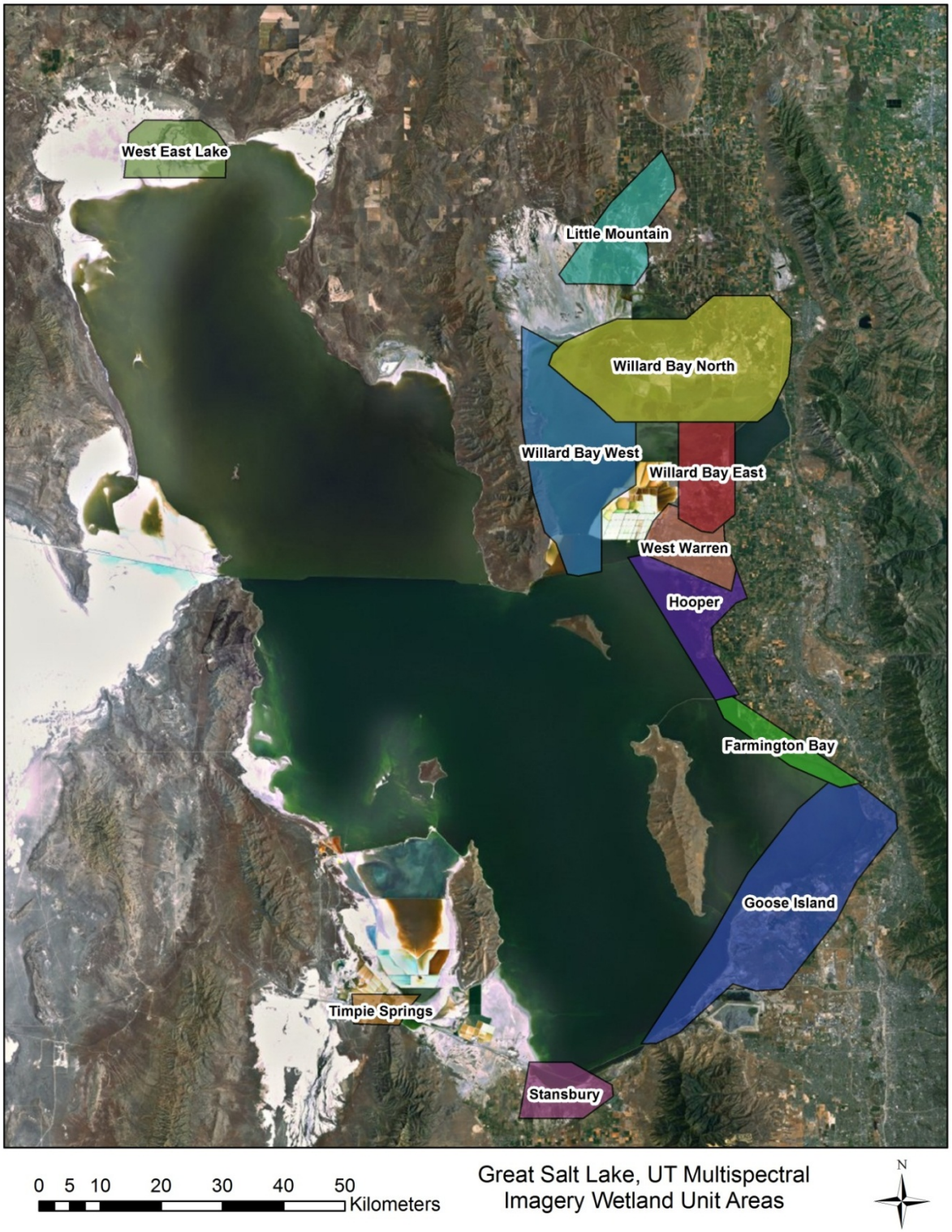


Figure 4. Wetland complexes around the Great Salt Lake where high resolution multi-spectral imagery was acquired in spring 2011.

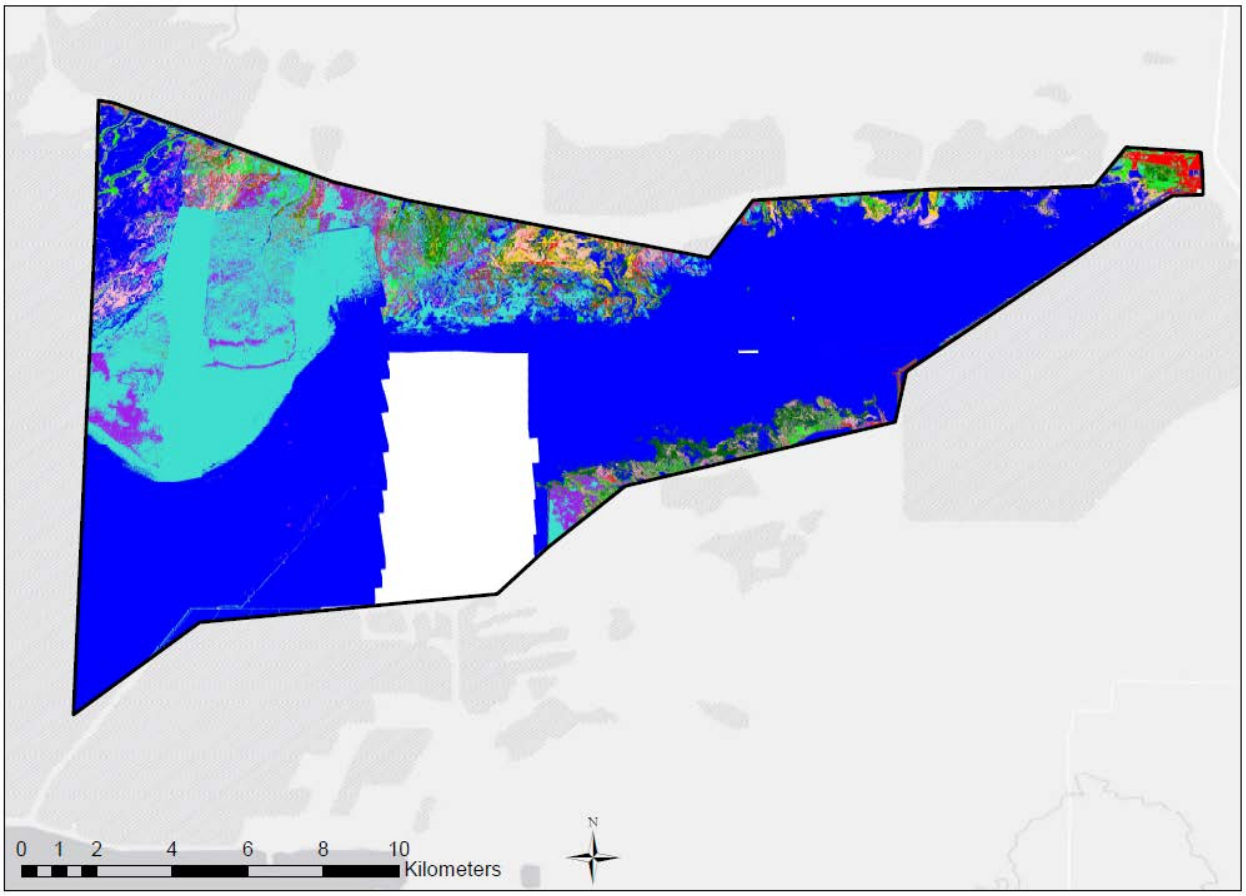


Figure 5. Classified imagery of the Willard Spur from the 2011 high resolution multi-spectral imagery flights.

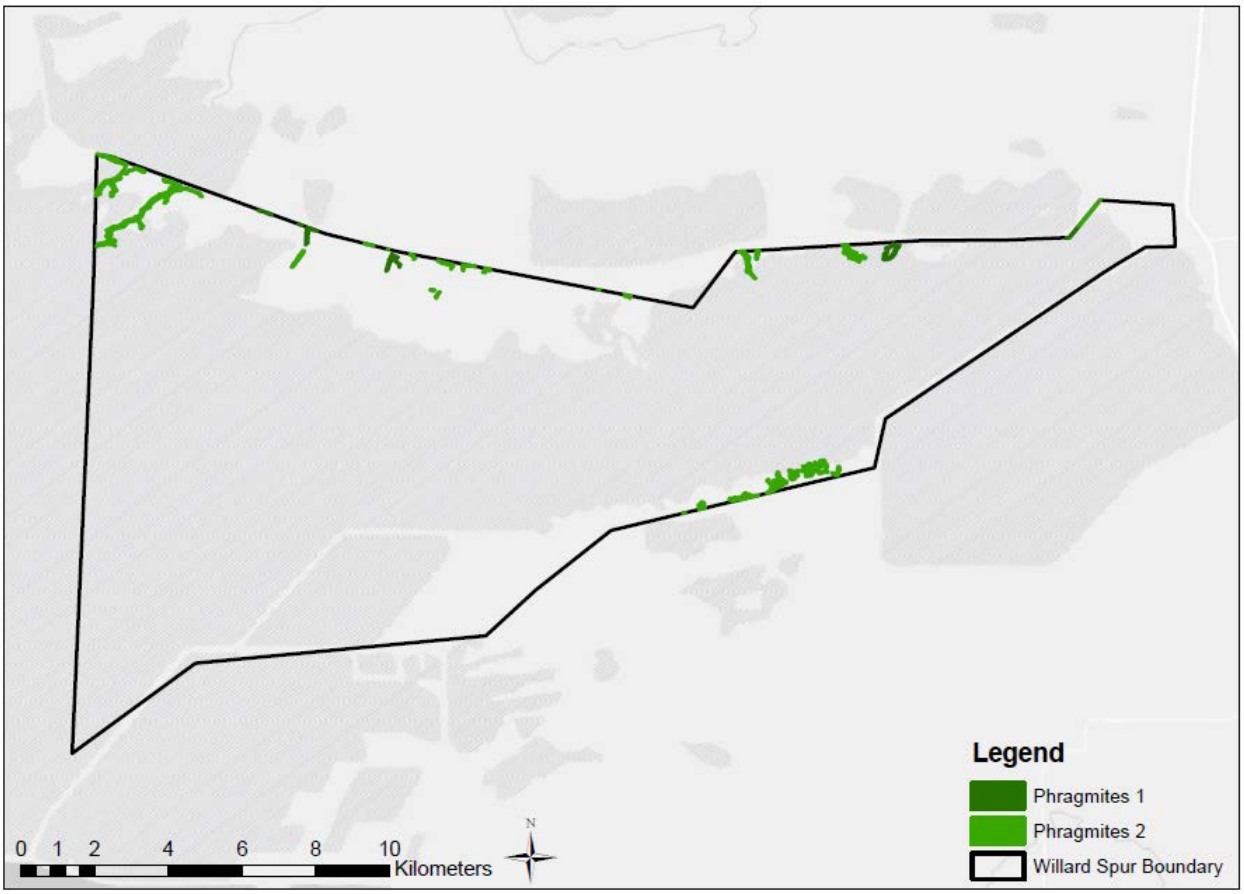


Figure 6. 2007 Ducks Unlimited Wetlands Assessment Project Data – Willard Spur, only *Phragmites* classes.

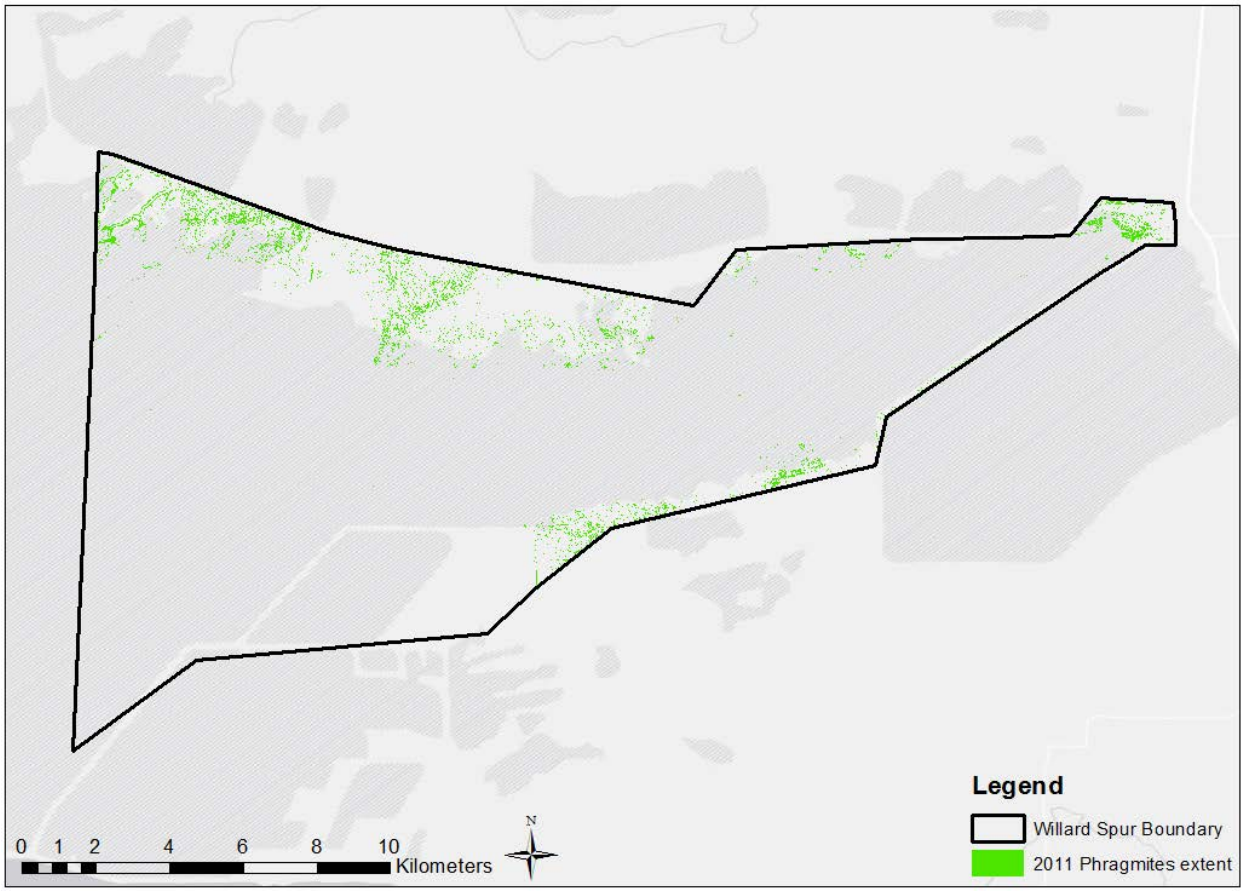


Figure 7. 2011 Great Salt Lake Wetland Vegetation Classification Project 1m classified data, only *Phragmites*.

Table 1. Major habitat types around GSL, their dominant plant species, target water depths, and observed or threshold salinity levels.

Habitat type	**Dominant plant species**[α,γ,θ,ε]	**Water depth (cm)**	**Goal of water depth recommendation**	**Salinity (mmhos/cm)**	**Target habitat or species**
Open Water	*Stuckenia pectinata,*	46-91[λ]	deep submerged marsh	1.3[θ]	open water wetlands
	Stuckenia filiformis, Ruppia	10-46[λ]	shallow submerged marsh	14-31[α]	open water wetlands
	maritima, Zannichellia	>25[η]	swan & diving duck use	32[β]	*Stuckenia pectinata*
	palustris	46[ν]	open water vegetation		
Emergent	*Schoenoplectus maritimus,*	30-60[λ]	deep	1.3[θ]	*Phragmites*
	Schoenoplectus acutus,	5-20[λ]	shallow	1.8[θ]; 3[α]	*Typha*
	Schoenoplectus americanus,	0-10[η]	geese use	1.0-6.9[θ] 5-7[β]	*Schoenoplectus acutus*
	Distichlis spicata, Typha			2.6-14.2[θ]; 7-9[β]	*Schoenoplectus maritimus*
	spp., *Phragmites australis*			8[α]	deep emergent marsh
				12-13[α]	shallow emergent marsh
Hemi-marsh	combination of open water and emergent species	20-30[λ] 5-25[η]	hemi-marsh dabbling duck use	2.8-27.9[ν]	most to least productive conditions for hemi-marsh
Playa	*Salicornia rubra,*	0-5[λ,η]	small shorebird use	<27.9[θ]	vegetated mudflat
	S*arcocornia utahensis,*	0-10[η]	larger shorebird use	6.26[ε] total salts	*Salicornia rubra*
	Suaeda calceoliformis			3.31[ε] total salts	*Suaeda calceoliformis*

α CH2M Hill 2005 – observational study at PSGWMA and FBWMA
β Christiansen and Low – experimental greenhouse study showing maximum tolerances for germination
γ Cox and Kadlec – observational study at BRMBR
ε Flowers 1934 – observational study in northern Bear River Bay
η Jasmer 2000 – target water depths for waterfowl use
[θ] Kadlec 1982 – observational study at OBWMA
[λ] Olson et al. 2004 – target water levels
[ν] Robel 1962 – Observational study at Bear River Club

Table 2. Vegetation in Willard Spur according to 2007 Ducks Unlimited wetland vegetation mapping project. Table adapted from 2007 Ducks Unlimited Project report.

Class name	**Description**	**Area (acres)**	**Percent**
Open water	Sago pondweed habitat	13,608	36
Playa / mudflat	Non-vegetated	12,377	32
Playa / mudflat 2	More than 25% cover of *Salicornia* spp. or *Distichlis spicata*	9,629	25
Alkali bulrush 2	Between 51-75% *Schoenoplectus maritimus*	1,666	4
Alkali bulrush 1	≥75% *Schoenoplectus maritimus*	482	1
Mixed emergent 1	Any vegetation other than what is already classified	217	<1
Phragmites 2	51-75% cover of *Phragmites*	167	<1
Upland	All upland	28	<1
Phragmites 1	More than 75% *Phragmites*	23	<1
Cattails / Bulrush	≥75% *Typha / Schoenoplectus acutus*	12	<1
Salt cedar	*Tamarix* spp.	8	<1

Table 3. Wetland vegetation in Willard Spur based on spring 2011 flights.

Class name	**Area (acres)**	**Percentage (%)**
Open Water	41,159	63
Phragmites australis	1,264	2
Playa wetlands	13,535	20
Salicornia spp.	735	1
Distichlis spicata	2,973	5
Schoenoplectus acutus	755	1
Typha spp.	1,998	3
Mixed emergent	2,391	4
Upland	426	<1

Table 4. Plant species found in the Willard Spur according to Flowers (1934). Present day Latin name equivalents are shown in Appendix 1.

Scientific name	**Common name**
Allenrolfea occidentalis (S. Watson) Kuntze	iodinebush
Allocarya nitens Greene	unknown
Atriplex hymenelytra (Torr.) S. Watson	desert holly
Atriplex truncata (Torr. ex S. Watson) A. Gray	wedgescale
Grindelia squarrosa (Pursh) Dunal	curlycup gumweed
Helianthus annuus L.	sunflower
Hordeum jubatum L.	foxtail barley
Hordeum marinum Huds.	Mediterranean barley
Lepidium perfoliatum L.	pepperweed
Lepidium pubicarpum A. Nels.	common peppergrass
Matricaria suaveolens (Pursh) Buchen.	wild chamomile
Polygonum aviculare L.	prostrate knotweed
Puccinellia nuttalliana (Schultes) Hitchc.	Nuttall's alkali grass
Ranunculus cymbalaria Pursh	alkali buttercup
Ranunculus eremogenes Greene	buttercup
Ruppia maritima L.	Wigeon grass
Salicornia rubra A. Nels.	pickleweed
Sarcobatus vermiculatus (Hook.) Torr.	greasewood
Sisymbrium altissimum L.	tall tumblemustard
Spergularia salina Presl.	salt sandspury
Stuckenia pectinata (L.) Böerner	Sago false pondweed

Appendix A. Plant species lists from surveys near or in portions of Willard Spur

A. Species list from BRMBR (BRMBR 2006)

Common Name	Scientific Name
GRASSES	
Alkali Grass	*Pucinellia distans*
Alkali Sacaton	*Sporobolus airoides*
Barnyard grass (L.) Beauv.	*Enchinochloa crusgallii*
Bearded Wheatgrass	*Agropyron subsecundum*
Bulbous Bluegrass	*Poa bulbosa*
Cheatgrass, Downy Chess	*Bromus tectorum*
Crabgrass	*Digitaria sanguinalis (L.) Scop*
Crested Wheatgrass	*Agropyron cristatum*
Desert Saltgrass	*Distichlis spicata var. stricta (Torr.) Beetle*
Foxtail Barley	*Hordeum jubatum*
Great Basin Wild Rye	*Elymus anerreus*
Hairy Chess	*Bromus commutatus Schrad.*
Intermediate Wheatgrass	*Agropyron intermediim*
Kentucky Bluegrass	*Poa pratensis*
Medusahead	*Taeniatherum caput-medusa*
Nuttall's Alkaligrass	*Puccinellia nuttaliana*
Prairie Cordgrass	*Spartina pectinata*
Rabbitsfoot Grass	*Polypogon monspeliensis (L.) Desf.*
Reed	*Phragmites communis Trin.*
Scratchgrass	*Muhlenbergia asperifolia (Nees. & Mey.)*
Squirreltail	*Sitanion hystrix*
Streambank Wheatgrass	*Agropyron riparium*
Wildrye	*Elymus glaucus Buckl.*
Witchgrass	*Panicum capillare*
AQUATICS	
Alkali Bulrush	*Scirpus maritimus L. (paludosus)*
Berchtold Pondweed	*Potamogeton berchtoldii*
Chara	*Chara spp.*
Common Cattail	*Typha latifolia L.*
Fluted Bulrush	*Scirpus fluviatilis (Torr.)A. Gray*
Hardstem Bulrush	*Scirpus acutus Muhl.*
Hornwort, Coontail	*Ceratophyllum demersum L.*
Mexican Rush	*Juncus mexicanus*
Narrowleaf Cattail	*Typha domingensis*
Narrow-leaved Bur-reed	*Sparganium angustifolium*
Olney Bulrush	*Scirpus olneyi Gray*
Saltmarsh Bulrush	*Scirpus maritimus*
Seaside Arrowgrass	*Triglochin maritimaL.*
Showy Milkweed	*Asclepias speciosa Torr.*
Spikerush	*Eleocharius palustris*

Swamp Milkweed	*Asclepias incarnata L.*
Wire Rush	*Juncus balticus Willd.*
Reed Canarygrass	*Phalaris arundinacea*
Common Reed	*Phragmites australis*
FORBS	
Pigweed, Redroot	*Amaranthus retroflexus L.*
Wild Onion	*Allium acuminatum Hook.*
Hound's Tongue	*Cynoglossum officinale L.*
Clammyweed	*Polanisia dodecandra*
Saltwort, Samphire, Pickleweed	*Salicornia rubra*
Pursh Seepweed	*Suaeda depressa*
Alkali Seepweed	*Suaeda fruticosa*
Black Seepweed, Inkweed	*Suaeda nigra (moquinii)*
Yarrow	*Achillea millifolium L.*
Western Yarrow	*Achillea lanulosa*
Mountain Dandelion	*Agoseris glauca*
Annual Ragweed	*Ambrosia artemisifolia L.*
Western Ragweed	*Ambrosia psilostachya*
Smaller Burdock	*Arctium minus*
Wild Aster	*Aster chilensis var. adscendens*
Siskiyou Aster	*Aster hesperius A. Gray*
Beggar's Ticks	*Bidens cernua L.*
Blue Sailors,	*Chickory Chichorium intybus L.*
Canada Thistle	*Cirsium arvense*
Bull Thistle	*Cirsium vulgare*
Curly-cup Gumweed	*Grindelia squarrosa*
Broom Snakeweed	*Gutierrezia sarothrae*
Annual Sunflower	*Helianthus annus*
Marsh Elder	*Iva axillaries*
False Ragweed	*Iva xanthifolia*
Blue Lettuce	*Lactuca pulchella*
Wire Lettuce	*Lactuca serriola*
Pineapple Weed	*Matricaria matricarioides*
Prickly/Spiny Sowthistle	*Sonchus asper*
Dandelion	*Taraxacum officinale*
Goatsbeard, Western Salsify	*Tragopogon dubius*
Field Bindweed, Wild Morning-glory	*Convolvulus arvensis*
Morning Glory	*Convolvulus sepium*
Black Mustard	*Brassica nigra*
Whitetop	*Cardaria draba*
Tansy Mustard	*Descurainia Sophia*
Dyer's Woad	*Isatis tinctoria*
Peppergrass	*Lepidium perfoliatum*
Perennial Pepperweed	*Lepidium latifolium*
Tumble Mustard	*Sisymbrium altissimum*

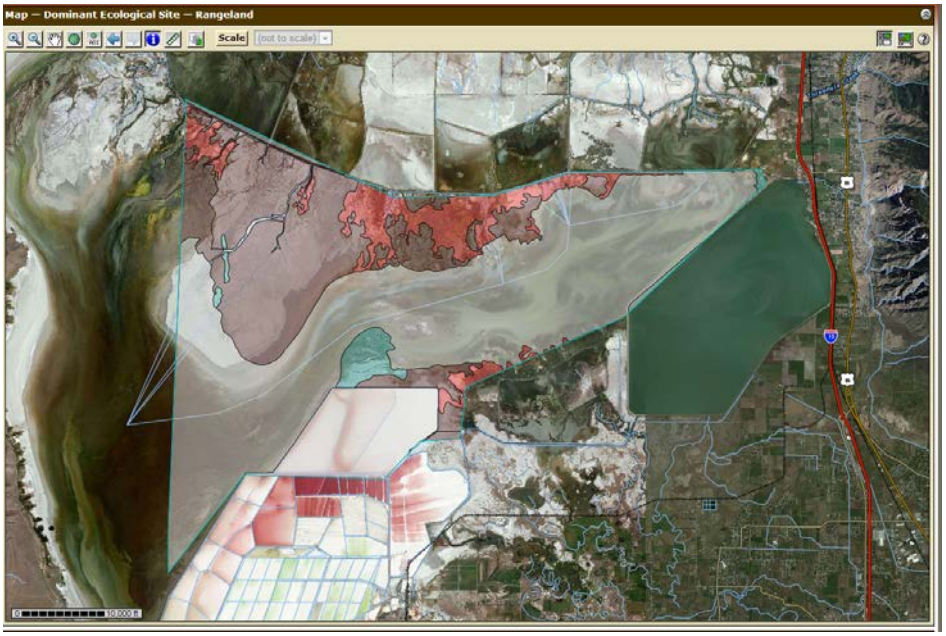
Common Teasel	*Dipsacus sylvestris Huds.*
Ridgeseed Spurge	*Euphorbia glyptosperma Engelm.*
Redstem Filaree, Storksbill	*Erodium cicutarium*
Bugleweed	*Lycopus asper Greene*
Catnip	*Nepeta cataria L.*
Skullcap	*Scutellaria galericulata L.*
Black Medic	*Medicago lupulina L.*
Alfalfa	*Medicago sativa L.*
White Sweetclover	*Meliotus alba*
Yellow Sweetclover	*Melilitus officinalis*
Clover	*Trifolium fragiferum*
Asparagus	*Asparagus officinalis L.*
Blazing Star	*Mentzelia laevicaulis*
Hollyhock	*Althaea rosea*
Flower-of-an-hour	*Hibiscus trionum*
Cheeseweed	*Malva neglecta*
Sticky willow herb	*Epilobium adenocaulon*
Gaura	*Guara parviflora*
Evening Primrose	*Oenothera biennis*
Plantain	*Plantago major*
Waterspot, Floating Ladysthumb	*Polygonum amphibium*
Knotweed	*Polygonum aviculare*
Curlytop Ladysthumb	*Polygonum lapathifolium*
Spotted Landysthumb	*Polygonum persicaria*
Bushy Knotweed	*Polygonum ramosissimum*
Curly Dock	*Rumex crispus*
Willow Dock	*Rumex salicifolius*
Purslane	*Portulaca aleracea*
Saltwort	*Glaux maritime*
Rocky Mountain Buttercup	*Ranunculus cymbalaria*
Celery-Leaf Buttercup	*Ranunculus sceleratus*
Silverleaf Cinquefoil	*Potentilla anserine*
Catchweed Bedstraw	*Galium aparine*
Annual Paintbrush	*Castilleja exilis A. Nels.*
Mullein	*Verbascum thapsus*
European Bittersweet	*Solanum dulcamera L.*
Tomato	*Lycopersicon esculentum Mill.*
Poison Hemlock	*Conium maculatum*
Slim Stinging Nettle	*Urtica dioca L. ssp. Gracilis (Ait.) Seland.*
Big-bract Verbena	*Verbena bracteata Lag. & Rodr.*
Puncturevine/weed, Caltrop	*Tribulus terrestris L.*
Chamomile	*Chamomile rescuita*
Indianwheat, Woolly Plantain	*Plantago patagonica*
Rocky Mountain Beeplant	*Cleome serrulata*
Flixweed	*Descurainia Sophia*
Field Pennycress	*Thlaspi arvense*

Shepherdspurse	*Capsilla bursa-pastoris*
Common Cocklebur	*Xanthium strumarium*
Western Groundsel	*Senecio integerrimus*
Spreading Alkaliweed	*Cressa truxillensis*
Dodder	*Cuscuta spp.*
Netseed Lambsquarter	*Chenopodium berlandieri*
Purple Aster	*Machaeranthera canescens*
Kochia	*Kochia scoparius*
Goldenpea	*Thermopsis rhombifolia*

TREES AND SHRUBS

Big Sagebrush	*Artemisia tridentata*
Box elder	*Acer negundo*
Dogbane	*Apocynum cannabinum*
Iodinebush	*Allenrolfea occidentalis*
Shadscale	*Atriplex confertifolia*
Nuttall Saltbush	*Atriplex nuttallii*
Spearscale	*Atriplex patula var. hastata*
Fourwinged Saltbush	*Atriplex canescens*
Gray Rabbitbrush	*Chrysothamnus nauseosus*
Green Rabbitbrush	*Chrysothamnus viscidiflorus*
Greasewood	*Sarcobatus vermiculatus*
Hoary Sagebrush	*Artemesia cana Pursh.*
Russian Olive	*Elaeagnus angustifolia L.*
Golden Currant	*Ribes aureum Pursh*
Red Ash	*Fraxinus pennsylvanica*
Oriental Arbor-vitae	*Thuja orientalis*
Wood's Rose	*Rosa woodsii*
Bolleana Poplar	*Populus alba L. var. bolleana Lauche*
Fremont Poplar	*Populus fremontii S. Wats.*
Peachleaf Willow	*Salix amygdaloides Anderss.*
Beak or Bebb Willow	*Salix bebbiana var. perrostrata Sarg.*
Sandbar Willow	*Salix exigua Nutt.*
Tamarisk, Salt Cedar	*Tamarix pentandra Pall.*
Siberian Elm	*Ulmus pumila*

B. Ecological Site Assessment from NRCS Web Soil Survey (USDA-NRCS 2013)



Ecological Site	Growth Form	Common Name	Latin Name
Alkali Bottoms	Primary Grasses	Douglas' sedge	*Carex douglasii*
		saltgrass	*Distichlis spicata*
		mountain rush	*Juncus arcticus ssp. littoralis*
		basin wildrye	*Leymus cinereus*
		Sandberg bluegrass	*Poa secunda*
		alkali sacaton	*Sporobolus airoides*
	Secondary Grasses	squirreltail	*Elymus elymoides*
		foxtail barley	*Hordeum jubatum*
		beardless wildrye	*Leymus triticoides*
		mat muhly	*Muhlenbergia richardsonis*
		western wheatgrass	*Pascopyrum smithii*
		Nuttall's alkaligrass	*Puccinellia nuttalliana*
		alkali cordgrass	*Spartina gracilis*
	Forbs	silverscale saltbush	*Atriplex argentea*
		fivehorn smotherweed	*Bassia hyssopifolia*
		lesser Indian paintbrush	*Castilleja minor ssp. minor*

		fiddleleaf hawksbeard	*Crepis runcinata*
		Drummond's goldenbush	*Isocoma drummondii*
		povertyweed	*Iva axillaris*
		King's mousetail	*Ivesia kingii*
		burningbush	*Bassia scoparia*
		alkali mallow	*Malvella leprosa*
		Pursh seepweed	*Suaeda calceoliformis*
		hollyleaf clover	*Trifolium gymnocarpon*
		seaside arrowgrass	*Triglochin maritima*
	Primary Shrubs	greasewood	*Sarcobatus vermiculatus*
		iodinebush	*Allenrolfea occidentalis*
		basin big sagebrush	*Artemisia tridentata ssp. tridentata*
		fourwing saltbush	*Atriplex canescens*
		Gardner's saltbush	*Atriplex gardneri*
		basin saltbush	*Atriplex tridentata*
		whiteflower rabbitbrush	*Chrysothamnus albidus*
		rubber rabbitbrush	*Ericameria nauseosa ssp. consimilis var. oreophila*
		green molly	*Bassia americana*
		skunkbush sumac	*Rhus trilobata var. trilobata*
Wet Saline Meadow	Primary Grasses	Nebraska sedge	*Carex nebrascensis*
		clustered field sedge	*Carex praegracilis*
		saltgrass	*Distichlis spicata*
		meadow barley	*Hordeum brachyantherum*
		arctic rush	*Juncus arcticus*
		scratchgrass	*Muhlenbergia asperifolia*
		Sandberg bluegrass	*Poa secunda*
		weeping alkaligrass	*Puccinellia distans*
		saltmarsh alkaligrass	*Puccinellia fasciculata*
	Seconary Grasses	common spikerush	*Eleocharis palustris*
		beardless wildrye	*Leymus triticoides*
		common reed	*Phragmites australis*
		annual rabbitsfoot	*Polypogon monspeliensis*

	grass	
	chairmaker's bulrush	*Schoenoplectus americanus*
	alkali cordgrass	*Spartina gracilis*
	prairie wedgescale	*Sphenopholis obtusata*
Forbs	silverweed cinquefoil	*Argentina anserina*
	meadow milkvetch	*Astragalus diversifolius*
	alkali marsh aster	*Almutaster pauciflorus*
	showy milkweed	*Asclepias speciosa*
	spear saltbush	*Atriplex patula*
	cutleaf waterparsnip	*Berula erecta*
	nodding beggartick	*Bidens cernua*
	giant red Indian paintbrush	*Castilleja miniata*
	red goosefoot	*Chenopodium rubrum*
	meadow thistle	*Cirsium scariosum*
	fiddleleaf hawksbeard	*Crepis runcinata ssp. glauca*
	spreading alkaliweed	*Cressa truxillensis*
	darkthroat shootingstar	*Dodecatheon pulchellum*
	American licorice	*Glycyrrhiza lepidota*
	sea milkwort	*Glaux maritima*
	Nuttall's sunflower	*Helianthus nuttallii*
	alkali mallow	*Malvella leprosa*
	seep monkeyflower	*Mimulus guttatus*
	boraxweed	*Nitrophila occidentalis*
	finebranched popcornflower	*Plagiobothrys leptocladus*
	lanceleaf goldenweed	*Pyrrocoma lanceolata var. lanceolata*
	alkali buttercup	*Ranunculus cymbalaria*
	slender grasswort	*Salicornia maritima*
	stiff blue-eyed grass	*Sisyrinchium demissum*
	Pursh seepweed	*Suaeda calceoliformis*
	seaside arrowgrass	*Triglochin maritima*
Shrubs	iodinebush	*Allenrolfea occidentalis*
	whiteflower rabbitbrush	*Chrysothamnus albidus*
	yellow rabbitbrush	*Chrysothamnus viscidiflorus*

		rubber rabbitbrush	*Ericameria nauseosa*
		Woods' rose	*Rosa woodsii*
		greasewood	*Sarcobatus vermiculatus*
Lakeshore Marsh	*No plant community data available*		
Desert Salty Silt	Primary Grasses	saltgrass	*Distichlis spicata*
	Secondary Grasses	Torrey's rush	*Juncus torreyi*
		alkali cordgrass	*Spartina gracilis*
	Forbs	clustered goldenweed	*Pyrrocoma racemosa var. racemosa*
		slender grasswort	*Salicornia maritima*
		Mojave seablite	*Suaeda moquinii*
	Primary Shrubs	iodinebush	*Allenrolfea occidentalis*
	Secondary Shrubs	sickle saltbush	*Atriplex falcata*
		whiteflower rabbitbrush	*Chrysothamnus albidus*
		greasewood	*Sarcobatus vermiculatus*

Appendix B. Phytoplankton species present in Farmington and Gilbert Bays, Great Salt Lake, Utah. From Wurtsbaugh and Marcarelli 2004.

Species
Amphora coffeaeformis
Amphora delicatissima
Amphora sp.
Carteira sp.
Chaetocerous sp.
Cyclotella sp.
Dunaliella salina
Dunaliella virdis
Glenodinium sp.
Microcoleus sp.
Navicula graciloides
Navicula lanceolata
Navicula sp.
Navicula tripuctata
Nitzschia accicularis
Nitzschia epithemoides
Nitzschia fonticola
Nitzschia palea
Nodularia sp.
Oocystis sp.
Phaedactylum sp.
Pseudoanabaena sp.
Rhopalodia musculus
Spermatozopsis sp.
Sphaerellopsis sp.
Spirulina sp.
Treubaria sp.
UNID Biflagellate
UNID Chrysophyte