



Universidad de Concepción

Facultad de Ciencias Ambientales
Programa de Doctorado en Ciencias Ambientales mención Sistemas Acuáticas
Continetales

Título

**Gestión de Descargas de Salmuera: un Enfoque Multidisciplinario
para la Sustentabilidad Ambiental de la Industria Desaladora**

Tesis para optar al grado de

Doctor en Ciencias Ambientales
con mención en Sistemas Acuáticos Continetales

Enzo René García Bartolomei

CONCEPCIÓN-CHILE
2024



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A mi familia y amigos.

The world ain't all sunshine and rainbows. It's a very mean and nasty place and I don't care how tough you are it will beat you to your knees and keep you there permanently if you let it.

You, me, or nobody is gonna hit as hard as life. But it ain't about how hard ya hit. It's about how hard you can get hit and keep moving forward. How much you can take and keep moving forward. That's how winning is done!

Now if you know what you're worth then go out and get what you're worth. But ya gotta be willing to take the hits, and not pointing fingers saying you ain't where you wanna be because of him, or her, or anybody! Cowards do that and that ain't you! You're better than that!

Rocky Balboa

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Consideraciones estadísticas para el diseño de programas de monitoreo ambiental y aplicaciones para la industria desalinizadora.

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2020

En: Programas de monitoreo del medio marino costero: diseños experimentales, muestreos, métodos de análisis y estadística asociada. Juan C. Castilla, José M. Fariña y Andrés Camaño. Ediciones Universidad Católica de Chile. Santiago, Chile.

Submitted - Thesis chapter

Environmental Risk Assessment of Brine Discharges: Insights from Field Studies in a Coastal Desalination Plant in Northern Chile

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Brine discharge from seawater desalination triggers ecophysiological and cellular stress responses in the model brown macroalga *Ectocarpus*

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Assessment of the Requirements within the Environmental Monitoring Plans Used to Evaluate the Environmental Impacts of Desalination Plants in Chile.

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Sola, I., Sánchez-Lizaso, J.L., Muñoz, P., García-Bartolomei, E, Saez, C., Zarzo, D.

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Ecological risk assessment of desalination brine plumes in Chilean coastal systems: a case study. Presentación oral. (11/2019 - Presente)

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Multidisciplinary Environmental Approach to the Sustainable
Management of Seawater Desalination Effluents

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Abstract [EN]

The increasing scarcity of freshwater resources, driven by climate change and overexploitation factors, has positioned seawater desalination as a cornerstone of water security strategies in arid and semi-arid regions worldwide. With its extensive coastline and highly variable precipitation patterns, Chile exemplifies this global trend. The nation has witnessed a rapid expansion of desalination capacity in recent decades, becoming the largest producer of desalinated water in the Americas. While this technological advancement has undoubtedly contributed to Chile's social and economic development, ensuring the long-term sustainability of this crucial industry requires a deeper understanding and mitigation of its potential environmental impacts.

A critical aspect often overlooked in conventional desalination assessments is the discharge of hypersaline brine back into the marine environment. This effluent, a concentrated byproduct of the desalination process, can significantly alter coastal ecosystems' salinity gradients, nutrient balances, and ecological integrity. Despite the growing body of international research highlighting the potential risks associated with brine discharge, a significant knowledge gap persists regarding its specific effects on Chilean coastal waters. This lack of localized understanding, coupled with the absence of standardized assessment methodologies and comprehensive environmental regulations tailored to the Chilean context, presents a significant barrier to the sustainable development of the desalination industry in the country.

This dissertation addresses this critical challenge by adopting a multidisciplinary approach to analyze and mitigate the ecological risks of brine discharge from Chile's desalination plants. Recognizing the unique geographic and oceanographic characteristics of the Chilean coast, this research integrates three interconnected areas of investigation:

a) Assessing the Environmental Risk of Brine Discharge on Benthic Communities:

This research focuses on characterizing the ecological risks associated with brine discharge from a Chilean desalination plant, moving beyond traditional physical dilution models to incorporate biological data for a more comprehensive assessment. Through a combination of field measurements and ecotoxicological analysis, this study investigates the behavior of the brine plume and its potential effects on benthic communities. Field data, including in-situ measurements of salinity and plume extent, are compared to model predictions to assess the accuracy of current modeling approaches. Additionally, species sensitivity distributions, derived from local and global ecotoxicological data, are used to establish salinity safety thresholds specific to the bay receiving the brine discharge. By integrating these thresholds into a spatial risk assessment framework, this study identifies areas of potential ecological concern and evaluates the overall risk posed by the desalination plant's brine discharge.

b) Guiding Sustainable Territorial Planning: Recognizing that the location of desalination plants is crucial in determining the potential impact of brine discharge, this research

component utilizes advanced modeling techniques to identify coastal areas most susceptible to adverse ecological effects. By integrating oceanographic data, environmental sensitivity maps, and projected desalination development scenarios, this analysis will inform spatial planning decisions, guiding the siting of future desalination plants to minimize environmental impacts and promote the long-term health of Chilean coastal ecosystems.

- c) Strengthening Environmental Governance:** By analyzing international best practices, identifying gaps in current regulations, and incorporating the findings from this dissertation's ecotoxicological and spatial planning components, this research will propose concrete recommendations for strengthening the environmental governance of the desalination industry in Chile. This includes promoting more comprehensive and ecologically relevant assessment criteria, incorporating adaptive management strategies, and fostering greater transparency and stakeholder engagement in decision-making.

By integrating these interconnected research areas, this dissertation aims to provide a comprehensive and scientifically grounded framework for the sustainable management of brine discharge from desalination plants in Chile—the expected outcomes of this research, including a refined understanding of brine plume.



Figure 0-1: Los Pelambres Sea Water Reverse Osmosis desalination plant, Chile. Photograph by Enzo García-Bartolomei.

Resumen [ES]

La creciente escasez hídrica, agravada por el cambio climático y la sobreexplotación, ha posicionado a la desalación de agua de mar como un pilar fundamental para la seguridad hídrica, especialmente en regiones áridas del mundo. Chile posee una extensa costa y patrones de precipitación irregulares, lo que ha catalizado en las últimas décadas una rápida expansión de la capacidad de desalación instalada, convirtiéndose en el mayor productor de agua desalada de América Latina.

Una de las principales preocupaciones ambientales de esta industria, guarda relación con la descarga de salmuera. Este subproducto concentrado del proceso de desalación puede bajo ciertas condiciones alterar la salinidad e integridad ecológica de los ecosistemas costeros. A pesar de la creciente investigación internacional sobre los riesgos potenciales de la descarga de salmuera, aún existe un vacío de conocimiento sobre sus efectos específicos en los sistemas costeros de Chile. Esta falta de comprensión local, aunada a la ausencia de metodologías de evaluación estandarizadas y regulaciones ambientales integrales adaptadas al contexto nacional, representa un obstáculo para el desarrollo sostenible de la industria desaladora en Chile.

Esta tesis aborda este desafío desde una perspectiva multidisciplinaria, buscando analizar y mitigar los riesgos ecológicos de la descarga de salmuera en las plantas desalinizadoras chilenas. Reconociendo las particularidades geográficas y oceanográficas de la costa chilena, la investigación integra tres áreas interconectadas:

- a. **Evaluación del riesgo ambiental de la descarga de salmuera en comunidades bentónicas:** Esta investigación se centra en caracterizar los riesgos ecológicos asociados a la descarga de salmuera de una planta desalinizadora chilena, trascendiendo los modelos tradicionales de dilución física e incorporando datos biológicos para una evaluación más integral. Mediante la combinación de mediciones de campo y análisis ecotoxicológicos, este estudio investiga el comportamiento de la pluma de salmuera y sus posibles efectos en las comunidades bentónicas. Los datos de campo, incluyendo mediciones in situ de salinidad y extensión de la pluma, se comparan con las predicciones de los modelos para evaluar su precisión. Además, se utilizan métodos estadísticos de evaluación de riesgo ecológico, para establecer umbrales de seguridad de salinidad específicos para la bahía receptora de la descarga. Al integrar estos umbrales en un marco de evaluación de riesgos espaciales, este estudio propone un lineamiento metodológico para la evaluación del riesgo ecológico y determinación de área de influencia de las plumas de salmuera.
- b. **Orientación hacia una planificación territorial sostenible:** Reconociendo que la ubicación de las plantas desalinizadoras es crucial para determinar el impacto potencial de la descarga de salmuera, este componente de la investigación utiliza técnicas de modelación territorial avanzada para identificar áreas costeras más susceptibles al desarrollo de la industria desaladora. Al integrar mapas de sensibilidad ambiental y

escenarios de desarrollo de la desalinización proyectados, este análisis busca informar las decisiones de planificación espacial, guiando la ubicación de futuras plantas para minimizar los impactos ambientales y promover la salud a largo plazo de los ecosistemas costeros chilenos.

- c. **Fortalecimiento de la gobernanza ambiental:** Analizando las mejores prácticas internacionales, identificando las brechas en las regulaciones actuales e incorporando los hallazgos de los componentes ecotoxicológicos y de planificación espacial de esta tesis, esta investigación busca proponer recomendaciones concretas para fortalecer la gobernanza ambiental de la industria de desalinización en Chile. Esto incluye promover criterios de evaluación más integrales y ecológicamente relevantes, incorporar estrategias de gestión adaptativa y fomentar una mayor transparencia y participación de todos los actores involucrados y afectados.

Al integrar estas áreas de investigación interconectadas, esta tesis aspira a proporcionar un marco integral y científicamente sólido para la gestión sostenible de la descarga de salmuera de las plantas desalinizadoras en Chile. Se espera que los resultados de esta investigación, permitan una comprensión más precisa del comportamiento de las plumas de salmuera y sus mecanismos de gestión, contribuyendo con prácticas más sostenibles en la industria.



Figure 0-2: Pretreatment system at Los Pelambres Sea Water Reverse Osmosis desalination plant, Chile. Photograph by Enzo García-Bartolomei.

I. Chapter I: Research framework and background

1. INTRODUCTION

1.1. Water sustainability, anthropogenic impacts, and climate change

Water is essential to all life forms and a fundamental resource for human needs, keeping the ecosystems healthy and allowing the constant/ongoing development of society and industry [1]. Only 2.5% of the total water sources on Earth are freshwater. Of this percentage, 70% is captured by ice and glaciers, and the remaining 30% is located in underground aquifers. Hence, hardly 0.007% of the total water volume on Earth is directly accessible through rivers, lakes, and reservoirs. Available water exhibits spatial heterogeneity, both temporally and geographically, meaning that more than a third of the world's population faces water shortages for survival [1].

Both social and economic development profoundly depend on the sustainable management of freshwater resources and ecosystems [2]. During the last decades, extreme natural events (such as climate change) or direct anthropogenic impacts have severely affected freshwater reservoirs. Water resources are intrinsic to all forms of development (e.g., food security, health promotion, and poverty reduction) by nourishing industry, energy generation, agriculture, and natural ecosystems. However, population growth, urbanization, industrial pollution, and extensive agriculture reduce ecosystem functioning and resilience. The United Nations Educational, Scientific and Cultural Organization (UNESCO) estimates that by 2050, nearly 52% of the world population will be at risk if natural environments and freshwater reservoirs continue being degraded at unsustainable rates [2]. Among these, poor and marginalized populations will be disproportionately affected, further exacerbating inequalities.

Global warming enhances the threat to water availability for human consumption. Because the saturation vapor pressure of water in the air is susceptible to temperature, in a climate change scenario, perturbations in the water cycle are expected at a large scale, causing a decline in precipitation and river runoff [3]. Climate change is likely to produce a strong negative effect on water availability in the arid regions of South America, affecting large areas principally located in Peru, Bolivia, and Chile, with extreme alterations in temperatures, precipitation as well as glacier recession and salinization of coastal aquifers due to sea level rise [4].

1.2. Seawater desalination as an alternative

The overexploitation of natural freshwater sources has increased the demand for non-conventional water uses, such as seawater desalination. Desalination removes salts and minerals from saline water to produce freshwater appropriate for human consumption or other industrial use (i.e., agricultural irrigation and mining). Different water sources suitable for desalination include brackish water, wastewater, and seawater. By 2015, the world-installed desalination capacity was 97,500,000 m³/day, expected to reach 192,000,000 m³/day by 2050 [5].

According to the separation method, desalination technologies can be classified into thermic and membrane technologies [6]. Thermic processes separate salts from water using evaporation and condensation (i.e., multi-stage flash distillation, multiple-effect distillation, and vapor-compression desalination). In contrast, in membrane desalination water, salts are retained and diffuse through a membrane (i.e., reverse osmosis, nanofiltration, and electrodialysis). Choosing between the two technologies is based on a series of parameters, such as water salinity and the required quality/quantity of the product, among other site-specific factors like energy consumption, labor cost, and geographic location.

Much of the world's desalination capacity is installed in Middle East countries, where thermal technology dominates the market mainly due to the low cost of fossil energy. Contrarily, in the rest of the world, with 61% of the global share [7], reverse osmosis (RO) is the most popular desalination technology because it has lower specific energy consumption and environmental footprint. The principle of RO technology relies on applying pressure to reverse the osmosis process. Therefore, the water in the solution travels across a semi-permeable membrane from lower to higher solute concentrations until freshwater is obtained, meeting the specified requirements. Despite the numerous benefits of RO and its widespread use, seawater desalination employing RO is still controversial, mainly because of the management and disposal of its main waste product, known as brine, which contains high levels of saline concentrations and is continuously discharged in large amounts during the desalination process to the near-coast environment.

1.3. Environmental effects of seawater reverse osmosis (SWRO) effluents on marine ecosystems

Historically, the pressing need for new freshwater sources has led to consider marine environmental issues related to desalination as secondary concerns [8]. Nevertheless, many existing studies in the scientific literature suggest that RO brine discharge has a strong potential to impact key ecological and physicochemical attributes of receiving coastal systems [9-12]. The intensity and extent of brine plumes in receiving waters have, so far, much of the attention and is, as the observed effects range widely from a few tens of meters [13, 14] to hundreds of meters [15] or even kilometers in some critical cases [16]. The observed differences are explained by several site-specific factors, among which diffuser design and hydrology of the area are the most important [17]. Nevertheless, in most cases, the plume diffuses fast, and, usually, salinities are not greater than 2 ppt above background salinity within 20 m of the discharge point [17].

Direct brine discharge in coastal systems is the most implemented alternative by SWRO desalination plants [18], which can, in turn, reduce water quality and endanger delicate ecosystems [14]. The concern with this practice is that as brine is denser than the receiving water, it tends to accumulate in the bottom near the outfall, exposing benthic habitats to the effluent discharge. The quantity, quality, and composition of SWRO brine effluent depend heavily on the feed water quality and the chemicals used in pre-treatment processes [5]. The potential damages of rejecting brine to the marine environment include eutrophication, pH fluctuations, DO depletion, and accumulation of heavy metals around discharge outlets [19]. Considering the

abovementioned, brine discharge effects on marine ecosystems are among the highest concerns among desalination project commissioners and stakeholders [20].

Different approaches have been used for the study of brine discharge impacts on marine life, but most of the available literature can be classified into three major categories:

- a) Ecotoxicological bioassays: although marine organisms are adapted to naturally high salinity in their environment, abnormally high concentrations of ions can be toxic [21]. Toxicity tests conducted in the laboratory have been used to study the effect of the discharges of the desalination industry on various aquatic organisms. These studies can take the form of tests with a single species [22] or multiple species [23] based on lethal or sub-lethal responses to brine stress [23, 24]. Toxicologic assays on the Mediterranean phanerogam/seagrass *Posidonia oceanica* showed that a growth reduction and necrotic lesions were observed when exposed to minor salinity variations (39 ppt) [25]. Pillard, Dufresne, Tietge and Evans [21] exposed adults of 3 estuarine species of invertebrates and fishes (*Cyprinodon variegatus*, *Mysidopsis bahia*, and *Menidia menidia*) to different water salinities during 48-hour periods. While *C. variegatus* tolerated salinities of up to 60 ppm, *M. bahia*, and *M. menidia* exhibited mortalities at concentrations around 38-40 ppm. Although these values provide reference threshold security levels, they apply only to those species' ecosystems. They do not help ensure environmental risk studies on osmotic stress to other coastal systems.
- b) Field experiments are relevant since they establish a causal relationship between an effluent (brine) discharge and the observed ecological effect. Despite the importance of this type of study, only three articles on this topic from 64 publications (less than 5%) were identified in a complete bibliographical review by Roberts, Johnston and Knott [17]. One of those experiments is essential since it showed that small salinity changes (1 -2 ppm) can negatively affect marine communities [25]. Field experimentation is challenging, but its information is highly valuable.
- c) Environmental monitoring: several studies have demonstrated that fish communities, sediment infauna, phytoplankton, marine plants, and algae display significant changes in their structure and diversity once exposed to desalination effluents [13, 25-27]. However, this impact can be minimized only in the discharge near-field if the desalination plants are built in areas with strong currents and pipeline designs that consider the use of diffusers [10, 28]. When hypersaline discharges are rejected in closed bays, these can have very long residence times, resulting in the reduction of plankton communities due to several factors, such as osmotic stress, decreased dissolved oxygen levels, hydrogen sulfide production or low pH levels [29]. Brine has high salinity concentrations and reduced DO levels that cause habitat degradation and can cause diversity loss in the area, including algae [25], several species of invertebrates [14, 30], and fish communities [22]. Much of the experimental research on brine exposure has focused on the toxic effects on the seagrass *Posidonia oceanica*, an endemic endangered species in the Mediterranean Sea that constitutes the habitat of many benthic fish and invertebrates [26]. Environmental

response to brine discharge stress is highly site-specific. Thus, research on particular ecosystems cannot be directly extrapolated to other areas. Moreover, its evaluation and monitoring could be even more challenging when desalination effluents are discharged in already impacted systems and become part of multiple cumulative stressors (e.g., industrial, sewage, pulp mill, etc.). For this reason, there is an urgent need to increase our understanding of the local impacts of brine discharge, as it happens in coastal systems of northern Chile, where no information is available so far, and desalination is growing quickly.

1.4. Desalination in Chile

In Chile, a nation highly threatened by climate change, SWRO has proven highly relevant for social and economic sustainability, providing suitable water for communities and industrial needs. Considering its geography, with 6400 km of coastline and an average width of 180 km seawater desalination, it is one of the most accessible water sources in Chile. Water availability in Chile shows high spatial heterogeneity: while in southern regions, there are up to 3 MM m³/person/year available, in the north of the country, such as the Antofagasta region, there are only 52 m³/person/year, much lower the minimum of 2000 m³/person/year suggested by the United Nations for the sustainable development of a country [31]. In these regions of significant water scarcity, seawater desalination is subsidizing the water deficit, concentrating much of the desalination capacity of the country (Figure I-1). With 17 running desalination plants and an installed desalination capacity of ≈700,000 m³/day, Chile is the largest producer of desalinated water in America, and it is expected that for the next ten years, this industry will keep growing up to 300% in desertic regions such as Antofagasta [32]. The main economic sectors of the country that currently operate desalination plants are the mining sector, responsible for 58.9% of the desalination capacity installed in the country, and the sanitation sector, responsible for 39.3% of the national production [33].

Although the desalination industry has proven to be invaluable for the development of the country, local communities and users are very skeptical regarding the industry's environmental externalities, as to date, there is a big gap in terms of scientific research regarding the environmental impacts of SWRO activities, together with a lack of environmental regulations associated to its social and political implications. One example relates to the cause-effects relationship that could produce the massive discharge of brine on the coastal systems of Chile.

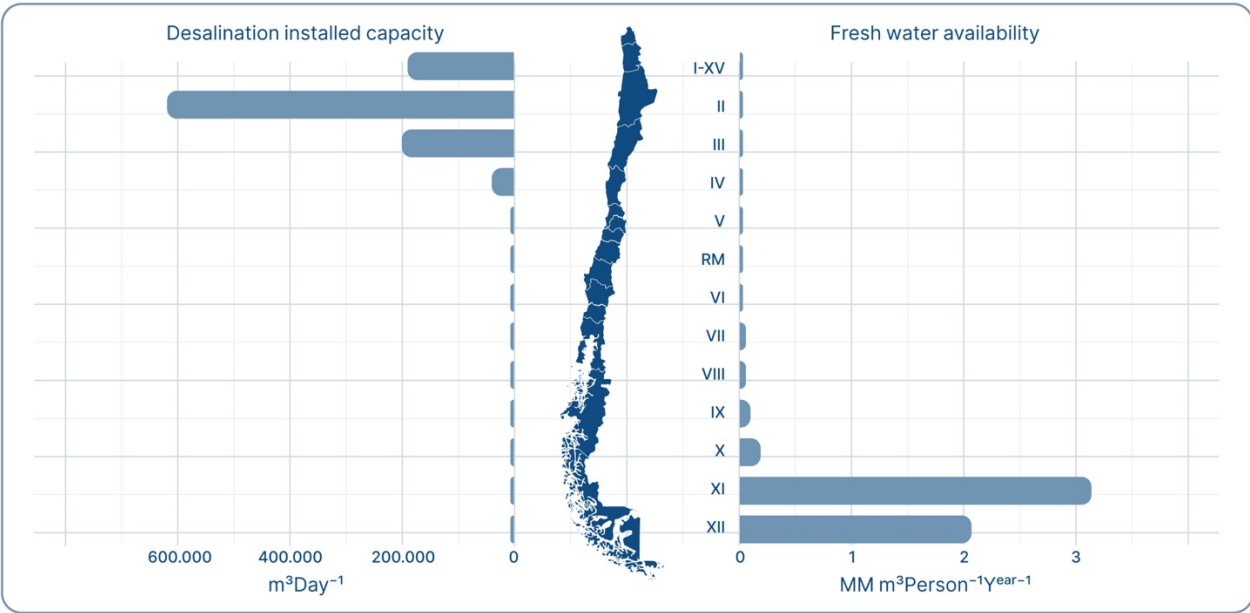


Figure I-1: Water availability versus desalination installed capacity per region in Chile. Source: own elaboration from National Water Strategy.

1.5. Protecting Chilean coastal systems from brine pollution

Even though the international scientific community agrees that brine discharge and osmotic changes may induce alterations in aquatic ecosystems, such as species richness and community structure of benthic environments [9-12, 34], Chilean legislation and normative it is still not updated. The only attempt to establish basic requirements for environmental protection over industrial desalination projects is a guideline from the Chilean Navy [35]. Nevertheless, this document is not binding to the national environmental legislation.

The uncertainty regarding the environmental impacts in coastal systems facing brine discharge from RO desalination plants is based on the absence of a standardized and specific methodology to evaluate its potential effects, representing a barrier to Chile's water sustainability and socioeconomic development. Considering the knowledge gaps, special efforts should be made to minimize impacts with preventive actions such as the proper plant site selection.

Site selection for a desalination plant and its brine discharge system is a critical initial step to avoid irreversible environmental damage [36]. Even though the final decision is most often based on space availability near the coastline and the strategic location of water end-users [37], several site-specific parameters and socioeconomic factors should be considered to minimize the ecological impacts of this industrial activity. The selection process optimizes several different desired objectives, in this case, for implementing a desalination plant and the location of its effluent discharge system. Such a process involves various decision factors, which are frequently

contradicting, and the results often consist of several possible sites, each with advantages and limitations [38]. Therefore, selecting a site for industrial use usually means complex multi-criteria analysis (MCA), which includes a complex array of features involving socioeconomic, technical, environmental, and normative issues that may result in conflicting objectives [38]. For desalination plants, these factors are summarized in the following list by Sepehr, Fatemi, Danehkar and Moradi [39]: a) Environmentally sensitive land and coastal/marine areas, b) Sea water quality (temperature, salinity, primary productivity), c) Slope, d) Bathymetry, e) Place of use, f) City and village area, g) Road Network, h) Electrical Network, i) Access to the beach, j) Infrastructure, k) Aquaculture areas, l) Cultural Heritage, and m) Presence of waste water discharge.

Industrial projects in coastal areas, such as a SWRO desalination plant, must be planned, considering that effluent-receiving coastal ecosystems are susceptible to anthropogenic impacts [20]. Together with a proper and strategic site selection, the planification of the project should be developed under the guidelines of the Environmental Impact Assessment (EIA) framework, which is an international instrument to evaluate possible impacts on the environment with a strong base on scientific research, proposing mitigation measures and management plans to diminish adverse effects on the environment [40]. Ultimately, based on the EIA results, a decision has to be reached that balances a project's societal and environmental impacts versus its benefits [41].

EIA is the most potent instrument for preventing unrecoverable environmental damage among the available management tools in the Chilean environmental legislation. However, available norms and regulations upon which protective measurements can be agreed are still under development for new industrial productive processes such as SWRO plants. As an example of this situation, the Chilean environmental legislation does not consider specific regulations to norm salinity variations due to brine discharge from RO desalination plants (Table I-1). To our knowledge, none of the available regulations of effluent discharge to marine coastal systems explicitly norm osmotic changes induced by the discharge. Industries are confronting essential challenges in their environmental monitoring design, such as the absence of a legislative framework to monitor osmotic changes. One of the main challenges SWRO desalination is facing is the standardization of monitoring methods and consensus about the responses that should be considered in a continuous plant marine ecosystem monitoring program, which could provide valuable information to determine the extent of environmental effects caused by hypersaline brine discharge, but also help to prevent potential irreversible damages.

In Chile, the environmental impact assessment is perceived to fulfil an essential part of environmental protection, sustainable development, and marine species conservation [42]. However, this will not be possible unless we fully understand the weaknesses within the EIA framework to evaluate the impacts of brine discharges in marine environments efficiently and regulation gaps, hence addressing potential new normative requirements for the sustainable development of this industry in the country.

Table I-1: Available environmental legislation in Chile, for the regulation of desalination plants effluent, none of which considers osmotic changes due to brine discharge.

Code	Regulation type	Name	Section	Year	Description
19300	Law	General environmental law		1994	Basic legal framework of all the country's environmental regulations. Regulates and develops the institutions and instruments necessary for the protection of the environment, including the Environmental Impact Assessment System.
18892	Law	General law on fisheries and aquaculture	Art. 136		Punish those who discharge to the sea, rivers, lakes or any other body of water, chemical, biological or physical pollutants that cause damage to the hydrobiological resources, without having previously been neutralized to avoid such damages.
DL 2222	Decree Law	Navigation law	Art. 142	1978	Prohibits the dumping of ballast, debris or rubbish and the spillage of oil or its by-products or residues, mineral tailings or other harmful or dangerous materials of any kind, able to cause damage to waters under national jurisdiction.
DS 95	Supreme decree	Regulation for the Environmental Impact Assessment System		2001	Defines the dispositions governing the Environmental Impact Assessment System, established by the 19300 law.
DS 1	Supreme decree	Regulations for the Control of Aquatic Pollution	Art. 1 & 2	1992	Establishes the regime for prevention and surveillance of pollution in sea, ports, rivers and lakes under national jurisdiction. Also prohibits throwing ballast, debris or rubbish and oil spill or its by-products, mineral tailing waters, that cause or could cause damage to waters under national jurisdiction.
DS 476	Supreme decree	Promulgates agreement on prevention of sea pollution by waste dump and other materials	Art. 3, a) & c)	1977	Prohibits waste dumping or other materials listed (Annex I) and requires a special permit prior waste dumping (Annex II).
DS 90	Supreme decree	Emission standard for the Regulation of contaminants associated to the discharge of liquid waste on marine and continental waters.	Table 5	2001	Establishes the physical and chemical properties that liquid effluents, discharge directly into terrestrial or maritime waters, must meet, with the aim of protecting and preserving the country's water resources

2. PROPOSAL: A MULTIDISCIPLINARY APPROACH TO BRINE DISCHARGE IMPACT MANAGEMENT

Regardless of the relevant amount of literature documenting impacts from desalination effluents discharged elsewhere, the available published information is of little use when trying to evaluate impacts on Chilean coastal systems. Model species for which impacts have been described are far from the ecological structure of marine benthic communities of the Humboldt system, dominant in the Chilean coast. The absence of local species toxicological effects assessment and environmental studies makes it difficult to envision recommendations for efficient environmental monitoring programs and new norms regulating the desalination activity and its effluent discharge. This industry's fast growth and economic projections make it urgent to understand the specific effects of brine discharge and how to regulate this activity based on the magnitude of potential impacts.

On the other hand, the projected SWRO's fast growth requires the development of strategic territorial planning tools, allowing the determination of potential coastal sites susceptible to receiving these impacts. Predicting areas likely to spatially support the development and construction of future desalination plants is vital when implementing mitigating measures and minimizing/anticipating detrimental effects of liquid waste discharge on marine coastal ecosystems. Available territory in the coastline is limited, and while Chile is preparing to lead the desalination markets in the LATAM region, systematic planning processes are often missing and desalination plants are usually established on a project-to-project basis [43]; hence, there is no

certainty regarding the available space for the installation of such industry, nor the capacity to anticipate the unknown cumulative negative effects not only of multiple desalination plants discharge close one to another, but also their interactions with other waste discharge (e.g. industrial, domestics, etc.), all of which could exacerbate the socio-environmental impacts of the industry.

The following proposal aims to analyze brine discharge management in Chilean coastal systems from a multidisciplinary environmental approach by a) studying impacts on local model species through Environmental Risk Assessment methods, reviewing local state-of-the-art knowledge on brine management and impact minimization, and b) modeling potential sites susceptible to desalination development and effluent discharge. In this way, different disciplines from environmental sciences interact to provide new insights into the sustainable management of brine discharge in the Chilean coastal ecosystems and impact minimization (Figure I-2).

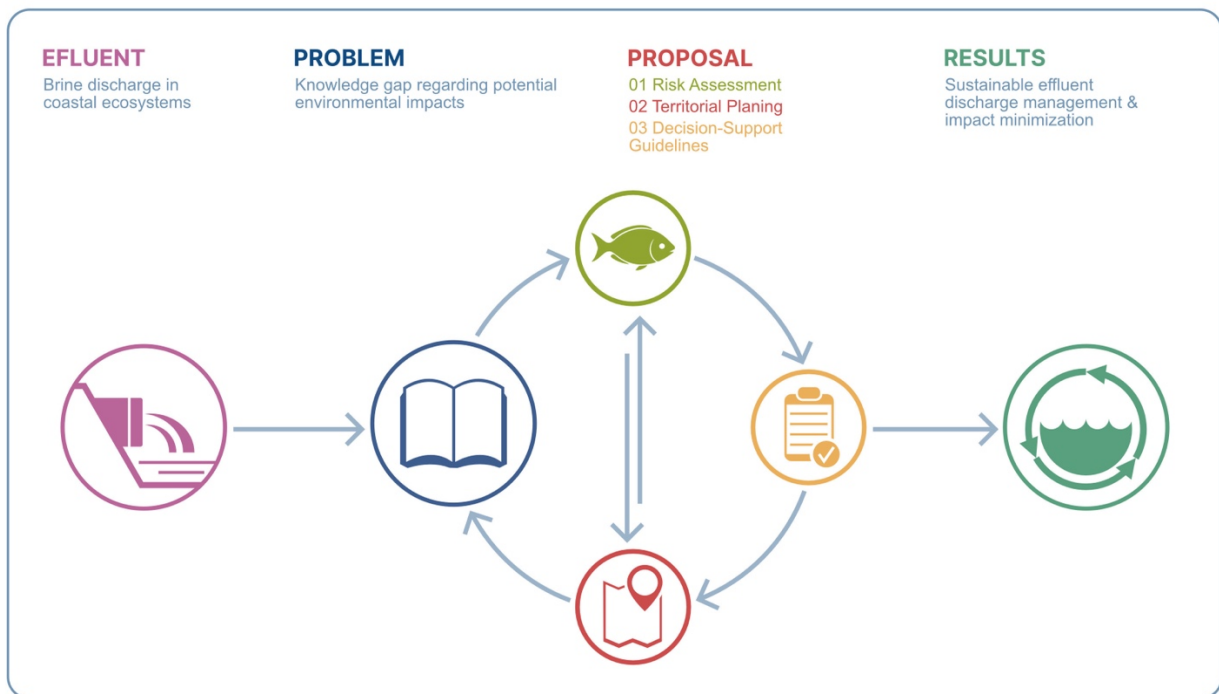


Figure I-2: Conceptual model of the proposed multi-disciplinary approach to brine discharge management on Chilean coastal systems.

3. SCIENTIFIC HYPOTHESIS

- H1: The optimal locations for desalination plants in Chile should be determined using spatial models that incorporate technical, environmental, and social criteria, considering the trade-offs and synergies among these factors.
- H2: The application of ecological risk assessment guidelines enhances the comprehension of the influence area and impacts on coastal ecosystems attributable to brine discharges from seawater desalination.

4. OBJECTIVES

4.1. General objective

- Develop a multi-disciplinary brine discharge management strategy based on Environmental Risk Assessment and territorial governance research toward the conservation of marine coastal ecosystems in Chile under the influence of the seawater desalination industry.

4.2. Specific objectives

- Determine salinity tolerance thresholds through environmental risk assessment guidelines to assess the ecological impacts of desalination brine discharge on benthic communities and key local species.
- Develop and apply a GIS-based multicriteria spatial analysis model to identify optimal locations for desalination plants in Chile, minimizing potential brine discharge impacts on coastal ecosystems while considering other relevant factors.

5. EXPECTED RESULTS

- Development of Environmental Risk Assessment guidelines specific to brine discharge in Chilean coastal waters, encompassing hazard identification, exposure assessment, and ecological risk characterization.
- Determination of salinity-based water quality thresholds for brine discharge, derived from a comprehensive ERA and considering the sensitivity of local benthic communities.
- Generate a spatially explicit decision-support tool for desalination planning in Chile, mapping areas of high ecological sensitivity and guiding the selection of plant locations to minimize environmental risks.

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II. Chapter: Defining priority areas for the sustainable development of the desalination industry in Chile: a GIS multi-criteria analysis approach

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Hypothesis 1: The optimal locations for desalination plants in Chile should be determined using spatial models that incorporate technical, environmental, and social criteria, considering the trade-offs and synergies among these factors.

1. ABSTRACT

The climate crisis is rapidly provoking water scarcity in several areas of the planet, where an exponential growth of the seawater desalination industry is expected. In this context, multiple efforts are currently under development to reduce potential impacts and promote the sustainability of this industry. The selection of a suitable site for a desalination plant is critical to ensure operational continuity and the environmental sustainability of its processes, optimizing the plant's productive performance and thus safeguarding water security for final users. In this study, we apply a GIS-based Multi-Criteria Analysis (GIS-MCA) approach to explore and assess potential areas suitable for the construction and operation of desalination plants in Chile. Different environmental, social, and technical criteria were evaluated and weighted by expert criteria using the Analytic Hierarchy Process (AHP) methodology. From a total of 114,450 km² analyzed, only 4.54% of the territory was classified as highly suitable, demonstrating the scarcity of space available to meet the growth expectations for the industry. These results suggest that GIS-based analysis provides a practical solution to determine suitable areas for developing desalination plants, highlighting the need to define priority areas for the sustainable development of the desalination industry in Chile with the required capacity to reach the national water security goals for the following decades.

2. KEYWORDS

AHP; plant location; reverse osmosis; seawater; site suitability.

3. INTRODUCTION

The climate crisis has provoked drastic changes in weather patterns, and the resulting scarcity of water is one of the most complex challenges facing humankind. As an alternative, seawater (SW) desalination and water reuse technologies have become the most feasible solutions to mitigate this issue [1]. According to the International Desalination Association, worldwide, more than 18,000 desalination plants produce around 80 million cubic meters of fresh water daily, and it is expected that global desalination capacity will increase almost two-fold by 2050 [2].

Site selection is crucial when planning for a SW desalination plant, requiring an adequate surface area, topography, and geological features that allow the appropriate construction and operation of critical infrastructures, such as marine structures and inland facilities [3,4]. In addition, supply access and interconnections to the power grid and freshwater network should be economically and technically viable. Proximity to highways and roads is also taken into account, although not considered a bottleneck factor. Furthermore, potential environmental, social, and economic impacts are relevant to ensure community acceptance and minimize risks during early stage project development [3]. Thus, defining specific criteria and stakeholders' requirements should be established to guarantee the optimal planification of the SW desalination plant settlement.

Different site-selection approaches are available, where some methods may be more desirable for a particular project to highlight facility-specific considerations or technical judgment from a multidisciplinary team [5]. To date, different site-selection methods have been described, such as TOPSIS [6], Fuzzy [7], Delphi [8], and analytical hierarchy process (AHP) [9]. These models can be strengthened by the use of geographic information systems (GIS) that allow a spatial projection of the territory based on the available public information [10,11]. In 2017, Sepehr, Fatemi, Danehkar, and Moradi [8] proposed 63 locations suitable for installing desalination plants on the coastal areas of the Persian Gulf and Oman Sea, based on an integrated Delphi-GIS model, highlighting that environmentally sensitive areas and SW quality were the most important criterion. Criteria for selecting suitable sites for desalination units construction in South Iran comprised environmental protection area, topography, atmospheric information, oceanography, energy supply, national gas transmission lines, and communication lines, amongst others [12]. Conversely, a multi-criteria analysis (MCA) tool coupled with GIS can be used to create interactive maps highlighting specific areas idoneous for a desalination plant construction [13]. Indeed, the integration of these two approaches has been increasingly applied in order to cope with several environmental and urban assessment problems, where MCA has proved to be a useful decision-support tool by combining diverse factors to produce a practical evaluation index [4,14,15]. For instance, a GIS-MCA method was employed to plan and manage the existing and proposed brackish-water desalination plants in the Gaza Strip [16]. The study revealed that 65% of this area was unsuitable for the construction of desalination plants, and that 53% of the already operating plants showed potential risks to the environment [16]. However,

there is still a lack of knowledge of what type of approach and methodology might be the most convenient combination involved in the development and prioritization of factors and/or restrictions to choose appropriate areas to build SW desalination plants.

In Chile, the ongoing megadrought event that has extended between 2010 and 2021 has become an impediment to economic growth for the arid and semi-arid regions [17]. To address this challenge, desalination plants have been proposed as one of the most reliable solutions [18]. According to the Chilean Ministry of Public Works, there are 24 SW desalination plants currently operating and 22 under construction/planning stages mainly in coastal zones in central and northern Chile. North Chile has a vast coastline extending across more than 2000 km. It is characterized by the presence of coastal mountains that rise close to the shoreline with steep cliffs, where only few beaches and natural harbors exist [19]. Moreover, the Atacama desert (>100,000 km²) covers most of the north's territory of Chile and has been rapidly advancing to the central zone of the country at an estimated rate of 0.4 km per year [20]. Therefore, the impending scenario points to the imminent propagation of the desalination industry to alleviate the water crisis situation in Chile.

In this study, we use the analytical and predictive advantages provided by GIS-MCA to assess the multifactorial suitability of potential sites and select priority areas for the construction of desalination plants between the regions of Arica and Parinacota, and the Metropolitan Region of Chile. Multi-criteria spatial evaluation and decision tools, such as hierarchical process analysis (AHP) approaches, are combined as a guide for planning desalination plants settlements. The results suggest that GIS-based analysis provides a cost-efficient solution to determine suitable areas for developing desalination plants, promoting desalination as a feasible solution to the national and global water security challenges.

4. MATERIALS AND METHODS

4.1. Study site features: Chilean Far and Near North, and Central zones

The study site comprised the Arica and Parinacota (362962 E, 7956813 S) to the Metropolitan regions (346816 E, 6296840 S) of continental Chile, corresponding to the Chilean Far- and Near-North zones, together with part of the Central zone of the country. This represents a total surface area of 332,825 km², representing 39.5% of the total national territory, with an estimated associated population of 11,136,000 inhabitants. The Far North is an extremely arid zone containing the Atacama Desert, where most of the population lives in the coastal area. The landscape is characterized by crisscrossing hills and mountains composed of several types of minerals. The coastline is mainly dominated by coastal cliff with elevations over 1000 m. Average annual temperatures oscillate between 14 and 20.5 °C, with almost no precipitation events, except for some areas nearby the Andes mountains [21]. The Near North is a semi-arid region with an annual average precipitation of 25 mm subjected to drought events and mean temperatures between 12 and 18.5 °C. Coastal elevations are often broken by river valleys, and microclimatic conditions appear due to maritime fogs, which can penetrate inland. The Central zone possesses

a Mediterranean-type climate with a progressive increment in precipitation events, and annual temperatures between 7.5 and 19.5 °C. This zone is the most densely inhabited part of Chile, which includes the country capital Santiago and Valparaiso region with more than 8 million people. Topography includes the coastal range mountains that form the central valleys and several coastal plains sometimes interrupted by the coastal cliff [22].

4.2. Establishment of selection criteria

In order to define the variables to be used in the multi-criteria analysis, two types of criteria were considered: factors, that is, criteria that improve the suitability of a specific alternative for the activity under consideration, and constraints that refer to spatial limitations that, for this study, restrict the distribution area of the desalination industry in Chile [23]. Based on this, six factors were established: altitude, distance to the coastline, land slope grade, distance to populated settlements, distance to power supply lines, and distance to the road network. In contrast, four constraints were established: conservation areas with a buffer area of 3000 m, indigenous communities with a buffer area of 1000 m, altitude, and land slope grade [3,24]. The last two have mixed features; that is, under a certain numerical range they are recognized as a factor and in another numerical range they behave as constrains. Thus, altitudes above 1500 m.a.s.l. and slopes above 15° were considered as constrains. Considering these restrictions is expected to minimize the effect of installing desalination plants near wild protected areas involving natural monuments, national parks, and reserves, established by Supreme Decree No. 531/67 of the Chilean law.

4.3. Systematization of geographical information

Factor definition used for the construction of spatial suitability models was conducted based on available information at the Chilean Environmental Impact Assessment Service (SEIA, <https://www.sea.gob.cl/>, accessed on 10 May 2021) and the Registry of Desalination Plants and Seawater Pumping Systems 2017/18. Both operating and planned projects were georeferenced in WGS 1984, UTM zone 19S coordinates. Additionally, spatial data were obtained from the Chilean Natural Resources Information Center (<https://www.ciren.cl/>, accessed on 10 May 2021), the National Energy Commission (<https://www.cne.cl>, accessed on 10 May 2021), the Chilean National Corporation for Indigenous Development (<https://siic.conadi.cl/>, accessed on 10 May 2021), the Chilean Meteorological Directorate (<http://geonode.meteochile.gob.cl/>, accessed on 10 May 2021), Chilean Spatial Data Infrastructure (<https://www.ide.cl>, accessed on 10 May 2021), and the Chilean Register of Protected Areas (<http://areasprotegidas.mma.gob.cl/>, accessed on 10 May 2021) (Table II-1).

Table II-1: Spatial data sources.

Geospatial Data	Source	Year
Wild Areas Protected by the State	Register of Protected Areas, Chilean Environmental Minister	2021
Populated areas	Chilean Meteorological Directorate	2016
Indigenous communities	National Corporation for Indigenous Development	2017
Administrative Political Division	Geospatial Data Infrastructure	2019
Coastline	Geospatial Data Infrastructure	2020
Power supply grid	National Energy Commission	2016
Alos Palsar Digital Elevation Model	Natural Resources Information Center	2019
Road network	Geospatial Data Infrastructure	2019

4.4. Multi-criteria factor weight analysis survey

To assess the preference between factor-type criteria, the methodology of Analytical Hierarchical Processes (AHP) was applied [24]. For this purpose, an analysis of hierarchies between variables using a square matrix, which compares the alternatives on a scale of 1 to 5, was performed to define relative priority, both one over another or equal priority [25]. Based on the AHP guidelines, a survey was constructed and sent to 22 international experts in the field of desalination. The survey was made up of three sections and consisted of a total of 22 multiple-choice questions, that aimed to answer the following inquiries: what was the relationship between the surveyed and the desalination industry (1 question), which factors were considered relevant or not in the multicriteria analysis (6 questions), and what factors had greater weight when compared to each other (15 questions). To determine the relationship of the surveyed experts with the industry and factor relevance, frequency was used as a description measure. On the other hand, to determine the weight of the factors when comparing them among themselves, the mode was applied as a central trend parameter. In cases where bi-modalities were obtained, the core research group in charge of the surveys decided how to proceed with these specific cases [24].

To measure the degree of consistency of the opinions and decisions made by the group of experts, quantitative indexes were used [24, 25]. In this study we measure the consistency index (CI), the random index (RI) and the consistency ratio (CR). The degree of consistency obtained will depend on whether the information collected through the AHP methodology is reliable or the survey process must be repeated.

The first index to be measured is the consistency index (CI), which is understood as the measurement of consistency produced when comparing between pairs and is expressed as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Where λ_{max} is the largest eigenvalue and n is the number of criteria. The random index (RI) can be calculated mathematically as the average CI of the largest sample from randomly generated comparison matrices [25]. It is expressed through the following expression:

$$RI = \frac{1.98 (n - 2)}{n}$$

Finally, the consistency ratio is established as the ratio between the consistency index and the random index [24], as follows:

$$CR = \frac{CI}{RI}$$

Consistency ratio assessments greater than 0.10 were considered inconsistent. Conversely, valuations less or equal to 0.10 were considered to have a reasonable level of consistency.

4.5. Implementation of the multi-criteria assessment

A proximity analysis was performed using ArcMap 10.3 to determine the linear distance that exist between each desalination project towards the different study factors. Once the distances between the projects and the factors were obtained, these distances were categorized into five groups, which referred to the potential use of the land for the installation of desalination plants (Table 2). Since all vector spatial data presented differences in scale, the layers were rasterized using an Euclidean distance tool and considering the categories mentioned in Table II-2 with a spatial resolution of 100 × 100 m (equivalent to 1 hectare). Constraints were rasterized to the same spatial resolution as factors (100 × 100 m). However, unlike the factors, constraints have pixel values equal to 0 and 1. The value 0 refers to areas that are not susceptible to the development of the desalination industry, because they present limitations in terms of the presence of conservation areas, indigenous communities, high slopes and altitudes above 1500 m.a.s.l., while value 1 represents territory that could potentially be used for the desalination industry.

Table II-2: Factors categorization based on potential use.

Suitability	Pixel value	Decile
Very high	1	10
High	2	25
Medium	3	50
Low	4	75
Very low	5	>75

Multi-criteria evaluation of raster images was combined with the weighted linear combination method (WLC) through a raster overlay operation in GIS [27], assuming that all overlaid layers have a standard scale. The WLC analysis considers the weighted sum of the factors from surveys and the AHP analysis, plus the product from restriction criteria integrated into the mathematical formula as follows:

$$S = \sum_{i=1}^n (F_i W_i) \prod_{k=1}^n (C_k)$$

Where S is suitability, F_i corresponds to factors, W_i is the normalized weight, and C_k to restrictors. The resulting raster image, covered pixel values from 6 to 30, were re-classified into 5 homogeneous categories, which presented the definitive potential areas for the desalination industry settlements. In order to have a better visualization of the cartographic areas, the speckled effect was eliminated, through the ArcMap tool “focused statistics”, to obtain equal neighborhood weighting range to nine pixels.

5. RESULTS

5.1. Selected Factors and Constraints

The considered social, technical, and environmental variables were chosen on the basis of a literature review and expert judgement [3,23,24]. These criteria were selected to find areas that allow the construction and operation of desalination plants with the lowest technical cost and environmental impact. Thus, the following factors were used to evaluate spatial feasibility models: altitude, distance to the coastline, land slope grade, distance to populated settlements, distance to power supply lines, and distance to the road network (Table 3). Based on expert criteria and observed desalination project’s location, optimal distance ranges were configured for each factor, which allowed categorizing the spatial feasibility of a desalination plant being built and operated under those conditions. Subsequently, raster maps were built to visualize the spatial distribution of each selected parameter (Figure II-1). On the other hand, constraints were defined based on

published research [3,23,24], considering natural conservation areas (buffer area = 3000 m), indigenous communities (buffer area = 1000 m), altitude (above 1500 m.a.s.l.), and land slope (above 15°). Thus, of a total of 332,825 km², encompassing the whole study site, the application of restrictor parameters reduced the area to a total of ~114,450 km² (Figure II-2).

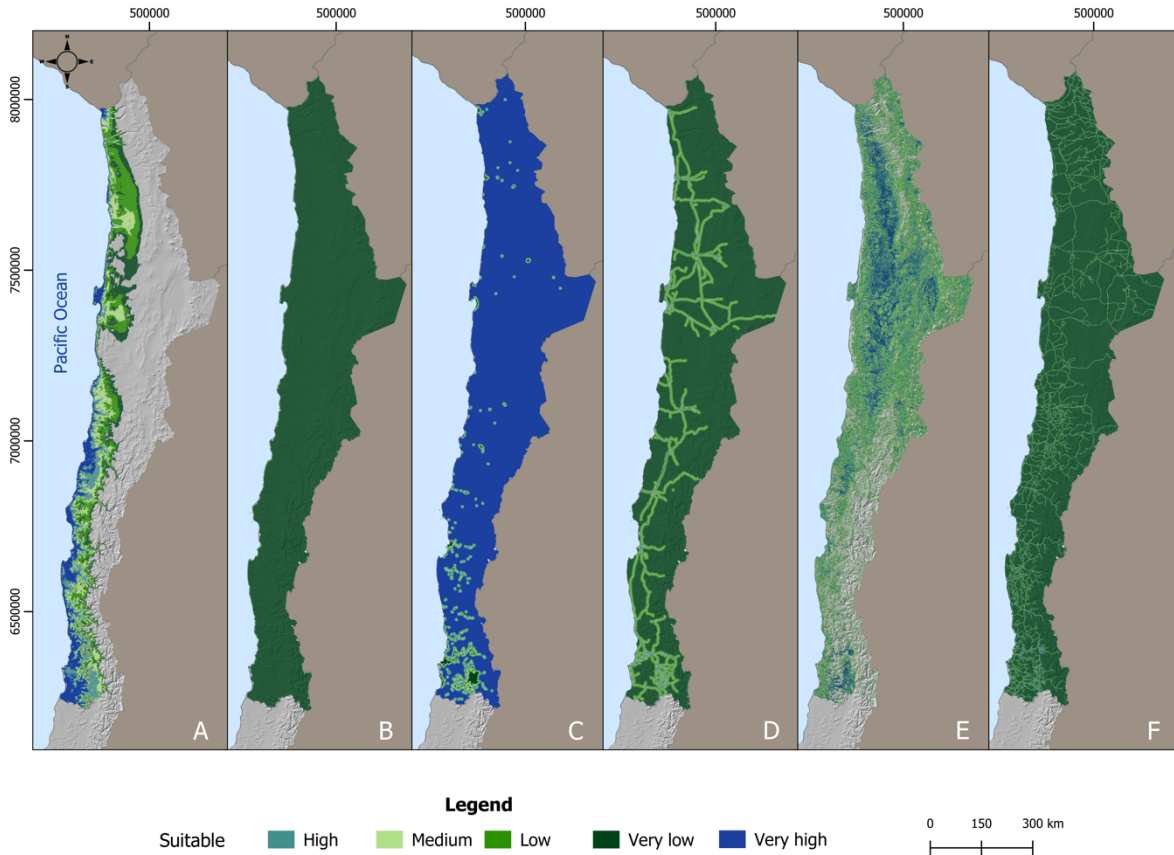


Figure II-1: Factors' spatial distributions in northern Chile. Altitude (A), coastline (B), populated settlements (C), power supply grid (D), land slope (E), and road network (F). Colors represent suitability for the installation of desalination plants according to the selected criteria.

5.2. Survey Application with a Multi-Criteria Approach

A survey to estimate the weights of each factor was conducted of a total of 22 desalination industry experts, including engineering, operation, and maintenance services; academia/research and development professionals; environmental science professionals; and state agencies (Figure 3A). Survey results consisted of ranked criteria based on the significance and severity impacts of each factor, where frequency and the mode were used as measures of dispersion and central tendency, respectively, to determine the relationship of the respondents with the relative weight of the factors (Figure 3B). In the case of bimodalities (e.g., altitude vs. distance to populated

settlements), values were decided through a sensitivity analysis according to the Saaty scale [25], testing values by comparison between pairs and deciding on those generating more reliable consistency indices ($w \leq 0.10$). Table 4 shows the preferred factors governing site suitability by the surveyed experts and their normalized weights. Preferred factors correspond to distance to the coastline ($w = 0.351$), followed by altitude ($w = 0.289$). These factors will have a greater incidence when identifying high-suitability emplacement areas, compared to lower normalized weight factors, such as populated settlements ($w = 0.057$) and distance to the road network ($w = 0.061$) (Table 4). When comparing the responses from surveyed experts according to their related job in the desalination industry, there was no preference bias in the weighted criteria. Furthermore, consistency was tested by employing an AHP matrix, where the consistency index was $CI = 0.08$ and the random index $RI = 1.24$. Hence, consistency ratio equals $CR = 0.064$, reflecting coherence between the analyzed data.

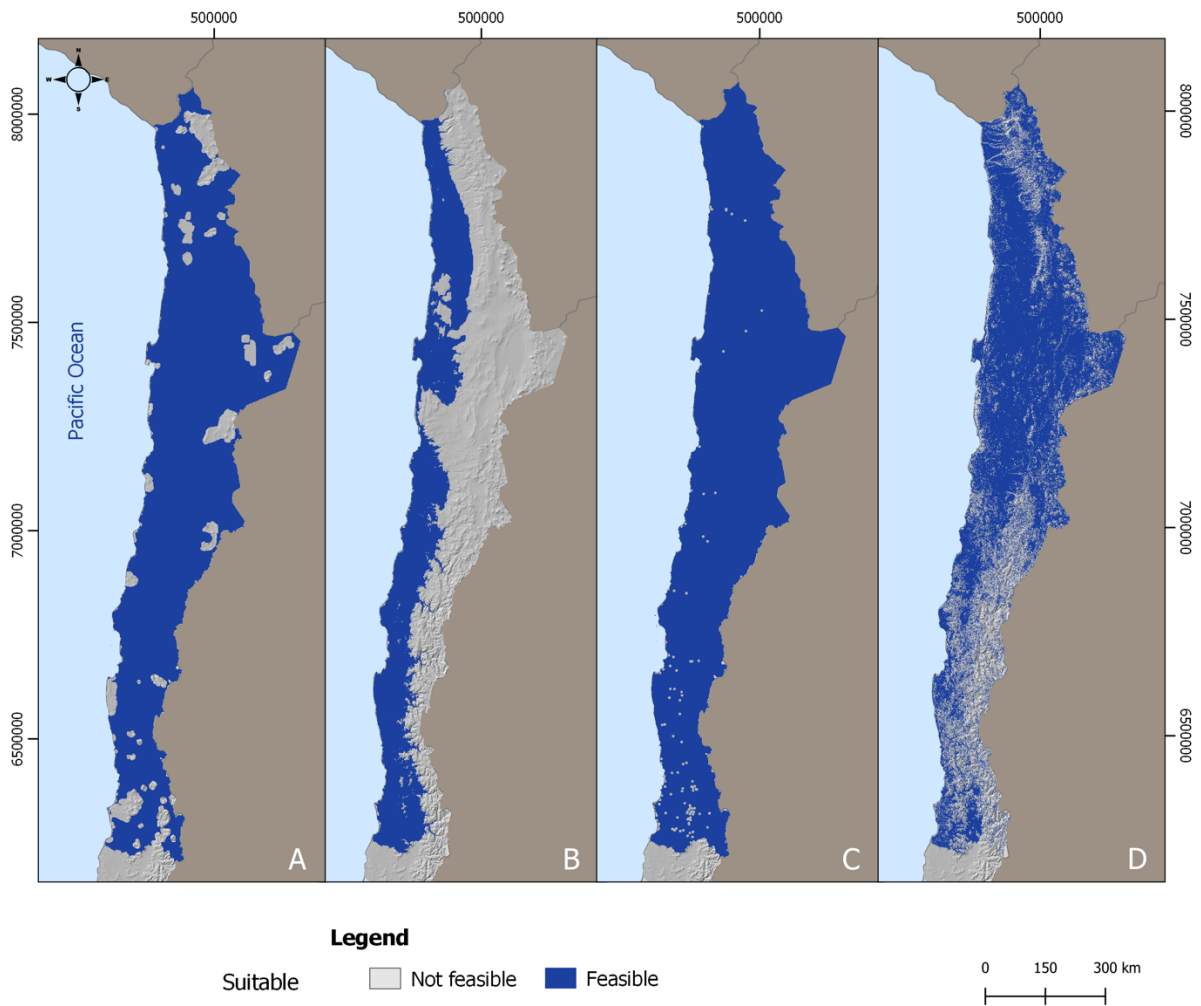


Figure II-2: Spatial constraints distribution in northern Chile. Conservation areas (A), altitude (B), indigenous communities (C), and land slope (D). Blue zones represent potential areas in which desalination plant construction is feasible.

Table II-3: Defined distances between positive factors and desalination project feasibility.

Feasibility	Factors					
	Altitude (m.a.s.l.)	Populated settlements (m)	Coastline (m)	Power supply grid (m)	Land slope (°)	Road network (m)
Very high	≤ 300	> 5,000	≤ 100	≤ 200	≤ 3	≤ 100
High	600	5,000	200	500	5	200
Medium	900	2,000	300	1,500	8	400
Low	1,200	400	800	5,000	12	900
Very low	1,500	≤ 100	> 2,500	> 5,000	15	> 900

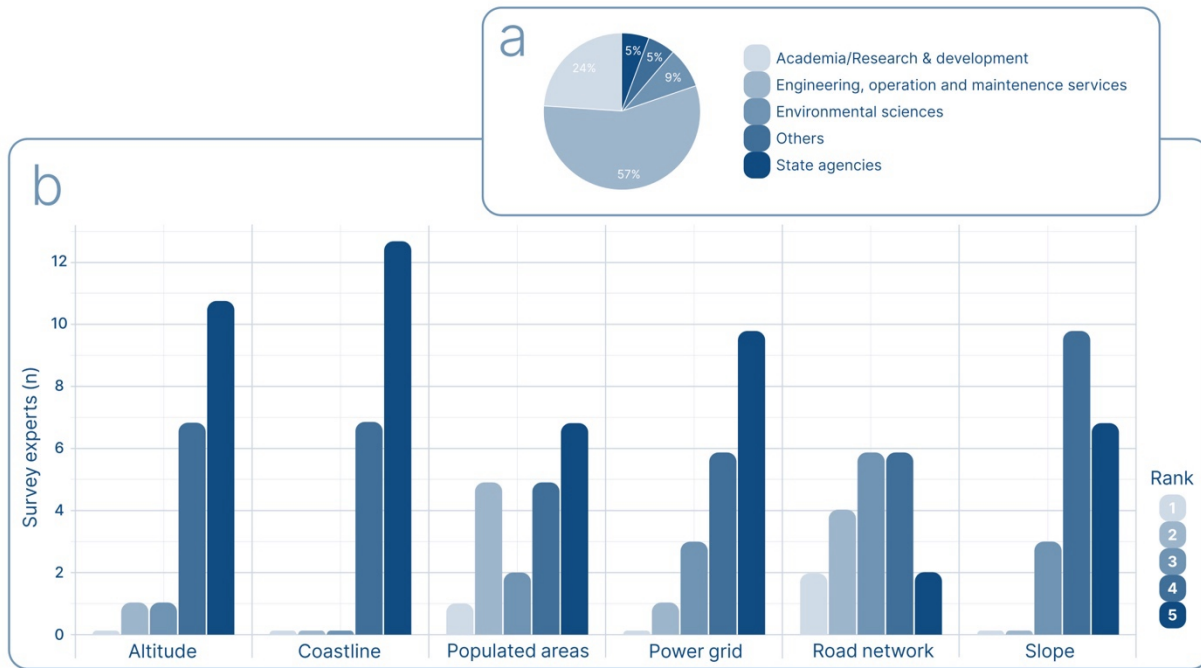


Figure II-3: Survey features with a multi-criteria approach. (A) Pie chart showing the relative number and the field of the different professionals surveyed. (B) Assessment of the evaluated factors.

Table II-4: Factor's weight determination through Analytic Hierarchy Process

Criteria	Altitude	Populated areas	Coastline	Power supply	Road network	Slope	W
Altitude	1	5	1	2	5	4	0,289
Populated areas	1/5	1	1/5	1/2	1/2	1	0,057
Coastline	1	5	1	4	5	6	0,351
Power supply	1/2	2	¼	1	5	5	0,176
Road network	1/5	2	1/5	1/5	1	1/2	0,061
Slope	1/4	1	1/6	1/5	2	1	0,065

5.3. GIS-MCA Site Suitability Model

The normalized weight multi-criteria model shows a clear definition of the areas with the most significant potential versus those with the least susceptibility to installing desalination plants. The distribution map generated shows that potential areas for the industry are present in all the regions under study (Figure II-4). As expected, those areas with the most significant installation potential are mainly associated with the distance to the coastline. Therefore, the sectors with the most significant potential for installation are the coastline around the Mejillones Bay in the Antofagasta region (II), between Copiapó and Vallenar in the Atacama region (III), and the southern coastal edge of the Valparaíso region (V) towards the Metropolitan region (Figure II-4).

Potential areas in km² calculated in regard to their suitability for the desalination industry are shown in Table 5. The total area with “very high” and “very low” suitability ranking are 5195 km² (4.54%) and 35,277 km² (30.84%) for the whole northern Chilean territory, respectively. The regions of Coquimbo (IV), Antofagasta (II), and Atacama (III) were highlighted as those with the most suitable areas (“very high” rank) for desalination plant settlements accounting for 1241 km² (1.08%), 1053 km² (0.92%), and 1039 km² (0.91%), respectively.

The GIS-MCA model can also be used at higher resolution scales, such as bay or communal levels. For example, Figure 5A shows the Mejillones bay in the Antofagasta region (II), one of the hotspots of the desalination industry in Chile. The spatial model presented is consistent with the layout of the desalination plants both online and projected, these being located significantly in areas of very high suitability. At the regional level, the suitability model shows us the spatial planning challenges that interregional projects may encounter, such as what happens with the supply of desalinated water for the Metropolitan region, which must cross the Valparaíso region to reach the coastline (Figure II-5B).

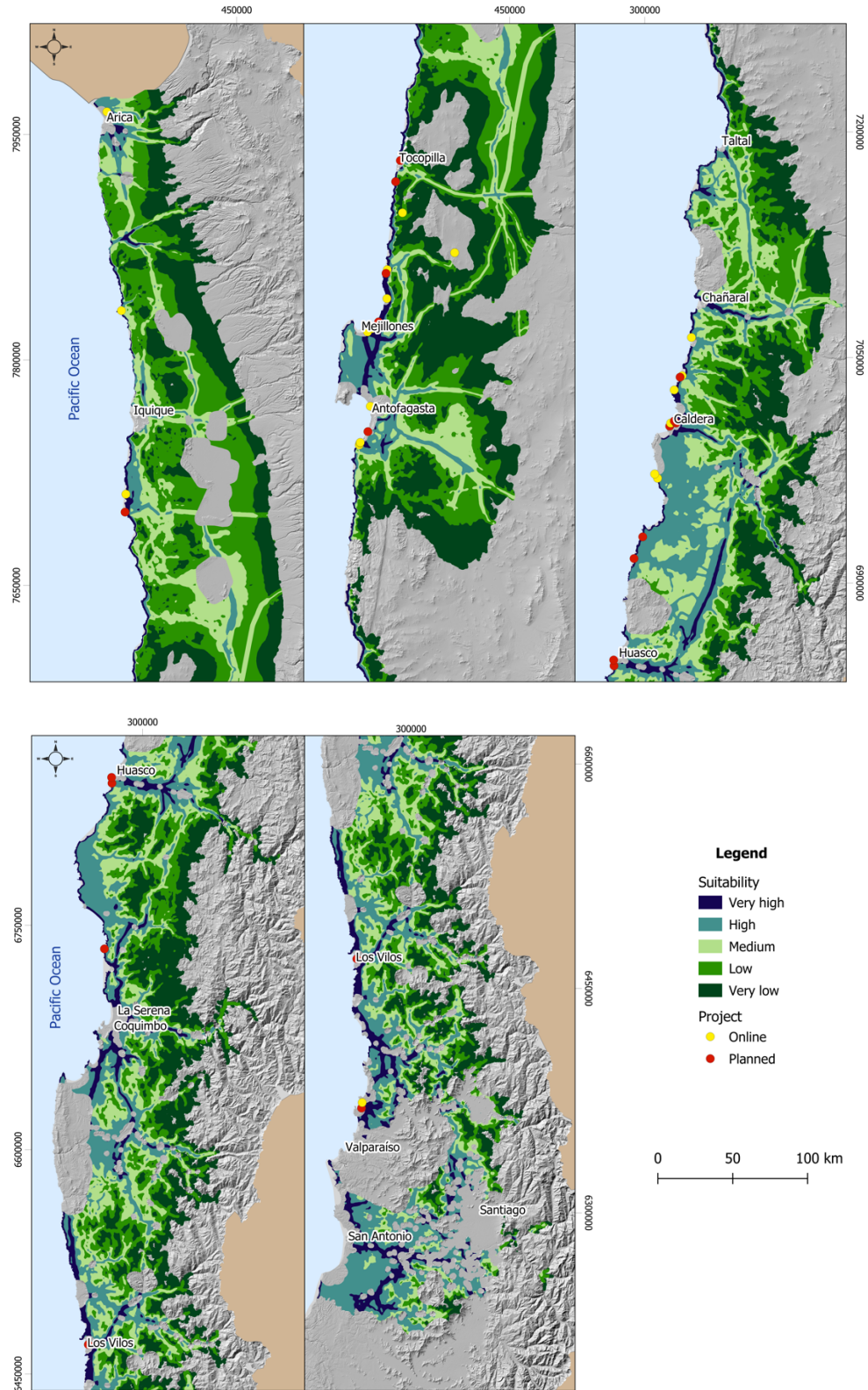


Figure II-4: GIS-MCA map of northern Chile showing potential areas suitable for the installation of desalination plants, and the current operative or planned desalination plants projects in the same territory.

Table II-5: Potential areas suitable for desalination plants installation by region.

Region	N°	Area										Total	
		Very High		High		Medium		Low		Very Low			
		km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Arica y Parinacota	XV	110	0.10	523	0.46	894	0.78	1357	1.19	1271	1.11	4155	3.63
Tarapacá	I	297	0.26	877	0.77	3686	3.22	7782	6.80	4606	4.02	17,247	15.07
Antofagasta	II	1053	0.92	2301	2.01	5206	4.55	9325	8.15	14,485	12.66	32,368	28.27
Atacama	III	1039	0.91	6373	5.57	7524	6.57	717	6.27	7081	6.19	29,187	25.50
Coquimbo	IV	1241	1.08	3796	3.32	4377	3.82	4711	4.12	5972	5.22	20,099	17.56
Valparaíso	V	800	0.70	2138	1.87	1144	1.00	992	0.87	1366	1.19	6439	5.63
Metropolitana	RM	656	0.57	2168	1.89	1012	0.88	610	0.53	515	0.45	4959	4.34
Total		5195	4.54	18,174	15.88	23,842	20.83	31,947	27.91	35,277	30.84	114,452	100

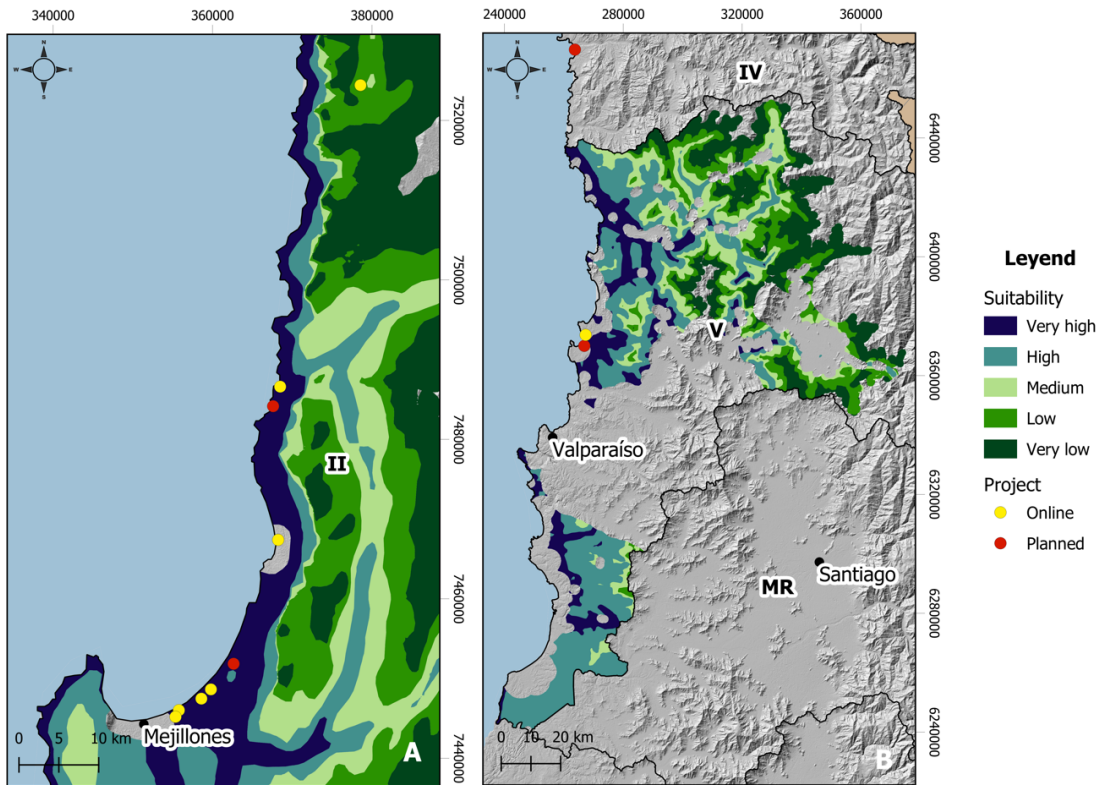


Figure II-5: (A) Suitability map for the Mejillones bay, a hotspot for the desalination industry in northern Chile (II = Antofagasta region). (B) Suitability map for the desalination industry in the Valparaíso region (IV = Coquimbo region; V = Valparaíso region; MR = Metropolitana region).

6. DISCUSSION

Site selection is a fundamental process for constructing and operating a desalination plant, ensuring its environmental and operational sustainability [3]. The process of selecting a site for a desalination plant usually involves a complex analysis, including a complex array of features involving socio-economic, technical, and environmental criteria, which must meet strict standards to secure technical and economic viability, minimizing risks in early-stage investment and project development [15,23]. The present study successfully implemented an AHP GIS model as a multi-criteria decision tool to evaluate and define the territorial capacity of the north-central region of the country to sustain the development of desalination projects.

Within the different selected factors, the weighted expert criterion using the AHP method indicates that the most essential criteria is proximity to the coastline, which is fundamental to avoiding the increase in costs from raw seawater supply transport, as well as a better brine final disposition directly to the marine environment employing subtidal diffusers with low environmental impact [12]. Secondly, the most crucial valued factor was site altitude. Operational costs and energy consumption associated with pumping water, either for processing or consumption for end-users, are critical for a plant operating expense (OPEX), so minimizing distribution in height is essential for the project's economic feasibility [28].

Local communities play an essential role in the feasibility of early stage desalination projects, where public perception is a fundamental factor for the operational sustainability and water security of the population depending on this water supply. In a perception study conducted on the California coast, evidence showed that the main factors impacting the negative perception of this industry were potential environmental impacts [29]. Therefore, our model was executed based on protecting all environmentally sensitive and preservation areas present in the study area, considering spatial exclusion buffers that ensure that these areas are not considered potential industrial development zones. Projects have to be extremely careful with the environment in order to not only ensure the operational continuity of its processes, but also to take care of the delicate balance regarding public opinion [30].

From a total of 114,452 km² analyzed, the GIS-MCA results show the critical situation regarding the availability of space for the development of the industry, where only 4.54% of the territory, equivalent to 5195 km², was classified as highly suitable and tended to be distributed mainly along the coastline. On the contrary, more than 60% of the territory under study has a low or very low suitability classification, distributed through the east of the country with steep slopes due to the Andes mountains range that dominates the landscape. These results are consistent with results from a recent study in the Gaza Strip, where the MCA models showed that only 2% of the territory was highly suitable for developing desalination plants, compared to 57% of the whole Gaza strip where conditions were unsuitable [16]. This situation is aggravated from a regional perspective, where no region significantly exceeds 1% territorial availability with a very high suitability classification, which is relevant considering that government's water security strategy is based on demand and growth models on a regional scale.

The presence of high-suitability areas distributed in the central valley of the country, even though they are considerably distant from the coast, are valuable for the desalination industry considering that metal mining and agriculture are intensively developed in this region, with both activities driving in water consumption and also being essential for the country's economy. Furthermore, the severe water crisis that Chile is going through is forcing these industries to explore new water sources, such as seawater desalination. For the last two decades, the Chilean copper mining industry has been developing desalination projects, representing more than 70% of the installed desalination capacity in the country, and by the year 2030, it is estimated that seawater will represent 93% of the water used in its production processes [31,32].

The ongoing southwards expansion of the Atacama Desert is exerting intense water pressure on agricultural production in the central zone of the country, where export crops essential for national food security and economy are developed [33]. As a result, agricultural activity, whose irrigation demands are responsible for 75% of water consumption in Chile, is being forced to assess new water sources, such as seawater desalination. Due to the higher costs that this entails, the sustainable supply of crops with desalinated water will face substantial challenges, not only in terms of implementing more complex technical irrigation systems, but also in finding models for the exploitation of desalinated water with multipurpose plants, which will make it possible to face the costs of producing desalinated water among a diverse network of end-users [34].

The mega-drought that the country is experiencing intensely affects the central zone, where the regions of Valparaíso and Metropolitana (main administrative centers of Chile) are the most affected [35]. The capital Santiago de Chile (RM) is the country's leading urban center with 6.2 million inhabitants and faces this year, for the first time in its history, a water rationing program due to the decrease in its water reservoirs [36]. Seawater desalination is a possible solution to the water crisis; however, as it is a Mediterranean region, it must cross the Valparaíso region to access seawater. Our results reveal significant challenges in conducting this type of infrastructure operation, as a high percentage of the Valparaíso region is represented by ecological preservation zones and coastal settlements, with considerable difficulties to build desalination plants and their distribution aqueducts, this without considering that the region has its own water security challenges.

7. CONCLUSIONS

This study is the first to address the need to identify the space available for the growth of the desalination industry, driven by the demand projections imposed by the current water crisis in Chile. The methodological approach used at a national, regional, or bay resolution level proved to be effective in providing a reasonable logical framework to support decision-making processes regarding the identification of appropriate sites for the installation of desalination plants. From a series of AHP-paired comparison matrices, it was possible to obtain a standardization of criterion scores and various multi-criteria suitability maps capable of integrating environmental, socio-economic, and technical variables, as a tool for the territorial feasibility analysis of the desalination industry in areas of the country with the greatest hydric stress.

Future studies should consider new socio-environmental variables, including coastal water quality, frequency of red tide events, tsunami risk areas, and economic models. Their inclusion will allow the elaboration of multi-criteria restriction maps at a higher spatial resolution, capable of describing in more detail the diversity of environments and territorial challenges faced by the desalination industry in Chile. This study does not replace the need to conduct baseline in situ evaluations to assess potential environmental impacts or the presence of human settlements that may have been left out of the analysis at the scale presented.

Chile has ambitious growth projections for the desalination industry, on which it is basing a large part of its water security strategy. However, this is not consistent with the results obtained in this study, showing a low availability of space on the coast for the development of desalination plants capable of meeting this demand. This situation can lead to increased competition processes for the use of the coastline and, eventually, the construction of plants one near the other could potentially exacerbate the processes of environmental degradation or negative social perception of an industry that today plays a key role in the water sustainability of an entire country. The results of this study highlight the need to evaluate spatial models for the definition of priority areas for the desalination industry in Chile, which allow safeguarding sufficient space on the coastline for the operation of plants with the desalination capacity required to reach the national water security goals for the next decades.

8. FUNDING

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9. INSTITUTIONAL REVIEW BOARD STATEMENT

The participation of an Institutional Review Board approval was not required for this research. The opinion poll developed during this study was voluntary and anonymous, with no personal information being collected, apart from participants' names, publically available contact details, and a record of consent. Therefore, the data is not considered sensitive or confidential; there is no risk of possible disclosures or reporting obligations for the participants, and the information was treated under Chilean Organic Law 19628 on the Protection of Personal Data. Vulnerable or dependent groups were not included, and the research objectives were not likely to upset or disturb participants.

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III. Chapter III: Environmental Risk Assessment of Brine Discharges: Insights from Field Studies in a Coastal Desalination Plant in Northern Chile

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Hypothesis 2: The application of ecological risk assessment guidelines enhances the comprehension of the influence area and impacts on coastal ecosystems attributable to brine discharges from seawater desalination.

1. ABSTRACT

The growing global demand for freshwater resources has fueled a surge in desalination, particularly in arid and semi-arid regions. While crucial for ensuring water security, desalination produces hypersaline brine, requiring careful assessment of its potential ecological impacts. This study presents a comprehensive environmental risk assessment of brine discharge from a Chilean desalination plant. We combined field measurements and ecotoxicological analysis to characterize the brine plume's behavior and potential effects on benthic communities. Field data revealed a wider plume extent than initially predicted by models, underscoring the importance of in-situ observations for accurate plume characterization. However, despite the wider plume, measured salinity increases remained within regulatory limits. Species sensitivity distributions, derived from local and global ecotoxicological data, established salinity safety thresholds for the bay. A spatial risk assessment incorporating these thresholds identified a limited area of medium risk (331 m²) near the discharge point. This research underscores the value of integrating biological data to move beyond traditional physical dilution models for a more accurate ecological risk assessment. Our findings suggest that while localized salinity increases may occur, the robust

nature of benthic ecosystems in high-energy environments, coupled with an appropriate Environmental Risk Assessment framework, can mitigate potential impacts, supporting the sustainable growth of desalination as a critical component of freshwater security.

2. KEYWORDS

Environmental Risk Assessment, Desalination, Brine Discharge, Species Sensitivity Distribution.

3. INTRODUCTION

Driven by a stable economy and responding to prolonged droughts along its extensive coastline, Chile witnessed a significant expansion of desalination efforts in the early 2000s, marking a turning point in the nation's approach to water security [1, 2]. Chile currently leads South America in desalination production, boasting a capacity of approximately 800,000 m³/day. Projections indicate a substantial expansion of this capacity, with estimates suggesting an increase exceeding 300% by 2030 [3-5].

Seawater reverse osmosis (SWRO), the dominant desalination technology employed in Chile, reverses the natural osmotic process under pressure to separate freshwater from brine [6, 7]. This process generates a hypersaline byproduct, known as brine, which contains concentrated levels of dissolved solids from the feed water, residual pretreatment chemicals (e.g., coagulants, flocculants, antiscalants), and particulate matter rejected by the RO membranes [8].

Despite the numerous benefits and widespread adoption of SWRO, concerns remain among some social and environmental groups regarding the management and disposal of brine. Discharged continuously through diffuser systems into coastal waters, brine has the potential, under certain conditions, to degrade seawater quality and pose risks to sensitive ecosystems [5, 9, 10]. The apprehension with this practice is that, under low-speed coastal current scenarios, brine tends to accumulate at the bottom near the outfall, exposing benthic habitats to effluent discharge and abnormally high salinity concentrations that can be toxic to marine flora and fauna [11-13].

Brine forms a high-density plume that drifts following the seabed topography, and its potential impacts will vary depending on effluent characteristics and local physical and biological conditions. Therefore, the effects of brine discharge on marine ecosystems represent a paramount concern for desalination project developers and stakeholders. In Chile alone, nearly 1.57 million m³ of brine are discarded daily into coastal waters [5, 13]. However, a comprehensive understanding of brine plume behavior, potential ecological effects, and standardized assessment methodologies within Chilean coastal systems remains limited, with available information primarily descriptive in nature [5, 14-16]. This lack of comprehensive knowledge presents a significant challenge—from technical, ecological, and economic perspectives—to ensuring the sustainable growth and development of the desalination industry. Therefore, refining brine disposal strategies and establishing standardized monitoring techniques are crucial steps toward

mitigating potential risks and ensuring the long-term ecological sustainability of desalination as a crucial solution to address Chile's water security strategy.

In Chile, the control and mitigation of potential environmental impacts from brine discharge are governed by a series of regulatory measures mandated by environmental authorities. These measures include periodic acute and chronic toxicity testing of industrial desalination effluents, designed to evaluate potential toxic effects [17, 18]. However, while providing valuable insights into chemical endpoints, these tests are limited in their ability to fully assess the spatial extent of environmental impacts on receiving ecosystems [19]. On the other hand, physical mixing models such as CORMIX and Visual Plume allow to understand the brine plume's spatial distribution and different dilution scenarios [20-22]. However, a standardized methodology that effectively integrates these physical models with assessments of biological effects on natural communities remains a challenge. Developing such an integrated approach is essential for accurately defining the environmental influence area of desalination discharge systems.

Environmental Risk Assessment (ERA) provides a valuable framework for evaluating the potential adverse consequences of environmental stressors, such as brine discharge, on receiving ecosystems. A widely used approach within ERA is risk characterization based on the risk quotient, which compares the toxicity threshold of a given chemical to its measured environmental concentration [23, 24].

This study focuses on assessing the potential ecological risks posed by brine discharge to benthic communities inhabiting coastal waters near the outfall of Chile's oldest desalination plant – La Chimba. Situated along the arid Atacama Desert coastline, this plant, established to address a critical shortage of drinking water, was the first desalination plant in Latin America to provide 100% desalinated water to a city of over 200,000 inhabitants [25, 26].

This study employed a statistical risk characterization approach to evaluate the potential ecological risks of brine discharge. The spatial distribution of exposure risk was assessed by integrating on-site salinity measurements, physical modeling, and biological toxicity data. This approach offers an invaluable tool for defining areas of influence and, ultimately, could help implement appropriate mitigation plans relevant to protecting coastal ecosystems and biodiversity.

4. MATERIAL AND METHODS

4.1. Study area

This study focuses on the La Chimba Desalination Plant (UTM 19S 7395714 E; 357180 N), located in the Antofagasta Region of Northern Chile (Figure III-1). Established in 2001, La Chimba desalination plant was initially designed to produce 150 liters per second (l/s) of potable water using seawater reverse osmosis technology, the plant has since undergone expansion and currently provides nearly 850 l/s of drinking water, serving a population of approximately 480,000 inhabitants [4]. The plant's brine outfall, spanning 350 meters in length and comprising four L-

shaped diffusers positioned at a depth of 15 meters (Figure III-2), discharges continuously into the near-coast environment, with a maximum discharge capacity of 89,760 m³/day [13].

4.2. Brine plume characterization

In May 2022, oceanographic fieldwork was conducted to estimate and map the spatial distribution of the brine plume from the La Chimba Desalination Plant. The field campaign involved measurements at 42 stations (Figure 6) arranged in a grid pattern, encompassing an area of 1.2 by 0.8 km² surrounding the brine outfall [27]. At each station, vertical profiles of salinity, temperature, and depth were recorded using a Sea & Sun Technology Multiparameter Probe CTD 75M device (conductivity sensor resolution: 0.0005 mS/cm; range: 0–300 mS/cm). All station locations were georeferenced using GPS (WGS84 - UTM coordinates).

Spatial analysis and visualization of the brine plume were performed using a data interpolation model. A geostatistical interpolation method - Kriging - was employed to predict salinity values at unsampled locations [28]. The resulting salinity model was represented as a contour map, providing a spatial representation of the brine plume's extent and characteristics. All spatial analyses and model development were conducted using the kriging package in R version 4.0.3 [29].

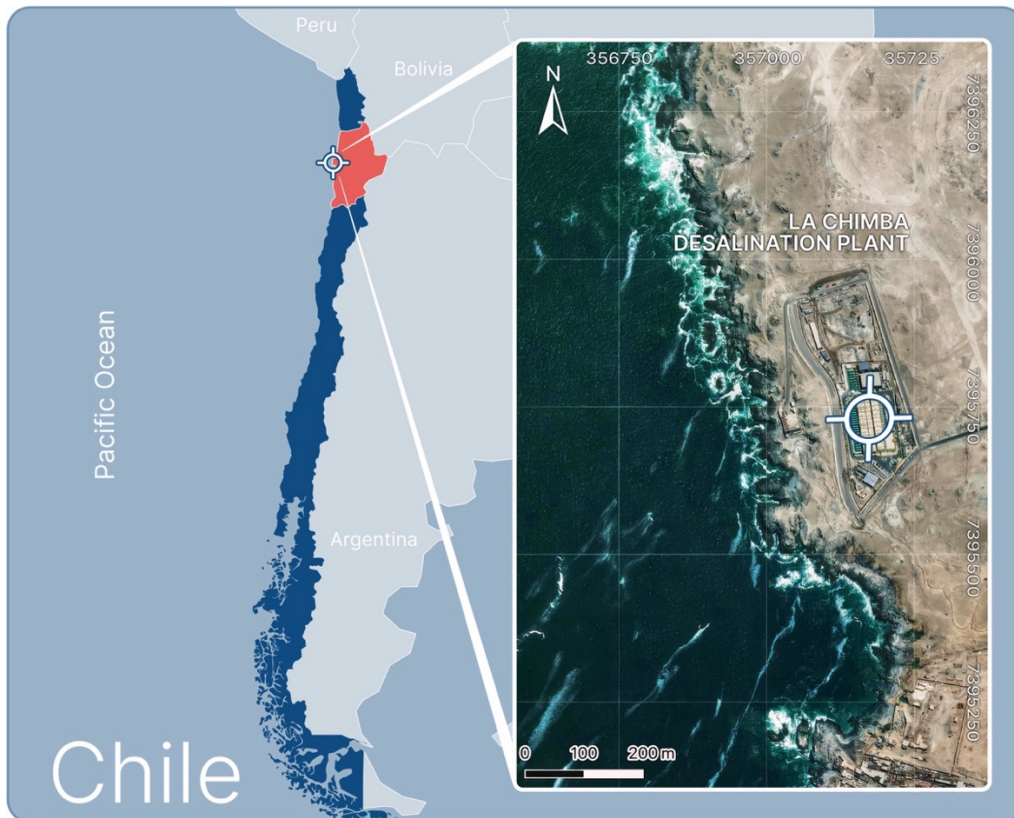


Figure III-1: Study site location at La Chimba desalination plant, Antofagasta, Chile.

4.3. Ecotoxicological data collection

To assess the sensitivity of marine organisms to salinity exposure, three trophic levels were considered: primary producers (microalgae), 1st level consumers (crustaceans and mollusks), and 2nd level consumers (fishes). Toxicity data, encompassing both acute and chronic exposures, were compiled for a range of species representing both global and local distributions. Data for global species were obtained from peer-reviewed literature and published studies [11, 30, 31].

Ecotoxicological data for local species were obtained from the National Environmental Control Information System (SNIFA, <https://snifa.sma.gob.cl/>), which is publicly accessible as part of the environmental impact assessment and monitoring program for the La Chimba Desalination Plant. The local species evaluated, *Loxechinus albus*, *Argopecten purpuratus*, and *Caprella* sp., are abundant and widely distributed within Antofagasta Bay, where the desalination plant is located [32-34].

4.4. Species sensitivity distribution (SSD) curve

Species sensitivity distribution (SSD) curves were constructed based on the previously collected ecotoxicological information for local and globally distributed species. A log-normal distribution adjustment was applied to predict salinity's hazardous concentration (HC), representing a dissolved salt concentration considered harmful [35]. This approach aimed to encompass the broadest possible range of species sensitivities, with a particular emphasis on local species.

Any concentration below HC_x is considered safe and acceptable as an environmental protection threshold. The subscript "x" represents the small percentile (p) of species that would be affected [36]. For example, HC₅ serves as a protection criterion, ensuring that at least 95% of the sample population remains unaffected while allowing for the assumption that 5% of species may be affected.

Several percentiles (%p) [1%, 2%, 3%, 4%, and 5%] were tested for this study, yielding different thresholds applicable to a brine risk management model. Model fitting, calculation of information criteria, and HC estimations were performed using the *fitdistrplus* R package [37].

4.5. Risk characterization

The estimation of an absolute risk quotient (RQ) provided a quantitative proxy for the likelihood and potential severity of adverse effects on the benthic system near the outfalls due to brine exposure. The RQ method involves calculating the ratio of a contaminant's measured environmental concentration (MEC) to its predicted no-effect concentration (PNEC). The RQ is

derived from the ratio of effect and exposure assessments, as represented by the following equation:

Equation 1:

$$RQ = \frac{MEC}{PNEC}$$

Where:

MEC: Measured Environmental Concentration.
PNEC: Predicted No-Effect Concentration.

The Hazardous Concentration (HC) serves as a reference point for determining the Predicted No-Effect Concentration (PNEC). Conversely, the Measured Environmental Concentration (MEC) corresponds to the salinity measurement directly obtained from the environment at each sampling station. For each sampling station, an RQ will be calculated using the risk estimation range proposed by Hernando, Mezcua [38] as follows:

$0.01 < RQ < 0.1$	low risks
$0.1 < RQ < 1$	medium risks
$RQ \geq 1$	high exposure risks

The SSD curves were calibrated using salinity sensitivity data from species native to the study area. Consequently, the calculated risk estimates and their spatial projections accurately represent the local environmental conditions. This approach accounts for both the specific salinity variations associated with brine discharge and the sensitivity of representative species in the bay to salinity anomalies.

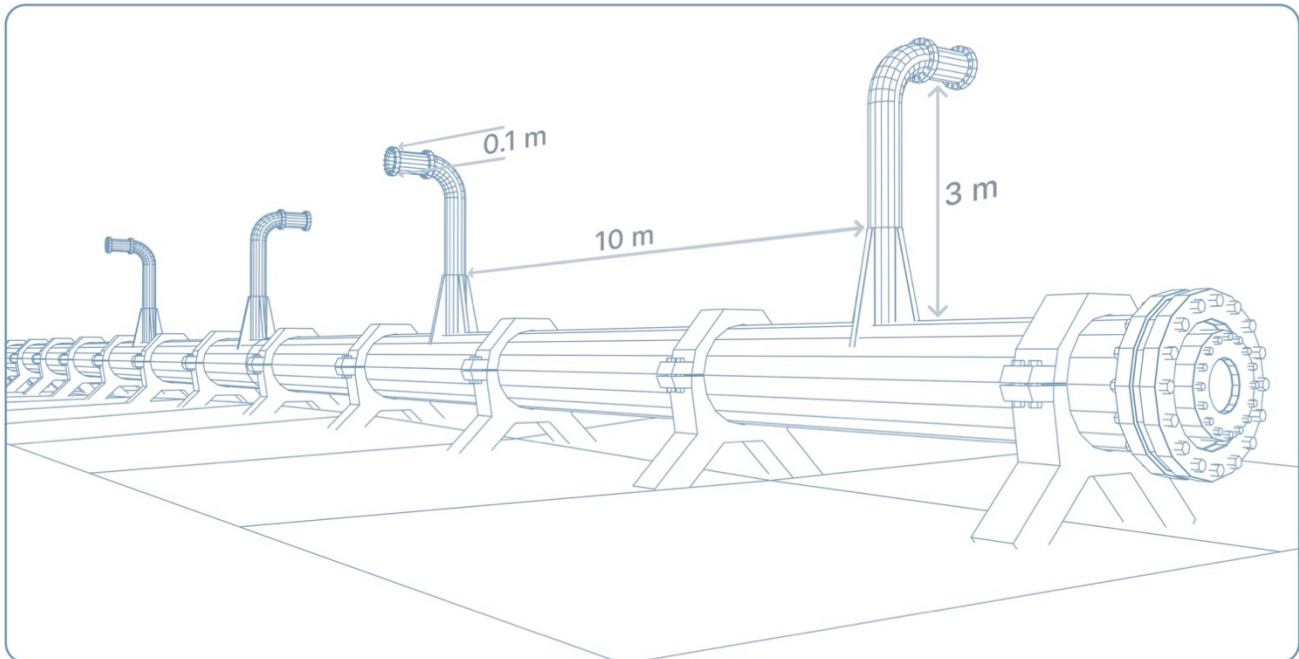


Figure III-2: Three-dimensional model of the brine diffuser system at the La Chimba Desalination Plant, Antofagasta, Chile.

5. RESULTS

5.1. Brine plume

On-site salinity measurements at the brine discharge point revealed that the shape and direction of the plume were influenced by the coastal bathymetry [39]. The brine mixing process extends away from the discharge point following the slope of the seafloor, and its shape is probably influenced by local wind-driven currents that fluctuate between South-South East and North-North West directions [40, 41].

The highest recorded salinity at the diffuser system was 35.85 PSU, a 1.45 PSU increase from background levels (Figure III-3a). Vertical profiles show stable surface salinity to a depth of 11 meters, contrasting with near-seafloor variations (Figure III-3a). This stability is attributed to strong stratification in deeper layers due to density differences between brine and seawater. Temperature exhibited an expected regional range, with a superficial thermocline reaching a minimum of 15.5°C near the seabed (Figure III-3a).

Maximum salinity values were detected near the seafloor within 50 meters around the diffuser system. Minor salinity increases (0.1 PSU) were observed up to 1000 meters from the diffusers (Figure III-3b).

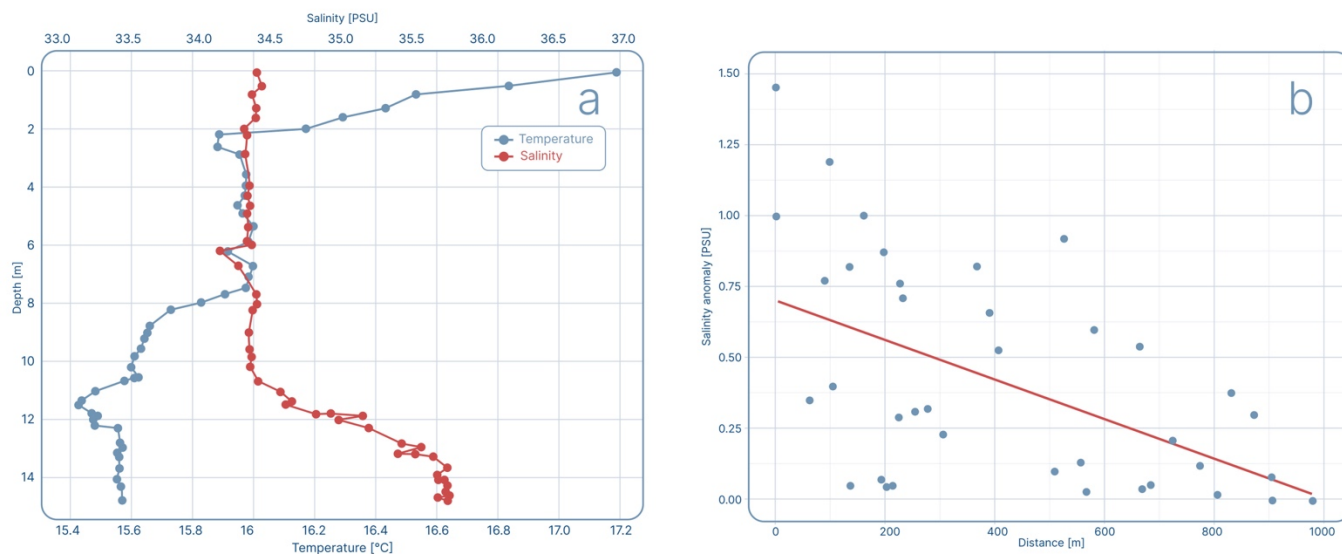


Figure III-3: a) Vertical salinity (psu) and temperature ($^{\circ}\text{C}$) profiles of the water column on top of the diffuser system (UTM 356831 E, 7395718 S) and b) horizontal salinity distribution (psu) measured at the La Chimba desalination plant, Antofagasta, Chile.

Field observations differed from CORMIX dilution model predictions made during the project's design and environmental qualification phase. While the CORMIX models accurately predicted maximum salinity values (35.84 PSU), even in the most conservative scenarios, they underestimated the plume's area of influence. The model predicted near-background salinity levels at approximately 300 meters from the discharge point (Figure III-4). However, observed mixing slopes from in-situ data ($m_{\text{on-site}} = 0.6$) compared to CORMIX scenarios ($m_{\text{cormix1}} = 1.9$; $m_{\text{cormix2}} = 2.9$) indicate differences in mixing velocities. This discrepancy results in a significantly larger estimated area of influence for the brine plume.

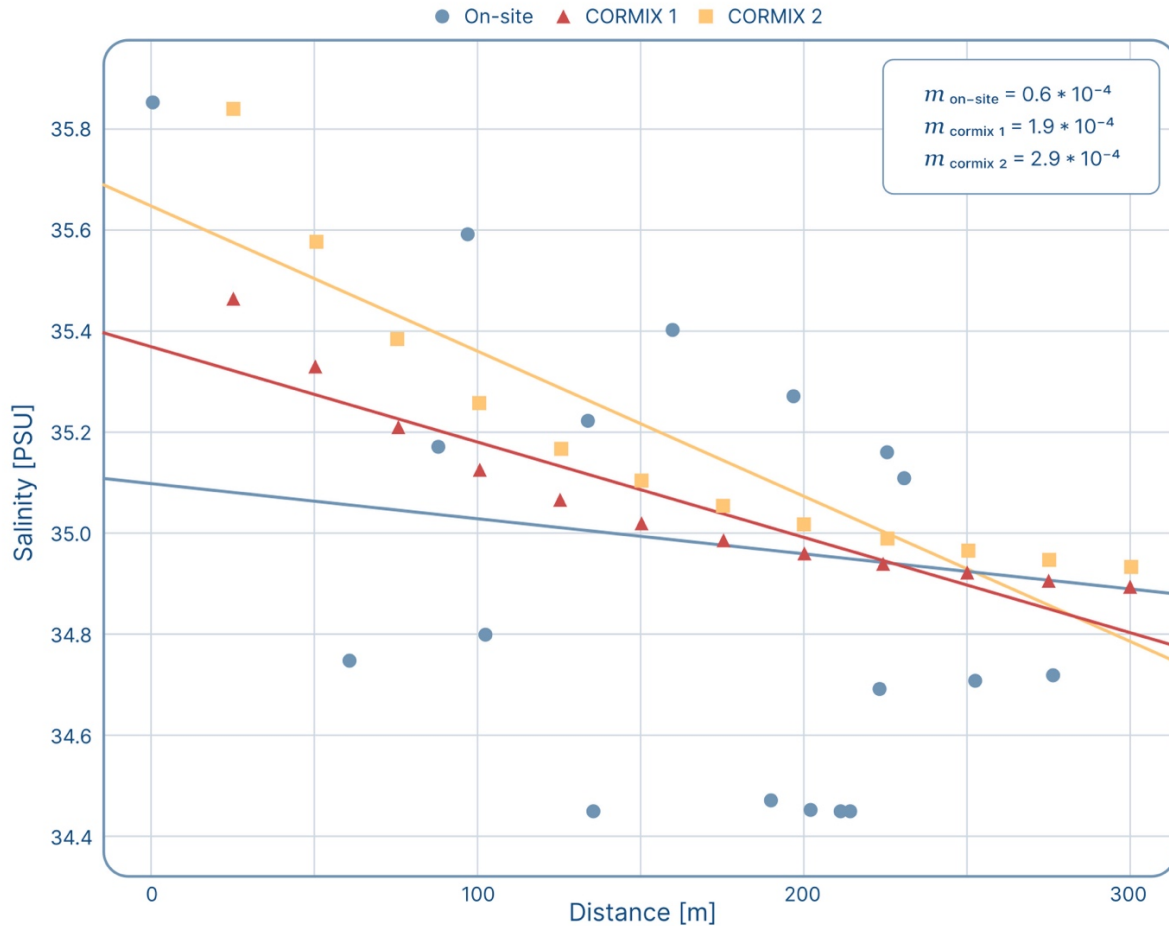


Figure III-4: Comparison of observed salinity and CORMIX Model Simulations at the La Chimba desalination plant brine discharge area.

5.2. Effects on local marine organisms

To assess the potential effects of salinity variations on marine organisms, a comprehensive literature review was conducted, examining acute and chronic toxicity indicators for both local and global species (Table 1). The review encompassed single and multiple species tests, focusing on lethal and sub-lethal responses to brine stress (Dupavillon & Gillanders, 2009; Iso et al., 1994; Mandelli, 1975).

Reported salinity toxicity values ranged from 37.33 PSU for the highly sensitive *Sabellaria alveolata* [31] to 69.61 PSU for the more resistant *Cyprinodon variegatus* [42]. Local species evaluated in this study exhibited mid-range salinity sensitivity, with LC50 values of 50.55 PSU for *Loxechinus albus* (48-hour exposure), 50.02 PSU for *Argopecten purpuratus* (96-hour exposure), and 47.04 PSU for *Caprella* sp. (96-hour exposure). Detailed ecotoxicological data are summarized in Table III-1.

Table III-1: List of available osmotic stress toxicity data published elsewhere, for both local species and international research works. Species arranged are shown from most to least resistant. *Available data from the Chilean National Information System for Environmental Control (<https://snifa.sma.gob.cl/>)

Species	Taxonomy	Salinity (PSU)	Test	Exposure (h)	Reference
<i>Cyprinodon variegatus</i>	Fish	69.61	LC50	48	Pillard et al. 1999
<i>Brachinonus plicatilis</i>	Zooplankton	68.10	LC50	24	Yoon et al. 2011
<i>Tigriopus japonicus</i>	Zooplankton	63.60	LC50	96	Yoon et al. 2011
<i>Chlorella vulgaris</i>	Phytoplankton	61.70	EC50	72	Yoon et al. 2011
<i>Tetraselmis suecica</i>	Phytoplankton	56.90	EC50	72	Yoon et al. 2011
<i>Skeletonema coastatum</i>	Phytoplankton	55.10	EC50	72	Yoon et al. 2011
<i>Ulva pertusa</i>	Macroalgae	53.30	EC50	96	Yoon et al. 2011
<i>Loxechinus albus</i>	Echinoderm	50.55	LC50	48	Local species*
<i>Argopecten purpuratus</i>	Mollusk	50.02	LC50	96	Local species*
<i>Paralichthys olivaceus</i>	Fish	48.60	LC50	96	Yoon et al. 2011
<i>Caprella sp</i>	Crustacean	47.04	LC50	96	Local species*
<i>Menidia beryllina</i>	Fish	44.00	LC50	48	Pillard et al. 1999
<i>Mysidopsis bahia</i>	Crustacean	43.03	LC50	48	Pillard et al. 1999
<i>Isochrysis galbana</i>	Phytoplankton	42.20	EC50	72	Yoon et al. 2011
<i>Mytilus galloprovincialis</i>	Mollusk	41.96	EC50	-	Quintino et al. 2008
<i>Paracentrotus lividus</i>	Echinoderm	40.87	EC50	-	Quintino et al. 2008
<i>Sabellaria alveolata</i>	Polychaete	37.33	EC50	-	Quintino et al. 2008

5.3. Risk assessment

A Species Sensitivity Distribution (SSD) analysis was employed to assess the risk of brine exposure from the La Chimba desalination plant. This analysis was tailored to local ecosystem sensitivity, incorporating various species representing different trophic levels and life stages commonly found in Antofagasta Bay [33, 34, 43].

A log-normal distribution model was used to depict the results, with the most sensitive species at the lower end and the most resistant at the upper end (Figure 4). A salinity safety threshold, the hazardous concentration (HC), was calculated from this distribution. Several HC percentages were examined to ensure consistency with the ambient salinity of northern Chile's coastal systems (Table 2). Since the baseline salinity of the Antofagasta Bay is 34.4 PSU (Figure 2a), the most conservative and protective HC should not fall below this value. Consequently, HC1 (33.86 PSU, Table 2) was excluded. HC2 (35.99 PSU, Table 2), representing the 2nd percentile and protecting the most sensitive 2% of the population, was selected as the protection criterion and used to estimate the Predicted No-Effect Concentration (PNEC).

A spatial risk quotient (RQ) analysis, using Equation 1, was then conducted to evaluate the potential effects of brine plume mixing processes. The RQ was calculated for each sampling

station and spatially plotted to generate a hazard map (Figure 5). The maximum RQ value (0.9558) indicated a medium exposure risk for benthic communities. The highest RQ values were concentrated directly above the diffuser system, encompassing an area of approximately 331 m².

Table III-2: Hazardous concentration values for different %p values from the SSD distribution model.

HC	Value	[CI 2.5%]	[CI 97.5%]
1%	33.85847	28.54726	39.61163
2%	35.99130	31.16709	41.28551
3%	36.59012	31.29999	41.87678
4%	37.43369	32.15612	42.71536
5%	37.99039	33.30431	43.12269

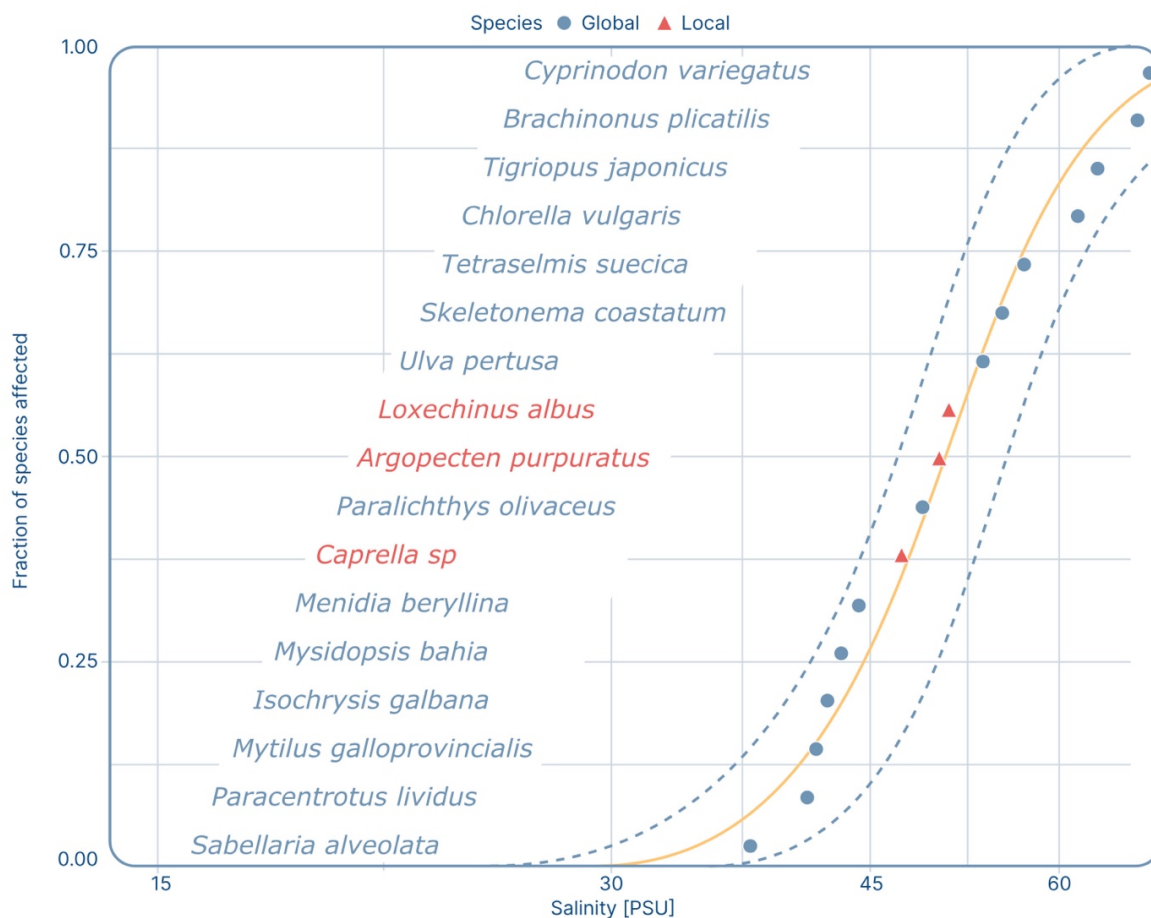


Figure III-5: Species sensitivity distribution (SSD) to salinity variations based on lethal and chronic endpoint for marine species.

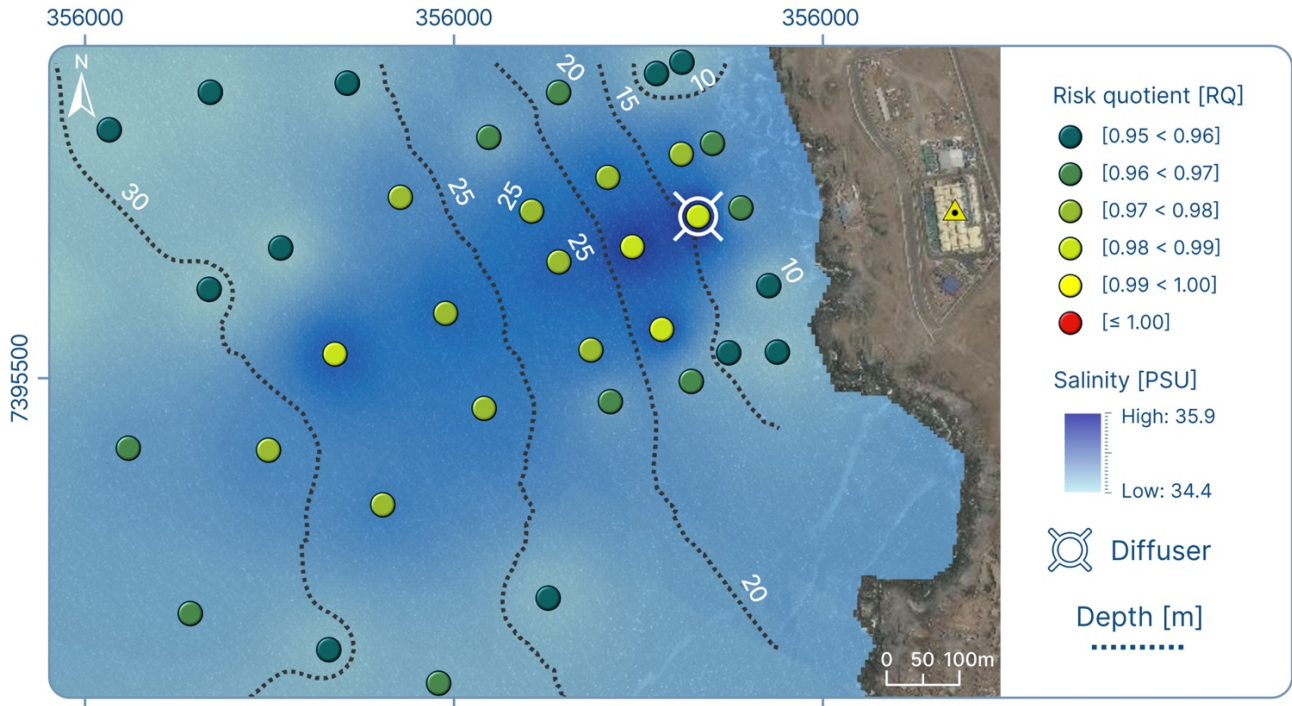


Figure III-6: Spatial distribution of Risk Quotient for brine discharge plume, representing potential salinity exposure risk to benthic communities.

6. DISCUSSION

6.1. Brine mixing processes

This study provides an in-situ assessment of brine plume mixing processes from the La Chimba desalination plant and verifies key salinity thresholds. The highest recorded salinity (35.85 PSU) indicates significant dilution capacity, considering the plant's effluent salinity of 67.2 PSU [41]. Rapid mixing of the brine with receiving waters occurs near the discharge point due to the effluent's kinetic energy, resulting in high dilution levels. This rapid mixing leads to observed salinities aligning closely with the maximum salinity predicted by the CORMIX model [41].

Despite the observed rapid dilution near the discharge point, this study detected small salinity variations up to 1.2 km from the diffuser system, indicating a larger plume extent and brine influence area than anticipated. This contrasts with the CORMIX physical model predictions, which anticipated complete dilution within 300 m. This discrepancy highlights the importance of validating models with empirical data and field measurements.

The influence area (IA) concept is pivotal in environmental regulation in Chile. It is defined as the geographic area or space whose natural or sociocultural attributes must be considered to determine whether a project or activity presents any impacts or to justify the absence of such effects [44, 45].

While specific Chilean regulations for salinity variations caused by brine discharges are still under development, environmental standards from Spanish and Australian legislation have been widely adopted. In particular, the Spanish secondary water quality standard (Royal Decree 927/1998), which limits salinity increases from brine discharges to a maximum of 10% above baseline, has been successfully implemented in much of the Chilean desalination industry [5].

It is important to note that although the observed plume extension exceeded theoretical predictions from the CORMIX model, even the highest recorded salinity increases during the winter marine campaigns remained below 4.2%. While this study's seasonal limitations restrict broader interpretation, the findings highlight the significant dilution capacity of the Chilean coast for brine diffusion systems, likely driven by the characteristic high-energy coastal dynamics of the region [46].

6.2. Brine Exposure Risk Characterization

Ecotoxicity data from the La Chimba Desalination Plant demonstrate that acute and chronic toxicity effects on local species occur within salinity ranges reported for other marine species, highlighting varying sensitivities to brine exposure [11, 30, 31]. The inclusion of local and global marine species from various trophic levels provides a comprehensive ecological perspective for risk assessment purposes [12, 13, 47].

While extensive literature exists on desalination effluent impacts elsewhere, this information is not directly applicable to Chilean coastal systems. Model species used in these studies do not accurately represent the ecological structure of benthic communities in the Humboldt Current System. Although recent efforts have focused on defining local biomarkers to better understand impacts on regional communities [12, 13, 47], the methodological complexities of these protocols make them difficult for routine implementation in corporate environmental management systems.

While mortality and LC50 values provide insights into acute exposure effects, toxicity tests alone are insufficient for establishing comprehensive environmental monitoring and control mechanisms [48]. Species Sensitivity Distribution (SSD) methods are emerging as valuable tools for ecological risk assessment and environmental monitoring. By analyzing toxicity data across multiple species exposed to a specific stressor, SSDs provide a statistical framework for estimating potential impacts on entire ecosystems.

Despite past criticisms regarding potential biases in species selection, ecological representation, and data uncertainties [36], Species Sensitivity Distributions have proven valuable in environmental risk management. For example, SSD-based risk analysis has successfully established water quality guidelines for varying salinity levels [49]. The integration of SSD models

into environmental monitoring programs, such as in a brine discharge system at an Australian desalination plant, further highlights their practical application for managing ecological risks [50].

In this study, an absolute Risk Quotient was calculated by integrating toxicological data on local species with observed salinity fluctuations at the discharge site. This provides an initial assessment of potential ecological risks posed by brine discharges to benthic ecosystems in northern Chile. To visually represent exposure risk, a spatial analysis employed a "traffic light" approach based on absolute RQ values, ranging from low risk (green) to high risk (red).

Spatial risk projections within the discharge influence area showed that the RQ did not exceed the medium-risk threshold, even directly above the diffusers where salinity fluctuations are highest.

While our study focuses specifically on salinity-related risks, our findings suggesting low to medium risk impact from this factor. These results in conjunction with long-term research like Clark, Knott [51] that highlights the potential ecological influence of diffuser hydrodynamics, underscore the importance of considering a broader range of physical stressors in future assessments. Investigating the role of diffuser design and operation, alongside salinity, will provide a more comprehensive understanding of how desalination discharges potentially impact benthic communities.

These findings provide a foundation for developing a conceptual brine discharge risk management model that moves beyond physical dilution models by incorporating biological data into the environmental assessment of marine systems impacted by desalination plants (Figure III-7). This approach can inform practical risk management practices, such as setting appropriate discharge limits, optimizing diffuser design, and implementing monitoring programs. While brine disposal remains a challenge, advancements in modeling and risk assessment methodologies, particularly those integrating biological data, offer promising avenues for mitigating ecological risks and promoting responsible water management practices in the face of growing freshwater demands.

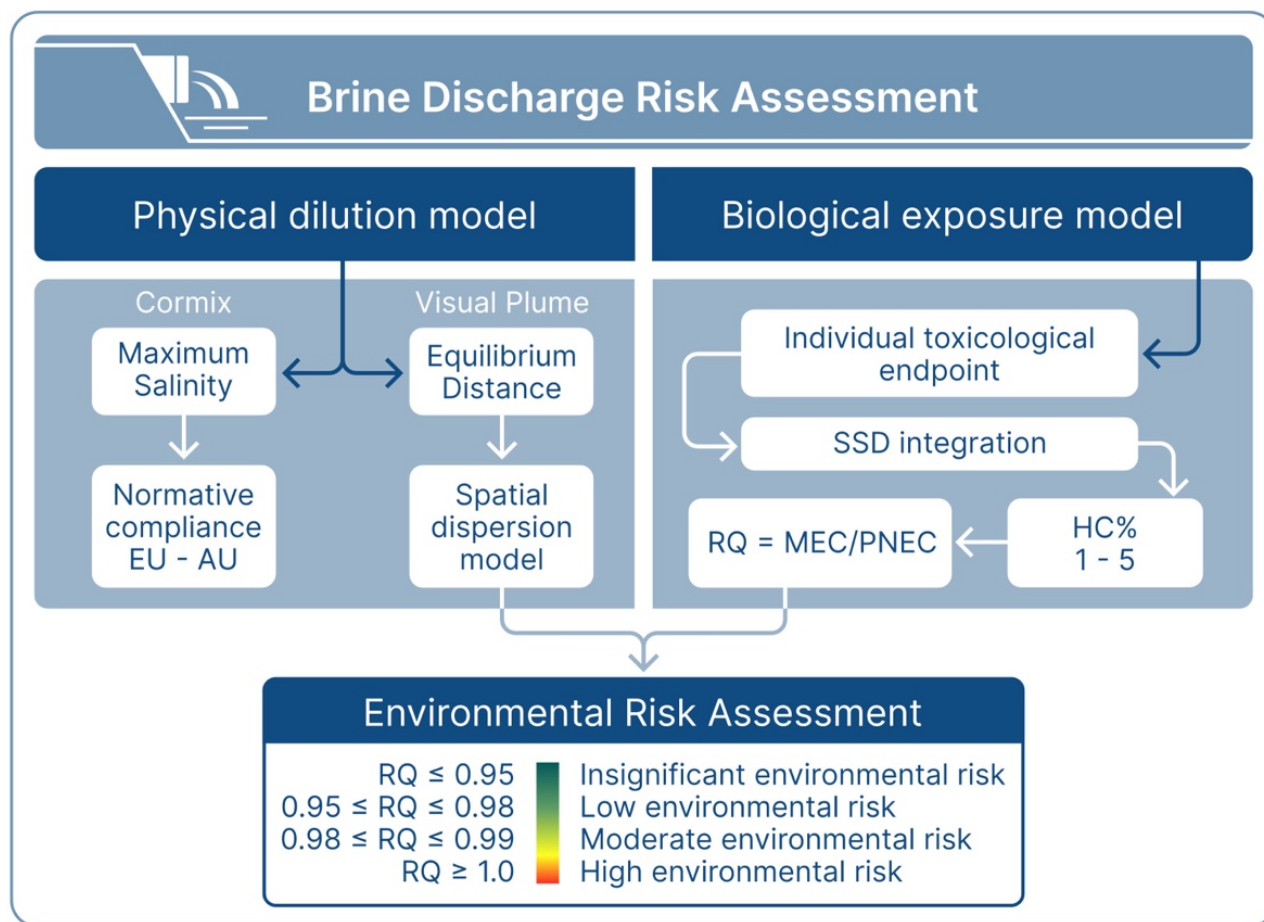


Figure III-7: Conceptual model for SWRO desalination brine discharge risk management.

7. CONCLUSIONS

- **Brine plume extent:** Field observations revealed a wider brine plume extent than predicted by physical models, highlighting the importance of in-situ data for accurate impact assessment.
- **Salinity increases within limits:** Despite the wider plume, measured salinity increases remained well below regulatory thresholds.
- **Importance of biological data:** Integrating biological data, such as Species Sensitivity Distributions and Risk Quotient analysis, is crucial for moving beyond traditional physical dilution models in assessing ecological risks.

- **Resilience of benthic ecosystems:** Findings suggest that the robust nature of benthic ecosystems in high-energy environments, coupled with appropriate diffuser design, can mitigate potential impacts from localized salinity increases.
- **Sustainable desalination:** Incorporating these findings into a comprehensive risk management framework can help ensure the sustainable growth of desalination as a critical component of freshwater security.

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IV. Chapter IV: Managing Desalination Brine Discharge: A Multidisciplinary Approach

1. BRIDGING THE GAP: SUSTAINABLE BRINE DISCHARGE MANAGEMENT IN CHILE

The pressing global challenge of water scarcity, exacerbated by climate change and escalating demands, necessitates innovative solutions to ensure water security. Chile, a country vulnerable to severe drought and arid conditions, increasingly relies on seawater reverse osmosis desalination as a crucial strategy to address its water needs. While Chile has emerged as a leader in desalination technology in the Americas, the industry's rapid growth has raised critical concerns about the potential environmental impacts of hypersaline brine discharge into the country's sensitive coastal ecosystems [1].

A multidisciplinary approach that integrates environmental monitoring, impact assessment, and sustainable management practices is crucial to mitigate the risks posed by desalination effluents.

Though existing research offers valuable insights, its applicability to Chile's unique context is often limited. While studies have demonstrated the potential for desalination brine to impact aquatic ecosystems globally, the distinctive ecological characteristics of Chile's coastal systems necessitate a tailored approach to understanding and addressing the associated risks. Moreover, Chilean legislation and environmental regulations have struggled to keep pace with the rapid expansion of the desalination industry. The absence of standardized methodologies for evaluating brine discharge impacts, particularly regarding osmotic changes, combined with inadequate environmental oversight, presents a significant obstacle to sustainable water management and socioeconomic development [2].

A comprehensive, multidisciplinary strategy that bridges the gaps between environmental science, policy, and industry is required to address these challenges. This approach should focus on three key pillars: (1) enhancing environmental monitoring plans to provide robust, location-specific data on the impacts of desalination brine; refining environmental impact assessments to better capture the complexity of coastal ecosystems and inform regulatory frameworks; and developing innovative, context-appropriate solutions for brine disposal and beneficial use.

By fostering cross-sectoral collaboration and integrating the latest scientific advancements, Chile's policymakers, regulators, and industry stakeholders can work towards a sustainable future for seawater desalination that balances the critical need for water supply with the imperative of environmental protection.

A multifaceted strategy is imperative to address this challenge. Strengthening the Environmental Impact Assessment (EIA) framework by incorporating specific regulations and standardized methodologies for evaluating the impacts of brine discharge, particularly regarding

osmotic changes, is critical. This necessitates establishing clear regulatory benchmarks for acceptable levels of salinity variation and mandating the use of validated monitoring techniques. Crucially, these efforts must be grounded in comprehensive research on local species and ecosystems to ensure their relevance and effectiveness. Such research should examine the sensitivity of native flora and fauna to changes in salinity, as well as the potential for long-term ecological disruption from brine discharge. By aligning the EIA process with a rigorous understanding of the local environmental context, policymakers and industry stakeholders can develop more informed and targeted mitigation strategies to safeguard the integrity of Chile's coastal ecosystems [3].

Conducting in-depth, long-term research to fully comprehend the ecological consequences of brine discharge on Chile's sensitive coastal ecosystems is of the utmost importance. Establishing and implementing robust, sustained monitoring programs to track changes in marine communities over time and detect early indicators of ecological stress is essential. Prioritizing research on locally representative species and their responses to salinity fluctuations will be crucial for developing effective, context-appropriate monitoring and mitigation strategies to safeguard the integrity of these valuable coastal environments. Such research should encompass comprehensive studies on the biology, physiology, and population dynamics of key indicator species, as well as their interactions within the broader coastal food web. This knowledge will enable the development of robust, evidence-based thresholds and early warning systems to guide regulatory decisions and industry practices, ensuring the long-term viability of Chile's precious marine ecosystems in the face of the growing desalination industry [4].

Effective communication and public engagement are also crucial components for the sustainable management of seawater desalination effluents. Transparently disseminating the findings of environmental impact assessments and long-term monitoring programs to the public cultivates trust and facilitates informed decision-making. Meaningfully involving the local community in the environmental impact assessment process can provide invaluable place-based knowledge and diverse perspectives, resulting in more robust, context-appropriate, and socially acceptable outcomes. Fostering ongoing dialogue and collaboration between industry, policymakers, and the public is critical to ensuring the responsible development of the desalination industry while safeguarding the integrity of Chile's valuable coastal ecosystems. By actively engaging the public and incorporating their input, the industry can build trust, address community concerns, and develop sustainable solutions that balance economic growth with environmental protection. Furthermore, transparent communication of research findings and monitoring data can empower citizens to participate in the decision-making process, leading to more inclusive and environmentally responsible outcomes for seawater desalination projects [5].

Proactive and comprehensive spatial planning is critical to address the anticipated rapid expansion of the seawater reverse osmosis industry. By carefully identifying suitable coastal areas for desalination plant development while thoroughly considering environmental sensitivities, potential cumulative impacts from multiple discharge sources, and long-term sustainability objectives, conflicts can be minimized, resource allocation can be optimized, and the long-term viability of both the industry and the coastal environment can be ensured. This strategic approach

to spatial planning will enable the sustainable growth of the desalination sector while safeguarding the ecological integrity of Chile's valuable coastal ecosystems. Such a planning process should involve rigorous environmental impact assessments, comprehensive mapping of ecologically sensitive areas, and the establishment of clear zoning regulations to guide the siting of desalination facilities. Additionally, it should incorporate mechanisms for monitoring and adaptively managing the cumulative effects of multiple brine discharge sources over time, ensuring the long-term resilience of the coastal environment. By proactively planning for the expansion of the desalination industry, Chile can chart a course towards a sustainable water future that balances economic development with environmental protection [6].

This dissertation presents a comprehensive, multidisciplinary approach to the sustainable management of seawater desalination effluents in Chile. By integrating rigorous environmental risk assessment, advanced spatial modeling, and a thorough review of existing knowledge and regulations, the research offers valuable insights to mitigate the adverse impacts of brine discharge on Chile's ecologically sensitive coastal ecosystems. The study bridges critical knowledge gaps, informs evidence-based policy decisions, and promotes the responsible and sustainable development of the desalination industry in the country. This holistic and strategic approach ensures a water-secure future for Chile while prioritizing protecting and preserving its ecologically sensitive coastal environments, fostering a balance between economic progress and environmental sustainability. The research represents a significant contribution, providing a robust and comprehensive framework for addressing the complex challenges associated with the responsible management of seawater desalination effluents. By offering a multidisciplinary perspective and integrating cutting-edge analytical tools, the study equips policymakers, regulators, and industry stakeholders with the necessary knowledge and strategies to effectively mitigate the environmental impacts of brine discharge and ensure the long-term sustainability of Chile's coastal ecosystems. The comprehensive and evidence-based approach outlined in this dissertation serves as a valuable model for other regions facing the environmental implications of the growing desalination industry, and its findings can inform the development of sustainable water management policies and practices worldwide [7].

2. BALANCING DESALINATION DEVELOPMENT AND COASTAL SUSTAINABILITY IN CHILE: A SPATIAL PLANNING PERSPECTIVE

Carefully selecting appropriate locations for desalination plants is crucial for ensuring these facilities' long-term environmental and operational sustainability. This site selection process necessitates thoroughly evaluating the intricate interplay between various socioeconomic, technical, and environmental considerations. Such a comprehensive assessment is essential to guarantee the overall feasibility of desalination projects and mitigate potential risks associated with their development and operation [8].

This study used a robust Analytic Hierarchy Process and Geographic Information System model as a multi-criteria decision-making framework to assess the suitability of potential desalination plant sites in north-central Chile. The AHP process involved expert-weighted criteria emphasizing the critical importance of proximity to the coastline. This factor minimizes both the

economic costs of seawater transport and the environmental impacts of brine discharge, as subtidal diffusers can more effectively disperse and dilute the concentrated brine. Furthermore, site altitude emerged as the second most significant factor, as reducing elevation differences lowers energy-intensive pumping costs, thereby enhancing the project's overall economic feasibility and sustainability [9].

The model identified optimal locations that minimize potential conflicts between desalination development and coastal conservation efforts by incorporating diverse environmental factors, such as proximity to marine protected areas, sensitive habitats, and existing industrial activities. This strategic site selection approach ensures that desalination infrastructure is situated in areas with the least environmental impact while also being technically and economically viable. The findings of this study underscore the importance of comprehensive spatial planning in supporting the sustainable expansion of Chile's desalination industry. Specifically, the model's consideration of environmental sensitivities, such as proximity to protected areas and ecologically fragile habitats, allows for strategically placing desalination plants in locations that avoid or minimize adverse impacts on these critical coastal ecosystems. This holistic approach to site selection balances the need for desalination capacity expansion with the imperative to preserve the long-term health and resilience of Chile's valuable marine environments. By prioritizing environmental protection alongside technical and economic feasibility, this study provides a robust framework for guiding the sustainable development of the desalination sector, ensuring that Chile's water security goals are harmonized with its broader coastal conservation objectives [10].

Furthermore, recognizing the critical role of public perception in the success of desalination projects, this study prioritizes environmental protection. The model incorporates spatial exclusion zones around environmentally sensitive areas, such as marine protected habitats and ecologically fragile coastal ecosystems, ensuring their exclusion from potential development sites. This approach acknowledges the significant public concern over the potential adverse environmental impacts of desalination, as evidenced by perception studies conducted in California. By prioritizing the preservation of these environmentally important areas, this study promotes a balanced approach that aligns desalination development with the long-term ecological and social well-being of the region. The strategic consideration of public sentiment and environmental safeguards is essential for garnering community support and facilitating the sustainable expansion of Chile's desalination industry [11].

This study presents a comprehensive assessment of spatial suitability for the expanding desalination industry in north-central Chile, a critical factor given the nation's current water crisis and projected demand. Employing a novel geographic information system-based multi-criteria analysis methodology at national, regional, and local scales, the research provides a robust framework for identifying suitable locations for desalination facilities. Through the use of analytic hierarchy process-paired comparison matrices, the study establishes standardized criterion scores and generates multi-criteria suitability maps that integrate a wide range of environmental, socioeconomic, and technical variables. This innovative approach offers a valuable decision-support tool for evaluating the territorial feasibility and sustainability of desalination projects in

water-stressed regions, ensuring that these critical water infrastructure investments are strategically located to balance economic, social, and environmental considerations [12].

The analysis reveals a critical mismatch between Chile's ambitious desalination growth projections and the limited availability of suitable coastal land. While only a small portion of the 114,452 km² study area exhibits high suitability for desalination plants, over 60% faces significant constraints. This disparity underscores the urgent need for strategic spatial planning to optimize resource allocation and mitigate potential conflicts arising from increased competition for limited coastal space. Uncoordinated development could exacerbate environmental degradation, disrupt fragile coastal ecosystems, and fuel negative public perceptions of this crucial industry. Proactive and comprehensive planning is essential to ensure the sustainable expansion of Chile's desalination capacity while preserving the long-term health and resilience of its valuable marine environments. Developing a well-coordinated and collaborative approach to coastal land use planning, involving stakeholders from various sectors, is crucial to balance the competing demands for desalination development and coastal conservation. This holistic planning framework should also consider the potential impacts of climate change, such as sea level rise and precipitation patterns, to ensure the long-term viability and resilience of both the desalination industry and the coastal ecosystems [13].



Figure IV-1: Escondida Water Supply 2500 l/s, largest SWRO desalination plant in Latin America. Photograph by Enzo García-Bartolomei.

Expanding the research scope to include additional socio-environmental factors, such as coastal water quality, red tide frequency, tsunami risk, and economic modeling, would enhance the analysis and provide a more comprehensive assessment of spatial suitability for desalination infrastructure. This expanded evaluation would help identify potential impacts on marine ecosystems, public health, and the overall economic viability of desalination projects, promoting a holistic approach to sustainable development in water-stressed regions. Furthermore, incorporating long-term climate change projections, including anticipated changes in precipitation patterns and sea level rise, would further strengthen the analysis and help ensure the resilience of desalination infrastructure and coastal environments in the face of future environmental challenges [14].

3. ASSESSING ECOLOGICAL RISKS OF BRINE DISCHARGE FROM DESALINATION

Chile's heightened dependence on desalination, particularly SWRO (seawater reverse osmosis) processes, has been instrumental in tackling the country's water security issues. However, the sustainable expansion of this industry necessitates effectively addressing the ecological uncertainties and potential environmental impacts associated with the discharge of brine, a byproduct of the desalination process. Although current regulatory measures in Chile prioritize assessing the chemical toxicity of brine, a critical gap exists for developing standardized methodologies that can integrate physical mixing models with comprehensive biological impact assessments. This integrated approach is vital for accurately delineating the environmental influence area of desalination discharge systems and ensuring minimal long-term impact on the health and resilience of Chile's marine ecosystems, which are crucial for the country's coastal communities and economies [6].

The large volumes of brine discharged daily from Chile's desalination plants underscore the potential for ecological impacts, particularly given the limited scientific understanding of brine plume dynamics and the absence of standardized assessment methods within the country's diverse coastal environments. Refining and optimizing brine disposal approaches while developing comprehensive monitoring techniques that consider both the physical and biological impacts of brine discharge are crucial steps towards mitigating the potential risks and ensuring the long-term ecological and economic sustainability of desalination as a critical component of Chile's overall water security strategy. Adopting a holistic, multidisciplinary approach to managing desalination brine is essential for safeguarding the health and resilience of Chile's marine ecosystems, which are essential to the livelihoods and well-being of coastal communities nationwide [6, 10].

To ensure the sustainable growth of desalination as a critical component of freshwater security, it is essential to effectively address the ecological uncertainties associated with brine discharge. This study adopts a comprehensive Environmental Risk Assessment framework to thoroughly evaluate the potential adverse impacts of brine discharge from desalination plants on receiving marine ecosystems. The research focuses on assessing the ecological risks posed by brine discharge to benthic (seafloor) communities in the coastal waters near the outfall of Chile's oldest desalination plant, La Chimba. By employing a rigorous statistical risk characterization

approach that integrates on-site salinity measurements, advanced physical modeling, and comprehensive biological toxicity data, this study provides a crucial tool for precisely delineating the areas of influence and informing the implementation of appropriate mitigation strategies. Ultimately, this holistic research contributes valuable multidisciplinary insights to guide the sustainable expansion of desalination activities while effectively protecting the health and resilience of critical coastal ecosystems and their biodiversity [15].

Investigating brine mixing processes at La Chimba revealed a larger brine plume extent than predicted by physical models, underscoring the necessity of conducting on-site data collection and analysis for accurate environmental impact assessment. Notably, the observed salinity increases in the receiving waters remained well below regulatory limits, suggesting the substantial dilution capacity of the Chilean coastline's hydrodynamic processes. These findings highlight the importance of developing a nuanced comprehension of site-specific environmental conditions and the critical need to integrate empirical environmental monitoring data with advanced modeling approaches to effectively manage brine discharge and ensure the long-term environmental sustainability of desalination operations in this region [2].

An evaluation of brine toxicity on local marine species was conducted to further understand the potential ecological impacts of brine discharge. While previous literature provided valuable insights, the unique environmental characteristics of the Humboldt Current System necessitated a tailored risk assessment approach. A comprehensive Risk Quotient analysis was employed, integrating detailed toxicological data on various local species with observed salinity fluctuations at the discharge site. The spatial analysis utilized a "traffic light" mapping technique to visually represent the exposure risk based on calculated Risk Quotient values, categorizing the risk levels from low to high. The spatial risk projections within the discharge influence area indicated that the Risk Quotient did not exceed the medium-risk threshold, even in the areas directly above the diffusers where the highest salinity fluctuations were observed. This multifaceted analysis yielded crucial insights into the potential ecological impacts of brine discharge, informing the development of appropriate mitigation strategies to safeguard the health and resilience of the local marine ecosystem [16].

Our study focused specifically on evaluating the salinity-related ecological risks associated with brine discharge. The findings indicate a relatively low to medium level of potential ecological impact from this factor. This suggests that carefully designed diffuser systems can effectively mitigate the potential risks posed by localized increases in salinity, especially considering the inherent resilience of benthic ecosystems in high-energy coastal environments. Crucially, incorporating comprehensive biological data, including Species Sensitivity Distributions and Risk Quotient analyses, is essential for moving beyond reliance on traditional physical dilution models when assessing the ecological implications of desalination brine discharge. These insights provide a foundation for developing a conceptual risk management framework that integrates biological data into the environmental assessment of marine systems impacted by desalination operations, going beyond the limitations of physical dilution models. This holistic approach can inform the development of practical risk management strategies, such as setting appropriate discharge limits, optimizing diffuser design, and implementing robust environmental monitoring

programs. By adopting this multidisciplinary perspective, we can better understand and address the complex interactions between the marine environment's physical, chemical, and biological components, ultimately supporting the sustainable expansion of desalination while safeguarding the health and resilience of critical coastal ecosystems [17].



Figure IV-2: Sand filters in the pretreatment system at Escondida Water Supply, Latin America's largest seawater reverse osmosis desalination plant. Photograph by Enzo García-Bartolomei.

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V. Chapter V: Conclusions

1. TOWARDS A SUSTAINABLE FUTURE FOR SEAWATER DESALINATION IN CHILE [EN]

This thesis has explored the complex challenge of managing seawater desalination effluents, particularly hypersaline brine discharge, in the context of Chile's growing reliance on desalination for water security. The research underscores that a sustainable desalination future hinges on a multidisciplinary approach, integrating environmental science, policy, and industry perspectives.

Our findings highlight the critical need to move beyond simplistic dilution models and embrace a more holistic understanding of brine discharge impacts. This requires strengthening Chile's Environmental Impact Assessment framework by:

- Establishing clear regulatory benchmarks for salinity variations based on robust, location-specific data.
- Employing validated monitoring techniques that capture the dynamic nature of brine plumes and their potential effects.
- Conducting comprehensive, long-term research on the ecological responses of local species and ecosystems to brine exposure.

Furthermore, strategic spatial planning for desalination plants is essential. By comprehensively evaluating environmental, socioeconomic, and technical factors, we can identify suitable locations that minimize conflicts and ensure the industry's and coastal ecosystems' long-term viability. Integrating public perception and environmental safeguards into planning will foster community support and promote responsible development.

This thesis provides a robust framework for navigating the complexities of seawater desalination effluent management. By offering valuable insights to policymakers, regulators, and industry stakeholders, it emphasizes the power of a multidisciplinary perspective and the integration of advanced analytical tools. This holistic approach supports the sustainable expansion of Chile's desalination industry and serves as a model for other regions grappling with similar environmental challenges.

Ultimately, this dissertation champions a future where seawater desalination thrives in harmony with healthy coastal ecosystems. By embracing a comprehensive, evidence-based approach, we can ensure the long-term viability of both, meeting the growing demand for freshwater while safeguarding the invaluable biodiversity of our oceans.

2. HACIA UN FUTURO SOSTENIBLE PARA LA DESALACIÓN EN CHILE [ES]

Esta tesis ha explorado el complejo desafío de gestionar los efluentes de la desalación de agua de mar, particularmente la descarga de salmuera hipersalina, en el contexto de la creciente dependencia de Chile en la desalación como estrategia para su seguridad hídrica. La investigación desarrollada subraya que un futuro sostenible para la desalación depende de una gestión ambiental con enfoque multidisciplinario que integre las ciencias ambientales, políticas públicas y las perspectivas de la industria.

En relación a la gestión de las descargas de salmuera, nuestros hallazgos destacan la necesidad crítica de ir más allá de los modelos de dilución físicos y adoptar una comprensión más holística de los potenciales impactos de la descarga. Esto requiere fortalecer el marco de Evaluación de Impacto Ambiental de Chile mediante:

- El establecimiento de referencias regulatorias claras para las variaciones de salinidad basadas en datos robustos y específicos de cada localización.
- El empleo de técnicas de monitoreo validadas que capturen la naturaleza dinámica de las plumas de salmuera y sus posibles efectos.
- La realización de investigaciones exhaustivas y a largo plazo sobre las respuestas ecológicas de las especies locales y los ecosistemas a la exposición a la salmuera.

Por otro lado, la planificación espacial estratégica para la gestión territorial del desarrollo de la industria desaladora es esencial. Al evaluar exhaustivamente los factores ambientales, socioeconómicos y técnicos, podemos identificar ubicaciones adecuadas que minimicen los conflictos y aseguren la viabilidad a largo plazo de la industria y los ecosistemas costeros. Integrar la percepción pública y medidas de gestión ambiental adecuadas en las etapas tempranas de planificación fomentará la aceptación social de la industria y promoverá el desarrollo responsable de la misma.

En este sentido, esta tesis proporciona un marco robusto para navegar por las complejidades de la gestión de los efluentes de la desalación de agua de mar. Al ofrecer una base metodológica robusta a los formuladores de políticas, reguladores y *stakeholders* de la industria, enfatiza el impacto de una perspectiva multidisciplinaria e integración de herramientas analíticas avanzadas. Este enfoque holístico apoya la expansión sostenible de la industria desaladora en Chile y sirve como modelo para otras regiones que enfrentan desafíos ambientales e hídricos similares.

En última instancia, el presente trabajo defiende un futuro en el que la desalación de agua de mar prospere en armonía con las comunidades y ecosistemas costeros. Al adoptar un enfoque integral y basado en la evidencia, podemos asegurar la viabilidad a largo plazo de ambos, satisfaciendo la creciente demanda de agua dulce mientras protegemos la invaluable biodiversidad de nuestros océanos.

VI. Annex

1. RESUMEN DE DIFUSIÓN [ES]

La creciente escasez hídrica, agravada por el cambio climático y la sobreexplotación, ha posicionado a la desalación de agua de mar como un pilar fundamental para la seguridad hídrica, especialmente en regiones áridas del mundo. Chile posee una extensa costa y patrones de precipitación irregulares, lo que ha catalizado en las últimas décadas una rápida expansión de la capacidad de desalación instalada, convirtiéndose en el mayor productor de agua desalada de América Latina.

Una de las principales preocupaciones ambientales de esta industria, guarda relación con la descarga de salmuera. Este subproducto concentrado del proceso de desalación puede bajo ciertas condiciones alterar la salinidad e integridad ecológica de los ecosistemas costeros. A pesar de la creciente investigación internacional sobre los riesgos potenciales de la descarga de salmuera, aún existe un vacío de conocimiento sobre sus efectos específicos en los sistemas costeros de Chile. Esta falta de comprensión local, aunada a la ausencia de metodologías de evaluación estandarizadas y regulaciones ambientales integrales adaptadas al contexto nacional, representa un obstáculo para el desarrollo sostenible de la industria desaladora en Chile.

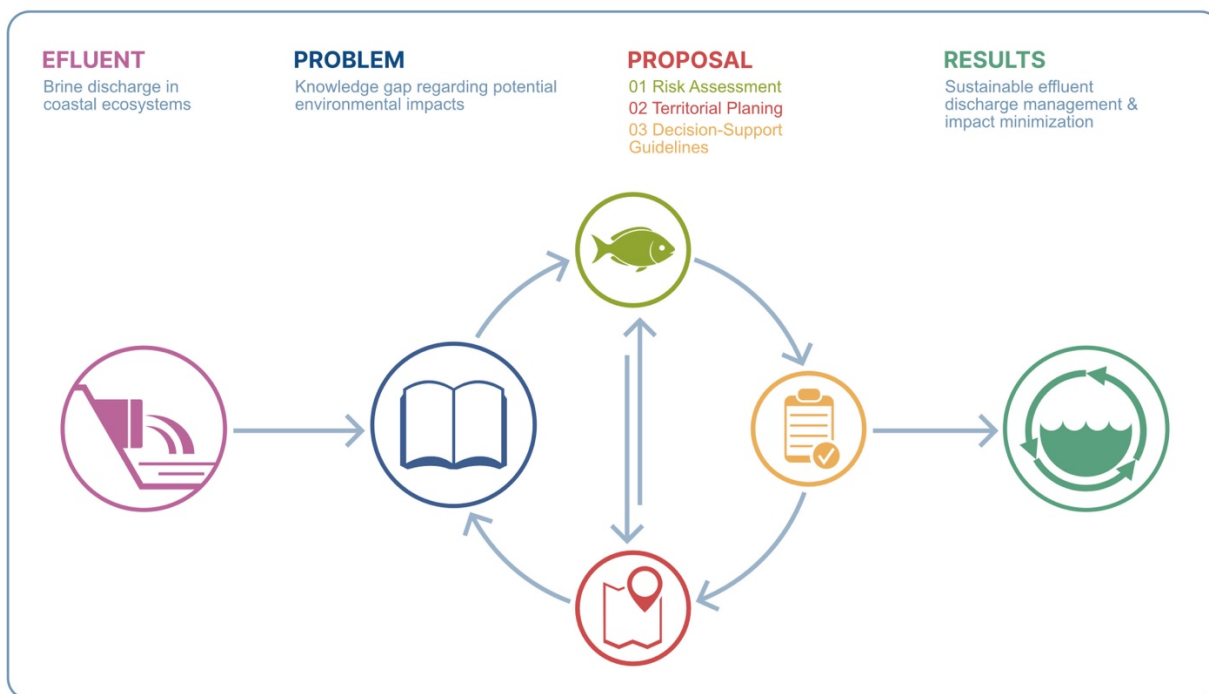
Esta tesis aborda este desafío desde una perspectiva multidisciplinaria, buscando analizar y mitigar los riesgos ecológicos de la descarga de salmuera en las plantas desalinizadoras chilenas. Reconociendo las particularidades geográficas y oceanográficas de la costa chilena, la investigación integra tres áreas interconectadas:

- a. **Evaluación del riesgo ambiental de la descarga de salmuera en comunidades bentónicas:** Esta investigación se centra en caracterizar los riesgos ecológicos asociados a la descarga de salmuera de una planta desalinizadora chilena, trascendiendo los modelos tradicionales de dilución física e incorporando datos biológicos para una evaluación más integral. Mediante la combinación de mediciones de campo y análisis ecotoxicológicos, este estudio investiga el comportamiento de la pluma de salmuera y sus posibles efectos en las comunidades bentónicas. Los datos de campo, incluyendo mediciones in situ de salinidad y extensión de la pluma, se comparan con las predicciones de los modelos para evaluar su precisión. Además, se utilizan métodos estadísticos de evaluación de riesgo ecológico, para establecer umbrales de seguridad de salinidad específicos para la bahía receptora de la descarga. Al integrar estos umbrales en un marco de evaluación de riesgos espaciales, este estudio propone un lineamiento metodológico para la evaluación del riesgo ecológico y determinación de área de influencia de las plumas de salmuera.
- b. **Orientación hacia una planificación territorial sostenible:** Reconociendo que la ubicación de las plantas desalinizadoras es crucial para determinar el impacto potencial de la descarga de salmuera, este componente de la investigación utiliza técnicas de

modelación territorial avanzada para identificar áreas costeras más susceptibles al desarrollo de la industria desaladora. Al integrar mapas de sensibilidad ambiental y escenarios de desarrollo de la desalinización proyectados, este análisis busca informar las decisiones de planificación espacial, guiando la ubicación de futuras plantas para minimizar los impactos ambientales y promover la salud a largo plazo de los ecosistemas costeros chilenos.

- c. **Fortalecimiento de la gobernanza ambiental:** Analizando las mejores prácticas internacionales, identificando las brechas en las regulaciones actuales e incorporando los hallazgos de los componentes ecotoxicológicos y de planificación espacial de esta tesis, esta investigación busca proponer recomendaciones concretas para fortalecer la gobernanza ambiental de la industria de desalinización en Chile. Esto incluye promover criterios de evaluación más integrales y ecológicamente relevantes, incorporar estrategias de gestión adaptativa y fomentar una mayor transparencia y participación de las partes interesadas en la toma de decisiones.

Al integrar estas áreas de investigación interconectadas, esta tesis aspira a proporcionar un marco integral y científicamente sólido para la gestión sostenible de la descarga de salmuera de las plantas desalinizadoras en Chile. Se espera que los resultados de esta investigación, permitan una comprensión más precisa del comportamiento de las plumas de salmuera y sus mecanismos de gestión, contribuyendo con prácticas más sostenibles en la industria.



Modelo conceptual de la propuesta de enfoque multidisciplinario para la gestión de descargas de salmuera en los sistemas costeros chilenos.