Lithium Water Study

Research Summary

Hydrological Conditions and Impacts of Lithium Production in South American Salares: Results and Challenges

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Introduction

Importance of Lithium as a Resource

Lithium powers the energy transition as an essential raw material in the production of batteries for electric vehicles. Questions have emerged about the impact of lithium mining on the environment and local communities. Scientists contribute research to these questions to build a more responsible future in lithium. One of the two primary ways to produce lithium, the other is rock mining, involves pumping *"brine[1]"*, a type of water that contains at least 3 times more salt than seawater, from lithium-rich *aquifers*[2]. We focus on lithium extraction from a group of salt flats, or *"Salares[3]"*, that are located in the high desert plateaus and basins of the north-central Andes (**Figure 1**). This area is known as the "Lithium Triangle," where greater than half of the global lithium reserves exist.

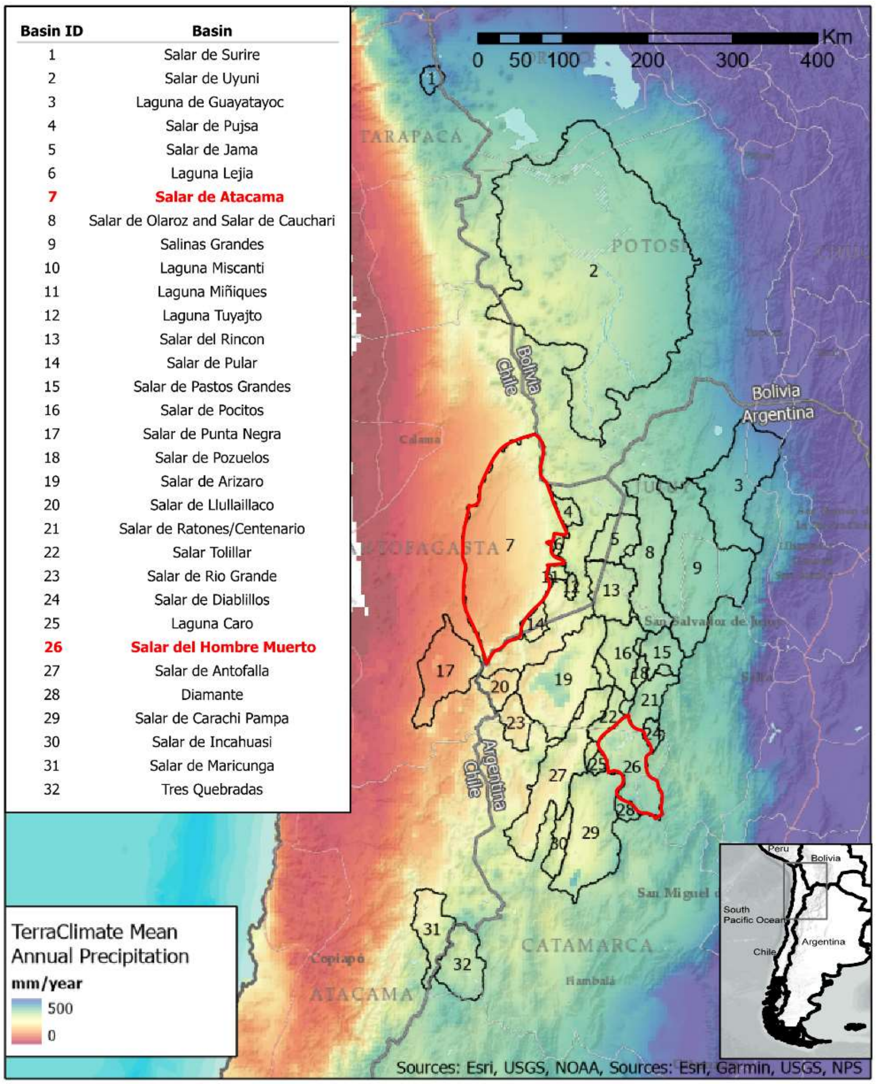

Figure 1. Map of the Lithium Triangle region of the South America. Major lithium *brine*-bearing *Salar* basins are outlined in black and average annual precipitation is shown on a color scale. The primary basins which are the focus of this report are outlined in red.

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[1] *Brine:* Highly saline *groundwater*, at least 3 times saltier than seawater, not suitable for drinking, irrigation, or livestock watering. A list of all key terms and their definitions is provided in the Appendix.

[2] *Aquifer:* Earth below ground that holds water

[3] *Salares:* Salt flats located on the floors of basins

Distinct Water Sources Associated with Lithium-rich Reserves

Groundwater[4] in the Lithium Triangle differs widely in salt and mineral concentration, depending on the location of *groundwater* relative to the *Salares* and evaporation. Most valleys and basins have no streams to drain water, so evaporation is the primary way water can leave the basins. Since evaporation outpaces rain and snow, the remaining unevaporated water accumulates higher concentrations of salts and minerals over time in a process known as *evapoconcentration*[5]. This results in a type of salty water, known as *brine*, which contains lithium. The lithium-rich *brine* is pumped to the surface and concentrated for use in lithium-ion batteries. Meanwhile, fresh *groundwater* flows from the rim of the basins towards the basin floor, where through *evapoconcentration* it gradually becomes saltier "*brackish water*[6]" and finally transitions to *brine* within the *aquifer*s at the basin floor (**Figure 2**). Given the importance of lithium and the preservation of fresh *groundwater*, it's important to understand the movement of *groundwater* through these unique ecosystems.

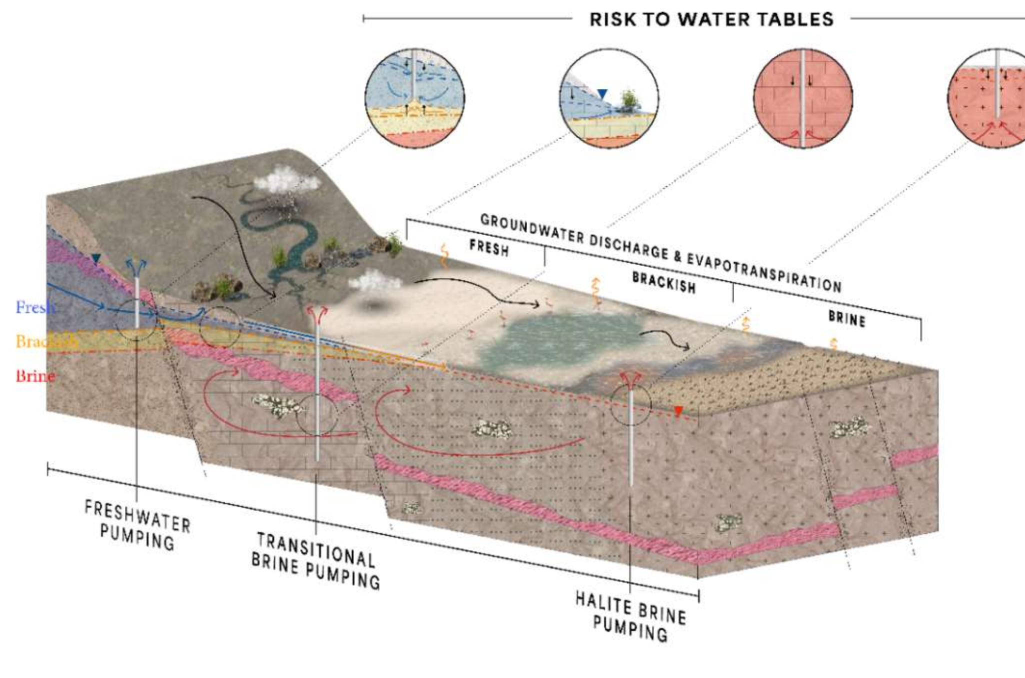

Figure 2. Conceptual illustration of *Salar* hydrological systems, with fresh water (blue) flowing towards the basin floor and over the *brine* (red). The fresh *groundwater* transitions to brackish (yellow) and then *brine* at the basin floor. Inset bubbles above show detail at a key fresh water inflow location and the potential *groundwater* pumping sites.

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4 *Groundwater:* Water that is located within the ground/under the Earth's surface

5 *Evapoconcentration:* Process of progressive evaporation increasing salt concentrations in water

6 *Brackish water:* Moderately salty water, between water suitable for livestock watering and up to 3x saltier than seawater. Not suitable for drinking, or irrigation.

Concerns about Groundwater Pumping for Lithium Mining

Questions about the impact of lithium mining on fresh *groundwater* and surface water availability exist. Surface water bodies, commonly known as *"Lagunas"*[7], provide feeding grounds and habitats for wildlife. *Lagunas* form at the border between the wetlands (*Vegas*[8]) and the *Salar* where a delicate balance between fresh inflow and *brine groundwater* exists. The location of the *Lagunas* also relies on where the *brine groundwater* exists, because the much denser *brine* effectively stops the lighter, more buoyant fresh *groundwater* from moving into the *brine aquifer*s at the basin floor. As a result, *Lagunas* form downstream from where fresh *groundwater* upwells. Since there is little rain or snow to sustain the *Lagunas*, they rely primarily on this *groundwater* to replenish them. There are concerns about pumping the *brine* for lithium mining and fresh *groundwater* for mining operations. Furthermore, *freshwater*[9] is used for agriculture, tourism, domestic use by local communities, and other mining. As pumping removes water from the ground, the concern is that decreasing *freshwater* and *brine* levels could lead to a destabilization of the position of the *Lagunas* and the *freshwater aquifer*s, and ultimately to less water flowing into the *Lagunas*. Research on the effects of *groundwater* pumping and climate-related impacts on *groundwater* flow is necessary to address the concerns of the local communities and the industry.

Support of Research Initiatives to Responsibly Mine Lithium in South America

Understanding the availability of water associated with lithium mining is important for the responsible production of electric cars. The BMW Group and BASF funded a research project led by scientists at the University of Massachusetts Amherst and the University of Alaska Anchorage to better understand *groundwater* flow in lithium-rich environments and quantify the environmental impacts of both *brine* and fresh *groundwater* pumping. Scientists involved in this project are experts in studying *groundwater* flow, hydrology, and climate in the Lithium Triangle. The research project forms part of the BMW Group's and BASF's engagement for understanding the impacts of lithium production on water availability in the *Salar de Atacama* (*SdA*) in northern Chile and *Salar del Hombre Muerto* (*SdHM*) in Argentina, which complements the work of the Responsible Lithium Partnership, a multi-stakeholder platform, of which both companies are members.

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[7] *Lagnuas:* Surface water bodies that lie on the edge of a *Salares*

[8] *Vegas:Groundwater*-fed wetlands that lie on the edge of *Salar*es or near permanent surface water bodies

[9] *Freshwater*: Water that has little or no salt and is suitable for drinking, irrigation, and livestock

Scope of Work

The research assesses connections between fresh, brackish, and *brine aquifer* systems to evaluate the environmental impacts of lithium production. Remote sensing (satellite-based) technologies were used to document past and current hydrological and environmental conditions in the *Salares*. Scientists also use ground-based physical measurements, water isotopes, and numerical simulations to describe the distribution and movement of *groundwater* and surface water. The result is a data-driven framework that evaluates lithium extraction in these desert regions and the responses to these human influences within the context of natural influences. The work was conducted as four work packages with distinct scopes and findings, therefore the results are presented in that format.

To make sure that research was carried out independently, as it was financed by industry, research results are published through a set of research papers (described in the Appendix) which undergo a broad and critical peer review process in the scientific community.

The research project investigated the following main questions relevant to *SdA*, *SdHM*, and region-wide. The answers to these questions are described within the findings section of each work package below.

1. What are the primary drivers of hydrologic changes observed in these basins?
2. How are the fresh, brackish, and brine aquifer systems hydraulically connected?
3. What are the impacts of historical, current and potential future lithium extraction?

The answers to questions 1, 2, and 3 can be found in chapters 4, 5, and 7, respectively. Chapter 6 further focuses on questions 1, 2, and 3 for *Salar* del Hombre Muerto as a specific test case.

Background

Geography and Current Water Use

Regional Overview

Major lithium *brine* extraction and processing at an industrial scale is currently focused at *SdA* in Chile, and the *SdHM* in Argentina (*Figure 1*). The mines rely on different water types, ranging from the *brine* resource itself to fresh water needed by industrial processes and related mine use (sanitation, drinking, etc). Because of the varied nature of the water types and the desert setting, water availability is largely dependent on salinity and proximity to *freshwater* springs, wetlands, and *aquifer*s (*Figure 2*). Mining companies choose sites based on lithium resource access and access to fresh and *brackish water* supply.

Salar de Atacama

"The Salar de Atacama contains the world's largest lithium reserve"

SdA is the largest salt flat in Chile and covers 3,000 km^2, which makes it the third largest in the world. Its average elevation is about 2,300 m above sea level at the edge of the Atacama Desert. Parts of this desert have gone without rain for as long as records have been kept. However, a large amount of *brine* lies below the surface. The *Salar* contains the world's largest lithium reserve and mining activities at its two active lithium mines have expanded substantially. These lithium mines withdraw *brine* from the *Salar* and fresh *groundwater* from its margin. Additional water is used in the basin by members of local communities, agriculture, a significant tourism industry, and a copper mining industry, all of which use fresh *groundwater* either directly or indirectly. The basin also contains wetlands of international importance as defined by the Ramsar Convention, and these wetlands depend on *groundwater* flowing into the basin. The Appendix A1 includes a detailed map of the basin and its important features.

Salar del Hombre Muerto

SdHM is a large *Salar* (~600 km^2) in Argentina, in the Antofagasta de la Sierra Department on the border between the Salta and Catamarca Provinces. *SdHM* lies at 4,000 m above sea level near the eastern edge of the plateau and is surrounded by mountains, including volcanoes with summits that exceed 5,000 m above sea level. The *watershed*[10] of *SdHM* has an area of 4,000 km^2 half of which is drained by the 150 km long Rio de Los Patos, constituting the primary source of *freshwater* in the basin. This river enters the *Salar* from the east but originates on Galán Caldera south of the *Salar* and supplies the *Laguna* Catal and nearby wetlands. The other important but smaller river is the Rio Trapiche which flows toward the *Salar* from the south. The wetlands (*Vegas*) Trapiche and Hombre Muerto are located on the southern margin of the *Salar* and extensive wetlands also exist at the edges of the Rio Los Patos. The western side of the basin is very dry with very little permanent surface water. *SdHM* is a hydrologically closed basin with no drainage outlets, therefore all water that leaves *SdHM* does so by evaporation or plant transpiration, collectively referred to as *evapotranspiration*.

The Fenix Mine, operated and owned by Livent Corporation is currently the only producing lithium mine in SdHM and sits in the western part of the basin. Water consumption from this mine constitutes only a small portion of the total natural *evapotranspiration* (the only outflow) from the basin and the total amount of freshwater (inflow) flowing into the basin.

[10] *Watershed:* The area within which all rainfall or snowfall that falls ultimately drains to a specific point or area

The Argentine government regulates water consumption and Livent maintains water consumption records. Total *freshwater* use was about ¼ of total *brine* withdrawals during the 2015 to 2020 period. As further discussed in Chapter 4, Livent manages *freshwater* consumption from a surface impoundment (dam) of the Rio Trapiche on a seasonal basis, whereby a greater percentage of surface water is used in wetter months and a greater percentage of *groundwater* is used in drier months. The Appendix A1 includes a detailed map of the basin and its features.

How does the extraction of lithium brine impact freshwater ecosystems like lagunas, wetlands, and springs?

Introduction

Salares are dynamic environments where fresh water flowing into the basins interacts with lithium-bearing *brine* to form fresh and brackish surface water wetlands (*Vegas*) and *Lagunas* (***Figure 2***). Because of the possible sensitivity of these wetlands and *Lagunas* to both *brine* and *freshwater* withdrawal, changes in the amount of water in these surface water features are a key metric of environmental change. *Lagunas* and the wetlands surrounding them are valuable habitats and are often protected by national and international law. However, to attribute changes in *Laguna* and *Vega* hydrological behavior to specific human activities (e.g. *brine* and *freshwater* use) it is important to understand how they respond to natural climatic variability on different time scales. The following questions were defined to address these issues, the answers to these questions are described in the Key Findings sections below.

1. What are the trends in surface water extents in each basin?
2. Do the data support concerns over surface water degradation?
3. What are the main drivers of any surface water extent changes?

"Changes in the amount of water in these surface water features are a key metric of environmental change"

Methods[11]

Multiple remote sensing data sets to assess the hydrological and climatological regimes at *SdA* and *SdHM* were utilized. These include high-resolution satellite imagery, satellite and weather station-derived estimates of precipitation, and satellite-derived gravity anomaly data. Streamflow, precipitation, and *groundwater* level measurements from locations throughout these basins and the surrounding region were used to assess changes in hydrologic conditions. Available data on water consumption within the *SdA* and *SdHM* basins were compiled into a comprehensive basin-wide assessment of human water consumption. The combination of these data sets allowed for an analysis of changes in these environments over the last decades. A detailed description of these methods can be found in the published article.

[11] *A detailed and comprehensive description of these findings and methods used is presented in the publication* "Relic Groundwater and Prolonged Drought Confound Interpretations of Water Sustainability and Lithium Extraction in Arid Lands"

Main Findings

Overview

Lithium *brine* extraction in South American *Salares* has various potential impacts on water resources and ecosystems. Since high-quality lithium *brine* resources are generated under conditions of natural water stress (where potential evapotranspiration greatly exceeds recharge), basins with lithium-rich *brine* are inherently water limited. Human consumption and climate influences beyond lithium extraction may also impact water availability, though competing uses may complicate observations of water availability. For example, both the *SdA* and *SdHM* regions experienced a prolonged *drough*[12], complicating interpretations of impacts on water and ecosystems from lithium mining (***Figure 3***).

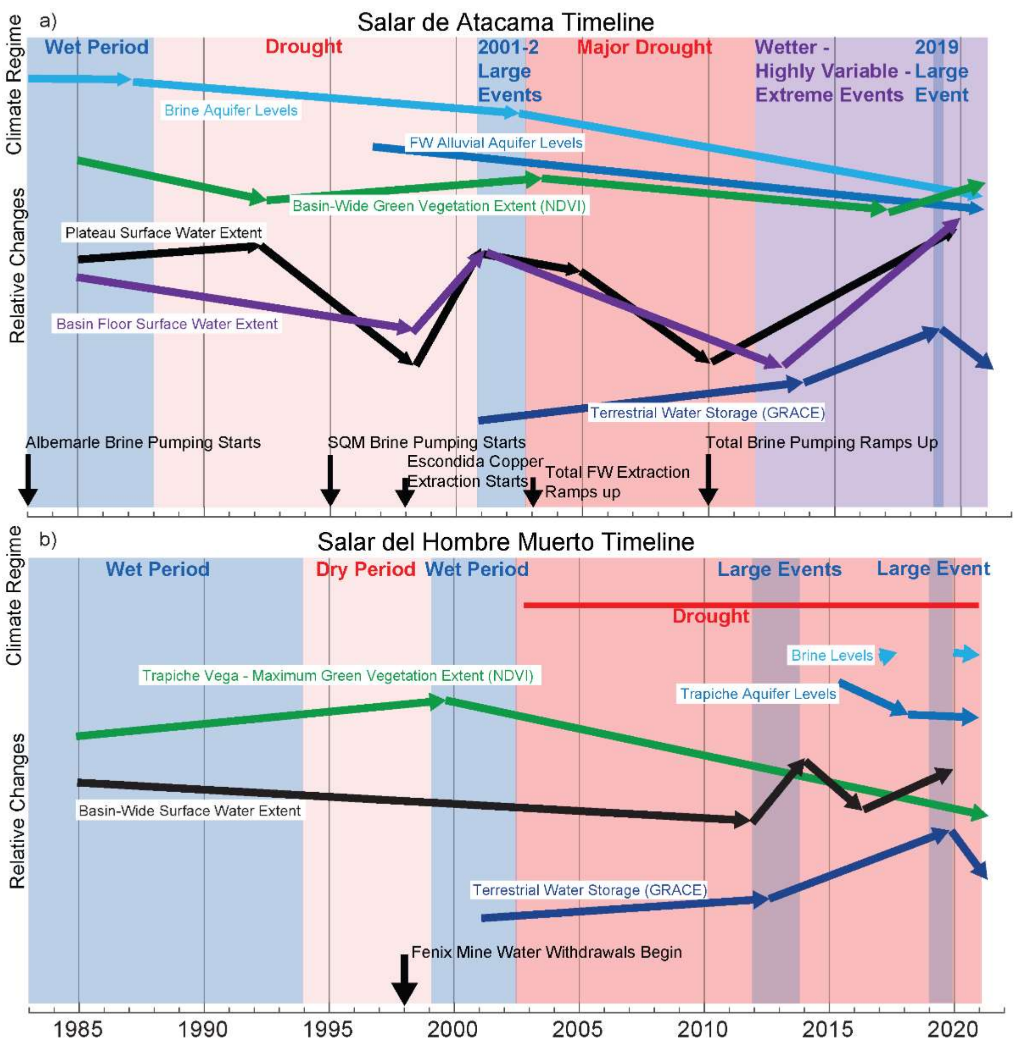

Figure 3. Relative hydroclimatic trends within the *SdA* (a) and *SdHM* (b) basins. Colored lines indicate the trend analysis from a different dataset, identified in white boxes. Climate intervals on the *Salar* floors are indicated by vertical bars and major extraction/withdrawal events are shown

This study demonstrates that in both basins *freshwater* withdrawal for lithium mining represents a small part of the total natural *freshwater* availability in the basin. It also documents the first quantification of high-resolution surface water extent changes at both *Salares* and their *watershed*s. Contradictory to claims that Salares such as *SdA and SdHM* are drying up, this study reveals that despite intensive lithium mining, both are wetter overall than 5-10 years ago. Results show limited impact on surface water features, with surface water bodies (i.e. *Lagunas*) showing more sensitivity to climate changes and *freshwater* withdrawals than lithium *brine* extraction. Thus, the fingerprint of lithium *brine* mining is not present in the *Lagunas*, and increased *brine* withdrawal does not correlate with past changes (***Figure 3***). This work establishes a key set of surface water observations that help determine their behavior. Importantly, these findings show that the impacts of climate variability and *freshwater* use are much more significant than *brine* consumption.

Salar de Atacama

Climate Variations

The *climate regime*[13] at *SdA* since 1985 was characterized by combining satellite-based and ground-based data (***Figure 3)***. This provides a framework to interpret hydrological and ecological changes over the last decades. Due to the significance and region-wide nature of the prolonged *drought* between 2003-2012, as characterized in this study, any analysis of hydrological changes since this *drought* began, needs to account for the impact it has had on the natural system. Since then, the climate at *SdA* has become wetter and more erratic, with several large precipitation events and years of above-average precipitation followed by years of below-average precipitation.

Surface Water Changes

Changes observed in the wetlands systems, such as surface water, vegetation, and streamflow correlate closely with the major *climate periods*[14]. The largest stream flowing into the basin, Rio San Pedro, also shows an overall decreasing trend through the record. The impact of the *drought*s on the river may last for several years after precipitation shortfalls end due to natural time lags in the *groundwater* system. Both the *drought*s and agricultural water use upstream of the river gauge could be causing a long-term decline in streamflow.

Water Use

Fresh water serves diverse purposes in the *SdA* basin, including mining, agricultural, and domestic use. The majority of water use permits were issued to copper mining companies, with only 10% to lithium mining companies. In 2020, the water use permits for the biggest copper mining company were withdrawn, and that water consumption ended (***Figure 4***). Actual consumption of this permitted water was calculated before and after the copper mine ceased consumption. Importantly lithium mining use remained at about 8% of the total. Agricultural *freshwater* use is primarily from surface water at a higher elevation than lithium mining withdrawals, therefore, fresh surface water resources are not impacted by mining, and they are primarily sensitive to climate variability.

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[12] *Drought:* Periods within which rain and snow are lower than average

[13] *Climate Regime:* The pattern of *climate period*s in a region over a certain time frame

[14] *Climate Period:* A period in which similar climate characteristics prevailed (i.e. *drought*, large rain events, etc.)

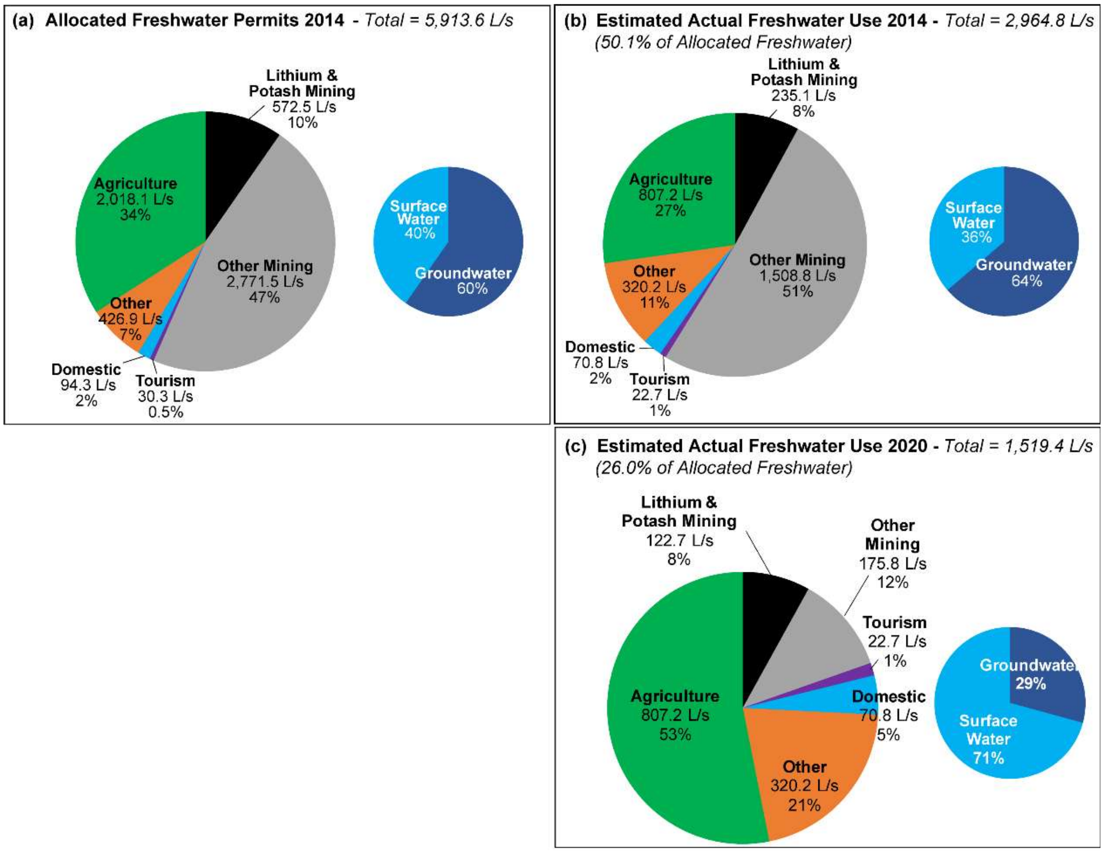

Figure 4. Allocated *freshwater* permits in the *SdA* basin in 2014, broken down by user and by water type (a); estimated actual *freshwater* use in 2014 (b); and (c) estimated actual *freshwater* use in 2020.

Impacts of Extraction

Potential drivers of change in surface water features include seasonal fluctuations in evaporation, precipitation, *groundwater* inflow, and the location and shape of the *brine-freshwater interface*[15]. Surface water extents in the *Lagunas* correlate strongly with seasonal fluctuations in evaporation. Accumulated precipitation deficits such as during the prolonged *drought* impact surface water and wetlands by decreasing *groundwater* inflows at the margin of the *Salar*. There is a strong correlation between the change in *groundwater* inflow and the change in surface water extent. An analysis of *groundwater* table elevations between 2007 and 2016 shows the largest changes occurred (2 meters of decline) in the southern *aquifer* where copper mines have extracted large amounts of *freshwater*. Elsewhere in the basin water levels have remained stable or declined by less than 0.3 meters.

The results show that previous *climate regime*s and/or fresh *groundwater* withdrawals upstream of the *Lagunas* can have a delayed impact on the *groundwater* inflow and changes in surface water extent. The strong correlation between *groundwater* inflow and surface water extent indicates that climate variations have been the primary driver of changes in surface water extent over the last few decades. This is supported by a comparison between the long-term precipitation variability and the surface water extent.

[15] *Brine-freshwater interface:* The boundary where fresh *groundwater* interacts with *brine groundwater*

Key Findings at SdA:

- A major *drought* that occurred between 2003 and 2012 is the most important factor influencing change in vegetation and surface water at *SdA* on record.
- The most recent period of extreme precipitation events is likely in part a direct result of ongoing climate change, and therefore the observed changes may be more common in the future.
- The total surface water extent in the *SdA* basin has increased by 13% since 2000.
- Changes in surface water extents adjacent to *brine* and *freshwater* withdrawal are indistinguishable from changes on the plateau in the elevated part of the basin *watershed* where no withdrawal has occurred.
- *Freshwater* consumption for lithium mining was approximately 8% of total consumption in the basin over the last decade.
- Evaporation drives seasonal changes that are evident in the expansion and contraction of the *Laguna(s)*.
- No statistically significant relationship was found between *brine* withdrawals and changes in the extent of the *Lagunas*.

Salar del Hombre Muerto

Climate Variations

The *climate regime* at *SdHM* was characterized by combining satellite-based and ground-based data to identify important changes and events (**Figure 3**). Like at *SdA*, there is a period of *drought* beginning in about 2002 which continues through the present. Also like at *SdA*, there have been several large precipitation events since 2012. Unlike *SdA*, the whole period is defined as a *drought* because annual precipitation remains below the long-term average throughout the period. The *drought* at *SdHM* was not as pronounced as at *SdA* but is connected to the same continent-scale *drought* period. This *drought* and the increase in large events in recent years have had an important impact on the natural hydrological regime in the basin.

Surface Water Changes

Changes observed in total surface water extent within the basin (excluding artificially created water bodies) are well correlated with the *climate regime* described above. Analysis of vegetation changes in the small vega near the Fenix mine shows that a correlation with precipitation was lost after the early 2000s, soon after *freshwater* pumping at the Fenix mine began to increase. Overall, the vegetation has decreased by more than half since pre-development. This reduction also coincides with the development of an artificial *laguna* over the naturally occurring wetland, which grew rapidly in size during the early 2000s presumably in response to Livent's practice of returning a mixture of *freshwater* and *brine* to the *salar* surface. According to satellite imagery and field observations, an area of permanent vegetation that existed downstream of the Trapiche River impoundment appears to have been significantly degraded, with most of the vegetation there drying up soon after its creation in the mid-1990s.

Water Use

At SdHM, there are very few long-term residents (i.e. <20 individuals) thus most of the water consumption is caused by mining. Since 1997, Livent Corp is the only lithium producer in

SdHM and they consume over 99% of extracted *brine* and *freshwater*. Though the Argentinian Ministry of Environment and Sustainable Development regulates water consumption, Livent Corp. maintains water consumption records. Total *freshwater* withdrawals have ranged from 90-120 l/s, whereas *brine* withdrawal was 300-450 l/s (2015-2020). Out of the *freshwater* consumption, 80-85% was extracted as groundwater from the Trapiche *aquifer* while the remaining *freshwater* has been extracted from the surface water created by the impoundment. Therefore, the majority of *freshwater* withdrawal occurs in a spatially confined area within the Trapiche *aquifer*.

Impacts of Extraction

Records of *brine* levels are available from 2016 to 2021 but due to the relatively short duration and inconsistencies in available data, it is not possible to establish statistically significant trends in *brine* levels at *SdHM*. *Freshwater* levels in 15 monitoring wells located in the Trapiche *Aquifer* measured from 2015 to 2020 were evaluated. Over this time, *groundwater* levels in the Trapiche *Aquifer* decreased by 0.9 m on average. For context, this change has occurred within a large aquifer of about 7 by 4 km, where the water table is quite deep (between 20 and 60 meters below the surface) and is up to 150 meters thick. Changes in water quality within the Trapiche *Aquifer* may occur due to *freshwater* withdrawals. Salinity, as a measure of water quality, was evaluated in monitoring wells located in the Trapiche *Aquifer* measured between 2016 and 2021. An increasing trend in salinity was found in 6 wells, a decreasing trend in 3 wells, and no trend in the remaining 6 wells. This indicates a reduction in fresh *groundwater* quality due to the upwelling of *brine* within some sectors of the *aquifer*. Sustained upwelling of *brine* will greatly increase the risk of a reduction in available fresh *groundwater* in the Trapiche *Aquifer* during pumping, which is a future outlook to consider in planned pumping. To this end, Livent actively manages its freshwater withdrawal program to mitigate brine upwelling from pumping in concentrated areas, including installing new production wells, decommissioning other wells, and adjusting individual well pumping rates.

Key Findings at SdHM:

- *Climate periods* in the region and within the basin were identified, correlating well with surface hydrology changes observed since the 1980s.
- Surface water occurrence in the *SdHM* basin has increased by 97% since 2000.
- At *SdHM* current water withdrawal is primarily linked to mining.
- Since pre-development, the vegetation in the wetland area near the Fenix mine camp has more than halved in size.
- *R*e-infiltration of *brine* and *freshwater* from lithium mining activities has formed an artificial *Laguna* in the vicinity of a former natural wetland.
- On average, *groundwater* elevations in the Trapiche *Aquifer* decreased slightly and some sections of the *aquifer* became more saline from 2015 to 2020.
- Changes in both climate and *freshwater* withdrawals affect *groundwater* levels and surface water extents, climate is the dominant driver of hydrological changes observed at SdHM.

How do groundwater storage changes influence groundwater discharge from the aquifer?

Introduction

This chapter focuses on the relationship between *groundwater* movement and stresses on *groundwater* availability. Fresh *groundwater* replenishes the *Lagunas*, and the extent of the *brine* determines their location, but little is known about how *brine* or fresh *groundwater* pumping impacts the *Lagunas* over space and time.

1. How hydraulically connected are the brine and freshwater?
2. What controls the extent of the freshwater Lagunas?
3. How would the evolution of the transition zone influence the Lagunas?
4. What is the role of climate variability on changes to Laguna extent?
5. What are the timescales of response to freshwater and brine pumping?

"Simulations and geologic models are the keys to more accurately predicting groundwater flow"

Geologic & Hydrogeologic Framework for Groundwater Flow Simulations

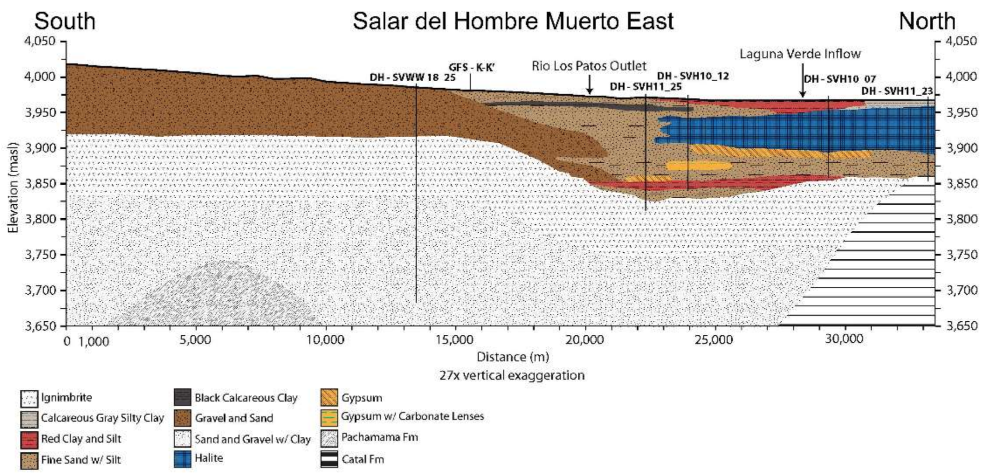

Figure 5. 2-Dimensional view of the geological conceptual model of the *SdHM* Eastern basin with surface geological units color coded. Data sites used to build the model are labeled.

Simulations and geological models are the keys to more accurately predicting *groundwater* flow. Based on drill core data from the *SdA* and *SdHM*, 2-dimensional geologic interpretations are developed (**Figure 5; Appendix A2**). Additional analysis of field hydraulic testing defines how fast water can flow through the studied rocks. The combined results provide the base for computer simulations of *groundwater* flow for each 2-dimensional hydrogeologic cross-section. Modelers apply different pumping rates for *brine* and fresh *groundwater*. The results of the simulations provide insight into both the timing and quantity of change in *groundwater* flow in response to different pumping scenarios.

[16] *Groundwater storage:* Amount of water that is stored in an aquifer at any given time

[17] *Groundwater discharge:* Water that naturally flows from beneath the ground to the Earth's surface

Findings

Analysis of Groundwater Discharge

In our analyses, we define *groundwater discharge* as the amount of fresh *groundwater* leaving the *aquifer* to the surface. *Groundwater discharge* is an important predictor of how much water potentially enters the *Lagunas* at each *Salar*. Results from the *groundwater* simulation experiments suggest that *groundwater discharge* significantly decreases during fresh *groundwater* pumping. When *brine groundwater* is pumped, the amount of *groundwater discharge* remains relatively unchanged. Since some lithium producers are planning to pump *groundwater* from the transition zone (**Figure 2**), scenarios also include pumping from the brackish areas of the *aquifer* where fresh *groundwater* transitions to *brine*. Simulations showed increasing *groundwater discharge* rates in the *brine groundwater* zone while rates decreased in the fresh *groundwater* zone. This highlights the importance of *freshwater* availability for *groundwater discharge* and therefore the ecologically valuable *Lagunas*.

Response Time Analysis

For each model, the time that it takes for the *groundwater* flow to respond to different pumping scenarios was analyzed. *Groundwater discharge* changed most rapidly when pumping from the transition zone and fresh *groundwater* and most slowly when pumping *brine*. This observation is likely due to the differences in the physical properties of each type of water: the denser *brine* underlies the fresh *groundwater* and acts as a more stable fluid, while the more buoyant fresh *groundwater* can upwell at the surface and move more quickly. These simulations further support the notion that the *brine* and fresh *groundwater* systems of the *aquifer* behave very differently, and are effectively disconnected from each other.

Spatial Evolution of Brine

Model scenarios show how the transition zone between *brine* and fresh *groundwater* would move in response to pumping. All scenarios demonstrate the transition zone migrating closer to the *brine*-rich areas of the *aquifer*. However, the transition zone extends furthest toward the *brine* during both the *brine* and the transition zone pumping scenarios. This expansion of the transition zone is important because it suggests that the *Lagunas*, which exist wherever the fresh *groundwater discharge*s and pools, may migrate under lithium extraction.

Implications for Groundwater Sustainability

While *brine* pumping may influence the location of the *Lagunas*, *freshwater* pumping mainly influences the extent of the *Lagunas*. As a result of the different flow behavior in *brine* versus fresh *groundwater*, pumping activities occurring in one area of the *aquifer* do not readily affect *groundwater discharge* at another part of the *aquifer*. However, it is important that pumping especially in fresh *groundwater* areas of the *aquifer* will potentially decrease surface water extents by decreasing *groundwater discharge*. Since temperatures are predicted to increase further due to global climate change, it is worth noting that evaporation rates will likely increase. *Laguna* extent may also decrease as a result of increased surface water evaporation and decreasing net fresh *groundwater recharge*[18].

[18] *Groundwater recharge:* Water that infiltrates from the surface and re-fills aquifers

Impacts of brine and freshwater removal in SdHM

Introduction

The magnitude of impacts and environmental sustainability depends on specific characteristics of the hydrogeological system and hydrological stresses on the water in the basins. This chapter focuses on climate influences, changes in hydrological functioning/conditions due to lithium extraction, as well as current and future rates of water use by different lithium producers. The following questions were targeted to address these issues, the answers to these questions are described in the Key Findings section below.

1. How responsible are current and projected brine and fresh groundwater withdrawals associated with lithium mining at Salar del Hombre Muerto?
2. What are the potential impacts of this water use on the environment?
3. What are the thresholds for impacts and how do these compare to those at Salar de Atacama?

Although Livent's project is currently the only Lithium mine operating at SdHM, two others are expected to be operational in the next few years, Allkem and Galan. A third is POSCO in the far northern part of the basin and outside the model domain. This chapter evaluates the potential for *brine* and *freshwater* withdrawals to impact the wetland and aquatic systems within each subbasin. In the Eastern Subbasin of *SdHM*, the Rio Los Patos is a river system that flows northward and westward, before infiltrating into the salar near *Laguna* Catal. Along its watercourse, the Rio Los Patos flows through a series of *lagunas* and hosts a variety of wetland and aquatic habitats that range from fresh to *brine* water quality. The Western Subbasin is at a lower elevation and is generally drier than the Eastern Subbasin. In the Western Subbasin, Rio Trapiche flows from towards the northwest, where it infiltrates into the Trapiche *Aquifer*. A map describing these features is provided in the Appendix A2.

"The magnitude of impacts […] depends on specific characteristics of the hydrogeological system"

Methods

The relative impacts of withdrawals on water quantity and quality around the critical wetland and aquatic systems in the *SdHM* Eastern Subbasin are defined using a three-dimensional, numerical, density-dependent *groundwater* flow model **(Figure 6**).

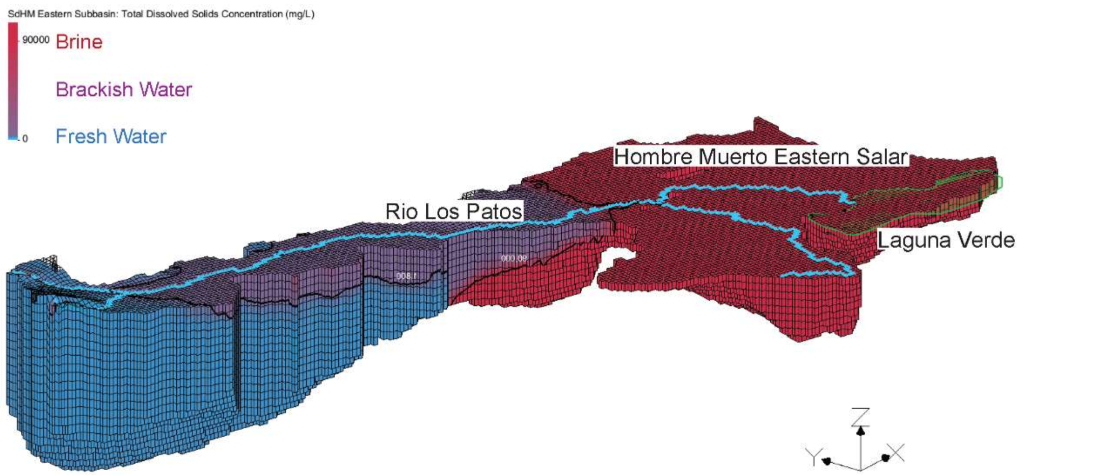

Figure 6. Numerical simulation salinity in the Eastern Subbasin of *SdHM* showing the position and distribution of the fresh (blue), *brackish* (purple), and *brine* (red) waters in the *aquifers* beneath the Rio Los Patos and the eastern subbasin *Salar* after simulated withdrawals.

In the Western Subbasin, *groundwater*-surface water interactions are investigated to identify zones of potential environmental impacts. Water movement throughout the basin and its *watershed* as well as precipitation, *groundwater recharge* (infiltration), streamflow, and evaporation were investigated.

The models were designed to visualize present natural conditions in the hydrological system of the basin. To predict possible impacts of mining operations in the future, a total of six extraction scenarios were defined with current rates (Livent) and two future projection intervals. The final extraction phase of each scenario ran for 30 years (to 2059).

1. Livent only
2. Allkem only
3. Galan only
4. All users at once
5. All users, minimum scenario (assuming Galan does not start production by 2030)
6. All users at once in a high extraction scenario - all rates multiplied by a factor of 3

Water age tracing data from the rivers, springs, and *groundwater* provides invaluable insight into sources and transport to specific locations and supports interpretations of the model results. The radioactive isotope tritium (^3H) allows the distinction between the proportion of recent precipitation and relatively old (>70 years) water in the body. About 30 sites were sampled in the *SdHM* basin between 2019-2021 providing an accurate survey of the major water bodies in each basin. A more detailed description of these methods can be found in the forthcoming publication, "Resilient *brine* and *freshwater* extraction for lithium resources in the *Salar* del Hombre Muerto basin".

Findings

Based on this analysis the key findings of this work are organized under the focus questions asked in the introduction:

1. *How responsible are future brine and fresh groundwater withdrawals associated with lithium mining at Salar del Hombre Muerto?*

- Expansion of extraction activity in the Eastern Subbasin will result in localized *groundwater* level drawdowns of less than 1 meter and will likely have no observable *aquifer*-scale impacts on *groundwater* levels over the next 100 years.
- Expansion of extraction activity in the Eastern Subbasin at expected *brine* and fresh *groundwater* withdrawal rates is unlikely to result in significant impacts on streamflow in the Rio Los Patos or on inflows to *Laguna* Verde and *Laguna* Catal over the next 100 years.
- Based on current projections, *freshwater* withdrawals from the western subbasin are expected to decrease with time, therefore no additional significant impacts are expected beyond those already documented in the Trapiche *Aquifer*.

2. *What are the potential impacts of this water use on the environment?*

- The impact of mining operations on one of the two wetlands and aquatic habitats in the Trapiche *Aquifer* as documented in Chapter 4 occurred because of their reliance on surface water rather than *groundwater*, and its restoration depends on restoring natural surface water flows.
- There currently is not sufficient data for other small *Vegas* in the Eastern Subbasin to estimate future impacts on them from *brine* withdrawals, but extraction rates and other

modeling results from Chapter 5 and the Eastern Subbasin model in this chapter 6 do not indicate further impacts in this area.

3. *What are the thresholds for impacts and how do these compare to those at Salar de Atacama?*

- Age tracer results at *SdHM* and *SdA* show basin *groundwater* is primarily composed of relic (old) waters, buffering any impacts from human and natural changes.
- Surface waters (streams and *Lagunas*) have a larger amount of young water in them which means these water bodies are more responsive to impacts from disruptions in flow and also climate changes.
- Since the flow direction of the Rio Los Patos is downward into the *aquifer* over most of the eastern subbasin model domain, *groundwater* pumping effects on streamflow will be minimal. However, this finding exposes the increased sensitivity of the system to climate-related changes and potential land use disruptions of surface water.
- The lower Trapiche vega, located along a narrow band at the margin of the *Salar*, which has already decreased as documented in Chapter 4, is unlikely to be restored under the expected development scenarios.

How does water consumption differ among lithium production techniques?

Introduction

While lithium extraction requires *brine* pumping, the refinement of lithium for use in batteries requires different amounts of *freshwater*. The determination of *freshwater* consumption is imperative to fully understand the environmental impacts of lithium production. This research project, therefore, addresses the following questions:

1. What is the freshwater use from lithium mining operations in relation to the production of lithium carbonate and lithium hydroxide?
2. What is the impact of freshwater use and how does it depend on the hydrological stresses in the basins?

This work specifically focused on the two main processes that are currently in use in the Lithium Triangle. One process primarily uses evaporation pools/ponds of pumped *brine* to concentrate lithium until it reaches a sufficient grade for transportation to an off-site processing facility. The second process involves a set of methods known as Direct Lithium Extraction (DLE), where the *brine* is pumped and the lithium is extracted and processed directly from that *brine* on-site. There are several DLE techniques currently in development that require varying amounts of freshwater. The only processes of this kind currently operating in the Lithium triangle utilizing a method known as adsorption was assessed here. *Freshwater* and energy demand of these two primary methods are compared to lithium extraction from hard rock.

"The refinement of lithium for use in batteries requires freshwater"

Methods

Two methods for characterizing the impacts of different lithium production techniques are applied: a direct assessment of fresh *groundwater* consumption and a comparison of *freshwater* consumption within the context of water scarcity for the basins in which lithium production is occurring.

Assessment of Freshwater Consumption from Different Lithium Extraction

Researchers focused on clarifying the demands on fresh *groundwater* consumption from each type of production by comparing the amount of *freshwater* used to develop one kilogram of battery-grade lithium product. Comparing the lower-energy options of evaporation pools and DLE, there is a distinct difference between *brine* and *freshwater* demands. For *brine* demands, evaporation pools create a 1:1 ratio between the rate of *brine* production and the consumption losses via evaporation to the atmosphere; whereas DLE through its absorption process returns an estimated 50-60% of *brine* back to the *aquifer*. However, compared to *brine*, this method uses five times more *freshwater* than evaporation ponds. Overall, current Direct Lithium Extraction (DLE) technologies require significantly more *freshwater* than conventional methods. While *freshwater* consumption is minor in comparison to *brine* consumption, given its importance in influencing *groundwater discharge* to surface water, it is important to note that *freshwater* consumption depends on the extraction process.

Water Scarcity Assessment in the Lithium Triangle

The utilized AWARE (Available WAter REmaining) method identifies available water after human and ecosystem consumption on an annual basis. Findings from all basins that have elevated concentrations of lithium show areas of relatively higher water availability, demand, and remaining water following the current *freshwater* consumption rates (***Figure** 7*). Focusing on the basins with the most available data findings indicate that *SdA* has a negative balance of remaining *freshwater* (more water is leaving the system through evaporation and withdrawal than is naturally entering) after considering all estimated consumption. Conversely, SdHM has a positive balance of remaining freshwater, even after considering the amount of fresh groundwater used for lithium production. These comparisons show the significance of environmental impacts from lithium production techniques and highlight the importance of considering surrounding water stress on current and future projects.

ID	Basin	AMD (mm/yr)
1	Salar de Surire	24
2	Salar de Uyuni	7
3	Laguna de Guayatayoc	24
4	Salar de Pujsa	5
5	Salar de Jama	6
6	Laguna Lejia	4
7	Salar de Atacama	2
8	Salar de Olaroz-Cauchari	8
9	Salinas Grandes	13
10	Laguna Miscanti	5
11	Laguna Miñiques	4
12	Laguna Tuyajto	5
13	Salar del Rincon	5
14	Salar de Pular	3
15	Salar de Pastos Grandes	10
16	Salar de Pocitos	5
17	Salar de Punta Negra	1
18	Salar de Pozuelos	6
19	Salar de Arizaro	3
20	Salar de Llullaillaco	2
21	Salar de Ratones-Centenario	9
22	Salar Tolillar	5
23	Salar de Rio Grande	3
24	Salar de Diablillos	10
25	Laguna Caro	7
26	Salar del Hombre Muerto	8
27	Salar de Antofalla	4
28	Diamante	10
29	Salar de Carachi Pampa	6
30	Salar de Incahuasi	5
31	Salar de Maricunga	2
32	Tres Quebradas	7

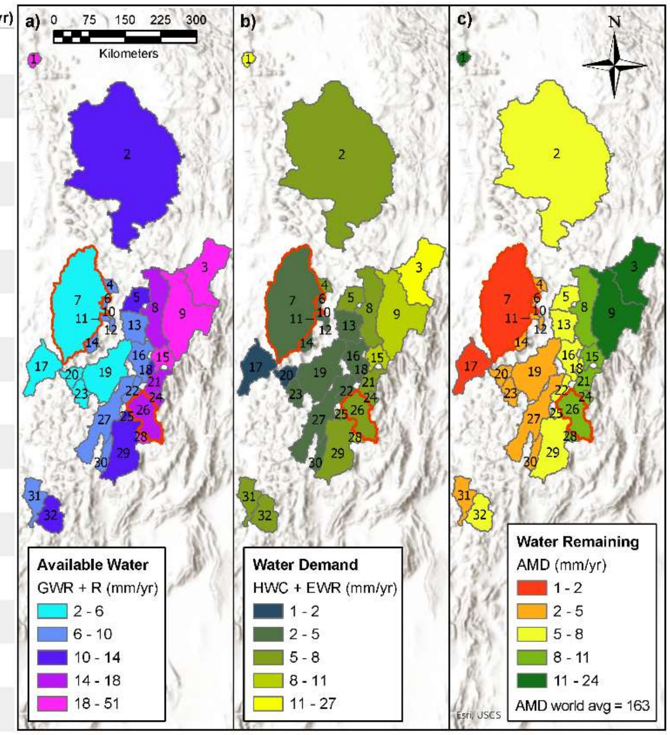

Figure 7. Inputs and outputs of the AWARE method showing available water (a), water demand (b), and availability minus demand (AMD) (c) for the 32 basins we studied with active or potential lithium projects in the lithium triangle. The components parts are defined as Groundwater Recharge (GWR), Runoff or streamflow (R), Human Water Consumption (HWC), and Environmental Water Requirements (EWC). The red text for basins in the left portion of the figure highlight which basins have active or advanced projects. AMD for these basins is extremely low compared to the world average (163 mm/yr). SdA and SdHM basins are outlined in red.

Findings

All types of lithium production from *brine* rely on pumping *brine* and fresh *groundwater*, but some refinement methods require more *freshwater* than others. This work compares two types of refinement for lithium in water: evaporation ponds versus DLE. A major finding is the higher amount of *freshwater* required for DLE compared to the evaporation pond process. While the AWARE method suggests that some basins still have available *freshwater* remaining after considering all estimated consumption, it is important to note that fresh *groundwater* pumping will impact *groundwater discharge*, as considered by the AWARE method.

This work highlights the importance of considering not only the *freshwater* demands during lithium production and the water stressors in the basins. In terms of Life Cycle Assessments (LCAs) for lithium-ion batteries, it is further important to note that consideration of *freshwater* consumption is still not commonly considered in the production of batteries. A major outcome of this work package is the need to incorporate *freshwater* consumption and specifically apply methods like AWARE into LCAs.

Conclusions

Conclusions

Research on lithium-rich desert basins in South America yields insight into the impact of climate and mining activities on the availability of water resources, important to ecosystems, communities, and industry. An important finding of the research is the importance of fresh *groundwater* withdrawal, which influences total *freshwater* availability for humans and the ecosystems that rely on it. *Brine* withdrawal has a limited influence on the surface water bodies that constitute important habitats. The timescales of impacts differ significantly between *freshwater* and *brine* withdrawal, with the effects of *brine* removal taking much longer to occur compared to *freshwater*. The analysis stresses not only the necessity of considering *freshwater* consumption in lithium production but also having *groundwater* monitoring programs in place to track changes in *groundwater* levels for long periods. Climate variations play a key role in the availability of *freshwater* and the variations in *Laguna* and wetlands size. The major *drought* between 2003-2012 affected the entire Lithium Triangle area, including Salares de Atacama and del Hombre Muerto, where most data was accessible. The data show a strong impact of the *drought* on *groundwater*-fed wetlands and surface water bodies in these areas, highlighting the importance of considering the current and future influence of global climate change on these environments when assessing water-related mining impacts.

This study was conducted focusing on the two primary *brine*-producing basins at present, *SdHM* and *SdA*. Every *Salar* in the Lithium Triangle has slightly different ecosystem and climate characteristics that influence *brine* concentrations, fresh *groundwater* availability, the position of the transition zone, and the sensitivity of wetlands ecosystems. This study offers a comprehensive methodology to be replicated at other *Salares* and lithium-bearing basins to research location-specific impacts of lithium production. This is especially important to evaluate the responsibility of new lithium producers.

Appendix

Peer-Reviewed Journal Articles

Published

1. “Relic Groundwater and Prolonged Drought Confound Interpretations of Water Sustainability and Lithium Extraction in Arid Lands” published 12, July 2022 in the journal “Earth’s Future” (https://doi.org/10.1029/2021EF002555)
    - Presents the findings in Chapter 4 from SdA. The findings from SdHM are included in the in-preparation publication below.

In Review

2. "Constraints on groundwater abstraction impacts in lithium brine systems" submitted 16 May 2023 to the journal Nature Geoscience
    - Presents the findings and detailed methods from Chapter 5 for SdA and SdHM

In Preparation

3. “Hydrologic signatures on Laguna complexes & wetland inundation in the lithium triangle” - expected submittal to the journal Nature Water in August 2023
    - Presents the findings on surface water, vegetation, and climate changes in Chapter 4 applied to the whole Lithium Triangle region
4. “Estimates of freshwater availability in and across the Lithium Triangle: Implications of lithium brine extraction” - expected submittal to the journal Nature Sustainability in August 2023
    - Presents the findings from Chapter 7 applied to the whole Lithium Triangle region
5. “Distinctions in surface water and groundwater interaction across a lithium brine producing basin: Implications for water resources” - expected submittal to the journal PLOS Water in October 2023
    - Presents the findings from Chapters 4 and 6 from SdHM
6. “Resilient brine and freshwater extraction for lithium resources in the Salar del Hombre Muerto basin” - expected submittal to the journal Scientific Reports in November 2023
    - Presents the findings from chapter 6 in SdHM
7. “Drivers of changes in surface water extents of the Salar de Atacama watershed, Chile” - expected submittal to the journal Hydrological Processes in November 2023
    - Presents the findings on surface water, vegetation, and climate changes in Chapter 4 with particular detail at SdA

Definitions

Aquifer	Earth below ground that holds water
Brackish water	Moderately salty water, between water suitable for livestock watering and up to 3 times saltier than seawater. Not suitable for drinking or irrigation.
Brine	Highly saline *groundwater*, at least 3 times saltier than seawater, not suitable for drinking, irrigation, or livestock watering
Brine-freshwater interface	The boundary where fresh *groundwater* interacts with *brine groundwater*
Climate period	A period in which similar climate characteristics prevailed (i.e. *drought*, large rain events, etc.)
Climate regime	The pattern of *climate periods* in a region over a certain time frame
Drought	Periods within which rain and snow are lower than average
Evapoconcentration	Process of progressive evaporation increasing salt concentrations in water
Evapotranspiration	The combination of evaporation and plant transpiration
Freshwater	Water that has little or no salt and is suitable for drinking, irrigation, and livestock
Groundwater	Water that is located within the ground/under the Earth's surface
Groundwater discharge	Water that naturally flows from beneath the ground to the Earth's surface
Groundwater recharge	Water that infiltrates from the surface and re-fills *aquifers*
Groundwater storage	Amount of water that is stored in an *aquifer* at any given time
Laguna/Lagunas	Surface water bodies that lie on the edge of a *Salares*
Salar/Salares	Salt flats located on the floors of basins
SdA	The *Salar* de Atacama, Chile
SdHM	The *Salar* del Hombre Muerto, Argentina
Vegas	*Groundwater*-fed wetlands that lie on the edge of *Salares* or near permanent surface water bodies
Watershed	The area within which all rainfall or snowfall that falls ultimately drains to a specific point or area
Water budget	The balance between all water entering a basin and all water leaving a basin over a specified timeframe. Can be positive or negative

Maps of SdA and SdHM Basins

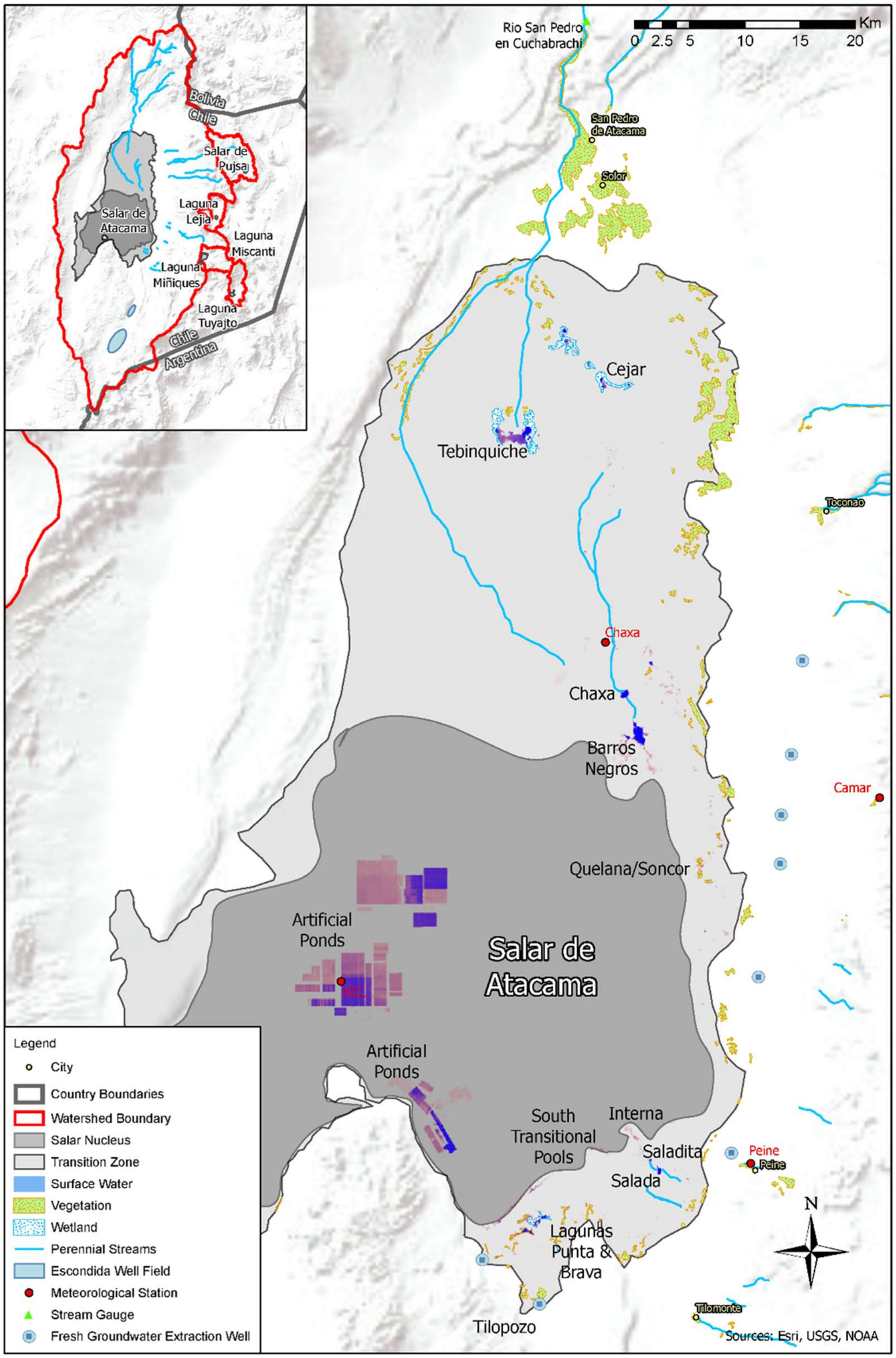

Figure A1. Map of SdA with identified surface water features, vegetation, local communities, and mining operations in the area.

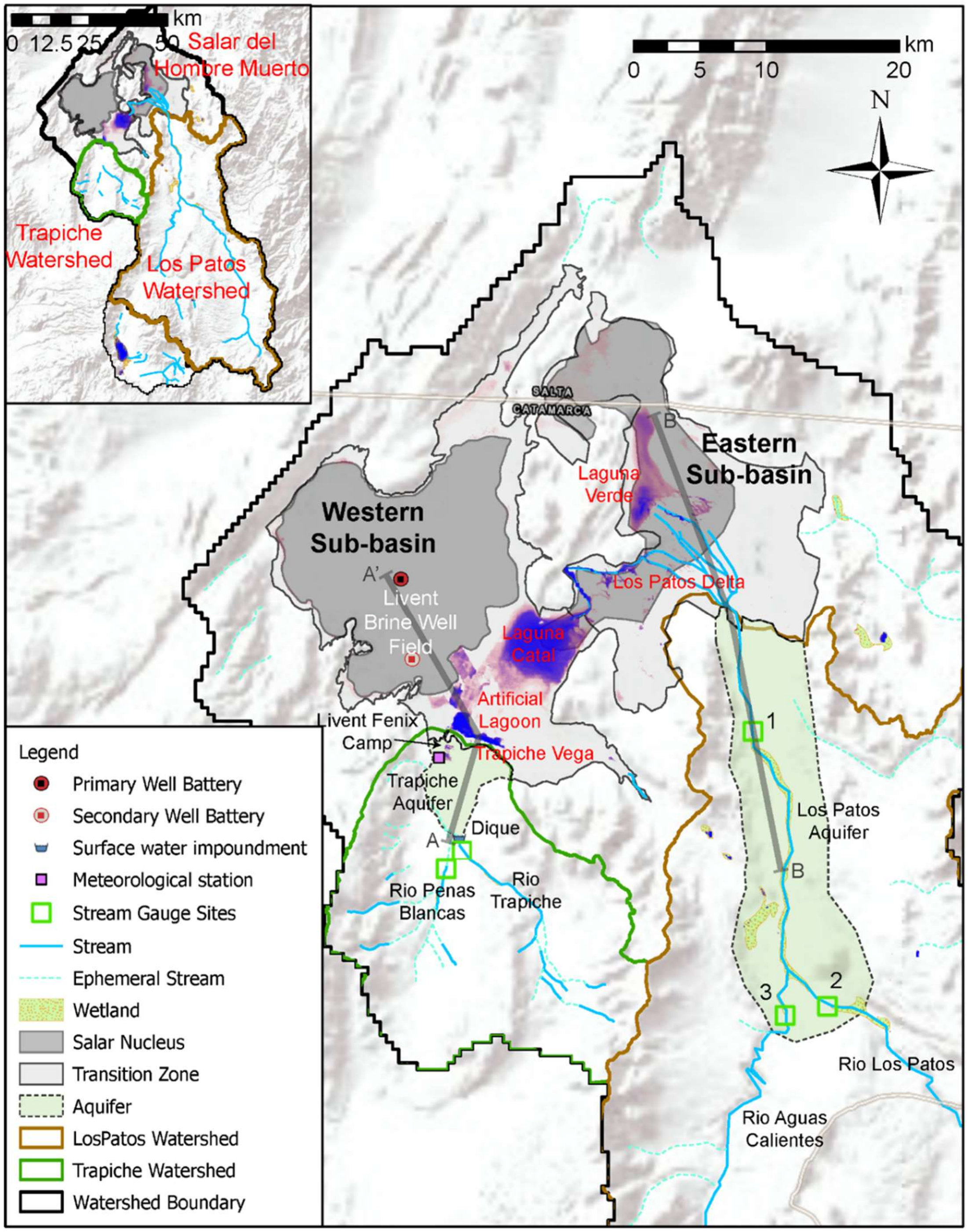

Figure A2. SdHM basin and its two subbasins (West and East) with important hydrological features and monitoring sites. The geological transects developed in this work are shown as gray lines, line B-B' is shown in **Figure 5** of the above document. The whole basin watershed (bold black line) is shown in the inset with the two primary sub-watersheds (Trapiche and Los Patos). The numbered stream gauge sites (green squares) correspond to the observation points identified in the document.