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Physicochemical Characterization of Desert Bay with Brine Discharge: A Case Study from Caldera Bay, Northern Chile

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Abstract

Seawater desalination is considered the first option to meet the domestic and industrial requirements of freshwater in desert areas, such as the Atacama Desert (Chile). However, its environmental implications remain poorly characterized. This study evaluated the effects of brine discharge from a desalination plant located in Caldera Bay, where fishing and tourism coexist. Sampling was conducted at increasing distances from the outfall to assess physicochemical parameters, sediment metal content, and nutrient concentrations. The results revealed a clear spatial gradient: salinity decreased from 57.75 to 34.87 PSU and nitrate from 10.49 to 4.05 µM. The sediment samples near the outfall showed elevated concentrations of Al, Fe, and Cr(VI). These findings suggest that brine discharge alters water chemistry and sediment quality. This study highlights the need for long-term environmental monitoring and regulatory frameworks to ensure sustainable desalination in sensitive coastal systems.

Keywords: desalination; impact; sediment; Atacama; seawater reverse osmosis desalination; nutrients

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1. Introduction

Water scarcity and water quality degradation are among the most pressing global environmental challenges in the 21st century. According to the United Nations, over two billion people live in countries experiencing high water stress, and climate change is expected to intensify this pressure by altering precipitation patterns and reducing freshwater availability in many regions [1]. Simultaneously, water quality continues to decline owing to pollution, salinization, and increased anthropogenic demand. Coastal areas are particularly vulnerable as they often support high population densities and industrial activities while facing limited freshwater inputs. Seawater desalination has emerged as a key strategy for enhancing water security, particularly in arid zones, islands, and the rapidly urbanizing regions of the Mediterranean, Middle East, North Africa, and Latin America [2]. However, their large-scale deployment raises critical environmental concerns that demand regionally adapted assessments and regulatory responses. One such example is the Atacama Desert in northern Chile, which is recognized as one of the driest regions on Earth, where urban populations coexist with industries crucial to the national economy. Specifically, the Atacama Region is one of the driest places on Earth, with negligible rainfall, limited surface water, and overexploited aquifers. Conventional freshwater sources are insufficient for meeting the demands of growing urban centers, mining operations, and other water-intensive industries. Seawater desalination offers a stable, drought-resistant, and scalable alternative. Its strategic significance lies in its capacity to decouple water availability from climate variability, ensuring supply continuity in regions where hydrological inputs are practically nonexistent. Therefore, the installation of both coastal and inland desalination plants has become a central water management strategy in this region [2]. Currently, four desalination plants operate along the 580 km coastline of the Atacama Region, and at least 22 additional national projects are under environmental evaluation [3,4], aiming to supply freshwater to thousands of residents and industrial operations [5]. These plants primarily use reverse osmosis (RO) technology, which typically recovers only 50–90% of the input water and returns the remaining volume of concentrated hypersaline brine into the marine environment [6]. The key advantages of RO are its modularity, lower carbon footprint relative to distillation, and compatibility with renewable energy sources. However, the limitations of this study are significant. RO membranes require extensive pre-treatment to prevent fouling, and the operational costs remain high owing to energy consumption and membrane replacement. Most critically, the environmental impact of brine disposal, including increases in salinity, temperature, and chemical additives, such as antiscalants and coagulants, poses risks to benthic and pelagic marine life, particularly in semi-enclosed or low-energy coastal systems. These trade-offs underscore the need for region-specific monitoring and mitigation strategies to ensure sustainable deployment of desalination infrastructure.

On the other hand, the northern Chilean coast is characterized by several particularities, including the Humboldt Current System (HCS), which is driven by persistent upwelling-favorable winds associated with the South Pacific Anticyclone. These winds, predominantly from the south, generate surface currents that flow northward, shaping both the biological productivity and pollutant dispersion patterns [7]. Seasonal fluctuations in wind intensity affect upwelling dynamics, with peak intensity occurring between July and October and weaker conditions prevailing during the austral summer [8]. Such variability must be considered when evaluating the environmental behavior of brine discharges. This coast also hosts several marine ecosystems with ecological relevance (coastal wetlands, submarine forests, endemic seagrass, hot-spot biodiversity islands and upwelling, etc.) and economic importance (artisanal fishing, algae recollection, benthic management and aquaculture, tourism, commercial ports, etc.) [9].

Desalination plants present various environmental issues, particularly with respect to brine disposal. Brine has the potential to raise salinity levels, change water temperature and oxygen content, and possibly introduce trace contaminants to the marine ecosystem environment. These changes may impose physiological stress on planktonic and benthic organisms, reducing biodiversity and altering ecosystem functioning [10,11]. Although studies along the Chilean coast have reported that brine plumes generally remain confined within a 100 m radius and produce salinity increases of less than 5% [12], site-specific monitoring is essential given the heterogeneity of local hydrodynamic conditions.

Caldera and Calderilla form a semi-enclosed coastal bay system in the Atacama Region (Figure 1), which is of ecological and economic importance owing to activities such as artisanal fisheries, aquaculture, and tourism [9,13], as well as intense seasonal upwelling events [7]. Owing to the bay's geomorphology, water exchange is restricted, making it especially vulnerable to anthropogenic discharges. The local SWRO plant, operated by the Nueva Atacama Water Company, began operations in 2021, with a freshwater production capacity of 300 L/s (1200 L/s maximum capacity) and a brine discharge flow of

1049.62 kg/m^3, exhibiting an average salinity of 65.3 PSU [14,15]. It serves the towns of Caldera, Copiapó, Chañaral, and Tierra Amarilla [16].

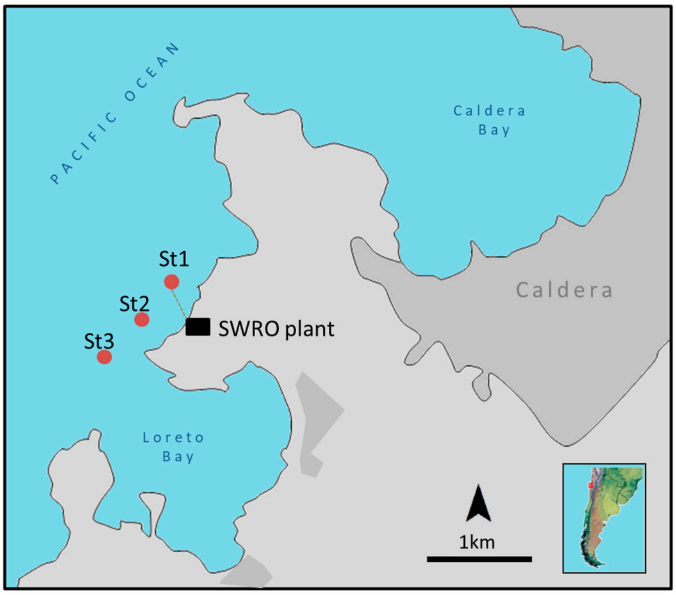

Figure 1. Location of the study area in Atacama (Chile), and the seawater desalination plant, the three studied stations at 0 m (St1), 500 m (St2), and 1000 m (St3) from brine discharge in Caldera.

The current regulatory framework in Chile lacks specific standards for key parameters such as brine salinity, temperature, and chemical composition. Although desalination projects are evaluated using the Environmental Impact Assessment System (SEIA), which requires EIAs or Statements (EISs), these processes do not impose enforceable discharge thresholds [3]. Therefore, there is an urgent need for regulatory reform and scientifically informed environmental monitoring to ensure the sustainable development of desalination infrastructure in the region [17]. The necessity of using new ZLD technologies to avoid brine discharge and the benefit associated with them is also highlighted, not only at the environmental level, but also economically for the commercialization of crystallized salts and raw materials like Li, etc.

This study evaluates the environmental status near the Nueva Atacama desalination plant outfall by analyzing the physicochemical properties, sediment metal concentrations, and nutrient distributions across a transect extending from the brine outfall of a desalination plant.

2. Materials and Methods

2.1. Sampling Survey

Sampling was conducted during daylight hours in October 2024 at the SWRO desalination plant in the Caldera district, using a research vessel equipped for scientific operations. The objective was to assess the physicochemical parameters at varying distances from the discharge point (170 m rejection system, 20 m depth). The extent of the study area and orientation of the sampling stations were set opposite to the direction of the diffuser's dispersion pattern (northeast), following the bathymetric contours of the seafloor.

Sampling stations were established at distances of 0 (St1), 500 (St2), and 1000 m (St3) from the brine outfall. This transect was designed based on two main criteria: (i) expected brine plume dispersion according to local hydrodynamic conditions and (ii) alignment with existing regulatory and scientific practices for near-field (<100 m) and mid-field (100–1000 m) impact assessment zones. The 0 m station was positioned directly above the discharge point to capture peak exposure. The 500 m and 1000 m stations were selected to track the attenuation of chemical and physical parameters along the dilution gradient while remaining within the semi-enclosed bay system. This spatial framework enables the assessment of immediate versus residual environmental effects and provides a basis for comparison with similar studies in coastal desalination contexts. Given that the high density of the effluent promotes plume descent toward the seafloor, measurements were taken at the substrate level at a depth of approximately 20 m at each station using a HI98194/40 multiparameter probe (Hanna Instruments, Woonsocket, RI, USA).

Sediment samples were collected at each station by a professional diver using acid-cleaned tools and were placed in clean polyethylene bags. Immediately after collection, the samples were stored in coolers with ice packs and subsequently refrigerated at 4 °C to preserve their physicochemical integrity until laboratory analysis.

Water samples for nutrient analysis were collected at the same depth as the physicochemical measurements, using a Niskin bottle (Chile-Oceanica, Concepcion, Chile). These samples were refrigerated immediately after collection and frozen for laboratory analysis.

2.2. Analytical Procedures

An aliquot of the sediment sample (~0.5 g) was subjected to total acid digestion using a mixture of ultrapure reagents: HNO_3 (65%), HCl (37%), H_2SO_4 (98%), and HF (40%). The metal concentrations in the diluted extracts were analyzed by AAS coupled with an Optical Emission Spectrometer (ICP-OES; PerkinElmer Optima 8000, Norwalk, CT, USA) at the Laboratories of Metallurgy, Universidad de Atacama. Blanks and certified reference materials (NIST SRM 2702, Baltimore, MD, USA) were included to ensure analytical quality control.

The nutrient concentration in the water was determined using an auto-analyzer following the techniques of [18] and a UV/VIS spectrophotometer (Metertech Sp-8001, Taipei, Taiwán) according to Strickland and Parsons [19], as well as the Standard Methods for the Examination of Water and Wastewater [20]. The certified reference material employed for nutrient determination was Kanso for nutrients in seawater, provided by SCOR WG147 (JAMSTEC, Yokosuka, Japan).

3. Results and Discussion

The analysis of samples from three stations (St1, St2, and St3) at distances of 0, 500, and 1000 m, respectively, reveals significant spatial variations in physicochemical parameters in water and metal concentrations in sediments, indicating potential anthropogenic influences, particularly near the Nueva Atacama desalination plant (Table 1).

Although the temperature remained relatively constant across stations, dissolved oxygen (DO) declined from 66.0% to 59.4%, potentially reflecting reduced gas solubility or biological oxygen demand. Lower oxygen concentrations can promote the accumulation of dissolved CO_2, leading to increased carbonic acid and a further reduction in pH [6]. In parallel, nutrient concentrations, such as nitrate, phosphate, and silicic acid, also decreased with distance from the outfall. These declines may have resulted from physical dilution or pH-mediated changes in nutrient speciation and solubility. For instance, phosphate availability is influenced by pH, and acidification can shift the equilibrium toward forms that are less available to phytoplankton. Similarly, trace metals, such as Fe and Cr, are more soluble and bioavailable under acidic conditions, which may explain the elevated Cr(VI) levels (94.08 mg/kg) observed in sediments near the outfall. These concentrations exceeded the typical background values for Caldera Bay [13] and pose potential risks to benthic organisms.

Table 1. Physicochemical parameters and element concentrations in sediment samples from Caldera Bay at three distances (0, 500, and 1000 m) from the desalination plant discharge point.

		St1	St2	St3
Distance from outfall	m	0	500	1000
Coordinates		27°04′02″ S 70°51′8.6″ W	27°04′25″ S 70°51′20″ W	27°04′13″ S 70°51′21″ W
Depth	m	17	15	18
T	°C	15.28 ± 0.3	15.24 ± 0.2	15.25 ± 0.3
pH		7.34 ± 0.2	7.39 ± 0.1	7.84 ± 0.1
EC	µS/cm	82,330 ± 3130	55,530 ± 2652	52,790 ± 2673
TDS	ppt	41.16 ± 3.3	27.76 ± 2.5	26.4 ± 2.8
Salinity	PSU	57.75 ± 3.8	36.9 ± 1.1	34.87 ± 0.5
DO	%	66 ± 2.4	62.2 ± 4.3	59.4 ± 3.1
Al	mg/kg	28,955.24 ± 5146.3	15,193.62 ± 4151.2	5307.12 ± 1280.7
As	mg/kg	205.87 ± 44.1	398.01 ± 57.9	278.14 ± 64.4
B	mg/kg	193.22 ± 12.8	288.1 ± 93.5	320.74 ± 33.7
Ba	mg/kg	156.65 ± 21.2	60.82 ± 49.7	73.19 ± 59.9
Bi	mg/kg	<0.02	<0.02	112.73 ± 26.7
Ca	mg/kg	10,744 ± 220	15,866 ± 4358	144,436 ± 54,628
Cr	mg/kg	79.07 ± 60.1	2.8 ± 3.2	13.62 ± 5.3
Cr(VI)	mg/kg	94.08 ± 63.2	12.95 ± 6.7	12.03 ± 9.8
Fe	mg/kg	14981 ± 2644	5931 ± 966	4947 ± 163
Hf	mg/kg	1.2 ± 0.4	0.6 ± 0.8	0.6 ± 0.1
Ir	mg/kg	89.58 ± 10.7	166.71 ± 36.4	148.4 ± 57.9
K	mg/kg	207 ± 12	1487 ± 224	733 ± 162
Li	mg/kg	301.23 ± 3.2	280.22 ± 49.2	305.99 ± 43.5
Mg	mg/kg	1747 ± 192	10,815 ± 1717	7865 ± 807
Mn	mg/kg	236.96 ± 30.1	93.8 ± 8.8	510.88 ± 612.1
Sn	mg/kg	<0.02	<0.02	3.48 ± 389.2
Sr	mg/kg	687 ± 25	1077 ± 218	904 ± 398
Ti	mg/kg	927.35 ± 86.1	583.33 ± 102.3	339.64 ± 87.7
Zn	mg/kg	<0.02	<0.02	46.14 ± 26.8
Zr	mg/kg	7.03 ± 0.6	6.68 ± 3.7	7.66 ± 9.4

The variation in pH observed in the study area (Table 1) varied from 7.34 at the brine discharge point (St1) to 7.84 at 1000 m (St3), reflecting localized alterations likely driven by the chemical and physical properties of the discharged hypersaline effluent. Brine discharge typically increases the salinity and ionic strength, both of which can influence the apparent activity of hydrogen ions, leading to subtle shifts in pH. A marked decrease in salinity (S) from 57.75 PSU at St1 to 34.87 PSU at St3, and total dissolved solids (TDS) from 41.16 ppt to 26.40 ppt, suggests a plume dilution effect on increasing distance within a mixing zone with high ionic load and low buffer capacity of the effluent. This pattern aligns with the findings by [21], who reported that brine discharge from desalination plants can elevate local salinity levels, thereby affecting marine ecosystems. DO decreases from 66.0% to 59.4% due to a reduction in gas solubility or biological oxygen demand [6]. Therefore, an increase in carbonic acid in water may also lead to a reduction in pH.

To contextualize the observed environmental alterations in Caldera Bay (Table 1), comparisons with internationally recognized regulatory thresholds are essential. For example, in Spain, the management of SWRO brine discharge includes ecological protection criteria based on the EU Water Framework Directive, which limits salinity increases in the vicinity of sensitive habitats to no more than two PSU above natural background values [22]. Our findings show a salinity of 57.75 PSU at the discharge point compared to ~35 PSU at 1000 m, indicating a >20 PSU increase that significantly exceeds these protective thresholds.

Furthermore, sediment contamination by Cr(VI) reached 94.08 mg/kg, exceeding the effects range median (ERM) value of 81 mg/kg proposed in the NOAA's Sediment Quality Guidelines, which is also applied in EU marine monitoring programs as a threshold for indicating probable adverse biological effects [23]. The elevated concentrations of Fe and Al in sediments adjacent to desalination plant outfalls are primarily attributed to the use of metal salt coagulants, specifically $FeCl_3$, $Fe_2(SO_4)_3$, $AlCl_3$, and $Al_2(SO_4)_3$, during pretreatment processes for colloidal particle and dissolved organic matter removal [24]. Recent studies have confirmed that these compounds accumulate substantially in the porous sediment matrix near discharge points [25,26]. A documented case in the Arabian Gulf revealed Fe concentrations in sediments that were 9-fold higher (an order of magnitude) than those at control sites [26], whereas Sadiq [27] confirmed a statistically significant increase ($p < 0.05$) in Fe and other metalloid concentrations near brine outfalls, establishing a direct correlation with desalination operations. Although hexavalent chromium is not a typical byproduct of desalination, its detection in the study area suggests an exogenous origin. This element, historically used as a corrosion inhibitor in coastal infrastructure, may have resulted from pre-existing residual contamination associated with the recent construction of desalination plants.

These comparisons emphasize the ecological relevance of our findings and the urgent need to define national regulatory standards in Chile for brine-related parameters, such as salinity, trace metals, and physicochemical conditions. Implementing evidence-based thresholds similar to those of the EU would contribute to more sustainable desalination practices, particularly in vulnerable coastal ecosystems, such as Caldera Bay.

The analysis of nutrient concentrations in seawater samples from Caldera Bay (Table 2) reveals significant spatial variations in transect, which may be indicative of anthropogenic influences, particularly from the nearby desalination plant.

Table 2. Dissolved nutrient concentrations in seawater samples from Caldera Bay at St1 and St3. Data are presented as average (av) ± standard deviation (sd), with n = 3.

Station		Nitrate (µM)	Nitrite (µM)	Acid Silicic (µM)	Phosphate (µM)
St1	av	10.493	1.145	9.156	2.856
	sd	0.908	0.189	0.663	0.295
St2	av	3.493	0.833	6.317	2.149
	sd	0.305	0.097	0.806	0.362
St3	av	4.045	0.696	6.500	2.269
	sd	0.002	0.122	0.442	0.055

At discharge (St1), the nitrate concentrations averaged 10.493 µM, decreasing to 4.045 µM at St3. This reduction suggests a dilution effect or potential uptake by phytoplankton as the water moves away from the discharge point. The average nitrite concentration decreases from 1.145 µM at St1 to 0.696 µM at St3, indicating a similar spatial trend of nitrates. Silicic acid concentrations decreased from 9.156 µM at St1 to 6.500 µM at St3. Silicic acid is essential for diatom growth, and its reduction may impact the local diatom population, which plays a crucial role in the marine silica cycle [28]. Phosphate, a limiting nutrient in many marine ecosystems, dropped from 2.856 µM at St1 to 2.269 µM at St3. Physicochemical changes dynamically interact with the behavior of nutrients and contaminants. The nutrient concentrations (Table 2) decreased with increasing distance from the discharge point.

In addition to its interaction with natural seawater parameters, pH modulates the environmental behavior of chemical additives used in desalination, such as antiscalants and coagulants. Polyphosphonate-based antiscalants are pH-sensitive and can undergo hydrolysis under acidic conditions, releasing free phosphate and contributing to a localized nutrient increase [25,29]. Metal-based coagulants (e.g., Al or Fe salts) are also subject to pH-dependent speciation. At low pH, Al^{3+} and Fe^{3+} become more soluble and potentially toxic to aquatic life [25,30]. Moreover, some organic residues from antiscalants may form persistent or bioactive by-products under mildly acidic conditions, further stressing microbial communities and disrupting oxidative processes [31].

The combined influence of salinity and pH alters the geochemical behavior of both nutrients and metals. High salinity increases the ionic strength of seawater, promoting the formation of stable metal–chloride complexes. This process reduces the amount of free metal ions, such as Cu^{2+} and Zn^{2+}, which are typically the most toxic and bioavailable forms [32].

For example, concentrations of Al decreased from 28,955.24 mg/kg at St1 to 5307.12 mg/kg at St3, and Fe decreased from 14,981 mg/kg to 4947 mg/kg (Table 1). These levels are significantly higher than those reported in previous studies of Caldera Bay, where average Al and Fe concentrations were 1000 and 900 mg/kg, respectively [13], indicating potential contamination near the desalination plant. Although Sn was below the detection limits at St1 and St2, it was present at 3.48 mg/kg at St3. Cr concentrations were higher at St1 (79.07 mg/kg) and decreased at St2 and St3, but the toxic form Cr(VI) was also highest at St1 (94.08 mg/kg). The presence of contaminants such as Cr(VI), which is known for its toxicity [33], raises concerns about the ecological health of the bay. These findings underscore the need for comprehensive environmental monitoring and the implementation of mitigation strategies to minimize the impact of desalination activities on marine ecosystems.

Sola [14] conducted a similar physicochemical assessment in the same study area, but extended their methodology by including biological evaluations through biomarker analyses in the red macroalgae *Rhodymenia corallina*. They reported that salinity increases were less than 3.5% within the dispersion area, aligned with our findings of a salinity decrease from 57.75 PSU at the discharge point to 34.87 PSU at a 1000 m distance. Also, their study suggests that while brine discharge can cause short-term stress in marine organisms, recovery is possible if exposure is limited. Some other species from Atacama have demonstrated special salinity sensitivity. In particular, the seagrass endemism *Heterozostera nigricaulis* (syn. *Zostera chilensis*, *Z. nigricaulis*, and *H. tasmanica*) showed short-term hypersalinity tolerance with changes in ecophysiology, oxidative stress, and gene expression [34]. However, despite their ecological relevance, the installation of nearby desalination plants must be avoided.

The discharge of hypersaline brine from RO desalination plants poses significant environmental risks to marine ecosystems, particularly in semi-enclosed coastal bays with limited water circulation, as in this case. Minimization of environmental impact adoption may be a preventive measure using proper diffuser design and strategic outfall placement [35]. However, various strategies can mitigate the adverse impacts of brine discharge, which can be categorized into technological innovations, nature-based solutions, and regulatory measures.

Zero liquid discharge (ZLD) systems represent a promising technological approach to eliminate liquid waste through the recovery of both water and salts. Although traditional ZLD processes are energy-intensive and often economically unfeasible at large scales, recent developments have proposed innovative pathways that may redefine the current paradigm. Notably, [36] presented a disruptive ZLD technology that integrates solar-assisted evaporation and crystallization within a modular framework to demonstrate the technical feasibility of achieving complete brine elimination, along with the potential recovery of critical raw materials such as Mg and Li. The adoption of such closed-loop systems could enhance the sustainability of desalination processes by transforming brine from a waste stream into a resource, in line with circular economic principles.

Nature-based solutions, such as integrated multi-trophic aquaculture, can also mitigate localized impacts. Certain macroalgae and bivalves can assimilate nutrients and moderate salinity levels in coastal discharge areas, thus supporting ecosystem resilience and generating economic value [37,38].

Finally, effective mitigation requires a robust regulatory framework. Countries such as Spain have implemented an SWRO monitoring plan that, alongside brine discharge monitoring, establishes critical salinity thresholds by controlling protected species of high environmental value and utilizing bioindicator species, such as the seagrass *Posidonia oceanica*, which are sensitive to salinity [22]. The integration of marine spatial planning with environmental impact assessments can help to identify optimal discharge locations and avoid cumulative impacts in ecologically vulnerable areas.

4. Conclusions

This study demonstrates that brine discharge from a Caldera desalination plant significantly alters the marine environment in the immediate vicinity of the outfall. A marked increase in salinity was observed at St1 (57.75 PSU), representing more than a 20 PSU rise above ambient levels at 1000 m (34.87 PSU), which far exceeds international thresholds, such as the 2 PSU limit applied in the EU WFD for sensitive coastal areas.

Nutrient concentrations also displayed a clear spatial gradient, with nitrate decreasing from 10.493 μM at the discharge point to 4.045 μM at the farthest station and phosphate declining from 2.856 to 2.269 μM. These trends may reflect dilution and geochemical shifts driven by pH and salinity, which affect nutrient speciation and biological availability.

In sediments, concentrations of Cr(VI) reached 94.08 mg/kg at the discharge point, exceeding the NOAA ERM threshold of 81 mg/kg for probable ecological effects, and declined to 12.03 mg/kg at 1000 m. Similarly, Al and Fe concentrations near the outfall (28,955 and 14,981 mg/kg, respectively) were substantially higher than the background levels previously reported for Caldera Bay, suggesting that localized metal enrichment is likely associated with the brine plume.

These findings confirm that brine discharge influences both the water column and benthic compartment through changes in salinity, dissolved oxygen, pH, and contaminant loading. The observed chemical gradients underscore the need to treat brine outfalls as dynamic geochemical interfaces rather than as inert discharge points.

Given the absence of enforceable environmental thresholds for desalination effluents in Chile, this study supports the urgent development of science-based regulatory standards that incorporate both chemical and biological indicators. Future efforts should prioritize long-term monitoring, seasonal variability, and the integration of ecotoxicological endpoints to guide the sustainable management of desalination in vulnerable coastal systems, such as Caldera Bay.

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