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Modeling the impacts of Lithium Brine Mining on Water Resources in South American Salars

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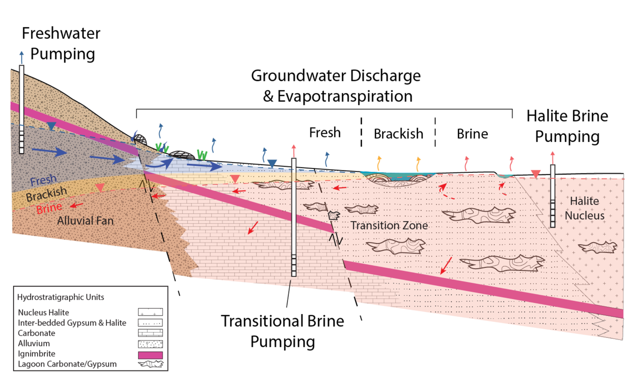
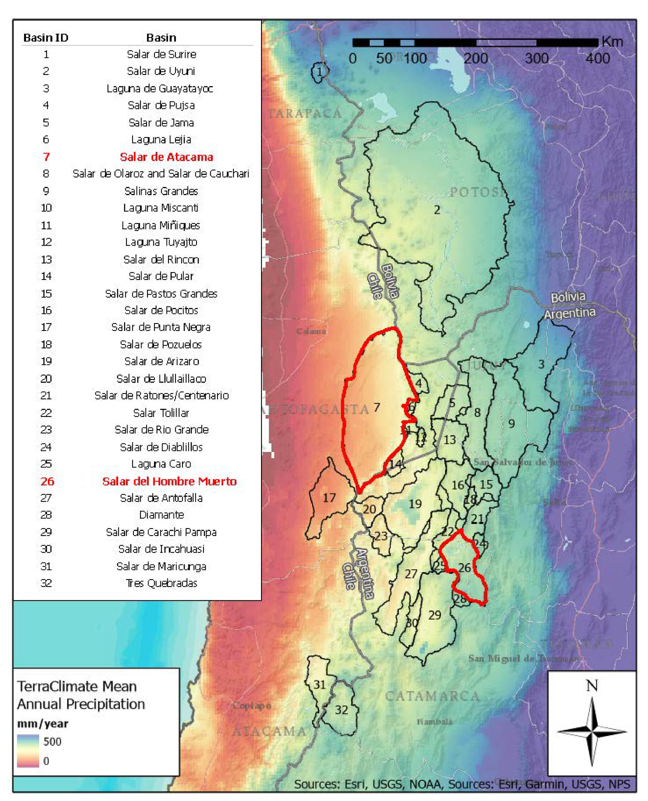
Introduction

The salar systems of the South American Altiplano are complex hydrogeologic environments occurring in arid and semiarid endorheic basins. In these systems, groundwater discharge is the most significant source of water to ecologically sensitive wetlands and lagoons surrounding the salar. Brine forms underneath these salars and their transition zones, and these brine aquifers host important mineral resources, most notably lithium. Mining these brine bodies involves withdrawals of large volumes of both brine and fresh groundwater. However, the potential impacts of these withdrawals on wetland and aquatic ecosystems are not well constrained. Moreover, recent increases in mining interest in two of these basins – Salar de Atacama and Salar del Hombre Muerto – has raised concerns over the sustainability of lithium extraction in these environments.

This study evaluates the potential impacts of brine and freshwater withdrawals at Salar de Atacama, Chile and Salar del Hombre Muerto, Argentina by utilizing numerical, density-dependent groundwater flow models. The contrast between these two basins with distinct hydrogeologic characteristics and climate regimes provides separate endpoints to compare and isolate the effects of brine and groundwater withdrawals. Salar de Atacama is a mature salar system with a large and well-defined halite nucleus, whereas the Salar del Hombre Muerto Eastern Subbasin is a less mature salar system with a poorly defined halite nucleus overlain by clastic sediments. This study evaluates the effects of fresh groundwater and brine withdrawal perturbations on simulated groundwater discharge and compares the relative sensitivity of each end member to changes in brine extraction and fresh groundwater withdrawals.



Conceptual cross section showing potential natural and anthropogenic drivers of groundwater discharge. Natural drivers include groundwater inflow, evapotranspiration, surface water features, and hydrogeologic properties of the subsurface (hydraulic conductivity). Anthropogenic drivers include fresh groundwater pumping and brine pumping from the halite nucleus or transition zone.

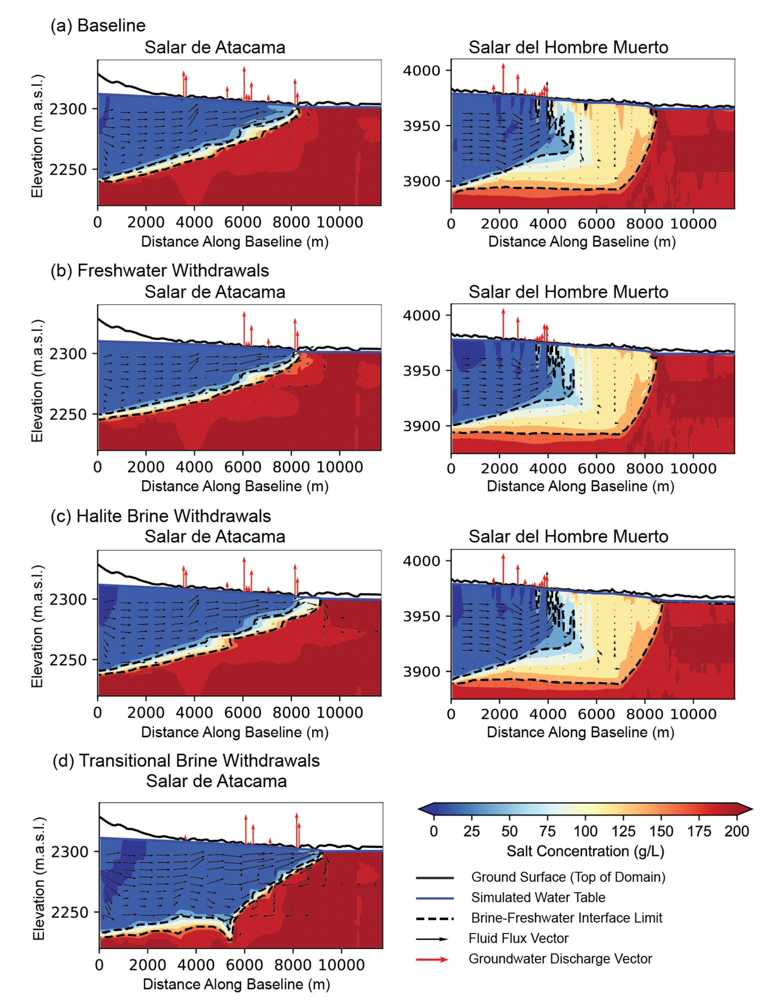


Map showing the locations of Salar de Atacama and Salar del Hombre Muerto with color relief of mean annual precipitation derived from the TerraClimate dataset.

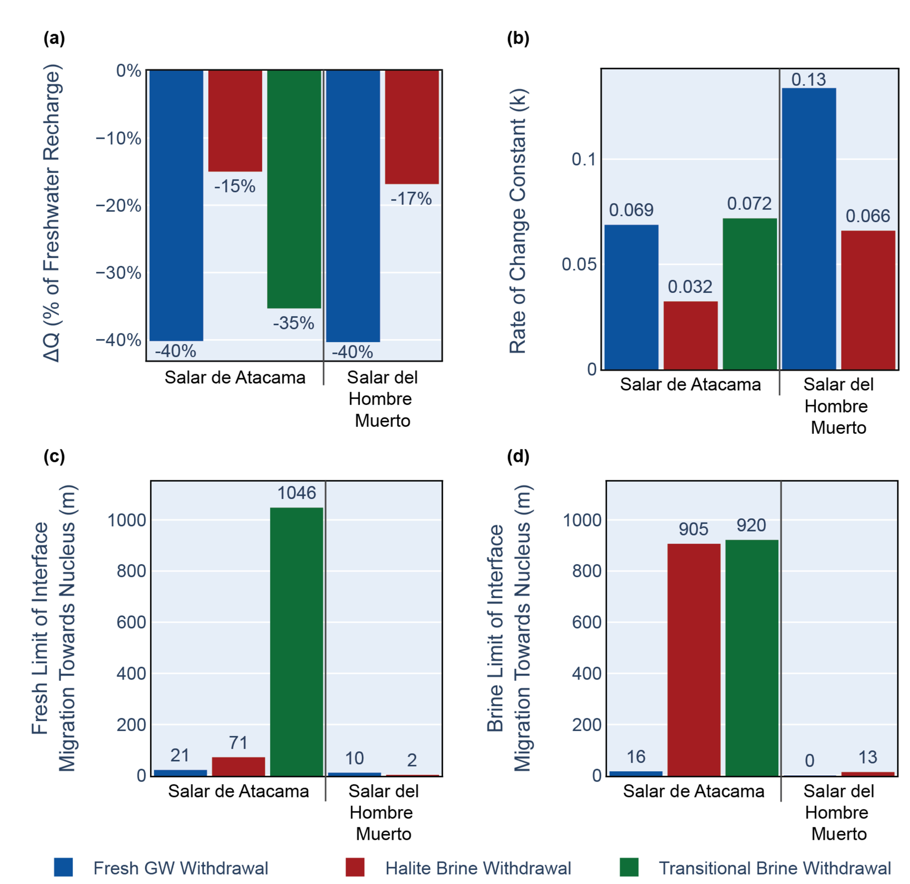
Background

Salar de Atacama and Salar del Hombre Muerto are located in the Lithium Triangle region of the South American Altiplano. These topographically enclosed basins have low groundwater recharge and high evaporation rates, which causes the formation of evaporites and high-salinity groundwater (brine). These brines are often enriched in lithium and are the target of expanding lithium mining activities in the region. Fresh groundwater flows towards the basin floor from the basin margins, where it encounters the brine body expanding out from the nucleus in the transition zone. Where these two fluids meet, a brine-freshwater interface forms which occurs as a relatively narrow zone of mixing between the two fluids with differing densities. Fresh and brackish groundwater comes to the ground surface (discharges) within the transition zone, forming springs and most of the recharge to wetlands, rivers, and lagoons. Surface water features in these environments are ecologically sensitive habitats for vulnerable species, including the Andean flamingo, and many are also culturally significant to indigenous peoples, collectively called Atacameños. Understanding the potential impacts of fresh groundwater and brine withdrawals on spring discharge in these basins is critical for protecting these ecologically and culturally significant habitats.

Salar del Hombre Muerto with ignimbrite outcrops in foreground and salar nucleus with lithium mine in background



Simulated flow dynamics for the Salar de Atacama and Salar del Hombre Muerto Eastern Subbasin models for four scenarios: (a) baseline with no freshwater or brine withdrawals, (b) freshwater withdrawals at 40% of the fresh groundwater recharge rate, (c) halite brine withdrawals at 40% of the fresh groundwater recharge rate, and (d) transitional brine withdrawals at 40% of the fresh groundwater recharge rate.



Salar de Atacama and Salar del Hombre Muerto Eastern Subbasin simulation results for fresh groundwater (blue), halite brine (red) and transitional brine (green) withdrawals at 40% of the fresh groundwater recharge rate for 4 metrics: (a) change in groundwater discharge (ΔQ) as a percentage of fresh groundwater recharge, (b) exponential decay rate of change constant (k) for simulated groundwater discharge, (c) migration of the fresh limit of the brine-freshwater interface towards the nucleus, and (d) migration of the brine limit of the brine-freshwater interface towards the nucleus.

Results

We evaluate the simulation results using four metrics: change in total groundwater discharge (ΔQ), rate of change in total groundwater discharge, and migration of the water table expression of the brine-freshwater interface fresh and brine limits. The change in total groundwater discharge characterizes the relative change in the amount of groundwater discharging to wetland and aquatic habitats. As withdrawals occur, groundwater discharge decreases according to an exponential decay function as defined by:

$$\Delta Q = Ae^{-kt} + c_0$$

where t is time, A is the initial groundwater discharge value, c_0 is an offset term, and k is the rate of change constant. Where k is higher, groundwater discharge decreases at a faster rate than when k is lower. The brine-freshwater interface is a zone of mixing, with a fresh limit and a brine limit. The position of the interface at the water table determines whether the quality of the groundwater discharge to wetland and aquatic habitats is fresh, brackish, or brine. As the interface limits move towards the nucleus, groundwater discharge becomes fresher.

We find that fresh groundwater withdrawals cause the greatest decrease in groundwater discharge, with a 1:-1 relationship between fresh groundwater withdrawals and ΔQ. For any amount of fresh groundwater withdrawn, total groundwater discharge will decrease by the same amount. Halite brine withdrawals reduce total groundwater discharge by considerably less, but transitional brine withdrawals reduce total groundwater discharge more than halite brine withdrawals. Additionally, groundwater discharge responds more rapidly to fresh groundwater and transitional brine withdrawals than halite brine withdrawals. We found considerable brine-freshwater interface migration in the Salar de Atacama model induced by brine withdrawals, but no significant migration in the Salar del Hombre Muerto Eastern Subbasin model. The pre-existing brine-freshwater interface in the Salar del Hombre Muerto Eastern Subbasin model is very wide, which buffers interface migration. Therefore, brine withdrawals may induce brine-freshwater interface migration towards the nucleus depending on hydrogeologic conditions.

Discussion

Lithium brine mining operations have a choice of a variety of traditional evaporation pond and direct lithium extraction (DLE) mining technologies. These technologies all involve a trade off between net brine withdrawal and freshwater consumption. Some withdraw more brine but use less freshwater, while others withdraw less brine but use more freshwater. These results indicate that technologies that minimize freshwater use may have less impacts on wetland and aquatic habitats. As demand for lithium increases, some mines may expand production from halite brine to transitional brines. These results indicate that transitional brine mining may have more impacts on wetland and aquatic habitats than halite brine mining.

Acknowledgements

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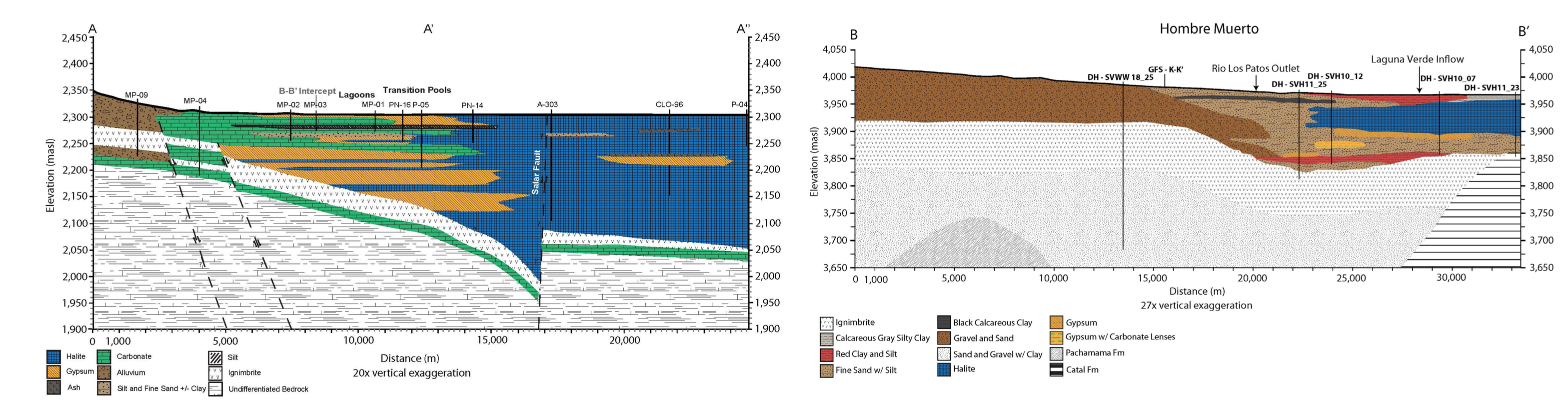
Laguna (wetland) at Salar de Atacama

Model Framework

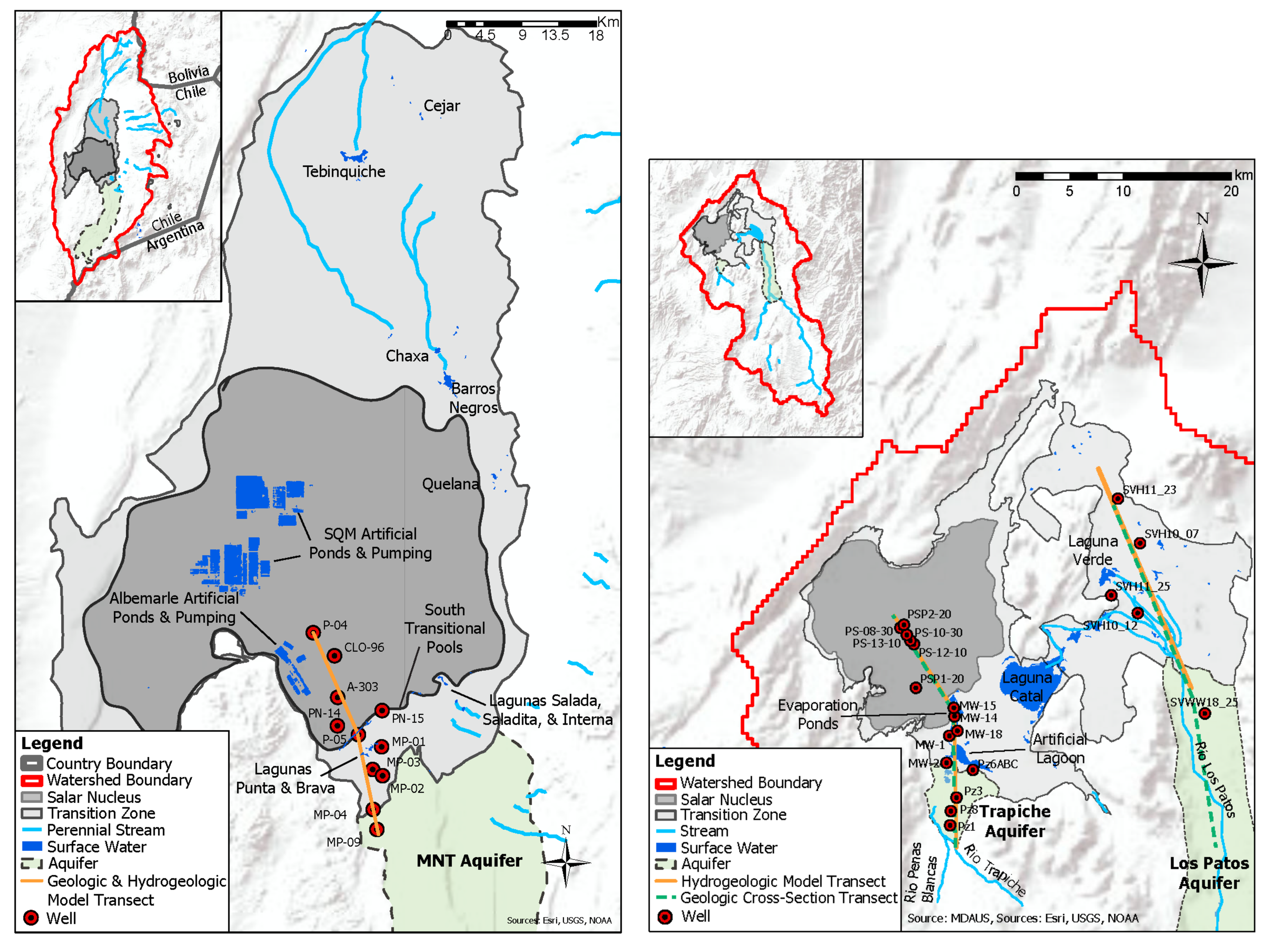
We developed hydrogeologic conceptual models for Salar de Atacama and the Salar del Hombre Muerto Eastern Subbasin. The conceptual models include hydrostratigraphic units with unique hydraulic conductivity and storativity values. We used these conceptual models to create two-dimensional, numerical, density-dependent groundwater flow models using the USGS program SEAWAT. Each model transect begins upgradient of the salar transition zone, passes through surface water features in the transition zone, and terminates in the salar nucleus. We used each model to test four scenarios:

1. Baseline – No fresh groundwater or brine extraction occurs.
2. Freshwater withdrawals – fresh groundwater extraction from the fresh groundwater inflow upgradient of the transition zone.
3. Halite Brine withdrawals – brine extraction from wells located in the halite nucleus.
4. Transitional Brine withdrawals – brine extraction from wells located in the transition zone beneath some surface water features. We evaluated this scenario only for the Salar de Atacama model.

For each withdrawal scenario, we ran 4 simulations with withdrawal rates ranging from 10% to 40% of the model's fresh groundwater recharge rate.



Geologic cross sections of the Salar de Atacama (A-A') and Salar del Hombre Muerto (B-B') models



Maps showing the locations of the groundwater flow model domains for Salar de Atacama (left) and Salar del Hombre Muerto (right) along with important geologic features.