INTERIM REPORT ON THE GREAT SALT LAKE LITHIUM RESOURCE

by Andrew Rupke

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Cover Photo: *Accumulated halite rafts on the shoreline of the halite-saturated north arm of Great Salt Lake. Photo by Andrew Rupke.*

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INTRODUCTION AND PURPOSE

This report documents a brief evaluation of the potential lithium resource (or mass) in Great Salt Lake (GSL) based on currently available data. The analysis presented here leans heavily on historical data from the Utah Geological Survey's GSL brine chemistry database from the 1960s through the 1990s; limited recent data are also available. 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 recent data.

The impetus behind this report is to begin to understand the lithium resource in GSL and how it has evolved over time as companies begin to explore and evaluate the lake as a source for lithium production. One company, US Magnesium, is already producing lithium as a byproduct at the lake and another company, Compass Minerals, intends to begin producing lithium from the lake in the next few years.

DATA SOURCES

Nearly all data used in this report come from the Utah Geological Survey's (UGS) GSL brine chemistry database (https://geology.utah.gov/docs/xls/GSL_brine_chem_db.xlsx) that includes brine data from 1966 through the present. Extensive lithium data were collected from 1966 through 1998, but only a small amount of lithium data have been collected since then. Recent data are intermittent and only from the last few years (2019 to 2023). Chemtech-Ford analyzed most of the recent UGS samples and they estimated a 5% to 10% error in their lithium analyses. A small amount of data that we present on figures are from the U.S. Geological Survey (USGS) that were collected at the new (2016) causeway breach. These data were not used in any resource estimate calculation since mixing at the breach may have affected those concentrations. Figure 1 shows the data used in this report from the north and south arms of the lake.

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 and RD2 (see previous link for locations). Recent UGS data also include analyses from some near surface sample sites at the Spiral Jetty (north arm), the Saltair Marina (south arm), and Black Rock (south arm). A significant weakness of our recent lithium resource estimates is the relatively few data points.

LITHIUM CONCENTRATION IN GSL

In the south arm of GSL, using the selected data (over 1300 measurements), lithium concentrations range from 3 to 46 mg/L based on measurements from 1968 through the present, but in 1966 and 1967 concentrations up to 76 mg/L were measured (figure 2). A simple average of all the measurements results in a lithium concentration of 24 mg/L. The high lithium concentrations in 1966 and 1967 may 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).

A correlative relationship exists between south arm lithium concentrations and lake brine density that is approximately exponential (figure 2). A similar correlative relationship has been noted in the past (e.g., Handy, 1967; Hahl and Handy, 1969). I used the relationship between brine density and lithium to examine the evolution of lithium concentration within the lake because density is one of the most reliable and repeatable measurements for characterizing brines (Great Salt Lake Salinity Advisory Committee, 2020; Bernau and others, 2023). Notably, some scatter exists within the data and outliers are present that presumably indicate measurement or other error. The available data indicate that the relationship between brine density and lithium has not changed appreciably in the south arm during the periods of measurement (figure 3), although a more detailed analysis may provide additional insight. A small decrease in lithium concentration in relation to brine density is apparent from the 1980s to the 1990s (figure 3), but our limited recent data suggest that is not a continued trend. The change from the 1980s to 1990s may be related to high lake levels resulting in dissolution of the north arm halite crust and an overall less evolved brine across the lake (see discussion below) or it may represent a change related to removal of brine during the West Desert Pumping Project (WDPP). Overall, although minor shifts may be discernible over the period examined, significant overlap exists within the data scatter.

North arm lithium concentrations range from 13 to 77 mg/L (based on nearly 800 measurements) (figure 4). A simple average of all the measurements shows a concentration of 43 mg/L of lithium in the brine. The data pattern of the north arm is markedly different from that of the south arm and is likely a function of the north arm typically being at or near a saturated state with respect to halite. At lower densities (~1.1 to 1.2 g/cm^3 at 20°C) there is a general increase in lithium concentration as brine density increases; however, at higher densities the relationship changes. This changing relationship is likely a function of the brine approaching a state of saturation with respect to halite as it nears 1.22 g/cm^3 at 20°C (Jagniecki and others, 2021). When saturated, the brine density plateaus to some degree as halite precipitates. However, as halite precipitates and brine density plateaus, lithium remains in the brine and becomes more concentrated. Additional complications in the relationship between brine density and lithium concentration may arise from other mineral phase changes that exist in the north arm such as mirabilite precipitation in the winter (Jagniecki and others, 2021). Additional data scatter may also be a function of analytical difficulties with dense brines. Similar to the south arm, I applied an exponential fit to the data albeit with a substantially poorer result.

LITHIUM RESOURCE ESTIMATES AND DISCUSSION

Several calculations of the in-place lithium resource (or lithium mass) in GSL were completed (table 1). The following equation was used to estimate the in-place 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 lithium concentration of the south arm (in mg/L), V_{NA} is the volume of the north arm (in L), LiC_{NA} is the lithium concentration of the north arm (in mg/L), and LiR_{GSL} is the lithium resource of the entire lake (in metric tons). The volumes used for this calculation are from Baskin (2005, 2006), where volumes of each arm of the lake are provided at 0.5 ft intervals. Where the lake level for a given calculation fell between an interval, I estimated volume using a linear interpolation between the two closest values.

I calculated the total in-place lithium resource of GSL in several instances when measurements of lithium concentration in the north and south arms were taken closely in time (typically less than one month apart). For a given sampling date, I averaged the available lithium concentration values to produce a single lithium value as representative for the sample date. In the south arm, I excluded data from the deep brine layer (DBL) so at times when a DBL was present the lithium resource is slightly underestimated. Volumetric estimates of the lake from Baskin (2005, 2006) are only available at 4200 ft and below so no calculations of lithium resource were made when either lake arm was above 4200 ft, with two exceptions from calculations when lake level was above but very close to 4200 ft (noted in table 1). Due to this constraint, no resource estimates were calculated for the late 1980s and early 1990s. Notably, our recent resource estimates are only based on a few lithium concentration measurements from each date.

Along with calculating the resource estimate using direct measurements of lithium concentration, I used the equation resulting from the exponential trend lines (from 1966–1998) for both the north and south arms to estimate the lithium concentration using the measured brine density. This estimate was calculated as a simple check given a probable ±10% error in a given lithium measurement. In general, the south arm trend equation was more predictive of the measured lithium value (on average within 15%, using values for resource estimates) than the north arm equation (on average within 19%, using values for resource estimates), which is unsurprising based on the quality of the trendline fit for each arm.

Figure 5 shows the in-place lithium resource estimate over time. A notable decrease is apparent between the first (late 1960s through early 1980s) and second (mid-1990s) data clusters (using the actual lithium measurements). This drop may be related to the WDPP. The estimates from the second (mid-1990s) and third (early 2020s) clusters are somewhat more comparable. I consider it important to note that two of the most recent estimates from 2023 (Feb. 7 and Mar. 28) do not take into account a denser lower brine layer (uncharacteristic of the "normal" DBL) in the south arm that developed in spring of 2023, so those estimates are likely low. The two most recent total lithium resource calculations are similar to the resource estimate developed by Havasi (2022) on behalf of Compass Minerals (our May 2023 calculation takes the spring 2023 stratification into account). Lithium concentration data collected in 2021, but analyzed in a different lab, show an appreciably lower resource. The variation between the 2021 estimates and most recent estimates highlight uncertainty and need for additional data. Future data collection should help constrain the resource and clarify how the lithium resource is changing over time.

The differences between the measured and calculated resources (figure 5) are largely driven by differences in the north arm estimates. In general, when the north arm is less evaporatively evolved (e.g., in the mid-1990s following high water years when the north arm salt crust was largely dissolved) the calculated lithium values are an overestimate, and when the north arm is more evaporatively evolved the calculated lithium values are an underestimate. Therefore, I consider the estimates based on actual analytical data to be more reliable than the calculated estimates using the trend fit.

The lithium resource estimates based on measurements from the 1990s and this year are comparable, which is notable because lithium withdrawal by mineral companies has been occurring over that period. Havasi (2022) made a similar observation in his technical/resource report. Compass Minerals' and US Magnesium's processes both cause consumptive withdrawal of lithium with presumably limited return. US Magnesium has been stockpiling lithium separated during processing at their plant and lithium has also left the system through Compass Minerals magnesium chloride brine products. Compass has also quantified the lithium held in interstitial brines in the halite beds of their evaporation ponds at 24,000 metric tons (128,000 tons of lithium carbonate equivalent [LCE]) of indicated and inferred lithium resource. Despite these fluxes, the overall lithium resource in GSL appears to have remained relatively stable since the 1990s based on the UGS's limited recent data and Havasi's (2022) resource estimate. A future version of this report will attempt to quantify lithium fluxes over the last couple of decades based on mineral company water withdrawals.

PRELIMINARY CONCLUSIONS

Using our limited recent lithium analytical data of GSL brine, the in-place lithium resource calculation in GSL ranges from about 310,000 to 450,000 metric tons (1.7 to 2.4 million metric tons of LCE) using laboratory measurements (figure 5, table 1). This range does not take into account the estimated 10% error for lithium concentration measurements. Our higher, most recent estimates are also comparable to the estimate by Havasi (2022) which includes a more robust dataset of recent measurements. Continued data collection of GSL's lithium concentration will increase the confidence of estimates.

Resource estimates based on measurements from 1968 through 1981 range from 470,000 to 610,000 metric tons of lithium (2.5 to 3.3 million metric tons of LCE). This study's and Havasi's (2022) recent estimates are more comparable to lithium resource estimates from 1993 to 1996 which range from 400,000 to 480,000 metric tons (2.1 to 2.6 million metric tons of LCE) (based on measurements, table 1). Given that lithium is annually removed from the system through mineral extraction, this result is unexpected. An updated version of this report will attempt to quantify annual lithium flux in the lake related to mineral extraction and will consider the implications of this result more closely.

In the south arm, brine density appears to be a reasonable proxy for lithium, but in the north arm the relationship is affected by complexities of halite and, possibly, mirabilite saturation. Ideally, actual lithium concentration measurements should be used when estimating the lithium resource of the north arm.

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ADDITIONAL NOTES

The UGS's Great Salt Lake brine chemistry database records lithium 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 lithium 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. The recent data are in mg/L.

Potential sources of error in the lithium resource calculations include analytical error (including dilutions), error in the available bathymetry (particularly in the north arm due to changing halite crust volumes), assumptions on temperature of density measurements from older analyses, heterogeneity in the lake brine, and not accounting for the deep brine layer.

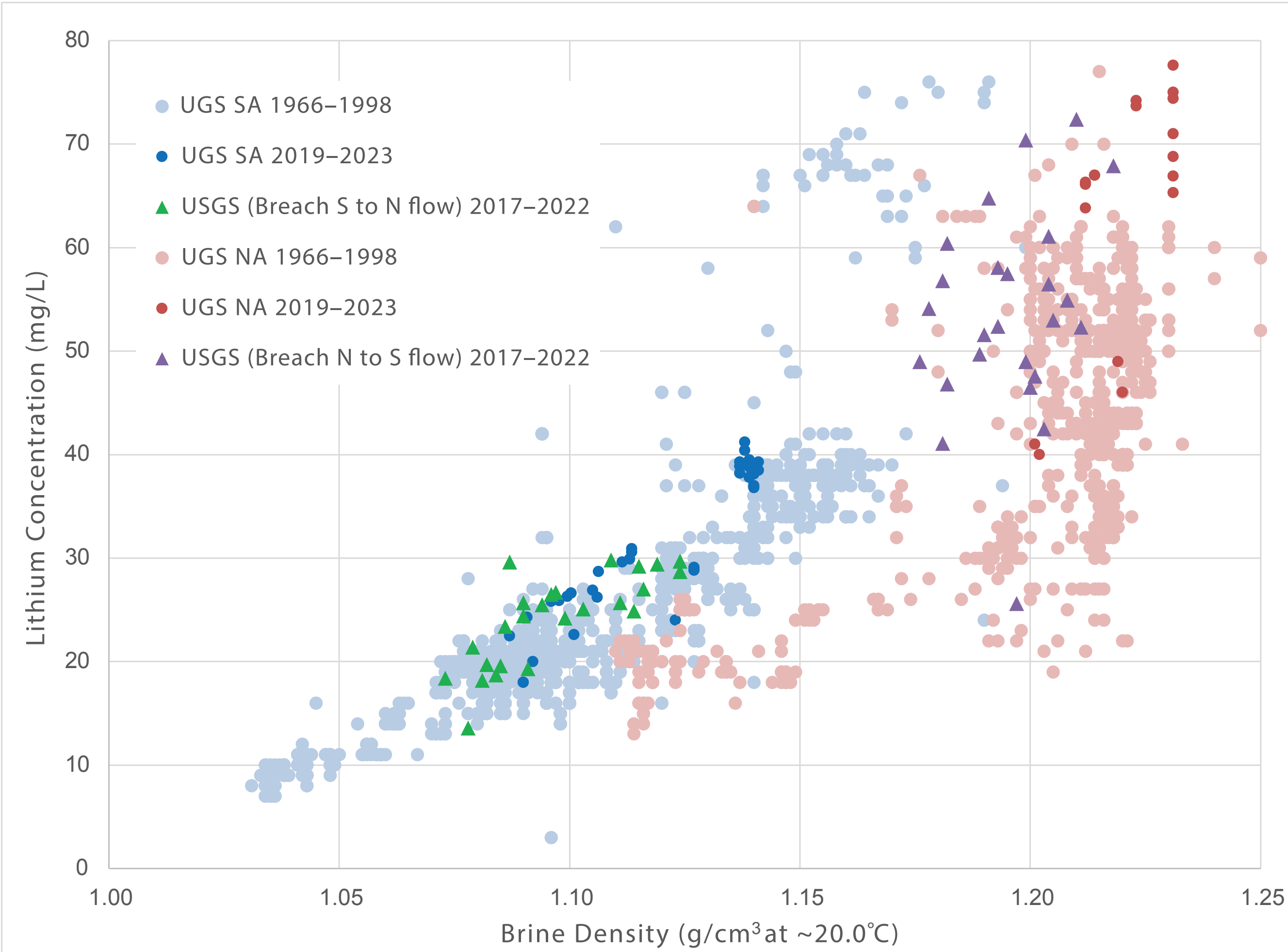

Figure 1. *Lithium concentration versus brine density from the south arm (SA) and north arm (NA) of Great Salt Lake used in this study. Sources: UGS Great Salt Lake brine chemistry database and USGS National Water Information System (NWIS).*

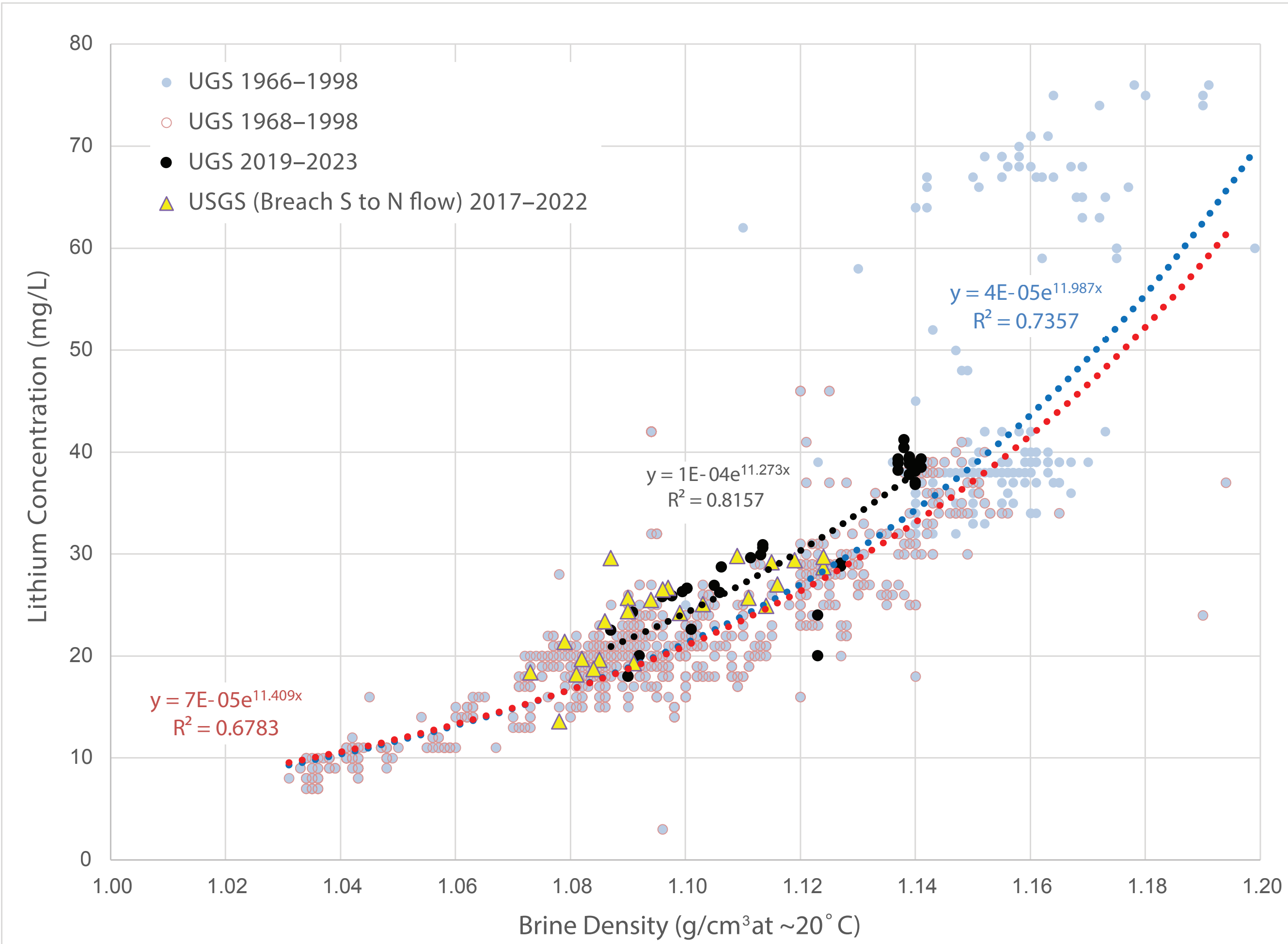

Figure 2. *Great Salt Lake south arm lithium concentration versus brine density. The trend lines are exponential. The blue equation represents the trendline of UGS data from 1966 to 1998, the red equation represents UGS data from 1968 to 1998, and the black equation represents UGS data from 2019 to 2023.*

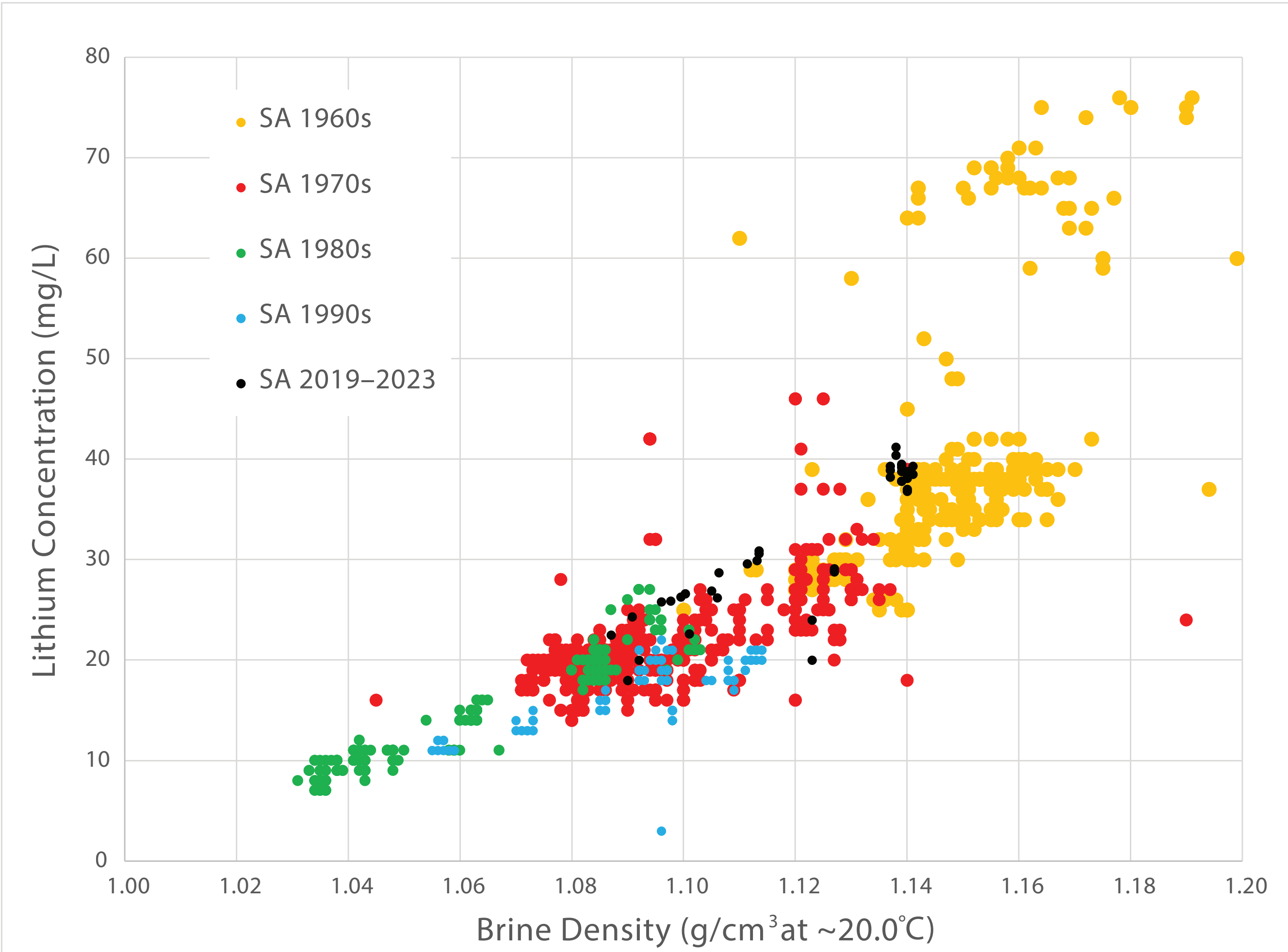

Figure 3. *Great Salt Lake south arm lithium concentration versus brine density through time. In general, data overlap exists over the period of record. An apparent but minor shift occurs from the 1980s to the 1990s that may be related to high water levels or the West Desert Pumping Project during those times. Recent data (2019–2023) fall within general historical trends. Source: UGS Great Salt Lake brine chemistry database.*

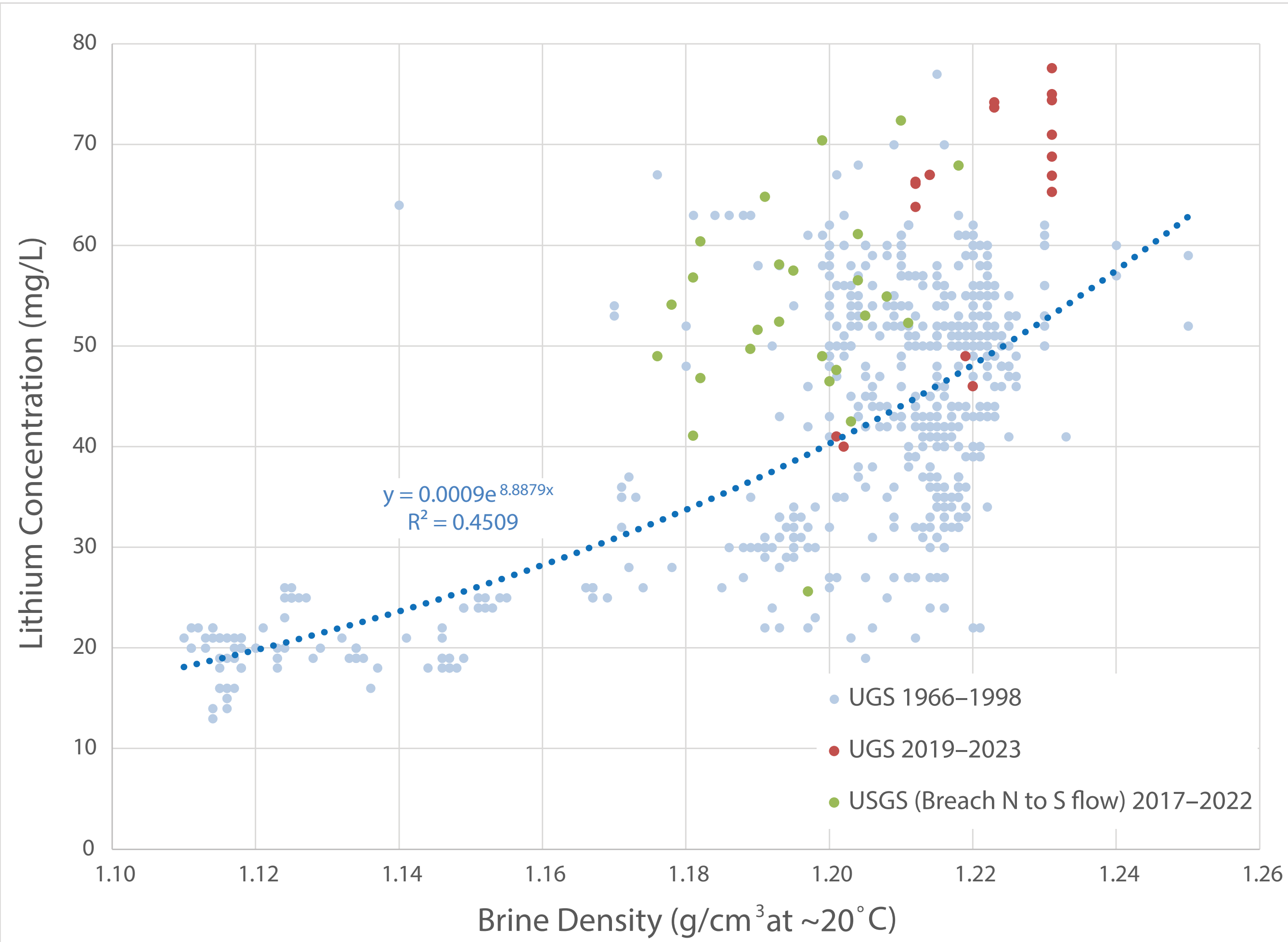

Figure 4. *Great Salt Lake north arm lithium concentration versus brine density. In the north arm, brine density plateaus as it nears saturation with respect to halite approaching a density of 1.22 g/cm*^{3} *at 20°C, and this likely causes the large lithium concentration spread seen near that density. The trendline of the data in the north arm is a poorer fit than data from the south arm (figure 2). Sources: UGS Great Salt Lake brine chemistry database and USGS National Water Information System (NWIS).*

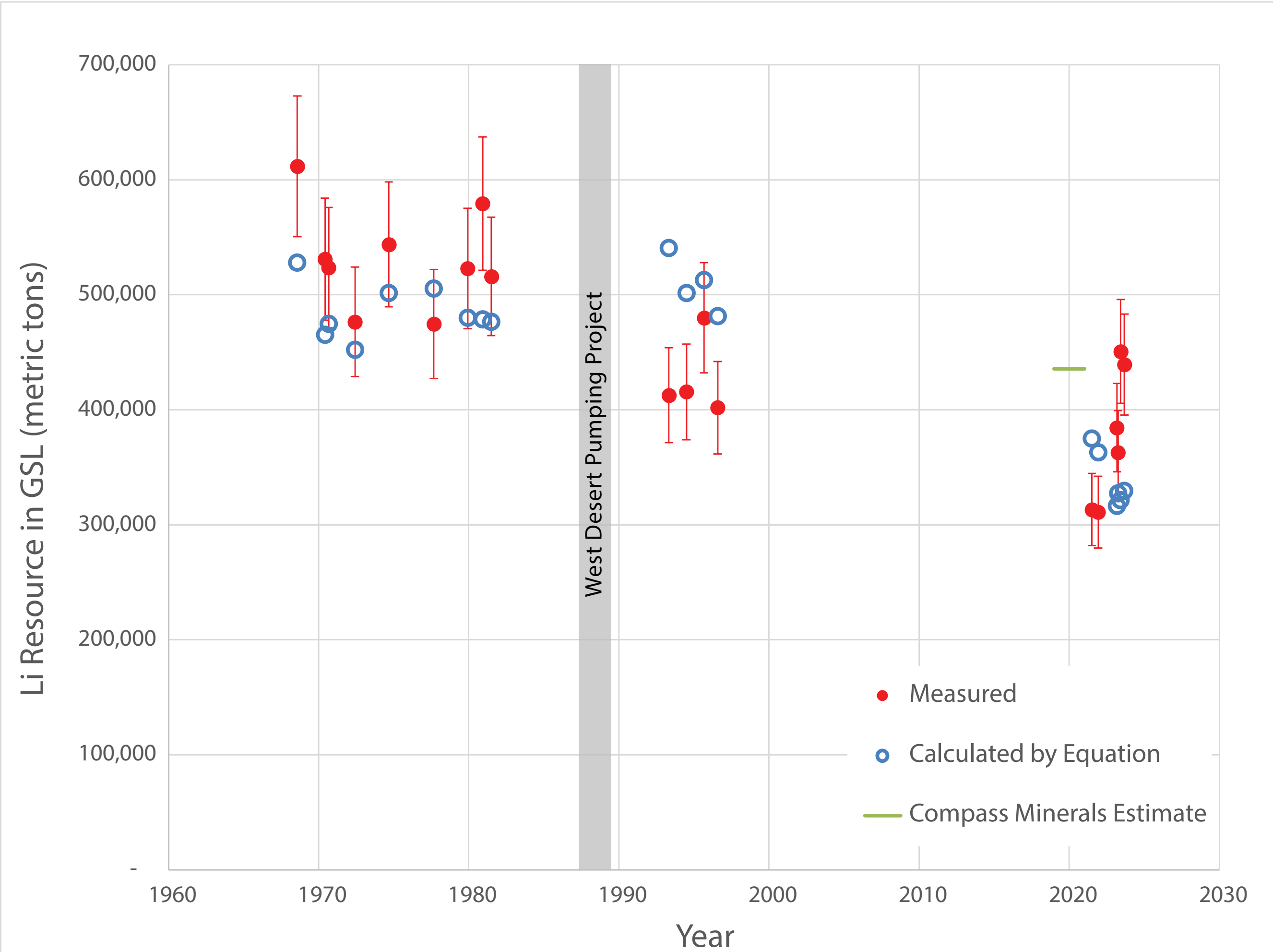

Figure 5. *Lithium resource (or mass) in Great Salt Lake versus time in metric tons. Estimates using the measured lithium concentration for a given time (red dots) show 10% error bars based on an approximation of analytical error. The calculated lithium resource (blue circles) is not always comparable depending on lake conditions, and large differences in the measured and calculated estimates are primarily driven by a poor-fitting trendline for the north arm.*

Table 1. *Lithium resource estimates for Great Salt Lake.*

Date	SA level (feet)	NA level (feet)	SA volume (liters)	NA volume (liters)	Measured SA Density (g/cm^3)	Measured NA Density (g/L)	Measured Li conc. SA (mg/L)	Measured Li conc. NA (mg/L)	Calculated Li conc. SA (mg/L)	Calculated Li conc. NA (mg/L)	Measured Li resource in SA (metric tons)	Measured Li resource in NA (metric tons)	Measured Li resource in GSL (metric tons)	Measured LCE in SA (metric tons)	Measured LCE in NA (metric tons)	Measured LCE in GSL (metric tons)	Calculated Li resource in SA (metric tons)	Calculated Li resource in NA (metric tons)	Calculated Li resource in GSL (metric tons)	Calculated LCE in SA (metric tons)	Calculated LCE in NA (metric tons)	Calculated LCE in GSL (metric tons)
July 1968	4195.4	4194.6	8.736E+12	4.821E+12	1.142	1.219	38	58	35	46	331,982	279,605	611,587	1,767,140	1,488,337	3,255,476	307,975	220,119	528,094	1,639,348	1,171,694	2,811,043
May 1970	4196.4	4195.4	9.287E+12	5.098E+12	1.119	1.211	27	55	27	43	250,745	280,366	531,111	1,334,717	1,492,389	2,827,106	248,495	216,782	465,277	1,322,739	1,153,933	2,476,672
August 1970	4195.3	4194.9	8.683E+12	4.921E+12	1.129	1.213	28	58	30	43	243,115	280,515	523,630	1,294,103	1,493,179	2,787,282	261,916	213,040	474,956	1,394,178	1,134,014	2,528,192
April/May 1972	4199.6	4197.9	1.117E+13	6.075E+12	1.091	1.202	16	49	19	39	178,736	297,688	476,424	951,409	1,584,593	2,536,003	213,685	238,499	452,184	1,137,447	1,269,531	2,406,978
August 1974	4199.9	4198.5	1.136E+13	6.334E+12	1.087	1.221	20	50	18	46	227,136	316,718	543,854	1,209,045	1,685,892	2,894,937	207,070	294,418	501,487	1,102,231	1,567,187	2,669,418
August 1977	4199.3	4198.4	1.099E+13	6.291E+12	1.090	1.223	18	44	19	47	197,755	276,800	474,555	1,052,650	1,473,405	2,526,055	207,651	297,642	505,292	1,105,324	1,584,347	2,689,671
October/November 1979	4197.6	4196.7	9.972E+12	5.586E+12	1.104	1.220	25	49	22	46	249,305	273,694	522,999	1,327,052	1,456,872	2,783,924	222,921	257,318	480,239	1,186,610	1,369,703	2,556,313
October/November 1980	4199.1	4197.8	1.086E+13	6.033E+12	1.093	1.215	25	51	20	44	271,594	307,708	579,302	1,445,695	1,637,930	3,083,625	212,851	265,870	478,721	1,133,006	1,415,227	2,548,233
May/June 1981	4200.0	4198.7	1.142E+13	6.423E+12	1.084	1.212	21	43	18	43	239,794	276,208	516,002	1,276,421	1,470,257	2,746,678	200,845	275,607	476,451	1,069,098	1,467,054	2,536,151
April 1993	4200.2	4198.0	1.142E+13	6.117E+12	1.109	1.215	19	32	24	44	216,956	195,745	412,701	1,154,857	1,041,952	2,196,810	271,024	269,552	540,576	1,442,662	1,434,825	2,877,487
June 1994	4199.9	4197.8	1.136E+13	6.033E+12	1.097	1.216	18	35	21	44	204,422	211,172	415,595	1,088,141	1,124,070	2,212,210	233,440	268,244	501,684	1,242,601	1,427,862	2,670,462
June/August 1995	4200.2	4198.1	1.142E+13	6.161E+12	1.095	1.220	21	39	20	46	239,794	240,260	480,053	1,276,421	1,278,902	2,555,324	229,153	283,803	512,956	1,219,782	1,510,684	2,730,466
July 1996	4199.9	4198.0	1.136E+13	6.117E+12	1.086	1.218	16	36	18	45	181,709	220,213	401,922	967,236	1,172,196	2,139,432	204,602	276,836	481,438	1,089,098	1,473,597	2,562,695
June 2021*	4191.9	4191.8	6.981E+12	3.935E+12	1.116	1.228	20	44	26	49	141,706	171,573	313,279	754,302	913,281	1,667,583	180,187	194,645	374,832	959,136	1,036,093	1,995,229
November 2021*	4190.6	4190.2	6.373E+12	3.471E+12	1.128	1.229	21	51	30	50	135,744	175,273	311,017	722,565	932,978	1,655,543	189,951	173,207	363,158	1,011,111	921,978	1,933,089
February 7, 2023	4190.0	4189.2	6.100E+12	3.193E+12	1.127	1.212	29	65	29	43	176,899	207,522	384,421	941,631	1,104,642	2,046,273	179,648	136,985	316,633	956,266	729,171	1,685,437
March 28, 2023	4191.1	4189.4	6.604E+12	3.248E+12	1.123	1.214	22	67	28	44	145,298	217,583	362,881	773,419	1,158,195	1,931,614	185,399	141,838	327,237	986,880	755,002	1,741,882
May 3(NA), 31(SA), 2023 (see notes)	4193.8	4189.4	6.708E+12	3.248E+12	1.097, 1.113	1.223	26, 30	74	21, 25	47	210,419	240,316	450,734	1,120,059	1,279,200	2,399,260	167,773	153,650	321,423	893,058	817,877	1,710,934
August 29, 2023	4192.7	4189.1	7.364E+12	3.165E+12	1.106	1.231	27	76	23	51	198,832	240,557	439,389	1,058,382	1,280,486	2,338,868	168,614	160,792	329,407	897,534	855,897	1,753,431
Reproduction of Havasi (2022); lake level and Li concentration from Havasi (2022)	4194.4	4193.5	8.213E+12	4.461E+12			25	51			205,323	227,527	432,850	1,092,933	1,211,128	2,304,061						
Tons reported in Havasi (2022)	4194.4	4193.5					25	51			208,711	226,860	435,571	1,110,969	1,207,576	2,318,544						

Notes:

These calculations are intended to be rough estimates; all Li data is sourced from the Utah Geological Survey brine chemistry database with the exception of 2021 Li estimates

SA = south arm; NA = north arm

"Measured" indicates use of lab results for Li concentration and "Calculated" indicates use of trendlines to estimate Li concentration

SA volume is slightly underestimated in April 1993 and June/August 1995 because lake level is above 4200 ft

Volumes are based on Baskin (2005, 2006)

Li resource for May 3(NA), 31(SA) includes two separately calculated horizons at different concentrations in the SA; SA is split into an upper and lower at 4176 ft

The deep brine layer (DBL) was not accounted for in our calculations for SA Li resource; the DBL is distinct from the lower brine layer observed on May 31, 2023

*Li concentrations from Bunce and others (2022)