European Journal of Sustainable Development (2025), **14**, 3, 373-388 ISSN: 2239-5938
Doi: 10.14207/ejsd.2025.v14n3p373

Environmental and socioeconomic evaluation of lithium mining: Proposed methodology and its application to Chilean projects

By Valentina Canales-Guerrero[1], Felipe Díaz-Alvarado[1], Rintaro Yamaguchi[2]

ABSTRACT
Lithium is critical for a sustainable energy transition, particularly regarding the battery market. For decades, traditional extraction methods from brine have adversely affected inland wetlands, which are considered fragile ecosystems. For instance, brine extraction in Chile has severely decreased the populations of three flamingo species and obstructed the livelihoods of indigenous communities. However, these negative externalities have not been included in the evaluation of lithium brine mining projects. The novelty of this study lies in developing a methodology to consistently quantify environmental and social impacts in monetary values. Moreover, the study will compare three metallic lithium production processes, including direct lithium extraction (DLE) technologies. The methodology determines how these processes disrupt ecosystem services and affect the environmental, economic, social, and process efficiency dimensions. Some impacts are measured using market and non-market valuations. Our results directly provide valuable insights to the recently developed Chilean National Lithium Strategy, which seeks to establish a sustainable, technological, and socio-economic framework for lithium production.

Key Words: Energy transition, Valuation, Wetlands, Ecosystem services, Lithium mining, Direct lithium extraction.

1. Introduction

Lithium is considered to be a critical metal to facilitate decarbonisation, as it is used in batteries for mobile devices and electric vehicles. They can be used as a power storage of electricity generated from renewable energy, which is susceptible to weather conditions. In 2019, the fastest-growing transport sector emitted approximately 8.9 gigatonnes of carbon dioxide equivalents, accounting for 15% of the world's greenhouse gas emissions (GHG) and 23% of the energy system's CO_2 emissions (Jaramillo *et al* 2022). Lithium is the lightest metal on Earth, and it is found in sources such as rock sediments, brines, and clay deposits, primarily in Australia, China, Chile, Argentina, and Bolivia. Among its many uses, it can be mentioned as an additive in ceramics and glass, and it is a crucial component in the design of ion-lithium batteries (COCHILCO 2024). The primary producer of metallic lithium is Australia, where the metal is extracted from Pegmatites, particularly Spodumene. The second-largest producer is Chile, situated in an area known as the Lithium Triangle. In this case, the reservoirs are located in brines deposited in aquifers (Bos *et al* 2024). To ensure the commercial availability of ion-lithium batteries,

| [1]Department of Chemical Engineering, Biotechnology, and Materials, Faculty of Physical and Mathematical Sciences, Universidad de Chile, Av. Beauchef 851, Piso 6-poniente, Center for Sustainable Design and Process Systems Engineering Santiago, 8370456, Metropolitan Region, Chile
[2]National Institute for Environmental Studies, Japan.

efforts such as national policies and projects are being proposed to guarantee access to lithium. In October 2023, Chile released a statement outlining the National Lithium Strategy (NLS), which aims to increase lithium extraction (Chilean Government, 2023). These cases underline the need for decision-support tools that provide policymakers with understandable data to design large, intersectoral projects.

The development of valuation methods aligns with the enhancement of decision-making tools that generate robust information for sound decision-making. To date, more than 40 methods for valuation have been extensively studied and refined. A considerable amount of literature has focused on valuation methods, which can be categorised into the following groups: nature-based, statement-based, behaviour-based, and integrated valuation (Freeman *et al* 2014). Although valuation methods are continually being developed, there have been fewer efforts to incorporate them into policy-making decisions thoroughly. This relates to concerns regarding the trustworthiness of the methods and the availability of resources for conducting these assessments. However, developing tailor-made solutions is a practice that can increase the uptake of valuation techniques as they are adjusted to policy objectives, frameworks, and timing (Pascual *et al* 2023). Additionally, it is essential to have values that are directly comparable in specific assessments. In fact, continuously identifying values across various depths and types can facilitate their integration into the decision-making process. According to other authors (Pascual *et al* 2023), one approach for stakeholders to incorporate and value various impacts is to utilise a common indicator, such as a monetary metric. Nevertheless, there are ecosystem services that cannot be measured, as they possess intrinsic or relational values that cannot be incorporated using the same indicator. Still, this is not an obstacle to incorporating these impacts into assessments, as they can be paired with reliable methods such as multi-criteria decision analysis.

In the case of lithium mining facilities in northern Chile, these are either placed or projected to be located in the Salar de Atacama, an inland wetland (*salar* in Spanish) situated in the Antofagasta region. Since 1986, lithium has been extracted from brine pumped out from the confined aquifers of the Salar de Atacama. The standard process involves a series of large and shallow solar evaporation ponds that contain the extracted brine, thereby improving evaporation rates. As a result, several salts precipitate as the brine passes through these large ponds until a solution containing a high concentration of lithium carnallite ($LiCl\text{-}MgCl2 \cdot 7H2O$) salt is obtained. This solution is further treated and purified to attain lithium carbonate. However, the evaporation process can take 12 to 24 months, involving intense water evaporation in a drought-prone area, with even values ranging from 100 to 800 m^3 per tonne of produced carbonate lithium (Vera *et al* 2023).

Notably, some of the goals defined in the NLS are (1) Sustainable development of lithium production potential, (2) Social and environmental sustainability, (3) Technological and supply chain development, and (4) Contribution to economic diversification and growth potential. The success of these goals relies on several factors, one of which is the chosen method for lithium extraction. Due to the increasing importance of lithium, research on the development and adaptation of extraction methods has also increased (Cubillos *et al* 2018), promoting the use of direct lithium extraction technologies (DLE), which can be divided into adsorption, ion exchange, solvent extraction, and membrane processes (Abdullah *et al* 2022). These processes differ in several key indicators and design parameters, such as pumping rate, energy balance, and waste generation, among others, which collectively affect overall process efficiency. Nonetheless, to this day, the NLS lacks assessment or comparison studies that outline the technology that aligns best with the presented goals, as well as an overview of the impacts incurred by each extraction method. Considering that it has only provided a brief and general framework that describes the goals and strategic designations.

It appears that the of pumping rate is a key indicator of the external effect of lithium mining on the environment (Gutiérrez *et al* 2023), as the intense regime conducted has impacted the hydrological interactions that sustain a unique and complex system developed over several thousand years since the Salar de Atacama's origins in the Oligocene-Miocene era (Marazuela *et al* 2019a). As hydrodynamics depend on a well-maintained water balance between precipitation and evaporation rates, anthropogenic mining activities may disrupt the ecosystem services sustained by the overall interactions within the Salar de Atacama basin. One of the observed impacts has been the decline in the viability of flora and fauna, most notably the decrease in three flamingo species: the Andean (*Phoenicoparrus andinus*), Chilean (*Phoenicopterus chilensis*), and James's (*Phoenicoparrus jamesi*) species. These species spend their mating and nesting seasons in both the Salar de Atacama and other salt flats and lagoons connected to the system's hydrodynamics (Gutiérrez *et al* 2022). It has been reported that the population of James's and Andean flamingos have decreased by 10% and 12%, respectively (Vera *et al* 2023). Another concern is the recreational activities sustained by the national park Los Flamencos, which has points of interest within the Salar de Atacama and its surroundings, as this park is divided into seven zones (CONAF 2008). According to CONAF records, the five parks and reserves in the Antofagasta region that belong to the National System of Protected Areas (SNASPE) show that Los Flamencos National Park was the most visited park until 2019. Moreover, records show that it is one of the most visited parks on a national scale under the SNASPE programme. In fact, in 2018, the park received 627,154 visitors, making Antofagasta the most visited region in Chile, with park attendants accounting for 78% of the total visitor numbers (SERNATUR 2019). Some of the activities enjoyed by tourists include visiting lagoons and hot springs, as well as trekking and birdwatching, among others (SERNAGEOMIN 2015). However, as mentioned earlier, the possibility of continuing to offer this service depends on the balance of the salt flat hydrodynamics; yet, the impact of lithium mining on tourism in Los Flamencos National Park remains unclear. Furthermore, these negative externalities have not been included in the evaluation of lithium brine mining projects.

Our study aims to conduct valuation methods that consistently quantify the environmental and social impacts of lithium brine mining projects in monetary values. Moreover, the study will compare three metallic lithium production processes, including DLE technologies, to assess their effects on ecosystem services. In particular, we focus on the impact on two ecosystem services—the flamingo population and recreational services of the national park—which will be later integrated into a broader evaluation of the mining project in Salar de Atacama. For this purpose, the travel cost method will be employed to determine the impact on recreational activities within Los Flamencos National Park. In contrast, the effects on flamingo abundance will be evaluated in terms of non-market value. Our analysis will provide valuable insights into the recently developed Chilean

National Lithium Strategy. This study can help decision-makers assess the social and environmental implications of industrial lithium production from brines, as it comprises the first evaluation of the NLS at the policy level.

2. Area under study

The Salar de Atacama is an inland salt flat located in the Antofagasta region of northern Chile. It is situated 2,300 meters above sea level and covers an area of approximately 17,007 km². Its location falls within the margins of the Lithium Triangle. This complex geological area encompasses the borders of Chile, Bolivia, and Argentina and is characterised by its large reserves of lithium and other essential minerals (Fornillo & Lampis 2023). This area has been designated a Ramsar site due to the unique and complex interactions of the hydrogeological system that sustains it (Marazuela *et al* 2019a). The local administration is located in San Pedro de Atacama, with a population of 10,996 inhabitants. Moreover, the community has a significant indigenous representation of 52%, comprising nine distinct groups. Among these, the "Lican Antai" people represent 73.7% of the group (Census 2017), with scattered communities around the area.

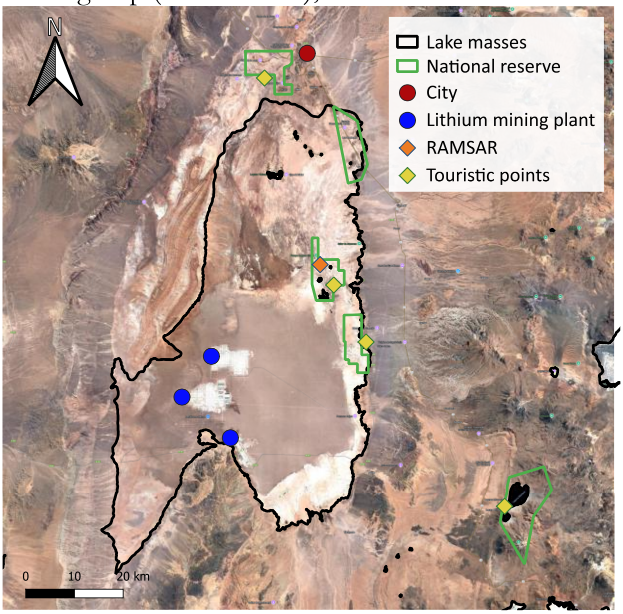

Figure 1: Salar de Atacama is located inside the black outlined lake mass.

The local weather in the Salar de Atacama is considered one of the driest on the planet, with precipitation levels ranging from 10 to 25 mm per year and evaporation rates being as high as 3,700 mm per year (Cubillos *et al* 2018). Mining activities were initiated in 1986 with a pre-operational phase; however, it was not until 1994 that the operational phase began. With this, the intensification of brine pumping led to significant changes in the area's hydrogeology in response to anthropogenic factors (Marazuela *et al* 2019b). Currently, there are three lithium mining facilities belonging to the companies SQM and Albemarle. The employed process utilises weather characteristics in favour of lithium extraction by employing large solar evaporation ponds to remove water from the brine. These evaporation ponds are situated in the southern part of the Salar de Atacama, with the closest town being the Peine community, approximately 40 km away (Van Pampus *et al* 2023).

The national park Los Flamencos is situated within the Salar de Atacama area and covers an area of 739.86 km². The observed ecosystems range from deserts to wetlands and steppes, which are located above 3,500 meters above sea level and are referred to as *altiplano* or *puna* (CIREN 2016). This biodiversity hotspot sustains the lives of several species of flora and fauna, including vicuñas, guanacos, flamingos, algarrobos, and brea, among others. Among the activities available to visitors are trekking, visiting and swimming in salt playas, stargazing and bird watching, among others. Additionally, this national park is highly visited by both national and international tourists due to its unique ecosystems, including Tebenquiche Lagoon, Moon Valley, and Tatio Geyser (CONAF 2008).

3. Methodology

3.1 Impact of lithium extraction on flamingo abundance

Our broader study covers the environmental and socioeconomic impacts of lithium mining projects in this area, but here we focus on two systems services that will be affected. Determining the correlations between flamingo abundance and changes in brine extraction rates involves first understanding the variations in the flamingo population through time. For this, a review of three different species — Andean, Chilean, and James's — and their population changes are studied by comparing periods before and during operational periods of lithium mining projects. Second, by reviewing historical trends in process parameters, such as the pumping rate of brine extraction, an analysis can be conducted to determine whether there are connections between changes in operational conditions and flamingo population behaviour. Third, by assessing indicators related to flamingo wellness, it can be revealed whether shifts in these biophysical indicators are connected to lithium mining activities. To determine how the selection of different lithium extraction technologies affects the viability of fauna, an equation is formulated by establishing a correlation between flamingo abundance and variations in the process indicators of lithium mining.

3.2 Selection of travel cost method

The concept of the travel cost method is rooted in a decline in visitation rates as the total travel cost increases with the distance from the site of interest; consequently, it can be used to estimate recreational values. In this study, we choose the zonal travel cost model, considering the unique characteristics of the reviewed area. With this model, a demand curve representing economic surplus is created by collecting data on the number of visits and expenditures for a round trip. A relationship is established between visitation rates and the assigned zone of the visitor, facilitating the implementation of the travel zone model. Firstly, distinct geographical zones are determined by the origin of visitors, ensuring similar costs for each designated area. Secondly, information about the number of visitors is collected to measure the visitation rate of each zone. To achieve this, the following equation is utilised to calculate the visitation rate of zone *i*:

$$Visitation\ rate\ of\ i = \frac{Number\ of\ visitors\ from\ zone\ i}{Population\ of\ zone\ i} \quad (1)$$

Thirdly, the average cost of a round trip from the visitor zone to the point of interest is calculated. The expenses considered include entrance fees, accommodation, food, transportation, and the cost of time, among others. The cost of time relates to the opportunity cost of choosing one activity over another, such as work, hobbies, pastimes, and other recreational activities. Measuring the cost of time has been a recurring issue among authors that emerges during valuation. One of the approaches employed is to use the hourly wage value, which is calculated by multiplying the wage value by a 15% factor; however, this approach is considered simplified and conservative. In the context of this study, the average hourly wage per country serves as a reference value, determining the time dedicated to the activity. This method helps to account for considerations such as visits that occurred during weekends and holidays, among other situations. Additionally, as visitors can allocate their time to other locations during their trip, it is foremost to integrate multipurpose trips. To determine the share of the trip intended for visiting the evaluated point of interest, a portion of the total travel cost is calculated. For this, a percentage factor is calculated based on the relationship between the time spent at the national park and the total trip time.

For the construction of the demand curve, three models will be tested and compared in terms of their prediction of visitation rates (*X*) based on travel cost (TC). The used models are linear $(X = B_0 + B_1 \cdot TC)$, semi-log ($X = exp(B_0 + B_1 \cdot TC)$) and double-log $(X = B_0 \cdot TC^{B_1})$. By running them using the calculated visitation rates, coefficients B_0 and B_1 will be determined, and then each model will be evaluated based on its predictive power.

4. Data and methodology

4.1 Flamingo population

Documentation of flamingo populations of Chilean, Andean, and James's flamingo has been studied since 1985 using simultaneous surveys of several salt flats (Gutiérrez *et al* 2022). In contrast, brine extraction rates have been documented since 1986 by mining facilities located at the Salar de Atacama. To ensure that this information was not biased, it was compared with available data from the National System of Environmental Enforcement Information System (SNIFA); however, the available reports were provided by the SQM company (SQM 2023).

4.2 Construction of travel cost model

For constructing the zonal travel cost model, secondary data was gathered from national and regional surveys conducted by state institutions, including the National Statistics Institute (INE) and the National Tourism Service (SERNATUR). The determination of distinct zones is based on detailed data regarding the origin of international visitors who visited National parks in the Antofagasta region during 2016. This information was cross-referenced with records from the Los Flamencos Park. A surplus of 2,911 people was identified, indicating that they had visited other facilities. An assumption regarding their nationality was made by distributing these people among the frontier nations of Argentina, Bolivia, and Peru, considering that they might not visit the park that year due to a higher likelihood of returning.

In the context of this study, records from Los Flamencos Park, maintained by SERNATUR, were examined to measure travel expenses using average daily rates for accommodation, the mean stay in Chile according to each visitor's country of origin, and the mean stay in the town of San Pedro de Atacama. For the cost of time, the average hourly wage values were collected from OECD databases (OECD 2023). Regarding the rest of the assessed countries, visitor data were collected from available datasets (Trading Economics 2025a). Additionally, to be able to compare the values of cost of time a conversion factor of purchasing power parity (PPP) for private consumption (ILO 2025) was used as the wage values from the OECD records used PPP US dollars with 2023 as a reference; consequently, an inflation component was added to adjust the value of average wage rates from visitors of non-participatory nations of the OECD. Moreover, PPP conversion factors were used to adjust values from accommodation and food expenses recorded in 2016.

Travel expenses were estimated by analysing customs data to determine whether tourists arrived in Antofagasta by flying from Santiago, crossing the land border from Argentina or Bolivia, or traveling by land within Chile (SERNATUR 2025). For the consumption of land vehicles, the road distance between border crossings and Santiago was estimated, and a value of 16 km per litre of fuel was considered using an average fuel price from Chile of $1.37 per litre (Trading Economics 2025b). Lastly, a mean entrance fee was calculated for foreigners and national visitors as disaggregated information of age and nationality was not available. It is worth mentioning that using answers from surveys directly presented to visitors at each park zone would provide a more accurate reflection of the total travel cost. Further data, such as disaggregated socioeconomic variables, were requested from SERNATUR and CONAF, but their response confirmed that the data does not exist. Finally, visitation rates were normalised using each zone's population number in 2016 (Population Reference Bureau 2017).

5. Results

5.1 Flamingo population

Considering the study area's characteristics and Chile's customary practices in mining other metallic minerals, such as copper, the most appropriate technologies for extracting lithium directly are adsorption and solvent extraction. Table 1 provides a comparison with the currently used method, highlighting both the advantages and disadvantages that need to be considered when pondering and designing the process.

Table 1: Description and comparison of lithium extraction methods (Farahbaksh et al 2024).

Method	Mechanism	Advantage	Disadvantages
Adsorption (TRL 9)	Chemical and physical interaction between Li ions and adsorbent.	-Selectivity of 95% -Industry plants application -Suitable for brine reinjection	-Dissolution of material - Decrease of adsorbent performance -Freshwater consumption
Solvent extraction (TRL 8)	Difference in partition efficiencies	-Conventional and continuous operation	-High waste generation -Risks of accidents managing corrosive additives.

	of aqueous and the organic phases.	-High capacity and scalability -High selectivity	-Acid treatments for the stripping phase.
Evaporation ponds	Solutions are evaporated using sunlight.	-Low energy use -Low initial investment -Does not need freshwater	-Selectivity of 50% -Intensive land use -Process time of 12-24 months

The determined biophysical indicators are displayed in Table 2, which reflect a change in flamingo abundance, such as the superficial water area (SWA) and the mining pond area. SWA during the winter season (June-August) declined from 1,662 to 979 hectares between 1985 and 2016. In contrast, SWA values remained constant during the summer season. Consequently, only data recorded during the winter season was considered in this study. Additionally, to examine the variation in the flamingo population of Andean, Chilean, and James's species, the period from 1979 to 1988 was excluded from the analysis, as pre-operational activities began in 1986; thus, only census data from 1989 to 2019 was included. With this data, a relationship between SWA and mining pond area was established using standardised β values (Gutiérrez *et al* 2024), which revealed a negative correlation between flamingo abundance and mining pond area and a positive correlation between flamingo abundance and SWA. Then, a regression model was used to construct a relationship between the mining pond area and pumping rate. In contrast, to understand the implications of pumping rate changes in SWA, it was necessary to use the water table value as an intermediate variable, then a numeric relationship between these three variables was established using empirical data (SQM 2025).

It is essential to state that the results of this study are based on datasets provided by state institutions, including CONAF, SNIFA, and SQM, as well as a private company. Therefore, the reliability of the results is subject to this. Nonetheless, the primary focus of this study is to develop a methodology that incorporates this data to measure environmental impacts, rather than creating new datasets.

Table 2: Flamingo population decline linked to lithium extraction methods.

Extraction method	Indicator	Pumping rate m^3 per second	Reduction in flamingo abundance		
			Andean	James's	Chilean
Evaporation pond	Mining pond area	2.0	894	54	-
Evaporation pond	SWA	2.0	-	0.31	0.37
Solvent extraction	SWA	1.5	-	0.26	0.31
Adsorption	SWA	1.0	-	0.23	0.27

5.2 Valuing recreational services by the travel cost method

Figure 2 provides information on the geographical zones determined for the zonal travel cost model. Six zones were identified by comparing the estimated travel costs and the distance from the national park.

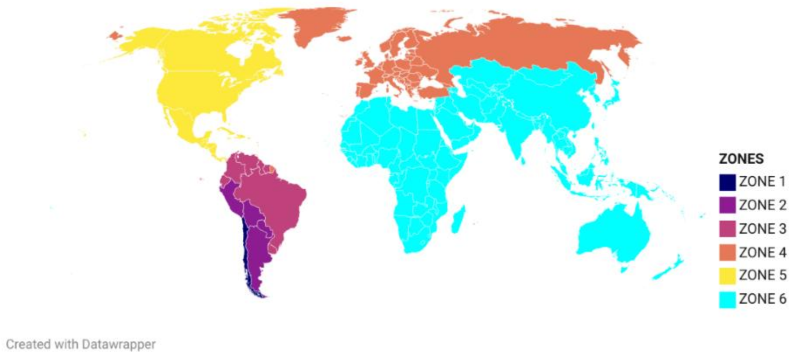

Figure 2: Designated zones for the zonal travel cost method.

The visitation rates showcased in Table 3 for each travel zone are consistent with the increase of price and distance of each zone. The highest visitation rate corresponds to zone one, which encompasses the national territory; zone two, which comprises the neighbouring countries Argentina, Bolivia, and Peru; zone three, which considers the rest of the nations from South America; zone four include nations from Central, and North America; zone five encompasses all countries in Europe, and zone six covers regions from Africa, Asia, and Oceania.

Table 3: Overview of travel costs (PPP converted), number of visitors and visitation rate per capita.

Zones	Travel cost ($)	Visitors	Population (millions)	Visitation rate
1	866	176,172	18.2	0.001769
2	843	8,340	86.1	0.000097
3	906	66,741	278.4	0.000240
4	1074	118,057	705.5	0.000167
5	1021	30,955	594.8	0.000052
6	1008	18,672	3507.2	0.000005

Table 4 shows the results of the zonal travel cost method, which predicts the number of visitation rates associated with travel costs. Aside from the coefficient of determination (R^2), model characteristics are examined by observing the values of the coefficients of intercept (B_0) and slope (B_1). For instance, the semi-log model exhibits a negative slope, which is consistent with the proposition that the visitation rate decreases as travel costs increase.

In the context of this study, the selected model was the semi-log model; however, modifications were made to align the model with data and to address outliers. Zone 1 behaved as an outlier in the model, significantly influencing regression results. To address this, the data was capped using the 80th percentile function based on the visitation rate of the zone, which limited the number of visitors by capping the visitation rate value at 0.0024. To adjust the choke price of the original model, which was $664, to a more realistic value aligned with the data, the intercept of the regression was calculated to ensure that the predicted visitation rates reflected the data from travel costs. This resulted in a calibrated semi-log model with a new choke price of $1200. Additionally, the constructed demand curve represented in Figure 3 reveals a consumer surplus of $6.41 per person, indicating an estimated value of $2.68 million for the recreational activities at Los

Flamencos National Park based on the number of visitors received in 2016. An assumption has to be made about how much of this consumer surplus will be lost due to mining operations. Suppose that the proportion is one-third, which amounts to the loss of $1 million each year. The capitalised loss would be $20 under the discount rate of 5%.

Table 4: Regression results of linear, semi-log and double-log models.

Model	Equation	R^2
Original linear	$X = 0.01983-0.00001 \cdot TC$	0.20
Calibrated linear	$X = 0.00539-0.000004 \cdot TC$	0.16
Original semi-log	$X = \exp(-3.87- 0.00539 \cdot TC)$	0.25
Calibrated semi-log	$X = \exp(3.6852- 0.01312 \cdot TC)$	0.14
Original double-log	$X = 77.8165 \cdot TC^{-12.63}$	0.25
Calibrated double-log	$X = 29.6409 \cdot TC^{-5.70}$	0.15

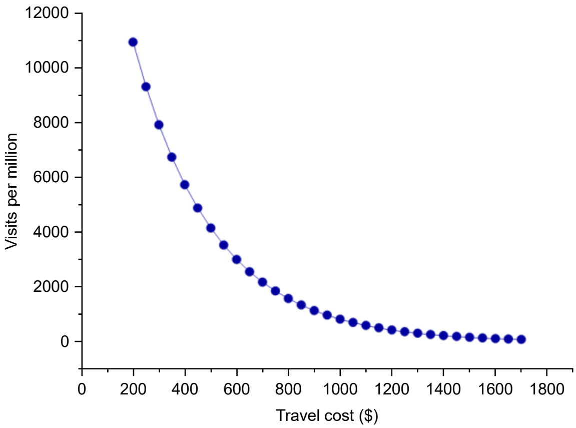

Figure 3: Demand curve for visitors of Los Flamencos National Park during 2016.

6. Discussion

The results of this study suggest that lithium mining projects have both instrumental and intrinsic impacts that must be accounted for during policy formulation and process design. Los Flamencos National Park offers a diverse range of recreational activities to visitors, with an average stay in the park of 1.78 days. The park provides visits to lagoons such as Chaxa and Piedras Rojas, along with activities like bird watching, stargazing, and trekking, among others. The zonal travel cost model assumes that the established relationship between travel cost and frequency of visits to the park serves as a proxy for the visitor's willingness to pay to visit the national park (Tourklias *et al* 2015).

In this study, we used records from 2016 and estimated a consumer surplus for Los Flamencos National Park of $6.41 per person, totalling $2.68 million for the 418,684 visitors received. Considering the characteristics of this study, this result aligns closely with those of other analyses (Rusciano *et al* 2023). Moreover, records from 2001 to 2019 indicate an average annual growth rate of 22% in visitations. It is worth noting that foreign visitors collectively account for an average of 66% of the total yearly visits (SERNATUR 2020). This suggests that the value of consumer surplus might have increased over the past years. Additionally, activities related to income from restaurants and hotels accounted for 2.1% of the region's GDP in 2021 (CORFO 2021). However, during the SARS-CoV-2 pandemic, the park administration decided to close the lagoons to promote the recovery of species and reconstruct tourist facilities. The lagoons were Salar de Tara, which is still closed, and Chaxa Lagoon, which reopened in October 2023. This decision aligns with the park's conservation principles; nonetheless, it appears that these efforts stem from degraded conditions that were most likely prompted by mining activities. Consequently, the degradation of park facilities seems to have significantly reduced the number of visitors to 103,814 (CONAF 2025). Notably, a significant limitation of the study is that we have used secondary data to calculate recreational services. Consequently, this study serves as an illustrative case, focusing on the methodology of the zonal travel cost method rather than creating and curating databases. Nonetheless, an original survey would unearth more specific attributes that park visitors value, as well as provide more accurate information regarding disaggregated demographics, including gender, occupation, age, education, and monthly income. Further work, following this methodology and incorporating datasets from an independent source, will increase the certainty of the exhibited visitors' willingness to pay. Moreover, the assumption that time is dedicated exclusively to visiting the park, when aggregated over the total trip time by country, potentially hinders the calculation of the cost of time. Additionally, there is no available data on the actual time spent on recreational activities, which excludes other recurring activities such as eating at local restaurants, visiting cultural or relevant local sites, or time spent commuting to and from these places. Overall, these assumptions might overestimate the final calculated consumer surplus.

Additionally, we compared the effects of three different lithium extraction technologies on the flamingo population, as reported by other authors (Gutiérrez *et al* 2022). The main driver of the decrease in the superficial water area is the intensive brine extraction, as the regularity of the activity imposes a substantial negative value in the water balance. It does not allow for a recuperation interval for the system to regain balance through recharges such as precipitation. Furthermore, the process indicator that determines the flow of brine extraction is the selectivity of the operation. Adsorption is the method with the highest selectivity, using adsorbents such as granulated Li/Al-LDH materials, achieve a 95% recovery of lithium within ten 240-minute cycles (Li *et al* 2022), resulting in the lowest brine extraction flow compared to the other selected methods. The selectivity of the solvent extraction method depends on the chosen organic phase. For one of the most commonly used solvents, tributyl phosphate sodium (TBP-sodium), it is reported to be 85% (Li *et al* 2023). For solar evaporation ponds, selectivity drops drastically to 50%. The reason behind this is the similarity of lithium with other ions, mainly magnesium, which prompts the precipitation of a significant amount of lithium carnallite that is subsequently discarded (Cubillos *et al* 2018).

The choice of adsorption technology may result in a slight reduction in the population of James's and Chilean flamingos at a flow rate of 1 m^3 per second, with the affected individuals exhibiting changes of 0.23 and 0.27. The case for solvent extraction exhibits a slightly higher value with changes of 0.26 and 0.31 for James's and Chilean flamingos, respectively. However, the number of individuals lost due to solar evaporation are 894, 54.31, and 0.37 for Andean, James's, and Chilean flamingos, respectively. This suggests that the current technology significantly disrupts the viability of flamingo establishments, placing an urgent call for the replacement of the extraction method. Furthermore, the Andean and James's flamingos are endemic to the region and are categorised as vulnerable and near-threatened species by the International Union for Conservation of Nature (Gutiérrez *et al* 2022). Moreover, indigenous communities are scattered across eight sectors surrounding the Salar de Atacama, belonging to the Lican Antai people, whose beliefs are deeply rooted in living in harmony with and respecting nature (FIMA 2023). Many Lican Antai ancient ceremonies include the presence of flamingo feathers used by ritual guides known as *yatiris*. Nonetheless, it has been reported (Gutiérrez *et al* 2023) that periods of sustained decline in SWA lead to a reduction in water and food availability, affecting the spatial distribution of flamingos as they may seek different lagoons or salt flats that can provide sufficient resources. Consequently, this change in the spatial distribution of flamingos may disrupt the livelihoods of these communities, as the distances between communities and lagoons are significant.

The physical phenomenon behind mining activities that disrupt both flamingo population and recreational activities is rooted in the nature of the Atacama basin, where the Salar de Atacama is located. This basin can be divided into four zones: the salt flat nucleus, the mixing zone, alluvial fans, and volcanic and basement rocks (Marazuela et al 2019a). Mining facilities and drilled wells for extracting brine are situated in the salt flat nucleus area because the concentration of lithium and other salts there is higher than in the rest of the basin. Although several studies have aimed to outline the complete hydrogeological system of the Atacama basin, it remains not fully understood; however, some models illustrate the interactions between these zones. More precisely, the numerical model proposed by Marazuela et al. suggests that the nature of the endoreic basin causes flows entering from the northern, eastern, and southeastern areas to converge at the point with the lowest water table elevation in the whole area of the basin, which not only is situated within the nucleus but has shifted in the last years towards the area where extraction wells are drilled for brine extraction (Marazuela *et al* 2019b). This specific phenomenon suggests that by further lowering the water level in the salt flat nucleus, surrounding areas will also experience a water level change, including the mixing zone where important lagoons, such as Chaxa Lagoon, part of Los Flamencos National Park (Figure 1), have been reported with flamingo presence. This information can be contrasted with empirical data from observation wells located in the mixing zone, as reported by CONAF, which confirms that water levels have decreased in recent years (SQM 2025). The hydrodynamics of the Salar de Atacama support the establishment between biophysical indicators of the ecosystem and process parameters. It is worth noting that authors (Kelly *et al* 2021) argue that the production of carbonated lithium in Chile, compared to extraction processes carried out in Australia, has a lower environmental impact when considering life-cycle energy, water consumption, and material inputs. However, this assessment overlooks essential characteristics of the hydrology system, thereby underestimating the disruption caused by evaporation ponds on the ecosystem and their impacts on ecosystem services.

7. Conclusions

The recently developed NLS is an important step in fully utilising natural resources in Chile and facilitating decarbonisation around the world. A comprehensive evaluation at policy and project levels would be essential in implementing the NLS. In this paper, we have focused on two ecosystem services that might be affected mainly by lithium mining projects in Salar de Atacama. Applying the zonal travel cost method, we found that a consumer surplus for Los Flamencos National Park was $6.41 per person, totalling $2.68 million for the 418,684 visitors in 2016. Moreover, we also examined a previous study on the relationship between the mining pond, superficial water, and the population of flamingos and connected it with the value of pumping rate. Taken together, they suggest that lithium mining facilities have a severe impact on both recreational activities and biodiversity conservation; more importantly, these impacts may depend on the method of lithium extraction.

Among the three evaluated methods, the adsorption operation is the best option, as it showcases the highest selectivity, with a 95% recovery of lithium, and does not require additives containing corrosive components, unlike solvent extraction. Additionally, plants of industrial scale have commenced the first phase of operation in Argentina, achieving a full capacity of 24 kilotonnes of LCE (Eramet, 2025), demonstrating their scalability. Notably, efforts to address freshwater use in the operation must be addressed, considering the scarcity of this resource in the area. These findings suggest that, in general, extraction methods that require significant brine flow are directly linked to environmental and economic impacts, which include recreational activities and fauna preservation. Thus, an analysis of the effects of lithium mining can be deduced from the involvement of an extraction method that relies on intensive brine extraction.

Our findings revealed that solar evaporation ponds, the current method of extraction, pose a severe threat to Andean and James's flamingo species. Moreover, representing environmental interactions using a set of common biophysical variables provides a broad range of correlations that facilitate impact assessment across dimensions. An implication of this is the possibility that flamingo's spatial distribution, which depends on SWA and pumping rate, might serve as a biophysical indicator to assess the interference of lithium mining activities. More importantly, this study serves as a reference to similar cases, where extraction processes are being carried out in ecosystems with shared characteristics and conditions. For example, Greenbushes, a lithium facility located in Australia, is situated in a critical habitat (Dolega et al., 2020). These areas are considered to represent threatened and unique ecosystems, boasting rich biodiversity that holds significant importance for endangered species, endemic species, and migratory species, as well as being associated with key evolutionary processes. Another example is the "uranium rush" that took place in the Namib Desert, specifically in Namibia. Here, several companies from China, India, Russia, Japan, Korea, Australia, and Canada hold licenses to extract uranium in this arid area. Similar to the Atacama Desert, the Namib Desert is considered a biodiversity hotspot. Moreover, the region boasts important national parks and numerous archaeological sites that attract tourists to visit the area (Corson *et al* 2013).

We have not addressed socioeconomic aspects, such as direct monetary benefits and costs, as well as the impact on indigenous peoples. For this, future studies could consider conducting surveys in the surrounding Lican Antai communities to characterise changes and disturbances on indigenous livelihoods, further comprehend the extent of the effect on rituals that depend on flamingo presence in the area, and determine other repercussions prompted by lithium mining activities. In addition, environmental aspects other than the two ecosystem services we have studied have not been treated. They will be integrated into a more comprehensive evaluation of the projects considered in the NLS, using social cost-benefit analysis and multicriteria analysis. For example, we can use the capitalised loss in the consumer surplus under specific mining methods. This value can be set against the other net socioeconomic benefits of the mining activities. Altogether, they will comprise crucial inputs in putting the NLS into practice in a sustainable and inclusive manner.

References

Abdullah K., Mohammed, S., Hashaikeh, R., Hilal, N. (2022) Lithium recovery from brine: Recent developments and challenges. Desalination 528, 115611.

Bos, V., Forget, M., & Gunzburger, Y. (2024) Lithium-based energy transition through Chilean and Australian mining scapes. The Extractive Industries and Society 17, 101384.

Census of Chile (2017). http://resultados.censo2017.cl/Region?R=R02 Accessed 28/03/2025.

Chilean Government. (2023) National Lithium Strategy. https://s3.amazonaws.com/gobcl-prod/public_files/Campa%C3%B1as/Litio-por-Chile/Estrategia-Nacional-del-litio-EN.pdf Accessed 28/03/2025.

Chilean Society of Chemistry and Mining (SQM) (2025) Seguimiento Ambiental Hidrogeológico. https://www.sqmsenlinea.com/env-systems?type=followup Accessed 29/03/2025

CIREN (Information Center of National Resources) (2016) Sistema de Información Territorial de Humedales Altoandinos. Climate Background II Region Antofagasta.

COCHILCO (National Comission of Copper) (2024) El mercado de litio: Desarrollo reciente y proyecciones al 2035.

CONAF (National Forestry Corporation) (2008) Actualización Plan de Manejo Participativo Reserva Nacional Los Flamencos. Antofagasta Region.

CONAF (2025) REPORTE: VISITAS A SISTEMA NACIONAL DE ÁREAS SILVESTRES PROTEGIDAS DEL ESTADO. https://datosturismo.sernatur.cl/siet/reporteDinamicoSNASPE Accesed 29/03/2025

Corson, C., MacDonald, K. & Neimark, B. (2013). Grabbing "Green": Markets, Environmental Governance, and the Materialisation of Natural Capital. Hum. Geogr. 6, 1-15. 10.1177/194277861300600101.

Cubillos, C. F., Aguilar, P., Grágeda, M., & Dorador, C. (2018). Microbial communities from the world's largest lithium reserve, Salar de Atacama, Chile: Life at high LiCl concentrations. Journal of Geophysical Research: Biogeosciences, 123, 3668–3681.

Dolega, P., Buchert, M. & Klinge, J. (2020). Environmental and socio-economic challenges in battery supply chains: graphite and lithium. https://www.oeko.de/fileadmin/oekodoc/Graphite-Lithium-Env-Soc-Eco-Challenges.pdf

Eramet (2025) Mina y planta. https://eramine.eramet.com/es/eramine/our-project/mina-y-planta/ Accessed 01/04/2025.

Farahbakhsh, J., Arshadi, F., Mofidi, Z., Mohseni-Dargah, M., Kök, C., Assefi, M., Soozanipour, A., Zargar, M., Asadnia, M., Boroumand, Y., Presser, V., & Razmjou, A. (2024). Direct lithium extraction: A new paradigm for lithium production and resource utilisation. Desalination, 575, 117249.

Freeman III, A.M., Herriges, J.A., Kling, C.L. (2014) The Measurement of Environmental and Resource Values: Theory and Methods (3rd ed.). Routledge. https://doi.org/10.4324/9781315780917

Fornillo, B., & Lampis, A. (2023). From the Lithium Triangle to the Latin American quarry: The shifting geographies of de-fossilisation. The Extractive Industries and Society, 15, 101326.

Gutiérrez, J. S., Moore, J. N., Donnelly, J. P., Dorador, C., Navedo, J. G., & Senner, N. R. (2022). Climate change and lithium mining influence flamingo abundance in the Lithium Triangle. Proceedings of the Royal Society B: Biological Sciences, 289, 20212388.

ILO (International Labour Organization) (2025) PPP conversion factor, private consumption (LCU per international dollar) – Annual. Database Prices, Costs and Currency Conversions (PRICES). https://rshiny.ilo.org/dataexplorer21/?lang=en&id=CCF_XPPP_CUR_RT_A Accessed 29/03/2025.

Jaramillo, P., Kahn Ribeiro, S., Newman, P., Dhar, S., Diemuodeke, O.E., Kajino, T., Lee, D.S., Nugroho, S.B., Ou, X., Hammer Strømman, A., Whitehead, J. (2022) Transport. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Kelly, J. C., Wang, M., Dai, Q., & Winjobi, O. (2021). Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. Resources, Conservation and Recycling, 174. https://doi.org/10.1016/j.resconrec.2021.105762

Li, J., Luo, Q., Dong, M., Nie, G., Liu, Z., & Wu, Z. (2022). Synthesis of granulated Li/Al-LDHs adsorbent and application for recovery of Li from synthetic and real salt lake brines. Hydrometallurgy, 209, 105828.

Li, R., Wang, Y., Duan, W., Du, C., Tian, S., Ren, Z., & Zhou, Z. (2023). Selective extraction of lithium ions from salt lake brines using a tributyl phosphate-sodium tetraphenyl boron-phenethyl isobutyrate system. Desalination, 555, 116543

Marazuela, M.A., Vázquez-Suñé, E., Ayora, C., García-Gil, A., Palma, T. (2019a) Hydrodynamics of salt flat basins: The Salar de Atacama example. Science of The Total Environment 651, 668–683.

Marazuela, M.A., Vázquez-Suñé, E., Ayora, C., García-Gil, A., Palma, T. (2019b) The effect of brine pumping on the natural hydrodynamics of the Salar de Atacama: The damping capacity of salt flats. Science of the Total Environment 654, 1118-1131

National Geology and Mining Service (SERNAGEOMIN) (2015) Anuario de la Minería de Chile. Subdirección Nacional de Minería, Servicio Nacional de Geología y Minería 253pp.

OECD (Organization for Economic Cooperation and Development) (2023) Average annual wages. https://data-explorer.oecd.org/vis?tm=average%20annual%20wage&pg=0&snb=26&vw=tb&df[ds]=dsDisseminateFinalDMZ&df[id]=DSD_EARNINGS%40AV_AN_WAGE&df[ag]=OECD.ELS.SAE&df[vs]=1.0&dq=..USD_PPP....&pd=2016%2C2016&to[TIME_PERIOD]=false&ly[rw]=REF_AREA Accessed 28/03/2025

ONG Environmental Prosecutor's Office (FIMA) (2023) Narrativas sobre la extracción de minerales críticos para la transición energética: Críticas desde la justicia ambiental y territorial. Santiago

Pascual, U., Balvanera, P., Anderson, C.B., Chaplin-Kramer, R., Christie, M., González-Jiménez, D., Martin, A., Raymond, C.M., Termansen, M., Vatn, A., Athayde, S., Baptiste, B., Barton, D.N., Jacobs, S., Kelemen, E., Kumar, R., Lazos, E., Mwampamba, T.H., Nakangu, B., O'Farrell, P., Subramanian, S.M., van Noordwijk, M., Ahn, S., Amaruzaman, S., Amin, A.M., Arias-Arévalo, P., Arroyo-Robles, G., Cantú-Fernández, M., Castro, A.J., Contreras, V., De Vos, A., Dendoncker, N., Engel, S., Eser, U., Faith, D.P., Filyushkina, A., Ghazi, H., Gómez-Baggethun, E., Gould, R.K., Guibrunet, L., Gundimeda, H., Hahn, T., Harmáčková, Z.V., Hernández-Blanco, M., Horcea-Milcu, A.-I., Huambachano, M., Hummel Wicher, N.L., Aydın, C.İ., Islar, M., Koessler, A.-K., Kenter, J.O., Kosmus, M., Lee, H., Leimona, B., Lele, S., Lenzi, D., Lliso, B., Mannetti, L.M., Merçon, J., Monroy-Sais, A.S., Mukherjee, N., Muraca, B., Muradian, R., Murali, R., Nelson, S.H., Nemogá-Soto, G.R., Ngouhouo-Poufoun, J., Niamir, A., Nuesiri, E., Nyumba, T.O., Özkaynak, B., Palomo, I., Pandit, R., Pawłowska-Mainville, A., Porter-Bolland, L., Quaas, M., Rode, J., Rozzi, R., Sachdeva, S., Samakov, A., Schaafsma, M., Sitas, N., Ungar, P., Yiu, E., Yoshida, Y., Zent, E. (2023) Diverse values of nature for sustainability. Nature 620, 813–823. https://doi.org/10.1038/s41586-023-06406-9

Population Reference Bureau (2017). 2016 World Population Data Sheet with a special focus on human needs and sustainable resources. https://www.prb.org/wp-content/uploads/2016/08/prb-wpds2016-web-2016.pdf Accessed 29/03/2025

Rusciano, V., Ruberto, M., Baralla, S., Fasolino, N. G., Pellegrini, E., & Zucaro, R. (2023). Assessing the touristic activities of wetlands through the travel cost method: A case study. Water, 15(23), 4146.

SERNATUR (National Tourism Service) (2019) Anuario de Turismo 2018. https://www.subturismo.gob.cl/wp-content/uploads/2015/10/Anuario-de-Turismo-2018.pdf Accessed 29/03/2025.

SERNATUR (2025) DataTurismo: Turismo receptivo: Llegadas de turistas extranjeros. https://www.sernatur.cl/dataturismo/movimiento-turistico-internacional/ Accessed 29/03/2025.

SQM (2023) INFORME VII ACTUALIZACIÓN MODELACIÓN SALAR DE ATACAMA https://snifa.sma.gob.cl/General/DescargarInformeSeguimiento/1060268 Accesed 29/03/2025.

Tourkolias, C., Skiada, T., Mirasgedis, S., & Diakoulaki, D. (2015). Application of the travel cost method for the valuation of the Poseidon temple in Sounio, Greece. Journal of Cultural Heritage, 16(4), 567-574.

Trading Economics. (2025a) Country list: Wages. https://tradingeconomics.com/country-list/wages. Accessed 29/03/2025.

Trading Economics. (2025b) Chile Gasoline Prices. https://tradingeconomics.com/chile/gasoline-prices Accessed 29/03/2025.

Van Pampus, M., Hogenboom, B., Hoorn, C., & Seijmonsbergen, A. C. (2023). Uncertainties in the debate on the environmental impact of lithium brine extraction in the Salar de Atacama, Chile. Evolving Earth, 1, 100024. https://doi.org/10.1016/j.eve.2023.100024

Vera, M. L., Torres, W. R., Galli, C. I., Chagnes, A., Flexer, V. (2023) Environmental impact of direct lithium extraction from brines. Nature Reviews Earth & Environment 4, 149-165.