Management of the Great Salt Lake Ecosystem: Water, Economic Values and Competing Interests

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Management of the Great Salt Lake Ecosystem: Water, Economic Values and Competing Interests

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Left: Ferry boat stranded by the low water level of Lake Urmia (Photo, Automobile causeway, 12 February 2014). Right: Scientist inspects the dried lakebed of a receding Great Salt Lake (Photo, Gilbert Bay, 12 August 2012).
Introduction

The Great Salt Lake in the western United States, and Lake Urmia in western Iran are remarkably similar in many characteristics (Figure 1), and both are threatened by agricultural water diversions and pollution from nearby cities. Although the size of both lakes fluctuates due to climatic cycles and water diversions, the normal areas of both are very similar (Great Salt - 4300 km²; Urmia – 5100 km²), and they lie at similar elevations (Great Salt – 1280 m; Urmia – 1275 m). The watersheds of both lakes pass through three different States or Provinces, thus complicating water management issues. The climate is similar for both, with hot summers and cold winters. The mean and maximum depths of the Great Salt Lake are currently near 4.4 and 14 m, whereas those for Lake Urmia are approximately 6 and 16 m. Both lakes are divided by causeways: the Great Salt Lake by a railroad causeway and Lake Urmia by an automobile causeway. Passage of water between the two major parts of the Great Salt Lake is restricted by an 82-m breach located in relatively shallow water and until recently, by two 5-m wide culverts. Consequently, lack of extensive water exchange allows major differences in salinity in north and south basins, which in turn allow distinct biota to grow (note color differences, Figure 1). A much larger 1500-m gap in Lake Urmia’s causeway apparently allows sufficient mixing between the basins, so that there may not be major differences in salinity (UNEP 2012). However, both lakes are hypersaline. Prior to major anthropogenic disturbances the salinity in the Great Salt Lake ranged from 60-330 grams per liter, but were usually <200 g/L (Null et al. 2013). Currently, the salinity north of the railroad causeway is at saturation (~330 g/L), and south of the causeway it fluctuates from 50-180 g/L (Figure 2). The salinity of Lake Urmia has not be tracked as frequently, but in 1915 a salinity of 177 g/L was measured (Alipour 2006). However, desiccation of the lake since 2000 has caused the salinity to rise markedly, and it is now over 300 g/L (UNEP 2012).

Both lakes have abundant populations of brine shrimp (Artemia spp.) and brine flies (Ephydra spp.) (Stephens 1990, Wurtsbaugh and Gliwicz 2001, Agh et al. 2007, Ahmadi et al. 2011, Wurtsbaugh et al. 2011) that support tremendous populations of migratory birds (Scott 2001, Aldrich and Paul 2002). The Great Salt Lake is designated as a Western Hemisphere Shorebird Reserve and the wetlands of Lake Urmia are designated as a RAMSAR site (Convention on Wetlands of International Importance, especially as Waterfowl Habitat). In recent years, salinities have increased greatly in Lake Urmia, and brine shrimp are nearly absent from the open waters. In the Great Salt Lake, brine shrimp populations are healthy in the southern basin, but the saturated salts in the basin north of the railway causeway allow only limited brine shrimp reproduction, and densities there are low (B. Marden, personal communication).
Both lakes have major population centers near their shores. The Great Salt Lake is bordered on its eastern and southern shores by a metropolitan area with 2.4 million people, whereas the city of Urmia, with 1.2 million residents, is situated just west of the lake. However, a total of 6.4 million people live in Lake Urmia’s watershed (UNEP 2012), far greater than that in the Great Salt Lake watershed (~2.7 million). Because both areas have arid climates, much of the agriculture is dependent on irrigation, and this has led to water depletion of the rivers reaching the terminal lakes. Compilations by Gwynn (1980) and Gwynn (2002) provide an excellent overview of the many other aspects of the Great Salt Lake’s ecosystem, history and cultural setting. Overviews of Urmia Lake’s limnology, hydrology and social aspects are provided by Eimanifar and Mohebbi (2007) and UNEP (2012).

Although there are remarkable similarities between the two lakes, there are major differences as well. In particular, the elevation and volume of Lake Urmia has declined remarkably since 1995 as a consequence of water development and drought in the basin, whereas the elevation of the Great Salt Lake is only declining slowly (Figure 2). The purpose of this paper is to describe some of the physical, social and management characteristics of the Great Salt Lake that may help inform decisions on how to reverse the catastrophic situation that Lake Urmia now faces.

**Economic evaluation of the Great Salt Lake**

A 2012 economic analysis of the Great Salt Lake (Figure 3) estimated that the total annual economic output of the lake was $1.3 billion US dollars (Bioeconomics 2012). This represents 8% of the gross economic product of the State of Utah. Approximately 85% of the economic value of the lake was attributed to the production of salts and minerals from brine. The principal products produced are potassium sulfate ($K_2SO_4$), magnesium, titanium, and common salt (NaCl). Recreation, including waterfowl hunting, bird watching, swimming and boating accounted for 10% of the valuation. Expenditures by duck and goose hunters accounted for the majority of the recreation valuation. The harvest of brine shrimp cysts (resting eggs) for aquaculture is a $57 million dollar industry, and accounted for approximately 4% of the valuation of the lake. Harvest of cysts began in the mid-1980s and quickly became highly competitive. However, in 2006, most of the brine shrimp industry joined together to form the Great Salt Lake Brine Shrimp Cooperative. Brine shrimp produce cysts throughout the spring, summer, and early fall (Wurtsbaugh and Gliwicz 2001) and a large portion of these float on the surface of the lake where they can be collected by boats (Figure 4B). Yields of cysts are highly variable, but in recent years have shown a general upward trend (Figure 4C).
In addition to traditional evaluations, the Bioeconomics (2012) study also recognized that the unique nature of the Great Salt Lake provides societal values that are difficult to evaluate quantitatively. These values include: “wanting to preserve a resource for future generations (bequest value); wanting to preserve the option of visiting the area at some undefined time in the future (option value); and simply wanting to preserve a resource for the value derived from knowing it exists (existence value).” Utilizing studies of another salt lake in the western United States (Mono Lake), the researchers suggested that the annual existence values of people living in Utah associated with the preservation of the Great Salt Lake would be approximately $100 million. Additional value would exist due to people from other states in the US and World who place existence values on this unique ecosystem.

**Threats to the Great Salt Lake Ecosystem**

Before 1980, the ecological and cultural values of the Great Salt Lake were underappreciated, and the system was viewed as a place where wastes could be disposed of, and where any fresh water reaching it was considered wasted. This view is changing radically, and many State agencies and non-governmental organizations are now working at preserving the ecosystem. Nevertheless, the lake is considered unhealthy in several respects (SWCA 2012). Currently managers and researchers recognize four major threats to the lake: metal pollution, eutrophication from sewage and non-point discharges, proliferation of non-native *Phragmites*, and desiccation.

*Metal pollution*—Metal pollution is probably the most widely recognized water quality problem for the lake (Naftz et al. 2009, Wurtsbaugh et al. 2011, SWCA 2012). The differences in salinity in the north and south part of the lake generate a peculiar circulation pattern, with high-density salts from the north flowing back through the causeway to create a deep brine layer (monimolimnion) that underlies about 44% of the lake’s south basin. The layer has no oxygen, has high concentrations of hydrogen sulfide and is devoid of brine shrimp and brine flies. The anoxic conditions have mobilized high concentrations of mercury (Hg), and particularly methyl mercury, from the sediments (Jones and Wurtsbaugh 2014). Concentrations of methyl mercury in this layer reach 34 ng/L, which is one of the highest reported concentrations reported for any water body in the United States. When the deep layer is mixed into the overlying water by wind action, appreciable amounts of mercury are taken up by brine shrimp and brine flies, and this is passed into waterfowl and other birds (Gardberg In prep.). Three species of ducks have high levels of mercury and are listed on a consumption advisory to discourage people from eating them. Other metals are also high in the sediments of the Great Salt Lake, likely as the result of extensive smelting activities in the Great Salt Lake Valley that began in the late 1800s and continue to this day.
Concentrations of most metals in the sediments have, however, decreased since the implementation of the U.S. Clean Air Act in the late 1970s.

Selenium is a metalloid that is also of concern in the Great Salt Lake. It is abundant in the soils in the region, and is being released into the Great Salt Lake watershed as the result of metal mining, and mining for phosphate rock. Concentrations of selenium in the water are higher than recommended for the protection of some species (Waddell et al. 2009), but the State of Utah recently set criteria above current lake levels (UDEQ 2008). Monitoring for this toxicant, as well as many others, is underway in the lake to insure that levels do not rise higher.

**Eutrophication**—The treated domestic wastes of most of the population of Utah are discharged into the Great Salt Lake, and particularly into a shallow Farmington Bay lying in the southeast portion of the lake near metropolitan Salt Lake City. This bay is partially separated by an automobile causeway, and this allows it to have lower salinities, and higher nutrient concentrations than other portions of the lake. Until the 1970s raw sewage was discharged into the lake, but subsequently secondary-treatment has been used. Although this treatment removes most organic wastes, it produces high concentrations of nitrogen and phosphorus nutrients that support the growth of phytoplankton in Farmington Bay and elsewhere in the lake. Algal chlorophyll levels are extremely high in Farmington Bay, but in other parts of the lake they are only moderate. Blooms of toxic cyanobacteria (Figure 5) occur in Farmington Bay when salinities are between approximately 1-4%. Additionally, complete water column anoxia is common many nights throughout the summer and odor problems are severe (Wurtsbaugh et al. 2012). These odors reduce the recreational use of the Great Salt Lake (Trentelman 2009). Paleolimnological analyses of sediments from the south basin of the lake indicate that eutrophication began in the early 1900s coincident with the increasing population in metropolitan Salt Lake City (Leavitt et al. 2012).

Despite the extreme levels of algae in Farmington Bay, and high levels elsewhere (Wurtsbaugh et al. 2012) actions have not been taken to reduce nutrient loading. In part, this is because fish occur only in the freshest parts of estuaries in the lake (Moore 2011), and most water quality criteria are designed to protect fish. Additionally, the heavy nutrient loading is believed to increase algal production in the south basin of the Great Salt Lake by approximately 10%, and this, in turn, may support higher densities of brine shrimp which are an asset to the cyst harvesting industry and to birds that utilize the lake. However, the anoxia within Farmington Bay likely limits the production of aquatic invertebrates in the sediments, but wading bird densities in the shallow littoral areas are nevertheless very high. Additional work is needed by managers to assess the net impact of eutrophication on the lake.
Invasion of non-native *Phragmites australis*—Although native *Phragmites* were moderately abundant in the wetlands of the Great Salt Lake, other emergent macrophytes such as cattails (*Typha latifolia*) and alkali bulrush (*Schoenoplectus maritimus*) dominated the native communities. However, over the past three decades, *P. australis* cover has increased from 20% to over 56%, and the increase is largely due to a non-native strain (Kulmatiski et al. 2010, Kettenring and Mock 2012). Vast stands of *Phragmites* now cover much of the wetland complex, and this species is less desirable because it does not support wildlife as well as other species of macrophytes. Studies are currently underway to find the best control measures. Burning, tillage, grazing, herbicide treatments and combinations of these are all being used in an attempt to reduce the dominance of this invasive strain.

*Desiccation*—Like many endorheic basins, the Great Salt Lake is also threatened by desiccation, but the magnitude of water loss is currently far less than in Lake Urmia (UNEP 2012)(Figure 2) or the Aral Sea (Micklin 2014). Good water level elevation data is available for the Great Salt Lake from the 1850s when pioneers settled in Utah. Greatly varying climatic conditions have been reflected in high fluctuations in lake levels. In the 1960s there was concern that the lake might dry up and dust storms from the dry lake bed were impacting Salt Lake City. Conversely, during a wet cycle in the mid-1980s the lake reached its highest level and flooding was severe on infrastructure that had encroached on the lake’s shore. Nevertheless, the overall trend in lake elevation has been significantly downward.

The decline in lake level is largely the result of water diversions for agriculture and other uses in the basin (Whitaker 1971, Miller 2008). Miller estimates that water diversions have lowered the lake 3.5 m (11.5 feet) from its natural level (Figure 6). Because of the hypsographic shape of the basin (USGS No date), a 3.5 m decrease in elevation represents approximately a 50% decrease in the volume of the lake. However, Miller suggests that this decline may be ameliorated because of two reasons. First, irrigated agricultural land in the basin is being converted to urban use, and water loss is not as great in urban areas as it is with irrigated land. From 1949 to 2003, irrigated land in the Great Salt Lake basin has declined from 1900 to 1600 km²— a 16% reduction. Secondly, water from the Colorado River Basin has been diverted into the Salt Lake Valley, partially making up for agricultural water withdrawals. However, this inter-basin water transfer only supplies about 1.5% of the lake’s water has taken over 50 years to complete, and when finished, will have cost approximately $3 billion US. The long delays and high costs inevitable in inter-basin water transfers must be taken into account when planning for Lake Urmia.

Nevertheless, despite the somewhat positive aspects of urbanization and water transfer, planning is underway to develop 20% of the flow of the Bear River, the major tributary feeding the Great Salt Lake.
(UDWR 2004). If this plan is implemented, additional loss in the volume of the Great Salt Lake is expected. Mohammed and Tarboton (2012) conducted a sensitivity analysis of the lake to changes in runoff and evaporation, and they estimate that a 25% reduction in flows would reduce the elevation of the Great Salt Lake by approximately another 0.7 meters. Climate change may also impact lake levels, but the uncertainty in local climate models makes predictions difficult (Grimm et al. 1997, Wang et al. 2010). Mohammed and Tarboton (2012) estimate that a 4°C increase in temperature would increase lake evaporation rates and decrease lake level approximately 0.3 meters. However, increasing temperatures in the basin will also likely decrease runoff, because of increases in evapotranspiration (S. Null, Utah State University, unpublished data). Consequently, the potential for increased water development, increased lake evaporation at higher temperatures, and decreased runoff pose serious threats to the long-term elevation and salinity of the Great Salt Lake.

The changes in lake elevation due to climatic and anthropogenic factors have caused significant changes in the salinity of the lake (Figure 7). Prior to the construction of the railway causeway, salinities fluctuated from 17% to approximately 27% (saturation). After the construction of the causeway, salinities have diverged markedly in the two basins, largely because nearly all rivers flow into the south basin (Gilbert Bay), and because only limited mixing occurs through the breach and culverts. In the south basin salinities decreased to near 6% during a series of unusually wet years in the mid-1980s, and became too low to support brine shrimp. However, the higher salinities in the north basin were excellent for the shrimp, populations were high (Wurtsbaugh and Berry 1990), and the brine shrimp harvesting industry shifted its harvesting activities to the north. Despite this short-term positive effect of the causeway, the overall trend has been for salt to migrate to the north basin and precipitate to the bottom. Consequently, the south basin is becoming increasingly dilute, although recent drought has maintained adequate salinities for brine shrimp and brine flies. Plans for modification of water flow through the causeway are ongoing, and hopefully these changes can maintain conditions adequate for the biota, as well as providing sufficiently concentrated brines for the salt and minerals extraction industries. In the face of water development, and climate change, it would be desirable to construct structures that would allow managers to modify the bi-directional flow of water through the causeway.

Although the Great Salt Lake has been lowered significantly by water development, and may be lowered more in the future, one can ask what factors have kept if from suffering the far more drastic declines in lake level and volume of Lake Urmia which has declined to approximately 20% of its original volume. In U.S. Western water law, rights to water are established by those who first claim them for beneficial
uses. Although companies that operate solar evaporation ponds around the lake do have rights to some water entering the lake, the Great Salt Lake itself does not have an established water right because it is too salty for irrigation or culinary use. Consequently, if other upstream interests wish to develop water resources for irrigation or other uses, the flow to the lake could conceivably be reduced much more than it has. Several cultural and geographic factors may have allowed the Great Salt Lake to remain in a functional state:

1. First, precipitation in the Great Salt Lake basin is less than in the Lake Urmia basin. Mean annual precipitation in the Great Salt Lake basin is 493 mm/year (Mohammed and Tarboton 2011, 2012), whereas that in the Urmia basin is only approximately 370 mm/year (Lotfi and Moser 2012, UNEP 2012). The difference in precipitation is reflected in the greater vegetation visible from satellite views of the two watersheds. Both watersheds store much of the precipitation as snow which is delivered as a pulse during spring snowmelt, necessitating the construction of large, expensive dams to store water for irrigation.

2. Secondly, population densities are far less in Utah than in Iran, and significant population growth only commenced with the arrival of pioneers in the 1850s, whereas Iran’s population growth was initiated far earlier (Figure 8). In 2010 population density in Utah was only 13 people km$^2$, whereas it is nearly three times higher in Iran (46 km$^2$), and consequently there is higher demand there for irrigation to grow food. The population density within the actual watershed of Lake Urmia (120/km$^2$) is 2.5 times higher than the density in the Great Salt Lake watershed (49/km$^2$), again indicating a higher local need for water to irrigate crops. However, the population growth rates in both Utah and Iran are near 2% per year, so that populations will double in approximately 35 years. This population increase will put additional demands on water use, particularly if food is largely produced in the basins. However, a large portion of the food used in Utah is imported from areas with more productive agriculture, thus partially relieving demands for water.

3. Thirdly, the frost-free growing season in much of the Great Salt Lake watershed is only 3-5 months, thus limiting the irrigation season, and limiting the types of crops that can grow. The overwhelmingly dominate crop is alfalfa hay (Godfrey 2005), which yields low prices. Consequently, the economic incentive to develop water in the Great Salt Lake watershed is relatively low. Additionally, the Bear River, the major tributary of the Great Salt Lake passes through relatively narrow valleys, limiting the amount of irrigable land, and most of this has already been developed. In contrast, the growing season in the Urmia Lake basin is
approximately 7 months, thus allowing greater time for irrigation withdrawals from rivers and aquifers.

4. Finally, in the last 30 years environmentalists in Utah and throughout the United States have been effective in stopping or slowing water development. Often, the oposition to development has focused on protecting sport fisheries, but there is also an important contingent of scientists and managers interested in protecting wetlands (Downard and Endter-Wada 2013). Diked freshwater wetlands at the margin of the Great Salt Lake are abundant. Many of these were developed in the 1920s–1950s to provide nesting and resting habitat for migratory waterfowl and other birds (Figure 9). The Federal, State and private refuges attract over 1 million ducks each year. The hunters and bird watchers that utilize these diked refuges are an active group who lobby to protect flows that reach the wetlands, and ultimately the Great Salt Lake itself. Moreover, the environmental movement in the United States is strong, and this contingent often effectively resists water development in the Great Salt Lake. As stated by one agency official, “So in the end, the environmental groups are watching the situation very closely and are performing functions that state government does not.”

**Other saline lakes in the US suffering from desiccation**

Unfortunately, desiccation of saline lakes in the United States is not restricted to the Great Salt Lake, and three other systems in the State of California offer good lessons that may be useful for managing Lake Urmia. Between 1908 and 1940, a 674-km long aqueduct was built to bring water from the eastern side of the Sierra Nevada Mountains to the city of Los Angeles. This aqueduct diverted water from Mono Lake, and important habitat for migratory birds, and from the shallow Owens Lake wetlands. The *Artemia* and birds in Mono Lake were threatened as water levels dropped progressively, and salinities increased. The completely desiccated Owens Lake bed caused huge dust storms that jeopardized human health in nearby small towns. Recent court decisions have forced the city of Los Angeles to release water to partially restore the ecological functions of these two water bodies (Owens ND, Wikipedia ND). The Salton Sea in southern California was formed when the Colorado River broke a dike in 1904 and flowed into a natural depression. The salinity of the water body was ideal for fish and birds, but gradually, the agricultural wastewaters that flowed into the lake have caused increased salinity and eutrophication, and the system no longer supports fish, and bird use is imperiled. The system is under study to determine if the lake could be divided in half by a large dike, and thus decrease the evaporative
area and help maintain the salinity at acceptable levels. However, the estimated high cost of the dike ($1 billion US) may impede this project (USGS 2007).

Management of the Great Salt Lake

There are a variety of Utah agencies involved in managing the lake and several Federal agencies that also provide regulation and oversight (Table 1). There is considerable overlap in the functions of these groups. However, there are integrative groups such as the Great Salt Lake Alliance, the Great Salt Lake Advisory Council, and the Great Salt Lake Technical Team that increase interactions among the groups. There is also good communications between the extractive industries (salts; brine shrimp) with these integrative groups and with the agencies that regulate them.

Because of the interest in the lake, and the involvement of many agencies, there is a great deal of monitoring of hydrological and limnological variables that influence the ecosystem. Precipitation, river discharge and lake levels are monitored continuously and the data for most stations is available on-line with real-time data. Most chemical and biological variables are monitored at approximately 10 stations in the south basin of the lake at 2-week intervals, or even more frequently during the brine shrimp cyst harvest in winter. The brine shrimp industry also monitors limnological parameters in the lake’s north basin. Most of the parameters monitored by the State and Federal Agencies are available on-line in updated data bases, or annually with published reports. The availability of frequently-monitored, high-quality data is critical for the effect management of the lake.

Water quality criteria for the Great Salt Lake and other waters of the United States are set based on the designated Beneficial Use for the particular water body. In the Great Salt Lake the different bays have different Beneficial Use designations. For example, the south basin (Gilbert Bay) has designated uses of contact recreation, waterfowl, shore birds and other water-oriented wildlife including their necessary food chain. In contrast, the other bays of the lake have less rigid protection for contact recreation because those waters are used infrequently by swimmers. Rivers in the watershed have other beneficial uses such as the protection of fishes, agricultural withdrawals, or for municipal water supplies. By assigning different Beneficial Uses, managers can provide the proper amount of control over pollution. For example, because the lake is salty and is not used for culinary supplies and it is not necessary to utilize criteria for the protection of human health. Note, however, that the Beneficial Use legal categorization only applies to the quality of the water—not the amount. If a river or lake is desiccated from water diversions, this problem is ironically not considered to have impaired the Beneficial Use.
At about 10-year intervals the Utah Division of Forestry, Fire and State Lands undertakes an extensive planning effort for managing the Great Salt Lake. This is a complicated process due to the many competing interests for the resources of the lake, and by the uncertainty in lake levels that are caused by climatic fluctuations and water management decisions. The complexity of managing this huge resource is shown by the length of the 2013 report (390 p) and a planning matrix which included over 70 individual locales divided into 10 major categories of habitats. The planning effort indicated that most of the habitats and uses in the lake have optimal function when the lake is at elevations between 1280 m and 1282 m.

Conclusions

The Great Salt Lake and Lake Urmia are remarkably similar in many aspects, and both face serious threats. However, the climatic differences between the two systems and the population pressure in Iran have caused much more severe declines in water level and increases in salinity in Lake Urmia than in the Great Salt Lake. Water diversions into the Great Salt Lake from the Colorado River Basin, although not expressly designed to help the lake, have nevertheless partially slowed the decline of lake levels. Land use changes from irrigated agriculture to urban environments have also reduced water demand in the Great Salt Lake Basin. For Lake Urmia, more efficient use of water for agriculture, and diversions of rivers from adjoining drainages could conceivably also help reverse its decline and restore it to its former importance.

Acknowledgements

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REFERENCES


Mohammed, I. N. and D. G. Tarboton. 2011. On the interaction between bathymetry and climate in the system dynamics and preferred levels of the Great Salt Lake. Water Resources Research 47.


### Table 1. Principal agencies and organizations involved in the management of the Great Salt Lake.

<table>
<thead>
<tr>
<th>Utah Agencies</th>
<th>Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Division of Water Resources and the Division of Water Rights</td>
<td>Development of fresh water for agriculture, urban uses</td>
</tr>
<tr>
<td>Department of Water Quality (DWQ)</td>
<td>Water quality for human health and aquatic organisms, permitting of wastewater discharges</td>
</tr>
<tr>
<td>Division of Forestry, Fire and State Lands (FFSL)</td>
<td>Salt extraction permitting; lake access; long-term planning</td>
</tr>
<tr>
<td>Divison of Wildlife Resources</td>
<td>Lake ecology--birds, brine shrimp, regulates brine shrimp industry</td>
</tr>
<tr>
<td>Division of State Parks</td>
<td>Recreation</td>
</tr>
<tr>
<td>Division of Oil Gas and Mining</td>
<td>Permitting for oil and gas exploration in lake bed</td>
</tr>
<tr>
<td>Utah Geological Survey</td>
<td>Monitoring of lake’s dissolved minerals</td>
</tr>
<tr>
<td><strong>Federal Agencies</strong></td>
<td></td>
</tr>
<tr>
<td>US Geological Survey (USGS)</td>
<td>Hydrology, contaminates, ecology</td>
</tr>
<tr>
<td>US Environmental Protection Agency (EPA)</td>
<td>Water quality; provides oversight to DWQ</td>
</tr>
<tr>
<td>US Army Corp of Engineers</td>
<td>Dredging; wetland management</td>
</tr>
<tr>
<td>US Fish and Wildlife Service (birds; ecology)</td>
<td>Contamination, bird, ecology</td>
</tr>
<tr>
<td><strong>Integrative organizations</strong></td>
<td></td>
</tr>
<tr>
<td>Great Salt Lake Advisory Council</td>
<td>Reports to governor; composed of representatives from industry, environmental groups, municipal governments and other State and Federal agencies</td>
</tr>
<tr>
<td>Great Salt Lake Technical Team</td>
<td>Run by the FFSL; composed of representatives from industry, environmental groups, municipal governments and other State and Federal agencies</td>
</tr>
<tr>
<td>Friends of Great Salt Lake</td>
<td>Environmental group interested in protection of the Great Salt Lake ecosystem, and particularly wetlands and birds</td>
</tr>
<tr>
<td>Great Salt Lake Alliance</td>
<td>Consortium of environmental groups</td>
</tr>
</tbody>
</table>
Table 2. Hydrological and limnological parameters monitored on the Great Salt Lake. The intervals and number of stations shown are approximate, and vary seasonally, with greater intensity during the brine shrimp harvest season in winter.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Interval (days)</th>
<th>Sites</th>
<th>Agencies/Groups</th>
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<td><strong>Hydrology</strong></td>
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<tr>
<td>Discharge of rivers</td>
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<td>&gt;30</td>
<td>US Geological Survey</td>
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<tr>
<td>Precipitation (rain and snow)</td>
<td>0.04</td>
<td>&gt;50</td>
<td>Utah Climate Center, others</td>
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<td>Lake level (both basins)</td>
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<td>2</td>
<td>US Geological Survey</td>
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<td><strong>Physical-Chemical</strong></td>
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<tr>
<td>Temperature</td>
<td>14</td>
<td>10</td>
<td>Utah Division of Wildlife Resources; Brine shrimp industry</td>
</tr>
<tr>
<td>Salinity</td>
<td>14</td>
<td>10</td>
<td>Utah Division of Wildlife Resources; Brine shrimp industry</td>
</tr>
<tr>
<td>Major ions (Na, Cl, Ca, Mg, etc.)</td>
<td>90</td>
<td>10</td>
<td>Utah Geological survey</td>
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<tr>
<td>Nutrients (N, P)</td>
<td>14</td>
<td>10</td>
<td>Utah Division of Wildlife Resources; Brine shrimp industry</td>
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<tr>
<td>Water transparency (Secchi depth)</td>
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<td>10</td>
<td>Utah Division of Wildlife Resources; Brine shrimp industry</td>
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<td>Toxins, eutrophication</td>
<td>90</td>
<td>10</td>
<td>Utah Division of Water Quality</td>
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<td><strong>Biological</strong></td>
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<tr>
<td><em>Artemia</em> densities</td>
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<td>10</td>
<td>Utah Division of Wildlife Resources; Brine shrimp industry</td>
</tr>
<tr>
<td><em>Artemia</em> cyst densities</td>
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<td>Utah Division of Wildlife Resources; Brine shrimp industry</td>
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<td>Utah Division of Wildlife Resources; Brine shrimp industry</td>
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<tr>
<td>Algal taxonomy</td>
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<td>10</td>
<td>Utah Division of Wildlife Resources; Brine shrimp industry</td>
</tr>
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<td>Ephydra densities</td>
<td>sporadic</td>
<td>4</td>
<td>Utah Division of Wildlife Resources; Utah State Univ.</td>
</tr>
<tr>
<td>Bird densities (airplane flights)</td>
<td>60</td>
<td>-</td>
<td>Utah Division of Wildlife Resources</td>
</tr>
</tbody>
</table>
Table 2. A small portion of the matrix developed for the 2013 Great Salt Lake Management Plan (FFSL 2013). The vertical column shows various lake levels, ranging from 1277 m (4188 feet) to 1284 m (4213 feet), and the categories across the top horizontal axes show various uses of the lake. Green colors indicate that lake elevations are beneficial for those uses, yellow areas indicate transitional quality, and orange areas indicate adverse conditions. The horizontal solid red lines at 1279.7 m (4198 feet) and 1281.8 m (4205 feet) indicate the range of lake levels that provide the most favorable conditions for most lake uses. The entire matrix (not shown) indicates the quality of the use for over 70 individual localities in, and around the lake.
Figure 1. Google Earth satellite images of the Great Salt Lake, USA (left) and Lake Urmia, Iran. Note that both are divided by causeways. The red color in the north basin of the Great Salt Lake is due to different phytoplankton and Archaea that grow there.
Figure 2. Lake elevation changes in the Great Salt Lake (south basin) and Lake Urmia. The regression line for the Great Salt Lake is highly significant ($p < 0.001$).
Figure 3. Estimated total economic effect of the Great Salt Lake showing the three major economic sectors. The total economic effect is the sum of the direct economic effect, indirect economic effect, and induced effects. Derived from (Bioeconomics 2012).
Figure 4. A. Brine shrimp female with a brood of resting eggs (cysts). B. Slick of brine shrimp cysts in the Great Salt Lake and a harvest boat utilizing oil-skimming technology to collect cysts. C. Annual harvest of brine shrimp cysts from the lake, and the number of permits issued for harvesting. The data is reported as the raw wet weight of cysts plus other materials collected when the cysts are skimmed from the surface of the lake. Processed dry cysts for the market would weigh far less. Although 79 permits are issued, most go to a single brine shrimp cooperative. Data on cyste harvest is from (DWR No date).
Figure 5. Algal bloom in the Great Salt Lake, 15 May 2005. The bloom occurred in Farmington Bay in the southeast section of the lake. The bloom was composed entirely of the cyanobacteria, *Nodularia spumigena*. This bay is partially isolated from the main lake by an automobile causeway, and this allows salinities that are frequently in the 10-40 g/L range needed by this species.
Figure 6. Actual measured elevations of the Great Salt Lake, and estimated “Natural” elevations that would have occurred if river and ground waters had not been diverted for agriculture and other uses. The modeling exercise indicates that the lake is >3 m lower than it would be without human diversions of water. Data of Craig Miller (2008), Utah Division of Water Resources, Salt Lake City.
Figure 7. Changes in the elevation of the Great Salt Lake (A) and the changes in the salinity measured in the south basin (Gilbert Bay) and north basin (Gunnison Bay). In 1959 a railway causeway was constructed, separating the lake in half. Since that time, salts have generally been moving to the north where they have precipitated, leaving the south basin with a declining salinity. The approximate tolerance range for brine shrimp (*Artemia franciscana*) is shown in blue shading. During high runoff years in the mid-1980s, the salinity in the south basin was reduced below the tolerance level for brine shrimp, but populations persisted in the north basin (Gunnison Bay), demonstrating one positive aspect of the railway causeway. Figure from Null et al. (2013).
Figure 8. Population growth (A) and human densities (B) in Iran and in the State of Utah.
Figure 9. Map of the Great Salt Lake showing diked wetlands along the eastern and northern shores (gray shading). These are managed for ducks, geese and other birds. The large island in the south east part of the lake is not a wetland, but rather Antelope Island State Park.