ESTIMATES OF LITHIUM, MAGNESIUM, AND POTASSIUM RESOURCES IN GREAT SALT LAKE BRINE

by
Andrew Rupke

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Cover Photo: The Promontory Mountains from the shore of Great Salt Lake's north arm.

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1594 W. North Temple, Suite 3110
Salt Lake City, UT 84116
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website: geology.utah.gov

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ABSTRACT

Understanding the available mineral resources in Great Salt Lake brine is an important component to managing these resources into the future. This study examined the in-place resource, or mass, of three economically important ions held within the brine: lithium, magnesium, and potassium. Interest in Great Salt Lake's lithium has risen in recent years with society's increased use of lithium in batteries, and magnesium and potassium have long been extracted from the lake. Using the Utah Geological Survey's Great Salt Lake brine chemistry database, which contains data from 1966 to the present, the resources of these ions held within the lake brine were calculated over time. This study estimates that the in-place lithium resource in Great Salt Lake brine, based on recent sampling, averages about 410,000 metric tons, which is comparable to other recent studies. Notably, the average lithium resource estimate from the 1990s is similar to the recent average; however, a gap in lithium concentration data exists from 1999 through 2018 so a continuous comparison is not possible. An examination of brine withdrawals by mineral operations indicates that roughly 200,000 tons of lithium may have been removed from Great Salt Lake via extractive processes for other commodities from 1988 through 2021 (although some of this lithium remains available to the overall Great Salt Lake system in evaporation ponds). Given the apparent minimal resource change from the 1990s to recently, some recharge of lithium to the lake brine is likely occurring through surface or groundwater inflow. The average estimates of in-place resources of magnesium and potassium in the lake brine since 2011 are 91 million metric tons and 57 million metric tons, respectively. The resources of magnesium and potassium also show limited change since around 2000, suggesting that those resources may also be recharging to some degree.

INTRODUCTION AND PURPOSE

This report provides estimates of the lithium (Li), magnesium (Mg), and potassium (K) resources (or masses) in Great Salt Lake (GSL) brine and how these resources have changed over time. The report also provides an estimate of how much Li may have been removed or displaced from GSL brine by mineral extractive processes since the late 1980s. The analysis presented here primarily utilizes data from the Utah Geological Survey's (UGS) GSL brine chemistry database, which includes data from 1966 to the present. For Li, however, a data gap exists from 1999 through 2018 and then few data are available from 2018 to 2022. Overall, recent Li data are limited.

The estimates in this report are not intended to be used as a resource estimate for potential mineral production and are not intended to represent indicated, measured, or inferred resources as they are legally defined. Ideally, this report will be updated in the future with more extensive data. This report is an expansion and update of Rupke (2024), which provided some initial Li resource information.

The impetus behind this report is to understand the Li, Mg, and K resources in GSL brine and how they have evolved over time. Data on this topic is important as companies explore and evaluate the lake as a source for mineral production, particularly in the context of recent low lake levels and expanding Li interest. Both US Magnesium and Compass Minerals have produced Mg products—magnesium metal and magnesium chloride, respectively. Compass Minerals produces K in the form of potassium sulfate. US Magnesium produced Li as a byproduct at the lake and Compass Minerals had planned to produce Li, but those plans are currently on hold. Recently, US Magnesium announced that it was idling its operations, so future production of Li and Mg at their facility is uncertain.

DATA SOURCES

Nearly all data used in this report come from the UGS's GSL brine chemistry database (https://geology.utah.gov/docs/xls/GSL_brine_chem_db.xlsx) that includes brine data from 1966 through the present. The database includes concentrations of the major ions in the lake brine: Na^{+}, Mg^{+2}, K^{+}, Ca^{+2}, Cl^{-}, and SO_4^{-2}; and concentrations of some trace elements including Br, Li, and B. Extensive Li data were collected from 1966 through 1998, but only a modest amount of Li data have been collected since then, intermittently and all after 2018. Based on discussions with labs and due to the challenges of analyzing brines, we estimate a minimum error of about 10% for most of the concentration data in the database.

Data from the south arm of GSL are primarily from UGS sample sites AS2, AC3, and FB2, and data from the north arm are primarily from sites LVG4, RD2, and SJ-1 (Figure 1). Recent Li data also include analyses from near surface sample sites at the Saltair Marina (south arm) and Black Rock (south arm).

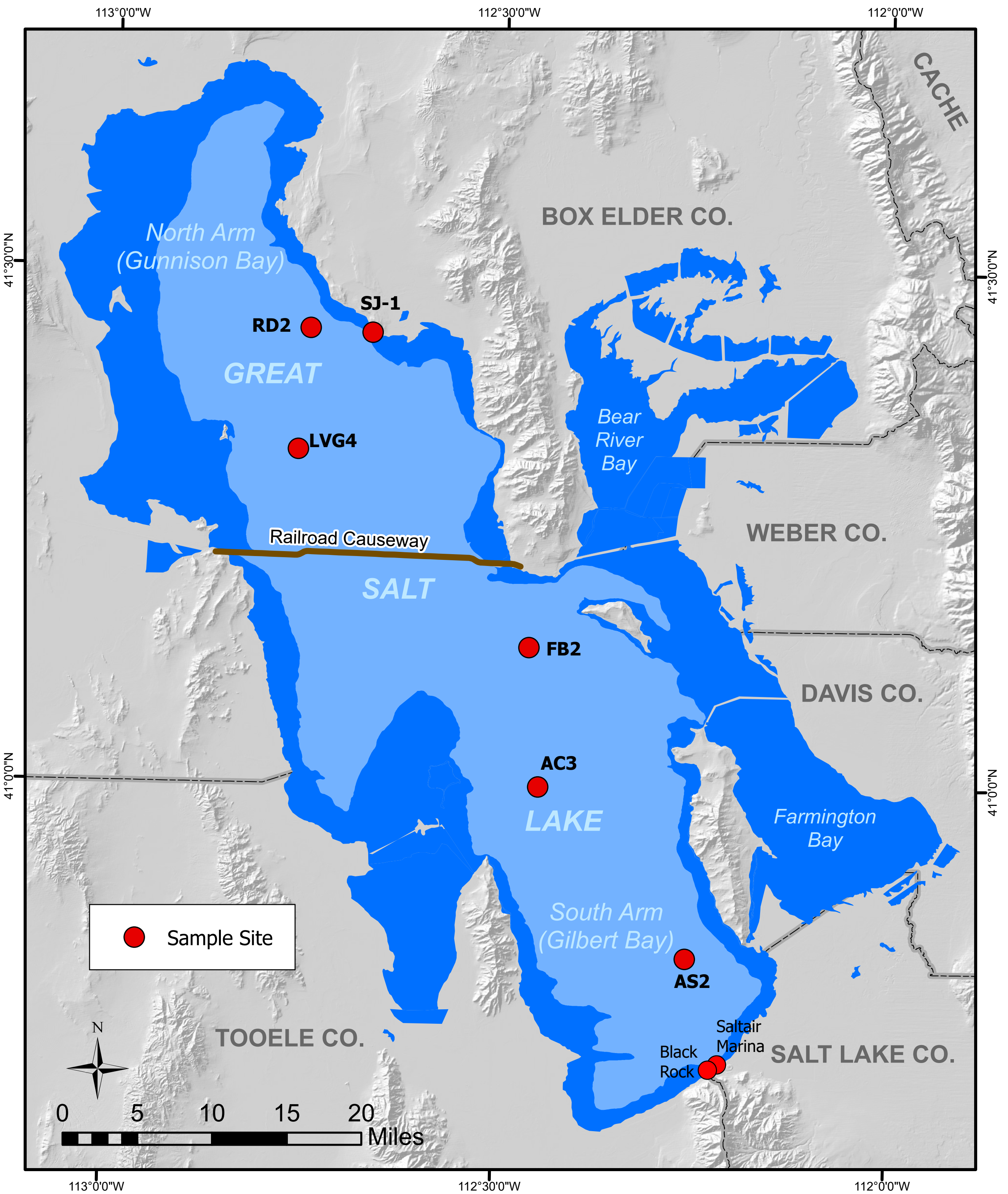

***Figure 1.** Sample collection sites at Great Salt Lake used in this study. Light blue indicates lake level at 4190 ft above sea level and dark blue is lake level at 4200 ft based on bathymetry from Baskin (2005, 2006).*

LITHIUM, MAGNESIUM, AND POTASSIUM CONCENTRATIONS

In the south arm of GSL, using selected data (over 1700 measurements), Li concentrations range from 3 to 52 mg/L based on measurements from 1968 through 2023, but in 1966 and 1967 concentrations up to 96 mg/L were measured (Figure 2). Concentrations of Li in the south arm most commonly range from 15 to 25 mg/L (Figure 3). The high Li concentrations in 1966 and 1967 likely reflect the fact that these early measurements were taken shortly after the lake was at a low point in 1963 and shortly after causeway construction so the lake was in the early stages of differentiation between arms. Around the time of the 1963 low, halite had precipitated throughout the lake, including in the south arm, leading to a more evolved brine than is typical of the south arm (Hedberg, 1970; Whelan, 1973). North arm Li concentrations range from 13 to 78 mg/L (over 750 measurements), but based on historical data, Li concentrations typically fall in the 45 to 60 mg/L range (Figures 2 and 3).

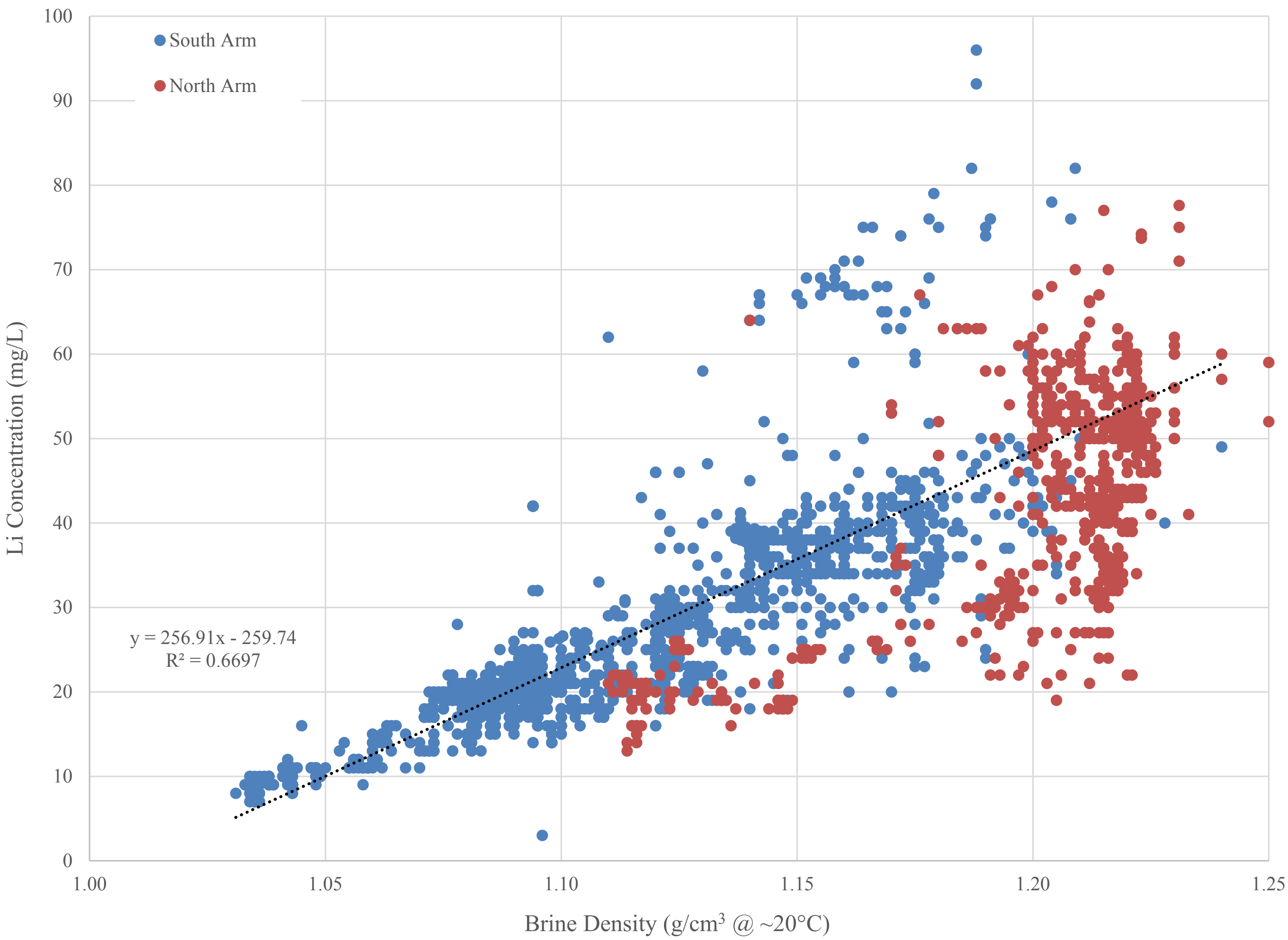

Figure 2. *Great Salt Lake brine density and Li concentration data from the north and south arms. Data are from 1966 through 1998 and from 2018 to 2023. Linear trendline is fit to the south arm data.*

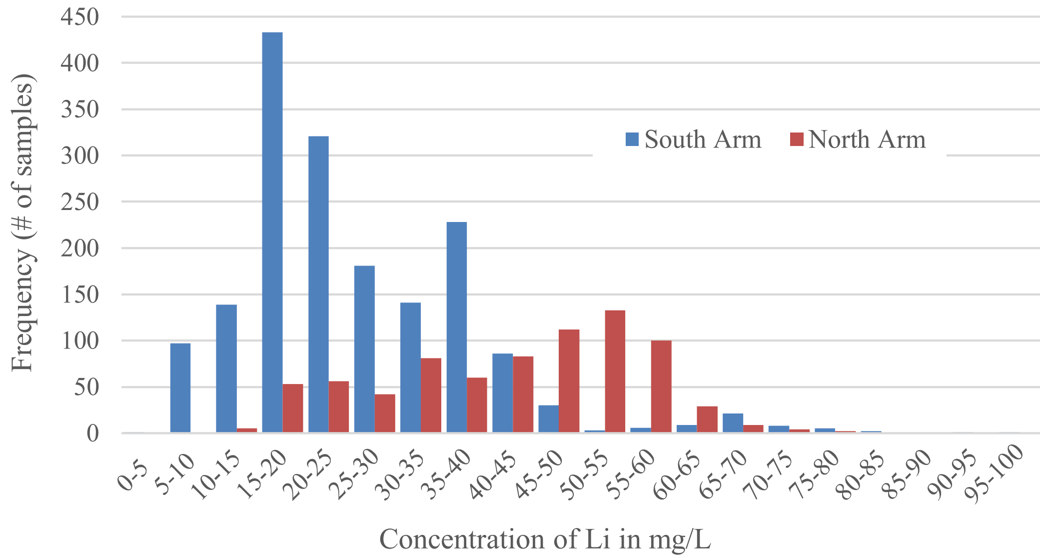

Figure 3. *Distribution of Li concentration range in the north and south arms. Data are from 1966 through 1998 and from 2018 to 2023.*

In the south arm of GSL, using selected data (over 2900 measurements), Mg concentrations range from 1.1 to 14.0 g/L based on measurements from 1966 through 2023 (Figure 4). However, concentrations of Mg in the south arm most commonly range from 4 to 6 g/L (Figure 5). North arm Mg concentrations range from about 5.2 to 16.8 g/L (nearly 1400 measurements), but Mg concentrations typically fall in the 8 to 14 g/L range (Figures 4 and 5).

In the south arm of GSL, using selected data (over 2900 measurements), K concentrations range from 1.0 to 9.5 g/L based on measurements from 1966 through 2023 (Figure 6). However, concentrations of K in the south arm most commonly range from 2 to 4 g/L (Figure 7). North arm K concentrations range from 2.6 to 13.8 g/L (nearly 1400 measurements), but K concentrations typically fall in the 5 to 9 g/L range (Figures 6 and 7).

A correlative relationship exists between various ions in GSL and brine density that is approximately linear until brine density begins to approach halite saturation (Figures 2, 4, 6, 8, 9, and 10). At lower densities (~1.0 to ~1.2 g/cm^3 at 20°C) there is a general increase in concentration of Li, Mg, and K as brine density increases; however, at higher densities the relationship changes. This changing relationship, most notable in data from the north arm, is likely a function of the brine approaching a state of saturation with respect to halite as it nears 1.2 g/cm^3 at 20°C (Jagniecki et al., 2021). When saturated, the brine density plateaus as halite precipitates; however, Li, Mg, K, and other ions remain in the brine and become more concentrated resulting in a continued increase in concentration. Concentration of Li in brine via halite precipitation has also been observed in other systems (Munk et al., 2018). Additional complications in the relationship between brine density and Li, Mg, and K concentrations in the north arm likely arise from other mineral phase changes that exist in the north arm such as mirabilite precipitation in the winter (Jagniecki et al., 2021). Given these differences between the north and south arms, the trendlines in Figures 2, 4, 6, 8, 9, and 10 are based on south arm data only. Additional data scatter that increases with density, even prior to reaching 1.2 g/cm^3, is likely a function of analytical difficulties with denser brines.

Similar, roughly linear, correlative relationships have been noted in the past (e.g., Handy, 1967; Hahl and Handy, 1969). The relationship between brine density and Li, Mg, and K was used to examine the evolution of the concentration of those ions in the south arm of the lake because density is one of the most reliable and repeatable measurements for characterizing brines (Great Salt Lake Salinity Advisory Committee, 2020; Bernau et al., 2023). Plate 1 illustrates how Li, Mg, and K concentrations in the south arm have changed relative to their respective linear trendlines. In general, concentrations through time for these ions tend to track with the linear trendline; however, some shifts over time are apparent. For instance, K concentrations appear to drop below the trend line in the 1980s through around 2015, but then track closer to the trend line in recent years. Although this may be a function of actual dynamics in the lake, it is notable that the UGS began using a different lab in 2013 which could contribute to the apparent change; lab differences could potentially apply to other shifts as well. Change over time in Li concentrations seems to be less significant, although concentrations seem to fall below the trendline in the 1980s, but track reasonably well with the trendline at other times. Additional investigation of these changes may be warranted in future work. Other dynamics to be considered regarding temporal shifts include: high water levels of the 1980s, brine removal during the West Desert Pumping Project (WDPP) (occurring from 1987 to 1989, an event that transferred a few hundred million tons of GSL salts to the West Desert [Loving et al., 2000]), causeway configurations (e.g., closure of culverts, opening of the new bridge, etc.), and salt cycle dynamics in the north arm as halite is precipitated and redissolved. An attempt was made to fit a trendline separately to north arm data and to data above about 1.2 g/cm^3 at 20°C, but the results were poor (low R^2 value) and did not produce meaningful relationships.

Also notable in the data for Li, Mg, and K is that concentrations from the north arm that are below saturation tend to fall below the trendlines (Figures 2, 4, and 6). When density in the north arm falls below saturation, significant amounts of sodium (Na) and chloride (Cl) are readily available and are returned to the north arm brine from dissolution of the halite crust on the north arm lake floor (Rupke et al., 2016; Jagniecki et al., 2021). This re-introduction of Na and Cl may suppress the relative concentrations of other ions (Li, Mg, K, and SO_4) until better mixing of the overall lake occurs. Notably, north arm concentrations of Na and Cl tend to be above their trendlines (although to a lesser degree because of their relative abundance) at densities below halite saturation (Figures 8 and 9) lending some credence to this theory.

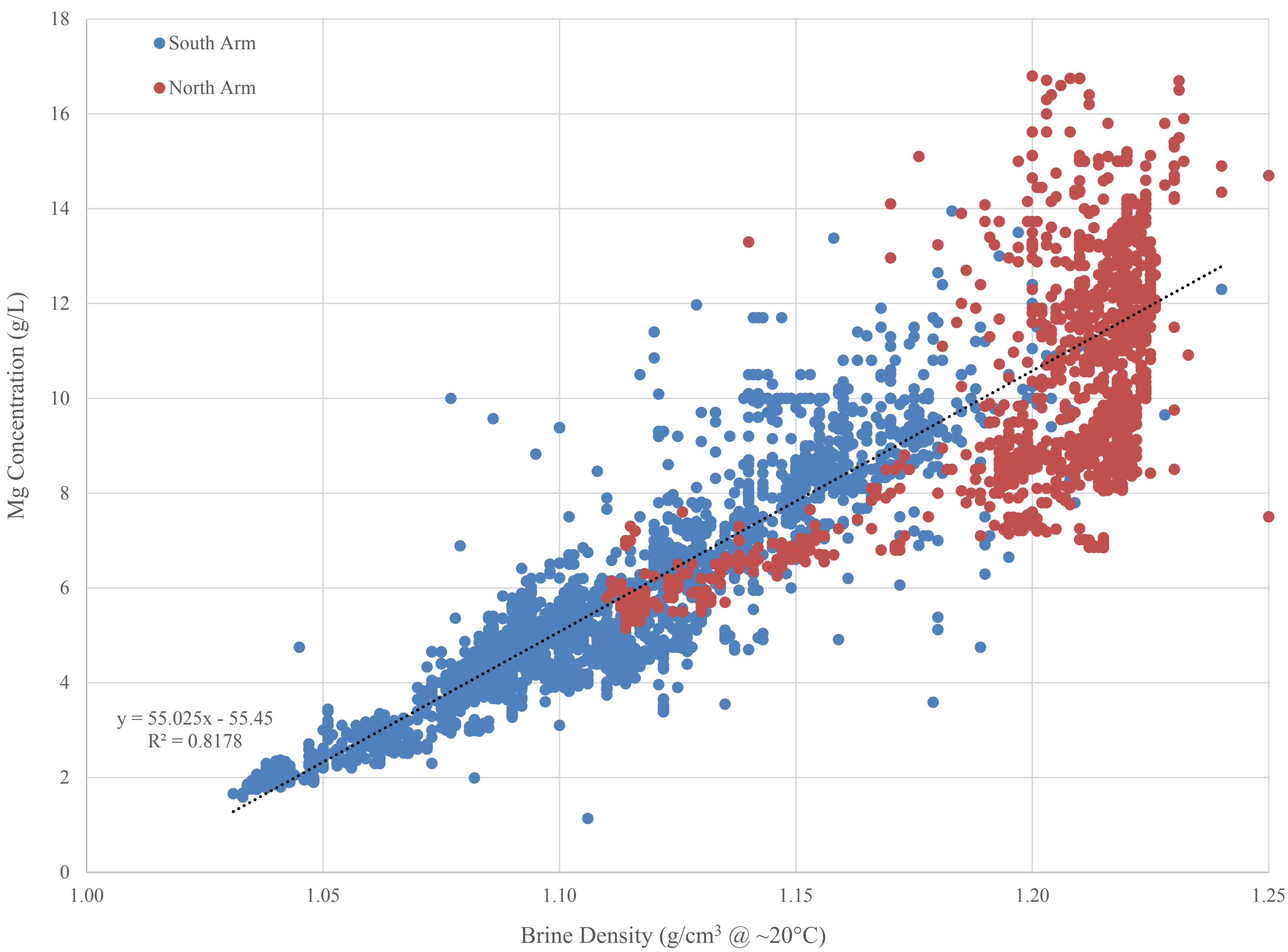

Figure 4. *Great Salt Lake brine density and Mg concentration data from the north and south arms. Data are from 1966 through 2023. Linear trendline is fit to the south arm data.*

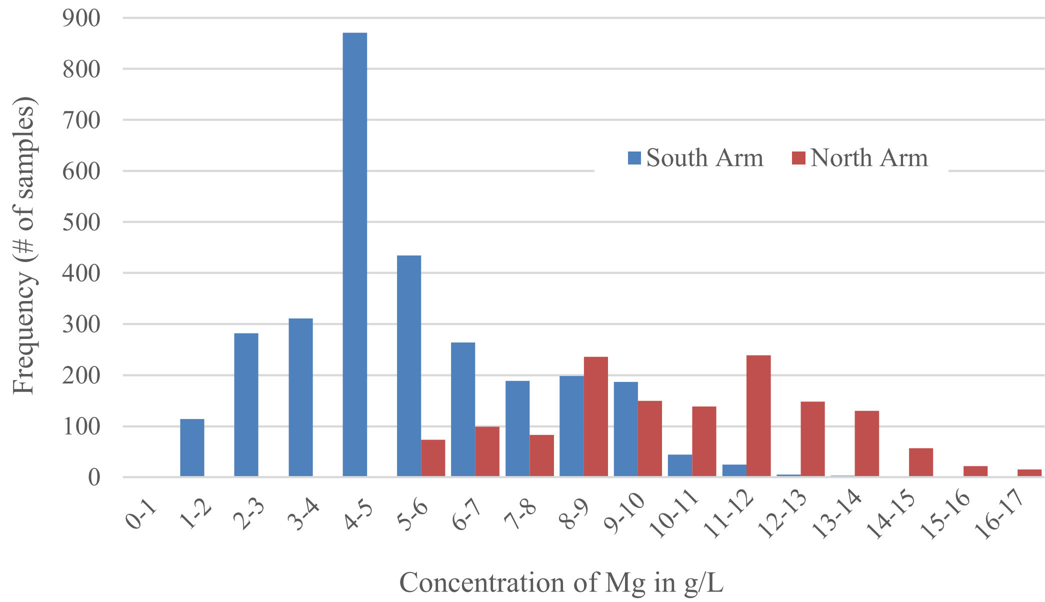

Figure 5. *Distribution of Mg concentration range in the north and south arms. Data are from 1966 through 2023.*

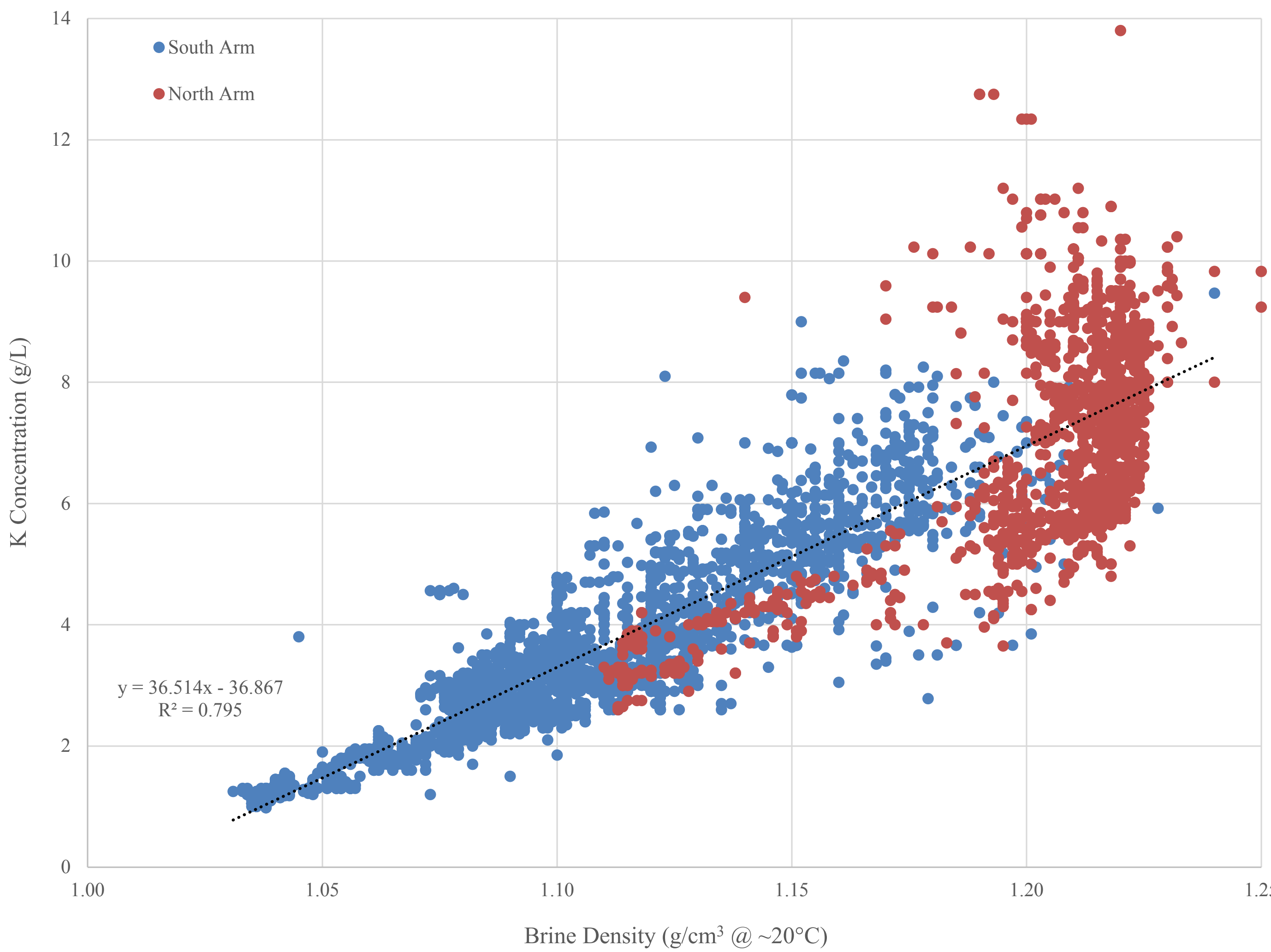

Figure 6. *Great Salt Lake brine density and K concentration data from the north and south arms. Data are from 1966 through 2023. Linear trendline is fit to the south arm data.*

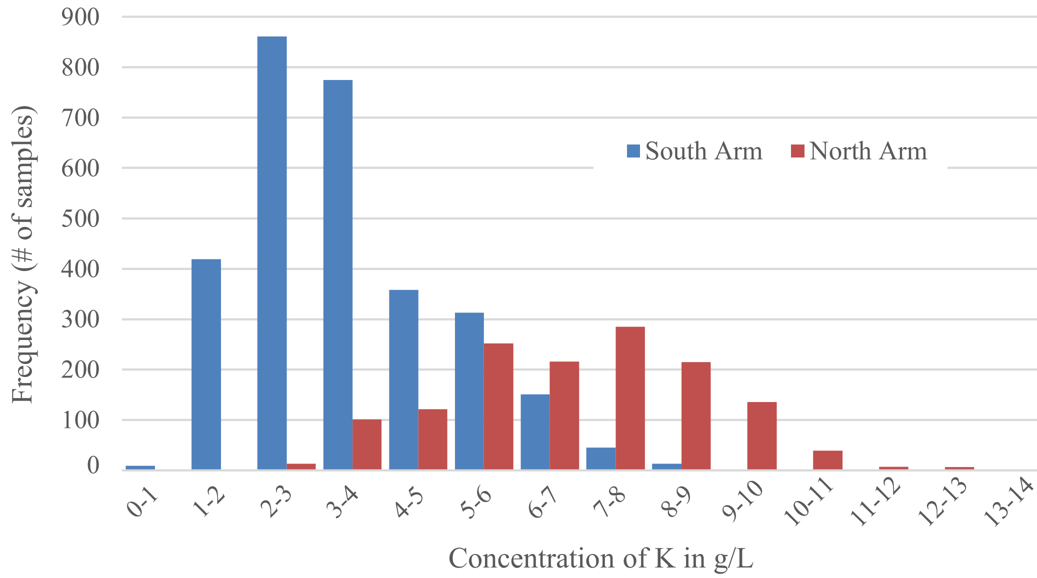

Figure 7. *Distribution of K concentration range in the north and south arms. Data are from 1966 through 2023.*

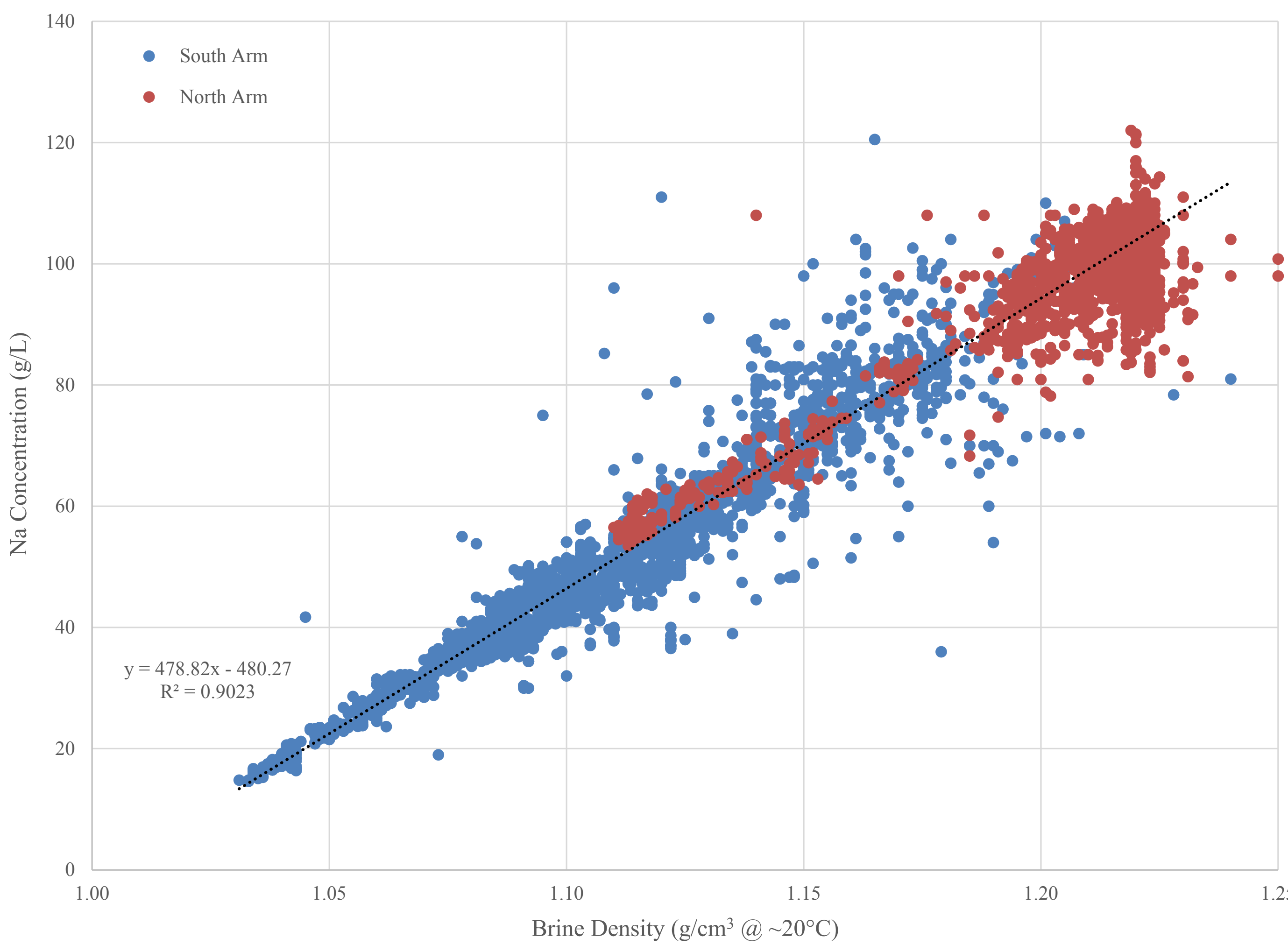

Figure 8. *Great Salt Lake brine density and Na concentration data from the north and south arms. Data are from 1966 through 2023. Linear trendline is fit to the south arm data.*

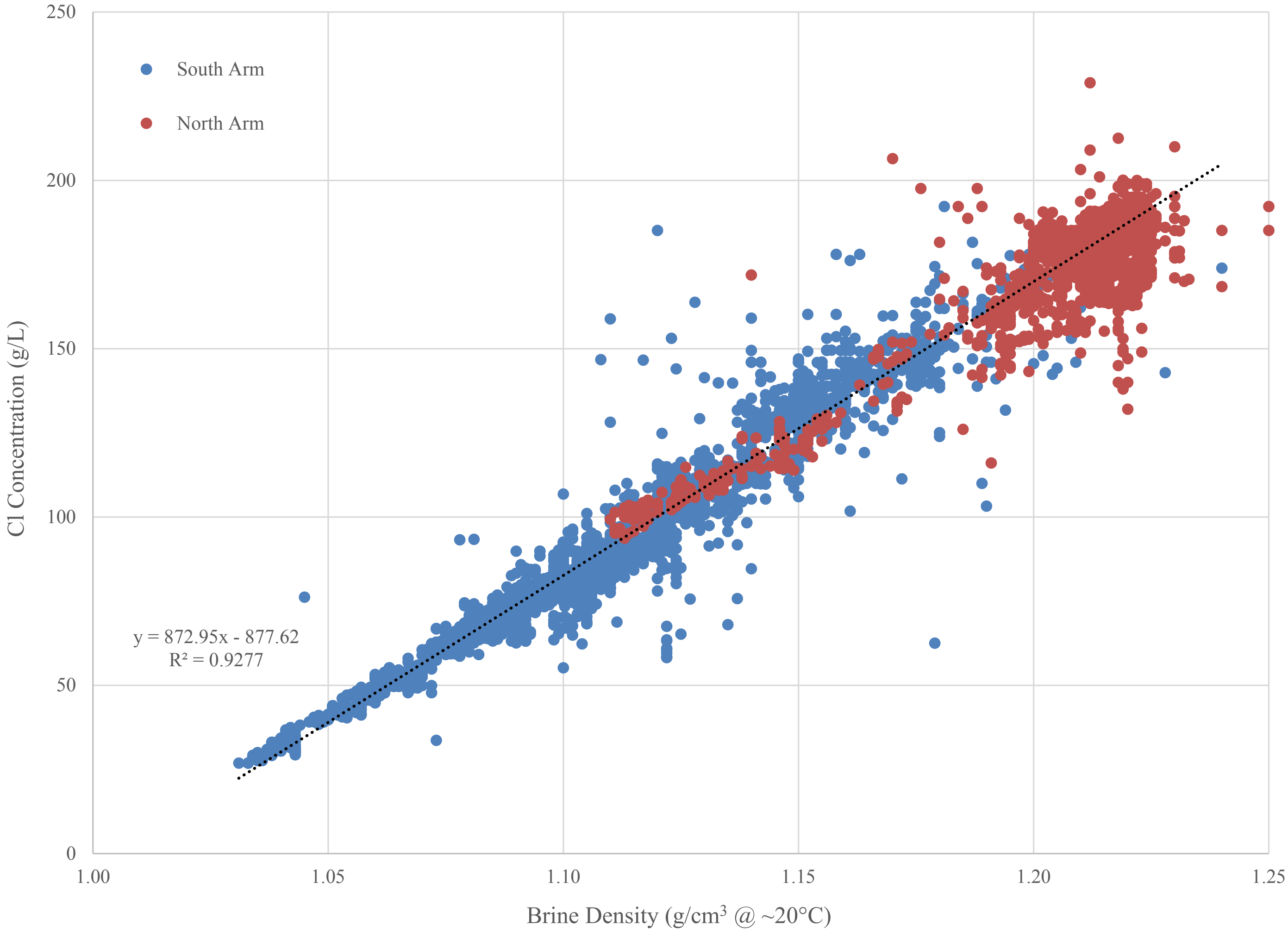

Figure 9. *Great Salt Lake brine density and Cl concentration data from the north and south arms. Data are from 1966 through 2023. Linear trendline is fit to the south arm data.*

LITHIUM, MAGNESIUM, AND POTASSIUM RESOURCE ESTIMATES

Several calculations of the in-place Li, Mg, and K resources (or masses) in GSL brine were completed (Table 1). The following equations were used to estimate the in-place resource:

Equation for Li resource:

$$([V_{SA} * LiC_{SA}] + [V_{NA} * LiC_{NA}])/(1*10^9) = LiR_{GSL}$$

where V_{SA} is the volume of the south arm (in L), LiC_{SA} is the Li concentration of the south arm (in mg/L), V_{NA} is the volume of the north arm (in L), LiC_{NA} is the Li concentration of the north arm (in mg/L), and LiR_{GSL} is the Li resource in the brine of the entire lake (in metric tons).

Equation for Mg and K resources:

$$([V_{SA} * (Mg,K)C_{SA}] + [V_{NA} * (Mg,K)C_{NA}])/(1*10^6) = (Mg,K)R_{GSL}$$

where V_{SA} is the volume of the south arm (in L), $(Mg,K)C_{SA}$ is the Mg or K concentration of the south arm (in g/L), V_{NA} is the volume of the north arm (in L), $(Mg,K)C_{NA}$ is the Mg or K concentration of the north arm (in g/L), and $(Mg,K)R_{GSL}$ is the Mg or K resource in the brine of the entire lake (in metric tons). The volumes used for these calculations are from Root (2023) who produced an updated set of volumetric calculations for GSL in National Geodetic Vertical Datum (NGVD) 1929.

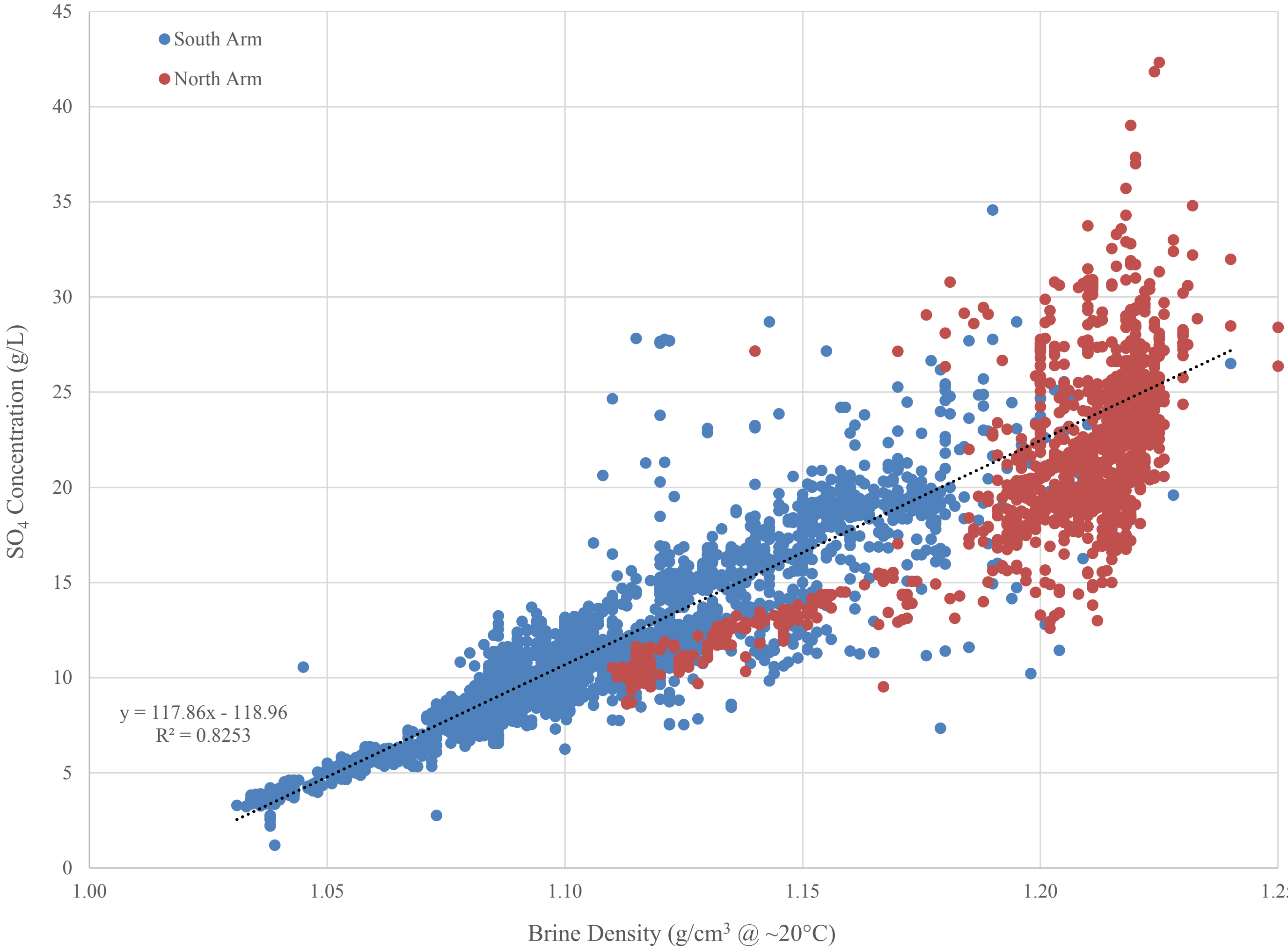

Figure 10. *Great Salt Lake brine density and SO_4 concentration data from the north and south arms. Data are from 1966 through 2023. Linear trendline is fit to the south arm data.*

This new dataset allowed for several additional resource calculations beyond those completed by Rupke (2024) which were limited to volumes at elevations equal to or below 4200 ft from older bathymetry provided by Baskin (2005, 2006). Potential sources of error in the resource calculations include analytical error (including those introduced by dilutions), error in the available bathymetry (particularly in the north arm due to changing halite crust volumes), data entry error from the UGS brine chemistry database, assumptions on temperature of density measurements from older analyses, and heterogeneity in the lake brine that was not captured in the available data.

The total in-place Li, Mg, and K resources within GSL brine were calculated in several instances when measurements of the particular ion concentration in the north and south arms were taken closely in time (typically less than one month apart). Li resources are reported as both Li and lithium carbonate equivalent (LCE), which presents Li content as Li_2CO_3 (achieved by multiplying Li by 5.323). For a given sampling date, the available concentration values were averaged to produce a single Li, Mg, or K value for each arm as representative for the sample date. If a deep brine layer (DBL) was present in the south arm, an average value was developed for both the upper brine and the DBL. Using an estimated elevation of the DBL based on sample profiles, the volume of the DBL was estimated using Root's (2023) data tables. The DBL volume was then subtracted from the total south arm volume based on lake surface elevation in order to estimate the volume of the upper brine layer. No stratification was taken into account for the north arm although, in a few instances, some stratification is present (see "Notes" column in Table 1). A limitation of the recent estimates is that, in some cases, only a few samples were taken to estimate average concentrations for each arm. For the north arm, robust recent sampling has been hampered by limited boat access.

***Table 1.** Li, Mg, and K resource (or mass) estimates for Great Salt Lake.*

South Arm (SA)															
Date	Decimal Date	Lake Level NGVD29 (ft)	DBL Level (ft)	SA Volume (liters)	Upper Brine Volume (liters)	DBL Volume (liters)	Mg Conc. Upper (g/L)	Mg Conc. DBL (g/L)	K Conc. Upper (g/L)	K Conc. DBL (g/L)	Li Conc. Upper (mg/L)	Li Conc. DBL (mg/L)	Mg Resource (metric t)	K Resource (metric t)	Li Resource (metric t)
6/16/1970	1970.46	4196.4	4173.4	9.55299E+12	8.83189E+12	7.21094E+11	6.58	10.82	4.32	6.77	24	42	65,916,098	43,035,588	242,251
8/25/1970	1970.65	4195.3	4170.8	8.94345E+12	8.68988E+12	2.53573E+11	7.20	9.63	4.30	5.60	28	43	65,009,028	38,786,483	254,220
3/16/1971	1971.21	4196.8	4171.8	9.78064E+12	9.36809E+12	4.12548E+11	6.09	7.83	4.19	5.82	25	30	60,281,936	41,653,339	246,579
11/3/1971	1971.84	4197.2	4172.2	1.0012E+13	9.52714E+12	4.84831E+11	5.49	8.49	4.34	6.54	21	33	56,420,204	44,518,575	216,069
5/10/1972	1972.36	4199.6	4174.6	1.14749E+13	1.04889E+13	9.85959E+11	4.65	8.06	3.66	6.00	16	31	56,720,194	44,305,112	198,387
8/16/1972	1972.63	4198.4	4173.4	1.07276E+13	1.00065E+13	7.21094E+11	4.58	9.59	4.01	7.41	16	37	52,745,143	45,469,443	186,785
6/19/1973	1973.47	4200.4	4175.4	1.19971E+13	1.082E+13	1.17714E+12	5.18	9.66	3.05	5.72	21	38	67,418,787	39,734,250	271,951
6/11/1974	1974.45	4201.3	4176.3	1.26099E+13	1.12059E+13	1.40404E+12	4.50	9.35	4.07	5.94	19	36	63,554,244	53,947,942	263,457
8/13/1974	1974.62	4199.9	4174.9	1.16657E+13	1.06092E+13	1.05644E+12	4.39	9.54	2.97	5.98	20	35	56,652,929	37,826,903	249,160
1/22/1975	1975.06	4199.6	4174.6	1.14749E+13	1.04889E+13	9.85959E+11	5.12	10.25	3.05	4.51	23	24	63,809,225	36,437,807	264,908
6/15/1975	1975.46	4201.6	4176.6	1.28176E+13	1.13353E+13	1.48227E+12	4.04	8.23	2.99	5.57	20	37	57,993,886	42,148,933	281,551
10/15/1975	1975.79	4199.9	4174.9	1.16657E+13	1.06092E+13	1.05644E+12	4.46	9.24	3.12	7.00	21	41	57,078,641	40,495,859	266,108
6/18/1976	1976.47	4202.0	4177.0	1.30966E+13	1.15079E+13	1.58874E+12	3.83	7.68	2.88	6.17	17	38	56,276,829	42,945,316	256,007
8/16/1976	1976.63	4200.9	4175.9	1.23359E+13	1.10341E+13	1.30173E+12	4.17	9.04	2.82	6.56	20	41	57,780,004	39,655,625	274,054
5/31/1977	1977.42	4200.7	4175.7	1.22E+13	1.09486E+13	1.25144E+12	4.19	9.08	3.04	6.58	15	33	57,237,745	41,518,245	205,527
8/23/1977	1977.65	4199.3	4174.3	1.12854E+13	1.03682E+13	9.1723E+11	4.68	9.18	2.80	5.86	18	35	56,943,220	34,405,852	218,730
7/6/1978	1978.52	4199.7	4174.7	1.15384E+13	1.05291E+13	1.00929E+12	4.64	8.83	2.96	5.52	19	34	57,766,961	36,737,357	234,368
10/6/1978	1978.77	4198.5	4173.5	1.07888E+13	1.00E+13	7.42063E+11	5.01	8.68	3.54	5.93	18	32	56,775,438	39,966,009	204,588
5/22/1979	1979.39	4199.9	4174.9	1.16657E+13	1.06E+13	1.05644E+12	5.14	9.72	2.70	5.51	18	30	64,800,000	34,465,887	222,659
11/1/1979	1979.84	4197.6	4172.6	1.02468E+13	9.68658E+12	5.60177E+11	5.74	9.02	3.96	6.04	25	36	60,653,791	41,742,343	262,331
6/8/1980	1980.44	4200.3	4175.3	1.19299E+13	1.07772E+13	1.1527E+12	4.33	7.46	3.00	5.19	20	32	55,264,461	38,314,143	252,431
11/5/1980	1980.85	4199.1	4174.1	1.11603E+13	1.02879E+13	8.72394E+11	4.73	7.79	3.22	5.09	25	39	55,457,686	37,567,503	291,221
6/1/1981	1981.42	4200.1	4175.1	1.17964E+13	1.06921E+13	1.10435E+12	4.55	7.66	2.91	4.94	20	31	57,108,216	36,569,398	248,076
8/29/1981	1981.66	4198.6	4173.6	1.08503E+13	1.0087E+13	7.63247E+11	5.33	9.69	3.32	5.95			61,159,727	38,030,255	-
6/2/1982	1982.42	4200.7	4172.7	1.22E+13	1.16204E+13	5.79603E+11	4.25	6.72	3.33	5.85	19	31	53,281,803	42,086,743	238,756
11/14/1982	1982.87	4200.7	4171.2	1.22E+13	1.18864E+13	3.13681E+11	4.08	7.64	2.58	5.27	18	27	50,892,881	32,319,914	222,424
7/13/1983	1983.54	4204.7	4174.7	1.50826E+13	1.40733E+13	1.00929E+12	2.94	5.08	1.89	3.66	14	24	46,502,593	30,292,472	221,249
12/7/1983	1983.94	4205.3	4170.3	1.55408E+13	1.53545E+13	1.86321E+11	2.90	6.64	1.91	4.60	11	26	45,765,176	30,184,142	173,744
7/12/1984	1984.53	4208.9	4178.9	1.83522E+13	1.62253E+13	2.12691E+12	1.93	3.74	1.21	2.32	11	16	39,269,505	24,567,065	212,509
11/15/1984	1984.87	4208.1	4178.1	1.7721E+13	1.58274E+13	1.8936E+12	2.17	5.02	1.37	3.30	10	18	43,851,305	27,932,402	192,359
6/4/1985	1985.43	4209.8	4179.8	1.90644E+13	1.66629E+13	2.40143E+12	1.83	5.53	1.20	3.59	8	18	43,773,091	28,616,663	176,529
10/29/1985	1985.83	4208.1	4183.1	1.7721E+13	1.42136E+13	3.50741E+12	2.20	5.08	1.27	3.53	9	17	49,087,513	30,432,400	187,548
2/20/1986	1986.14	4209.5	4184.5	1.88269E+13	1.48052E+13	4.02173E+12	1.94	5.04	1.27	3.30			48,991,576	32,074,293	
6/18/1986	1986.47	4211.2	4186.2	2.01762E+13	1.5493E+13	4.68326E+12	1.82	5.54	1.13	3.09	9	18	54,142,503	31,978,351	223,736
6/10/1987	1987.44	4211.2	4186.2	2.01762E+13	1.5493E+13	4.68326E+12	2.10	5.94	1.17	3.28	9	19	60,353,843	33,487,891	228,419
3/3/1988	1988.17	4209.1	4184.1	1.85105E+13	1.46385E+13	3.87199E+12	2.38	5.24	1.35	3.18	11	17	55,128,837	32,074,891	226,847
12/20/1988	1988.97	4205.9	4175.9	1.60026E+13	1.47009E+13	1.30173E+12	2.92	5.56	1.68	3.13			50,164,256	28,771,932	
5/3/1989	1989.34	4206.1	4181.1	1.61574E+13	1.33386E+13	2.81877E+12	2.95	5.16	1.79	3.03	15	23	53,893,666	32,416,933	264,910
8/8/1990	1990.61	4202.5	4172.5	1.34499E+13	1.29089E+13	5.41005E+11	4.13	5.05	2.32	3.00			56,045,903	31,571,703	
6/26/1991	1991.49	4202.0	4172.0	1.30966E+13	1.26484E+13	4.48281E+11	3.97	4.63	2.27	2.58	19	21	52,289,559	29,868,359	249,733
12/4/1991	1991.93	4200.5		1.20646E+13	1.20646E+13		4.07		2.52				49,102,834	30,402,738	
6/2/1992	1992.42	4200.8		1.22677E+13	1.22677E+13		4.19		2.68		15		51,401,691	32,877,454	184,016
4/1/1993	1993.25	4200.2		1.18632E+13	1.18632E+13		5.00		3.05		19		59,316,083	36,182,810	225,401
6/9/1994	1994.44	4199.9		1.16657E+13	1.16657E+13		4.39		2.77		18		51,212,241	32,313,874	209,982
1/1/1995	1995.00	4200.2		1.18632E+13	1.18632E+13		4.98		2.57		21		59,078,818	30,488,467	249,128
11/14/1995	1995.87	4198.4		1.07276E+13	1.07276E+13		4.81		2.93				51,599,815	31,431,904	
7/12/1996	1996.53	4199.9		1.16657E+13	1.16657E+13		4.20		2.41		16		48,995,766	28,114,237	186,651
7/9/1997	1997.52	4201.1		1.24727E+13	1.24727E+13		3.77		2.11		14		47,022,094	26,317,405	174,618

Table 1 Continued. *Li, Mg, and K resource (or mass) estimates for Great Salt Lake.*

South Arm (SA)															
Date	**Decimal Date**	**Lake Level NGVD29 (ft)**	**DBL Level (ft)**	**SA Volume (liters)**	**Upper Brine Volume (liters)**	**DBL Volume (liters)**	**Mg Conc. Upper (g/L)**	**Mg Conc. DBL (g/L)**	**K Conc. Upper (g/L)**	**K Conc. DBL (g/L)**	**Li Conc. Upper (mg/L)**	**Li Conc. DBL (mg/L)**	**Mg Resource (metric t)**	**K Resource (metric t)**	**Li Resource (metric t)**
11/7/1997	1997.85	4200.0		1.17298E+13	1.17298E+13		3.19		2.23				37,418,103	26,157,483	
7/30/1998	1998.58	4202.7	4174.7	1.35931E+13	1.25838E+13	1.00929E+12	2.93	3.13	1.85	2.03	12	13	40,029,496	25,328,816	164,126
10/28/1998	1998.83	4202.0		1.30966E+13	1.30966E+13		2.39		1.81				31,300,990	23,704,934	
7/22/1999	1999.56	4203.6	4168.6	1.42541E+13	1.42265E+13	27584442830	2.32	3.80	1.31	2.10			33,110,316	18,694,651	-
11/4/1999	1999.84	4202.3	4172.3	1.33078E+13	1.28045E+13	5.03302E+11	2.32	3.22	1.32	1.70			31,327,171	17,757,610	
8/22/2000	2000.64	4201.4	4171.4	1.2679E+13	1.23338E+13	3.45226E+11	2.58	3.42	1.68	2.35			33,001,804	21,532,018	-
11/30/2000	2000.92	4201.1	4176.1	1.24727E+13	1.20946E+13	3.78072E+11	2.57	3.27	1.68	2.20			32,319,499	21,150,740	
5/10/2001	2001.36	4201.3	4171.3	1.26099E+13	1.22806E+13	3.29282E+11	2.62	3.98	1.76	2.86			33,485,824	22,555,676	
7/18/2001	2001.55	4200.4	4175.4	1.19971E+13	1.082E+13	1.17714E+12	2.64	3.59	1.91	2.55			32,790,736	23,667,910	-
2/20/2002	2002.14	4199.3	4171.3	1.12854E+13	1.09561E+13	3.29282E+11	3.13	4.13	2.13	2.75			35,652,592	24,242,062	
7/12/2002	2002.53	4198.8	4170.8	1.09735E+13	1.07199E+13	2.53573E+11	3.69	4.90	2.38	3.25			40,799,009	26,337,519	-
2/26/2003	2003.15	4197.7	4172.7	1.03061E+13	9.7265E+12	5.79603E+11	4.11	4.81	2.39	2.90			42,763,799	24,927,180	-
6/6/2003	2003.43	4197.4	4177.4	1.01288E+13	8.43134E+12	1.69742E+12	4.33	5.14	2.58	2.86			45,232,448	26,607,482	
2/12/2004	2004.12	4195.5		9.05265E+12	9.05265E+12		4.71		2.98				42,637,976	26,976,893	
7/14/2004	2004.54	4195.2	4170.2	8.8894E+12	8.7154E+12	1.73996E+11	4.41	5.04	3.11	3.85			39,311,862	27,774,784	-
3/11/2005	2005.20	4195.6	4175.6	9.10753E+12	7.88104E+12	1.2265E+12	4.43	4.71	3.10	3.20			40,689,782	28,355,996	-
8/4/2005	2005.59	4196.6	4171.6	9.66654E+12	9.28847E+12	3.78072E+11	4.08	4.30	2.98	3.20			39,522,649	28,889,457	
1/10/2006	2006.03	4196.0	4170.0	9.3287E+12	9.17861E+12	1.5009E+11	4.45	5.95	3.22	4.20			41,737,870	30,185,517	
6/12/2006	2006.45	4198.0	4171.0	1.04853E+13	1.02022E+13	2.83104E+11	4.01	5.44	2.64	3.70			42,450,778	27,981,208	-
3/9/2007	2007.19	4197.3	4173.3	1.00701E+13	9.36979E+12	7.00316E+11	4.24	5.05	2.65	3.50			43,264,492	27,281,041	-
6/20/2011	2011.47	4198.4	4172.4	1.07276E+13	1.02056E+13	5.22053E+11	3.54	3.55	2.15	2.55			37,980,968	23,273,187	-
11/9/2011	2011.86	4197.6	4169.6	1.02468E+13	1.01407E+13	1.06032E+11	3.68	4.84	2.72	4.10			37,831,080	28,017,516	
7/19/2012	2012.55	4197.4	4173.4	1.01288E+13	9.40767E+12	7.21094E+11	3.69	4.20	2.77	3.48			37,742,887	28,568,646	-
10/23/2013	2013.81	4194.3	4171.3	8.40954E+12	8.08026E+12	3.29282E+11	4.97	6.52	3.00	3.71			42,305,790	25,462,404	-
10/23/2014	2014.81	4193.4		7.94716E+12	7.94716E+12		4.97		3.34				39,497,364	26,543,500	-
4/29/2015	2015.33	4194.0		8.25353E+12	8.25353E+12		4.74		3.02				39,121,747	24,925,670	-
5/23/2016	2016.40	4194.2		8.35749E+12	8.35749E+12		5.16		3.07				43,124,625	25,657,481	
10/13/2016	2016.79	4192.3		7.4009E+12	7.4009E+12		5.38		3.26				39,816,842	24,126,934	
5/11/2017	2017.36	4195.3	4171.8	8.94345E+12	8.5309E+12	4.12548E+11	3.83	4.39	2.52	2.83			34,484,443	22,665,385	
8/24/2017	2017.65	4193.8		8.15049E+12	8.15049E+12		4.71		2.73				38,388,807	22,250,837	-
9/18/2018	2018.72	4192.4	4172.4	7.45002E+12	6.92797E+12	5.22053E+11	5.28	7.49	3.19	4.36			40,489,860	24,376,376	-
9/12/2019	2019.70	4193.3	4169.3	7.89674E+12	7.81883E+12	77914398250	5.29	8.12	2.98	4.41	20	20	41,994,261	23,643,707	157,935
9/23/2020	2020.73	4192.6	4172.6	7.54857E+12	6.98839E+12	5.60177E+11	5.33	6.03	3.39	3.82			40,625,999	25,830,526	-
5/25/2021	2021.40	4192.4	4169.9	7.45002E+12	7.31146E+12	1.38563E+11	5.41	7.73	3.55	5.00			40,626,092	26,648,499	-
9/15/2021	2021.71	4190.7	4170.7	6.63722E+12	6.39789E+12	2.39326E+11	6.46	8.13	3.89	4.75			43,276,084	26,024,587	-
5/5/2022	2022.35	4190.9		6.73023E+12	6.73023E+12		6.19		3.75				41,660,116	25,238,358	-
2/7/2023	2023.10	4190.0		6.31484E+12	6.31484E+12		7.27		4.28		29		45,908,907	27,027,527	183,130
3/28/2023	2023.24	4191.1		6.82389E+12	6.82389E+12		6.33		3.84		22		43,195,211	26,203,730	150,126
5/31/2023	2023.42	4193.8	4176.0	8.15049E+12	6.82334E+12	1.32715E+12	5.12	6.03	3.07	3.62	26	30	42,938,214	25,751,936	217,221
8/29/2023	2023.66	4192.7		7.598E+12	7.598E+12		5.80		3.38		27		44,068,418	25,681,251	205,146
10/17/2023	2023.80	4192.2		7.3521E+12	7.3521E+12		6.02		3.44		25		44,259,671	25,291,241	183,803
11/21/2023	2023.89	4192.2		7.3521E+12	7.3521E+12		5.37		2.97		24		39,480,803	21,835,752	173,510
Reproduction of Havasi (2022) calculations:															
9/1/2021	2021.67	4194.4		8.21291E+12	8.21291E+12				3.06		25		-	25,131,515	205,323
9/1/2021	2021.67	4194.4		8.46206E+12	8.46206E+12				3.06		25		-	25,893,904	211,552

Table 1 Continued. *Li, Mg, and K resource (or mass) estimates for Great Salt Lake.*

										Lake Totals				
North Arm (NA)														
Date	Decimal Date	Lake Level NGVD29 (ft)	NA Volume (liters)	Mg Conc. (g/L)	K Conc. (g/L)	Li Conc. (mg/L)	Mg Resource (metric t)	K Resource (metric t)	Li Resource (metric t)	Mg Resource (million m t)	K Resource (million m t)	Li Resource (thousand m t)	LCE Resource (thousand m t)	Notes
6/19/1970	1970.47	4195.2	5.00783E+12	14.40	9.30	54	72,112,773	46,572,833	270,423	138	90	513	2729	
8/4/1970	1970.59	4195.0	4.93758E+12	13.63	9.35	58	67,299,234	46,166,386	286,380	132	85	541	2878	
3/29/1971	1971.25	4195.8	5.22495E+12	14.63	11.84	56	76,441,082	61,863,459	292,597	137	104	539	2870	
11/9/1971	1971.86	4196.1	5.3367E+12	13.24	10.12	49	70,657,881	54,007,383	261,498	127	99	478	2542	
4/21/1972	1972.31	4197.9	6.05306E+12	11.60	8.83	49	70,215,531	53,448,547	296,600	127	98	495	2635	
8/18/1972	1972.63	4197.3	5.80505E+12	12.44	9.52	47	72,214,805	55,264,063	272,837	125	101	460	2447	omitted some erroneous Mg values
6/20/1973	1973.47	4198.7	6.39447E+12	13.21	7.78	52	84,470,985	49,748,998	332,513	152	89	604	3218	
6/12/1974	1974.45	4199.3	6.65804E+12	11.89	8.02	42	79,164,107	53,397,488	279,638	143	107	543	2891	
8/21/1974	1974.64	4198.5	6.30815E+12	11.75	9.40	50	74,120,809	59,296,647	315,408	131	97	565	3005	
1/29/1975	1975.08	4198.3	6.22233E+12	12.24	9.20	50	76,161,327	57,245,442	311,117	140	94	576	3066	
6/20/1975	1975.47	4199.2	6.61362E+12	10.77	7.30	55	71,228,662	48,279,408	363,749	129	90	645	3435	omitted an erroneous Mg value
10/10/1975	1975.78	4198.8	6.48168E+12	11.51	8.46	51	74,604,101	54,834,986	330,566	132	95	597	3176	
6/9/1976	1976.44	4200.2	7.06447E+12	10.41	8.42	52	73,541,181	59,482,877	367,353	130	102	623	3318	
8/19/1976	1976.64	4199.7	6.83719E+12	11.05	8.77	55	75,550,926	59,962,137	376,045	133	100	650	3460	
6/3/1977	1977.42	4199.4	6.70264E+12	10.82	7.35	40	72,522,573	49,264,409	268,106	130	91	474	2521	
8/26/1977	1977.65	4198.4	6.26515E+12	11.33	7.21	44	70,984,139	45,171,725	275,667	128	80	494	2632	
6/21/1978	1978.47	4198.5	6.30815E+12	10.86	7.21	42	68,506,552	45,481,790	264,942	126	82	499	2658	
10/27/1978	1978.82	4197.3	5.80505E+12	11.96	8.68	48	69,428,381	50,387,822	278,642	126	90	483	2572	
5/15/1979	1979.37	4198.4	6.26515E+12	11.88	7.16	40	74,429,971	44,858,467	250,606	139	79	473	2519	
10/17/1979	1979.80	4196.7	5.5659E+12	12.28	8.49	49	68,349,266	47,254,501	272,729	129	89	535	2848	
6/18/1980	1980.47	4198.5	6.30815E+12	10.81	8.60	44	68,191,144	54,250,124	277,559	123	93	530	2821	
10/31/1980	1980.83	4197.8	6.01115E+12	11.48	7.72	51	69,008,029	46,406,096	306,569	124	84	598	3182	
6/2/1981	1981.42	4198.7	6.39447E+12	11.30	7.71	43	72,257,542	49,301,385	274,962	129	86	523	2784	
9/11/1981	1981.70	4197.4	5.84585E+12	12.21	9.50		71,377,828	55,535,575	-	133	94			
6/7/1982	1982.44	4198.7	6.39447E+12	10.97	8.48	44	70,147,366	54,225,129	281,357	123	96	520	2769	
11/12/1982	1982.87	4198.8	6.43799E+12	10.84	7.27	33	69,787,795	46,804,176	212,454	121	79	435	2315	
7/12/1983	1983.53	4201.7	7.76636E+12	9.41	5.80	31	73,081,460	45,044,896	240,757	120	75	462	2459	
12/16/1983	1983.96	4203.0	8.40195E+12	9.59	6.33	31	80,574,680	53,184,330	260,460	126	83	434	2311	
7/13/1984	1984.54	4205.6	9.74273E+12	8.50	5.16	26	82,813,188	50,272,477	253,311	122	75	466	2480	
11/16/1984	1984.88	4207.4	1.07243E+13	7.63	5.04	26	81,826,507	54,050,537	278,832	126	82	471	2508	
6/6/1985	1985.43	4209.3	1.1822E+13	7.12	4.68	20	84,172,696	55,326,997	236,440	128	84	413	2198	NA has some stratification
10/30/1985	1985.83	4207.8	1.09508E+13	7.36	4.86	19	80,597,910	53,220,903	208,065	130	84	396	2106	NA has some stratification
2/27/1986	1986.16	4209.1	1.17051E+13	6.60	4.52		77,253,438	52,906,900	-	126	85			NA has some stratification
6/17/1986	1986.46	4211.0	1.28243E+13	6.67	3.69	21	85,538,369	47,321,826	269,311	140	79	493	2624	
6/9/1987	1987.44	4211.0	1.28243E+13	6.28	3.53	22	80,536,875	45,269,931	282,136	141	79	511	2718	NA has some stratification (minor)
3/3/1988	1988.17	4209.0	1.16465E+13	5.98	4.11	17	69,646,166	47,867,181	197,991	125	80	425	2261	
12/12/1988	1988.95	4205.8	9.84873E+12	6.01	3.68		59,190,886	36,243,338		109	65			
5/2/1989	1989.34	4206.0	9.95544E+12	6.75	3.60	26	67,199,251	35,839,601	258,842	121	68	524	2788	NA has some stratification
7/10/1990	1990.53	4203.2	8.5019E+12	6.86	4.11		58,323,058	34,942,823		114	67			
6/12/1991	1991.45	4201.6	7.7188E+12	7.04	4.36	35	54,340,381	33,653,986	270,158	107	64	520	2767	
12/12/1991	1991.95	4199.8	6.88242E+12	8.19	4.56		56,366,980	31,383,813		105	62			
6/2/1992	1992.42	4199.6	6.79233E+12	8.56	4.96	30	58,142,348	33,689,959	203,770	110	67	388	2064	
4/27/1993	1993.32	4198.0	6.09517E+12	9.25	5.29	32	56,380,279	32,243,425	195,045	116	68	420	2238	
6/22/1994	1994.48	4197.8	6.01115E+12	9.50	5.60	35	57,105,947	33,662,453	210,390	108	66	420	2238	
8/3/1995	1995.59	4198.1	6.13745E+12	9.85	5.86	39	60,453,864	35,965,446	239,360	120	66	488	2600	omitted one erroneously low Li value
11/8/1995	1995.86	4197.1	5.72439E+12	10.23	6.53		58,560,543	37,380,288		110	69			
7/26/1996	1996.57	4198.0	6.09517E+12	9.36	5.74	36	57,050,748	34,986,249	219,426	106	63	406	2162	
7/8/1997	1997.52	4199.0	6.52554E+12	9.53	5.79	36	62,188,424	37,782,894	234,920	109	64	410	2180	

Table 1 Continued. *Li, Mg, and K resource (or mass) estimates for Great Salt Lake.*

North Arm (NA)										Lake Totals				
Date	**Decimal Date**	**Lake Level NGVD29 (ft)**	**NA Volume (liters)**	**Mg Conc. (g/L)**	**K Conc. (g/L)**	**Li Conc. (mg/L)**	**Mg Resource (metric t)**	**K Resource (metric t)**	**Li Resource (metric t)**	**Mg Resource (million m t)**	**K Resource (million m t)**	**Li Resource (thousand m t)**	**LCE Resource (thousand m t)**	**Notes**
11/5/1997	1997.85	4199.0	6.52554E+12	9.80	6.04		63,950,321	39,414,279		101	66		-	
7/31/1998	1998.58	4202.0	7.91069E+12	8.81	4.39	34	69,693,209	34,727,944	268,964	110	60	433	2305	
11/13/1998	1998.87	4201.6	7.7188E+12	8.35	5.47		64,452,015	42,221,859		96	66			
7/21/1999	1999.56	4203.1	8.45197E+12	8.56	5.10		72,348,896	43,105,067	-	105	62			
11/10/1999	1999.86	4201.9	7.86234E+12	8.51	5.48		66,908,485	43,085,605		98	61			
9/29/2000	2000.75	4200.8	7.3418E+12	8.44	6.12		61,964,822	44,931,838	-	95	66			
12/5/2000	2000.93	4200.5	7.20266E+12	6.94	5.72		49,986,448	41,199,205		82	62			
5/9/2001	2001.36	4200.8	7.3418E+12	7.26	5.41		53,301,494	39,719,157		87	62			
7/2/2001	2001.51	4200.2	7.06447E+12	7.45	5.46		52,630,336	38,572,032	-	85	62			
2/21/2002	2002.14	4198.9	6.48168E+12	7.97	5.75		51,658,965	37,269,642		87	62			excluded a strange Mg value
7/26/2002	2002.57	4198.0	6.09517E+12	8.13	5.93		49,553,694	36,144,330	-	90	62			
3/13/2003	2003.20	4197.2	5.76449E+12	8.51	6.18		49,055,835	35,624,567	-	92	61			
6/27/2003	2003.49	4196.5	5.48859E+12	8.75	6.24		48,025,144	34,248,788		93	61			
2/5/2004	2004.10	4195.1	4.97266E+12	9.06	6.73		45,052,318	33,466,016		88	60			
7/16/2004	2004.54	4194.7	4.83376E+12	8.43	6.93		40,748,623	33,497,979	-	80	61			
3/31/2005	2005.25	4195.0	4.93758E+12	8.97	6.77		44,290,105	33,427,426	-	85	62			
7/21/2005	2005.56	4196.2	5.3742E+12	9.36	6.69		50,302,480	35,953,375		90	65			
1/6/2006	2006.02	4195.2	5.00783E+12	8.76	7.12		43,868,604	35,655,760		86	66			
6/27/2006	2006.49	4196.9	5.64459E+12	8.83	6.39		49,841,692	36,068,903	-	92	64			
3/15/2007	2007.21	4196.6	5.52717E+12	8.90	6.54		49,191,854	36,147,722	-	92	63			
7/5/2011	2011.51	4197.0	5.68436E+12	8.46	6.64		48,089,645	37,744,119	-	86	61			
12/2/2011	2011.92	4196.8	5.6051E+12	9.07	7.90		50,838,253	44,280,287		89	72			based on limited data from NA
6/13/2012	2012.45	4197.3	5.80505E+12	8.51	6.63		49,400,964	38,487,472	-	87	67			excluded an erroneously high Mg value in SA
8/15/2013	2013.62	4194.7	4.83376E+12	10.25	6.47		49,546,072	31,274,448	-	92	57			
10/16/2014	2014.79	4192.8	4.21296E+12	10.90	7.41		45,921,285	31,218,048	-	85	58			
6/17/2015	2015.46	4192.3	4.05927E+12	12.65	7.66		51,329,440	31,081,813	-	90	56			
7/1/2016	2016.50	4190.4	3.50244E+12	15.15	9.06		53,061,996	31,732,124		96	57			based on limited data from NA
8/18/2016	2016.63	4189.4	3.22378E+12	15.50	9.92		49,968,622	31,963,799		90	56			based on limited data from NA
4/12/2017	2017.28	4193.5	4.43563E+12	12.35	7.70		54,780,037	34,154,355		89	57			
8/24/2017	2017.65	4193.3	4.37113E+12	13.15	7.78		57,480,361	33,985,537	-	96	56			
9/18/2018	2018.72	4192.1	3.99876E+12	14.20	8.46		56,782,389	33,825,509	-	97	58			
9/12/2019	2019.70	4192.9	4.24416E+12	13.50	7.78	48	57,296,113	33,011,050	203,720	99	57	362	1925	only 1 Li value from SA
9/23/2020	2020.73	4192.2	4.02887E+12	12.00	7.66		48,346,484	30,849,086	-	89	57			
5/25/2021	2021.40	4191.9	3.93871E+12	11.50	7.87		45,295,128	30,983,049	-	86	58			only 2 data points from NA
8/24/2021	2021.65	4190.6	3.55934E+12	12.30	7.82		43,779,943	27,834,078	-	87	54			only 2 data points from NA
5/4/2022	2022.34	4190.4	3.50244E+12	13.20	8.11		46,232,234	28,387,292	-	88	54			only 2 data points from NA
2/7/2023	2023.10	4189.2	3.16898E+12	16.30	9.60	65	51,654,407	30,422,227	205,984	98	57	389	2071	
3/28/2023	2023.24	4189.4	3.22378E+12	15.00	8.98	67	48,356,731	28,947,951	215,993	92	55	366	1949	SA data likely reflect dilution at marina
5/3/2023	2023.34	4189.4	3.22378E+12	13.90	8.20	74	44,810,571	26,435,013	238,560	88	52	456	2426	only 2 data points from NA; Atypical DBL (not anoxic)
8/29/2023	2023.66	4189.2	3.16898E+12	16.50	9.60	76	52,288,203	30,422,227	240,843	96	56	446	2374	
10/10/2023	2023.78	4189.2	3.16898E+12	16.35	9.66	78	51,812,856	30,612,366	246,547	96	56	430	2291	based on limited data from NA
11/21/2023	2023.89	4189.3	3.19635E+12	16.10	9.04	70	51,461,198	28,894,983	225,023	91	51	399	2121	SA data likely reflect dilution at marina
Reproduction of Havasi (2022) calculations:														
	1900.00	4193.5	4.46132E+12		7.32	51	-	32,656,854	227,527	-	58	433	2304	volumes from Baskin (2005, 2006)
	1900.00	4193.5	4.43563E+12		7.32	51	-	32,468,815	226,217	-	58	438	2330	updated with volumes from Root (2023)

In-place Li resource estimates of GSL brine based on measurements from 1970 through 1998 range from about 390,000 to 650,000 metric tons of Li (2.1 to 3.5 million metric tons of LCE) (Figure 11). A decrease is apparent between the mid 1970s and mid 1980s. Using our limited recent (after 2018) Li analytical data of GSL brine, the in-place Li resource ranges from about 360,000 to 460,000 metric tons (1.9 to 2.4 million metric tons of LCE) (Figure 11, Tables 1 and 2). The most recent Li resource estimates are comparable to the resource estimate developed by Havasi (2022) on behalf of Compass Minerals (~430,000 metric tons Li or ~440,000 metric tons Li using Root's [2023] updated bathymetry). However, Li concentration data published by Bunce et al. (2022) from the north and south arms from two different dates in 2021 result in an appreciably lower Li resource (306,000 and 317,000 metric tons of Li based on only 1 sample from each arm). This notable difference from recent UGS data highlights analytical uncertainty and need for additional and continued data collection. Future data collection should help better constrain the resource and continue to clarify how the Li resource is changing over time. The Li resource estimates based on measurements from the 1990s and recent years are comparable, which is notable because Li withdrawal by mineral companies has been occurring over that period (see following section). Havasi (2022) made similar observations in his technical/resource report.

The in-place Mg resource in GSL brine has ranged from about 80 to 150 million metric tons over the period of record from 1970 to 2023, and the K resource has ranged from 50 to 110 million metric tons (Figure 12, Table 1).

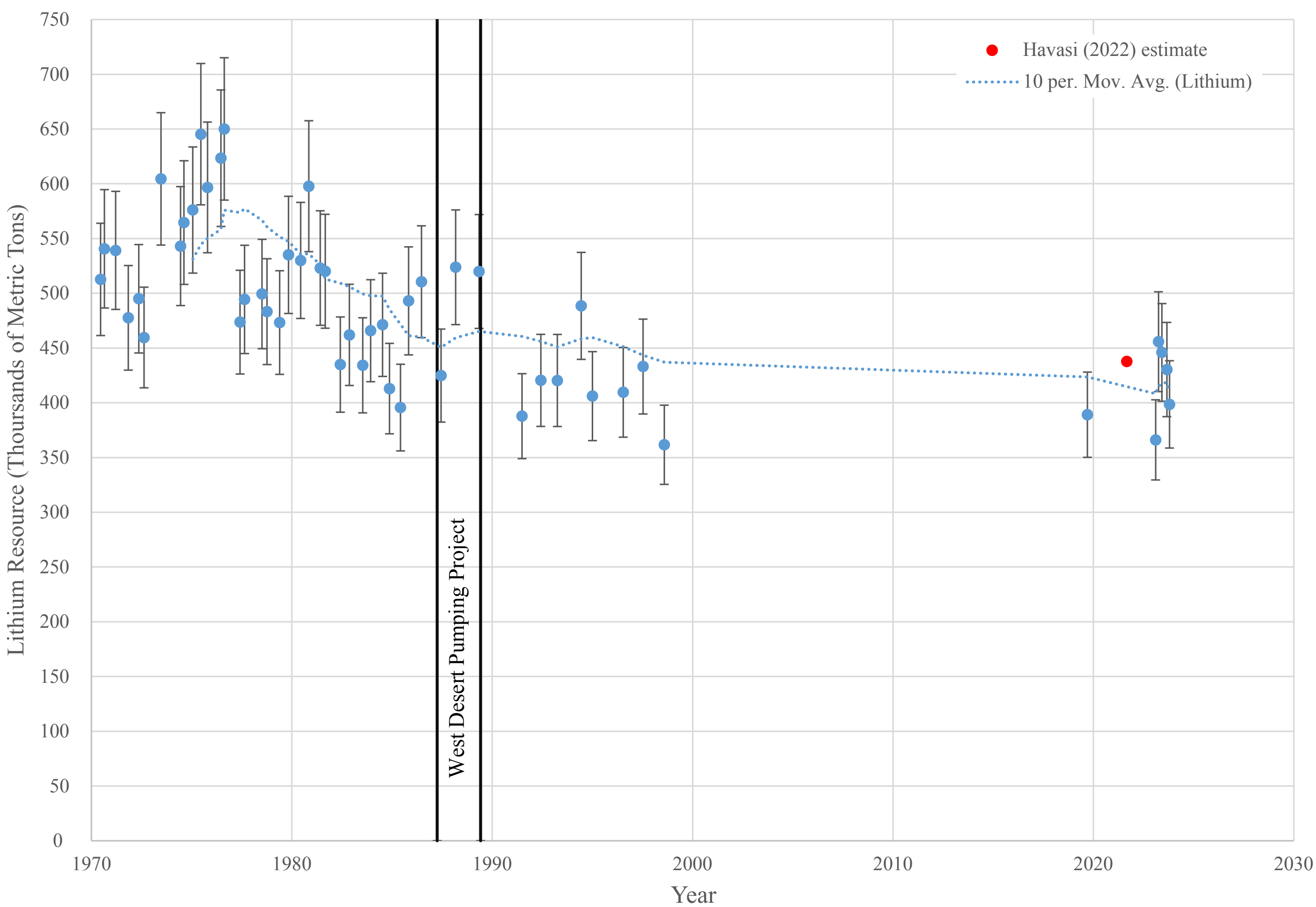

Figure 11. *Estimated in-place Li resource in Great Salt Lake brine from 1970 through 2023. Dotted line represents a moving average with a period of 10. No Li concentration data are available from 1999 through 2018. Error bars are shown at 10% to indicate a minimum estimated error.*

Table 2. *Decadal averages and ranges of estimated Li, Mg, and K resources. Estimates are shown with two significant figures.*

Time Period	**Estimated Li Resource Average (Range)** (thousands of metric tons)	**Estimated LCE Resource Average (Range)** (millions of metric tons)	**Estimated Mg Resource Average (Range)** (millions of metric tons)	**Estimated K Resource Average (Range)** (millions of metric tons)
1970s	540 (460–650)	2.9 (2.4–3.5)	130 (120–150)	93 (79–110)
1980s	480 (400–600)	2.6 (2.1–3.2)	130 (110–140)	82 (65–96)
1990s	440 (390–520)	2.3 (2.1–2.8)	110 (96–120)	65 (60–69)
2000s	no data	no data	88 (80–95)	63 (60–66)
2011 to present	410 (360–460)	2.2 (1.9–2.4)	91 (85–99)	57 (51–+72)

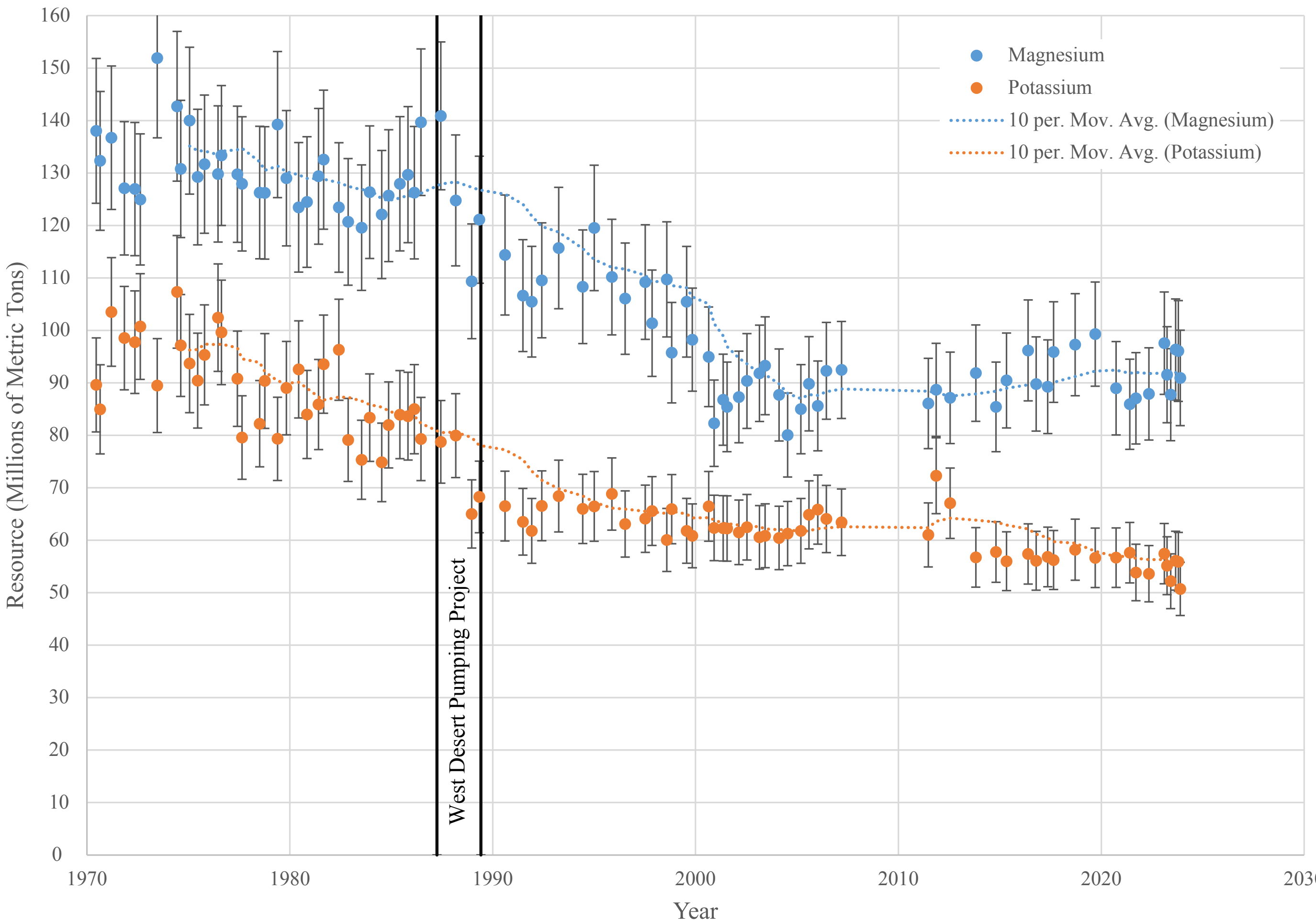

Figure 12. *Estimated in-place Mg and K resources in Great Salt Lake brine from 1970 through 2023. Dotted lines represent a moving average with a period of 10. No Mg and K concentration data are available for the north arm from 2008 through 2010. Error bars are shown at 10% to indicate a minimum estimated error.*

Both of these resources appear to show a general decline in the 1970s and into the 1980s, and a more abrupt drop as a result of the WDPP, which was previously identified by Loving et al. (2000). Following the WDPP, the Mg resource appears to decline during the 1990s, but the resource seems to have leveled off since the 2000s. The K resource does not appear to have shifted substantially since the WDPP, but appears to show a modest decline since the 1990s. Since 2011, the Mg resource has ranged from 85 to 99 million metric tons (averaging 91 million metric tons) and the K resource has ranged from 51 to 72 million metric tons (averaging 57 million metric tons). In general, both the Mg and K resources appear to have been relatively stable since around 2000 (Figure 12, Table 2).

ESTIMATED LITHIUM REMOVED FROM GREAT SALT LAKE BRINE

Compass Minerals' and US Magnesium's processes for producing commodities other than Li cause withdrawal of Li from GSL brine with presumably limited return. Two notable Li withdrawals are US Magnesium's stockpiling of Li separated during processing at their plant, and Li contained in Compass Minerals' magnesium chloride brine products (Havasi, 2022). Li also resides in the interstitial brine of the salts in evaporation ponds. Compass Minerals has quantified the Li held in interstitial brines in the halite beds of their evaporation ponds at 24,000 metric tons (128,000 tons of LCE) of indicated and inferred Li resource (Havasi, 2022). Li is presumably held in the interstitial brines of evaporation ponds of other mineral extractors as well. Some of the Li removed, while no longer within GSL brine, is likely still available to the overall system and could potentially be returned. Currently, US Magnesium does not flush material back to the lake, but Compass Minerals periodically flushes solids back to the lake at a rate of perhaps 10% of the material withdrawn.

Using brine withdrawal data from Utah Division of Water Rights, the annual and cumulative amount of Li displaced from GSL brine during the period of 1988 to 2021 was estimated (Table 3; Figure 13). However, *significant* uncertainties exist in the estimates and they should be considered rough approximations. In years where Li data are available, an average Li concentration from multiple sites and dates was used to represent an approximate average Li concentration (in mg/L) for the year. In several cases, measurements are only available for one sample day during the year so the Li concentrations from that singular date were averaged. In those cases, the estimated annual Li concentration might be high or low as an average depending on the time of sampling (e.g., low during periods of high inflow or high during periods of high evaporation); the timeframe within a year that brine was pumped from the lake by operators is not accounted for in the calculations. Table 3 shows the month(s) in which the samples were collected for the Li values used. For the south arm, data from sites AS2, AC3, and FB2 were used and, for the north arm, data from sites LVG4, RD2, and SJ-1 were used. For the south arm, the DBL was excluded in the averages under the assumption that no brine from the DBL was withdrawn.

In years for which Li data are not available, the Li concentration was estimated based on an average brine density for the year. For the south arm, the average brine density was calculated from site AS2 and for the north arm, the average brine density was calculated from sites LVG4 and SJ-1. Again, the DBL data was excluded from the average south arm density. To calculate the Li concentration of the south arm, a trendline fit to Li concentration data from 1968 through 1998 that excluded the DBL was used; data from 1966 and 1967 was also excluded because brine densities were near saturation during those years (Figure 14). This method provides a reasonably good correlation (R^2 of 0.70). For the north arm, a linear trendline was also applied to Li concentration data from 1966 to 1998 to calculate Li concentration for periods of no data. As previously discussed, because the north arm is near saturation, a linear correlation provides a poor fit (R^2 of 0.46). However, other fits (e.g., exponential) do not provide a better solution. Because the north arm was near saturation during the period of no data from 1999 through 2018, our estimates may be conservative and lower than actual concentrations during that time.

For the 34-year span of our calculations, roughly 225,000 metric tons of Li are estimated to have been displaced from the lake brine by mineral operators. If 10% of the Li withdrawn from the north arm was flushed back to the lake, the amount would be reduced to about 208,000 metric tons (Figure 13). Despite these potential fluxes, the overall Li resource in GSL brine appears to have remained relatively stable since the 1990s based on the UGS's limited recent data and Havasi's (2022) resource estimate (Figure 9).

Table 3. *Estimates of Li removed from Great Salt Lake annually and cumulatively by mineral operators.*

Year	US Magnesium Brine Withdrawals South Arm (SA) (acre-feet)	Compass Minerals Brine Withdrawals North Arm (NA) (acre-feet)	US Magnesium Brine Withdrawals SA (liters)	Compass Minerals Brine Withdrawals NA (liters)	Estimated SA Li Concentration (mg/L)	SA M or C	Estimated Brine Density for Calculation SA (g/cm^3)	SA Note	Estimated SA Li Withdrawal (metric tons)	Estimated SA LCE Withdrawal (metric tons)	Estimated SA Cumulative Li Withdrawl (metric tons)	Estimated North Arm (NA) Li Concentration (mg/L)	NA M or C	Estimated Brine Density for Calculation NA (g/cm^3)	NA Note	Estimated NA Li Withdrawal (metric tons)	Estimated NA LCE Withdrawal (metric tons)	Estimated NA Cumulative Li Withdrawl (metric tons)	Estimated NA Li Withdrawal w/ 10% Return (metric tons)	Estimated NA LCE Withdrawal w/ 10% Return (metric tons)	Estimated NA Cumulative Li Withdrawal w/ 10% Return (metric tons)	Estimated Total GSL Li Withdrawal (metric tons)	Estimated Total GSL LCE Withdrawal (metric tons)	Estimated Total GSL Li Withdrawal w/ NA 10% Return (metric tons)	Estimated Total GSL LCE Withdrawal w/ NA 10% Return (metric tons)	Estimated Total GSL Cumulative Li Withdrawal (metric tons)	Estimated Total GSL Cumulative Li Withdrawal w/ NA 10% Return (metric tons)
1988	0	59,773	0.000E+00	7.370E+10	11	M		Mar	-	-	-	19	M		Jan Mar	1400	7454	1400	1260	6708	1260	1400	7454	1260	6708	1400	1260
1989	83,697	47,493	1.032E+11	5.856E+10	15	M		May	1548	8240	1548	26	M		May	1523	8104	2923	1370	7294	2631	3071	16,344	2918	15,534	4471	4179
1990	194	56,515	2.388E+08	6.968E+10	19	C	1.086	Aug, AS2	5	24	1553	33	C	1.165	Jul, LVG4	2300	12,240	5222	2070	11,016	4700	2304	12,265	2074	11,041	6775	6253
1991	2609	32,733	3.217E+09	4.036E+10	19	M		Jun	61	325	1614	35	M		Jun	1413	7519	6635	1271	6767	5971	1474	7845	1332	7093	8249	7585
1992	2283	78,781	2.815E+09	9.714E+10	15	M		Jun	42	225	1656	30	M		Jun	2914	15,512	9549	2623	13,961	8594	2956	15,737	2665	14,185	11,205	10,250
1993	1298	56,950	1.601E+09	7.022E+10	19	M		Apr Nov	30	162	1686	32	M		Apr	2247	11,961	11,796	2022	10,765	10,616	2277	12,123	2053	10,927	13,482	12,303
1994	5377	65,886	6.630E+09	8.124E+10	20	M		Jun Oct	133	706	1819	35	M		Jun	2843	15,135	14,639	2559	13,621	13,175	2976	15,841	2692	14,327	16,458	14,994
1995	68,941	47,891	8.500E+10	5.905E+10	21	M		Jun	1785	9502	3604	39	M		Aug	2303	12,259	16,942	2073	11,033	15,248	4088	21,761	3858	20,535	20,546	18,852
1996	119,090	62,790	1.468E+11	7.742E+10	16	M		Jul	2349	12,506	5953	36	M		Jul	2787	14,836	19,729	2508	13,352	17,757	5137	27,342	4858	25,858	25,683	23,710
1997	43,949	55,016	5.419E+10	6.783E+10	14	M		Jul	759	4038	6712	36	M		Jul	2442	12,999	22,172	2198	11,699	19,954	3201	17,037	2957	15,737	28,884	26,666
1998	65,639	25,242	8.093E+10	3.112E+10	12	M		Jul	971	5170	7683	34	M		Jul	1058	5633	23,230	952	5069	20,907	2029	10,802	1924	10,239	30,913	28,590
1999	77,148	72,216	9.512E+10	8.904E+10	12	C	1.055	Jul Nov, AS2	1141	6076	8825	44	C	1.203	Jul Nov, LVG4	3882	20,664	27,112	3494	18,598	24,401	5024	26,740	4635	24,674	35,936	33,225
2000	78,664	98,666	9.699E+10	1.217E+11	14	C	1.063	Aug Nov, AS2	1358	7228	10,183	47	C	1.214	Sep Dec, LVG4	5691	30,293	32,803	5122	27,264	29,523	7049	37,522	6480	34,492	42,985	39,705
2001	33,975	132,096	4.189E+10	1.629E+11	16	C	1.073	May Jul Dec, AS2	670	3568	10,853	42	C	1.198	May Jul, LVG4	6865	36,544	39,668	6179	32,890	35,701	7536	40,112	6849	36,458	50,521	46,554
2002	73,493	99,305	9.062E+10	1.224E+11	20	C	1.089	Feb Jul Nov, AS2	1812	9647	12,665	47	C	1.215	Feb Jul Nov, LVG4	5763	30,678	45,432	5187	27,610	40,888	7576	40,325	6999	37,257	58,097	53,554
2003	107,394	119,458	1.324E+11	1.473E+11	24	C	1.107	Feb Jun Aug Dec, AS2	3178	16,916	15,843	48	C	1.219	Mar Jun Sep, LVG4	7103	37,811	52,535	6393	34,030	47,281	10,281	54,728	9571	50,947	68,378	63,125
2004	96,419	77,375	1.189E+11	9.540E+10	26	C	1.119	Feb Jul Nov, AS2	3091	16,453	18,934	46	C	1.211	Feb, LVG4	4380	23,316	56,915	3942	20,984	51,224	7471	39,769	7033	37,438	75,849	70,158
2005	58,743	84,468	7.243E+10	1.041E+11	24	C	1.108	Mar Aug, AS2	1738	9253	20,672	48	C	1.218	Mar Jul, LVG4	4993	26,576	61,908	4493	23,918	55,717	6731	35,829	6232	33,171	82,580	76,389
2006	71,232	112,345	8.783E+10	1.385E+11	22	C	1.099	Jan Jun, AS2	1932	10,285	22,605	47	C	1.214	Jan Jun, LVG4	6480	34,493	68,388	5832	31,044	61,549	8412	44,779	7764	41,329	90,993	84,154
2007	120,104	160,937	1.481E+11	1.984E+11	22	C	1.101	Mar Sep, AS2	3258	17,342	25,863	45	C	1.207	Mar, LVG4	8881	47,274	77,269	7993	42,546	69,542	12,139	64,616	11,251	59,888	103,131	95,405
2008	65,601	137,725	8.089E+10	1.698E+11	25	C	1.113	Jun Nov, AS2	2022	10,764	27,885	40	est.		estimate (no NA data)	6793	36,157	84,061	6113	32,541	75,655	8815	46,921	8,135	43,305	111,946	103,540
2009	99,184	130,988	1.223E+11	1.615E+11	24	C	1.107	Jul Dec, AS2	2935	15,623	30,820	40	est.		estimate (no NA data)	6460	34,388	90,522	5814	30,949	81,470	9395	50,012	8749	46,573	121,342	112,289
2010	57,553	156,501	7.096E+10	1.930E+11	25	C	1.112	Nov, AS2	1774	9443	32,594	40	est.		estimate (no NA data)	7719	41,086	98,240	6947	36,978	88,416	9493	50,530	8721	46,421	130,834	121,010
2011	79,969	90,110	9.860E+10	1.111E+11	17	C	1.078	Jun Nov, AS2	1676	8923	34,270	44	C	1.205	Jul, LVG4	4908	26,127	103,149	4417	23,514	92,834	6584	35,049	6094	32,437	137,419	127,104
2012	80,069	154,135	9.873E+10	1.900E+11	19	C	1.085	Jul Oct, AS2	1876	9985	36,146	42	C	1.199	Jun, LVG4	8066	42,934	111,214	7259	38,641	100,093	9942	52,919	9135	48,626	147,360	136,239
2013	104,652	136,968	1.290E+11	1.689E+11	22	C	1.097	Jun Oct, AS2	2839	15,111	38,985	48	C	1.219	Aug, LVG4	8145	43,354	119,359	7330	39,018	107,423	10,983	58,465	10,169	54,129	158,344	146,408
2014	47,997	157,184	5.918E+10	1.938E+11	23	C	1.106	May Oct, AS2	1361	7245	40,346	49	C	1.222	May Oct, SJ-1	9515	50,648	128,874	8563	45,583	115,987	10,876	57,893	9925	52,829	169,220	156,332
2015	107,178	119,858	1.322E+11	1.478E+11	25	C	1.115	Apr Oct, AS2	3304	17,586	43,650	50	C	1.225	Jun, C, LVG4	7384	39,303	136,258	6645	35,373	122,632	10,687	56,889	9949	52,959	179,907	166,282
2016	65,585	69,988	8.087E+10	8.630E+10	25	C	1.111	May Oct, AS2	2,022	10,761	45,671	51	C	1.227	6 Mos, SJ-1	4361	23,216	140,619	3925	20,894	126,557	6383	33,977	5947	31,656	186,290	172,228
2017	32,380	140,377	3.992E+10	1.731E+11	19	C	1.087	May Aug Nov, AS2	759	4038	46,430	49	C	1.220	Aug, LVG4	8397	44,699	149,016	7558	40,229	134,115	9156	48,737	8316	44,267	195,446	180,545
2018	71,404	114,799	8.804E+10	1.415E+11	21	C	1.094	May Sep Nov, AS2	1,849	9841	48,279	50	C	1.224	Sep, LVG4	7031	37,427	156,048	6328	33,684	140,443	8880	47,268	8177	43,525	204,326	188,722
2019	39,110	71,318	4.822E+10	8.794E+10	20	M		Sep	964	5134	49,243	48	M		Sep	4221	22,468	160,268	3799	20,221	144,242	5185	27,602	4763	25,355	209,512	193,485
2020	57,388	125,415	7.076E+10	1.546E+11	18	M		Jan	1274	6780	50,517	40	M		Jan	6185	32,925	166,454	5567	29,633	149,809	7459	39,705	6841	36,412	216,971	200,325
2021	41,458	117,470	5.112E+10	1.448E+11	21	M		Jun Nov, pub	1073	5714	51,590	48	M		Jun Nov, pub	6952	37,007	173,406	6257	33,307	156,066	8026	42,721	7331	39,021	224,997	207,656
Total									51,590	274,615						173,406	923,042		156,066	830,737		224,997	1,197,657	207,656	1,105,353		

Notes:
Brine withdrawal data was provided by Craig Miller (Utah Division of Water Resources) from data that he compiled from the Utah Division of Water Rights.
The estimated SA lithium concentration excludes the Deep Brine Layer.
The “SA M or C” column indicates whether the estimated Li concentration was measured or calculated; see text for details.
When Li concentration was calculated, the “Estimated Brine Density for Calculation” column shows the density used to calculate the estimated Li value.
The columns “SA Note” and “NA Note” indicate the month(s) from which data are available and the site from which density data was used.
2021 Li concentrations are from Bunce et al. (2022).
All Compass Minerals’ withdrawals are assumed to be from NA; all US Magnesium’s withdrawals are assumed to be from SA.
From 2008 to 2010, no NA density data are available and a conservative Li estimate of 40 mg/L is used to calculate Li withdrawal.

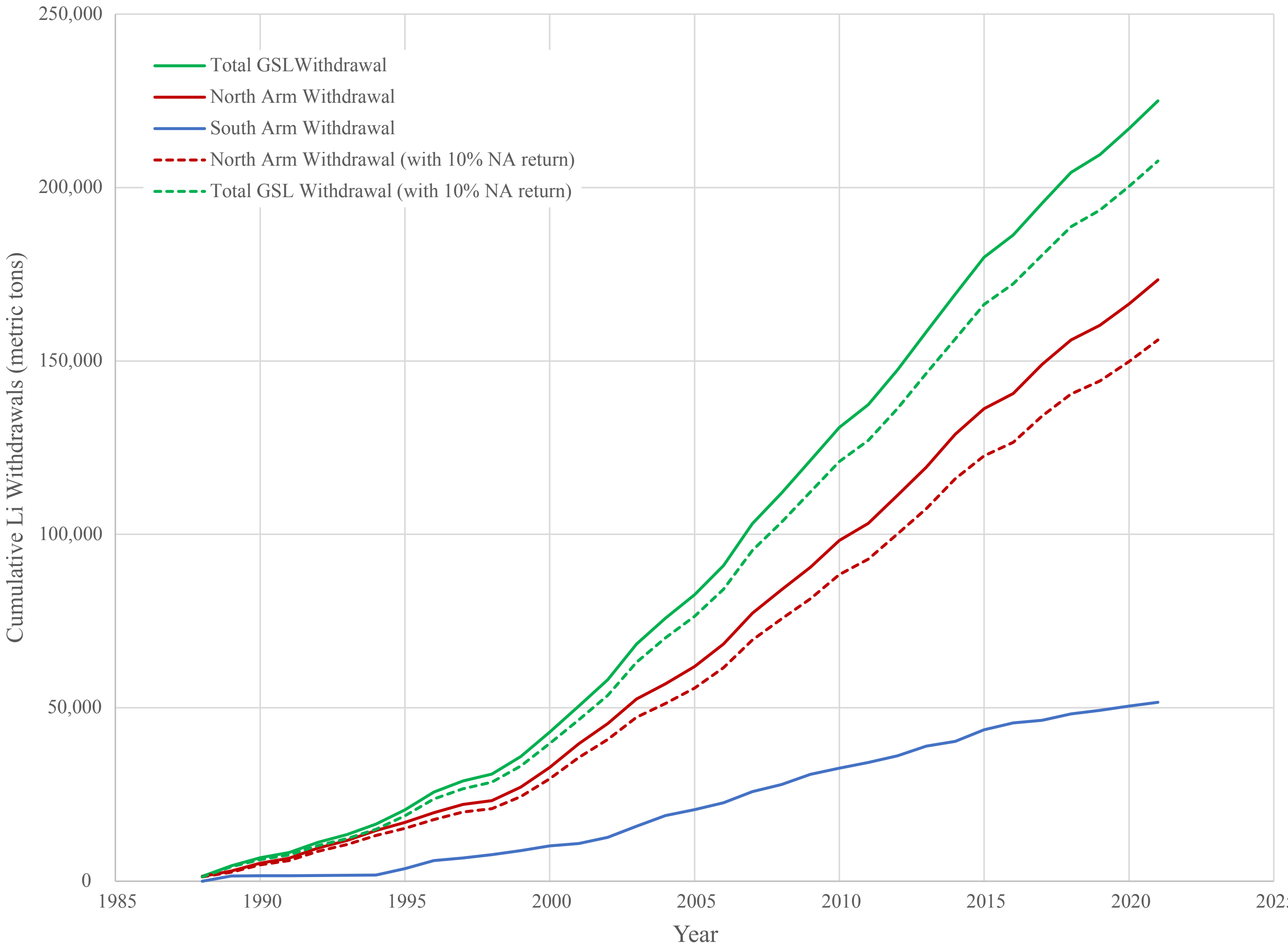

Figure 13. *Potential cumulative Li withdrawal from Great Salt Lake by mineral operators from 1988 through 2021.*

DISCUSSION AND CONCLUSIONS

Using the somewhat limited Li analytical data of GSL brine, the recent (2018 to 2023) in-place Li resource in the brine ranges from about 360,000 to 460,000 metric tons (1.9 to 2.4 million metric tons of LCE) and averages 410,000 metric tons (Figure 9, Table 1). This range does not take into account the minimum estimated 10% error for Li concentration measurements. The most recent estimates from this study are comparable to the estimate by Havasi (2022) which includes a more robust dataset of recent measurements. Continued data collection of Li concentration will increase the confidence of estimates and clarify trends.

This study's and Havasi's (2022) recent estimates are comparable to Li resource estimates in GSL brine from 1991 to 1998 which range from 390,000 to 520,000 metric tons (2.1 to 2.8 million metric tons of LCE) and average 440,000 metric tons (Figure 11, Table 1). Roughly 200,000 metric tons (a rounded lower estimate) of Li is estimated to have been removed from GSL brine via mineral extraction for other commodities since 1988 (assuming minor return of north arm brine). Given that potential level of removal and that the Li resource does not appear to have appreciably decreased since the 1990s, some amount of Li recharge to the lake brine is likely occurring within the system. Havasi (2022) made a similar observation. Some possible sources of Li recharge include riverine inflow, marginal spring inflow, and groundwater inflow. Lacustrine sediments have been identified as a possible source of Li input into continental brines such as GSL (Coffey et al., 2021), potentially providing Li to GSL via groundwater input. Riverine Li input to GSL is currently being investigated by the U.S. Geological Survey and initial results indicate that input may be an important contributor to Li recharge (Scott Hynek, U.S. Geological Survey,

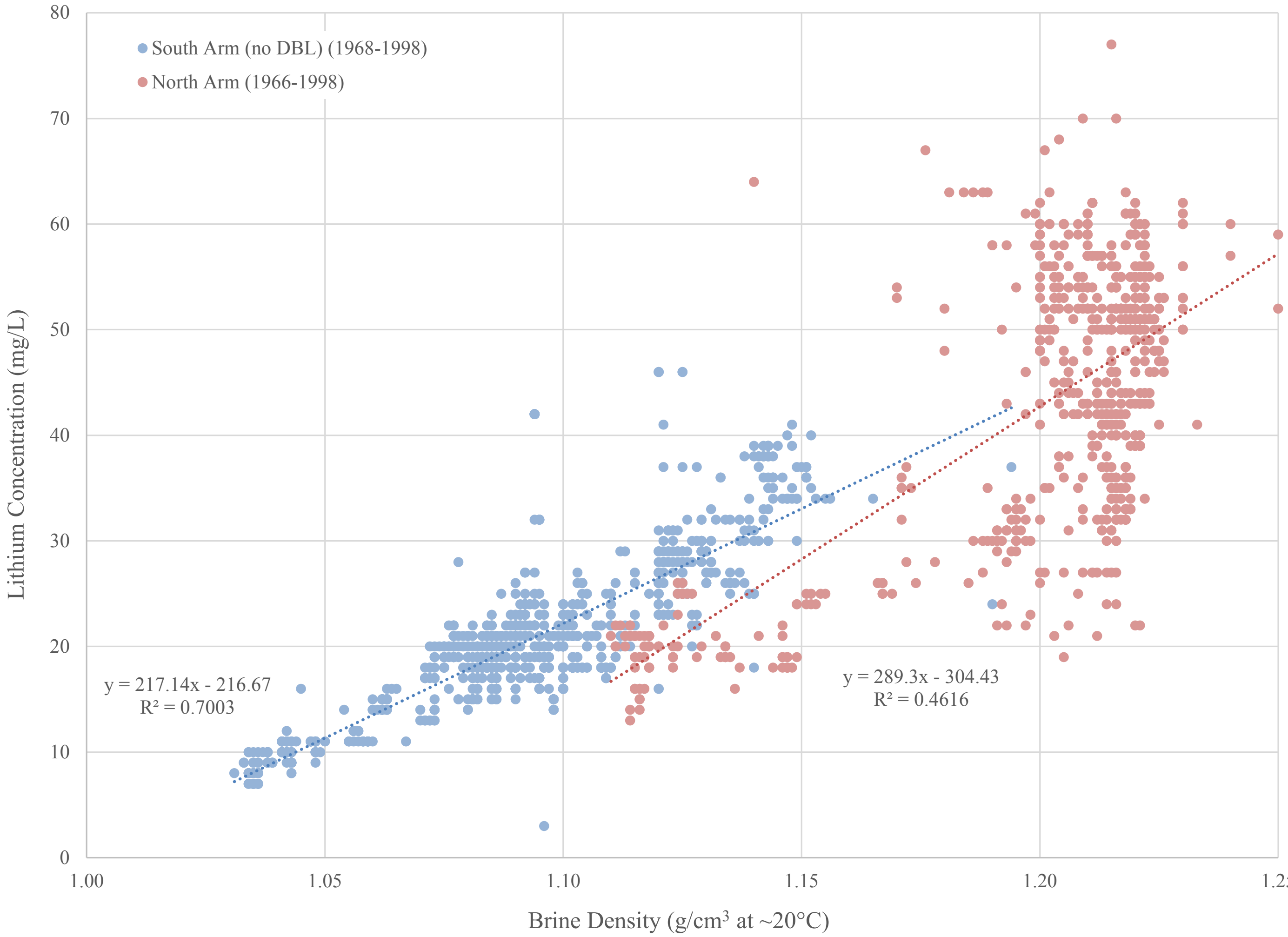

Figure 14. *Li data used to develop trendlines for estimating Li concentrations from 1999 through 2018. South arm concentrations exclude the deep brine layer.*

per. communication). Notably, some of the Li removed from GSL brine via extractive processes remains within the larger GSL system, partially residing in interstitial brines of mineral evaporation ponds such as the Li measured by Compass Minerals.

Mg and K resources in GSL brine show some change over time, but appear to be relatively stable since around 2000. In contrast to the Li resource estimates (Figure 11), a drop/offset is apparent in the Mg and K resources due to the WDPP (Figure 12). Why an offset is not apparent in the Li data is unclear, but could represent the challenge of analyzing trace elements in GSL brines or may represent an unidentified system dynamic within GSL. Additional subtle changes in the resource levels (e.g., the apparent decline in Mg resource from 1990 through 2000) are present and may be worth additional future evaluation, including past withdrawal estimates for Mg and K. Since 2011, the estimated Mg resource has ranged from 85 to 99 million metric tons (averaging 91 million metric tons) and the K resource has ranged from 51 to 72 million metric tons (averaging 57 million metric tons). Given the relative stability of the Mg and K resources since 2000 and the withdrawal and production of these ions in mineral commodities, these resources are also likely being recharged at some level.

A summary of conclusions follows:

- Based on recent sampling, estimates of the in-place Li resource in GSL brine range from 360,000 to 460,000 metric tons (1.9 to 2.4 million metric tons of LCE) and average 410,000 metric tons. This range is comparable with Compass Minerals' Li resource estimate for GSL, 438,000 metric tons based on volumes from Root (2023), prepared by Havasi (2022).

- Roughly 200,000 metric tons of Li might have been removed from GSL brine by mineral operators during production of other commodities between 1988 and 2021. However, this estimate has a large uncertainty. Although this Li has been removed from the lake brine, some of the extracted Li resides in interstitial brines and should still be available to the overall GSL system.

- Given estimates of Li withdrawal and that the Li resource in GSL brine appears to have remained stable since the 1990s, Li in GSL brine is likely being replenished to some extent.

- Based on measurements since 2011, the estimated Mg resource in GSL brine ranges from 85 to 99 million metric tons (averaging 91 million metric tons) and the K resource in GSL brine ranges from 51 to 72 million metric tons (averaging 57 million metric tons).

- The Mg and K resources in GSL brine have been mostly stable since around 2000 showing limited increases or decreases, indicating that, similar to Li, they are also being replenished to some extent.

- Similar to Li, developing estimates of Mg and K withdrawal over the last few decades could be helpful in understanding the future viability of those resources.

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ADDITIONAL NOTES

The UGS's Great Salt Lake brine chemistry database records Li concentrations as parts per million (ppm). This unit is somewhat problematic because ppm can be an indication of mg/L or mg/kg. In a case where the liquid media is fresh water, these two units are essentially interchangeable, but in the case of dense brines, such as those in GSL, the difference can be over 20% based on the higher densities measured in GSL. In the course of this study, we investigated the probable units for the historical samples (1966–1998) with Li data. Based on old data sheets preserved in the UGS files and communication with lab personnel involved with the historical analyses, I concluded that most or all of the historical measurements are in mg/L and I made that assumption throughout this study. Recent data are in mg/L.

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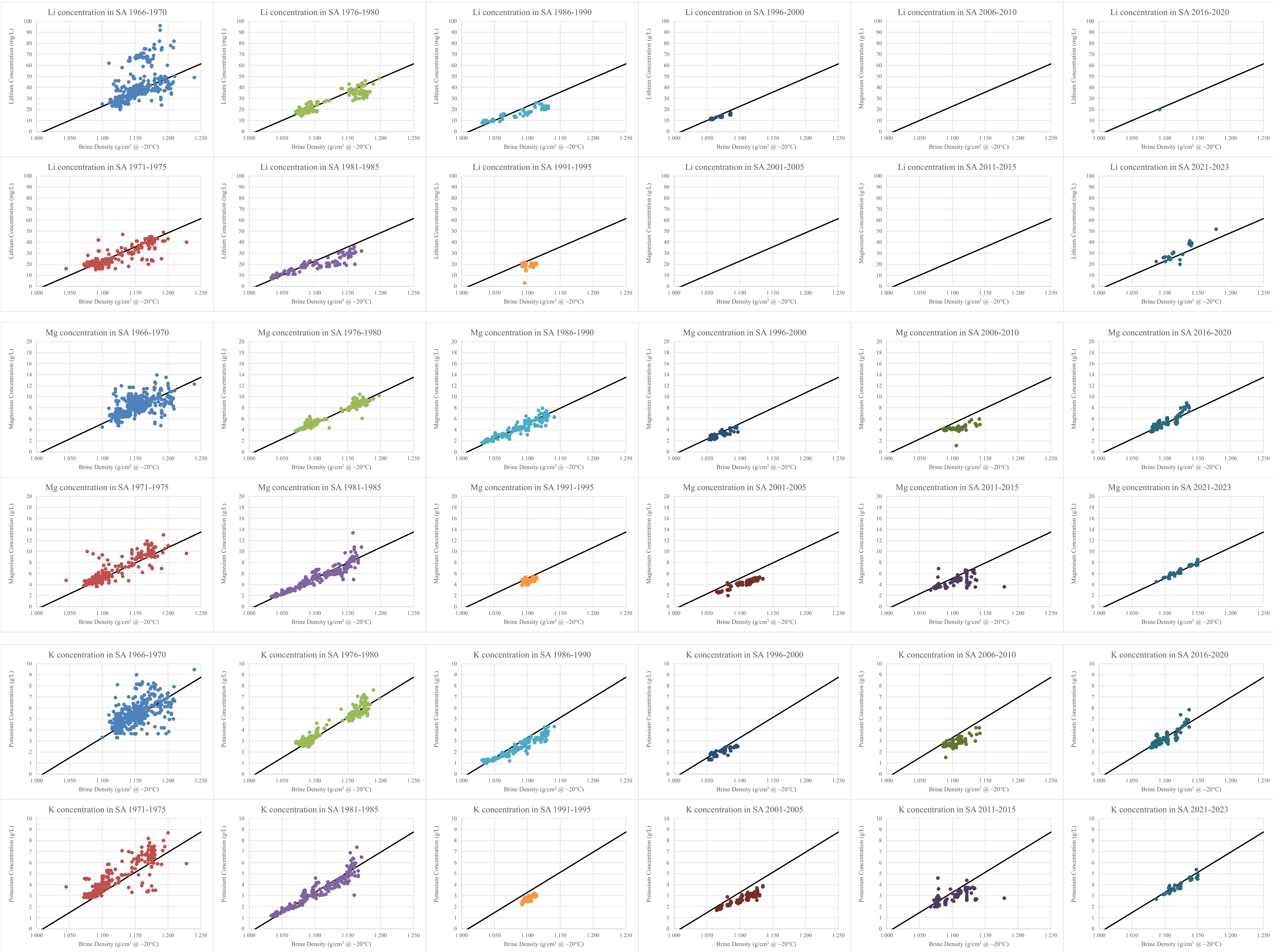

Plate 1*. Li, Mg, and K concentrations in the south arm of Great Salt Lake at five-year time intervals. The equations of the trendlines for each ion are shown in Figures 2, 4, and 6.*