Great Salt Lake
Salinity Advisory Committee

Memorandum

Subject Influence of Salinity on the Resources and Uses of Great Salt Lake

Completed by **Great Salt Lake Salinity Advisory Committee**

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The salinity of Great Salt Lake (GSL) plays a very influential role in shaping the lake's unique ecological, recreational, and mineral resource uses. This memorandum summarizes a review of the literature and GSL databases to describe critical salinity ranges that influence these resources and uses. It presents a GSL Salinity Matrix intended to provide decision-makers with an important illustration; not to predict how GSL's salinity will change, but to illustrate the potential consequences of salinity changes.

All Salinity Advisory Committee (SAC) members and subcommittee participants are thanked for their participation, discussion, input, and review of this document. The participation of the individuals listed in Table 1 was critical for completion of this work.

Table 1. GSL SAC Subcommittee Members

Ecology Subcommittee	Geochemistry Subcommittee
Bonnie Baxter/Westminster	Joe Havasi/Compass Minerals
Thomas Bosteels/GSLBSC	Elliot Jagniecki/UGS
Jaimi Butler/Westminster	Bill Johnson/Univ of Utah
Jim Harris/DWQ	Jim Harris/DWQ
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Brian Tavernia/National Audubon Society	Tom Tripp/Tooele County
Laura Vernon/FFSL	Laura Vernon/FFSL

Notes:
DWiR = Division of Wildlife Resources
DWRe = Division of Water Resources
DWQ = Division of Water Quality
FFSL = Division of Forestry, Fire and State Lands
GSLBSC = Great Salt Lake Brine Shrimp Co-operative
UGS = Utah Geological Survey
USGS = U.S. Geological Society

1. Purpose and Need

A high priority identified by the GSL SAC was to develop a means to interpret salinity data and evaluate their significance. A means was needed to answer questions such as, does the observed or forecasted salinity support the lake's uses? Or, how might a change in salinity influence those uses? Answering these questions was determined to be central to many of the SAC's objectives. Completing this task as a committee facilitated important discussions and understanding among committee members (Objective Number [No.] 1 in the SAC's charter). Completion of the task will support efforts to identify gaps in data and understanding of the lake (Objective No. 2 in the SAC's charter). It will also be used to better understand how changes in the lake's salinity may influence changes in the lake's uses and to make recommendations to FFSL and DWQ (Objective No. 3 in the SAC's charter). Such a tool will be valuable for effective adaptive management of the lake.

2. Methodology

The 2013 Great Salt Lake Comprehensive Management Plan (UDNR 2013) includes a lake water level matrix that illustrates the benefit or impact of different lake water levels (y-axis) to the numerous resources and uses of GSL (x-axis). The SAC decided to develop a similar matrix for salinity to serve as a companion to the GSL water level matrix. The GSL Salinity Matrix will provide lake users, researchers, managers, and regulators a practical means to interpret salinity data and evaluate their significance for GSL. The SAC intends for this matrix to be a starting point. It is intended to be a tool that is useful today but will continue to be improved into tomorrow.

The GSL SAC (Table 1) formed two subcommittees (ecology and geochemistry) in April 2020 to develop the GSL Salinity Matrix. SAC members began by identifying key GSL resources and uses to include in the evaluation. The two subcommittees then worked to identify and review historical data, survey the literature, review and discuss findings, and summarize the results in a matrix. The GSL Salinity Matrix included in Figure 1 is thus the product of several evolutions; the SAC expects that this evolution will continue. The effort to develop the GSL Salinity Matrix has already resulted in several new lines of inquiry. It is important to note that Figure 1 is a summary of a more detailed salinity matrix, with references, that is included in Attachment A.

3. Discussion

The GSL Salinity Matrix is focused largely upon the open water systems of GSL, including Farmington Bay and Bear River Bay but with a primary focus upon Gilbert Bay (South Arm) and Gunnison Bay (North Arm). As such, the GSL Salinity Matrix may not include all beneficial uses, especially in upland, shoreline, or estuarine areas of the lake. Additional uses may be added and changes may be made as the GSL Salinity Matrix continues to evolve.

There are simply inadequate data to precisely isolate and fully describe the ecological response to changes in salinity. Describing GSL's salinity, isolating the influence of salinity from the myriad of variables that influence the lake's resources, and interpreting what might be physiological limits versus other ecological influences are just some of the significant challenges to be overcome. The GSL Salinity Matrix attempts to differentiate between salinities that are "ideal", or where the abundance or productivity of a use is high, and salinities that may be "unfavorable", or where conditions may limit the abundance or productivity of the use based upon the SAC's best understanding of the lake and literature. The reader is advised to not interpret the GSL Salinity Matrix as a listing of thresholds, but rather as a guide that describes how uses may change even as the lake's salinity changes.

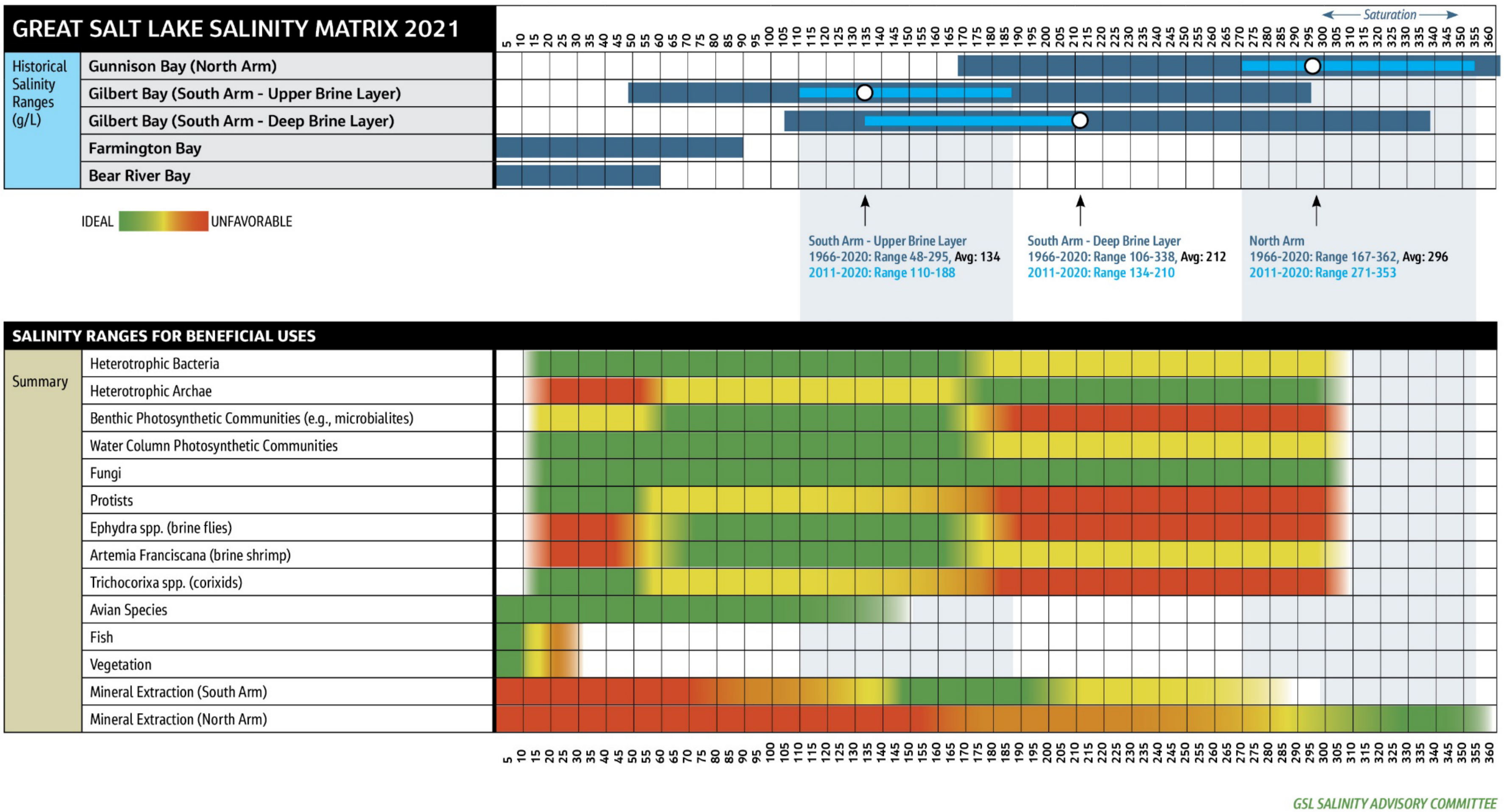


Figure 1. Great Salt Lake Salinity Matrix, 2021

The SAC recognizes that any attempt to simplify and describe these complex dynamics in one figure comes with a risk of oversimplification. Thus, the SAC provides the following discussion to augment the noted references in interpreting and understanding the GSL Salinity Matrix.

3.1 Typical Salinity Ranges Observed in Great Salt Lake

Contributed by Andrew Rupke

The salinity of the brine in GSL depends upon a variety of factors, but GSL's water level and constructed divisions in the lake are primary drivers. In general, as GSL's water level rises, salinity decreases and vice versa (Figure 2). The division of the lake by the rockfill railroad causeway has resulted in the North Arm and South Arm of the lake developing different salinity regimes. The vast majority of fresh water enters the lake in the South Arm, and water flow through the causeway is restricted; thus, the North Arm of the lake is more saline than the South Arm and is often at or near saturation with respect to halite. The salinity (and density) and head differential between the North and South Arms has also resulted in bi-directional flow through the causeway openings and the development of a discrete deep brine layer (DBL) in the South Arm that is higher in density and salinity than the rest of the South Arm water column (Figure 2).

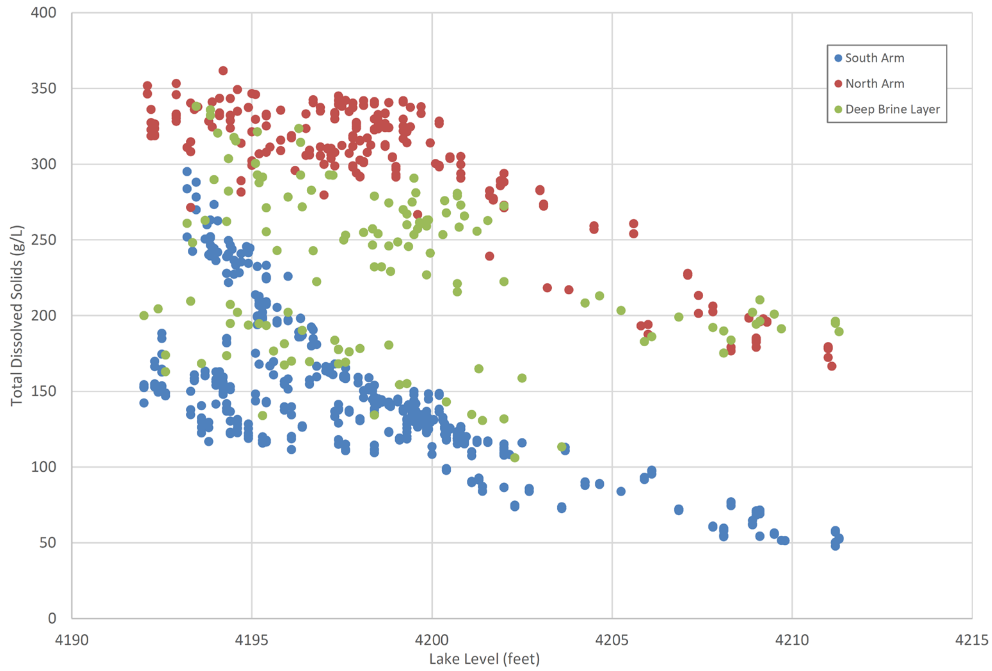
From 1966 through 2020, the measured salinity of the South Arm (excluding the DBL) has ranged from 48 to 295 grams per liter (g/L) (average of 134 g/L [based on an average of the annual averages]), but has not been above 200 g/L since 1970 (Figures 3 and 4). An inverse relationship between salinity and lake level exists, but an overall freshening of the South Arm has occurred since the 1990s that cannot simply be attributed to changing lake level (Figure 4). The lowest salinities in the South Arm occurred during high lake levels of the late 1980s. In the last 10 years (2011 to 2020), salinity in the South Arm has ranged from 110 to 188 g/L (with an average of 137 g/L). Available data show a discernible DBL in the South Arm as early as 1966, and the salinity of the DBL, when present, ranges from 106 to 338 g/L (Figures 2 and 3) and averages 212 g/L. In the last 10 years, the salinity range of the DBL, when present, is 134 to 210 g/L (with an average of 178 g/L) (Figure 3).

The measured salinity in the North Arm, from 1966 through 2020, has ranged from 167 to 362 g/L (Figures 2 and 3) (with an average of 296 g/L) and, in the last 10 years, has fluctuated between 271 and 353 g/L (with an average of 316 g/L) (Figure 3). Similar to the South Arm, the lowest salinities in the North Arm also occurred during high lake levels in the late 1980s.

The freshening of the South Arm over time, as noted previously and shown in Figure 4, is likely indicative of a net migration of salt from the South Arm to the North Arm since the completion of the railroad causeway. This net movement of salt sustains the higher salinities of the North Arm as well as the substantial salt crust that resides on the floor of the North Arm (Rupke et al. 2016). While mineral and salt extraction accounts for some removal of salt from the overall lake system (Mills et al. 2020), available data suggest that riverine input of dissolved solids to the lake either exceeds or substantially offsets the amount of salt removed by extraction (Shope and Angeroth 2015).

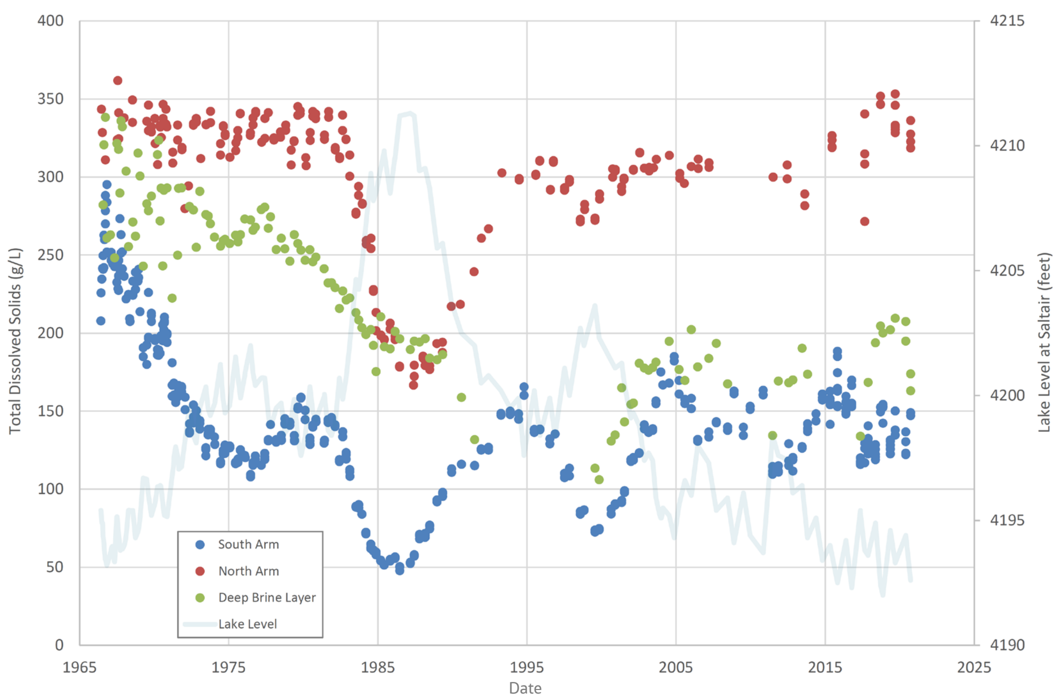
This discussion is based on the UGS's Brine Chemistry Database, which includes data from 1966 through the present. Ranges for the North and South Arms are based on brine measurements near a depth of 10 feet at South Arm sites AS2, FB2, and AC3 and North Arm sites LVG4 and RD2. Data from the DBL are from the deepest samples at site AS2 when a DBL is discernibly present. Salinities are calculated as the sum of sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), chloride (Cl), and sulfate (SO_4) ion concentrations from laboratory analysis. The UGS database can be found at https://geology.utah.gov/docs/xls/GSL_brine_chem_db.xlsx.

Based on observations, experimentation, and modeling, the North Arm lake waters appear to reach saturation at about 1.22 grams per cubic centimeter at 20.0 degrees Celsius (Jagniecki and Rupke, in preparation). Based on historical data from the UGS Brine Chemistry Database, salinity levels in the North Arm range from about 300 to 350 g/L at that density.



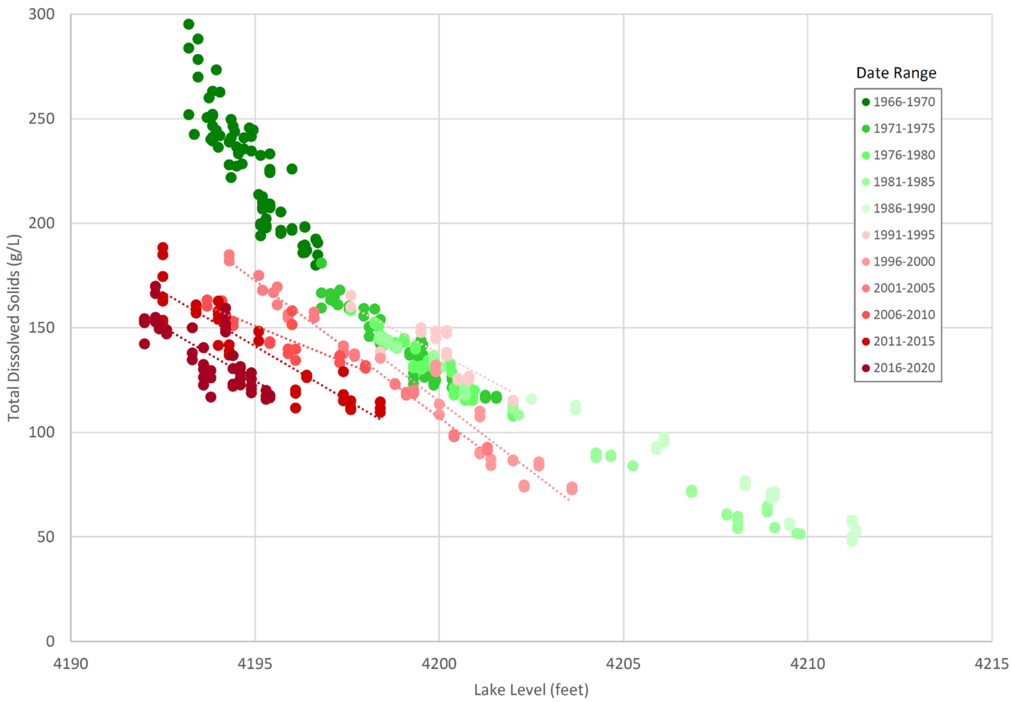
Source: Utah Geological Survey Great Salt Lake Brine Chemistry Database (south arm data are from sample sites AS2, AC3, FB2 at ~10 feet deep; north arm data are from sites LVG4 and RD2 at ~10 feet deep; deep brine layer data are from the deepest sample at site AS2 when a deep brine layer is present)

Figure 2. Great Salt Lake Water Salinities Generally Decline as Water Levels Increase (1966 to 2020)



Source: Utah Geological Survey Great Salt Lake Brine Chemistry Database (south arm data are from sample sites AS2, AC3, FB2 at ~10 feet deep; north arm data are from sites LVG4 and RD2 at ~10 feet deep; deep brine layer data are from the deepest sample at site AS2 when a deep brine layer is present); Lake level data are from U.S. Geological Survey

Figure 3. Great Salt Lake Salinity and Water Level Changes (1966 to 2020)



Source: Utah Geological Survey Great Salt Lake Brine Chemistry Database (data are from sample sites AS2, AC3, FB2 at ~10 feet deep; trend lines are linear)

Figure 4. Salinities of the South Arm, Great Salt Lake (1966 to 2020)

3.2 Microbial Diversity

Contributed by Bonnie Baxter, PhD

The microbial communities in GSL are composed predominantly of halophilic (salt-thriving) archaea and bacteria; however, eukaryotic algae, protozoa, and fungi are also present. In general, the higher the salinity, the more archaeal genera are present relative to bacterial genera, and the less diversity is expected of the eukaryotic microorganisms. These assemblages of microorganisms must be dynamic, responding to the changes in salinity that GSL experiences. Salinity gradients especially impact the microbial communities in the less saline South Arm of the lake. The hypersaline North Arm resident microorganisms are more stable over seasons, have a lower phylogenetic diversity, and are not as impacted by changes in salinity (since their range begins above 180 g/L, and this brine has not dropped below that concentration in many years). Environmental, temporal, and spatial factors that impact salinity can drive which species are represented in the community. Salinity stratification, such as the occurrence of the DBL, may impact the microbial communities, affecting nutrient availability and sequestering bacterial species in the sediment that methylate mercury. Metabolic activities in GSL microbes, such as nutrient cycling, in general, occur more slowly as the salinity increases. Salinity is not the only driver of changes in microbial communities; the organisms also stratify due to light penetration or anaerobic/aerobic compartments.

The primary productivity of the lake is certainly higher in the South Arm, as microbes that do photosynthesis are mostly located there, with the exception of *Dunaliella salinia* and *Tetracystis* sp. in the North Arm. GSL has a thriving photoautotrophic, or phytoplankton, community, the diversity of which is controlled by salinity, but also temperature, and seasonal grazing by invertebrates. *Dunaliella virdis* in the South Arm water column may be the most important food source for *Artemia*. Current studies (in progress) seek to measure photosynthetic activity in the water column versus the microbialites on the lake bottom. Preliminary data reveal productivity is far higher in the benthic region, and there may be both primary and secondary producers, making the lower rung of the GSL food web very complex. Experiments in the laboratory (lab) and lake have identified a cyanobacteria species from the genus, *Euhalothece*, and the diatom, *Navicula,* as architects of the microbialites, which are organosedimentary calcium carbonate structures produced by microbial action. In GSL, the microbialites are lined with mats that contain these dominant species alongside less prevalent bacteria and archaea. *Artemia* adults and *Ephedra* larvae graze on the mats, while the flies pupate here, but their contribution to the nutrient supplies in the lake is likely more profound. The salinity threshold for productive microbialites is not clear; however, at 250 g/L salinity and above, microbialites in the North Arm become vestiges, as confirmed in both biology and geology experiments. Lab studies indicate a drop in chlorophyll when grown in concentrations as low as 150 g/L salt, but we do not have data between 150 and 250 g/L. These structures are likely the most significant microbial communities of GSL in terms of supporting the consumers of the food web, and they should be designated a "keystone" microbial community to monitor alongside salinity changes.

All of the information in Section 3.2 is reviewed in Baxter and Zalar (2019).

3.3 Brine Flies

The genus *Ephedra*, more commonly known as brine flies, have been a common sight along the shorelines of GSL; they have been observed by Fremont (1845) and Captain Stansbury (1852) through present times. *Ephydra* are an essential food source for the bird populations using the lake (Belovsky et al. 2011) and an essential component of the lake's food web (Winget et al. 1972, Collins 1980).

Ephydra have been observed to be tolerant of a wide range of salinities in GSL. Nemenz (1960) documented *E. cinerea* at GSL at salinities of greater than 260 g/L; however, Collins (1980) further noted that fly populations were low at these high salinities. Aldrich (1912) documented large numbers of *E. gracilis* and *E. hians* at GSL at an estimated salinity of 195 g/L in 1908. Winget et al. (1972) noted numbers of *Ephydra* had been observed to be increasing over the period of 1968 to 1971, to the point where they were considered a considerable nuisance along the shoreline and plans were actively being developed to eradicate them. Collins (1980) estimated that the lake's salinity had ranged from 240 to 170 g/L over that time (1968 to 1971). Contemporary observations confirm that *Ephydr*a have been present at GSL at the lower salinities of 180 to 115 g/L observed in the South Arm in the last 10 years.

There are likely many ecological factors that influence the *Ephydra* of GSL. Herbst (1999) observed that the occurrence of different species of *Ephydra* (*E. gracilis* and *E. hians*) at GSL may be a factor of water chemistry in addition to salinity. Barrett and Belovsky (2020) noted that the lake substrate (*Ephydra* prefer microbiolites) and water nutrients, temperature, and salinity all influence *Ephydra* populations. Belovsky et al. (2011) found that brine fly larvae are impacted seven times more by temperature than by salinity and the availability of food. Analyses by Barrett and Belovsky (2020) of potential future conditions affected by climate change indicate that lower salinities and warmer water temperatures could positively influence the abundance of *Ephydra*. However, they concluded that the lack of long-term *Ephydra* datasets prevents an analysis that could adequately describe how *Ephydra* population dynamics are impacted by GSL salinity.

Herbst's (1999) overview of the dynamics of *Ephydra* in the saline waters of the Great Basin notes that the geochemistry of the lake and the physiology of different *Ephydra* species play an important role in which species are present. Herbst (1999) states that the optimum salinity range for *E. hians* is from 25 to 100 g/L; for *E. gracilis,* it is 100 to 200 g/L. This is consistent with Collins' (1980) observations that dilution of GSL's chloride waters increased the abundance of *E. hians* where otherwise only *E. gracilis* was present before.

3.4 Artemia

Contributed by Thomas Bosteels and Phil Brown

The genus *Artemia* is renowned for its ability to survive both extreme salinities and a very broad range of salinity. The *Artemia franciscana* population in the GSL does appear to exemplify this durability, persisting for millennia in a dynamic lake system with a remarkable disparity in salinity across time and space. However, this legendary plasticity may create the misleading impression that this population can survive any salinity range present in the dynamic GSL, and that the population was healthy and thriving across every salinity observed during the past 40 years of record. The critical reality is more complicated. An abundance of evidence from GSL and elsewhere demonstrates that the GSL *Artemia* population has an optimal salinity range in which the population is likely to thrive, and outside which the population will be strongly limited by ecological interactions and physiological stress.

Artemia are remarkable osmoregulators, which can survive in salinities ranging from merely brackish (5 g/L) to nearly salt-saturated (260 g/L). *Artemia* do so by maintaining a dilute haemolymph through the active expelling of salts from the body at a metabolic cost (Croghan 1958a, b, c). Hypersaline waters are oxygen-poor, particularly during periods of lower phytoplankton production, and *Artemia* manage this stress through the production of efficient respiratory pigments (Gilchrist 1954). *Artemia* also manage the detrimental effects of extreme salinity, desiccation, and heat through a suite of internally produced proteins, enzymes, and polysaccharides that protect cell structure and function (Feder and Hofmann 1999, Gajardo and Beardmore 2012). Finally, dormant cysts are produced to endure periods of hostile environmental conditions that exceed the ability of free-swimming age classes to survive.

Numerous studies demonstrate the ability of *Artemia* to survive very high salinities. *Artemia* from U.S. origin (defined at the time as *A. salina* and possibly from GSL) survived in salinities of 285 g/L under laboratory conditions in Croghan (1958a, b, c). Other *Artemia* species and populations may have higher ultimate thresholds, such as 310 g/L for *A. urmiana* and *A. parthenogenetica* (Mohammadi et al. 2009) and 340 g/L for populations in some solar evaporation ponds (Clegg and Trotman 2002). The GSLBSC has observed live *Artemia* periodically in the North Arm at salinities exceeding 260 g/L.

However, these lower and upper salinity tolerance values are misleading from an ecological perspective. The intermediate salinity hypothesis put forward by Herbst (2001) dictates that a population will be limited by interspecies interactions such as predation and competition at the lower end of the salinity range, and physiological stress at the upper, resulting in an optimum that is narrower than the strict physiological survival range. For the GSL *Artemia* population, this optimum is much narrower—evidence from field data and literature reviews sets this optimal salinity range at 120 to 160 g/L.

The ecological limitations supporting the 120 g/L lower limit have been abundantly documented in GSL. The corixid *Trichocorixa verticalis* will prey effectively on *Artemia* (Céspedes et al. 2007, Wurtsbaugh 1992). Wurtsbaugh and Berry (1990) measured a multi-year precipitous decline in South Arm *Artemia* and increase in *T. verticalis* in the 1980s, when salinities declined from 100 g/L to 50 g/L. Similar removal of *Artemia* and other zooplankton by *T. verticalis* has been noted in seasonal zooplankton dynamics in Farmington Bay (Marden and Richards 2017). The strong predatory effect makes the salinity tolerance of *T. verticalis* the clearest criteria for setting the lower optimal salinity range for GSL *Artemia*, and this is generally considered to be 90 g/L. However, the closely related *T. reticulata* survived in *Artemia*-producing evaporation ponds until 100 g/L (Herbst 2006). Furthermore, the salinity of the South Arm typically declines by 20 g/L during spring runoff, suggesting that this safety buffer should be applied to the 100 g/L corixid threshold for a lower optimal salinity range of 120 g/L.

Interspecific competition and phytoplankton assemblage shifts are additional factors. Filter-feeding rotifers and copepods that may compete with *Artemia* were also observed in Wurtsbaugh and Berry (1990). In other years, lower salinities have corresponded with shifts in GSL phytoplankton assemblages that may have been unfavorable to the *Artemia* population. A period of rising lake volume in the mid- to late-1990s lowered South Arm salinities to 76 g/L, and the phytoplankton assemblage shifted from dominance by *Dunaliella* to primarily centric and pennate diatoms (Stephens 1998), then co-dominance by diatoms and chlorophytes (GSLBSC unpublished) or perhaps cyanobacteria (Belovsky et al. 2011). Stephens (1998) hypothesized that the pennate diatoms may have been too large for the nauplii to consume, and *Artemia* cyst production was so poor during several of those years that the brine shrimp cyst harvest could not be opened on the South Arm in 1999.

GSLBSC monitoring data and published studies demonstrate that the upper salinity bound for GSL *Artemia* is far lower than the near-saturation range of the short-term survival studies cited herein. Osmoregulation becomes increasingly expensive from a metabolic standpoint as salinities increase, reducing energy available for reproduction and growth, and thereby reducing individual and population fitness well before the upper short-term survival salinity is reached. Following 13 years of continuous *Artemia* population monitoring on the South Arm and periodic measurements of the North Arm, a marked decline was revealed in *Artemia* densities above 160 g/L (Figure 5). A GSLBSC microcosm test produced similar results, with the survival of the test specimens declining sharply in treatments above 160 g/L by Day 22 (Figure 6). Other studies have demonstrated reduced survival (Dana and Lenz 1986, Wear and Haslett 1986, Triantaphyllidis et al. 1995) and reproduction (Dana and Lenz 1986, Browne and Wanigasekara 2000, Abatzopoulos et al. 2003) in the 150 to 170 g/L range for various *Artemia* populations. Decleir et al. (1980) determined the critical oxygen tension for *Artemia* occurred at 170 g/L, suggesting increasing oxygen stress at salinities above this. The convergence of results strongly suggests that the 160 g/L upper salinity bound would be protective of the GSL *Artemia* population and prevent the longer-term detrimental impacts of reduced fitness and reproduction that the short-term survival studies are unable to address.

The 120 g/L to 160 g/L optimal salinity range for GSL *Artemia* attempts to incorporate the complicated ecological processes and physiological stresses that underpin the intermediate salinity hypothesis and, by doing so, that protect the *Artemia* population. Salinities below 120 g/L risk predation, interspecific competition, and phytoplankton changes that have demonstrably harmed the *Artemia* population in the past. Salinities greater than 160 g/L risk increased metabolic costs, oxygen stress, and reduced reproduction that accumulate into long-term population impacts that are often missed by acute survival trials. The salinity range between provides the highest likelihood of a healthy *Artemia* population according to substantial information available from GSL and other *Artemia* biotopes.

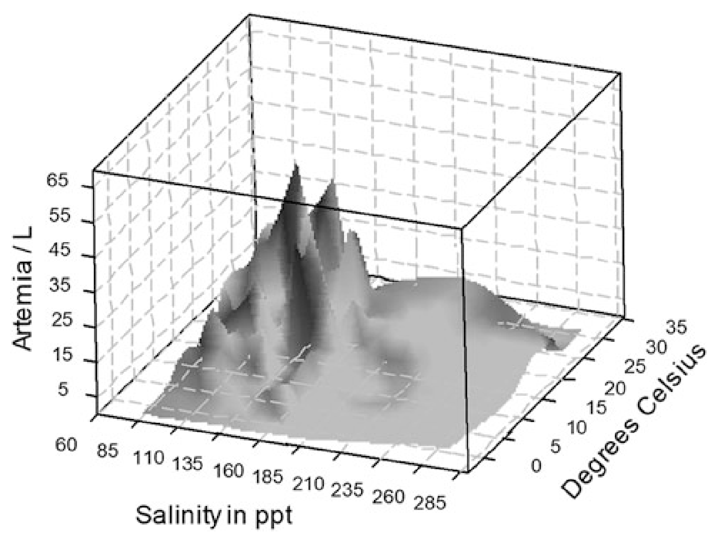


Figure 5. GSL *Artemia* Population Densities across Salinity and Temperature from GSLBSC Monitoring of the South and North Arms
The surface graph represents several thousand individual samples across 20 years.

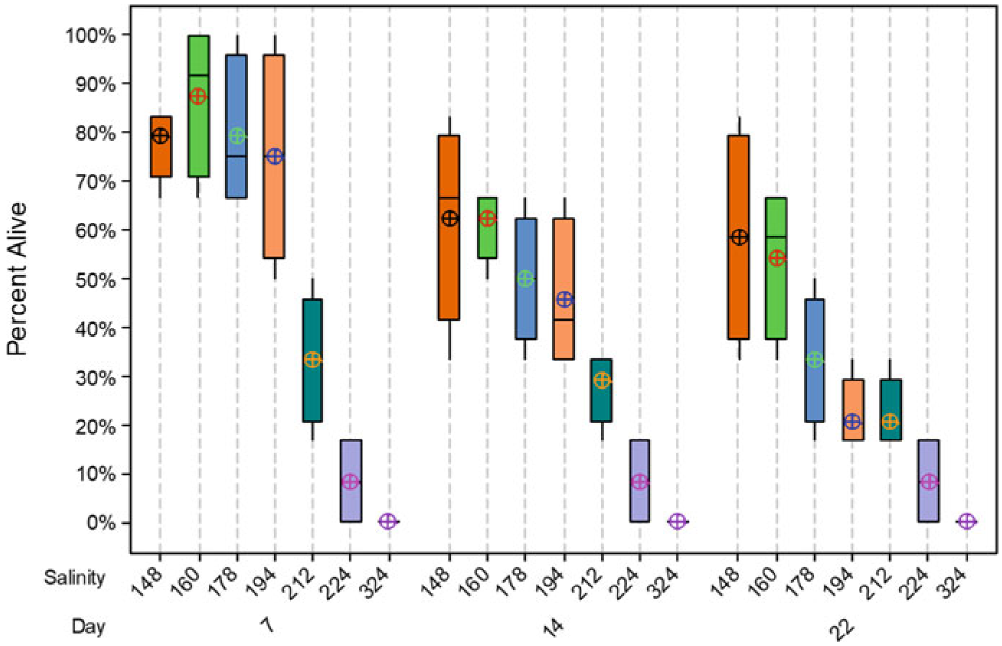


Figure 6. Microcosm Test Measuring GSL *Artemia* Survival across Salinity Treatments over a 22-day Course of Study

3.5 Corixids

Trichocorixa verticalis, also known as corixids or waterboatman, have a significant role in the foodweb of GSL. They exert predatory pressure upon *Artemia* and other zooplankton and serve as an important food source for birds at GSL (Belovsky et al. 2011, Céspedes et al. 2007, Marden and Richards 2017, Mellison 2000, Wurtsbaugh and Berry 1990, Wurtsbaugh 1992). They are most commonly found in the wetlands, littoral zones, and estuarine areas near freshwater inflows to GSL (Marden and Richards 2017, Mellison 2000). They were also observed in the open water of the South Arm (Gilbert Bay) during the high-water levels and lower salinities of the mid-1980s (Wurtsbaugh and Berry 1990, Wurtsbaugh 1992). The potential of *T. verticalis* to influence a trophic cascade in GSL make it important to consider the influence of lake salinity upon *T. verticalis.*

Salinity does appear to be a significant factor in the distribution of *T. verticalis* at GSL (Mellison 2000); however, their densities in GSL cannot be explained by any single environmental factor (Belovsky et al. 2011). Suitable prey, substrate type, water salinity and temperature, and the ability of *T. verticalis* to adapt all play a role in where they may be found (Mellison 2000, Keltz 1979). Each of these factors, as summarized here, make *T. verticalis* ideally suited to the highly dynamic and saline environment of GSL:

- The predatory role of *T. verticalis* is well-documented and has been described in this document. *T. verticalis* have been found to have a strong top-down control on *Artemia* juveniles and other zooplankton of GSL and other similar saline water bodies (Belovsky et al. 2011, Keltz 1979, Marden and Richards 2017, Wurtsbaugh and Berry 1990, Wurtsbaugh 1992) but are not likely the only explanation for observed brine shrimp population declines in the 1990s (Mellison 2000).

- Mellison (2000) found *T. verticalis* to prefer rock habitats over mud and vegetation habitats in Farmington Bay. Keltz (1979) found *T. verticalis* in high salt waters with silt substrates but they preferred floating algae habitats when available; this was posited as a means to avoid predation by birds, fish, and other invertebrates. Wurtsbaugh and Berry (1990) found *T. verticalis* in the open waters of the South Arm.

- *T. verticalis*' well-developed capability for osmoregulation and to hypo-regulate in saline water (Tones and Hammer 1975) provide them with a competitive advantage in the saline waters of GSL. *T. verticalis* have been found to thrive at salinities of between 2 and 6 percent salinity (Hammer et al. 1990, Mellison 2000) and have a maximum salinity tolerance of 9.0 percent (Hammer 1986). Lab experiments by Keltz (1979) found that salinities of 5.5 to 7.0 percent were lethal to all *T. verticalis* instars, with mortality most rapid at 7.0 percent salinity. Mellison (2000) found a sharp decline in *T. verticalis* numbers above 6.0 percent and few at 9.0 percent salinity. These salinity tolerance thresholds are also consistent with where and when they have been observed by others at GSL (Belovsky et al. 2011, Hayes 1971, Marden and Richards 2017, Wurtsbaugh and Berry 1990, Wurtsbaugh 1992).

- Keltz's laboratory studies (1979) found that *T. verticalis* generally had less tolerance for higher salinities at higher water temperatures but that the summer generation of *T. verticalis* was more tolerant of higher water salinity and temperature than the winter generation. This may help, in part, explain discrepancies in observations by Hayes (1971) and Mellison (2000) noting that *T. verticalis* at GSL are most frequently located in shallow waters where water temperatures are highest.

- Corixid eggs can survive hypersaline and frozen waters and desiccated conditions (Keltz 1979) and, thus, can survive the fluctuating water levels of GSL. *T. verticalis* typically exhibit two generations in a calendar year that often coincide with generations of *Artemia* in GSL. Overwintering corixid eggs typically hatch in the spring (April to May) and summer eggs hatch in the late summer (July to August) (Keltz 1979, Wurtsbaugh 1992).

- Uniquely among the zooplankton of GSL, *T. verticalis* can both swim, even to depths of 3.6 meters (m) (Wurtsbaugh and Berry 1990), and fly (Keltz 1979) to find suitable habitat and prey. Keltz (1979) found that while juvenile *T. verticalis* could only escape a stressed environment by swimming, adult *T. verticalis* could also fly to habitat they found more tolerable. Hayes (1971) similarly found that *T. verticalis* could fly between the more saline waters of Farmington Bay and surrounding brackish waters to find suitable prey.

3.6 Birds

Contributed by Brian Tavernia

Internationally and locally, the management of salinity is seen as important to supplying high-quality habitat for waterbirds, shorebirds, and waterfowl (Ma et al. 2010, Sorenson et al. 2018). Salinity directly and indirectly affects bird survival and reproduction. Direct effects may include increased energy cost associated with salt regulation (Gutiérrez et al. 2011, Gutiérrez et al. 2012), reduced immune response (Gutiérrez et al. 2013), weight loss due to saltwater intake (Hannam et al. 2003), and reduced feather insulation (Rubega and Robinson 1997, Jehl et al. 2012). Regarding indirect effects, salinity changes may affect plant cover, composition, and invertebrate food resources important to birds (Ma et al. 2010). For example, high salinity in shoreline, remnant, and playa wetlands associated with saline lakes promotes bare ground and mudflat areas favored by shorebirds (Sorenson et al. 2018).

Focusing on indirect effects is one possible approach to managing salinity for birds. Under this approach, salinity goals are based on the salinity tolerance limits and responses of cover and food habitat resources for birds. Thus, the underlying assumption is that, if one meets the salinity needs of habitat resources, one also meets birds' salinity needs. This approach does not address direct effects or the possibility of interactions between direct and indirect effects, and these omissions may have potentially detrimental effects on birds.

The following hypothetical example (Figure 7) conceptually illustrates the importance of accounting for direct effects. A bird species depends on an aquatic invertebrate as a primary food resource while at GSL, and its ability to capture and consume the invertebrate increases as invertebrates become more abundant. If one were managing salinity indirectly, the salinity management goal might be to maximize the abundance of the aquatic invertebrate

(Figure 7). However, as the invertebrate becomes more abundant with increasing salinity, the direct energetic cost (basal metabolic rate) of dealing with an additional salt load also increases. Such energetic costs might be due to physiological (e.g., salt glands) or behavioral (e.g., frequent trips to freshwater) responses by the birds. Thus, management considering direct and indirect effects would lead to an intermediate salinity goal different from the goal based on indirect effects only (Figure 7).

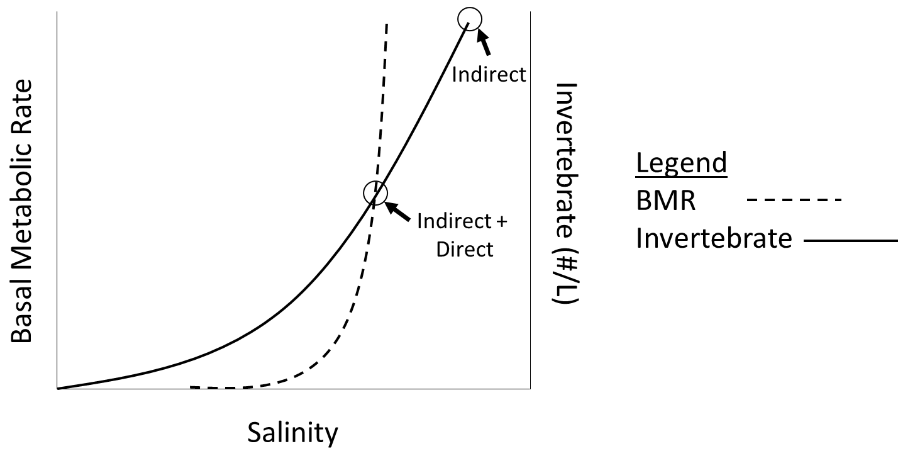


Figure 7. Hypothetical Effects of Salinity on Bird Basal Metabolic Rate and Aquatic Invertebrate Density.
This graphic illustrates the setting of salinity management goals based solely on indirect effects (invertebrate density) versus setting salinity management goals based on indirect and direct (basal metabolic rate) effects.

While it is ideal to consider both direct and indirect effects, data may be lacking to address immediately both effect categories when setting salinity management goals. In this case, indirect effects can be used to set salinity goals in the near term, and these goals can be updated as new research provides necessary data and information to address and incorporate direct effects.

3.7 Fish

Fish are often assumed to be completely absent in GSL (Utah.com 2021) because of its salinity. This assumption, however, does not account for the historical variability of salinity in the South Arm or the lower salinities found in Bear River Bay and Farmington Bay as a result of freshwater inflows. Fish can survive and have been observed in areas of the lake with salinities as high as 4 percent but more frequently when salinities are less than 1 percent:

- Fish were observed on one occasion in the South Arm in 1986 when lake water levels were at their historical high and salinities were less than 5.5 percent. Rainwater killifish (*Lucania parva*), only about 1 inch in length, were observed in the South Arm near Stansbury Island where the salinity was approximately 4 percent. They were thought to have been introduced by inflows from the Timpie Springs Waterfowl Management Area and had found the salinity in the South Arm tolerable enough to breed (Associated Press 1986).

- More recent studies in Willard Spur of Bear River Bay (Penne 2012a; Penne 2012b; Moore 2011) confirmed that several species of fish were present including common carp (*Cyprinus carpio*), Utah chub (*Gila atraria*), black bullhead (*Ameiurus melas*), yellow perch (*Perca flavescens*), black crappie (*Poxomis nigromaculatus*), channel catfish (*Ictaluris punctatis*), and gizzard shad (*Dorosoma cepedianum*). Willard Spur's location above an approximate elevation of 4201.8 feet (NVGD 29) has made it largely a freshwater ecosystem since 2002 (CH2M HILL 2016). All fish species were found to be present in the Willard Bay outflow channel on the eastern side of Willard Spur (salinities of less than 5 g/L [Ostermiller and Hooker

2015]) with only the common carp and Utah chub found in the main body of Willard Spur (salinities of less than 10 g/L [Ostermiller and Hooker 2015]).

- The Utah Division of Wildlife Resources completed a fish survey in Bear River Bay, Willard Spur, and Farmington Bay in 2020 (unpublished data, Edwards 2021). Common carp, Utah chub, channel catfish, gizzard shad, and black bullhead were found downstream of the Bear River Migratory Bird Refuge in Bear River Bay. Common carp, Utah chub, channel catfish, gizzard shad, black bullhead, Striper X White Bass, and black crappie were found in Willard Spur. Only common carp and Utah chub were found in the open water of Farmington Bay. All fish were found at estimated salinities of less than 22 g/L, with the vast majority of fish found at estimated salinities of less than 5 g/L (unpublished data, Edwards 2021).

3.8 Vegetation

Contributed by Heidi Hoven

Vegetation (or lack thereof) in and along GSL's shoreline is best characterized by soil salinity as influenced by salt deposited by Lake Bonneville and GSL flooding events and subsequent leaching by freshwater flows and precipitation. Shorebird mudflat habitat is associated with water flowing through GSL bays such as Farmington Bay and Bear River Bay as well as wetlands associated with GSL along its fringes. Although the lake is in a probable long-term decline, separating the lake level further and further from its shoreline, the salt deposits it has left behind will influence vegetation for the long term as well. Salt is a key component to controlling the vegetative species and abundance in wetlands of the lake. Exceptions to the influence of salt on wetland habitat are, of course, where managed wetlands have flushed salts from the system or along the upper reaches of tributaries and drainages onto the lake's shores. The following characterizes soil salinities in the various shorebird habitat niches around the lake (as described by Sorensen et al. 2020, with soil salinity ranges added from other literature):

- Unvegetated mudflat zone: 5 to 20% soil salinity (Flowers 1955; and Vest 1962) as summarized in Bradbury and Parrott (2020)
- Pickleweed zone: 3 to 6.5% soil salinity (sodium chloride dominant, Flowers and Evans 1966)
- Saltgrass zone: up to 2.5% soil salinity (sodium chloride dominant, Flowers and Evans 1966)
- Sedges and alkali bulrush zone: 30 to 60 mmhos at 30 to 40 centimeters (cm) in the sediment, only intermittently flooded (Kadlec 1982)

However, shorebirds are not only queuing in on plant cover. Water depth and available macroinvertebrates as described by Sorensen et al. (2020) are important additional factors that define shorebird habitat of Great Salt Lake.

Habitat for waterfowl and wading birds is somewhat different, in that they are also accessing open waters. The following characterizes sediment or water salinities in these preferred habitats:

- Dominated by hardstem bulrush, cattail, alkali bulrush or Phragmites continuously flooded during the growing season: 4 to 16 mmhos at 30 to 40 cm in the sediment (Kadlec 1982)
- Dominated by salt grass, alkali bulrush, (Phragmites, or cattail to a lesser extent) only intermittently flooded: 30 to 60 mmhos at 30 to 40 cm in the sediment (Kadlec 1982)

- Sago pondweed optimum range: Cl- and SO_4 dominated waters is 3 to 6 g/L and 2 to 15 g/L, respectively (Jensen 1940; Stewart and Kantrud 1972; and Millar 1976 in: Kantrud 1990) (water column salinity)

- Ruppia-dominated communities' optimum range in SO_4- dominated waters: greater than 26 g/L (water column salinity) (Stewart and Kantrud 1972; in: Kantrud 1990)

3.9 Mineral Extraction

Contributed by Tom Tripp

There are multiple mineral extractors currently operating on GSL with only one extractor operating on the North Arm. All mineral extractors on the lake bring lake water into a solar evaporative system and increase the concentration to some level of saturation where salts will be precipitated. For some extractors, their desired solar evaporation will only go to a point where sodium chloride is being precipitated to the pond floor. The other extraction companies, including US Magnesium, will go beyond that first precipitation targeting different salts or concentrated brines.

The extracted minerals are derived from the dissolved ionic species that naturally exist in GSL water. A company's production capacity is in part limited by "solar evaporation capacity" that is partially defined by evaporative area and the summertime climatic conditions. The other component of solar evaporation capacity is the inlet brine concentration—the dissolved mineral content in the lake water. Lower than "normal" mineral concentrations in the starting brine result in lower than normal production capacity, given a fixed evaporative pond area and normal weather patterns.

For production capacity, a mineral extractor will prefer the maximum available concentration, but there are some limitations on that maximum based on systems available to protect the solar ponding pumping equipment. Pumping saturated brine requires the ability to deal with ongoing salt precipitation. Saturated brines will coat all wetted components of the pumping system. The usual protection method is to "desalt" pumps and pipelines by periodically flushing them with unsaturated water or brines. Failure to flush pumps will result in problems with pump impeller imbalances that will lead to early bearing failures and other physical damage to pumps. Most of the inlets pumping areas for GSL mineral extraction are remote with only limited water resources. (There are some exceptions where flush water may be available to mineral extractors.) This salt coating problem is a key consideration when trying to determine an optimum inlet brine concentration.

In US Magnesium's situation on the South Arm, the preferred salinity for inlet brine for the lake is just short of sodium chloride saturation or about 0.8 to 0.9% magnesium. Compass Minerals' operation on the North Arm also prefers salinities just short of sodium chloride saturation, or near 2% potassium. In these cases, lake brine (lake water) can be brought into the solar evaporation ponds without a need to do water flushing to desalt pumps. The current lake water magnesium and potassium content is about half of that preferred target concentration.

In summary, extractors generally prefer the highest concentration they can handle. Lower salinities or concentrations can limit production unless the "solar evaporative capacity" is increased by adding additional evaporation area (additional mineral leases) and pumping capacity to maintain production. Note that a declining lake to very low levels is also an important factor requiring significant investment to maintain production.

Salinities indicated in the GSL Salinity Matrix (Appendix A) as green generally illustrate ideal conditions, where production has been maintained and further investments in infrastructure have not been required. Salinities indicated by yellow illustrate salinities that have occurred since 2011 and that have required mineral extractors to make additional investments or reductions in production. Salinities indicated by orange illustrate salinities that may require extractors to make new investments or result in reductions in production. Salinities indicated by red illustrate salinities that are unprecedented for the mineral extractors and likely represent significant impacts to their operation.

4. Conclusions

The SAC developed the GSL Salinity Matrix (Figure 1 and Appendix A) to illustrate the important influence salinity has upon the wide variety of uses of GSL. The matrix illustrates our current understanding of how each use can adapt and has adapted to change. GSL is a harsh environment; however, the organisms that use GSL are adapted to that environment. The matrix illustrates how the uses are tightly interwoven; they are closely dependent upon each other and upon the lake's water level and salinity. A change in one element of the ecosystem has a rippling effect throughout the system. An adaptation of one trophic level likely requires an adaptation in others. The complexity of these interdependencies is what has made GSL such a unique, thriving, and resilient ecosystem and benefit to industry, recreational users and the communities within its watershed. As a result, the matrix also illustrates that the salinity of GSL cannot be managed to a singular value or threshold. The lake's salinity is very dynamic and has varied, does vary, and will vary spatially and temporally.

However, even as GSL adapts to change, the Salinity Matrix also illustrates how an induced change(s), intentional or unintentional, upon the system could have consequential impacts. Changes that happen too quickly or at too large of scale, or that make up a new long-term trajectory can inflict costs to the system. The potential for these impacts is what must be understood to enable well-informed decisions. The GSL Salinity Matrix will provide decision-makers with an important illustration, not to predict how GSL's salinity will change, but to illustrate the potential consequences of a salinity change.

5. Recommendations

The SAC voted unanimously to recommend that a salinity range of 120 to 160 g/L is most protective of the beneficial uses in the South Arm.

The SAC makes the following recommendations to further advance development of the GSL Salinity Matrix:

1. Cross-reference the GSL Salinity Matrix with the GSL Aquatic Life Use Resident Taxa Summary prepared with the Utah Division of Water Quality and U.S. Environmental Protection Agency in 2016 (Horsely Witten Group 2016).

2. Expand upon the current review of literature describing how salinity influences the various uses of GSL. The intent is to continue to improve the accuracy and deepen our understanding of the potential consequences of changing lake salinity.

3. Compare the GSL Salinity Matrix to results from the Division of Wildlife Resources' ecological model of GSL. Are similar patterns observed in the results of the model for changing lake salinity?

4. Compare results of forecasted changes in the water and salt balance of GSL to the GSL Salinity Matrix.

6. References

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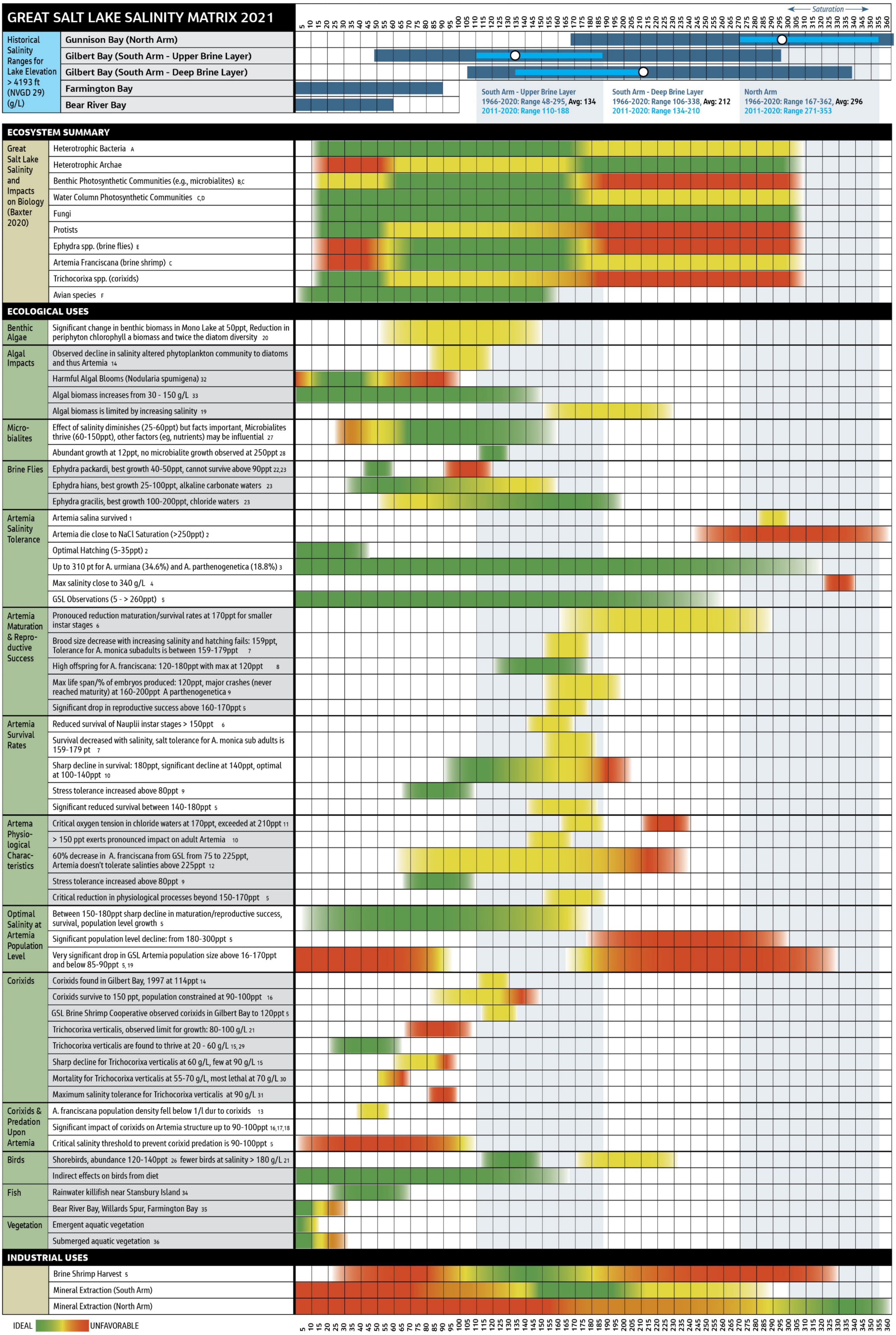
Attachment A



1 Croghan 1957
2 Sorgeloos et al , 1986, Lavens and Sorgeloos 1996
3 Mohammadi et al 2009
4 Gonzalo and Beardmore 2012
5 Bosteels 2012
6 Wear et al. 1986
7 Dana and Lenz 1986
8 Browne & Wanigasekera 2000
9 Abatzopoulos et al 2003
10 Triantaphyllidis et al 1995
11 Decleir et al 1980
12 Barnes and Wurtsbaugh 2015
13 Wurtsbaugh and Berry 1990
14 Stephens 1998
15 Mellison 2000
16 Herbst 2006
17 DeMeutter et al 2010
18 Tanner et al 2014
19 Belovsky et al 2011
20 Herbst and Blinn 1998
21 Herbst 2006
22 Ping 1921
23 Herbst 1999
24 Por 1980
25 Harbst 2001
26 Warnock et al 2002
27 Anderson et al 2020
28 Lindsay et al 2017
29 Hammer et al 1990
30 Kertz 1979
31 Hammer 1986
32 Jacobs 2018
33 Belovsky 2005
34 Associated Press 1986
35 Penne 2012, Edwards 2021
36 Steward and Kantrud 1972, Kantrud 1990

A. Includes potentially harmful cyanobacterial blooms, but only at the 10-50 ppt salinity range
B. Microbialite-associated
C. Includes both bacterial and eukaryotic photosynthesizers
D. Dunaliella salina and Tetracystis spp are prevalent in the north arm, no evidence of other eukaryotic algae, so diversity is limited.
E. Predation by Trichocorixa spp. at lower salinities
F. Avian diets are particular to the species and will be tied to the success of their food source, which is controlled by salinity. The high salinities provide little in food source, but much in protection (e.g. American White Pelican colony on Gunnison island), which is tied to lake level and not salinity.

All data cited in: Baxter, B.K and Butler, J.K., Eds. Great Salt Lake Biology: A Terminal Lake in a Time of Change. Springer, Cham, 2020.

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