

MAPPING GROUNDWATER QUALITY AND CHEMISTRY ADJACENT TO GREAT SALT LAKE, UTAH

by Stefan M. Kirby, Paul C. Inkenbrandt, and Andrew Rupke



OPEN FILE REPORT 699
UTAH GEOLOGICAL SURVEY

a division of

UTAH DEPARTMENT OF NATURAL RESOURCES

2019

Blank pages are intentional for printing purposes

MAPPING GROUNDWATER QUALITY AND CHEMISTRY ADJACENT TO GREAT SALT LAKE, UTAH

by Stefan M. Kirby, Paul C. Inkenbrandt, and Andrew Rupke

Cover photo: View to the east across the south arm of Great Salt Lake with Promontory Point in the distance.



OPEN FILE REPORT 699
UTAH GEOLOGICAL SURVEY

a division of

UTAH DEPARTMENT OF NATURAL RESOURCES

2019

STATE OF UTAH

Gary R. Herbert, Governor

DEPARTMENT OF NATURAL RESOURCES

Michael Styler, Executive Director

UTAH GEOLOGICAL SURVEY

R. William Keach II, Director

PUBLICATIONS

contact

Natural Resources Map & Bookstore

1594 W. North Temple

Salt Lake City, UT 84116

telephone: 801-537-3320

toll-free: 1-888-UTAH MAP

website: utahmapstore.com

email: geostore@utah.gov

UTAH GEOLOGICAL SURVEY

contact

1594 W. North Temple, Suite 3110

Salt Lake City, UT 84116

telephone: 801-537-3300

website: <https://geology.utah.gov>

This open-file release makes information available to the public that may not conform to UGS technical, editorial, or policy standards; this should be considered by an individual or group planning to take action based on the contents of this report. Although this product represents the work of professional scientists, the Utah Department of Natural Resources, Utah Geological Survey, makes no warranty, expressed or implied, regarding its suitability for a particular use. The Utah Department of Natural Resources, Utah Geological Survey, shall not be liable under any circumstances for any direct, indirect, special, incidental, or consequential damages with respect to claims by users of this product.

CONTENTS

ABSTRACT.....	1
INTRODUCTION	1
DATA COMPILATION	2
New Sampling	6
DATABASE SUMMARY.....	6
Summary of Geochemistry Adjoining GSL.....	6
Trace Constituents	8
Nutrients	12
Stable Isotopes	12
WETLAND DATA.....	14
CONCLUSIONS.....	17
ACKNOWLEDGMENTS	17
REFERENCES	18

FIGURES

Figure 1. Conceptual diagram of groundwater flow adjoining Great Salt Lake and its wetlands	2
Figure 2. Map showing compiled data symbolized by source.....	5
Figure 4. Major ion water type for select groundwater samples near Great Salt Lake.....	7
Figure 5. Piper diagram of select groundwater samples near Great Salt Lake	8
Figure 6. Interpolated concentration of total dissolved solids (TDS) near Great Salt Lake.....	9
Figure 7. Dissolved metal concentrations of arsenic and selenium in groundwater near Great Salt Lake.....	10
Figure 8. Dissolved metal concentrations of boron and lithium in groundwater near Great Salt Lake.....	11
Figure 9. Nutrients including nitrate and phosphorus in groundwater near Great Salt Lake	13
Figure 10. Meteoric water line plot of stable isotope data.....	14
Figure 11. $\delta^2\text{H}$ in groundwater adjoining Great Salt Lake.....	15
Figure 12. Measured groundwater TDS and interpolated groundwater TDS, against wetland TDS measurements.....	16
Figure 13. Wetland TDS versus interpolated calculated TDS	17

TABLES

Table 1. Example of a parameter-by-row data structure.....	4
Table 2. Example of a sample-by-row data structure.....	4

GEODATABASE

https://ugspub.nr.utah.gov/publications/open_file_reports/ofr-699/ofr-699.zip

MAPPING GROUNDWATER QUALITY AND CHEMISTRY ADJACENT TO GREAT SALT LAKE, UTAH

by Stefan M. Kirby, Paul C. Inkenbrandt, and Andrew Rupke

ABSTRACT

Great Salt Lake (GSL) and its adjoining wetlands are located at the lowest elevation of the regional GSL watershed. As such, GSL must be a sink for not only surface water but also groundwater over a large area. Despite the potential for groundwater discharge, previous work on water and solute budgets, as well as various dissolved trace constituents in GSL and its wetlands, has relied on estimated groundwater contributions or has not considered groundwater at all. The goal of this project was to provide a comprehensive ArcGIS format geodatabase of existing and select new geochemical isotopic samples of groundwater adjoining the entire GSL. Samples were compiled from publicly available databases, technical reports, and peer reviewed journal articles. Additional new samples were collected and added to the database. All data were checked for spatial and temporal uniqueness and geochemical consistency. From these data a subset of high quality data were chosen and used to create a map of total dissolved solids and several other maps that summarize various aspects of the data. Available state-level wetlands mapping data and wetlands geochemistry were also compiled and added to the database. Groundwater chemistry adjoining GSL spans a significant range of both dissolved compositions and concentrations. Most samples along the west shore of GSL are Na-Cl water type, along the east shore Ca-HCO₃ water type is common. Variations in water type and total dissolved solids that are likely controlled by relative amounts of recharge and water-rock interaction surrounding GSL. Select trace constituents, including potential metal contaminants As and Se, indicate that concentrations of those metals in groundwater are generally low, but locally groundwater may contain elevated concentrations that could be contributed to GSL. Other metal ions of B and Li may indicate localized geothermal contributions to the groundwater system. Nutrients including nitrate and phosphorus occur in low concentrations near GSL and may only locally contribute high nutrient concentrations. Stable isotopes in groundwater record regional and locally unique recharge and mixing conditions, and may also represent older, cooler climatic conditions. A comparison of existing chemistry from wetland sites

with groundwater chemistry may show at least local correlation and could support groundwater contributions to wetlands at some locations. All of the data gathered by this study are provided in a single interconnected ArcGIS format geodatabase. These data provide important baseline geochemistry for the groundwater system that can be used by a variety of future studies relating to GSL and its wetlands. This dataset and related future studies will provide an improved understanding of GSL's groundwater system that will be important for making informed land management decisions related to GSL and adjoining areas.

INTRODUCTION

Groundwater chemistry influences the ecology of wetlands and groundwater-dependent ecosystems in areas near Great Salt Lake (GSL) (Carling and others, 2013). The chemical character and salinity of the groundwater system near GSL also control water usage for a variety of industrial, agricultural, and domestic sources and likely play an important role in the total salt budget of GSL. Despite this, previous work has not focused specifically on groundwater quality and chemistry surrounding GSL. However, scientists have been measuring the chemistry of surface water sources since the 1850s (e.g., Spencer and others, 1985b), examining how the lake chemistry varies over time (Spencer and others, 1985a; Jones and others, 2009) and space (Lin, 1976).

The goal of this project was to characterize groundwater and its potential input to GSL and its wetlands, by compiling existing chemistry data and collecting new samples in areas that immediately adjoin GSL. These data (including site location, major ion chemistry, trace constituents, and stable isotope composition) were combined into an ArcGIS format geodatabase to create GIS-based maps of groundwater quality and chemistry. We compared the data with existing wetland water quality data available from the Utah Geological Survey (UGS), Utah Department of Environmental Quality, and other

organizations. This work is the first systematic basin-wide assessment of groundwater chemistry in areas near the lake that potentially feed the lake system. The data can form a basis for future work to better delineate the interplay of groundwater and surface water supplying important wetlands adjoining GSL. The data may also lend insight into salinity contributions to GSL from groundwater.

GSL is the endpoint for groundwater and surface water across a large part of the eastern Great Basin (figure 1) (Spencer and others, 1985b; Duffy and Al-Hassan, 1988; Arnow and Stephens, 1990). Water chemistry in GSL and adjoining wetlands is a combination of groundwater and surface water that is typically modified by evaporation. Groundwater must contribute significantly to the GSL system, but the contribution of water quantity and quality is largely unknown.

Salinity inputs govern wetland habitat health, the salt budget of GSL, and usable water supplies adjoining GSL, and therefore salinity characterization is crucial to management decisions. Salinity also determines the flora and fauna of wetland ecosystems. For example, Sago pondweed (i.e., *Potamogeton pectinatus*), a key food source for migratory waterfowl around GSL, has a much higher tolerance for salinity than hardstem bulrush (Cyperaceae), which provides a nesting and hiding habitat for birds. Identifying wetlands that have substantial groundwater inputs and determining the salinity of those inputs will help land managers understand ecological constraints related to wetland management. Groundwater salinity near GSL also controls the usage of groundwater for

agricultural, municipal, and industrial uses. The database constructed as part of this project provides current and future groundwater users with an understanding of the spatial distribution of salinity concentrations near GSL.

Previous studies have identified groundwater salinity as a potentially major input to GSL's overall salt load (Hahl and Mitchell, 1963; Hahl, 1968; Spencer and others, 1985a; Spencer and others, 1985b; Loving and others, 2000). Despite this potentially important input, the connection between groundwater chemistry and GSL salinity has not been well defined. The U.S. Geological Survey (USGS) has constrained salt loading from surface water inputs to the lake for water year 2013, but a detailed analysis of the groundwater inputs of salinity has yet to be undertaken (Shope and Angerth, 2015).

This ArcGIS format geodatabase provides the first systematic basin-wide assessment of groundwater chemistry in areas adjoining the lake that could provide input into the lake system. These data will form the basis for future work that better delineate the interplay of groundwater and surface water that supply important solutes to the wetlands adjoining GSL. These data may also be used in the future to better constrain the sources of GSL salinity and its relationship to the adjoining groundwater systems.

DATA COMPILATION

We compiled data from multiple federal and state government sources including the National Water Quality Monitoring Council Water Quality Portal (WQP) at <https://www.waterqualitydata.us/>, the Utah Division of Drinking Water Safe Drinking Water Information System (SDWIS), and the Utah Department of Environmental Quality (UDEQ) Ambient Water Quality Monitoring System (AWQMS) database (<https://awqms.utah.gov/Login.aspx>) (Utah Division of Drinking Water, 2015; National Water Quality Monitoring Council, 2018). Initial data downloads from these sources were based on location and data type. These databases include the bulk of publicly available samples from areas adjoining GSL. To augment these data, a literature review was completed and data were compiled from additional published reports.

From 1944 to 2003, the Utah Department of Natural Resources produced a series of Technical Publications in collaboration with the USGS and the UGS (Hood and others, 1969; Price and Bolke, 1970; Hood, 1971; Hood, 1972; Steiger and Lowe, 1997). These reports provide important data across the western and southern shore of GSL, and across Promontory Point. Much of this data was not included in the available databases discussed above. Station locations were manually digitized from available figures and maps, and compared to existing data for wells and springs to confirm proper location. Chemistry data were compiled from tables accompanying the various reports.

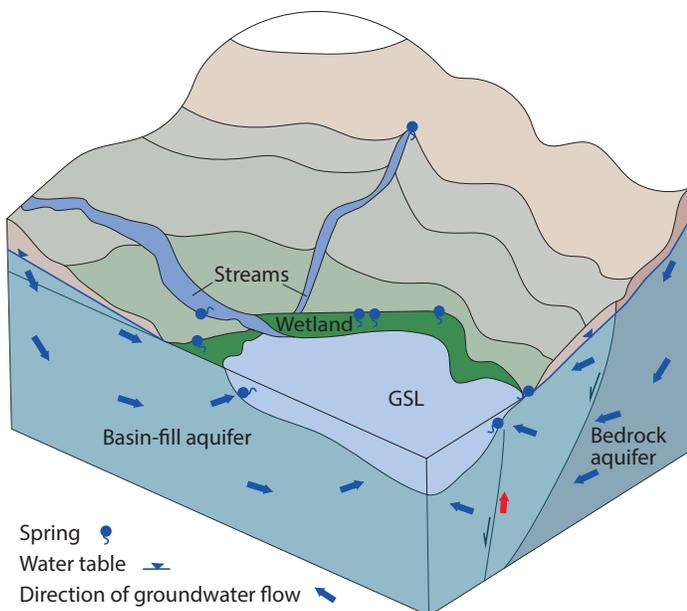


Figure 1. Conceptual diagram of groundwater flow adjoining Great Salt Lake (GSL) and its wetlands. The lake is the endpoint and discharge area for groundwater and surface water in the GSL watershed. Red arrow indicates potential input of hydrothermal water.

The UGS has completed a number of local groundwater investigations near GSL. Various geochemical samples were collected as part of these studies and in many cases these data provide the most current and complete information for groundwater chemistry in a given area. These reports provide important data along the north and northwest parts of the lake as well as along parts of the east shore area ((Hurlow and Burk, 2008; Wallace and Lowe, 2009; Wallace and others, 2010; Wallace and others, 2012).

Lastly, we searched available peer reviewed scientific literature for groundwater chemistry data. We compiled water

quality data from journal articles that contain data of sufficient quality and scope. Two relevant articles (Cole, 1982; Mayo and Klauk, 1991) provided important geochemical and stable isotopic data that cover Antelope Island and the north part of the east shore. Location data for these samples were digitized from figures and geochemical data were compiled from tables.

Data by source is shown on figure 2. Most compiled data is taken from the SDWIS state level database and the WQP federal database. Data compiled from the Utah Department of Natural Resources, UGS reports, and journal articles rep-

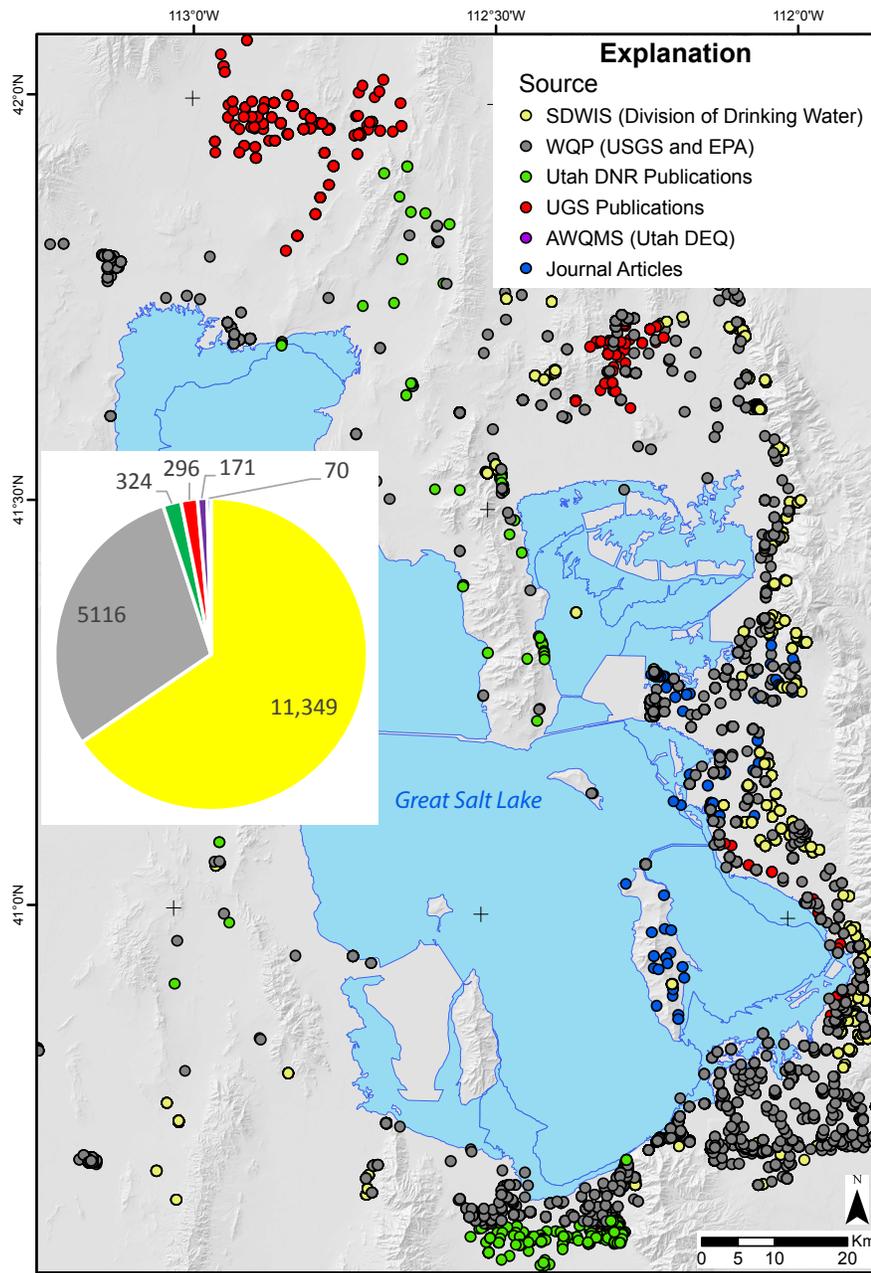


Figure 2. Map showing compiled data symbolized by source. The inset pie diagram color scheme matches the source map and the numbers are the total number of samples. Most SDWIS samples represent time series samples at various locations.

resent important fractions of the database across Antelope Island and areas west of GSL. Much of this data has not been previously available in a digital form.

Compiled data included basic data such as station location, sample date, general chemistry (major solutes: Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , HCO_3^- , CO_3^{2-}), and additional data at select sites that includes trace metals, nutrients, and stable isotopes. All station and sample data were assigned a unique identifier based on datasource information and the relative order of the compilation process. These unique IDs allowed discrete processing, correlation, and tracking of all data from source to the final database.

We compiled, processed, and vetted the data in Python via scripting available at <https://gist.github.com/inkenbrandt/33fc4253d2d7510a0768be93c4dd8c87>. The final database is a series of related tables, features, and grids packaged as a ArcGIS format geodatabase. This processing produced consistent station and sample data based on the varying input datasets. Compilation was complex, as each dataset had a different way of naming and quantifying the different variables. We matched field names and split fields where necessary. We made all units consistent, converting to mg/L for all concentrations, and made measures by species (i.e., NO_3^- -N vs NO_3) consistent as well. Initial compilation of the various data sources yielded duplicate records for both stations and samples. In each instance of duplicate records, a single unique station or sample was chosen based on data completeness. When duplicate records had the same level of data completeness the most recent sample was selected.

To best utilize the datasets created by this study, it is important to discuss how chemistry data can be organized. The major datasets (SDWIS, WQP, and NWIS) are organized in

a format where each parameter of each sample from each station is contained in a row. For example, the concentration of calcium measured on a certain day at a specific station is in a separate row in the data table than the measure of magnesium from the same sample. This table format is called a parameter-by-row data structure (table 1).

While the parameter-by-row structure is an efficient way to organize chemistry data, it is hard to visualize the total chemistry of a sampling instance when each chemical is in a separate row. An alternative table format includes a sampling instance for each row that is used to determine the best samples, calculate charge balance, and plot the data based on solute chemistry. This format is called a sample-by-row data structure (table 2). The process of transforming a parameter-by-row table (table 1) to a sample-by-row table (table 2) is called “pivoting,” where the various parameter abbreviations for each sample are turned into column headings. Metadata about individual chemicals can be lost during the pivot process. Examples of the metadata lost are detection conditions, result units, minimum detection limits, and analysis techniques. To conduct the pivoting process, we abbreviated each parameter and then used the abbreviations as column headers for the pivoted tables. Parameters were abbreviated to ensure that the column headers were compliant with the requirements for ArcGIS column headers (no spaces or special characters and limited length). Once the data were pivoted, we were then able to analyze the data by sample.

To create total chemistry plots such as piper plots and stiff diagrams, all major solutes are necessary, including calcium, magnesium, sodium, potassium, sulfate, bicarbonate, and chloride. Carbonate (CO_3^{2-}) can also be a major solute, but is commonly negligible in natural waters. Sometimes, the carbonate species are reported as measured alkalinity. For these

Table 1. Example of a parameter-by-row data structure.

StationId	SampleId	Date	Param	ParAbb	Detected	Result	Units
Well-A	Sample-1	1/1/2004	Calcium	Ca	<	10	mg/L
Well-A	Sample-1	1/1/2004	Magnesium	Mg		25	mg/L
Well-A	Sample-2	5/3/2016	Strontium	St		6	ug/L
Well-A	Sample-1	1/1/2004	Chloride	Cl		15	mg/L

Table 2. Example of a sample-by-row data structure. This table is a pivoted version of table 1. Note how pivoting required the removal of the “Detected” and “Units” fields.

StationId	SampleId	Date	Ca	Mg	St	Cl	Units
Well-A	Sample-1	1/1/2004	10	25		15	mg/L
Well-A	Sample-2	5/3/2016			0.006		mg/L

samples, we converted from alkalinity to bicarbonate by determining the relationship between alkalinity and bicarbonate for samples where both values were reported, then applying that relationship to the samples without reported bicarbonate (figure 3). After infilling missing bicarbonate values, samples with a complete suite of major solutes were assigned a value of 1 to the “complete” field. If a sample had complete major solutes, we estimated the total dissolved solutes by summing the concentrations of all of the solutes in the sample. Comparing calculated TDS to measured TDS is a first-pass quality assurance check for a water chemistry sample. For all sites that contain data for all seven solutes, a major ion water type is calculated that describes the dominant cation and anion based on meq/L concentrations.

For each sample that includes a complete set of the seven solutes, a charge balance was calculated. To calculate charge balance, we first converted concentration in milligrams per liter to equivalence in milliequivalents per liter by dividing concentration by the atomic mass of each ion and multiplying by the valence charge of that ion. Next we calculated the sums of the major anions and cations for each sample. Charge balance error was the difference between the anions and cations over the total of the anions and cations. The charge balance of natural fluids is generally in equilibrium and as such should be nearly zero. Charge balance can therefore be

used as an additional data quality assurance measure where values near zero are considered most accurate and values significantly less than or greater than zero are less accurate. Samples with calculated charge balance are grouped to delineate different qualitative levels of data quality. We created a field in our pivoted data feature class that lumps the data into three groups based on their charge balance error. Group one consists of samples with charge balance error less than 5%, group two has error between 5% and 10%, and group three had error greater than 10%. The final filtered table (labeled Selectchempivot) of the groundwater chemistry data consists of the most recent sample from each station that has all of the major solutes and a charge balance error of less than 5%. This Selectchempivot feature class is considered the highest quality subset of the database and is used to produce simple summary maps of groundwater chemistry discussed in subsequent sections.

Once the chemistry quality assurance was complete, we examined the station locations using aerial photography and the Utah Division of Water Rights data as references. When possible, stations in the same location but from different agencies were merged together, and sample locations that were obviously misplaced were corrected. The resulting station feature class includes unique station ID's, coordinates, and summary location information for all analyses in the database.

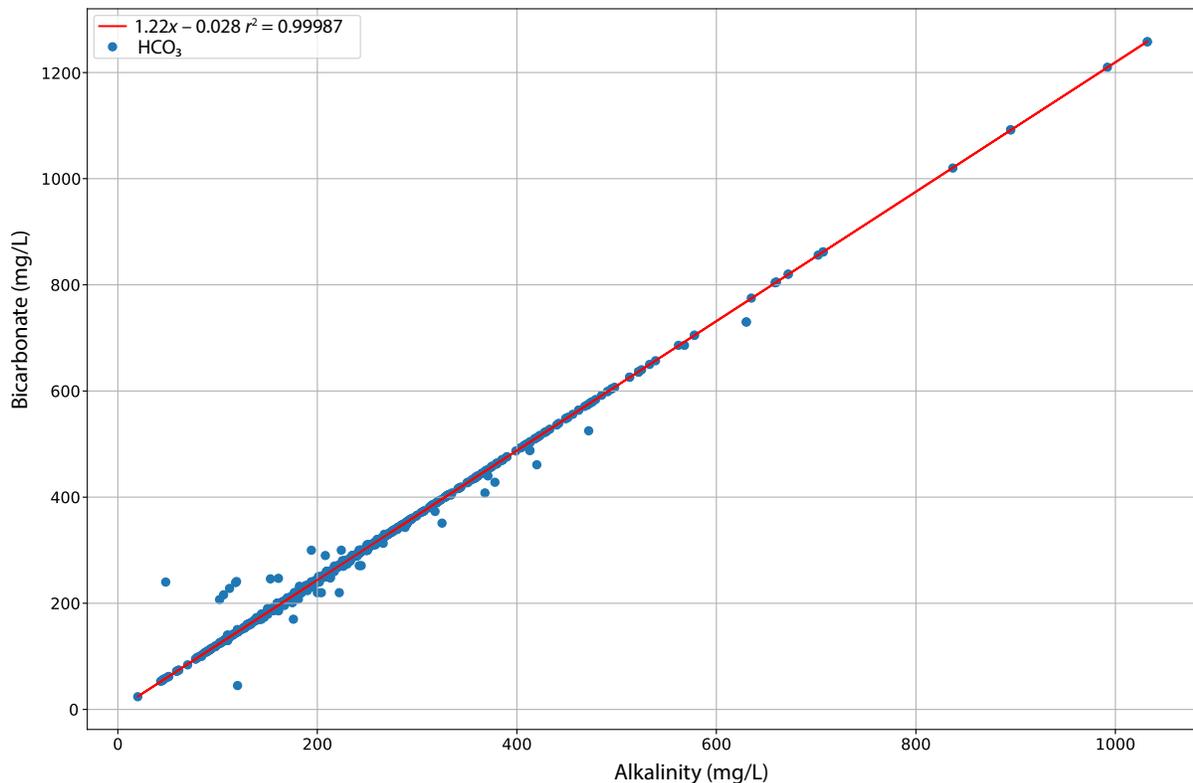


Figure 3. Plot of bicarbonate versus alkalinity based on compiled data. This linear relation was used to estimate bicarbonate at sites that only contain alkalinity data.

For simplification and depiction of chemistry relative to location, we split the region into localized areas of interest that include: Tooele Valley, East Shore, Northwest, Bear River, Promontory, Island, and Southwest. The localized areas are based mostly on the areas of the eight-digit hydrologic unit codes (HUC8), with minor modifications to some of the boundaries. All HUC8s on the southwest side of the lake were combined in a single Southwest grouping. Additional more detailed hydrologic unit codes (HUC 10 and HUC 12) are also included in the station feature class. Station type is listed as spring or well when known for a given sample. Additional station information that includes the well or hole depth, geologic unit, well identification numbers, and site elevation are included when available. Field descriptions are included in the metadata that accompanies the feature class data.

New Sampling

New geochemical samples of groundwater were collected from springs and wells surrounding GSL. The goal of this sampling was to fill apparent data gaps and attain recent data to check for temporal consistency with compiled data samples in areas of preexisting data. All samples were analyzed at the Brigham Young University hydrogeology laboratory for major ion chemistry and select minor element chemistry that included Li, B, and Se. All chemical analyses were performed using a variety of standard techniques described by Fishman and Friedman (1989). A series of samples were also collected solely for stable isotopes. Field sampling followed standard techniques and also included measurement of field parameters of temperature, pH, and conductivity at sites sampled for geochemistry and stable isotopes. Simple specific gravity was recorded for all new samples. All new sample data were added to the compiled database and are included in subsequent maps that summarize various aspects of the geochemistry adjoining GSL.

DATABASE SUMMARY

Within the database, a complete set of all compiled samples is presented in the Allchempivot feature class. This feature class includes a total of 17,313 unique compiled samples at 1772 different sites. When available, sample date is included. Sample events span just over 100 years for the entire database from 1911 to 2018. Samples included in the Allchempivot feature class represent time series sampling or discrete sampling events for a particular analyte. Stations having multiple samples compose the majority of the dataset. Only 797 of the total 17,313 samples had a single sample. Sites with multiple samples include repeat sampling for the same constituents through time or discrete samples of different constituents. Time series data contained in the database provide constraints on groundwater chemistry changes through time surrounding the lake. Discussion and analysis of this time series data are beyond the scope of this project, but could yield important information regarding geochemical change in groundwater near GSL.

The database contains a series of analytes that is meant to be broadly relevant if not comprehensive. In addition to data for the seven major solutes, data for a range of trace constituents, isotopes, and nutrients are included. All sample-level data include at least one analyte; however, distribution of data across the various analytes is irregular. For subsequent discussions that focus on various aspects of the chemical data the Selectchempivot file is used as the data source. This file includes 888 samples that have complete major ion chemistry and high quality analysis based on calculated charge balance as discussed previously. Most samples in the select database are located along the eastern and southeastern parts of the lake, with significantly fewer samples are located along western and northern parts of the lake.

Summary of Geochemistry Adjoining GSL

Major ion groundwater chemistry provides basic information concerning the character of groundwater adjoining GSL. Major ion chemistry defines the dominant cation and anion in a sample based on meq/L concentrations (Kehew, 2001). These simple two-component water types depict large-scale geochemical transitions in the groundwater systems near GSL. Across the study area chemistry varies from Ca-HCO₃ to Na-Cl dominated, and the majority of samples are Na-Cl water type (figure 4). Na-Cl waters occur surrounding the lake with the notable exception of the east shore of GSL where Ca-HCO₃ water types are common. Na-Cl water types commonly occur in areas of groundwater that have experienced significant water-rock interaction and or evaporative concentration in areas of discharge. Mayo and Klauk (1991) attributed Na in groundwater across Antelope Island to wind-borne salt deposition. Similar processes may occur in many areas that directly adjoin GSL. Ca water types generally represent groundwater that has not experienced long-term water-rock interaction such as in areas of active recharge. This setting is typical of the areas of Ca-HCO₃ waters along the east shore of GSL. Along flow paths groundwater chemistry may evolve from Ca-HCO₃ to Na-Cl as waters move from areas of recharge to discharge.

More detailed depictions of major ion chemistry show the variability and complexity in groundwater chemistry near GSL (figure 5). Location and therefore hydrogeologic setting appear to play a significant role in the hydrochemistry of the samples. Differentiation of chemistry among various regions appears most distinct for samples from the east shore area. Other regions have chemistry that broadly overlaps and likely results from similar groundwater processes surrounding GSL, that may include similar aquifer material, recharge settings, and flow paths. Samples in the east shore area likely are distinct due to the relatively significant amount of recharge in this area.

Salinity or the total dissolved load is a basic measure of the quality and chemical characteristics of a fluid. In groundwater, total dissolved solids (TDS) is the equivalent measure

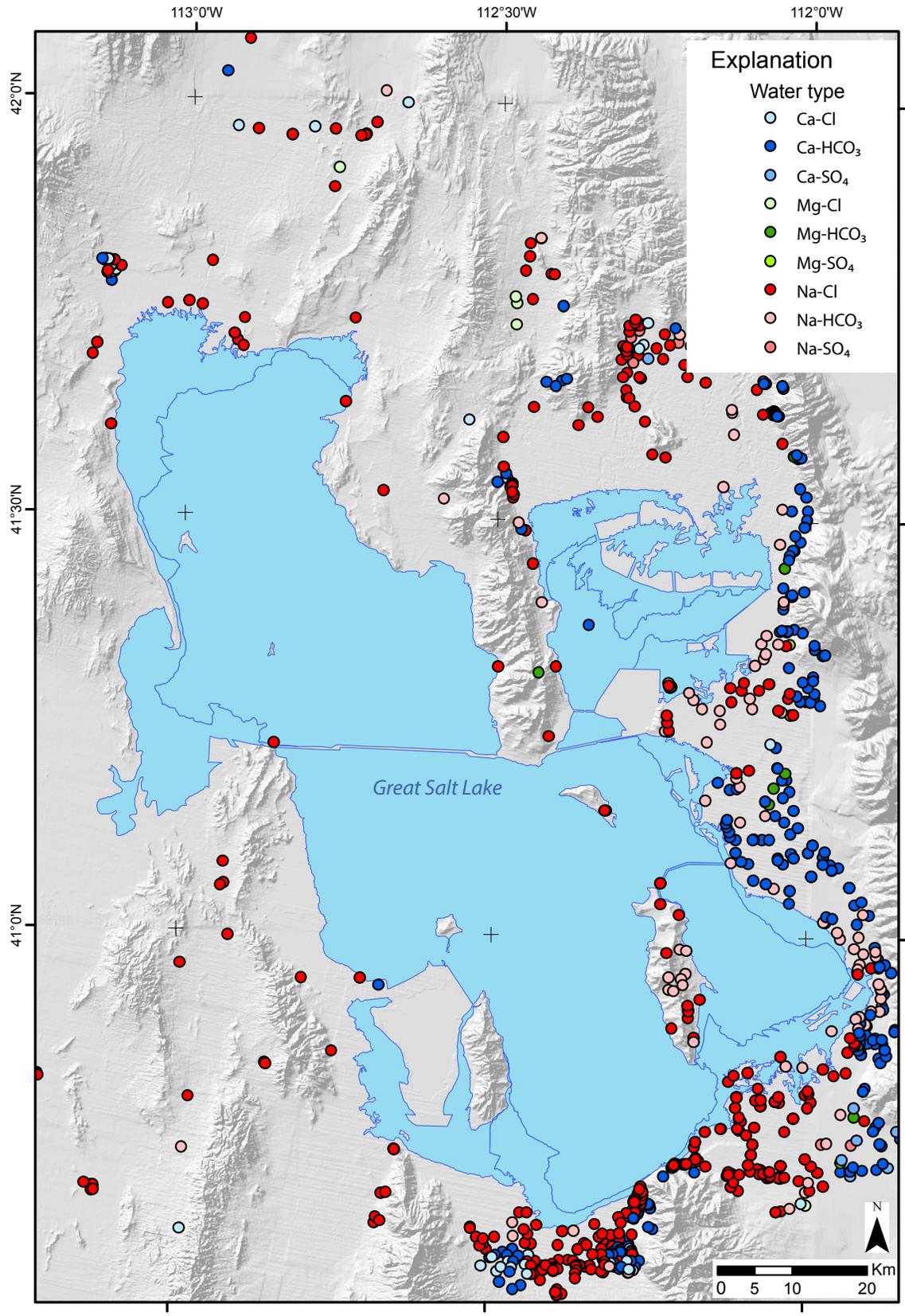


Figure 4. Major ion water type for select groundwater samples near GSL.

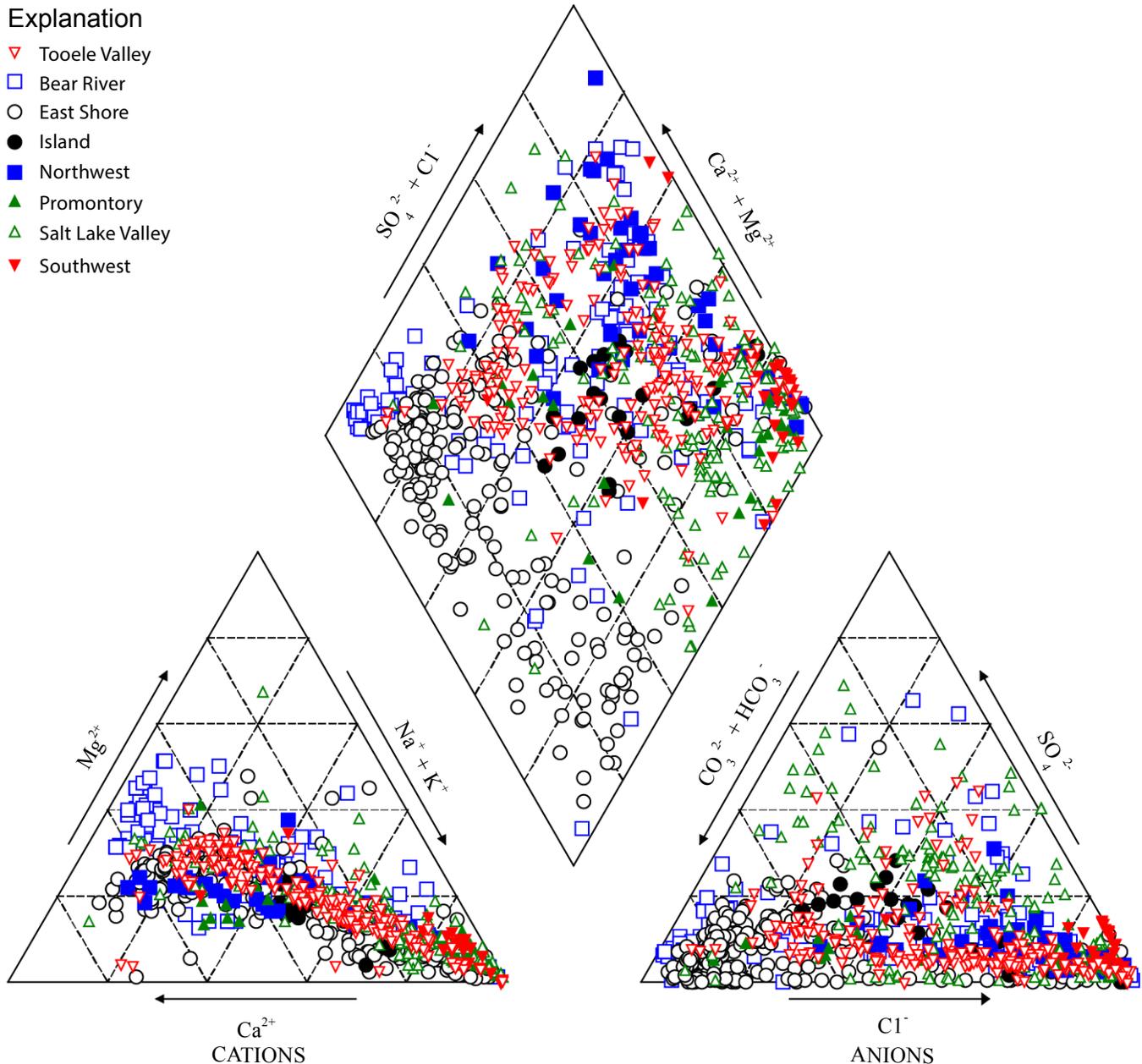


Figure 5. Piper diagram of select groundwater samples near GSL.

of salinity. TDS concentrations were calculated as the sum of dissolved constituents for each sample and listed in units of mg/L or ppm. Calculated TDS values at the select sample sites were used to create a TDS grid using an iterative kriging method with the geostatistical wizard in ArcMap. This method allowed for an iterative approach where fitting parameters were varied until a smooth fit of the grid with the data was obtained. The resulting grid is used to map TDS and salinity in the groundwater system adjoining GSL (figure 6). Groundwater TDS ranges from dilute water with less than 500 mg/L along the east shore to highly concentrated groundwater with TDS greater than 50,000 mg/L along the southwestern part of the lake.

Trace Constituents

The compiled database contains analyses for trace solutes and metals that include As, B, Ba, Be, Br, Cd, Co, Cr, Cu, F, Fe, Hg, Li, Ni, Pb, Sr, Sb, Mn, V, and Zn. All of these constituents have complex geochemical behaviour that may be relevant to GSL and its adjoining wetlands. Discussion of all these constituents is beyond the scope of this report. To depict the data availability and variability of trace constituents, four trace constituents are presented on a series of maps (figures 7 and 8). The mapped analytes include As, Se, B, and Li, and these metals are meant to provide examples of trace metal concentrations in groundwater that could be

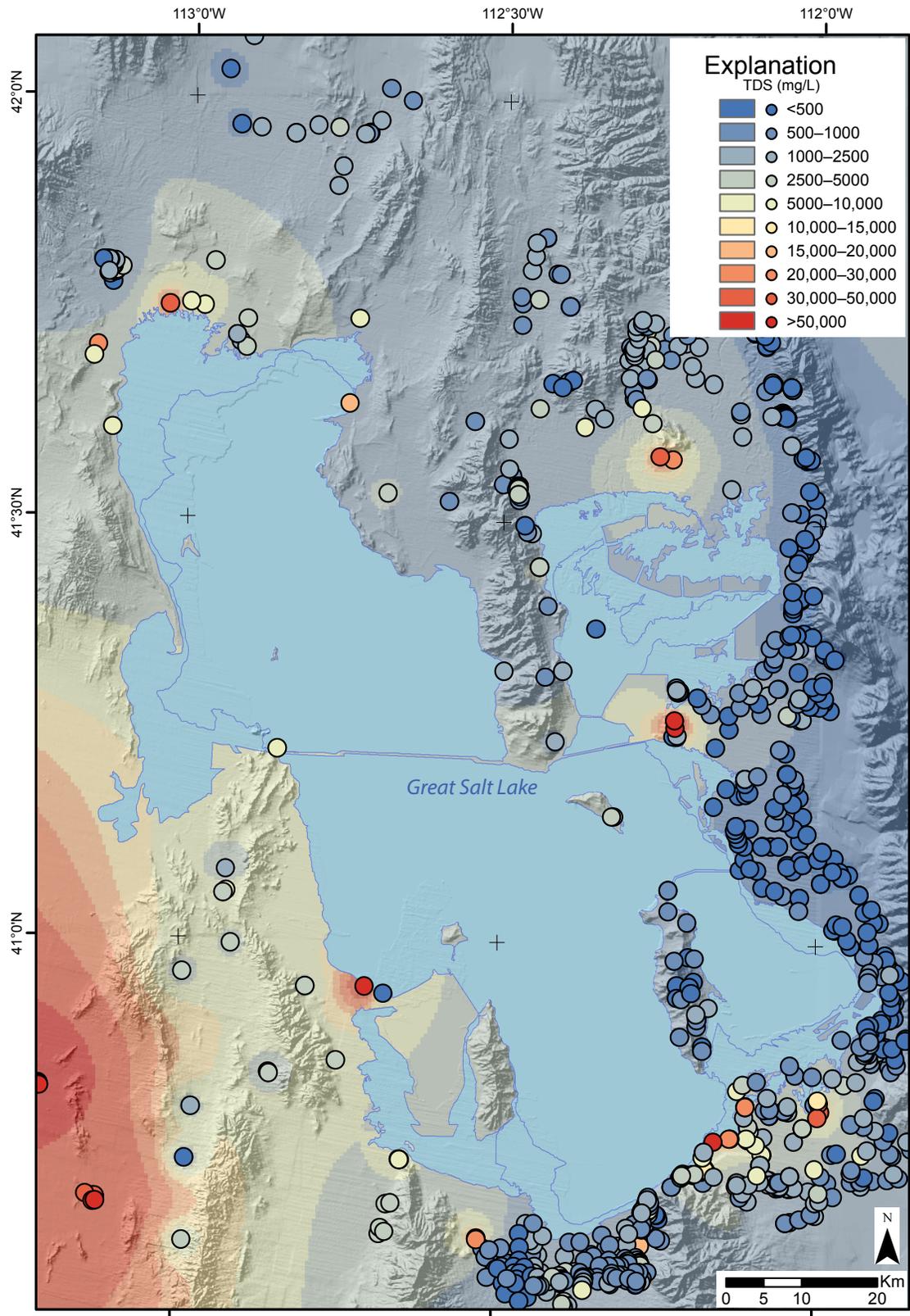


Figure 6. Interpolated concentration of total dissolved solids (TDS) near GSL. Interpolation is based on the Selectchempivot feature class points that are shown here. The interpolation followed an iterative kriging approach using the ArcGIS statistical analyst toolset.

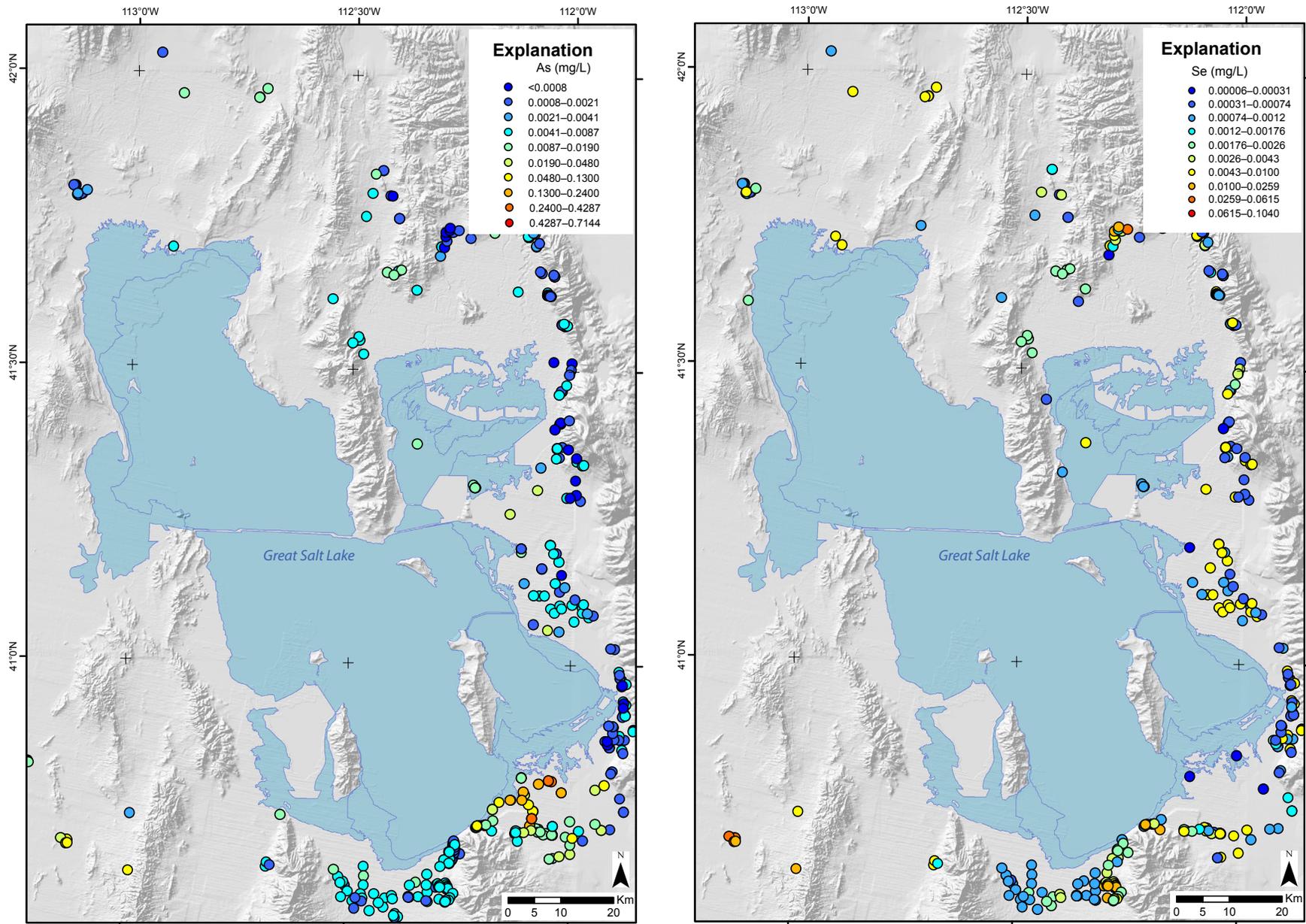


Figure 7. Dissolved metal concentrations of arsenic (left) and selenium (right) in groundwater near GSL.

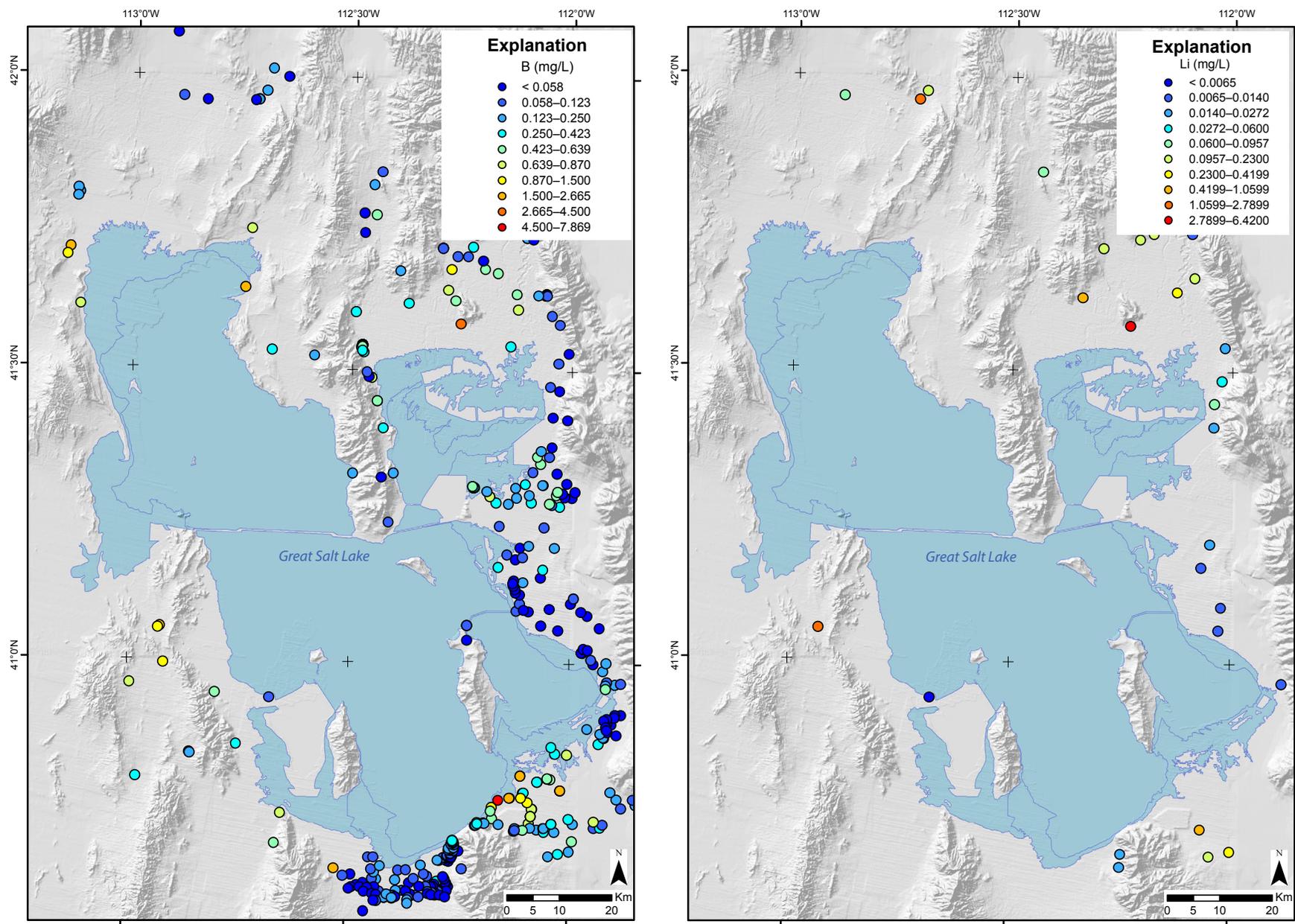


Figure 8. Dissolved metal concentrations of boron (left) and lithium (right) in groundwater near GSL.

relevant to both potential contaminants (As and Se) and trace constituents that may record other groundwater processes including potential addition of geothermal fluids (B and Li).

Many of the trace metals may be considered potential contaminants in significant concentrations. Both As and Se have been identified as potential contaminants both in the lake and in adjoining wetlands (Diaz and others, 2009; Johnson and others, 2010; Carling and others, 2013). Concentrations of these two constituents are shown in figure 7. Arsenic in groundwater occurs in concentrations that range from less than 0.00001 mg/L to 0.7 mg/L. Most groundwater samples near GSL have arsenic that is below the drinking water standard of 0.01 mg/L. High values of arsenic occur in groundwater along the south-east margin of the lake in northern Salt Lake County. Elsewhere arsenic concentrations are low, particularly along the east shore of the lake where high values occur only at specific sites. Therefore, groundwater may only supply significant amounts of As to GSL and its wetlands in localized areas and near the northern part of Salt Lake Valley.

Selenium is a potential constituent of concern in groundwater and surface water and also in wildlife. High levels of selenium have been found in various bird species and in GSL. The concentration of selenium in groundwater ranges from 0.000002 mg/L to 2.8 mg/L. Most groundwater samples have selenium less than 0.002 mg/L and higher values occur sporadically around the lake. Several significant spring systems contain relatively high Se concentrations, particularly Locomotive Springs. It is possible that groundwater discharge at various springs contributes significant quantities of Se to GSL and adjoining wetlands. It may be assumed that other trace constituents follow a similar pattern where significant concentrations of these trace metals are discharged at discrete point sources surrounding the lake and its wetlands.

Trace metal concentrations including those of B and Li can be evidence of deep groundwater mixing and the presence of thermal waters in shallow groundwater. As such, both B and Li can be excellent tracers of large-scale groundwater processes (Ingebritsen and Sanford, 2001). Some trace constituents such as lithium may represent important potential mineral resources. Maps showing concentrations of B and Li are shown in figure 8.

Data for lithium concentrations in groundwater are limited compared to other trace constituents and relatively few samples are mapped in figure 8. Lithium concentrations span a large range, from less than 0.0006 mg/L to 6.4 mg/L. Following a similar pattern to that of selenium, most lithium concentrations are low, and show a bimodal distribution with high values at discrete isolated locations. The highest Li concentrations are located at Locomotive Springs and at a warm spring north of Bear River Bay. Moderate concentrations occur in groundwater of northern Salt Lake Valley.

Springs that contain high lithium may contribute significant relative amounts of this constituent to the lake system.

Boron is a trace metal that is closely tied to geothermal fluids. Significant boron concentrations commonly occur in thermal water and the ratio of B to other constituents can provide constraints on the relative proportions of thermal and non-thermal groundwater. Boron concentrations from samples in the database range from 0.0001 mg/L to just over 8 mg/L. Most groundwater samples have low concentrations of B and are generally less than 0.25 mg/L. The highest boron concentrations occur only at several localized springs near Bear River Bay. Several of the large springs elsewhere around the lake such as Locomotive Springs have low boron concentrations.

Nutrients

A subset of the database contains analyses of various nutrients that include nitrate, phosphate, and phosphorus. The presence and concentration of nutrients can drive biologic activity and may contribute significantly to algal blooms and other plant growth in both wetlands and brackish areas of GSL, such as Farmington Bay (Miller and others, 2009). Figure 9 shows nitrate and phosphorus concentrations in groundwater. Nitrate concentrations range from less than 0.5 mg/L to greater than 80 mg/L. Values greater than 5 mg/L occur in relatively discrete and spatially isolated locations, and most locations have values less than 2 mg/L. The potential for significant nitrate additions from groundwater into wetlands adjoining the lake appears low. There are fewer analyses for phosphorus than nitrate but these analyses generally follow a similar pattern where most analyses have low levels of phosphorus. Most phosphorus samples have concentrations less than 0.1 mg/L and higher values occur locally along the east shore of GSL. High phosphorus in these areas may result from urban or agricultural recharge and runoff. Taken together nutrients in groundwater are in relatively low concentrations, and groundwater may not be a significant source of nutrients to GSL and its adjoining wetlands.

Stable Isotopes

The abundance of the stable isotopes deuterium and oxygen-18 (expressed as $\delta^2\text{H}$ and $\delta^{18}\text{O}$, respectively) in water provides information about various fluid processes that include source of recharge, mixing and high-temperature water-rock interaction, and surficial processes including evaporation (Clark and Fritz, 1997). Not considering potential mixing and high-temperature recharge, stable isotopic composition is generally assumed to be fixed at recharge. As such, stable isotopes make excellent tracers of groundwater and surface water. Available stable isotope data are included in the database and are augmented with a series of new samples collected as part of this study. These data provide basic constraints on the stable isotopic composition of groundwater adjoining GSL.

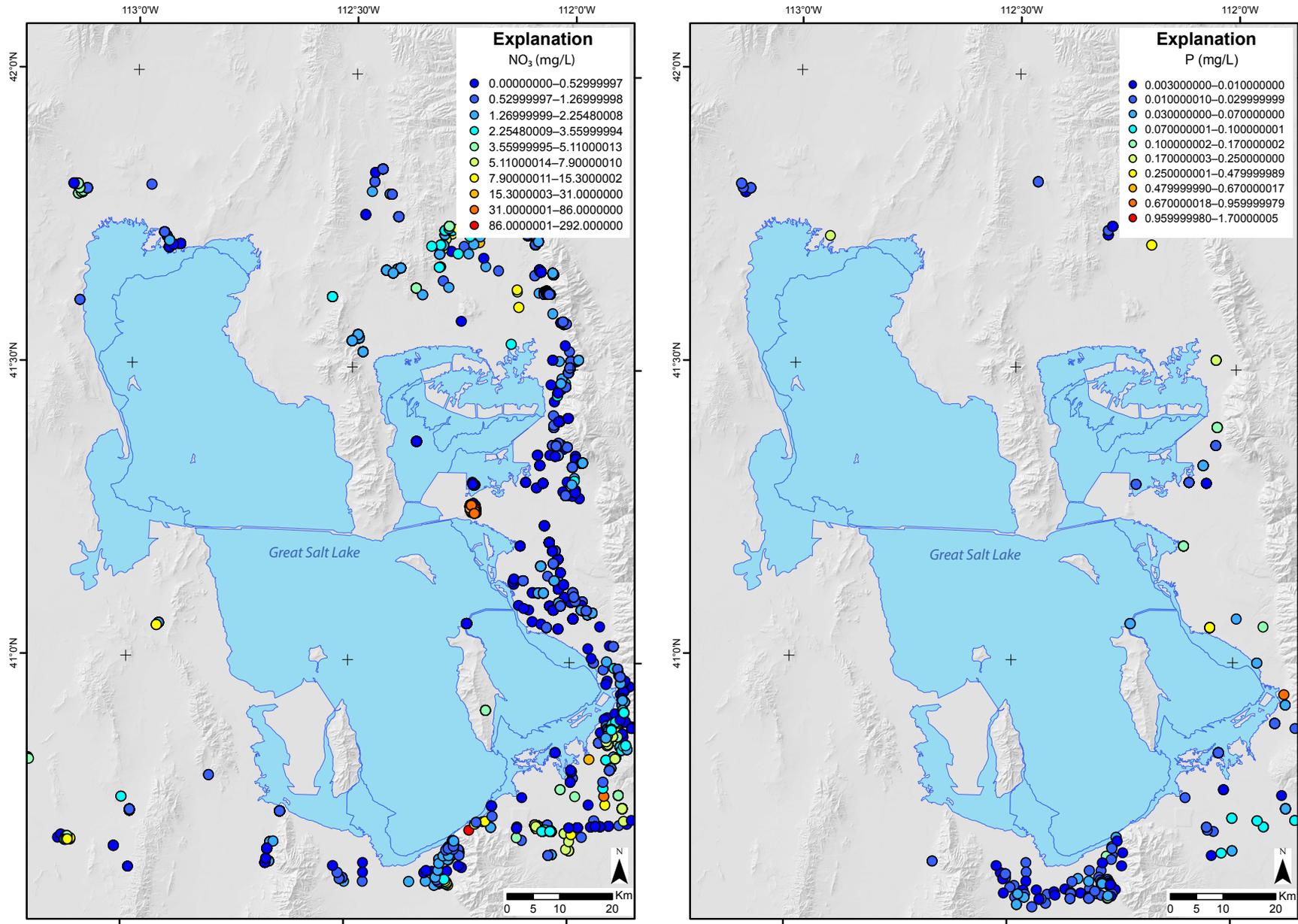


Figure 9. Nutrients including nitrate (left) and phosphorus (right) in groundwater near GSL. Concentrations of both nitrate and phosphorus are generally low in groundwater adjoining GSL.

The stable isotopic composition of groundwater is shown on a meteoric water line plot where isotopic compositions typical of precipitation in Utah (Kendall and Coplen, 2001) and globally (Craig, 1961) are plotted as a series of lines (figure 10). Samples are subdivided by area and plotted against the precipitation trends. Groundwater compositions span a range between -147 and -95 $\delta^2\text{H}$, and between -18.5 and -11 $\delta^{18}\text{O}$. Most samples plot near or below the Utah meteoric water line and thus appear to match expected compositions for regional precipitation. Cool or upland precipitation, and groundwater recharged from such sources, tends to plot on the lower left part of the graph, whereas warm or lowland precipitation tends to plot on the upper right part of the graph. Other samples plot away from the meteoric water lines, such as a series of samples from the east shore, and may be a result of isotopic fractionation caused by localized evaporation affecting shallow groundwater or high-temperature water-rock interaction.

Stable isotopic compositions of the various geographic locations overlap to a significant degree and most areas have groundwater stable isotopic conditions that are not unique and are instead found at various areas surrounding the GSL. A map of $\delta^2\text{H}$ composition shown in figure 11 follows a similar pattern where multiple areas around the GSL have similar if not identical values of $\delta^2\text{H}$. This pattern likely results from

similar sources of precipitation and recharge for different areas. Samples that likely recharged from low elevation or warmer precipitation at areas such as Antelope Island (Mayo and Klauk, 1991) and Promontory Point are contrasted with samples derived from recharge of cooler precipitation such as along the northern part of Salt Lake Valley and along the northern part of the east shore area (Cole, 1982). Alternatively, samples with low values of $\delta^2\text{H}$, shown by blue colors on figure 11, may have recharged during cooler climatic periods in the past. Stable isotopes can be a useful tool in future site-specific and process-scale groundwater and wetland studies and the data included in this database provide an important baseline.

WETLAND DATA

The compiled database includes wetland data available from the UDEQ and the state wetlands program (UGS). The database includes a series of water chemistry analyses collected at discrete points as well as updated wetland-type mapping adjoining GSL. The inclusion of the wetland data allows for comparison with existing groundwater chemistry and makes existing water chemistry collected as part of wetland studies publicly available.

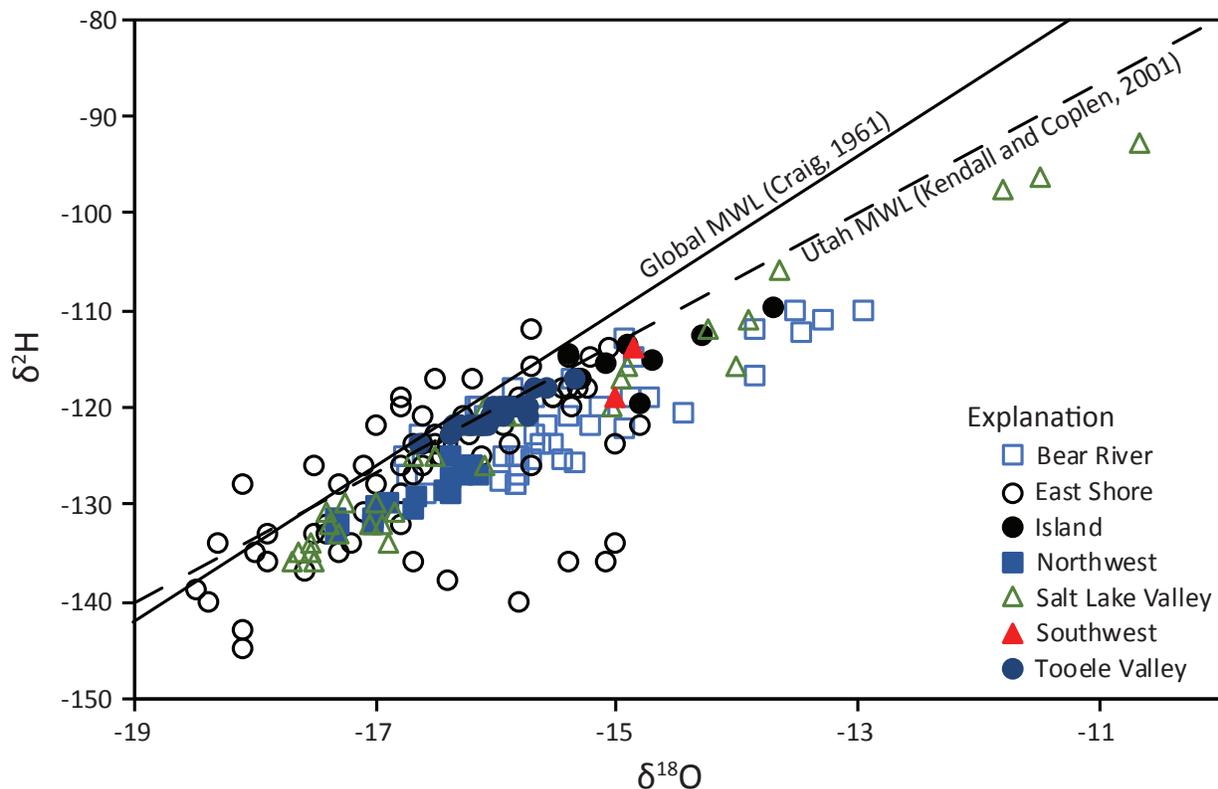


Figure 10. Meteoric water line plot of stable isotope data. Most samples plot near and just below both the global meteoric water line and the Utah meteoric water line.

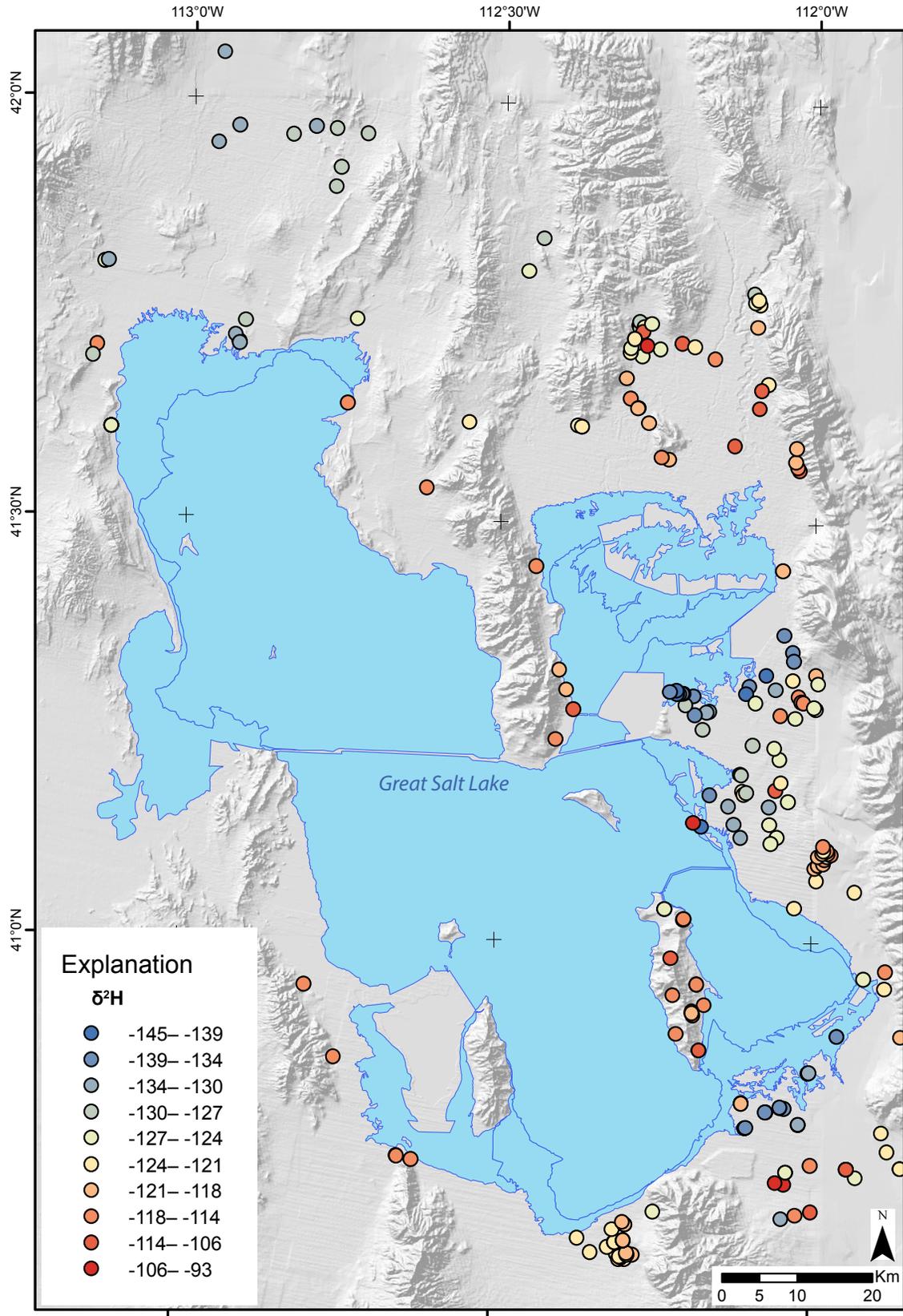


Figure 11. $\delta^2\text{H}$ in groundwater adjoining GSL. Low values of $\delta^2\text{H}$ occur near the northern part of Salt Lake Valley and the northern part of the east shore area. Elsewhere there is significant $\delta^2\text{H}$ overlap across the various areas.

We compared interpolated calculated groundwater TDS concentrations to TDS concentrations measured in the wetlands adjacent to GSL. Most of the groundwater samples in the compiled dataset are farther inland from GSL than the wetland samples. Because wetland sample points did not spatially align with the compiled groundwater data, we used the interpolated values (figure 12) for comparison.

There is some spatial correlation of groundwater and wetland water TDS concentration. However, any observed cor-

relation is not necessarily indicative of groundwater influence on the wetland systems. The wetlands surrounding GSL are influenced by anthropogenic impoundment, complicating our understanding of water sources for these systems. Due to the diversity of hydrogeologic and flow systems in the wetland complexes surrounding GSL, groundwater influence on wetland systems is best understood on a case-by-case or local scale. The data need careful statistical GIS analysis to pull out details, which is beyond the scope of this study.

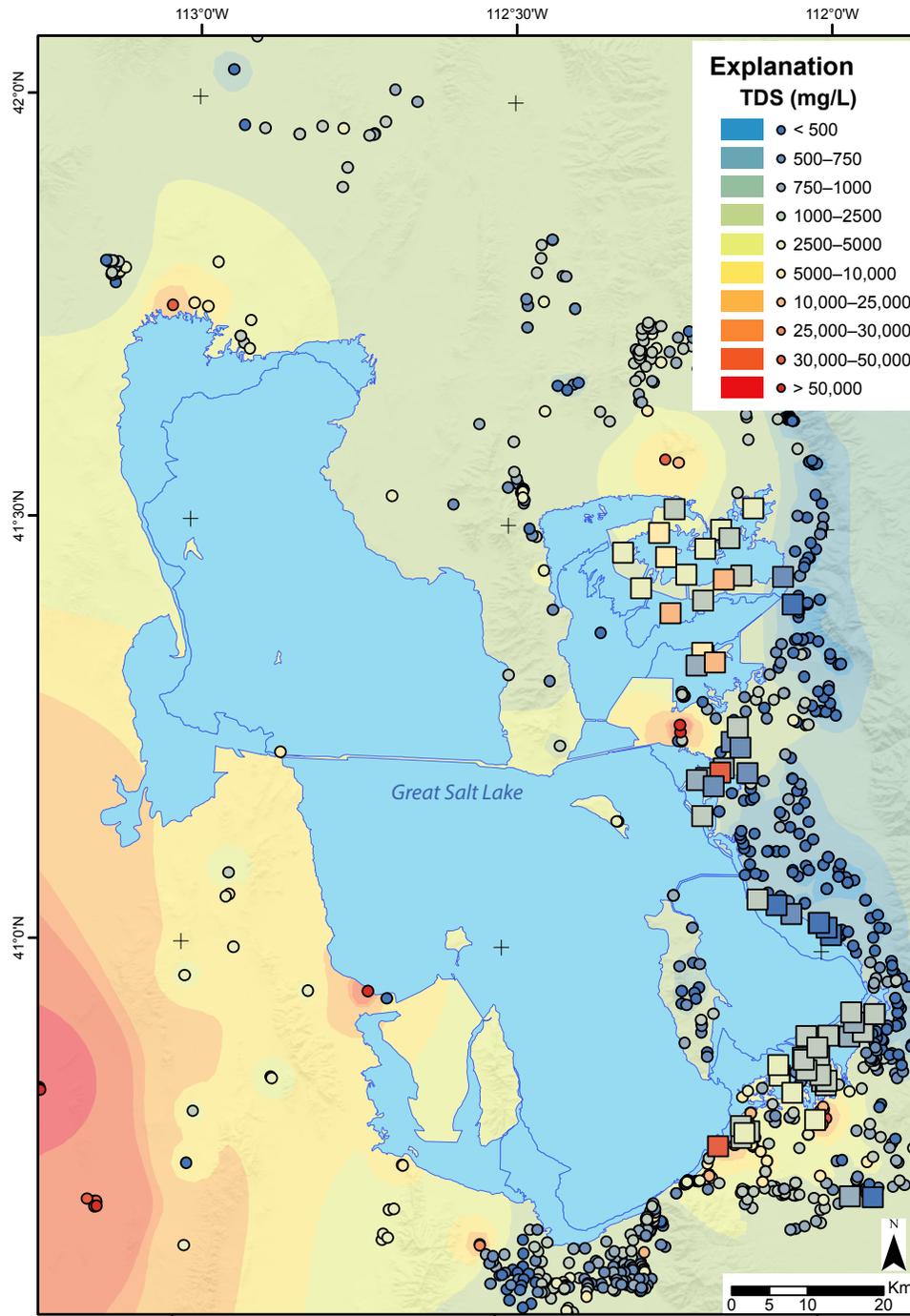


Figure 12. Measured groundwater TDS (circles) and interpolated groundwater TDS, against wetland TDS measurements (squares). Values of wetland TDS qualitatively correlate with similar groundwater TDS.

A scatterplot of the wetlands TDS data and the interpolated groundwater TDS (figure 13) shows that wetland TDS concentrations are generally less than the estimated groundwater TDS concentrations—below the one-to-one line on the plot. This could be caused by surface water influence, error in the interpolation, or groundwater sources not measured for the interpolation. Points above the one-to-one line could be caused by additional evapotranspiration, or influence from saline surface water or groundwater.

CONCLUSIONS

The compiled dataset provides the most current and most complete groundwater chemistry data adjoining GSL and fills a significant data gap. The dataset also includes available wetland-related type and chemistry data. This chemistry database is a first step towards understanding and better constraining the role of groundwater in various GSL processes and habitats and provides important baseline chemistry. This better understanding is critical for making future informed land-management decisions for GSL and adjoining areas.

Mapping the chemistry, salinity, and water quality in groundwater improves understanding of the subsurface transport of water between groundwater, GSL, and the surrounding wet-

lands. Using groundwater chemistry data compiled for this project, future studies could conduct a chemical mass balance of salinity and dissolved ion loads to 1) wetlands adjoining the lake, and 2) GSL itself. In combination with stable isotope data (which we compiled and collected), a mixing model could be produced that estimates the probable quantity of groundwater that contributes to the surface water systems. Before such models can be produced, researchers need baseline measurements of groundwater quality around the lake. A similar basic compilation is needed on other aspects of groundwater adjoining GSL, including potentiometric surface, spring locations, and flow rates.

ACKNOWLEDGMENTS

Partial funding for this project was provided by the Utah Division of Forestry, Fire, and State Lands as part of the Great Salt Lake research grant program. We thank Elliot Jagniecke, Hugh Hurlow, and Michael Hylland of the Utah Geological Survey for prompt reviews of this report. Nathan Payne, also with the Utah Geological Survey, provided a detailed review of the geodatabase. We thank Lynn de Freitas of the Friends of the Great Salt Lake for the opportunity to present an early version of this work at the 2018 Great Salt Lake issues forum. We also thank Laura Vernon with the Utah Division of Forestry, Fire, and State Lands for patience during completion of this report.

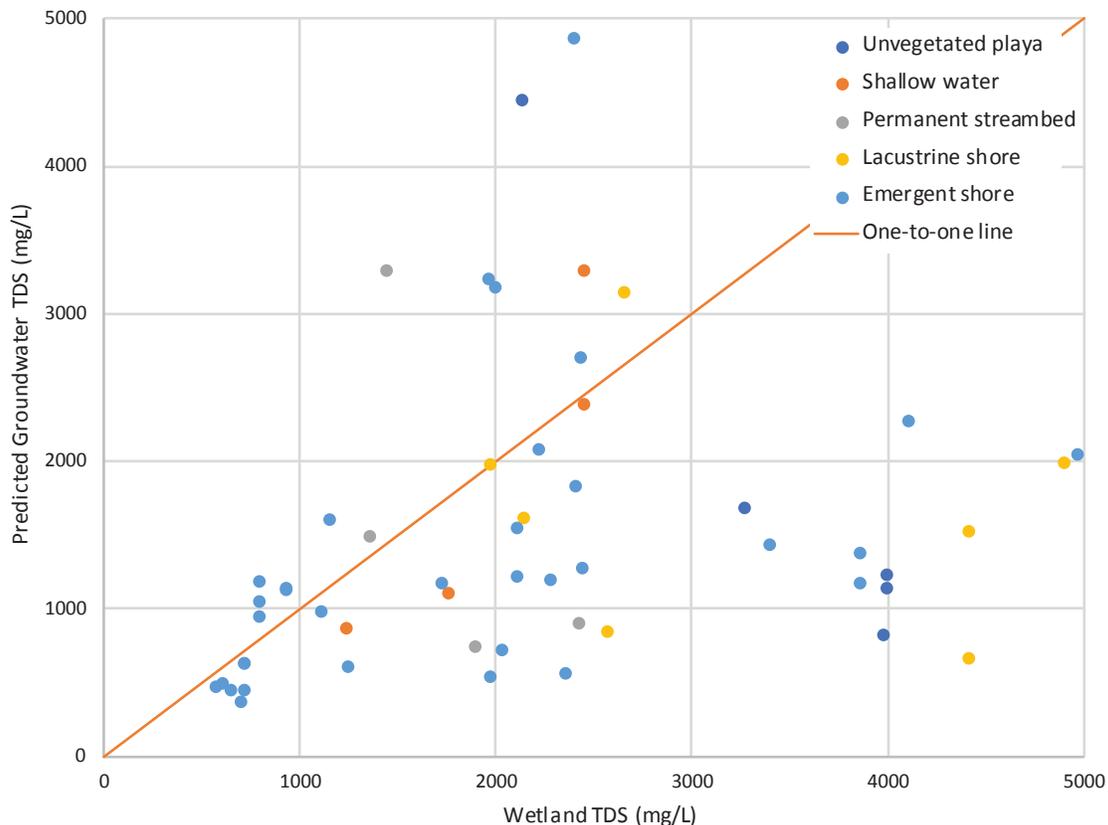


Figure 13. Wetland TDS versus interpolated calculated TDS. Samples of wetland TDS that plot near the one-to-one line correlate closely with groundwater TDS as predicted by interpolated TDS in figure 6. Most samples plot away from this line and imply sources other than or in addition to groundwater.

REFERENCES

- Arnow, T., and Stephens, D.W., 1990, Hydrologic characteristics of the Great Salt Lake, Utah, 1847-1986: U.S. Geological Survey, Water Supply Paper 2332, 32 p.
- Carling, G.T., Richards, D.C., Hoven, H., Miller, T., Fernandez, D.P., Rudd, A., Pazmino, E., and Johnson, W.P., 2013, Relationships of surface water, pore water, and sediment chemistry in wetlands adjacent to Great Salt Lake, Utah, and potential impacts on plant community health: *Science of the Total Environment*, v. 443, p. 798–811.
- Clark, I., and Fritz, P., 1997, Environmental isotopes in hydrogeology: Boca Raton, Florida, CRC Press, 328 p.
- Cole, D.R., 1982, Tracing fluid sources in the East Shore area, Utah: *Groundwater*, v. 20, no. 5, p. 586–593.
- Craig, H., 1961, Isotopic variations in meteoric waters: *Science*, v. 133, no. 3465, p. 1702–1703.
- Diaz, X., Johnson, W.P., and Naftz, D.L., 2009, Selenium mass balance in the Great Salt Lake, Utah: *Science of the Total Environment*, v. 407, no. 7, p. 2333–2341.
- Duffy, C.J., and Al-Hassan, S., 1988, Groundwater circulation in a closed desert basin—Topographic scaling and climatic forcing: *Water Resources Research*, v. 24, no. 10, p. 1675–1688.
- Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations 05-A1, 545 p.
- Hahl, D.C., 1968, Dissolved-mineral inflow to Great Salt Lake and chemical characteristics of the salt lake brine—Summary for water years 1960, 1961, and 1964: Utah Geological and Mineralogical Survey Water-Resources Bulletin 10, 37 p.
- Hahl, D.C., and Mitchell, C.G., 1963, Dissolved-mineral inflow to Great Salt Lake and chemical characteristics of the salt lake brine—Part I, Selected hydrologic data: Utah Geological and Mineralogical Society Water-Resources Bulletin 3–I, 51 p.
- Hood, J.W., 1971, Hydrologic reconnaissance of Hansel Valley and northern Rozel Flat, Box Elder County, Utah: Utah Department of Natural Resources, Division of Water Rights Technical Publication 33, 46 p.
- Hood, J.W., 1972, Hydrologic reconnaissance of the Promontory Mountains area Box Elder County, Utah: Utah Department of Natural Resources, Division of Water Rights Technical Publication 38, 48 p.
- Hood, J.W., Price, D., and Waddell, K.M., 1969, Hydrologic reconnaissance of Rush Valley, Tooele County, Utah: Utah Department of Natural Resources, Division of Water Rights Technical Publication 23, 66 p.
- Hurlow, H., and Burk, N., 2008, Geology and Ground-Water Chemistry, Curlew Valley, Northwestern Utah and South-Central Idaho: Implications for Hydrogeology: Utah Geological Survey Special Study 126, 193 p.
- Ingebritsen, S.E., and Sanford, W.E., 2001, Groundwater in geologic processes: Cambridge, Cambridge University Press, 365 p.
- Johnson, W.P., Conover, M., Wurtsbaugh, W., and Adams, J., 2010, Conceptual model for selenium cycling in the Great Salt Lake: Utah Department of Environmental Quality, 38 p.
- Jones, B.F., Naftz, D.L., Spencer, R.J., and Oviatt, C.G., 2009, Geochemical evolution of Great Salt Lake, Utah, USA: *Aquatic Geochemistry*, v. 15, no. 1–2, p. 95–121.
- Kehew, A.E., 2001, Applied chemical hydrogeology: Prentice Hall, 386 p.
- Kendall, C., and Coplen, T.B., 2001, Distribution of oxygen-18 and deuterium in river waters across the United States: *Hydrological Processes*, v. 15, p. 1363–1393.
- Lin, A., 1976, The meromictic Great Salt Lake: *Journal of Great Lakes Research*, v. 2, no. 2, p. 374–383.
- Loving, B.L., Miller, C.W., and Waddell, K.M., 2000, Water and salt balance of Great Salt Lake, Utah, and simulation of water and salt movement through the causeway, 1987–98: U.S. Geological Survey Water-Resources Investigations Report 2000–4221, 111 p.
- Mayo, A.L., and Klauk, R.H., 1991, Contributions to the solute and isotopic groundwater geochemistry, Antelope Island, Great Salt Lake, Utah: *Journal of Hydrology*, v. 127, no. 1, p. 307–335.
- Miller, T., Hoven, H., and Cavitt, J., 2009, Farmington Bay wetlands of Great Salt Lake—nutrient criteria, macroinvertebrate studies and beneficial uses: *Natural Resources and Environmental Issues*, v. 15, p. 11.
- National Water Quality Monitoring Council, 2018, Water quality portal: Online, <https://www.waterqualitydata.us/>, accessed February 2018.
- Price, D., and Bolke, E.L., 1970, Hydrology reconnaissance of the Sink Valley area, Tooele and Box Elder Counties, Utah: Utah Department of Natural Resources, Division of Water Rights Technical Publication 26, 41 p.
- Shope, C.L., and Angerth, C.E., 2015, Calculating salt loads to Great Salt Lake and the associated uncertainties for water year 2013—updating a 48 year old standard: *Science of the Total Environment*, v. 536, p. 391–405.
- Spencer, R.J., Eugster, H.P., and Jones, B.F., 1985a, Geochemistry of Great Salt Lake, Utah II—Pleistocene-Holocene evolution: *Geochimica et Cosmochimica Acta*, v. 49, no. 3, p. 739–747.
- Spencer, R.J., Eugster, H.P., Jones, B.F., and Rettig, S.L., 1985b, Geochemistry of Great Salt Lake, Utah I: Hydrochemistry since 1850: *Geochimica et Cosmochimica Acta*, v. 49, no. 3, p. 727–737.

- Steiger, J.I., and Lowe, M., 1997, Recharge and discharge areas and quality of groundwater in Tooele Valley, Toole County, Utah: Water-Resources Investigations Report 97-4005.
- Utah Division of Drinking Water, 2015, Safe Drinking Water Information System (SDWIS): Online, <http://www.drinkingwater.utah.gov/>, accessed November 2015.
- Wallace, J., Inkenbrandt, P.C., and Lowe, M., 2012, Groundwater quality classification for the principal basin-fill aquifer, East Shore area, Davis County, Utah: Utah Geological Survey 592, 94 p.
- Wallace, J., and Lowe, M., 2009, Ground-Water Quality Classification for the Principal Basin-Fill Aquifer, Salt Lake Valley, Salt Lake County, Utah: Utah Geological Survey Open-File Report 560, 80 p.
- Wallace, J., Thomas, K., and Lowe, M., 2010, Evaluation of Sources of Poor Quality Ground Water in the Bothwell Pocket Area, Lower Bear River Valley, Eastern Box Elder County, Utah: Utah Geological Survey Special Study 135, 56 p.