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Balancing Lithium Extraction with Andean Salar Habitat

A site-scale and regional analysis — Salar de Atacama, Chile

Andrew Boyd, with Aaron Wolfe · Yale School of the Environment, 2026 · public-assembly.org

Contents

Introduction

Lithium extraction is expanding across one of the world's most distinctive and hydrologically fragile wetland regions (Marconi, 2022). Across the Andean salares of Chile, Argentina, Bolivia, and Peru, lithium-rich brine deposits often occur in the same closed-basin landscapes that support high-elevation lagoons, wetlands, and shallow saline habitats used by Andean, James's, and Chilean flamingos (Gutiérrez, 2022). These systems are defined by sharp ecological gradients where small changes in biogeochemical processes alter lagoon margins and affect habitat integrity (Dorador, 2018). As global demand for lithium accelerates, the conservation challenge of identifying an extraction regime with minimized impact to adjacent ecosystems grows in urgency. Chile's Salar de Atacama, one of the largest and most industrially developed lithium deposits in the world, provides a leading-edge case study in the impacts of lithium extraction that can be extrapolated to the broader extents of development planning (Munk, 2016).

This project evaluates that challenge through a multi-scalar analysis of lithium development, salar protection, flamingo habitat suitability, groundwater monitoring, and remote-sensed lagoon condition. The analysis first places lithium extraction in a regional ecological context by examining the extent to which existing and proposed development intersects watersheds containing suitable habitat for Andean and James's flamingos. Because flamingos depend on brine-associated lagoon systems that frequently occur along the margins of lithium-bearing salares, the regional analysis identifies where mineral development pressure coincides with habitat areas across different suitability levels.

The second component examines Chilean salar protection status. Chile contains a large and diverse network of salares, but protection is unevenly distributed across biome, salar type, and lagoon habitat. This analysis compares protected, unprotected, and unclassified salares to assess whether existing conservation designations adequately represent the lagoon systems most relevant to flamingo habitat. Attention is given to the Pre-Andino biome and the Salar de Atacama, where globally significant lithium extraction overlaps with important wetland and lagoon habitats.

The third component compares flamingo habitat suitability in the Salar de Atacama against the broader regional lagoon network. The goal is to understand whether Atacama lagoons are marginal, typical, or disproportionately important as flamingo habitat, especially during breeding and year-round occupancy periods.

The fourth component narrows to site-scale impacts from lithium extraction using in-situ monitoring data. Groundwater monitoring records from the lithium mining firm Sociedad Química y Minera de Chile (SQM) at the Salar de Atacama site are used to evaluate spatial patterns of groundwater level change in relation to lagoon and wetland areas. This portion of the analysis distinguishes between areas closer to the salar nucleus, where extraction-related drawdown may be more pronounced, and lagoon-margin environments where even modest groundwater declines may be ecologically significant.

Finally, the project uses remote sensing to assess water quantity and optical water-quality indicators in the Salar de Atacama relative to broader regional lagoon systems. Water extent metrics are used to evaluate changes in standing water area, while optical indicators such as NDVI and related spectral proxies help characterize variation in lagoon condition. By comparing Atacama lagoons with broader Andino and Pre-Andino lagoon groups, the analysis asks whether the Salar de Atacama exhibits distinctive patterns in water persistence, productivity, turbidity, or potential habitat quality, and whether any variance can plausibly be attributed to lithium extraction operations.

Together, these analyses frame lithium extraction as a regional conservation and water-governance problem. The Salar de Atacama is both a major lithium production landscape and a significant node in a broader flamingo habitat network. By combining regional habitat analysis, protection-status assessment, in-situ groundwater monitoring, and remote-sensed lagoon indicators, this project begins to evaluate the scale and nature of risks to flamingo habitat and where conservation planning can intervene to clarify solutions.

Dorador, C., Fink, P., Hengst, M. *et al.* Microbial community composition and trophic role along a marked salinity gradient in Laguna Puilar, Salar de Atacama, Chile. *Antonie van Leeuwenhoek* 111, 1361–1374 (2018). https://doi.org/10.1007/s10482-018-1091-z

Marconi, P., Arengo, F. & Clark, A. The arid Andean plateau waterscapes and the lithium triangle: flamingos as flagships for conservation of high-altitude wetlands under pressure from mining development. *Wetlands Ecol Manage* 30, 827–852 (2022). https://doi.org/10.1007/s11273-022-09872-6

Munk, Lee Ann, Scott A. Hynek, Dwight C. Bradley, David Boutt, Keith Labay, and Hillary Jochens. “Lithium BrinesA Global Perspective.” In *Rare Earth and Critical Elements in Ore Deposits*, by Philip L. Verplanck and Murray W. Hitzman. Society of Economic Geologists, 2016. https://doi.org/10.5382/Rev.18.14.

Gutiérrez, Jorge S., Johnnie N. Moore, J. Patrick Donnelly, Cristina Dorador, Juan G. Navedo, and Nathan R. Senner. “Climate Change and Lithium Mining Influence Flamingo Abundance in the Lithium Triangle.” *Proceedings of the Royal Society B: Biological Sciences* 289, no. 1970 (2022): 20212388. https://doi.org/10.1098/rspb.2021.2388.

Lithium Extraction Impacts to Flamingo Species in the Salar de Atacama and the Broader Andean Region

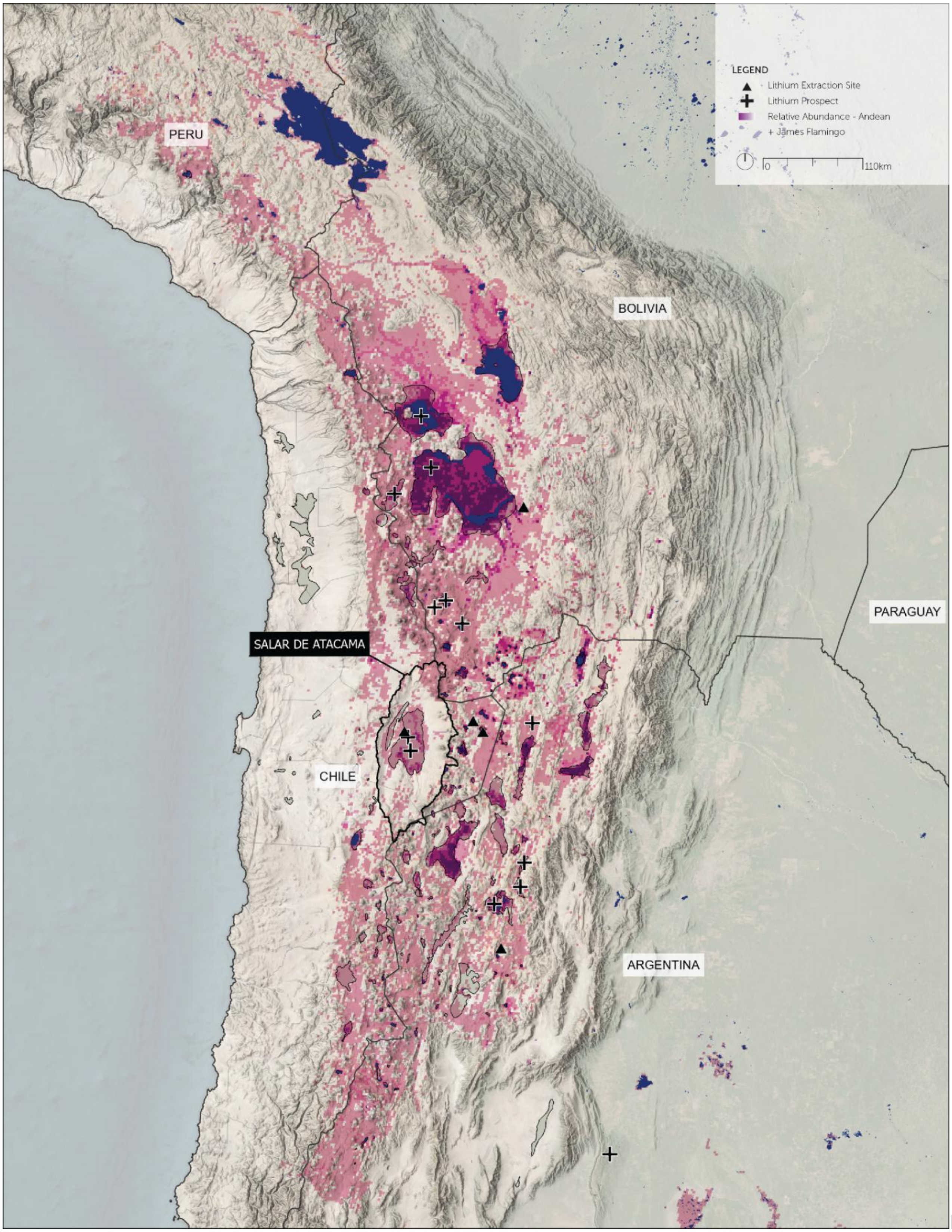

Figure 1 Lithium Development and Flamingo Habitat

Spatially explicit species abundance metrics from the Cornell E-Bird database were collected for at-risk flamingo species in the Andean Basin (Fink, 2023). These metrics were summarized within regional hydrobasins from the HydroSHEDS continental database (Linke, 2019). A conservative scenario assuming a broader catchment impact scenario was modeled using Level 6 Basin deliniations, which corresponds to an average catchment 5,000 sq km. A more permissive scenario assuming narrower regional hydrologic exposure was modeled using Level 7 Basin deliniations which correspond to roughly 3,000 sq km catchments. Each basin was indentified for the presence of existing or proposed Lithium Development based on the USGS Mineral Resource Spatial Database (Mason, 1996).

This spatial analysis found that existing and proposed lithium extraction is occurring in potentially half of all watersheds that contain Andean and James' flamingo habitat, spanning the full range of modeled habitat suitability. Assuming a narrower scope of impact, roughly a quarter of flamingo habitat is potentially impacted. Impacts of other water-intensive mineral extraction operations that are wide-spread in the region and proximate to salsares such as copper, boron, and potassium salts were not considered in this analysis, so the broader industrial impact to these habitats is more wide-spread than indicated here.

While the majority of these sites are in the exploratory phase and not yet in production, given the breadth of potential regional disturbance and the rapidly growing demand for lithium, this analysis points to the urgency in understanding site-level impacts of lithium production on adjacent salar and lagoon habitat and pathways to mitigating disturbance. Additionally, regional actors must ensure that expansion of lithium operations fits within a coherent strategy of managing salar habitat within the regional context.

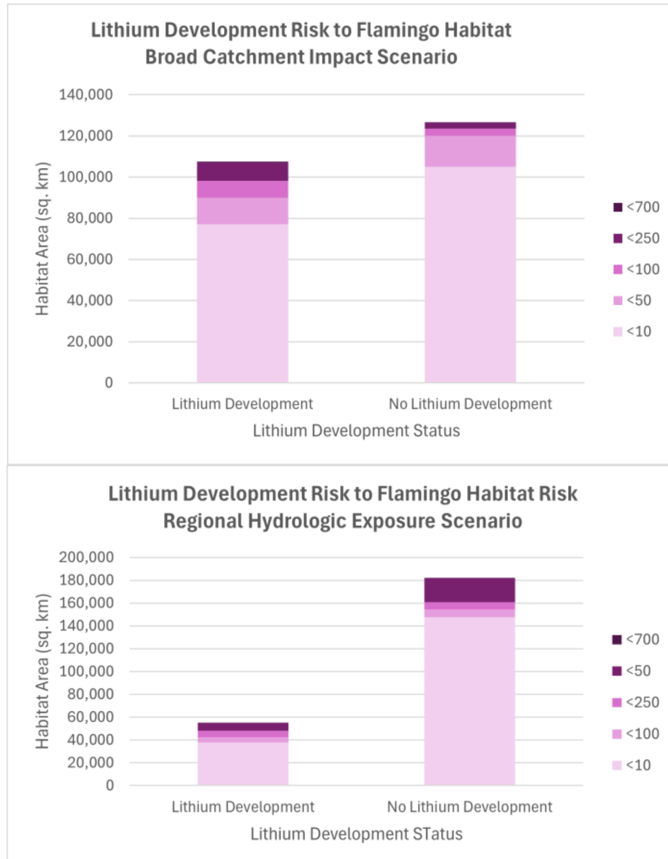

Figure 2- Regional Flamingo Habitat Risk to Lithium Development, ranked by relative species abundance quantiles. Abundance is measured by expected count on a 1-hour, 2-km traveling checklist, modeled across a regular spatial grid with one estimate per roughly 3 km × 3 km cell.

Fink, D., T. Auer, A. Johnston, M. Strimas-Mackey, S. Ligocki, O. Robinson, W. Hochachka, L. Jaromczyk, C. Crowley, K. Dunham, A. Stillman, C. Davis, M. Stokowski, P. Sharma, V. Pantoja, D. Burgin, P. Crowe, M. Bell, S. Ray, I. Davies, V. Ruiz-Gutierrez, C. Wood, and A. Rodewald. 2024. *eBird Status and Trends, Data Version: 2023; Released: 2025*. Cornell Lab of Ornithology, Ithaca, New York. https://doi.org/10.2173/WZTW8903

Linke, S., Lehner, B., Ouellet Dallaire, C., Ariwi, J., Grill, G., Anand, M., Beames, P., Burchard-Levine, V., Maxwell, S., Moidu, H., Tan, F., & Thieme, M. 2019. Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. *Scientific Data*, 6, 283. https://doi.org/10.1038/s41597-019-0300-6

Mason, G.T., and Arndt, R.E., 1996, *Mineral Resources Data System (MRDS)*: U.S. Geological Survey Data Series 20, https://doi.org/10.3133/ds20

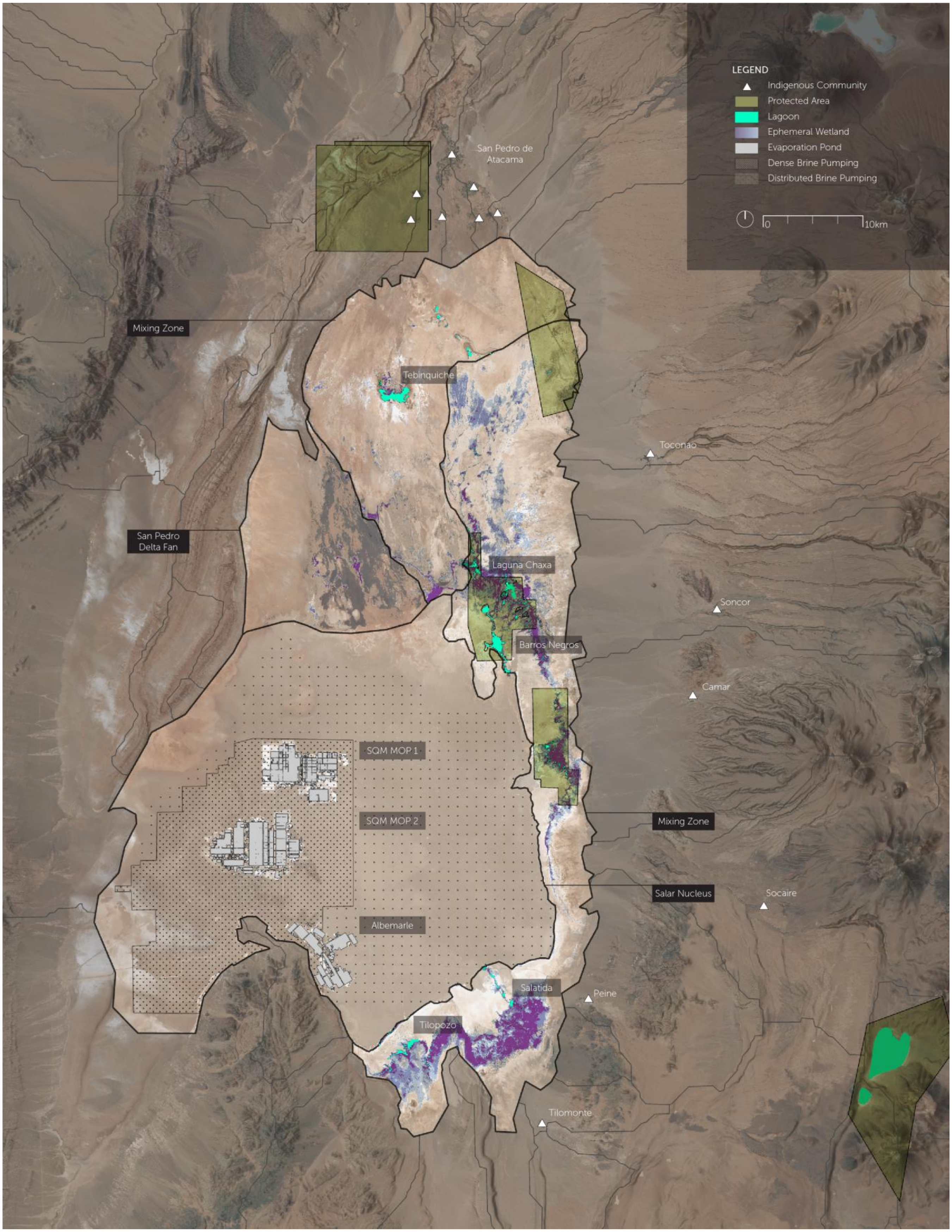

Figure 3 Site Map of the Salar de Atacama

Chilean Salar Protection

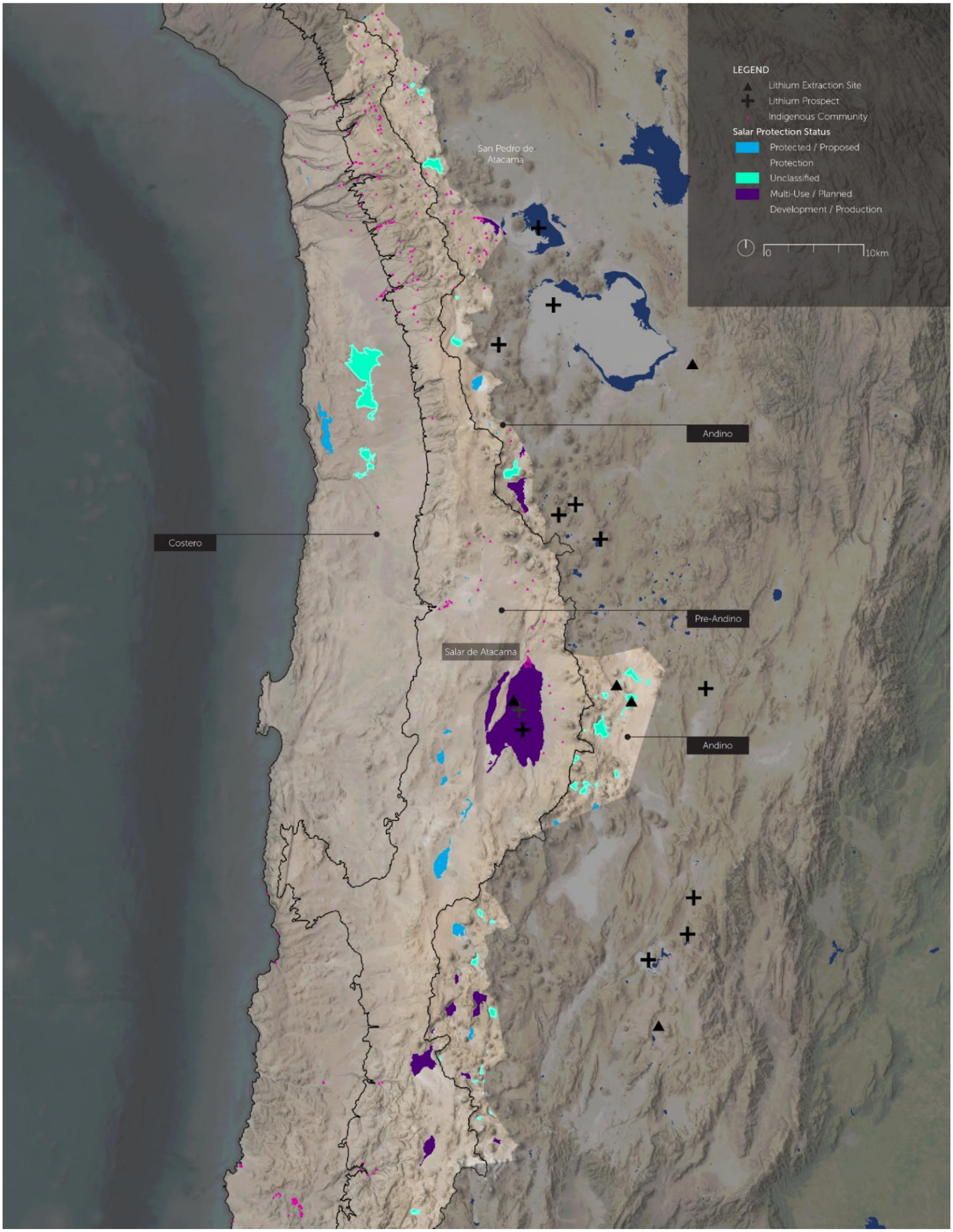

Figure 4 - Chilean Salar protection status based on geographic distinctions of Costero, Pre-Andino, and Andino regions.

In response to growing concern over the ecological and hydrological impacts of lithium extraction, the Chilean government announced the National Lithium Strategy in 2023, which included the creation of a proposed Network of Protected Salt Flats. The strategy frames protected-area designation as a means of safeguarding critical salar, lagoon, and wetland ecosystems while enabling continued expansion of lithium production. This analysis assesses whether the proposed protected-area network is spatially representative of Chile's lagoon habitat, with specific attention to how protection is apportioned across regional salar biomes.

Salar de Atacama dominates the Pre-Andino biome by total mapped extent and is larger than the combined area of the Andino and Costero salars. However, its perennial lagoon system is relatively small compared with the aggregate lagoon area associated with roughly 120 designated salars across Chile. In Atacama, intermittent wetland area is much closer in scale to the salar's total mapped extent, while many other salars occur in smaller catchments with more limited intermittent wetland coverage. This distinction is important because mapped salar extent alone can overstate the amount of persistent aquatic habitat available to flamingos, while intermittent wetland extent may better capture the broader hydrologic margin that supports seasonal habitat dynamics, brine mixing, shallow water availability, and ecological connectivity around lagoon systems.

Protection status is unevenly distributed across the salar network. It is disproportionately concentrated in Costero salars, many of which contain little or no lagoon habitat, while protected lagoon systems occur exclusively in the Andino biome. The vast majority of Pre-Andino lagoons remain unclassified by protection status, making them a time-sensitive priority for conservation planning and for building a more representative protected-area network. The figures underscore that protection status does not yet appear to track lagoon habitat value in a consistent way. Instead, protected status is concentrated in some regions and habitat types, while Pre-Andino systems with high ecological importance remain underrepresented in formal conservation categories.

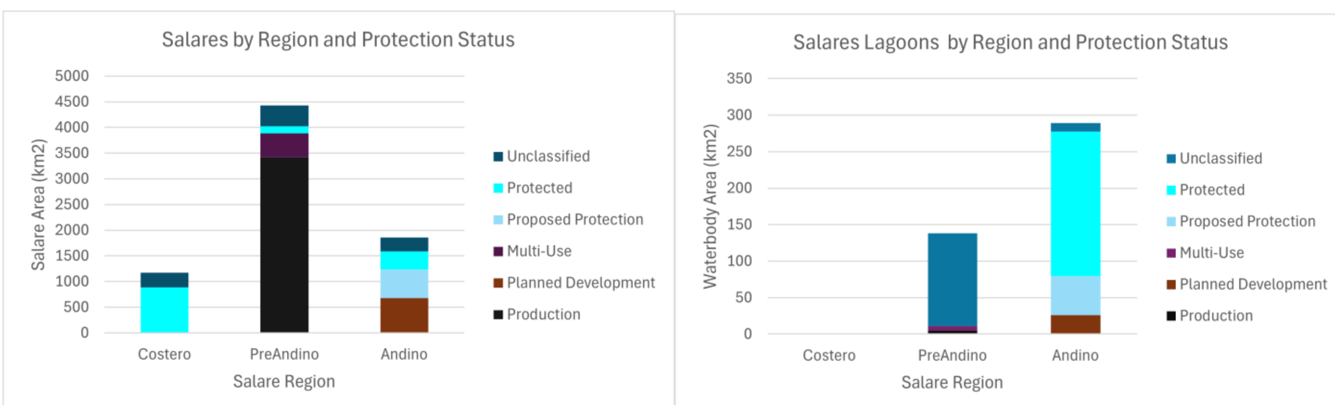

Figure 5 - Protection status of Chilean Salares based on region, absolute area, and lagoon area.

Flamingo Habitat Suitability in the Salar de Atacama and the Regional Context

Building from the spatial distribution of Chile's proposed salar protections, this analysis overlays flamingo habitat suitability to assess whether the protected-area network captures the lagoon systems most important to regional flamingo populations. This added ecological layer helps evaluate the adequacy of proposed protections and contextualizes the potential risk posed by ongoing lithium production in the Salar de Atacama

Within the Pre-Andino biome, Atacama lagoons represent the dominant habitat for Andean Flamingo breeding-season and year-round relative abundance. Atacama lagoons rank above the broader average for the more numerous Andino lagoons, with only a small number of Andino lagoons exceeding Atacama in area-normalized relative abundance. Atacama lagoons are also significant for James' Flamingo habitat, though their values are closer to the overall Andino and Pre-Andino means. For both species, breeding-season and full-year relative abundance are strongly correlated, suggesting that lagoons with high seasonal importance also tend to function as important year-round habitat rather than only as temporary breeding-season refuges. Chilean Flamingo was excluded from this analysis because of its broader regional distribution and substantially wider abundance pattern relative to Andean and James Flamingos.

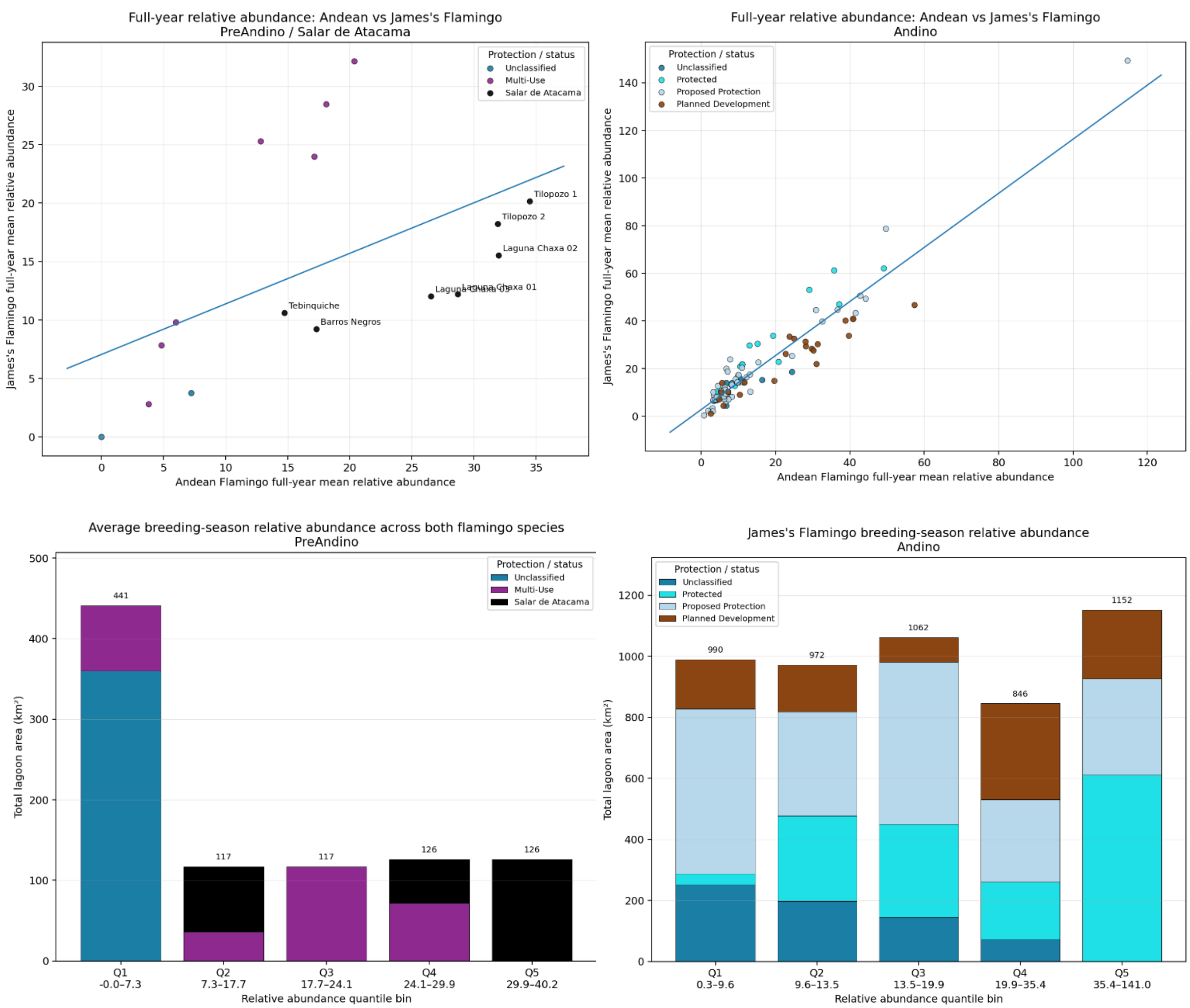

Figure 6 – Classification of Chilean lagoons based on relative Flamingo Abundance and protection status.

The quantile-area figures add a second dimension to the interpretation by showing where habitat area is concentrated across the relative abundance distribution. Planned development in the Andino biome is disproportionately represented in high-abundance quintiles when measured by absolute area. This suggests that future development pressure may overlap most strongly with lagoon systems that carry outsized habitat value, reinforcing the need to align protection status with observed flamingo relative abundance and wetland extent. In the Pre-Andino biome, Salar de Atacama accounts for a substantial share of higher-quintile lagoon area, while large areas of unclassified lagoon habitat remain present in lower and mid-range bins. Together, these patterns suggest that conservation prioritization should not rely solely on existing protection categories, but should integrate species abundance, lagoon area, hydrologic permanence, and development exposure.

The analysis points to a mismatch between ecological value and conservation coverage. The most relevant question is not only whether individual lagoons are protected, but whether the protected-area network captures the full range of salar wetland types that sustain flamingo populations across seasons. For Andean and James Flamingos, that means treating Pre-Andino lagoons, especially those in Salar de Atacama, as a distinct conservation problem rather than assuming that protection of Andino lagoons alone is sufficient. A more representative network would explicitly account for the different roles of Andino high-elevation lagoons, Pre-Andino extraction landscapes, and intermittent wetland margins in supporting regional flamingo habitat.

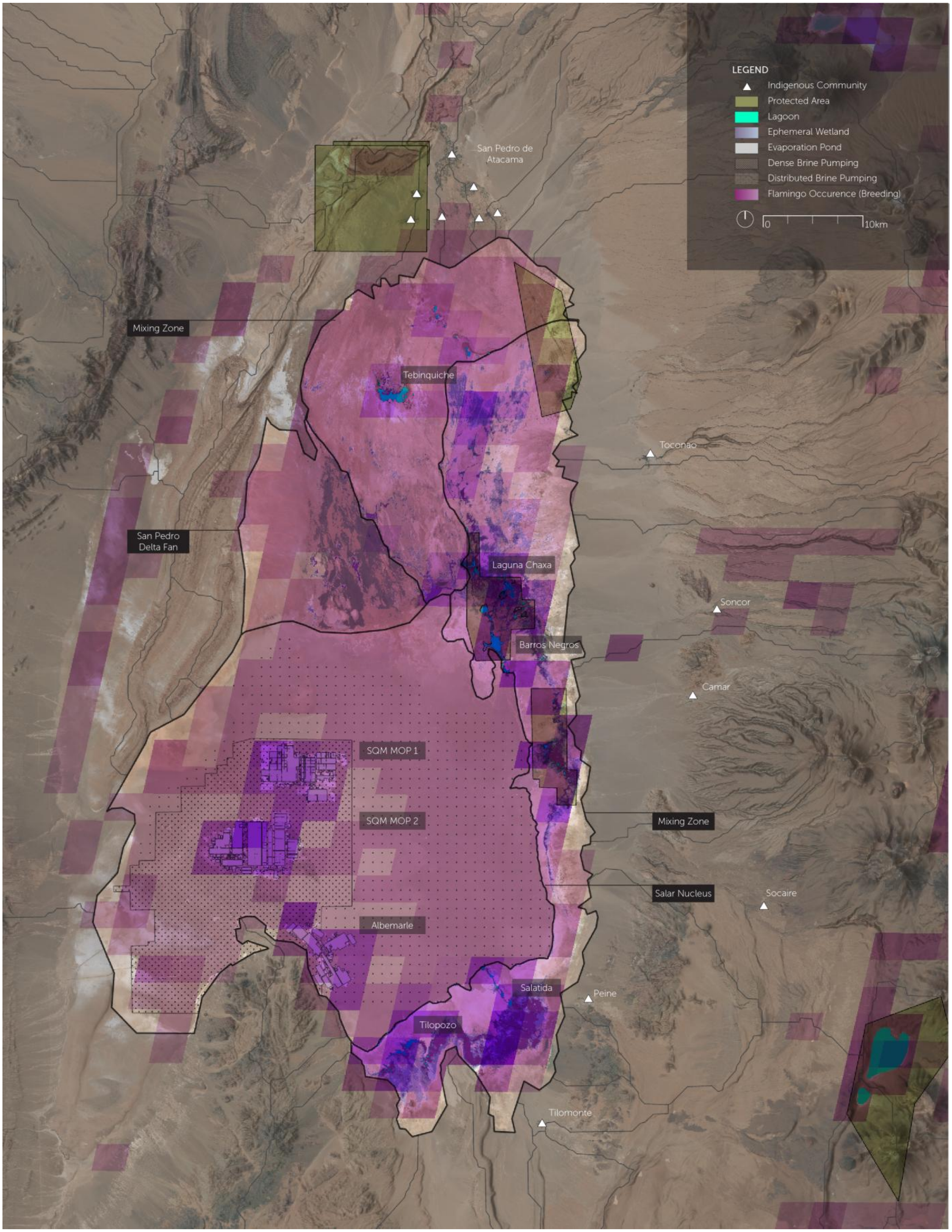

Figure 7 - Breeding Season Relative Abundance of Andean and James Flamingos in Salar de Atacama

Site Impacts from Lithium Extraction – In Situ Measurments.

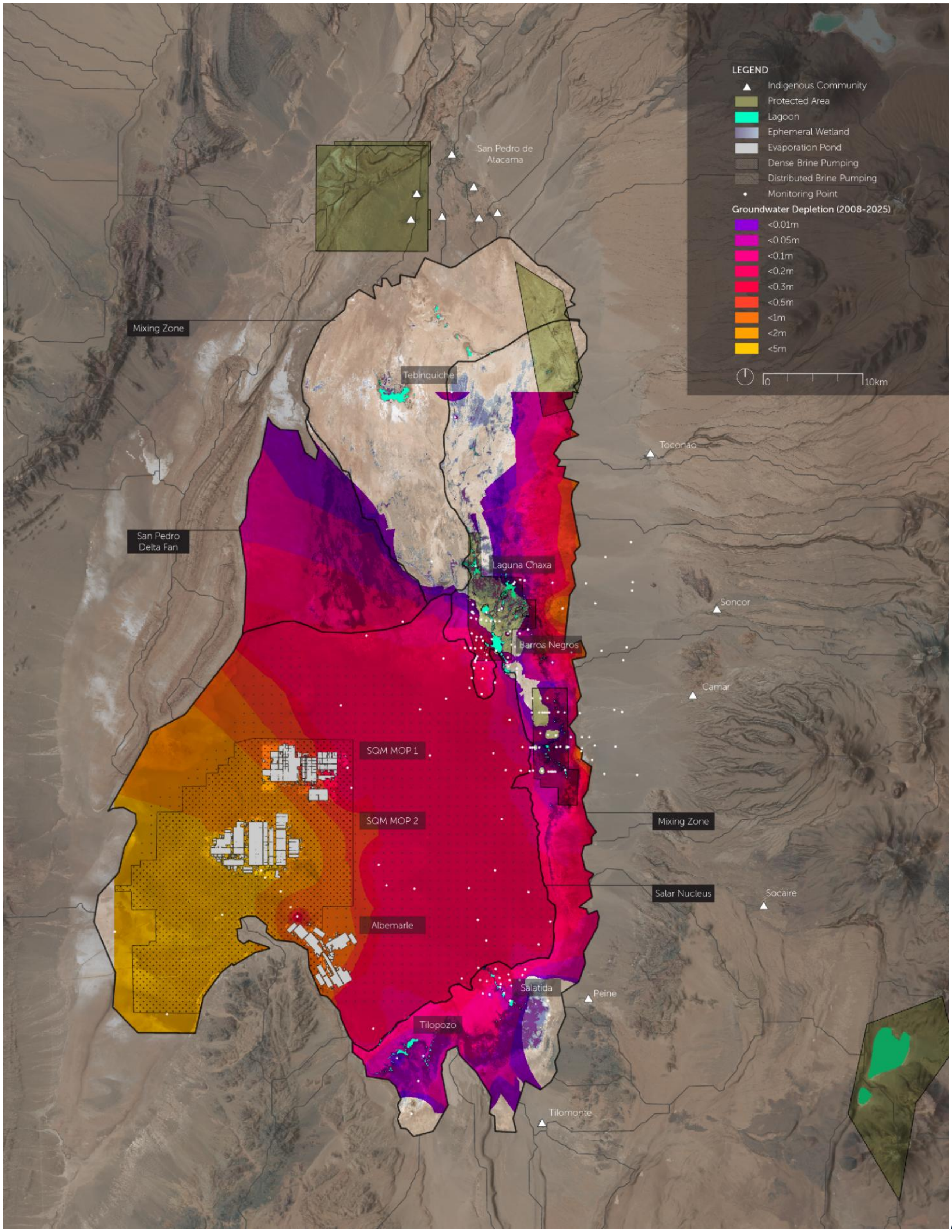

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Figure 8 - Groundwater Depletion in the Salar de Atacama. 2008 - 2024

SQM has accumulated a large database of hydrologic and biogeochemical indicators that are reflective of lagoon and wetland habitat integrity. For this study, groundwater extraction was selected as one of many potential indicators to evaluate the extent of lithium extraction impacts on lagoon habitat.

Field-collected groundwater depletion data was acquired from the SQM data portal and spatially attributed to the location of the sampling points. A time-series spatial raster was interpolated from these points, and comparisons were made between 2008 and 2024, which coincides with the extent of the monitoring regime.

The lagoon corridor along the eastern margin of the Salar de Atacama occupies a sensitive position relative to the mapped groundwater depletion field. Laguna Chaxa and Barros Negros lie near the edge of the depletion gradient, where the stronger drawdown signal from the salar interior approaches the lagoon and wetland margin. This edge condition matters because it places these lagoons at the interface between the extraction-influenced salar core and the shallow groundwater-dependent habitats along the eastern flank.

Farther south, Tilopozo and Salada appear more embedded within the depletion field itself, even where mapped drawdown magnitudes are more moderate, generally on the order of 0.05 to 0.2 m. Even relatively modest groundwater declines may be significant where lagoon persistence depends on shallow hydraulic gradients and narrow salinity thresholds.

The map suggests two related but distinct lagoon-risk conditions. Chaxa and Barros Negros may function as edge or transition lagoons, where the depletion front approaches ecologically important habitat from the salar interior. Tilopozo and Salada, by contrast, appear to sit within a broader zone of lower-grade but more spatially continuous depletion.

Groundwater depletion should also be interpreted in relation to the salar's broader water balance. Under pre-extraction conditions, the salar nucleus would lose water through natural evaporation. In theory, if lithium brine extraction displaced an equivalent amount of natural evaporative loss from the nucleus, net pumping could remain closer to a hydrologic replacement condition. However, SQM's net pumping has consistently exceeded the estimated natural evaporative quantity of the nucleus since 2009, though net pumping has declined since 2019. Recent groundwater declines in key areas of the Transition Zone, beginning around 2016, may therefore reflect a lagged hydrologic response to a prolonged period of extraction above the nucleus evaporation benchmark.

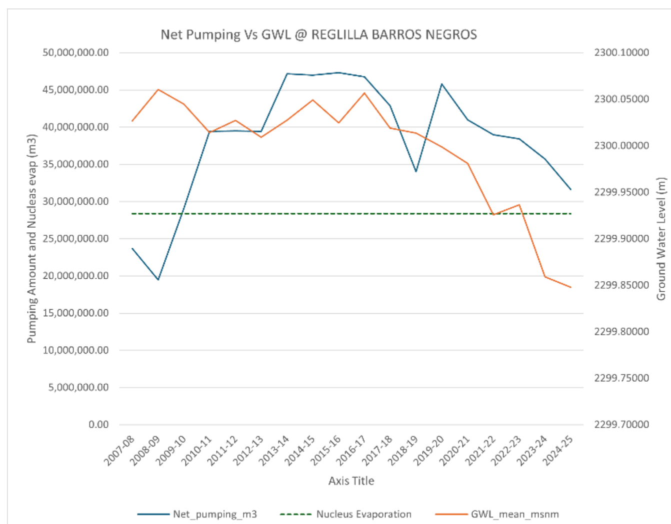


Figure 9 – Net annual groundwater pumping in comparison to groundwater levels at Barros Negros lagoon. Additionally, the Nucleus Evaporation Rate is overlaid for comparison.

Even if future pumping reductions improve the water-balance position, hydrologic recovery may not be immediate or complete. Groundwater response can lag extraction changes, and lagoon condition may also depend on geochemical pathways that are not captured by water-level recovery alone. Lithium extraction can alter the distribution of brine, freshwater, and mixing-zone waters; therefore, restored volumetric balance would not necessarily eliminate risks to salinity gradients, wetland margins, or lagoon habitat quality.

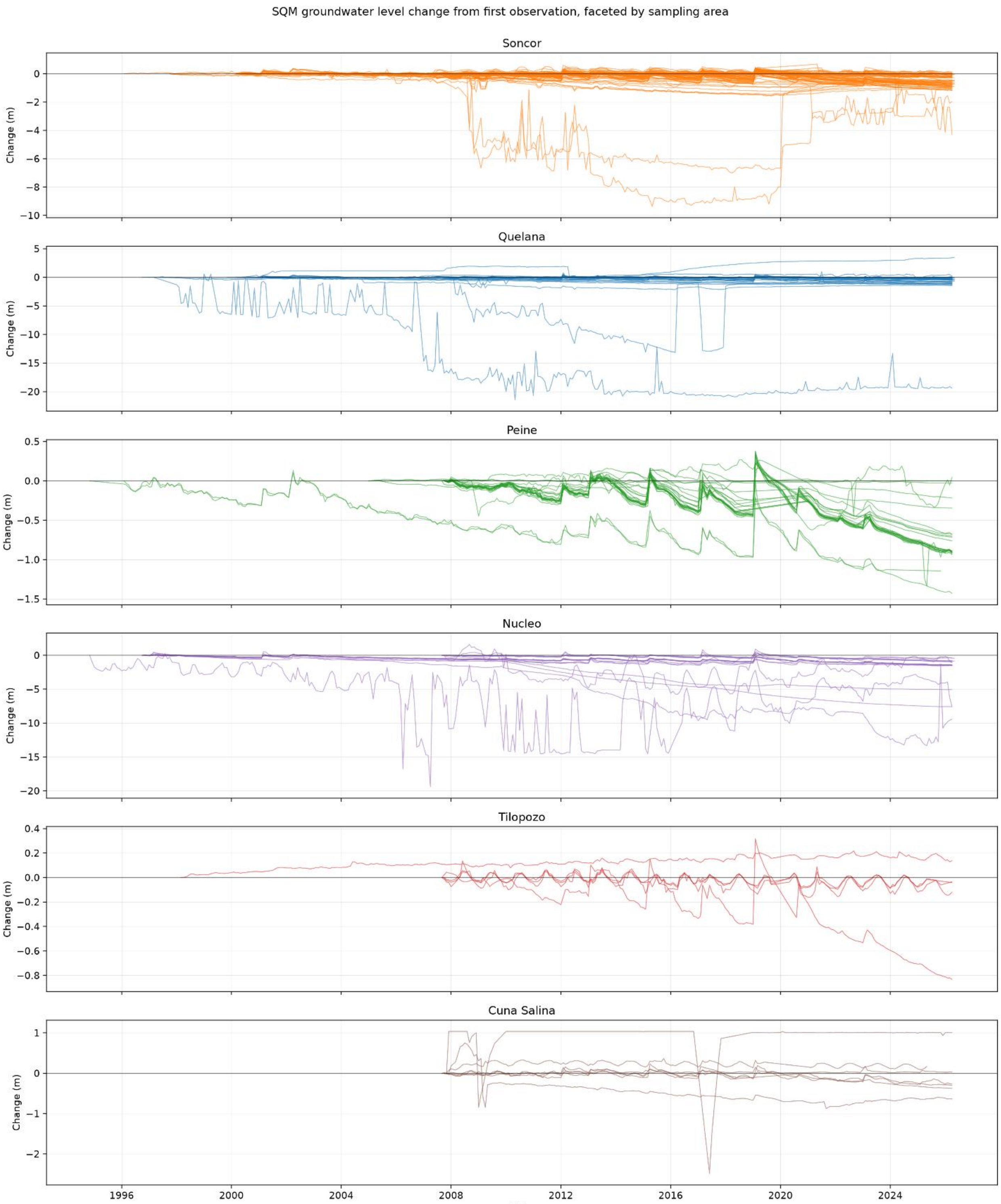


Figure 10 Absolute Groundwater Depletion by Monitoring Point Group in the Salar de Atacama

Regional and Site-Level Remote Sensed Metrics of Lagoon Water Quantity and Quality

To understand the local trends of Atacama lagoons in relation to broader regional dynamics, a remote-sensing analysis was conducted to compare trends in surface water and NDVI. A regional comparison may potentially begin to disambiguate broader climatic influences from local impacts of lithium extraction, and is not bound by the more limited time-series of field sampling.

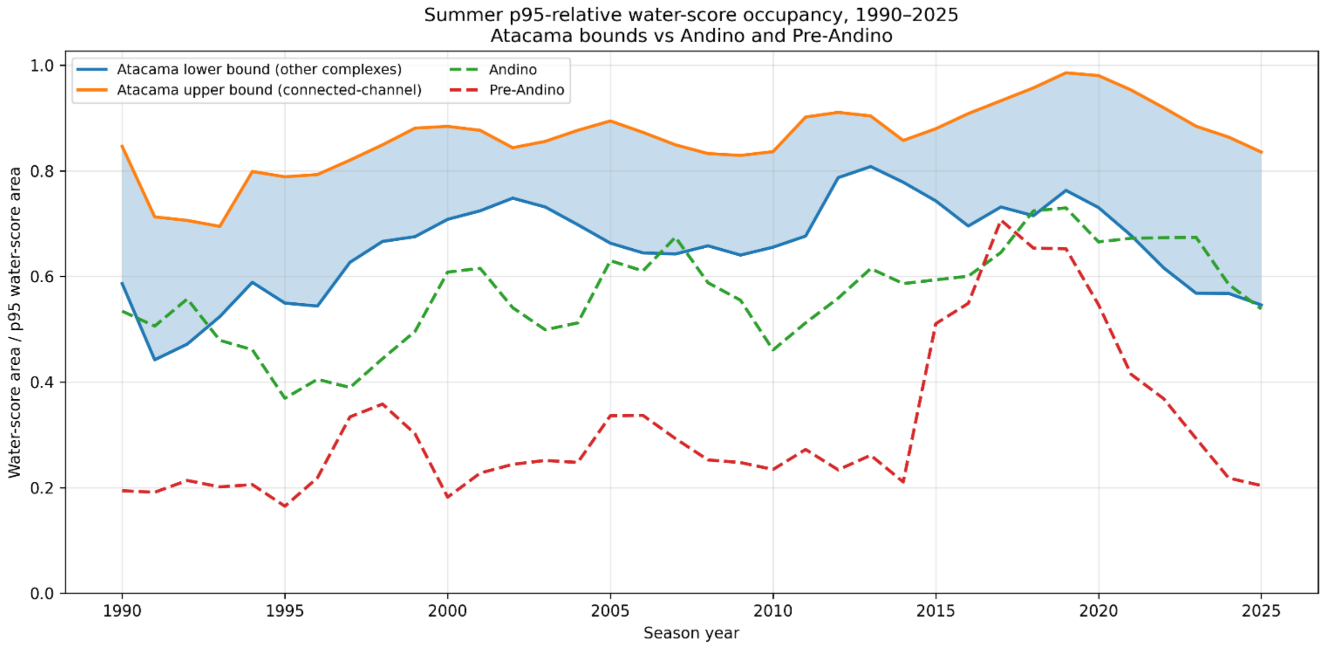
Given the variable surface water levels from year-to-year, the upper extent of standing surface water was calculated statistically rather than by a manual delineation. Broader inclusive containers were drawn for each Atacama complex, while salar boundaries were used for regional Pre-Andino and Andino search containers.

Cloud, cloud-shadow, snow, fill, and saturated pixels were masked using Landsat QA bands. Landsat 5/7 and Landsat 8/9 bands were harmonized to common blue, green, red, near-infrared, and SWIR1 bands. Seasonal median composites were then used to calculate NDVI, which is cautiously interpreted as a general proxy for lagoon-level primary productivity and overall habitat integrity.

Water and wet-surface extent were evaluated using three masks. A conservative mask was used to represent lower-bound standing water. A loose mask was used as an upper-bound wet-surface indicator. A water-score mask was used as the primary middle-path indicator, designed to avoid being either overly restrictive or overly permissive. The water score combines five spectral tests: MNDWI greater than 0.00, MNDWI greater than 0.15, NDWI greater than -0.05, SWIR1 less than 0.10, and NIR less than 0.15. Pixels meeting at least 60% of these tests were classified as water-score wet surface.

For each lagoon complex and season, annual water-score area was normalized by the 95th percentile of water-score area observed for that same complex and season. This produced a p95-relative water occupancy metric, where values near 1 indicate seasons approaching the observed high-water benchmark for that lagoon complex. Optical indicators were summarized over detected water and water-plus-margin zones. The water-plus-margin zone was defined by expanding detected water pixels by 90 m to capture wet-edge habitat and mixed shallow-water margin conditions.

Regional Andino and Pre-Andino comparisons use salar boundaries as search containers and existing regional p95-relative water metrics. Atacama is represented separately using lagoon-complex results, with connected-channel systems treated as an upper-bound group and other lagoon complexes as a lower-bound group. This avoids relying on the full Salar de Atacama polygon as a single regional unit and better reflects internal hydrologic heterogeneity.



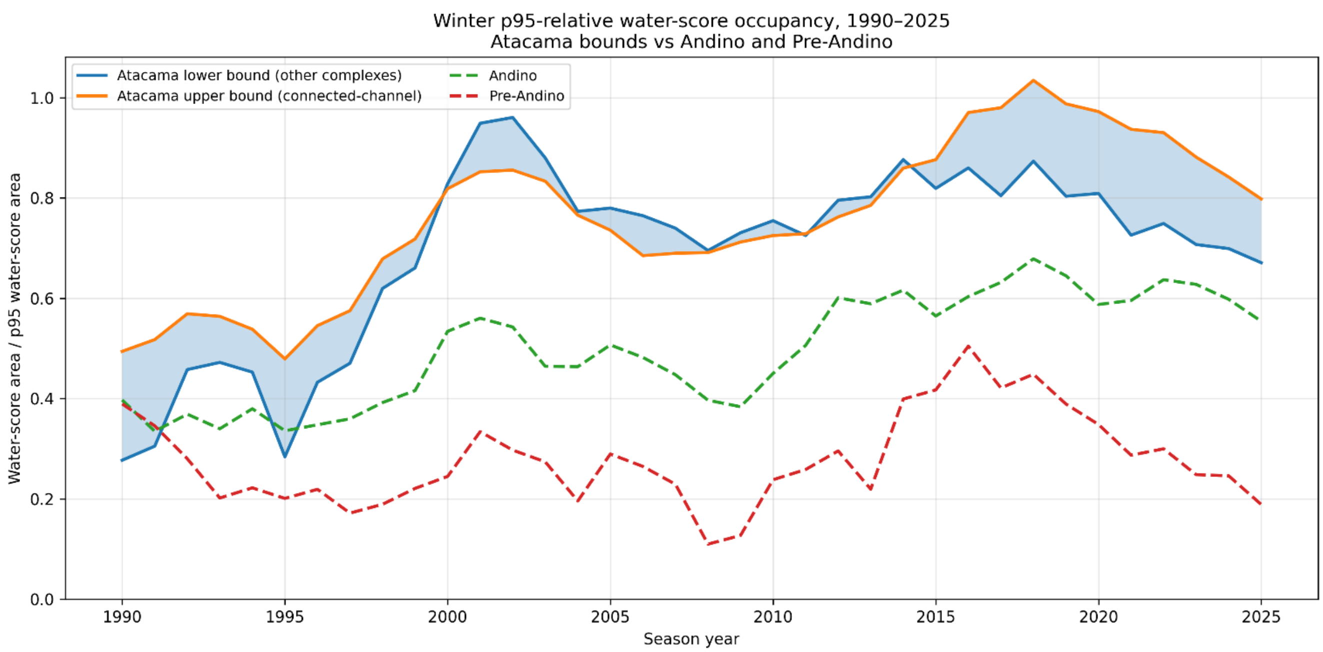
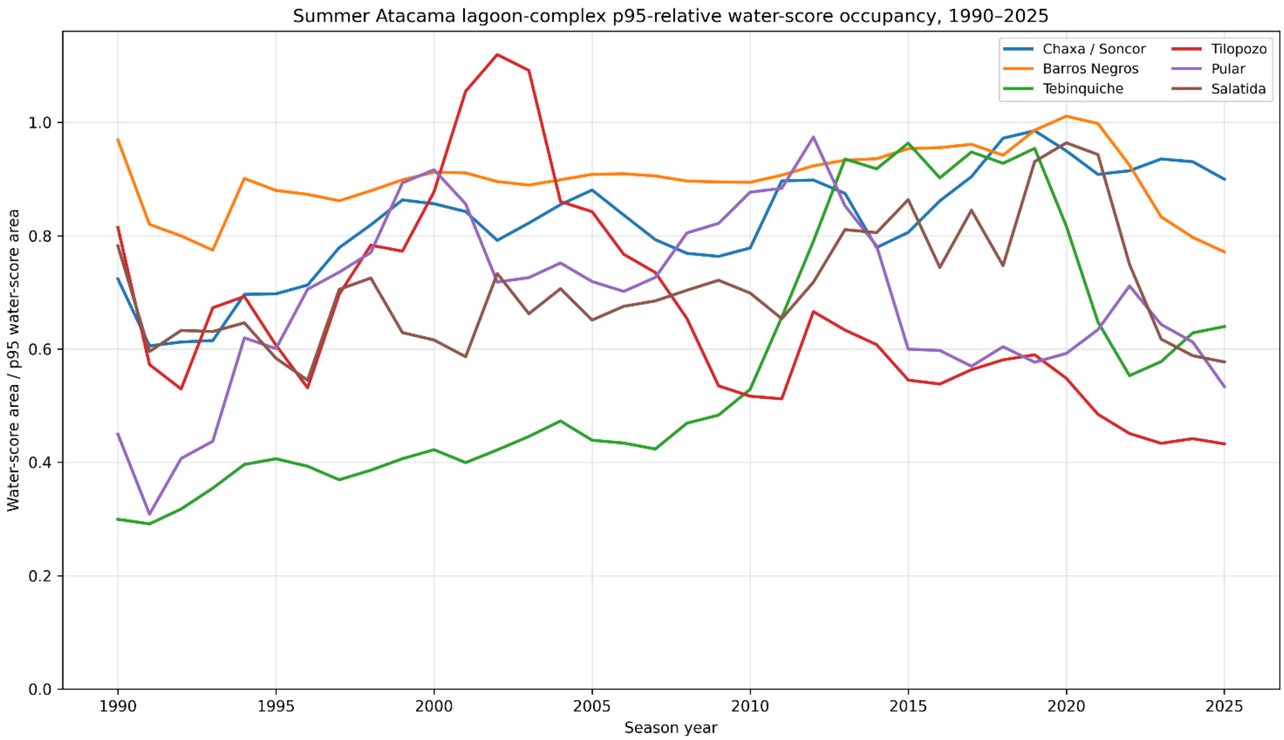


Figure 11 Summer and Winter Water Occupancy for Salar de Atacama, Andino, and Pre-Andino Biomes

The extended Landsat record places the Salar de Atacama within a broader regional wetland cycle. Across Atacama, Andino, and Pre-Andino systems, wet-surface occupancy generally increases toward a mid- to late-2010s high before weakening after approximately 2018–2020. This pattern is most evident in winter, while summer conditions show greater overlap and variability among regions. Importantly, the longer hydrologic record suggests that recent fluctuations in surface-water extent remain within the historical range observed before the most recent period of intensified lithium extraction. This does not rule out operational effects on surface water in the Salar de Atacama; rather, it indicates that formal attribution would require a more rigorous statistical analysis capable of separating extraction effects from regional hydroclimatic variability.



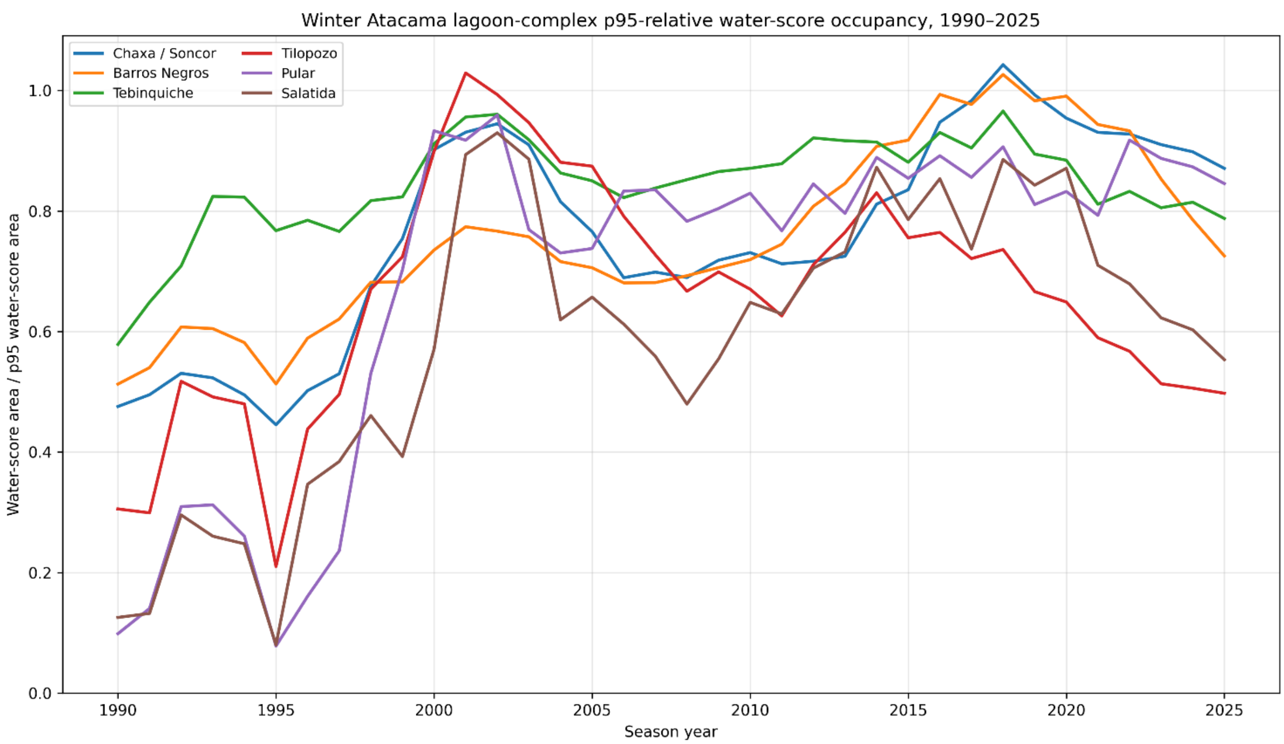


Figure 12 - Summer and Winter Water Surface Variability in Salar de Atacama

Within Atacama, the lagoon complexes remain hydrologically distinct and internally uneven. Chaxa/Soncor and Barros Negros generally define the upper bound of wet-surface occupancy, while Tebinquiche, Salatida, Pular, and Tilopozo form a lower and more variable bound. This suggests that Atacama should not be interpreted as a single uniform lagoon system.

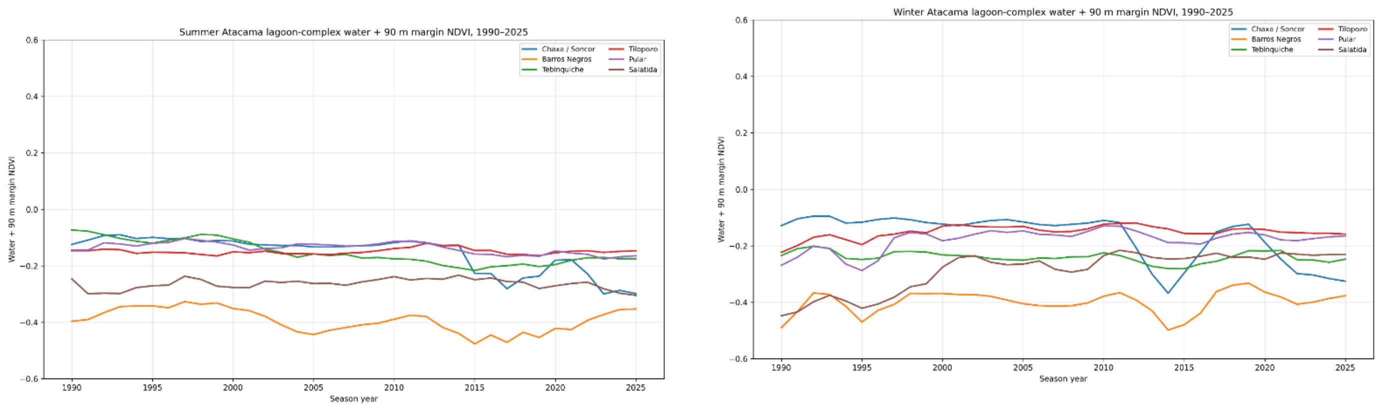
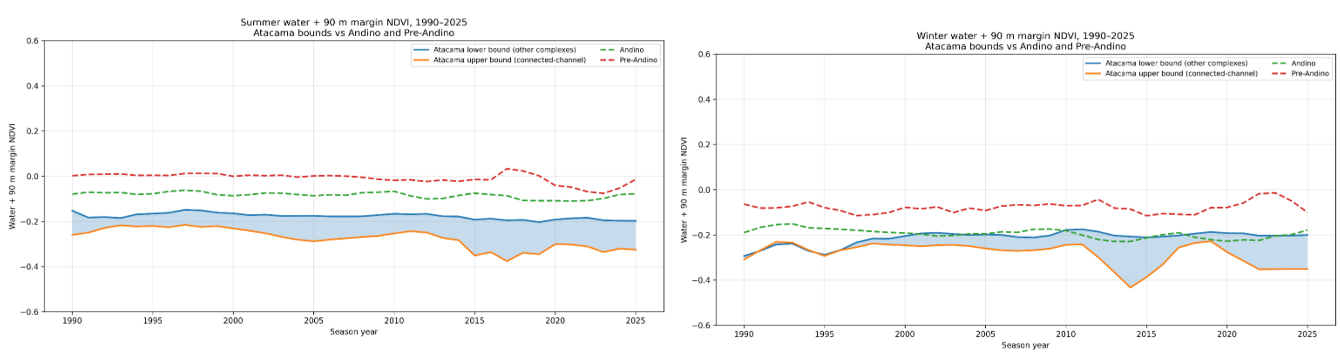


Figure 13 Summer and Winter trends in NDVI for Atacama Lagoons

Across the Atacama lagoon complexes, water-plus-margin NDVI remains mostly low or negative, consistent with saline water, brine, exposed mineral substrates, and optically dark or sparsely productive shallow-water conditions. Barros Negros is especially distinct, showing persistently low NDVI despite relatively high wet-surface occupancy, suggesting that the system may retain surface water without producing a strong NDVI signal associated with chlorophyll-bearing biomass or shallow-water productivity. Because NDVI over water is sensitive to depth, salinity, suspended material, bottom reflectance, and microbial or algal biomass, it should be interpreted as a broad optical indicator rather than a direct measure of productivity. These results show why water extent and water-column condition should be evaluated together: a lagoon can remain spatially wet while changing in the optical and biogeochemical conditions that shape flamingo foraging habitat.

The relative decline of NDVI from 2015 to present for Chaxa Lagoon is an important indicator as this lagoon contains the most flamingo abundance. This recent period also corresponds with a precipitous decline in flamingo hatchling recruitment, and the potential connection of this NDVI signal as an indicator for flamingo reproductive success should be investigated.



In the regional NDVI comparison, Atacama appears as a relatively low-NDVI wetland system. This is important because it indicates that the Salar de Atacama's regional significance for flamingo habitat is not driven by unusually high greenness or NDVI-based productivity. Instead, its importance likely reflects the extent, persistence, salinity regime, shallow-water structure, and food-web conditions of its lagoons. The NDVI results therefore caution against interpreting high wet-surface occupancy as equivalent to high biological productivity.

In addition to a lower persistent NDVI score, Salar de Atacama also shows a more significant decrease in NDVI which accentuates over time, particularly in comparison to its Pre-Andino peers. This could be another fruitful metric to investigate more systematically for the potential to disambiguate regional bio-climatic trends from impacts of local lithium exraction.

Conclusion

This analysis shows that lithium extraction in the Salar de Atacama is not only a site-specific mining issue, but part of a broader regional conservation challenge involving salar hydrology, lagoon habitat, and flamingo population support. At the regional scale, lithium development overlaps substantially with watersheds containing suitable Andean and James's Flamingo habitat, while Chile's proposed protected-salar network does not yet appear to fully capture the distribution of lagoon habitat across biomes. At the site scale, groundwater monitoring suggests that key lagoon systems occupy sensitive positions relative to mapped depletion gradients, even where surface-water extent remains within the range of longer-term regional variability. Remote-sensing results further show that surface-water persistence and lagoon condition are not interchangeable: Atacama lagoons may remain wet while exhibiting low NDVI and potentially changing optical or biogeochemical conditions relevant to flamingo foraging habitat.

Together, these findings suggest that conservation planning should move beyond a simple protected-versus-unprotected framework and incorporate hydrologic exposure, lagoon permanence, groundwater response, salinity and mixing-zone dynamics, and species-specific habitat value. The Salar de Atacama remains a critical flamingo habitat system within a globally significant lithium production landscape. Managing it effectively will require impact standards that are regional in scope, site-specific in monitoring, and precautionary in how they interpret early changes in groundwater and lagoon condition.