Recycling Brine for a Greener Future

Best Practices for Recycling and Reinjecting Lithium Brine

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Executive Summary

1. Executive Summary

Introduction

The lithium industry must urgently adopt best practices for reinjecting lithium-depleted brine into salar reservoirs – a process we refer to as 'brine recycling'. As Direct Lithium Extraction (DLE) technologies become more widespread, managing the large volumes of lithium-depleted brine presents a significant challenge.

This document provides a comprehensive guide to best practice brine recycling within salar environments, aiming to help industry stakeholders implement effective brine recycling systems that reduce environmental impact and optimize resource use.

Why recycle brine?

Brine that is extracted for lithium production should be recycled back into the subsurface for several reasons:

To minimize environmental and social impacts: By recycling brine, the lithium industry can significantly reduce its environmental and social footprint:

- *Maintain groundwater resources*: Recycling prevents the depletion of groundwater levels and the encroachment of fresh or brackish water into the reservoir, ensuring the sustainability of local water supplies for communities and ecosystems.
- *Preserve surface water features*: Proper brine management in unconfined aquifers prevents the disruption of surface water features such as streams and lagoons around salars, which are crucial for local hydrology and biodiversity.
- *Prevent ground subsidence*: Recycling spent brine helps maintain reservoir pressures, thereby reducing the risk of land subsidence and protecting the structural integrity of the aquifer when fine clastic sediments are dominant.

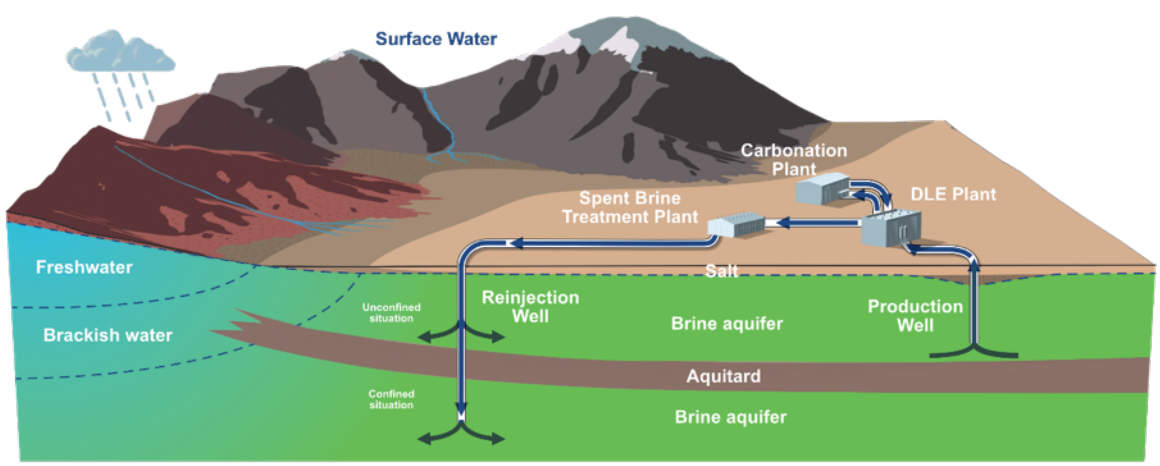
To improve the efficiency of lithium production: Recycling brine improves the overall efficiency of lithium extraction operations by:

- *Maintain reservoir conditions*: Recycling spent brine helps maintain the pressure and fluid volume of the brine reservoir, thereby preventing the influx of fresh to brackish water from the margins of the salar, which would adversely affect production.
- *Enable scale up with Direct Lithium Extraction (DLE)*: DLE allows lithium to be selectively extracted from brine, but this requires disposal management of large volumes of spent brine. Without

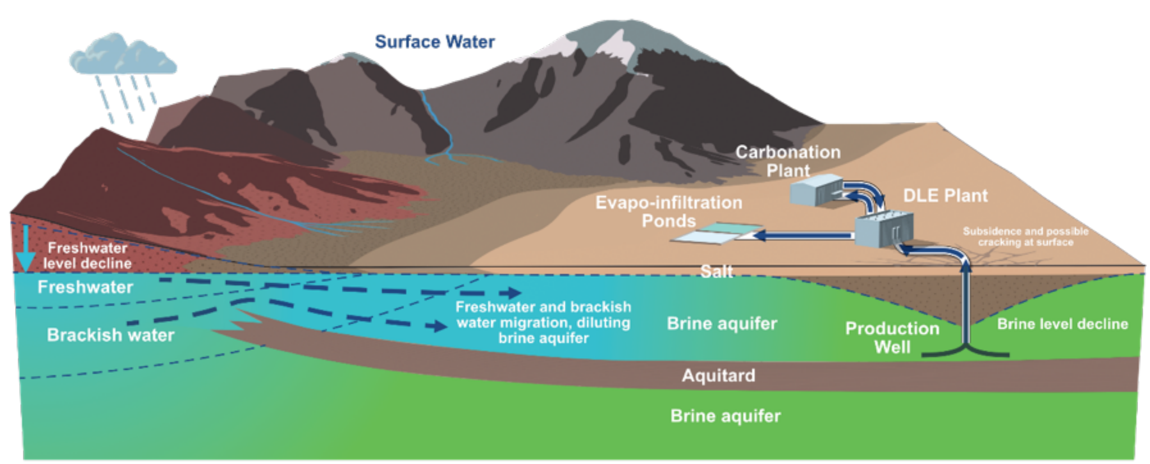
reinjection, extensive evapo-infiltration ponds would be needed which are costly to construct and operate.

Illustration of the reasons to recycle lithium brine

With reinjection



Without reinjection



Source: Zelandez

Key challenges for sustainable brine recycling

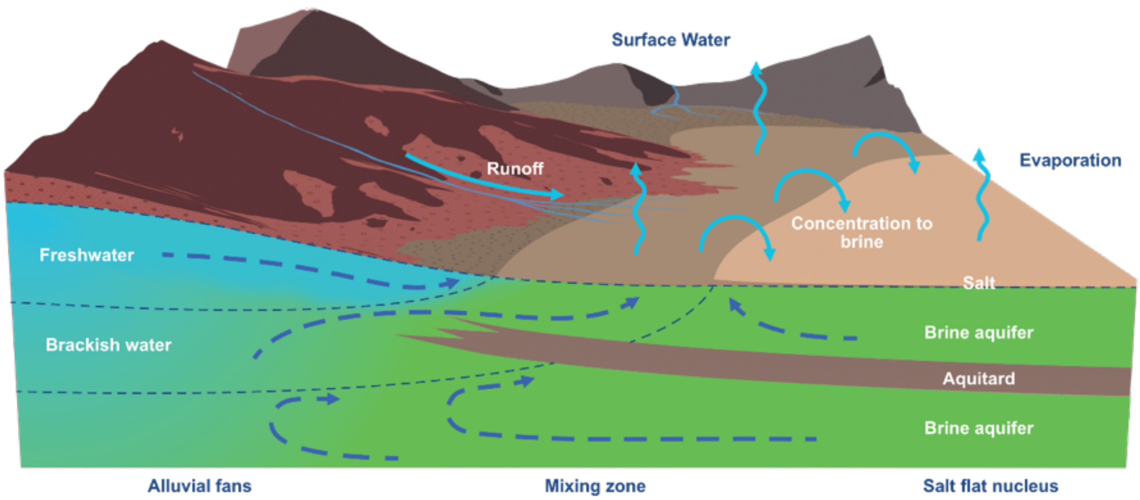
Sustainable brine recycling is challenging for several reasons, particularly when compared to typical reinjection practices in the oil and gas industry:

Salars have sensitive hydrogeology: Brine reservoirs are often located in environmentally extreme environments:

- *Shallow brine reservoirs*: Brine reservoirs are often located close to the surface, which requires careful consideration of geological layers, pressures, and mineral precipitation.

- *Unique fluid dynamics*: Brine recycling involves complete mixing of fluids, unlike hydrocarbon projects where fluids remain separate. Careful planning is needed to maximize lithium recovery by understanding fluid movement through geological layers.

Illustration of salar hydrogeology



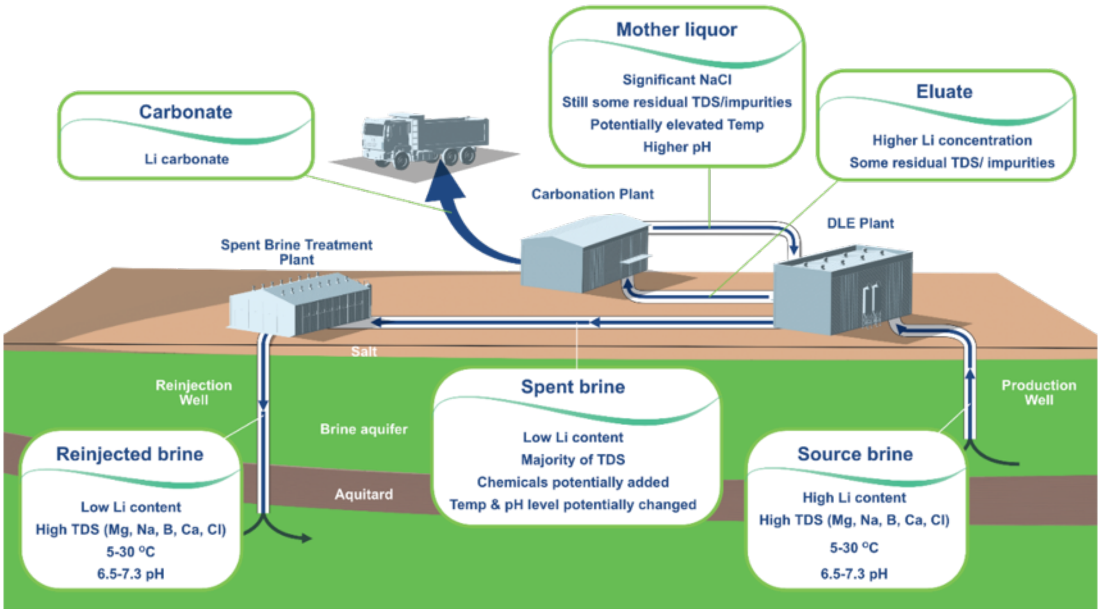
Source: Zelandez

Brine geochemistry changes when solids are extracted and processed: It can be challenging to ensure that the reinjected brine has similar geochemistry as the source brine because:

- *Brine chemistry changes on extraction*: Extraction alters brine geochemistry, requiring careful consideration for reinjection, especially in environments with brackish to freshwater overlying and peripheral to the brine.

- *DLE reagents change brine chemistry*: DLE processes can change brine composition, potentially causing clogging in reinjection wells. Technologies vary in their impact, with some generating brine chemistry changes that could create reservoir precipitates that reduce productivity.

Illustration of changing brine characteristics



Source: Zelandez

Current regulatory frameworks for brine recycling may not be adequate or appropriate:

- *Lack of environmental oversight*: Currently there are no countries that have established a regulatory framework specific to brine recycling for salars. Regulators should, at a minimum, monitor key sustainability parameters.
- *Cross-boundary concerns*: Rules are needed to minimize impacts across property/concession boundaries and ensure well placement is appropriate to minimize potential negative effects. It is desirable to have coordinated reinjection strategies in reservoirs where multiple companies are operating.
- *Industry and regulatory structures vary widely*: Different countries have very different industry structures and, in some cases, multiple institutions with regulatory oversight, which makes introducing best practice models difficult.

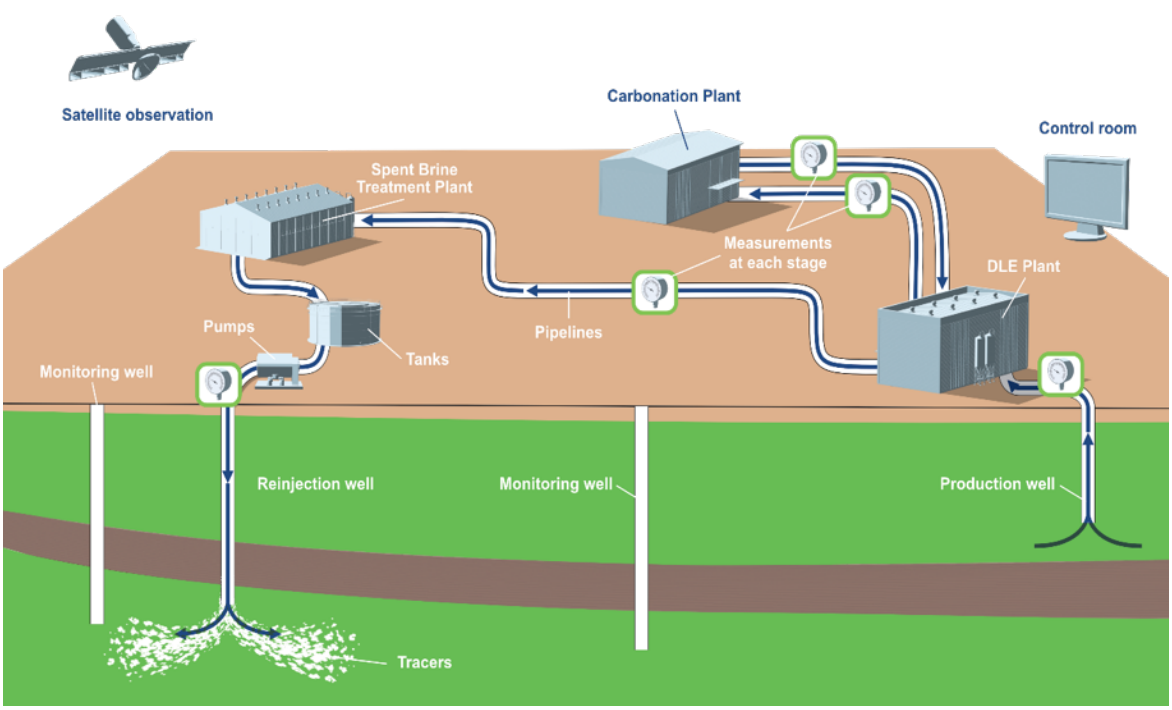
Components of a brine recycling system

A successful brine recycling system will share similarities to those used in the oil and gas industry for waterflooding, but there are some important differences. A brine recycling system should be specially designed to suit the distinctive hydrogeology of salars and geochemistry of lithium brine:

- **Reinjection wells**: Strategically placed wells that manage reservoir pressures and fluid volumes to ensure efficient reinjection.

- **Monitoring equipment**: Continuous monitoring systems that track the effectiveness and safety of the reinjection process, providing real-time data on reservoir conditions. Remote sensing and tracers can provide data to better understand the movement of fluids in the reservoir.
- **Control equipment**: Automated systems that regulate reinjection pressures and volumes to maintain optimal conditions within the reservoir.
- **Pumps, pipelines, and tanks or possibly ponds**: Infrastructure for transporting and storing brine, ensuring it is efficiently moved from extraction sites to reinjection points.
- **DLE Plant:** Upstream facilities that extract lithium from brine, which produce most of the spent brine for reinjection and have a major impact on its geochemistry (and therefore the requirements for further treatment).
- **Carbonate Plant:** Midstream facilities that convert the eluate from the DLE plant into lithium carbonate, which also have an impact (although lesser than DLE) on the geochemistry of spent brine for recycling.
- **Spent brine treatment:** Facilities that treat spent brine, received from the DLE and carbonate plants, to remove impurities and ensure it is suitable for reinjection, preventing issues such as clogging and mineral buildup in the wells and the reservoir. This includes removal of any chemicals related to the DLE process.

Illustration of a brine recycling system

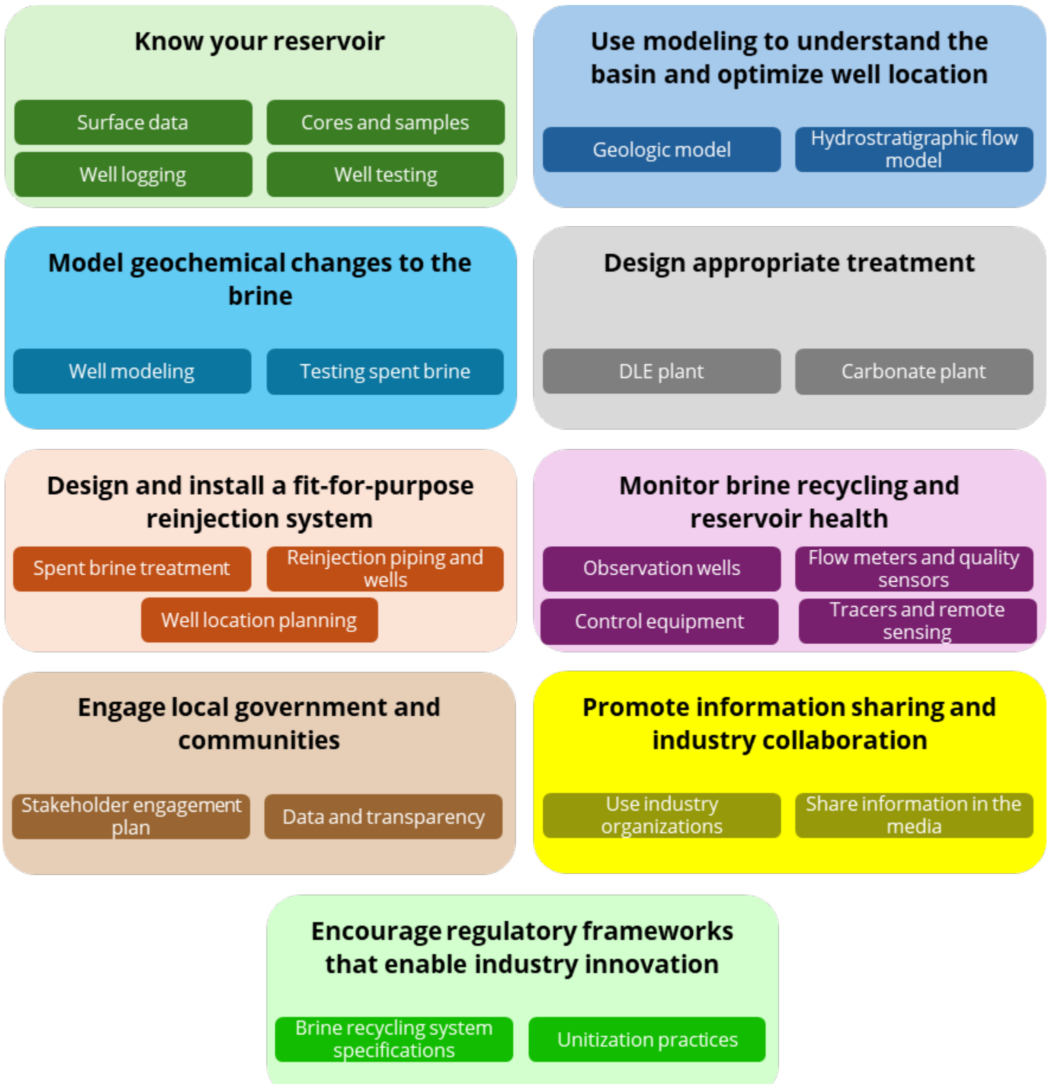


Source: Zelandez

Recommendations for best practice brine recycling

We recommend the following to ensure that lithium brine projects recycle brine in a way that minimizes environmental impacts and optimizes the efficiency of lithium production:

Recommendations for brine recycling



Source: Zelandez

Know your reservoir (collect extensive geological data for monitoring and modeling): Effective long-term brine recycling requires a comprehensive understanding of basin hydrogeology and brine chemistry, which means gathering data from various sources for development of the groundwater flow model:

- *Surface data*: Electrical, gravity, and seismic methods can be used to collect data for large areas. Electrical techniques excel in initial mapping of near-surface brine and water reservoirs, while gravity and seismic methods identify major subsurface contacts. They all struggle with depth and detail, so they need to be combined with well logging and testing for better accuracy.
- *Cores and samples*: Cores provide crucial geological details such as mineralogy, lithology, sedimentary structures, mechanical properties, textures, and contacts, although they have their limitations in poorly consolidated sediments. Cores also provide information on total porosity and specific yield or effective porosity and specific retention.
- *Well logging*: Borehole geophysics complements core data by providing continuous, high-density measurements during drilling. It assesses fluid types (using formation resistivity, borehole conductivity, and temperature), lithology (using spectral gamma ray, borehole images, and formation resistivity), and porosity and permeability (using nuclear magnetic resonance).
- *Well testing*: Provides essential hydraulic and pressure information, which is used to verify well logging data, inform wellbore/reservoir connectivity, and enhance groundwater model predictions. Testing also provides information on permeability (hydraulic conductivity), transmissivity and storativity.

Use modeling to understand the basin and optimize well location: Developing a detailed 3D geological/hydrostratigraphic model is essential for planning production and reinjection wellfields, optimizing resource development, and minimizing groundwater level decline. There are two stages to model development:

- *Geologic model*: This model involves identifying all elements of the basin, or at least the portion under study, to classify all lithostratigraphic and hydrogeological units. It also considers their distribution and interrelation, as well as their connection and interaction with topographic and atmospheric processes.
- *Hydrostratigraphic / groundwater flow model*: Building on the geologic model, this stage incorporates additional numerical information such as recharge rates, rainfall, evapotranspiration, hydraulic conductivity, transmissivity, etc. The goal is to understand the fluid flow behavior of the basin or an area.

Model geochemical changes to the brine: Understanding the variations in brine elemental concentrations and fluid chemistry are crucial for ensuring that reinjected brine does not damage the reservoir or the reinjection equipment. This is done by:

- *Well modeling*: Brine from different wells will have varying lithium and other elemental concentrations, which can change over time due to natural flow or pumping. To ensure smooth operations and manage risks, modeled profiles of brine chemistry changes are essential, using tools like Phreeqc for geochemical modeling and practical methods like microfluidics, along with observations from reinjection trials and downhole camera inspections.

- *Testing spent brine*: Testing spent brine for reinjection is necessary to confirm the model predictions and ensure compatibility with the reservoir (it should enter the brine layer well below any mixing zones) and prevent unwanted interactions.

Design appropriate treatment: The design of the treatment flowsheet, including the selection of DLE technology, directly impacts not just the quality of the final lithium product but the overall success of the recycling system. The main processing facilities include:

- *DLE plant*: This 'upstream' plant is the most important choice because it will produce most of the spent brine that needs to be reinjected and because the type of DLE will significantly affect the chemistry of spent brine.

- *Carbonate plant*: This 'midstream' plant is an important choice to make in parallel to the DLE because it will cycle significant amounts of mother liquor (the residual liquid containing impurities left after crystallization) back into the DLE process and will directly impact the quality of the final lithium product.

Design and install a fit-for-purpose reinjection system: Key components, which deserve particular attention for the reinjection system, include:

- *Spent brine treatment*: A robust filtration system is needed to remove sediment and suspended particles, followed by degassing towers to reduce dissolved gases and prevent corrosion and microbial growth. Depending on the type of DLE processes used, other steps may include removing sulfur compounds, balancing pH, and ensuring total dissolved solids (TDS) are compatible with the source brine. Regular monitoring and optimization are essential – both manual and automated, to maximize real-time data collection.

- *Reinjection piping and wells*: Decisions on well number, depth, filters, and materials are crucial for long-term pumping and reinjection system design. High-quality cementing and casing bond logs are essential for structural integrity, especially in saline environments, where choosing the right cement is critical; additional tools like packers and gel plugs may be needed for proper reinjection, but their installation can be challenging in salars.

- *Well location planning*: Extraction wells and reinjection wells should be strategically located based on hydrogeological models, with careful consideration given to well spacing, extraction rate, and positioning in relation to each other. Reinjection wells should be placed laterally to extraction wells to distribute brine, maintain pressure, and minimize hydrological impacts, considering aquitard layers as natural barriers. Reinjection can potentially damage a resource, due to dilution from the spent brine, and care is required with the selection of reinjection sites and volumes, particularly when salars have more than one property owner.

Monitor brine recycling systems and reservoir health: Models provide predictions of fluid interactions with limited certainty. Therefore, monitoring through field tests is crucial as the ultimate validation. A good monitoring program will include:

- *Observation wells*: A comprehensive monitoring network with multiple observation wells and downhole sensors around each reinjection well is essential for thorough data collection and goal achievement. Observation wells should be positioned carefully to avoid acting as a shortcut for reinjected brine.
- *Flow meters and quality sensors*: Flow meters and pressure gauges provide real-time data for rate control and adjustments. Quality sensors monitor parameters like pH and conductivity, guiding adjustments to injection rate and brine treatment processes.
- *Control equipment*: Control equipment, including valves, chokes, and programmable logic controllers, enables real-time response to ensure operational and environmental objectives are met.
- *Tracers and remote sensing*: Use inert tracers in injected fluids to monitor reservoir connectivity and fluid distribution, and combine with satellite-based InSAR or ground-based LIDAR for estimating pore pressure and confirming fluid movement.
- *Long-term maintenance plan*: Regularly monitor and maintain equipment in harsh environments, using camera and visual inspections. Update maintenance schedules as needed.
- *Risk assessments*: Create a risk register and Risk Assessment Matrix to manage risks and ensure emergency measures comply with local regulations.

Engage local government and communities: While salars are often located in remote areas with sparse populations, the partnership of any local communities, alongside relevant government institutions, are essential for ensuring a lithium project's viability and sustainability. Engagement should include:

- *Stakeholder engagement plan*: Develop a comprehensive plan early, identifying and documenting stakeholder groups to address their concerns and safeguard their interests. Use simple, informative graphics in communication to convey complex information effectively.
- *Data and transparency*: Transparently communicate project plans, including aquifer management strategies, to build trust. Provide real-time field data on reinjection system performance to gain support.

Promote information sharing and industry collaboration: Brine recycling should be viewed as an opportunity to minimize environmental impacts, rather than as a threat. But without proper information sharing and education, it could be misunderstood or misrepresented. Actions that industry can take to front foot the issue include:

- *Use industry organizations*: Organizations like the International Lithium Association can develop guidance and share best practices for brine recycling, ensuring industry standards remain relevant and effective.

- *Share information in the media*: Proactively engage with the media and stakeholders to share accurate information about brine recycling, minimizing the risk of misrepresentation.

Encourage regulatory frameworks that enable industry innovation: Industry should take the lead in encouraging practical and flexible regulatory frameworks that are specific to brine recycling, so that regulations and permits do not unnecessarily hold up the acceleration of sustainable lithium production. This should include:

- *Brine recycling system specifications*: Requirements on key parameters such as void space replacement, well placement, rate limitation, barrier establishment, geochemical compatibility testing, and pressure and flow monitoring.
- *Unitization practices*: Many salars have multiple property owners, raising concerns about cross-boundary impacts of reinjection due to the fluid nature of brine resources. Adopting the oil industry practice of unitization, which involves brine flow modeling and periodic reconciliations between companies based on pumping records, can ensure accurate ownership accounting and mitigate potential impacts, alongside establishing minimum buffer or setback rules.

By following these recommendations, the lithium industry can achieve significant improvements in environmental sustainability, operational efficiency, and community relations, ultimately supporting the global transition to net-zero emissions and a more sustainable future.

2. Glossary

- **Aquifers** – Geological units from which brine can be readily extracted or reinjected.
- **Aquitards** – Geological units from which brine cannot be readily extracted or reinjected.
- **Concessions** – Properties granted by provincial or federal governments for the extraction of brine for lithium brine production.
- **Casing bond log (CBL)** – An evaluation of the integrity of a casing cement job using a sonic–type tool. Principally, whether the cement is adhering consistently to the outside of the casing.
- **Confined aquifer** – A confined aquifer underlies layers of low permeability material, causing it to be under pressure, so when the aquifer is penetrated by a well, the brine will rise above the top of the aquifer.
- **Direct Lithium Extraction Technology (DLE)** – Technology which allows selective extraction of lithium from brine, while other ions remain in solution in the brine. The technology can involve sorbents, resins, membranes, or the use of solvents.
- **Eluate –** Term used for the brine waste product from DLE processing, which is spent brine.
- **Evaporation ponds** – Shallow, artificial basins used in the lithium extraction process to concentrate brine by evaporating the water content. The brine, which contains dissolved lithium and other elements, is pumped into these ponds and left to evaporate under natural sunlight and wind. Over time, as the water evaporates, the concentration of lithium increases, allowing for the extraction of lithium carbonate or lithium hydroxide.
- **Evapo-infiltration ponds** – Designed to manage both evaporation and infiltration processes. These ponds are used to dispose of spent brine by allowing water to evaporate into the atmosphere while simultaneously facilitating the infiltration of brine into the ground. The dual process helps reduce the volume of brine that needs to be managed and minimizes the environmental impact by preventing surface water contamination. They are used in lieu of spent brine reinjection.
- **Extraction** – Removal of brine from the reservoir by pumping at an extraction well.
- **Extraction wells** – Wells used for production pumping extraction.
- **Geological model** – 3D model that contains the interpretation of different hydrogeological or hydrostratigraphic units within the brine reservoir and can be used for estimation of the project resource.

- **Groundwater (hydrogeological) model** – 3D model which simulates pumping, reinjection and flow within the reservoir in software such as Modflow or Feflow.
- **Interferometric Synthetic Aperture Radar (InSAR)** – A remote sensing technique that uses radar signals to create detailed maps of surface deformation. By comparing radar images of the same area taken at different times, InSAR can detect and measure changes in the Earth's surface with high precision.
- **Light Detection and Ranging (LIDAR)** – A remote sensing method that uses laser light to measure distances and create detailed, high-resolution maps of the Earth's surface. LIDAR works by emitting laser pulses and measuring the time it takes for the light to bounce back after hitting an object. This data is then used to generate precise, three-dimensional information about the shape and characteristics of the terrain and other surfaces.
- **Recycling** – Alternative term for reinjection, which highlights the environmental sustainability of reinjecting brine, as part of the recycling "cycle" of activities.
- **Reinjection** – The addition of brine back into the reservoir, involving pumping brine under pressure to force it into the reservoir surrounding a reinjection well.
- **Reinjection wells** – Wells used for reinjecting spent brine.
- **Reservoir** – The body of brine beneath the salar surface and surrounding area that can be exploited for production of lithium, and which will interact with surrounding brackish to freshwater.
- **Wells** – Also referred to as bores or boreholes.
- **Salar** – Is a sedimentary basin developed in an endorheic region under arid climate which is characterized many times at surface by a salt flat or playa lake. In the case of South American salars, they are in an active tectonic and volcanic region, promoting the interaction of volcanic/pyroclastic, clastic and evaporitic processes, leading to complex basin sedimentology.
- **Spent brine** – Also referred to as lithium–depleted brine. This is natural brine from which lithium has been removed by DLE or other process.
- **Unitization** – Widespread activity in the oil and gas industry, where an oil field is divided into cells or units and the extraction of those from different property holdings is modelled, to ensure compensation to companies where cross–border pumping of oil or gas occurs.
- **Void space replacement** – Refers to pore space within aquifer units, with replacement of the original brine with reinjected brine.

3. Table of contents

Introduction

1. Introduction

In this section we describe the objective of this white paper and introduce its authors.

1.1 Objective of this white paper

A foundational resource that guides the lithium industry towards best practices for continental brine recycling

The lithium brine extraction industry is gradually embracing the concept of brine recycling, which is the term we use to describe the reinjection of lithium-depleted brine into the brine reservoir below a salar (which is the Spanish term for a salt flat).

Brine recycling is essential for minimizing environmental impacts and enhancing the efficiency of lithium production, particularly with the increasing adoption of Direct Lithium Extraction (DLE) technologies. Lithium producers will soon widely utilize these technologies, resulting in significant volumes of lithium-depleted brine requiring disposal.

However, brine recycling presents inherent challenges, differing from those encountered in reinjection practices within the oil industry. This is primarily due to the shallow and intricate nature of salar hydrogeology and brine geochemistry.

Collaborative efforts within the lithium industry are pivotal for sharing knowledge and establishing fundamental principles to avert reputational harm that could impede the global transition to net-zero emissions, where lithium plays a pivotal role.

The primary objective of this document is to serve as a foundational resource for steering the lithium industry toward best practices in brine recycling.

1.2 Distinguishing recycling from infiltration and recharge

This White Paper focuses on the recycling of continental lithium brines in salar environments. Recycling is distinguishable from brine infiltration and recharge:

- **Infiltration:** This method involves disposing of spent brine onto the surface of the salar within a natural depression or pond, allowing it to seep back into the subsurface. The infiltration capacity is limited by the natural constraints of the terrain, the volume of brine that can be absorbed, and the rate of salt precipitation through evaporation.

- **Recharge:** In this approach, spent brine is introduced into shallow wells without the application of pressure, aiming to naturally recharge a shallow aquifer. This method is commonly used in the groundwater industry and is currently being employed by Albemarle in the Atacama region. Historically, lithium extraction has occurred within the top 30 meters of the salar, making this method practical for that depth. However, its effectiveness decreases at greater depths and with larger volumes of brine.
- **Recycling:** This method involves injecting spent brine under pressure into specific locations. Compared to the other methods, it offers more control and precision, allowing for a targeted and efficient recycling process.

1.3 Authors, reviewers, and supporters

Authors

This White Paper is co-authored by Zelandez and Summit Nanotech, two leaders in the theory and practice of brine recycling:

Zelandez – Zelandez Limited ('Zelandez'), is the leading integrated services provider to the lithium brine industry. Zelandez provides a comprehensive suite of advanced exploration and extraction tools, leveraging advanced geophysical technologies and expert geoscience know-how. Zelandez works with leading lithium mining companies in Argentina, Bolivia, Chile and North America. Zelandez's reinjection team provides a comprehensive service, believed to be an industry first, combining hydrochemistry with reinjection techniques used extensively in oil and gas.

Summit Nanotech – Summit Nanotech was founded in 2018 to amplify the performance of today's lithium miners and meet the global demand for electric vehicles (EVs). Deploying our patented direct lithium extraction (DLE) technology, greater quantities of high-purity lithium product are collected faster while preserving the natural resources of communities. Grounded in values of trust and adaptability, we work with customers to refine our technology for the complexities of their brine.

The following experts led the authorship of this White Paper:

- **Dr. Stuart Weston (Zelandez) – CTO and Principal Reservoir Engineer:** Ph.D 25+ years reservoir evaluation and management, now reinjection patent leader, experience across dozens of reinjection projects.
- **Murray Brooker (Zelandez) – Principal Hydrogeologist:** 25+ years in global exploration and resource definition, with 15 years managing lithium project exploration programs and feasibility assessments throughout the lithium triangle.
- **Stefan Walter (Summit Nanotech) – VP, Geoscience & Asset Development:** Professional geologist with over 16 years of diverse experience in technical leadership, joint ventures, energy policy, and resource characterization of unconventional resources and disposal plays including lithium brines, liquids-rich gas, source rocks, and carbonates.
- **Fernando J. Lourenco Cidades (Zelandez) – Director of Geosciences**: 15+ Years geologist and petrophysicist. Expert in borehole geophysics applied to the lithium brine industry.
- **Azul Ma. Giménez Moreno (Zelandez) – Director of Process Performance**: Chemical engineer with on-field experience in lithium production from brines and managing and optimizing DLE processes at commercial scale.

Reviewers

This White Paper was reviewed by the following industry experts:

Albemarle – Albemarle leads the world in transforming essential resources into critical ingredients for mobility, energy, connectivity, and health. It partners to pioneer new ways to move, power, connect and protect with people and planet in mind. Its diverse, world-class resource base is geographically situated in low-risk environments with robust infrastructure and top performance in health and safety.

Arcadium – Arcadium is charging ahead toward a more sustainable future. From the first lithium-ion battery to the breakthrough technologies of today, it has helped lead the way. Arcadium joins forces with its customers and communities to drive progress. Progress toward a world enabled by lithium.

Controlled Thermal Resources (CTR) – CTR is a U.S. company specializing in lithium and battery material products and renewable energy with projects in advanced development in the United States. CTR's leadership team has successfully developed and managed renewable energy projects in the Salton Sea region for over 30 years.

Dr. Eleonora Erdmann – Eleonora has a PhD in Material Science and Chemical Engineering from the National University of Salta. Eleonora is helping pioneer the technological and HR transfer from petroleum upstream to lithium upstream. She specializes in Engineering, Materials Science, and Petrochemistry.

Eramet – An essential component of electric batteries, lithium is a metal of the future, in which Eramet is investing with one ambition: to become a leading global producer of metals for the energy transition. In Argentina, Eramet operates a lithium production plant designed to extract and produce 24,000 t of battery-grade lithium carbonate per year at full capacity, thanks to an exclusive extraction process developed by its R&D teams.

Hatch – Hatch is passionately committed to the pursuit of a better world through positive change. Its global network of 10,000 professionals work on the world's toughest challenges, with experience spanning over 150 countries around the world in the metals, energy, and infrastructure sectors.

Power Minerals – Power Minerals Limited is a diversified ASX-listed mineral resources exploration company focused on the systematic exploration and development of projects in demand-driven commodities. These include the Salta Lithium Brine Project in Argentina's prolific lithium triangle.

SQM – SQM is the world's largest lithium refiner and leading lithium producer with more than 25 years of experience in lithium production in the north of Chile. The company has a global presence and provides solutions for human development through its five business lines: Specialty Plant Nutrition, Iodine, Lithium, Potassium and Industrial Chemicals.

Wood – With 35,000 professionals, across 60 countries, Wood is one of the world's leading consulting and engineering companies operating across Energy and Materials markets.

WSP – WSP is one of the world's leading engineering and professional services firms. Its 69,300 passionate people are united by the common purpose of creating positive, long-lasting impacts on the communities it serves through a culture of innovation, integrity, and inclusion.

Upflow – Upflow brings geothermal science into the real world. Its experts build the solutions you need to do things better, faster, and smarter. They take on the challenging research and development tasks so that you don't have to.

Supporters

The purpose of this White Paper, to steer the lithium industry toward best practices in brine recycling, is strongly supported by the following industry stakeholders:

International Lithium Association (ILiA) – The International Lithium Association (ILiA) is the global industry association of the lithium value chain. ILiA's vision is to represent the lithium industry, promote sustainable and responsible market growth, and be recognised as a global authority on lithium information. It is a not-for-profit membership organisation, run by and for its members

Fastmarkets – Fastmarkets is one of the most trusted cross-commodity price reporting agencies (PRA) in the agriculture, forest products, metals and mining, and new generation energy markets. Its price data, forecasts, and market analyses give its customers a strategic advantage in complex, volatile and often opaque markets.

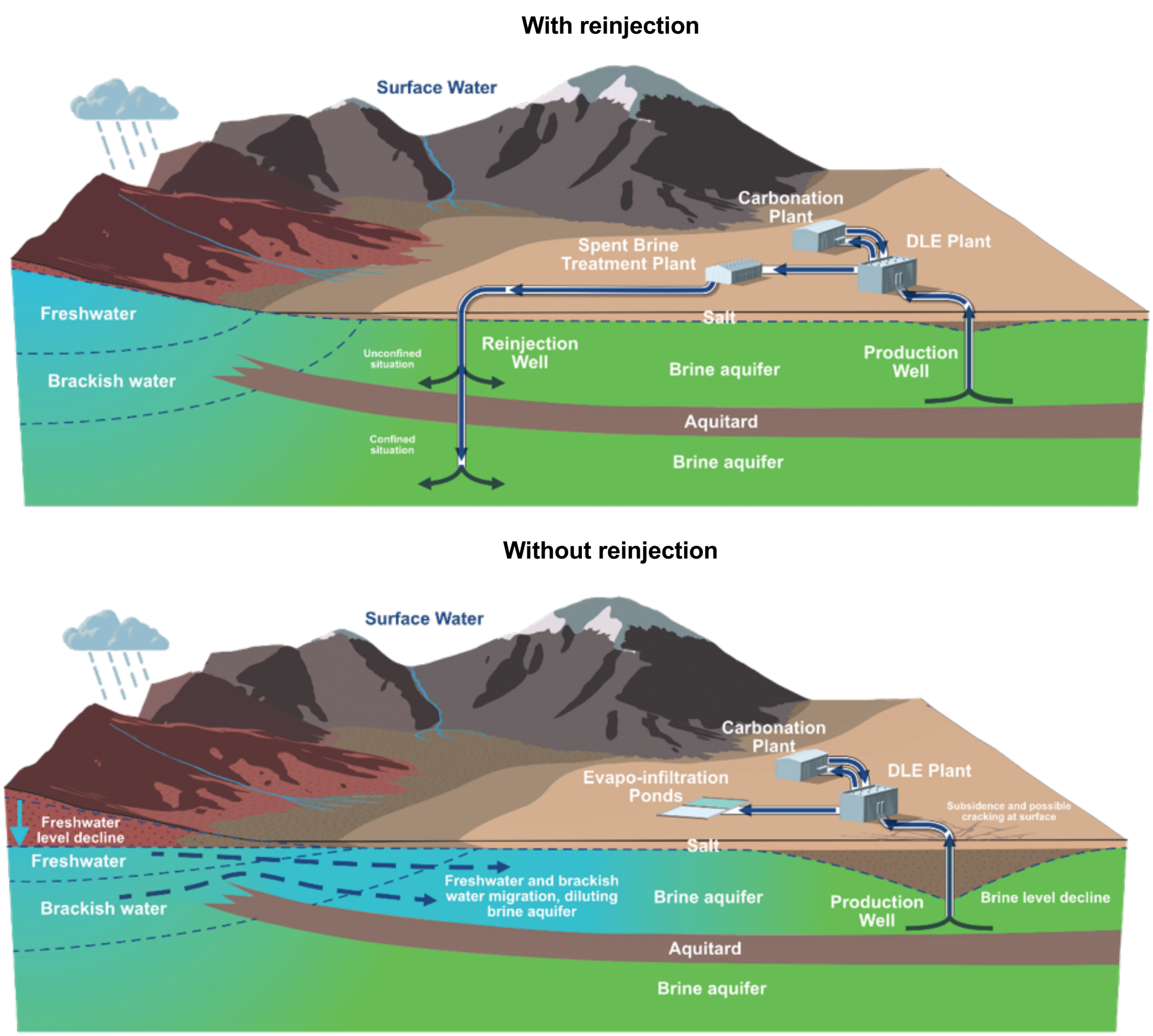
Why recycle brine?

2. Why recycle brine?

In this section we explain the importance of recycling brine extracted for lithium production back into the subsurface, both to minimize the environmental and social impacts, and to improve the efficiency of lithium production.

The figure below summarizes the key reasons to recycle brine.

Figure 2.1: Overview of the reasons to recycle lithium brine



Source: Zelandez

2.1 To minimize environmental and social impacts

The figure below summarizes how brine recycling can minimize impacts on groundwater, surface water, and subsidence.

Brine recycling can minimize environmental and social impacts in three main ways:

- Maintain groundwater resources
- Preserve surface water features
- Prevent ground subsidence

These are described in the following sub-sections.

Maintain groundwater resources

Salars are characterized by arid conditions where evaporation exceeds precipitation[1]. Water sources that feed a salar and create brine come from three main sources:

- Direct groundwater flow from aquifers discharging into the basin
- Surface water flowing on to salars (streams)
- Precipitation (rain or snow) directly on a salar and into surface and groundwater

Water from surface streams and precipitation infiltrates into the ground within the basin or near the stream, carrying dissolved solids and salts. This water flows underground towards the lowest point of the basin, becoming more concentrated as it flows, accumulating dissolved elements, and evaporating around the salar edges, leaving behind hypersaline brine in the salar. The denser brine then sinks deeper into the ground, creating density convection cells. Brine reservoirs under salars become more concentrated than seawater, typically reaching a fluid density of 1.2 g/cc or higher (compared to freshwater at 1 g/cc) and approaching saturation in sodium chloride.

Fresh and brackish groundwater often sits immediately above the hypersaline brine reservoirs. A natural mixing zone exists around the salar margins, both vertically and laterally, caused by contrasting fluid densities. Therefore, extracting brine can lead to changes in the phreatic level and shift adjacent mixing zones, promoting the invasion of fresh or brackish water from the margins[2]. This process incorporates salts and increases salinity. This phenomenon has been studied in the Salar de Atacama, where it poses a threat to local ecosystems composed of vegetation and fauna[3] that are

1 *Corenthal et al, 2016*

2 *Zourek, 2020*

3 *Garces, 2021*

adapted to specific water conditions. Declines in groundwater levels can also negatively affect local communities and companies that use it for drinking or industrial processing.

Reinjecting lithium-depleted brine back into the reservoir can help prevent or control these processes.

Preserve surface water features

Streams and lagoons sometimes form around the edges of salars where fresh or brackish water emerges from underground. This occurs due to the topography (the salars are where the land flattens in the low point of a basin) or because clay soils (which have low permeability) force the water to the surface. However, streams that flow year-round are typically rare due to low rainfall rates and high evaporation in mountainous, arid environments. Stream flow is, therefore, typically limited to the wet season (January to March in the Andes) or related to snow melting.

Brine extraction without reinjection can lead to a disruption of nearby groundwater sources, which in turn can affect these surface water features.

Springs can sometimes form along faults in salar basins or in permeable ground beneath low-permeability layers. Brine extraction can lead to the development of surface waters on the edges of salars due to changes in the balance of brine to brackish and fresh water or release of brine at surface, potentially causing negative environmental impacts.

To prevent this, it is crucial to carefully manage reinjection pressure, especially in areas with high vertical permeability, to stop the reinjected brine from rising to the surface (a phenomenon known as 'vertical breakout') and contaminating nearby freshwater sources.

Prevent ground subsidence

Brine is stored in the pore spaces between sediment grains and in fractures and cavities in rigid lithologies such as halite or volcanic rocks. When brine is extracted through pumping, it can lead to the compaction and consolidation of sediments, causing subsidence. This happens because decreasing pore pressure (or emptying of the pores) allows the weight of the overlying sediments to close the pore spaces. This process can also permanently affect aquifer quality by changing the physical structure of the sediments. This effect is usually minimal and likely to be local in most projects, but it is attracting increasing attention and may become a larger issue as the scale of extraction increases.

Fine-grained sediments are more challenging because they drain and consolidate very slowly over time, releasing only a small portion of their total porosity as brine. This slow and leaky nature of brine release makes these sediments less productive, but more susceptible to compaction, resulting in subsidence.

Subsidence can result from brine extraction in confined aquifers, due to the loss of pore pressure. Reinjecting spent brine into the reservoir can reduce subsidence by maintaining aquifer pressures and groundwater levels. However, injecting into fine-grained sediments like clays is not feasible due to their very low permeability.

2.2 To improve the efficiency of lithium production

Brine recycling improves the efficiency of lithium production in two main ways:

- Maintain reservoir conditions
- Enable scale up with DLE

These are described in the following sub-sections.

Maintain reservoir pressure and fluid volume

Brine reservoirs consist of various geological or hydrogeological units, some of which may serve as excellent aquifers (with high porosity and permeability), while others may act as aquitards (barriers) with lower permeability, limiting their contribution to brine production but serving as effective barriers to constrain reinjected volumes.

Over time, extraction of brine without reinjection will eventually lead to a loss of reservoir pressure and fluid volume, although the extent of this loss will depend on the type of salar and the distance from the extraction wells.

If depleted lithium brine has similar characteristics to the source brine, it can be reinjected back into the reservoir, but outside the extraction area, to maintain reservoir pressure and fluid volume. If strategically placed, reinjection wells can counteract increased inflows of fresh to brackish water from the margins of the salar, driven by the pressure sink caused by extraction-related drawdown in the salar core.

Enable the scale up of lithium production using DLE

The lithium brine industry is expanding rapidly to meet the increasing demand for lithium. Lithium extracted from brine is generally more cost-effective than lithium sourced from hard rock and clays, making it a highly appealing option.

Direct Lithium Extraction (DLE) comprises various technologies that enable the selective extraction of lithium from brine, eliminating the need to construct evaporation ponds that concentrate the brine. This expands the potential for developing brine deposits that would otherwise not be economically viable with conventional evaporation technology. Each DLE technology has its own set of advantages and disadvantages, and the choice of DLE method will vary for each project.

DLE operates continuously, producing lithium-depleted brine at a rate roughly equivalent to the inlet pumping rate. Without reinjection, this brine would need to be disposed of through extensive evapo-infiltration ponds, which are costly to construct and operate. Evapo-infiltration ponds are generally less environmentally sustainable than brine reinjection because the infiltrating brine is not returned to a similar location in the aquifer and often has a significantly different chemistry from the source brine. This method may also face regulatory restrictions in the future, as has recently been the case in Chile.

What are the key challenges for sustainable brine recycling?

3. What are the key challenges for sustainable brine recycling?

In this section we describe the reasons why sustainable brine recycling is challenging, particularly when compared to reinjection practices in the oil and gas industry. These reasons include the sensitive and dynamic nature of salar hydrogeology, brine chemistry, and, relatedly, immature regulation by governments.

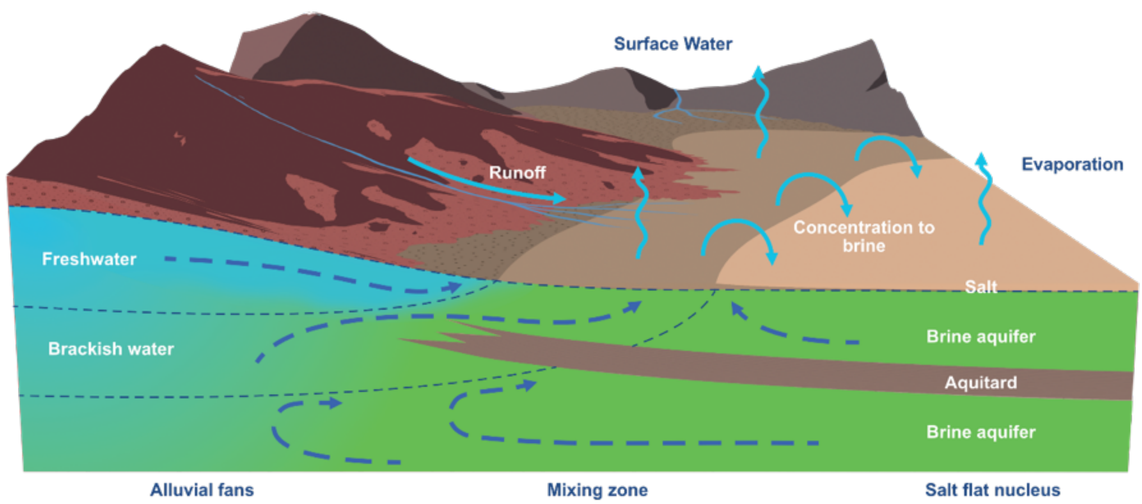
3.1 Salars have sensitive hydrogeology

There are two main ways that the hydrogeology of salars makes brine recycling challenging:

- Shallow brine reservoirs
- Unique fluid dynamics

These are summarized in the figure below and described in the following sub-sections.

Figure 3.1: Overview of salar hydrogeology



Source: Zelandez

Brine reservoirs are often shallow and require careful understanding of different geological layers

Continental brine reservoirs are much closer to the surface compared to most oil and gas reservoirs. This proximity requires brinefield managers to be particularly careful about the pressures applied and the sediment layers that act as barriers or seals. They must also closely consider how minerals might precipitate out of the brine during both extraction and reinjection stages.

Given the shallow depth of brine reservoirs, careful attention must be paid to the depth at which spent brine is reinjected and the geological layers selected for injection. Injecting brine into low-permeability layers, like clays or silts, is not feasible, but these layers can serve as effective barriers to prevent brine from leaking to the surface. Understanding the thickness and extent of these layers requires a combination of drilling and geophysical surveys.

Pore plugging can occur when lithium-depleted brine, rich in cations like calcium and magnesium, is reinjected into sediments or halite areas. Therefore, reinjection wells must be optimally spaced, and there should be continuous monitoring and refining of reservoir models, especially in areas with multiple property owners or operations, such as the Salar de Atacama or Hombre Muerto.

Lithium brine fluids mix, which makes understanding the geological layers important

Comparing brine recycling to hydrocarbon waterflooding (for enhanced oil recovery) shows some similarities, but the way the fluids behave is quite different. In hydrocarbon projects, the oil and the injected water do not mix, so the water can push the oil towards the wells for extraction (although this does not always work perfectly and can leave some oil behind).

In brine recycling, the fluids mix, which can help maintain better flow through the sediments. However, it is important to plan carefully to ensure the lithium is recovered efficiently. This means building strong conceptual understanding, from detailed geological and hydrogeological studies, of how the fluids move through the subsurface to get the most lithium out.

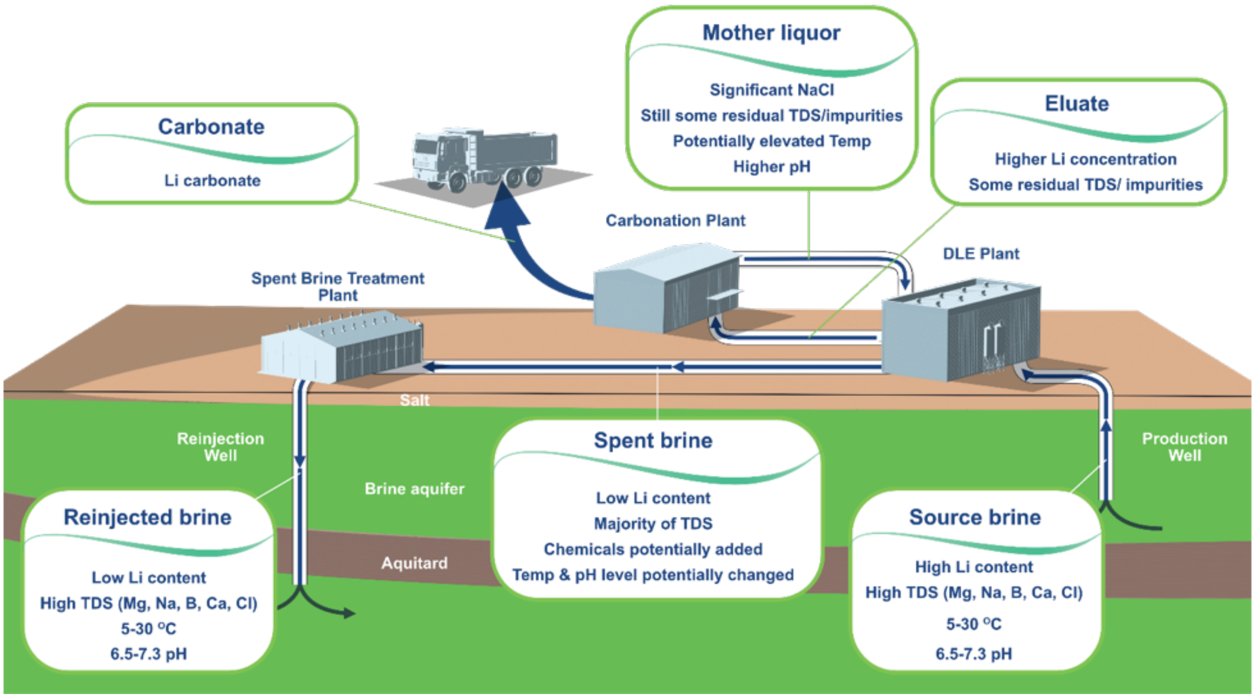
3.2 Brine geochemistry changes when extracted and processed

There are two main ways that brine geochemistry makes recycling challenging:

- Brine chemistry changes on extraction
- DLE reagents change brine chemistry

These are summarized in the figure below and described in the following sub-sections.

Figure 3.2: Overview of changing brine characteristics



Source: Zelandez

The geochemistry of brine changes when it is removed from the reservoir

Simple reinjection techniques historically used in the oil and gas industry will not achieve the desired results for brine recycling. Changes in brine conditions happen, after it is extracted from the subsurface, pipped, processed, and then returned to the subsurface. This demands that the brinefield operator has an excellent understanding of hydrochemistry in the design and testing of reinjection in these sensitive environments, where brine, brackish water, and freshwater exist, overlying and peripheral to the main brine zones.

Key characteristics of salar brine typically include:

- Extremely high quantities of dissolved solids, significantly more than typical oilfield brines.
- Slightly acidic nature, with a pH between 6.5 and 7.3, and densities ranging from 1.1 to 1.2 g/cm³. Dissolved oxygen levels vary, generally decreasing with depth.
- Reservoir temperature, influenced by medium to high geothermal gradients due to volcanic/tectonic activity, especially in South American salars. Within 600 meters of the surface, the temperature gradient is typically 5°C per 100 meters of depth.

- Surface temperatures also vary widely throughout the year, dipping below zero in winter. These temperature variations affect salt solubility, which is crucial for recycling processes.

The total dissolved solids content of brine changes as it becomes more concentrated, nearing saturation, which leads to the precipitation of salts and other chemical changes. Brine remains stable in the reservoir but can change upon extraction. Pressure, temperature, composition, and pH changes between extraction and reinjection can cause scaling in pipes, wells, and holding tanks, reducing efficiency.

DLE processes can significantly alter brine composition

Reagents used in Direct Lithium Extraction (DLE) can alter brine composition, potentially causing clogging in reinjection wells and surrounding reservoirs.

DLE effluent (spent brine) can have a wide range of chemical characteristics depending on the primary technology used. The water used to elute lithium from a sorbent, or the acid employed as the eluent solution in ion exchange resins will impact the spent brine chemistry, with some technologies creating an acidic or basic solution that could generate precipitates in the reservoir when reinjected.

Some DLE technologies will require an adjustment of the brine temperature, prior to the lithium extraction, either by heating the brine (e.g. continental brines in South America) or cooling it down (e.g. geothermal brines).

Technologies that use relatively inert elution methods may have an advantage in environmentally sensitive areas, by having the capability to produce an effluent that is compatible with the host reservoir.

The choice of DLE technologies is further described in Section 4.5.

3.3 Countries do not currently have adequate regulatory frameworks for brine recycling

Regulation is an important part of ensuring that brine recycling, and lithium production more generally, is done in an environmentally friendly way. There are three key challenges to the current situation:

- Lack of environmental oversight
- Cross-boundary concerns
- Industry and regulatory structures vary widely

These are further described in the following sub-sections.

At a minimum, regulatory frameworks need to ensure environmental impacts are monitored

Currently there are no countries that have established a regulatory framework specific to brine recycling. This lack of regulation means there are no minimum requirements established, such as void (pore) replacement, well placement, rate limitation, barrier establishment, geochemical compatibility testing, or pressure and flow monitoring for reinjection processes.

Regulations are needed to a manage cross-boundary impacts

Many salars have multiple property owners, raising concerns about potential cross-boundary impacts of reinjection. While concessions have hard boundaries from a regulatory and paper-based view, a brine resource does not follow those regulatory boundaries. Brine resources can be extracted from outside of concession boundaries. Similarly, reinjection wells placed on an owned concession can impact the resource in adjoining non-owned concessions. However, there are no regulations in place regarding compensation for such cross-boundary pumping or reinjection.

Relatedly, there are no minimum buffer or setback rules enforced for wells from the edge of an owner's concession. These rules are essential to prevent the trespass of brine by pumping. Additionally, there is a lack of protection for offsetting concessions undergoing extraction that could be affected by nearby reinjection of spent brine.

Differing industry structures and responsible bodies add challenges to introducing regulations

Regulatory responsibilities are often spread across multiple regulatory bodies (including for mines, water, and environment) and there is significant disparity between countries and states, both in terms of industry structure and regulatory responsibilities for brine extraction and reinjection. In some cases brine may be regulated as groundwater. A brief overview is as follows:

- **Chile:** Chile has a complex history around lithium regulation, resulting in a complicated regulatory framework. In 1979, Law No. 2886 defined all lithium reserves as state property, with the exception of concessions granted prior to 1979. The National Lithium Commission was formed in 2014 to ensure stricter oversight of lithium-rich brine extraction. In Chile officials are still evaluating the creation of a national lithium company. The Ministry of Mining has indicated a shift away from evaporation ponds, implying the exclusive use of Direct Lithium Extraction (DLE). However, the Chilean mining industry has no specific regulations regarding brine reinjection.
- **Argentina:** Argentina's national mining law sets the details of mining legislation but is administered by the provinces, which own the mineral resources and can collect a mining royalty

of up to 3% from extracting companies. Lithium in Argentina is concentrated in the northern provinces of Jujuy, Salta, and Catamarca. Each province has a mining department and environmental authorities to approve project impact studies. Although no specific regulations exist, discussions with local mining departments have facilitated some brine reinjection testing.

- **Bolivia:** Bolivia's lithium industry development has been government-controlled, but it has engaged with foreign companies (Chinese and Russian) through a bidding process. While there are no known regulations regarding brine reinjection for lithium extraction, foreign companies are working on developing different project areas.
- **USA and Canada**: In the Western USA, brine resources are present in salar basins, primarily in Nevada, California, and southern Oregon. Lithium brine is also found in oilfield basins in the southern USA (Smackover Formation) and the Western Canadian Basin. These resources are subject to varying state legislation.
- **Mexico**: Mexico has salars in states such as Zacatecas, San Luis, Sonora, and Baja California. The Mining Law nationalized lithium, making exploration, exploitation, and use exclusive to the Mexican government. The new mining legislation further restricts exploration and exploitation to the state, closing the possibility of granting concessions, licenses, contracts, permits, or authorizations.

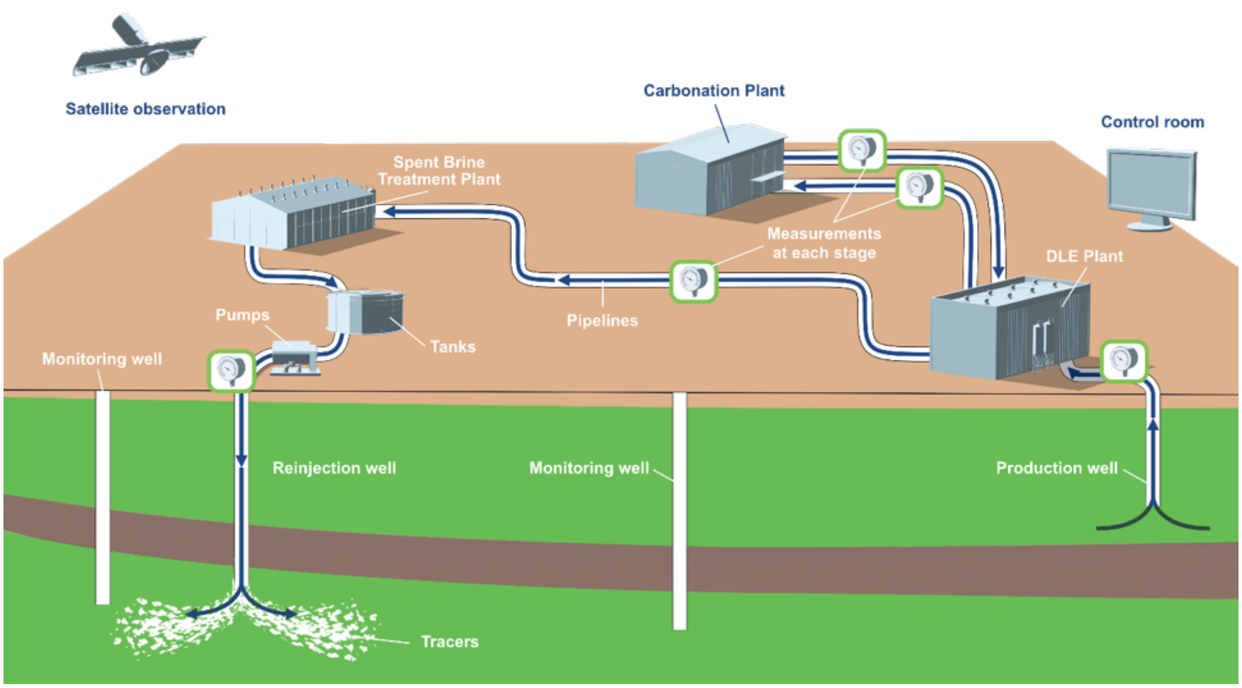
What are the components of a brine recycling system?

4. What are the components of a brine recycling system?

In this section, we outline the main components of a system designed to extract and recycle lithium brine. This system is comparable to the one used in the oil and gas industry for waterflooding, which boosts oil recovery from reservoirs. While there are similarities in some components, the system must be specially designed to suit the distinctive hydrogeology of salars and geochemistry of lithium brine.

The figure below summarizes the components of a brine recycling system.

Figure 4.1: Overview of a brine recycling system



Source: Zelandez

4.1 Reinjection wells

Reinjection wells need to be strategically positioned around the reservoir

A lithium brine project recycling brine will require pumping/extraction and reinjection wells. Both types must be installed to depths that support the extraction and reinjection strategy and will involve different types of wells at different lateral locations or depths:

- **Extraction wells** should be designed carefully considering several factors. These include the spacing between wells, the extraction rate, and the positioning of the extraction wells relative to reinjection wells. This harmonious design is crucial for an efficient extraction and reinjection scheme.

- **Reinjection wells** should be strategically positioned lateral to extraction wells to deliver brine to specific areas of the reservoir while maintaining hydrostatic pressure and minimizing hydrological impacts. The layout of reinjection wells in brine recycling systems may differ significantly from those in oilfield waterflooding. When situating reinjection wells, it is crucial to consider the depth and extent of aquitard geological layers, as these can serve as natural barriers to pressurized brine reinjection. Considering the depth of reinjection wells and the presence of different aquitard units, attention to reinjection pressures is vital for effectively operating reinjection wells.

Geological surveys should ensure that exploration and test wells accurately reflect subsurface conditions where potential reinjection wells and extraction wells will be located. Too close to extraction wells, reinjection wells can threaten the economic upstream extraction process through earlier-than-expected dilution. Too far from extraction wells, and reinjection wells may require more energy to pump depleted brine back into the reservoir as they may not sense the pressure drawdown from extraction wells.[4]

Maintaining well integrity is crucial, especially given the relatively shallow depths of reinjection in salars. High-quality cementation of reinjection wells, particularly above well screens, is essential to prevent pressurized fluid loss around well heads. This requires the use of casing bond logs (CBL), similar to those used in the petroleum industry, to validate the cementing of well casing and ensure it is suitable for reinjection purposes.

4.2 Reinjection monitoring equipment

Use monitoring wells and equipment to ensure brine is reinjected safely and efficiently

Key equipment is needed to monitor the reinjection process to ensure brine is injected correctly. It includes pressure sensors, flow meters, and temperature sensors providing real-time data to the control room. Key components include:

- **Injection pressure monitoring** is the primary activity to ensure reinjection well and reservoir integrity. Both surface and downhole measurements are recommended to maximize system efficiency and reinjection potential. Of particular interest is the accurate measurement of pore pressure using a formation testing tool to establish baseline pressure measurements. Surface

4 *Grant, 2020*

monitoring remote sensing methods are readily available and used in the geothermal and other industries.

- **Flow meters** are used to measure the flow rate of the injected brine. Pressure gauges are used to measure the pressure of the injected brine. They can both be installed at various points along the reinjection line, including the reinjection wellhead and the pipeline leading to the reservoir. Flow meters and pressure gauges provide real-time data on the injection rate, which can be used to control the injection rate and adjust it as needed.
- **Brine quality sensors** are used to monitor the quality of the injected brine. They can measure various parameters, including pH, temperature, and conductivity. Brine quality sensors provide real-time data on the quality of the injected brine, which can be used to adjust the injection rate and adjust the brine treatment process as needed.
- **Monitoring wells** should be established within and around the perimeter of a salar, along with property boundaries and close to extraction well sites, to assess the performance of a brine pumping and reinjection operation. These wells will offer crucial data on shifts in groundwater levels and aquifer pressures, essential for effectively managing the pumping and reinjection operations.
- **Tracers** can be used to study the movement of fluids in the reservoir and importantly determine fluid pathways between reinjection, extraction, and monitoring wells. This data can confirm reservoir architecture and ensure that reinjected fluid is flowing as per expectations.

Other monitoring solutions include fiber optics, LIDAR, and satellite-based observations such as InSAR (Interferometric Synthetic Aperture Radar) which help monitor subsidence and upheaval.

4.3 Reinjection control equipment

Control equipment enables calibration and automation of brine recycling

Control equipment includes valves, chokes, and other devices to regulate brine flow into the reinjection wells. Controlled from a central room, operators can monitor and adjust the injection rate and pressure. Key components include:

- **Pressure relief equipment** is essential at surface to ensure safe injection pressures are maintained at all times.
- **Control valves** are used to regulate the flow rate and pressure of the injected brine. They can be installed at various points in the system, including the reinjection wellhead, the reinjection pipeline, and the brine treatment system. Control valves can be automated or manually controlled to adjust the injection rate and pressure as needed.

- **Programmable logic controllers** (PLCs) are used to control and automate the brine reinjection system. They can be programmed to control the injection rate, pressure, temperature, and brine quality based on real-time data from the monitoring equipment. PLCs can also be used to detect and respond to system alarms and shutdowns, ensuring the safe and efficient operation of the system.

4.4 Reinjection pumps, pipelines, and tanks

Spent brine needs to be transported from treatment plants to reinjection wells

Reinjection pumps, pipelines and tanks are needed to transport brine to the reinjection wells:

- **Reinjection pumps**: These pumps deliver brine from the surface into the reinjection wells. They are often positive displacement pumps, ensuring a constant flow rate and pressure. They are built to withstand harsh conditions, including high pressures.
- **Reinjection pipeline** transports brine from the surface to the reinjection wells. It's usually made of HDPE, stainless steel or corrosion-resistant alloys to withstand corrosive brine. In high salinity environments, other materials may be used. Furthermore, in regions with sub-zero temperatures, it is essential to protect reinjection pipelines and prevent the freezing of spent brine, which can be achieved through insulation and heat tracing.
- **Tanks** need to be sized to allow produced brine to be passed through the treatment equipment at the required rate and allow for process interruptions and minor maintenance. The reinjection system will produce brine into the storage tanks where a transfer pump will typically push the spent brine through the treatment equipment and either into a storage tank or directly to the reinjection wells. Ponds may be required in certain circumstances, with different jurisdictions having prescribed codes and standards for design and construction as well as integrity.

4.5 Upstream DLE plant

The Direct Lithium Extraction (DLE) plant, sometimes referred to as the 'upstream' treatment plant because it is the first step in the treatment of source brine from wells, is an important component of a brine recycling system because it will produce the majority of the spent brine that needs to be reinjected.

As described below, there are different types of DLE technologies, each of which will have different pre-treatment and DLE requirements that could affect the spent brine chemistry and temperature. Additional treatment may be required to condition the spent brine for reinjection.

There are very different types of DLE technologies, which impact on brine chemistry

Today, the market offers three main types of DLE solutions, each designed to address an operator's specific brine treatment needs:

- Sorbent-based systems
- Ion exchange (IX) systems
- Liquid-to-liquid systems

Some systems combine these approaches to create a comprehensive pre-treatment and processing technology stack, effectively managing the challenges of processing salar brines.

The choice of technology will depend on project specifics

An operator's choice of a DLE system depends on various factors, such as:

- Brine feed characteristics, such as temperature, pH and the impurity profile, which is influenced by geology and in turn impacts the performance of the DLE process.
- The operator's treatment and reinjection objectives, as well as regulatory requirements.
- Considerations regarding site location, footprint, emissions, accessibility of utilities (power, water), and reagents.
- Operational and capital expenditure constraints.

Each salar brine is unique, and even within a single salar, there can be geochemical variations. Apart from reservoir geochemistry, local regulations or physical constraints may influence the selection of a DLE system. Each system offers specific advantages that can enhance lithium recovery. For instance, an ion exchange system might be preferable for high-impurity salar brines and petrobrines (e.g., the Smackover Formation in Arkansas or oilfield brines in Western Canada and the USA), but it may require the use of acid and base reagents for extraction support.

Current sorbent systems, on the other hand, require fewer reagents but may not be as effective at managing harsh impurities. Fortunately, the DLE industry has various technologies with unique strengths to suit different scenarios. A thorough evaluation of a brine asset's characteristics, along with an assessment of environmental and regulatory considerations, is necessary during the testing and procurement phase.

There is unlikely to be a single 'best' DLE solution for all situations, and the DLE sector itself is developing and bringing new innovations to market on a regular basis.

4.6 Midstream carbonate plant

The product from DLE, a lithium chloride or lithium sulphate solution, known as eluate, exiting the upstream Direct Lithium Extraction (DLE) plant is high in lithium and can contain notable impurities like calcium, magnesium, and boron. To refine this eluate into a lithium solution suitable for lithium carbonate processing, further treatment is required.

Mid-stream treatment potentially involves many different steps

The mid-stream treatment will typically include the following steps:

- **Impurity removal using lime (Calcium Hydroxide) and soda ash (Sodium Carbonate)**: To achieve the desired purity levels for carbonation, the eluate undergoes treatment with lime and soda ash to remove impurities, with solid impurities precipitating out and being separated by filtration.
- **Eluate concentration by reverse osmosis**: The eluate stream, containing concentrated lithium, is further processed through reverse osmosis to increase lithium concentration further. The reverse osmosis process has two outputs, the lithium concentrate already mentioned, and, in addition, a dilute solution called "permeate", which can be recirculated to the DLE plant.
- **Lithium concentration using mechanical vapor recompression**: Evaporation using mechanical vapor recompression (MVR) technology can be employed to further increase lithium concentration, preparing the solution for processing into lithium carbonate. Both the reverse osmosis and MVR systems are designed to recover water for recycling, minimizing process water consumption.
- **Impurity removal through ion exchange**: Residual trace impurities can be removed through ion exchange before carbonation, ensuring that the lithium solution meets the purity standards required for further processing into battery-grade lithium carbonate.
- **Carbonation, dewatering and purification:** Sodium carbonate can be added to the lithium solution, causing lithium carbonate to precipitate. This pulp is then centrifuged, repulped, and washed with ultra-pure water in two stages to achieve the desired product purity. The separated mother liquor can be sent to direct lithium extraction (DLE) to maximize lithium recovery, while the purified lithium carbonate is dried and packaged for sale.

4.7 Treatment of spent brine before reinjection

The spent brine that comes from the DLE plant is very likely to need further treatment before it can be injected. If the spent brine has different physical and chemical conditions than the raw brine in the reservoir, then it can:

- Damage the reservoir itself, by changing the geochemistry through water/rock interaction such that the formation becomes clogged or loses permeability and/or pollutes nearby groundwater resources.
- Damage the reinjection equipment, and pipelines by causing corrosion and scaling.

The possible steps involved in spent brine treatment may include the following, although not all are likely to be required in every case:

- **Filtration**: Ensures reservoir integrity and optimal operation by removing sediment and suspended particles, and maintaining system performance through regular maintenance and replacement of filters.
- **Degassing**: Prevents equipment damage and microbial growth by removing dissolved gas from injected spent brine, reducing the risk of corrosion, scale formation, and clogging.
- **pH adjustment**: The pH of the brine can vary in the DLE process, so it can be necessary to adjust it to the original values in the reservoir.
- **Total dissolved solids (TDS)**: The TDS of the brine can vary in the DLE process, so it can be necessary to adjust it to the original values in the reservoir.
- **Temperature adjustment**: The temperature of the brine may be modified to improve the performance in the DLE process, so it can be necessary to heat or cool the spent brine to the same temperature that it has in the reservoir.
- **Sulfur removal**: Ensures environmental compliance and prevents reservoir damage and steel equipment corrosion by removing sulfur from the recycling stream before reinjection.

These are further described in the subsections below.

Filtration is essential as the first step to removing impurities

Proper filtration is crucial to prevent reservoir damage, maintain reinjection system integrity, and optimize the performance of the operation. Regular maintenance, cleaning, and replacement of filters are important to ensure continued filtration effectiveness and smooth operation of the process.

A filtration system for a brine recycling operation typically includes the following types of filters:

- **Sand filters**: These capture smaller suspended solids (100 µm - 5 mm) like sand, grit, and other particulate matter, further protecting downstream filters and equipment.
- **Cartridge filters**: These filters provide finer filtration, typically removing particles in the range of 5 µm to 100 µm. The specific pore size of the filter cartridge is chosen based on the desired level of filtration and the nature of the contaminants present. Common materials include pleated paper, wound string, or ceramic.

In some cases, where the spent brine produced by the DLE plant is particularly high in particles or impurities, additional microfiltration may be required.

Degassing helps prevent corrosion and scaling

Injected spent brine should be degassed to prevent serious integrity and injectivity issues. Dissolved gasses can damage the equipment used in reinjection systems, such as pumps, pipelines, and reinjection wells. By removing dissolved gases from the reinjected spent brine, the risk of corrosion can be significantly reduced, which can help to extend the lifespan of the equipment.

Dissolved gases can also contribute to the formation of mineral scale deposits within the reservoir and the reinjection system. Scale can reduce the permeability of the reservoir and block the flow of brine, which can negatively impact the efficiency of the reinjection. Degassing the reinjected spent brine reduces the risk of scale formation.

Finally, it is important to avoid microbial growth. Dissolved gases can promote the growth of bacteria and other microorganisms in the reinjection system and reservoir. Microbial growth can lead to clogging, fouling, and corrosion of the equipment, which can reduce the efficiency of the process. By removing dissolved gases from the spent brine, the risk of microbial growth can be minimized.

Chemical agents are needed to adjustment of the pH of the spent brine

Chemical agents can be necessary to adjust the pH of the spent brine in DLE processes. The pH variation of brine is crucial, directly affecting process efficiency and quality. During lithium extraction from brine, various factors such as reagents, air contact, or process conditions can alter its pH. Consequently, the pH of the spent brine may deviate significantly from its original reservoir values.

To maintain environmental integrity and process sustainability, it is essential to restore the spent brine's pH to its original levels. This is achieved by adding chemical corrective agents like hydrochloric acid or sodium hydroxide as needed to raise or lower the pH appropriately. Restoring the pH not only preserves the brine's natural chemical composition but also facilitates its safe reintroduction into the environment.

In DLE plants, automatic pH control is typical, employing monitoring and dosing systems to ensure continuous and efficient operation.

Temperature adjustment for the spent brine

In the Direct Lithium Extraction (DLE) process, the recovery and selectivity can be significantly influenced by the temperature of the brine. Because of that, it can be necessary to heat or cool the brine before the lithium extraction process, and consequently, spent brine temperature will change too.

If the temperature of the brine in the extraction system deviates too much from the reservoir temperature, it can affect the solubility of ions within the spent brine solution, and it can lead to conditions that may cause precipitation of salts in the reinjection system, wells, and reservoir.

Therefore, careful monitoring and control of the spent brine temperature are imperative. This often involves the use of heating or cooling systems to adjust the temperature of the spent brine before it is recycled. By ensuring that the spent brine is at the optimal temperature it is possible to avoid salt precipitation conditions in the reinjection process

Sulfur removal may also be needed

In a similar way to oxygen, produced brine can contain sulfur which may need to be removed from the recycling stream before reinjection. Sulfur is a hazardous material that can be harmful to the environment if not properly treated or disposed of. Environmental regulations may require the removal of sulfur from reinjected spent brine to ensure that it meets the required discharge standards.

Sulfur can also cause reservoir damage by reacting with minerals in the reservoir, leading to the formation of scales and deposits that can clog the formation and reduce permeability. This can negatively impact the efficiency of the recycling process and ability to inject brine. Sulfur can also cause corrosion of any steel equipment used in reinjection, such as pumps, pipelines, and reinjection wells. Corrosion can lead to leaks, equipment failures, and unplanned downtime, which can increase operating costs and reduce the efficiency of the recycling process.

For brines containing high amounts of dissolved hydrogen sulfide (more probable in oilfield or geothermal than salar brines), additional challenges above and beyond those found in traditional brine management are to be expected. Higher temperatures and higher salinities will impact the solubility of hydrogen sulfide which could potentially even dissociate into the gaseous phase in infrastructure, depending on concentration.

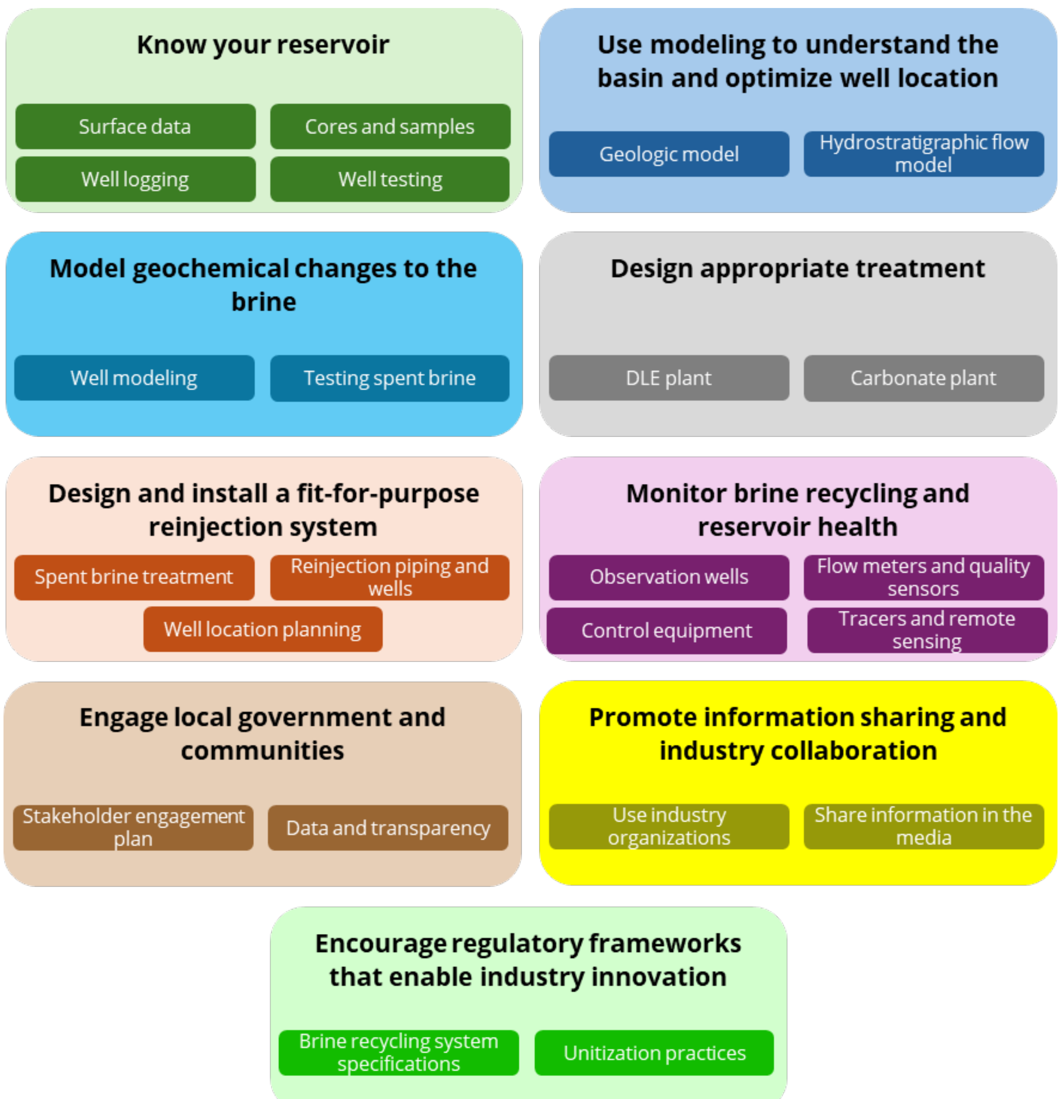
Recommendations for best practice brine recycling

5. Recommendations for best practice brine recycling

In this section we recommend actions that developers of lithium brine projects should take to recycle brine in a way that minimizes environmental impacts and optimizes the efficiency of lithium production.

The figure below summarizes these recommendations.

Figure 5.1: Overview of recommendations for brine recycling



Source: Zelandez

5.1 Know your reservoir (collect extensive geological data for modeling)

To optimize reservoir performance and minimize environmental impacts, effective long-term brine recycling requires a comprehensive understanding of basin hydrogeology. This entails gathering data from various sources to develop a groundwater flow model, a process that continues throughout a lithium brine project. Most brinefield projects already do a reasonable job of this.

Achieving sufficient data density, both spatially and in depth, is crucial for detailed data correlation across the asset and for crosschecking data from different sources. Identifying aquifer units, determining their lateral extent, identifying vertical permeability barriers, and understanding geochemical variations are essential elements that must be properly defined. This ensures the selection of reinjection points that can be sustained over time and align with environmental and economic considerations.

This information also needs to meet the reporting requirements for the appropriate reporting jurisdiction (e.g. JORC, CIM, SEC).

The required data can be grouped into the following categories:

- Surface geophysical data
- Cores and samples
- Well logging
- Well testing

These are described in the subsections below.

Collect data from surface geophysics

Surface geophysical data, obtained from various sources such as electrical (TEM, MT, CSAMT, VES), gravity, and seismic techniques, offer significant advantages in terms of areal coverage. Ideally, these techniques should encompass the entire basin area, including its margins. However, they are limited in vertical resolution, and some techniques may be imprecise in determining the depth of detected changes. To overcome these limitations, surface geophysics should be integrated and complemented or expanded with borehole geophysics.

Electrical techniques are particularly effective for initial mapping of brine and brackish water reservoirs, especially those closer to the surface. To further refine and extend this information to greater depths, borehole formation resistivity and a detailed lithological understanding are essential.

Gravity and seismic techniques are useful for identifying major sediment/rock contacts beneath the surface, especially for pinpointing basement contacts and understanding their geometry. However, the inferences drawn from surface geophysics must be confirmed through drilling and downhole geophysics.

Analyze cores and samples

Cores provide crucial geological details such as mineralogy, lithology, sedimentary structures, textures, and contacts. They serve as the basis for laboratory analysis, offering insights into porosity, mineralogy, and grain density. Typical laboratory tests provide data on porosity, mineralogy, and grain density, although more tests may be added as the industry evolves including mechanical property testing. This information forms the foundation of any robust geological model.

However, in unconsolidated to partially consolidated sediments, cores have limitations, particularly in core recovery and preservation, which can render some laboratory tests unreliable or impossible. Additionally, the data density provided by laboratory tests is often insufficient to fully support a groundwater model.

Conduct well logging to understand borehole characteristics

Borehole geophysics addresses the weaknesses of core data. It can be conducted during diamond and rotary drilling, providing continuous measurements with high data density. These measurements are essential for interpreting core data, integrating it into the broader context, and establishing well correlation.

Well logging assesses four key aspects:

- **Fluid types**: Identifying and mapping the distribution of fresh water and denser brines is crucial for determining project feasibility, ensuring long-term sustainability, and maintaining environmental equilibrium. Key measurements for this purpose include formation resistivity, borehole conductivity, and temperature.
- **Lithology evaluation**: Well logging provides additional information beyond what cores can offer due to limitations in preservation or recovery. To enhance well correlation, a minimum set of geophysical measurements is recommended, including spectral gamma ray, borehole images, and formation resistivity.
- **Porosity and permeability data**: Nuclear magnetic resonance (NMR) is particularly effective for assessing these critical properties. Its high vertical resolution allows for estimations of specific yield and retention, along with the ability to compute permeability and hydraulic conductivity, making it a comprehensive method.

- **Pore pressure and fluid sampling**: Formation testers, which are wireline-based tools, provide crucial data about the movement of fluids from the reservoir to the wellbore. This detailed pressure and permeability data aids in characterizing hydraulic flow units, establishing connectivity between wells, and understanding geomechanical data to define injection limits. This information is critical for planning effective reinjection strategies.

Apply well testing techniques

Well testing compliments well logging by providing essential hydraulic and pressure information. This data not only verifies downhole logging estimations but also supplies the groundwater model with crucial information, aiding in predicting the behavior of the fluid system.

In conclusion, combining cores and samples, borehole geophysics, and well testing techniques provides a robust framework for developing a detailed and reliable groundwater model.

5.2 Use modeling to understand the basin and optimize well location

Developing a detailed 3D geological/hydrostratigraphic model is essential for planning production and reinjection wellfields, optimizing resource development, and minimizing groundwater level decline. This model informs the placement, depth, and number of wells, which is crucial for balancing stable brine reinjection with operational costs.

The model development process consists of two stages:

- Geologic model
- Hydrostratigraphic / groundwater flow model

These are described in the subsections below.

Develop a conceptual geologic model

Understanding the basin area begins with developing a conceptual model to outline the subsurface arrangement. This model provides insights into the lithostratigraphic units, their distribution, thicknesses, and lateral variations across the basin. By incorporating laboratory and borehole geophysical data, particularly porosity and textural information, the model aims to classify units as aquifers or aquitards, seals, or vertical permeability barriers. Geochemistry data further refines the model, providing crucial input for estimating resources and reserves.

The conceptual model should also include topographic data and geological mapping to identify (from a conceptual perspective) areas of recharge, sediment sources, margins, and zones of fresh/brackish water and brine.

This understanding enables the interpretation of sedimentary infill and the evaluation of basin evolution over time. It helps determine how depocenters, paleo-topographic highs, and margins migrated within the basin, and how sediment types and thicknesses responded to these migrations. It also considers major deformation structures within the sedimentary succession, providing insights into the distribution and potential interaction between hydrogeological units.

A comprehensive conceptual model enhances the realism and value of the numerical data used in the next step: the numerical model or groundwater model. After creation, the conceptual model should be reviewed by independent assessors to ensure all relevant components and their relative importance are considered. Any data gaps identified should be addressed through additional data collection.

Develop a full groundwater model and plan field development

After developing the conceptual model, the next step is to integrate numerical data from various sources, primarily from well testing, field tests, and weather stations. Well testing, borehole geophysics, and laboratory data (when available) provide information on permeability, hydraulic conductivity, transmissivity, flow rates, dynamic levels, and hydraulic connectivity, which are used to create a numerical model (typically using Modflow or Feflow software). This model aims to understand subsurface flow behavior.

Surface data collection involves measuring recharge to the basin (e.g., rainfall, snowfall, river flows, hydrogeologic lateral recharge), evaporation patterns, and seasonal variations in recharge and evaporation.

The numerical model should reflect field investigation findings, including prolonged extraction and reinjection tests in proposed hydrogeological units for production operations. It should be calibrated against static pre-pumping conditions and transient conditions from extraction and reinjection.

The model should simulate different wellfield layouts and predict freshwater and lithium extraction rates, as well as drawdown. It should incorporate Monte Carlo simulations to predict resource extraction under different scenarios, assess impacts on groundwater levels and quality, and identify operational constraints to minimize impacts. This modeling approach enables the planning of field development, extraction rates, and project ramp-up.

5.3 Model geochemical changes to the brine

Understanding the variations in brine concentration and chemistry is crucial for ensuring that reinjected brine does not damage the reservoir. Inadequately or improperly treated brine can clog the formation, pollute groundwater sources, and corrode or clog reinjection equipment. Ultimately, prevention is the best way to avoid poor reinjection performance.

There are two key ways to develop this understanding:

- Well modeling
- Testing spent brine

These are described in the subsections below.

Model the brine chemistry of all planned wells

Brine extracted from different wells will have varying lithium and other element concentrations, which can change over time as more dilute brine flows from the salar margins toward the center, either naturally or due to pumping or reinjection. It's important to develop modeled profiles of changes in brine chemistry for all planned wells, not only from the perspective that DLE plants will generally require a well-defined inlet chemistry to ensure orderly operations, but that risks associated with effluent chemistry should be evaluated prior to operations. Evaluations should use geochemical modeling software like Phreeqc, which assesses the solubility of different mineral species at various pressures and temperatures. In the case of the studies referenced in Annex 1, practical methods like microfluidics can provide empirical evidence of scaling rate and scale composition. Additionally, observations from reinjection trials and examination of test holes with downhole cameras should accompany this data, in order to evaluate any precipitation of scale material in holes. Monitoring of chemistry trends in extraction and reinjection wells is important for understanding of the brine system.

Test the chemistry of spent brine before reinjecting

Laboratory testing of scaling potential, brine-rock interaction, and geochemical modelling of spent brine for reinjection is essential to ensure compatibility with the reservoir, minimizing unwanted interactions. Injected fluid should enter the brine layer well below any mixing zones or overlying fresh water, supporting ongoing extraction operations and preventing drawdown.

5.4 Design appropriate treatments

The design of the treatment flowsheet, including the selection of DLE technology, directly impacts not just the quality of the final lithium product but the overall success of the recycling system. The major process facilities include:

- DLE plant
- Carbonate plant

These are described in the sub-sections below.

The choice of DLE technology matters most

Selecting the appropriate Direct Lithium Extraction (DLE) technology is crucial when planning brine reinjection due to several key factors. The DLE plant is a pivotal component in a brine recycling system, responsible for producing the majority of the spent brine earmarked for reinjection. Different DLE techniques, such as sorbent-based, ion exchange, and liquid-to-liquid systems, each impact the chemical composition of the spent brine, influencing the necessary additional treatment before reinjection.

The choice of DLE system hinges on various factors, including the impurity profile of the salar brine, operational objectives, regulatory requirements, and site-specific considerations like location, footprint, power, water, and emissions. Since each salar brine is unique, with geochemical variations even within a single salar, the selection of a DLE system must be tailored to meet specific requirements. While ion exchange systems may be preferable for high-impurity brines, sorbent systems require fewer reagents but may not be as effective with harsh impurities. The diversity of DLE technologies allows for a customized approach, ensuring that the selected system aligns with the brine's characteristics and operational goals.

The carbonation plant is also important

The steps in mid-stream treatment may include the use of lime and sodium carbonate for impurities precipitation, reverse osmosis, thermal evaporation, ion exchange, and centrifuging. The choice and combination of these particular technologies has important implications for the quality of the final product and the characteristics of other effluents generated.

5.5 Design and install a fit-for-purpose reinjection system

For a successful brine recycling system, it is crucial to carefully assess and select key components. This includes choosing the right equipment for the reinjection and treatment plant, well materials, screen size and area, gravel pack, well head installation, pumps, surface pipes, and details of the DLE plant, as well as tanks and ponds.

Key components, which deserve particular attention for the reinjection system, include:

- Spent brine treatment
- Reinjection piping and wells
- Well location planning

These are described in the subsections below.

Treat spent brine before reinjection

Efficient brine reinjection starts with a robust filtration system designed to remove sediment and suspended solids, safeguarding the longevity of both the reservoir and injection infrastructure. This process typically involves a sequence of strainers, such as bar screens and perforated plates, to weed out larger debris, followed by sand filters to capture finer solids. For enhanced purity, cartridge filters with a specific micron rating may also be incorporated.

To mitigate corrosion caused by dissolved gases, a common culprit, as well as to curb microbial growth, degassing towers, whether the vacuum or packed bed type, are employed. Furthermore, the removal of sulfur compounds is achieved using stripping towers or chemical oxidation systems, while pH imbalances, known to cause mineral scaling, are rectified through acid or base dosing systems, accompanied by continuous monitoring.

Some DLE processes may change brine temperature, needing a heating or cooling system to adjust spent brine temperature to the same value as the reservoir.

Design robust reinjection wells

Decisions regarding the number of wells, depths, filter lengths, and materials for extraction and reinjection test wells are critical for designing optimal long-term pumping and reinjection systems. It is crucial to use high-quality cement in the upper part of the wells, above the well screens, to ensure structural integrity, considering the location of aquitard units. Casing cement bond logs (CBL) should be conducted after cementing to identify any weaknesses that could affect performance and should be performed at regular intervals to ensure long term cement integrity and to monitor for metal corrosion.

Given the highly saline environment, selecting the right cement is essential for reliable results, as cement behaves differently in highly saline reservoirs compared to low salinity environments. Additional tools like packers and gel plugs may be necessary to ensure proper reinjection of spent brine into the intended horizon, though installing these in salars can be challenging due to the geology and limited availability of suitable drilling rigs.

Carefully plan the locations and depths of production and reinjection wells

The location of both extraction wells (production wells) and reinjection wells (reinjection wells) should be planned cohesively based on hydrogeological models.

For extraction wells, careful attention should be paid to well spacing, extraction rate, and extraction well positioning in relation to reinjection wells.

Reinjection wells should be strategically laterally to extraction wells to distribute brine to specific reservoir areas, to maintain hydrostatic pressure and minimize hydrological impacts. It is crucial to account for the depth and extent of aquitard geological layers, which act as natural barriers to pressurized brine reinjection.

5.6 Monitor brine recycling systems and reservoir health

Models provide predictions of fluid interactions with limited certainty. Therefore, monitoring through field tests is crucial as the ultimate validation for a reinjection program, providing key data inputs for modeling. Strong data collection is essential for accurate forecasting, aiding in predicting future operational requirements and capital expenditures for mature projects. This data ensures there is enough useful information on changes in brine levels within the reservoir and surrounding brackish to freshwater zones and their quality, aiding in decision-making before and during extraction and reinjection tests. Monitoring should encompass brine, brackish water, and freshwater zones to comprehend interactions around the margins of the salar.

Key components of brine recycling monitoring system include:

- Observation wells
- Flow meters and quality sensors
- Control equipment
- Tracers and remote sensing

Furthermore, effective monitoring should include:

- A long-term maintenance plan
- Use of a risk register

These are further described in the subsections below.

Use observation wells

To ensure thorough data collection and goal achievement, a comprehensive monitoring network with multiple observation wells and downhole sensors around each reinjection well is essential. Observation wells should be positioned to avoid acting as a potential shortcut for reinjected brine. This requires ensuring that open monitoring wells are not near reinjection wells. A monitoring system with wells and equipment capable of assessing pressure distribution in the target reservoir is crucial, providing insights into injected and produced fluids across different depths in various aquifers and aquitards.

Use flow meters and quality sensors

Flow meters and pressure gauges are other key components of brine reinjection monitoring system. Flow meters measure the flow rate of injected brine, while pressure gauges measure its pressure. These instruments are installed at various points along the reinjection line, including the wellhead and pipeline leading to the reservoir, providing real-time data on injection rate for rate control and adjustments. Brine quality sensors are also critical, monitoring parameters like temperature, pH and conductivity. This real-time data guides adjustments to the injection rate and brine treatment processes as necessary.

Use control equipment to respond to monitoring

Control equipment is an important complement to monitoring equipment, because it enables real-time response when monitoring shows that operational and environmental objectives are not being met. This includes valves, chokes, programmable logic controllers, and other devices to regulate brine flow into the reinjection wells.

Use tracers and remote sensing to monitor fluid flow in the reservoir

Tracers are additives to injected fluid that are inert to the environment and not naturally occurring. By monitoring the time taken from injection to the arrival of the tracer at a monitoring or extraction well, reservoir connectivity and fluid distribution can be established.

Tracking surface movement via satellite-based InSAR or ground-based LIDAR can provide a proxy measurement of pore pressure within the reservoir. This data can be used in conjunction with tracer studies and models to confirm fluid movement in the reservoir.

Implement a long-term maintenance plan

Equipment will operate in a harsh environment and regular monitoring of equipment condition is required, together with a long-term maintenance plan for repairs or replacement of equipment. This should include camera evaluation of pumping and reinjection holes, pipelines and visual evaluation of other equipment. The information collected should be clear to and acted on by the operations team, and maintenance schedules modified if required.

Establish a risk register, which covers the risk of brine spills

It is recommended that lithium project operators establish a risk register as early as possible, in combination with a suitable Risk Assessment Matrix. This will help identify and manage the risks associated with large-scale lithium extraction and reinjection, such as brine spillage outside the salar environment. Operators should ensure that their emergency response measures comply with local permits and relevant legislation in their geographical areas of operation.

Brine spills are a particularly important risk to be mindful of. They affect soil and vegetation by increasing soil conductivity, causing swelling and reducing water penetration, and by decreasing water availability and adding toxicity to plants. To mitigate the impacts of any spills, projects should adhere to local legislation, implement containment measures, and choose between in situ (chemical treatments) or ex situ (soil removal) remediation. Regular soil monitoring and preventative measures are essential to manage and prevent spills.

5.7 Engage local government and communities

Engaging local stakeholders is critical for the success of brine recycling operations. The support and partnership of these stakeholders, including local communities and governments, are essential for ensuring the project's viability and sustainability. While salars are often located in remote areas with sparse populations, overlooking stakeholder engagement can pose significant risks to project advancement. Failing to engage with stakeholders can lead to misunderstandings, mistrust, and opposition, which can seriously delay projects.

Key aspects of stakeholder engagement include:

- Stakeholder engagement plan

- Data and transparency

These are described in the subsections below.

Develop a stakeholder engagement plan early on

All stakeholder groups, including local landowners and communities, regulatory bodies, contractors, and shareholders, should be identified and their viewpoints documented to ensure their concerns are addressed and their interests are safeguarded throughout the project lifecycle.

Developing a comprehensive stakeholder engagement plan early in the project planning phase is advisable. This plan should include strategies for engaging with different stakeholder groups, tailored to their specific needs and expectations. Potential stakeholders include:

- Local land owners/nominal land owners/communities
- Mines Departments
- Water Resource regulators
- Environmental regulators
- Company contractors and personnel
- Suppliers, such as drilling companies, who are a critical contributor to success
- Shareholders
- Local municipality, in appropriate circumstances

Stakeholder engagement activities may range from single informative meetings to regular ongoing communication, depending on the stakeholder group and their level of interest or involvement in the project. Utilizing simple and informative graphics in communication materials can help convey complex information effectively to stakeholders with varying levels of technical expertise.

Use data and transparency to build confidence in brine recycling

Transparent communication of project plans, especially regarding aquifer management strategies, is essential for building trust and confidence among stakeholders. This transparency helps address any skepticism about the effectiveness of reinjection in mitigating hydrodynamic impacts associated with brine extraction.

A key aspect of stakeholder engagement is providing data and information that demonstrates the efficacy of the reinjection system. Operators who can transparently offer real-time field data highlighting the performance of their reinjection systems are more likely to receive support from communities and regulatory bodies. This data not only instills confidence but also aids in meeting Environmental Impact Assessment reporting requirements, showcasing the project's commitment to environmental stewardship.

5.8 Promote information sharing and industry collaboration

The concept of brine recycling / reinjection is relatively new in the lithium brine industry. Without proper information sharing and stakeholder education, there is a risk of misunderstanding or misrepresentation, especially with polarizing activities such as fracking in the oil and gas industry. Brine recycling should be viewed as an opportunity to minimize environmental impacts, rather than a threat.

Key recommendations include:

- Use industry organizations
- Share information in the media

These are described in the subsections below.

Use organizations such as the International Lithium Association

To promote best practices in brine recycling, organizations such as the International Lithium Association can play a pivotal role. Establishing a dedicated working group under the association's umbrella can facilitate the development of guidance documents and the sharing of best practices and lessons learned as the industry evolves. This collaborative approach ensures that industry standards remain current and relevant, enhancing the overall sustainability and effectiveness of brine recycling projects.

Proactively share information in the media

To prevent misrepresentation and confusion, a proactive approach to sharing information with the media is advisable. Developing a standard "Media Package" through the association can serve as a reliable and consistent source of information for stakeholders and media outlets. This approach not only helps to accurately portray the objectives and processes of brine recycling but also minimizes the risk of misinformation or misinterpretation. Regular updates and engagement with the media can further enhance transparency and understanding of brine recycling practices.

5.9 Encourage regulatory frameworks that enable industry innovation

Mining regulations in most countries are often not well-suited for lithium brine development, as they were primarily designed for traditional hard rock mining. Additionally, there is a lack of specific regulatory frameworks focused on brine recycling. To address this, we recommend that the industry take the lead in introducing such frameworks in key lithium brine jurisdictions. These frameworks should be practical and flexible, rather than overly prescriptive, to unlock the potential of brine recycling to accelerate sustainable lithium production.

Two areas where industry might propose brine recycling regulations include:

- Brine recycling system specifications
- Unitization practices

These are described in the subsections below.

Propose minimum requirements for brine recycling systems

Minimum requirements would include factors such as void space replacement, well placement, rate limitation, barrier establishment, geochemical compatibility testing, and pressure and flow monitoring for reinjection processes.

These requirements will ensure orderly operations and protect the resource. For instance, it may be appropriate to require operators to leave some lithium resource in place (rather than fully deplete the resource) to prevent resource sterilization.

In addition, testing and data collection for review by regulators and the public will serve to enhance the credibility of the operation and avoid potentially permanent damage to the hydrological systems associated with salars.

Propose unitization practices to address cross-boundary impacts

Many salars have multiple property owners, which raises concerns about potential cross-boundary impacts of reinjection. Unlike concessions, which have strict boundaries, a brine resource does not adhere to property lines.

One proposed solution is to adopt a well-established oil industry practice known as unitization. This approach involves estimating the extraction of brine from across property boundaries through brine flow modeling and conducting periodic reconciliations between companies based on pumping records. This process ensures accurate accounting of the ownership of pumped lithium. The authors believe that a similar practice can be implemented in the lithium industry. Unitization rules in use in oil and gas vary between countries and states. However, a standard definition and rules in a jurisdiction would provide the framework to use this methodology for lithium brine. Additionally, minimum buffer or setback rules should be established to further mitigate potential impacts.

Annex 1: Case study on geochemical issues at Atacama and Maricunga

4. Annex 1: Case study on geochemical issues at Atacama and Maricunga

1. A1.1 Desktop Well Simulation Model

Introduction

Summit operated a conceptual study to test the potential minimum well-based requirements at a commercial-scale DLE operation using known analogues, based on public data from the Atacama and Maricunga salars.

It showed that adding heat reduced risk of mineral precipitation and scaling from reinjected brine, but it comes at the cost of increased energy usage and associated greenhouse gas emissions. In many areas of the Andes, continually supplying heating fuel such as propane can be logistically complex, while significantly increasing project cost. On the other hand, because so few environmentally compatible workover solvents are readily available to clean the well skin or screens of wellbores, injecting the fluid at higher temperatures may be a viable prevention measure.

Overall modeling approach

Using available public data, two simplified numerical groundwater models were constructed based on SQM Atacama[5] and Lithium Power International Maricunga[6] data, to demonstrate the feasibility of DLE as a low-impact and environmentally friendly technology.

For the purposes of the models, freshwater was defined as fluid with 1.000 to 1.002 g/cm^3 density, and brine as 1.220 to 1.223 g/cm^3 density. Although each salar has different evaporation rates based on depth to the brine reservoir, the threshold beyond which brine flows into the mixing zone, rather than evaporating before it can integrate, is expected to be between 10 and 13 L/s[7] or relatively minimal. Evaporation rate by depth, along with moderate seasonal evaporation variation through the year, was ignored for this study given their low overall impact on the model relative to the rates established in the study.

The groundwater model for each salar type was built in MODFLOW software, considering a constant fluid injection density. An area of influence was estimated for multiple reinjection scenarios to

5 *SQM, 2022*

6 *LPI, 2022*

7 *Grant & Morgan, 2021*

simulate drawdown impacts. Each production scenario is modeled at 20,000 m^3/d, a frequently cited "commercial scale" DLE production rate. All simulations model injection over a five-year period. Each scenario also considered extraction well spacing of 825m (depths between 30m and 150m), injector inter-well spacing of 315m (depths between 100m and 150m), and single well extraction rates of up to approximately 13L/s.

Salar de Atacama - approach

The Salar de Atacama, approximately 20,000 km^2 in size, is located in northern Chile in the Antofagasta region, within the San Pedro de Atacama community boundary. It is bound by the Cordillera de la Sal on the east and the Cordillera de los Andes to the west which is the assumed source of lithium-rich source water. While the salar only experiences 20 mm/yr of precipitation, the Andes to the west experience 160mm/yr[8]Outflow (from extraction and evaporation) far exceeds inflow at Atacama forming a negative water balance[9].

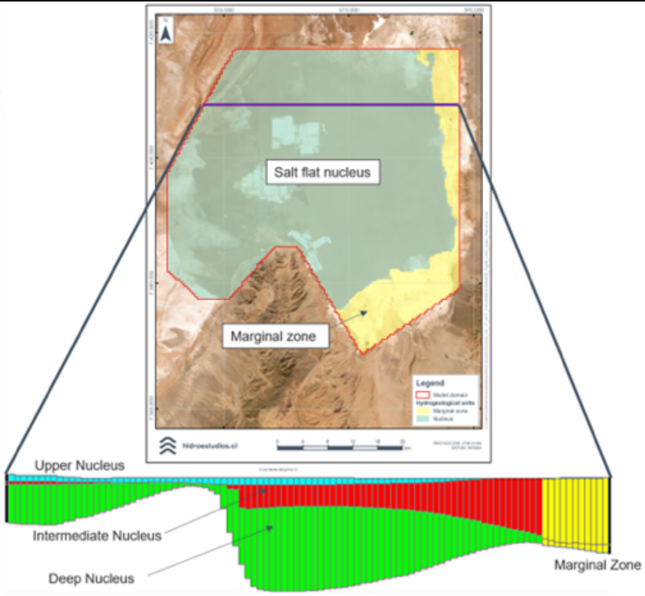
The model for the SQM properties in Atacama[10] used hydrogeological units from existing references. The salar is split up into the eastern and western block. Impermeable basement is set to 100-400m in the east block and 60-80m in the west block.

8 *SNIFA, 2017*

9 *Marazuela, 2018*

10 *SQM, 2022*

Figure: Atacama hydrogeological units



HU	Description	h (m)	K (m/d)	Ss (1/m)
1	Upper nucleus	15-45	1E-02 to 4E+04	0.05
2	Intermediate nucleus, evaporites and organics	E: 100 to 150 W: 1 to 5	6E-04 to 5	0.01
3	Deep nucleus, halite and gypsum	E: >300 W: 20 to 50	2E-03 to 120	4E-05
4	Marginal zone, silt and carbonate	100 to 200	1E-03 to 50	0.08

Source: Hidroestudios proprietary study referencing hydraulic parameters from Atacama Water (2021) NI 43-101 Technical Report. Lithium resources update MSB Stage 1 (old code concessions), III Region, Chile and SQM (2022 a) Modelo Conceptual Hidrogeológico Regional Salar de Atacama

Salar de Atacama - findings

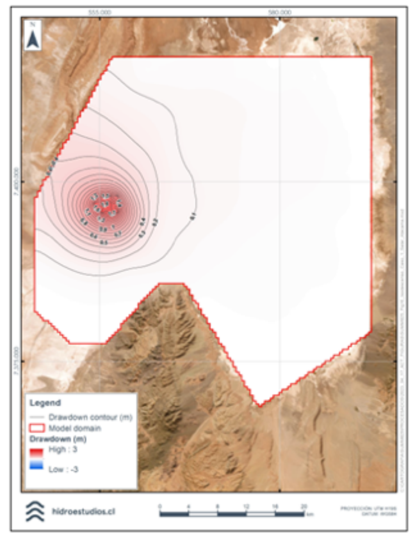
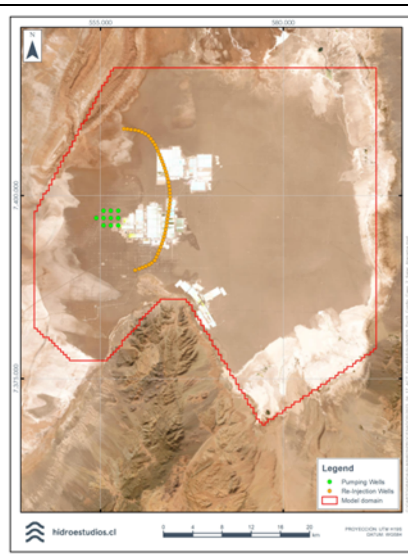
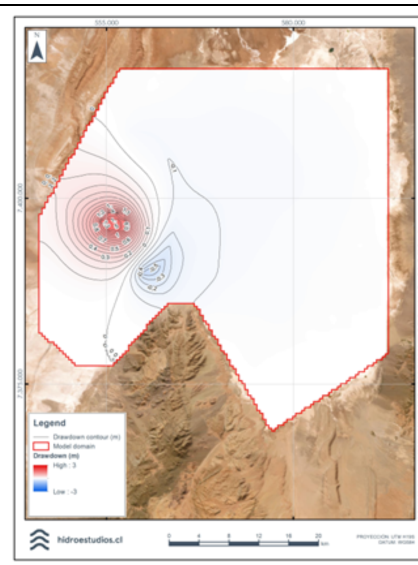
Over 25 years, the brine level in the salar has dropped 1m in the eastern block and 10m in the western block (SQM, 2022) as a result of several extraction wells over a 25km^2 area. The two operators in the salar, SQM and Albemarle, extract roughly 1,500L/s on aggregate. HU-1, the halite or "upper chlorides" brine reservoir was the primary focus of the simulation, as the deeper HU-2 acts as a moderate aquitard to the lower halite zone, HU-3.

Four simulations were conducted in the Atacama salar for future reinjection scenarios. According to the preliminary well optimization model at the high-permeability Salar de Atacama, reinjection can fulfill a barrier function and prevent drawdown of nearby freshwater resources and brackish water to the east around the margin of the salar. In Atacama, high permeability allows for fewer injection points than Maricunga to achieve a barrier function.

Particle tracking modeling was completed with MODPATH in a basic advective transport function. The results show that particles being extracted over the five-year period can migrate up to 2.5km from their origin, and the injected water can move up to 3.5km.

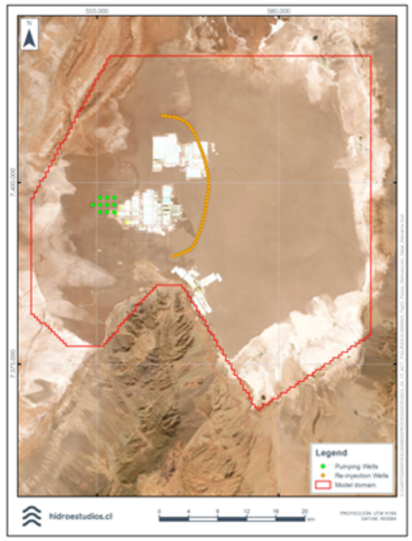
The case that simulated a ratio of two reinjection wells to one extraction well to support 250L/s of commercial operations offered an optimal solution that both established the barrier to protect eastern margin brackish water lagoons while also controlling cost. However, the primary takeaway from these simulations is that high permeability affords a wide degree of flexibility in the design of the reinjection program and the placement of wells, without significant impact associated with increased rates at fewer wells. While this is a positive sign for future capital programs at Atacama, the uncharacteristically high permeability and reservoir volume at Salar de Atacama relative to other high Andean salars suggests that these findings are less applicable to most other reinjection programs.

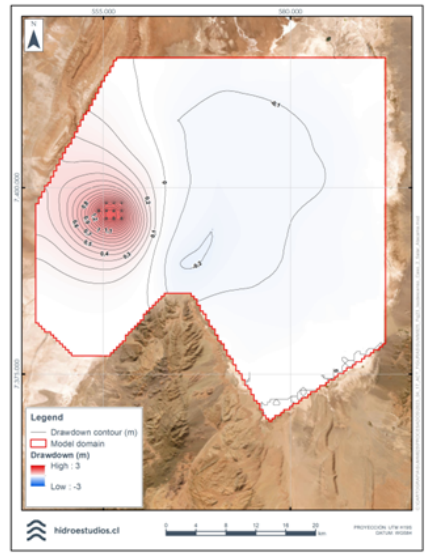
Figure: Findings - Atacama

Scenario and Findings	Well Placement	Drawdown Map
Case 1 Extraction: 250L/s Extraction wells: 10 Injection: 250 L/s Injection wells: 10 Drawdown in levels extends across the domain, with drawdown of 5cm being observed up to 28km away from the pumping area.		
Case 2 Extraction: 250L/s Extraction wells: 10 Injection: 250 L/s Injection wells: 50 Reinjection achieves a barrier function, preventing the drawdown caused by the pumping wells from extending to the east. Head increases by approximately 0.5m around the reinjection wells.		

Case 3
Extraction: 250L/s
Extraction wells: 10
Injection: 250 L/s
Injection wells: 50

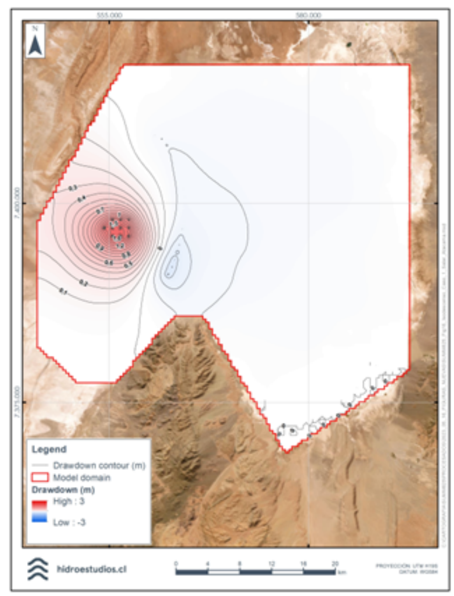
Injector distance was increased in comparison to Case 2. This case is less effective at reducing drawdowns in the pumping area, and the draw-ups in the injection extend further in the domain, as a result of Atacama's high permeability.





Case 4
Extraction: 250L/s
Extraction wells: 10
Injection: 250 L/s
Injection wells: 20

Simulated drawdown is similar to Case 2, but draw up near the reinjection area is reduced. Head increases by approximately 0.5m near the reinjection wells



Source: Hidroestudios proprietary study

Salar de Maricunga - approach

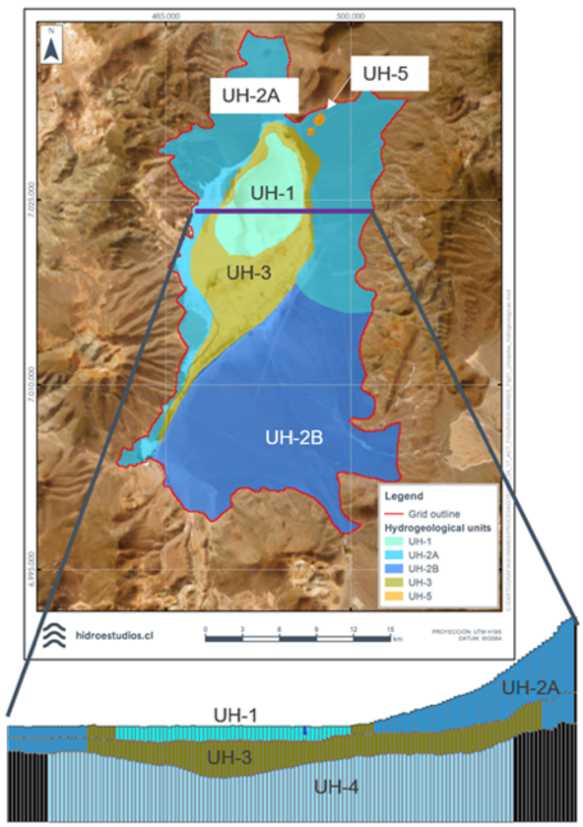
Maricunga is a pre-Andean salar that is composed primarily of halite crusts in its northern section, and sulphate-rich evaporites in the south. Like many salars in the Andes, it features a brackish water lagoon, in this case, located on the southern end named Laguna Santa Rosa. The basin is surrounded by andesites and dacites which are assumed to be the lithium source[11]. It experiences up to 300mm/yr precipitation and up to 2,400mm/yr evaporation. Direct recharge into the salar from groundwater

[11] *Sernageomin, 2017*

flows is estimated at 435L/s with lateral recharge at 992L/s. Natural evaporation is estimated at 939L/s and natural drainage at 488L/s.

Maricunga is considered a balanced hydraulic system. Today, no industrial extraction occurs, though this is expected to come online in the near future. Salar de Maricunga, with its lower overall porosity and permeability expression and smaller overall volume, was selected as the primary analogue for future studies given its closer similarities to the vast majority of current undeveloped lithium-rich salar.

Figure: Maricunga hydrogeological units



HU	Name	Description	h (m)	K (m/d)	Ss (1/m)
1	Halite	Confined and fractured evaporites	<34	100 to 640	E-05 to E-03
2A 2B	Alluvial deposits	Semiconfined alluvial fan clastics	<46	0.1 to 280	E-05 to E-03
3	Lacustrine unit	Fine grained sand with moderate clay	<180	1E-02 to 1E-01	E-07 to E-03
4	Volcanic clastics	Confined volcanic clastic material	<100	0.1 to 1	E-05 to E-03
5	Basement	Fine-grained volcanic clastics over impermeable basement	<40	1E-02 to 1	E-05 to E-05

Source: Hidroestudios proprietary study

Hydraulic units of note are the halite unit (HU-1) and the laterally deposited alluvial units (HU-2A and 2B). Below a lacustrine clay aquitard (HU-3) are volcanoclastics with moderate permeability (HU-4, referred to as "Layer 3" in the MODFLOW package and subsequent map figures). This is a primary extraction target[12], though is not expected to significantly affect drawdown due to the presence of

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HU-3 as an effective aquitard. Therefore, it is crucial to mitigate the lateral and vertical effects of extraction using reinjection to protect nearby water sources.

Six simulations were conducted in the Maricunga salar for future reinjection scenarios. All scenarios consider extraction primarily from the permeable volcanoclastic units ("deep aquifer" or HU-4, denoted as "Layer 3" in the map figures) beneath the central halite expression. A single case ("Case 4") was modeled with "offsetting" reinjection to test the benefit of reinjecting brine into the volcaniclastic unit while extracting from the overlying halite, which was modeled to assess extraction primarily from the halite with ongoing reinjection at depth.

Salar de Maricunga - findings

Extraction wells were modeled at depths between 50m and 150m at 825m lateral spacing, with reinjection wells planned for 250m to 350m depth at 315m lateral spacing.

The lower overall permeability in Maricunga, compared to Atacama, necessitates a great number of reinjection wells to achieve a barrier function. Spacing and rate will play a significant role in reducing drawup while maintaining the hydrostatic pressure of the brine layer. In reinjection scenarios that place injectors at a larger distance, the number of wells generally make little difference because of low reservoir permeability. But in the areas immediately adjacent to the injection wells, a lesser number of injectors resulting in a lower volumetric dispersion of reinjection rates, naturally yields a greater head increase, Particle tracking was modeled with MODPATH in a basic advective transport function. The results show that particles being extracted over the five-year period can migrate up to 330m from their origin, and the injected water can move up to 250m.

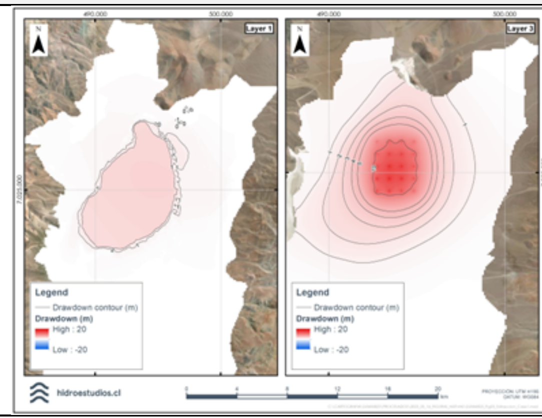
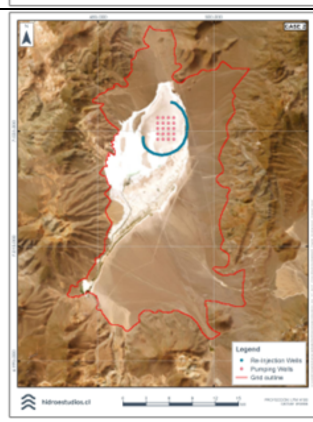
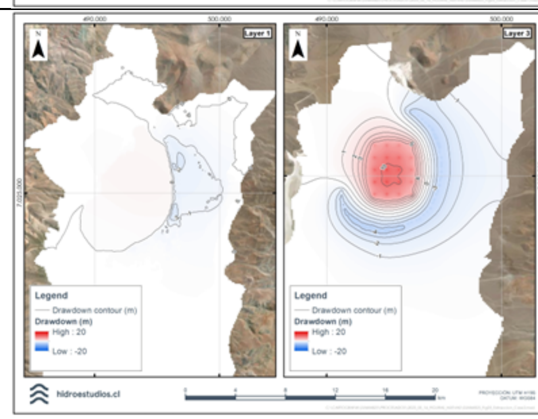
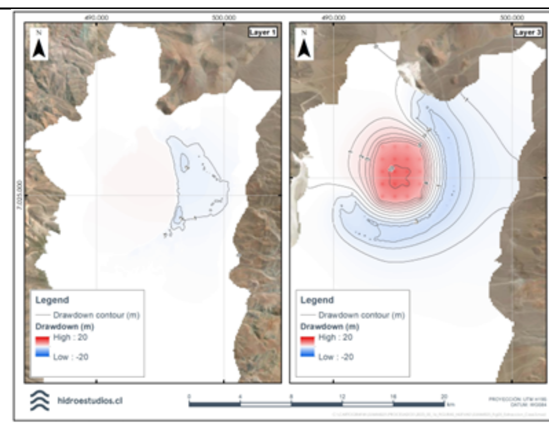
Findings from the numerical model illustrate the impact of permeability on future well array programs. The optimal scenario, which spreads injection volumes out over several wells at a ratio of five injection wells for every one extraction well, offers the safest approach when injecting below the primary lacustrine unit (HU-3) into the "deeper aquifer" or volcanoclastic unit, HU-4 to directly mitigate extraction drawdown. A modified case with 2.5 injection wells to 1 extraction well ratio, offers a balanced solution without significantly impacting the groundwater level in the overlying halite unit (HU-1).

Optimal positioning of the reinjection array in relation to offset freshwater resources requires field study to determine. Brackish and freshwater-trending areas of the salar are found in the region of least hydraulic head on the fringes. There are two potential scenarios:

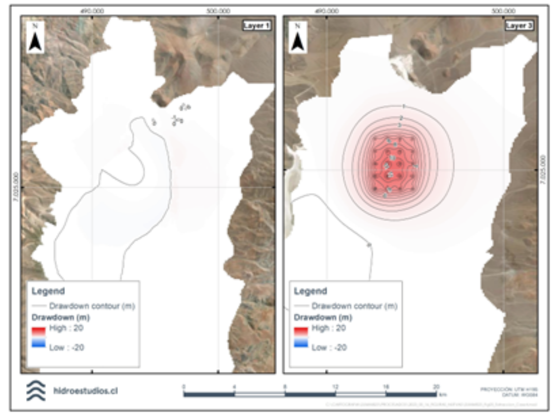
Extraction wells are placed to the outside of the salar with injectors in the core of the salar. This decreases the likelihood of reinjection impacts on the freshwater resources but increases the likelihood of drawdown-related freshwater depletion.

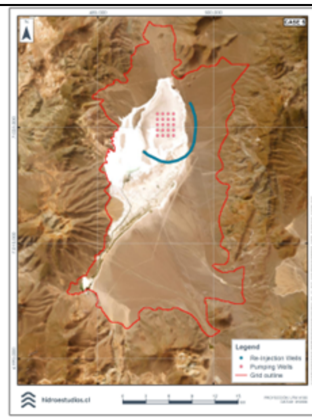
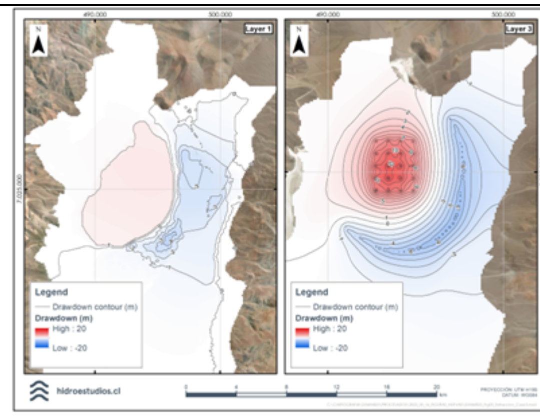
Extraction wells are placed in the core of the salar with injectors on the outside of the salar. This scenario utilizes the potential barrier effect to prevent pressure communication from extractor drawdown from impacting nearby freshwater, while raising the risk of freshwater contamination by the injection array.

Figure: Findings - Maricunga

Scenario and Findings	Well Placement	Drawdown Map
Case 1 Extraction: 250L/s Extraction wells: 20 The base case extraction simulation shows a significant drawdown up to 10m, with an area of influence that extends 5km around the extraction wells.		
Case 2 Extraction: 250L/s Extraction wells: 20 Injection: 250 L/s Injection wells: 50 Spacing: 315m Drawdown is reduced by reinjection. Head increases ~3-5m near the reinjection wells with only minor impact to the halite unit.		
Case 3 Extraction: 250L/s Extraction wells: 20 Injection: 250 L/s Injection wells: 100 Spacing: 275m Drawdown is reduced by reinjection. Head increases ~1-3m near the reinjection wells but is moderate due to injection rate dispersion across wells.		

<table>
<tr>
<td>Case 4
Extraction: 250L/s
Extraction wells: 20
Injection: 250 L/s
Injection wells: 50
Spacing: 315m

Attempting to protect halite-oriented brackish water sources through reinjection directly into the halite predictably shows little to no benefit due to compartmentalization via the clay aquitard unit.</td>
<td></td>
<td>
</td>
</tr>
<tr>
<td>Case 5
Extraction: 250L/s
Extraction wells: 20
Injection: 250 L/s
Injection wells: 50
Spacing: 315m

This case is not particularly effective as the drawdown in the halite is not significantly reduced, but drawups increase significantly laterally due to increased distance (relative to Case 2) to extraction wells.</td>
<td></td>
<td>
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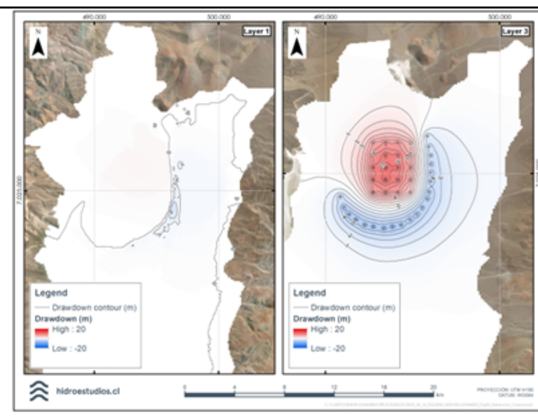
</tr>
<tr>
<td>Case 6

Extraction: 250L/s
Extraction wells: 20
Injection: 250 L/s
Injection wells: 20
Spacing: 600m

Drawdown is similar to case 2 indicating similar mitigation, but with more severe drawup, ~5-8m near the reinjection wells indicating the need for tighter spacing.</td>
<td></td>
<td>
</td>
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</table>

Source: Hidroestudios proprietary study

The results from the MODFLOW study above suggest that a balance between spacing, distance, and rate are required to support simultaneous and orderly extraction and reinjection. The implication of this is that field studies should be designed to ensure sufficient experimentation and minimize risk to the aquifer.

2. A1.2 Microfluidics Study

Introduction

Summit operated a study conducted by Interface Fluidics in Edmonton, Alberta, Canada to assess the risk of downhole fluid interactions between DLE effluent and reservoir brine in an unconfined aquifer. Case studies were undertaken at the evaluation of two salars, Maricunga and Atacama, both in Chile.

Approach

A reservoir analogue was constructed using a two dimensional "thin section" of Salar de Maricunga, supporting the ability to visualize pore-scale fluid flow and increase the speed of testing and repeatability. To design the reservoir analogues, the permeability and porosity are calculated with the following equations. The first maps the porosity of the analogue to an equivalent value that is representative of the 3-D rock. The second takes this equivalent porosity to calculate the permeability of the analogue based on the Kozeny-Carman relation.

Figure: Permeability and porosity equations

$$\varphi = \frac{\frac{H}{h_{throat}}(\varphi_{pore}) + \varphi_{throat}}{H/h_{throat}}$$

$$k = a\left(\frac{\varphi^3 h_{throat}^2}{(1-\varphi)^2}\right)$$

Where $a = 1.013 \times 10^{12}\ D/m^2$

Source: Interface Fluidics proprietary study

Scenarios

Two scenarios were run to generate specific outputs at atmospheric pressure to simulate unconfined conditions:

1. Co-injection: effluent and reservoir fluid are combined just prior to injection into the salar analogue to maximize contact between the two fluids and precipitation, while settling the fluids in the porous media. Temperature varied between 15 and 60°C to simulate a DLE effluent point versus natural reservoir temperature.

2. Displacement/regain: the porous media is filled with reservoir fluid and effluent is injected to simulate real-world conditions. Temperature was varied between 0 and 60^{o}C to simulate field reinjection that could include colder ambient conditions in the Andes.

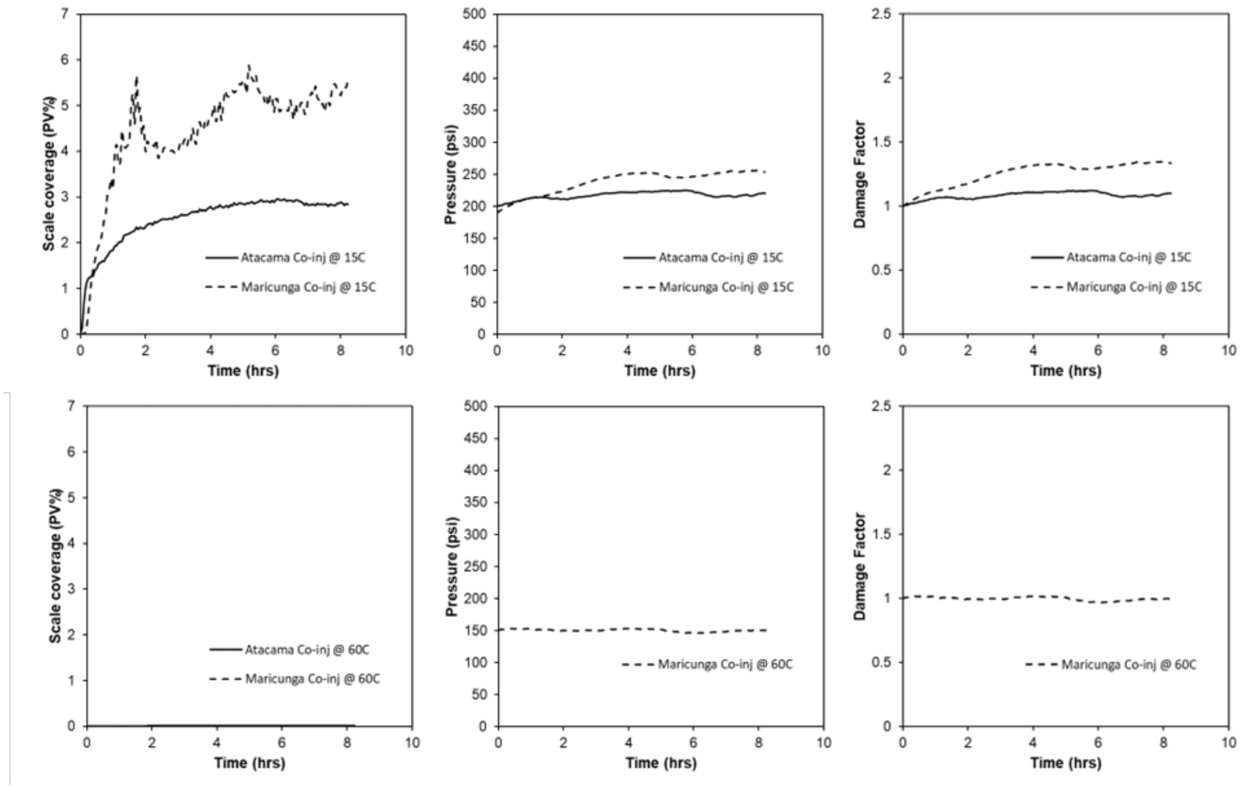
With respect to brine, the scenarios were run using denaLi™ effluent from Maricunga as the only available compositional data point for effluent chemistry. This effluent was used on both Atacama reservoir synthetic brines and Maricunga synthetic reservoir brines to generate scale coverage, pressure, and damage factor curves.

Key findings

Because denaLi™ has such low impact on the composition of the reservoir brine post-processing, pH (between 5.5 and 7.5) and density (approximately 1.195g/cc to 1.205g/cc) were largely unchanged and did not significantly affect precipitation in either Atacama or Maricunga analogues.

In both scenarios (co-injection and displacement), a higher level of precipitation and formation damage was observed at 15 ^{o}C, considered to be representative of average salar conditions, compared to 60 ^{o}C. That said, the Atacama example did show minor scale coverage under the displacement scenario, which may be the result of subtle geochemical contrasts between the Maricunga effluent used in the study and Atacama brine. More analysis is required to confirm this hypothesis.

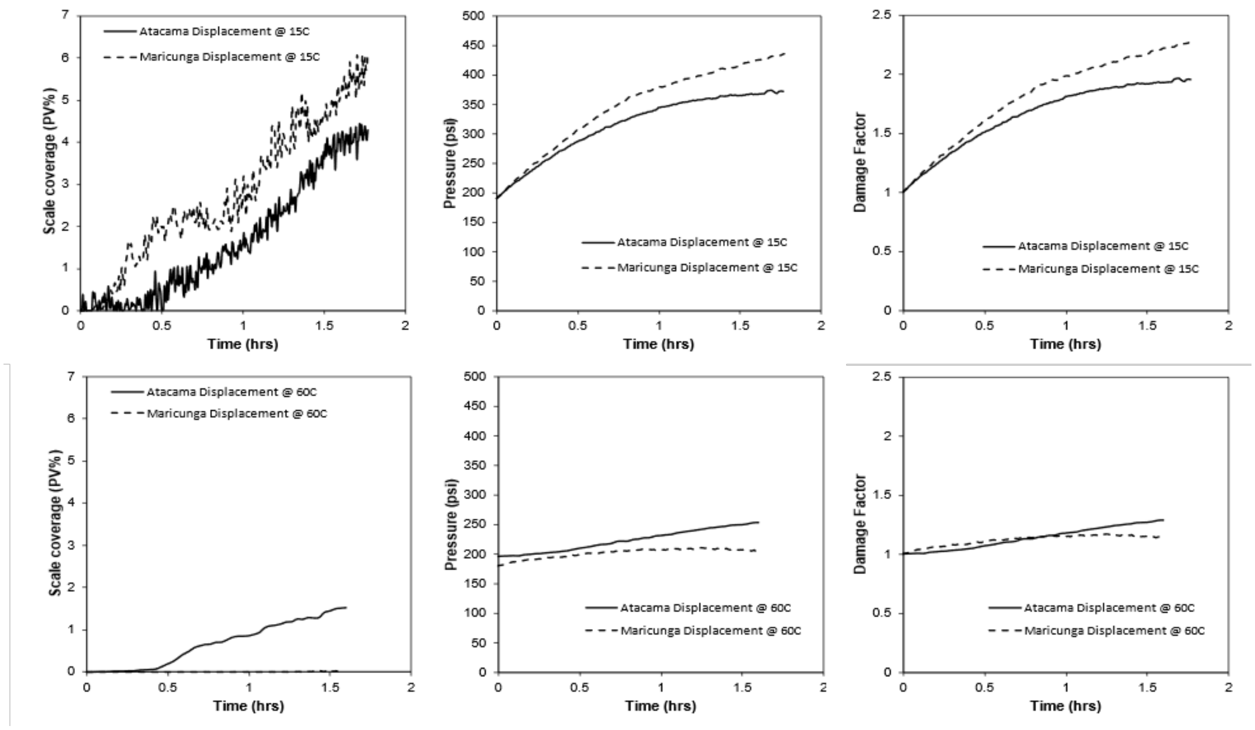
Figure: Scale coverage, Atacama



Source: Interface Fluidics proprietary study

Coinjection results demonstrating impact of maximum fluid contact. At 0 °C and 15 °C, Maricunga brine shows more precipitation and formation damage than the Atacama brine. At 60 °C, neither brine show any detectable precipitation. The precipitation from Atacama and Maricunga brine is maximum at 15 °C.

Figure: Scale coverage, Maricunga



Source: Interface Fluidics proprietary study

Displacement results analogous to an injection scenario. At 0 °C and 15 °C, Maricunga brine shows more precipitation and formation damage than the Atacama brine. At 60 °C, Atacama brine shows precipitation and blockage, while Maricunga brine does not. Both brines showed increase in precipitation from 0 °C to 15 °C and then decrease in precipitation at 60 °C. Atacama and Maricunga brine has the largest amount of precipitation at 15 °C and both brines did not reach plateau when the tests were terminated indicating potentially more damage may occur if the tests continued at this condition.

In case of injecting at these temperatures, Atacama reservoir may face less injectivity issues than the Maricunga reservoir. At 60 °C, Atacama brine shows small amounts of precipitation and formation damage in the displacement test while Maricunga does not show any scale. In case of injecting at 60 °C, Maricunga reservoir may face less injectivity issues. The precipitation from the Atacama and Maricunga brines is at its maximum at 15 °C and is mostly gypsum. In general, the Maricunga examples demonstrate the highly effective role of temperature in preventing scaling—evident in both displacement and co-injection scenarios.

Annex 2: References

5. Annex 2: References

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