Marine Pollution Bulletin 207 (2024) 116905

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Assessment of brine discharges dispersion for sustainable management of SWRO plants on the South American Pacific coast

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ARTICLE INFO

Keywords:
Brine discharge
Saline plume
Desalination
Environmental impact
Seawater reverse osmosis

ABSTRACT

Seawater desalination is one of the most feasible technologies for producing fresh water to address the water scarcity scenario worldwide. However, environmental concerns about the potential impact of brine discharge on marine ecosystems hinder or delay the development of desalination projects. In addition, scientific knowledge is lacking about the impact of brine discharges on the South America Pacific coast where desalination, is being developed. This paper presents the first monitoring results of brine discharge influence areas from seawater reverse osmosis desalination plants (SWRO) on the South America Pacific coast, using Chile as case study. Our results indicate that the combination of favorable oceanographic conditions and diffusers, results in the rapid dilution of brine discharge on coastal ecosystems; showing a faster dilution than other SWRO plants in other regions, such as Mediterranean or Arabian Gulf, with similar production characteristics. Also, the increase in salinity over the natural salinity in the brine-discharge-affected area was <5 % in a radius of <100 m from the discharge points. Further, according to the published literature and on our monitoring results, we propose a number of considerations (environmental regulation, best scientifically tested measures, environmental requirements) to achieve a long-term sustainable desalination operation.

1. Introduction

Water scarcity is a critical challenge in many regions worldwide (Greve et al., 2018). Water resources are strongly affected by the continuous increase in global freshwater demand for several uses, such as human consumption, industrial activities, and agriculture. In addition, climate change plays a significant role in reducing the available water resources in many regions (He et al., 2021; Sun et al., 2019). South America Pacific coast is one of the main regions affected by climate change, and scientific models predict drastically reduced precipitation, higher evaporation, more frequent droughts, and higher temperatures, which will severely affect the availability of its water resources (Garreaud et al., 2019; Valdés-Pineda et al., 2014). Moreover, some countries such as Chile, prediction models estimate alarming figures for 2030–2060 for the central–northern region, projecting a reduction of up to 50 % in available water resources; this can have serious socio-economic consequences, especially on productive activities (e.g., agriculture) or the population's consumption of drinking water (DGA, 2017; Garreaud et al., 2015). In addition, freshwater reservoirs and aquifers have been strongly affected by the increase in water demand for multiple uses, especially agricultural production, mining, and manufacturing, coupling with an increase in the fresh water demand (DGA, 2017; Garreaud et al., 2015).

Considering this water scarcity scenario, traditional water sources should be augmented by incorporating new alternatives that ensure the welfare of the population and the subsistence of agricultural activity. Among these alternatives, seawater desalination is considered a feasible technology worldwide for producing quality fresh water for multiple

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https://doi.org/10.1016/j.marpolbul.2024.116905
Received 18 July 2024; Received in revised form 19 August 2024; Accepted 27 August 2024

uses (Zarzo and Prats, 2018). It is also more advantageous than other alternatives; in the context of climate change, seawater is an unlimited water source; moreover, the quality of the desalinated water is suitable for human consumption, and this method can reduces the pressure on conventional water resources, such as underground basins or rivers (Eke et al., 2020; Sun et al., 2019).

Desalination is continuously growing, with >18,000 desalination plants in >170 countries (Eke et al., 2020). Among the South America Pacific coast, Chile is the leading country with the highest number of desalination projects; 22 seawater reverse osmosis (SWRO) projects are operating, and nine are being developed and/or constructed with environmental approval from the Environmental Assessment Service (SEA) (ACADES, 2023). These projects have a total production capacity of approximately 708,500 m^3/day (8200 L/s). In addition, the 12 projects currently being evaluated by the SEA may further increase Chile's desalination capacity to 2,150,000 m^3/day (25,000 L/s). Further, some other countries along the South America Pacific coast (e.g., Peru, Ecuador) are experiencing continued growth in desalination (Eke et al., 2020).

Reverse osmosis (RO) is the most widely used desalination technology worldwide because it has higher energy efficiency and lower cost of producing desalinated water compared with other technologies (Jones et al., 2019; Zarzo and Prats, 2018). This process mainly involves separating salts and minerals from seawater intake to produce fresh water for drinking water, agriculture, industrial activities (e.g., mining and power plants), tourism, and other purposes (Eke et al., 2020). Desalination via RO yields fresh water and effluent called brine discharge. This effluent is mainly characterized by a high salinity concentration that can double seawater salinity, depending on the seawater intake salinity and the process recovery rate (Abessi, 2018). It may contain certain chemicals that are commonly used during pretreatment and membrane and filter cleaning, including antiscalants (e.g., phosphonates and polyacrylic acid), disinfecting agents (e.g., sodium hypochlorite), coagulants (e.g., ferric chloride and iron sulfate), scaling agents, biocides, and defoamers; these chemicals, which are commonly released along with brine discharge, affect the physicochemical quality of RO effluent (Belkin et al., 2017; Panagopoulos and Haralambous, 2020; Rivero-Falcón et al., 2023; Sisma-ventura et al., 2022).

Different methods are used to dispose of brine discharge, (e.g. deep wells, discharges mixed with other industrial or sewage effluents, evaporation ponds) but submarine outfalls to the sea (or coastal discharge) are the most commonly used globally because they have lower economic costs than other methods (Fernández-Torquemada et al., 2019; Missimer and Maliva, 2018). When released to seawater, brine discharge forms a high-density saline plume, which advances through the seabed of the receiving marine environment, affecting the water column stratification (Fernández-Torquemada et al., 2009; Sola et al., 2020a).

The dispersion of a saline plume depends on several factors, such as brine salinity after desalination process, the production capacity of the desalination plant, oceanographic conditions (e.g., currents, natural salinity, and depth), the geomorphological conditions of the seabed (e.g., bottom type, slope, and bottom viscosity), and the technology used in the submarine outfall (Fernández-Torquemada et al., 2019; Loya-Fernández et al., 2018). Saline plumes can extend from tens of meters to kilometers from the discharge point, with the maximum salinity increment (over the natural salinity) ranging from 1 % to 16 % (Kress et al., 2020). For example, at the Mostaganem desalination plant in Algeria, researchers observed salinity increments of up to 9 % and a saline plume reach of up to 200 m (Belatoui et al., 2017); at the Hadera desalination plant in Israel, salinity increments of up to 10 % were observed, and the saline plume extended to 2.5 km (Kress et al., 2020); at the Carlsbad desalination plant in California, salinity increments of up to 13 % and a plume extension of 1 km were seen (Petersen et al., 2019).

The potential impact of brine discharge on marine ecosystems is one of the most significant environmental impacts associated with the development of desalination plants (Heck et al., 2018; Kress, 2019). Therefore, the brine plumes from desalination plants should be characterized to determine their impact on seawater quality and benthic communities near brine discharge locations (Fernández-Torquemada et al., 2019; Sola et al., 2019b). Brine discharge can induce biotic and abiotic disturbances in ecosystems when it is incorrectly diluted under the adopted corrective and preventive measures (Sadhwani Alonso and Melián-Martel, 2018; Sirota et al., 2024). It mainly affects sessile organisms or organisms with low mobility capacity, which cannot escape impact areas, and low tolerance for salinity changes. It may also affect planktonic stages of fish and crustaceans which do not have a wide range of salinity tolerance during their early development (De-la-Ossa-Carretero et al., 2016b; Del-Pilar-Ruso et al., 2015; Petersen et al., 2018; Sharifinia et al., 2019; Sirota et al., 2024). However, these negative effects may depend on different factors, such as the maximum salinity increment, the duration of exposure to this salinity, and species sensitivity (Petersen et al., 2018; Sharifinia et al., 2019).

Negative effects have been observed in the growth rate, photosynthetic rate, survival, oxidative stress, osmotic potential, density, and/or cover of seagrasses. For example, in the Mediterranean and Australian regions, adverse impacts have been seen in the endemic species *Posidonia oceanica* and *P. australis*, respectively (Cambridge et al., 2017; Capó et al., 2020; Sola et al., 2020b). Likewise, impacts on benthic fauna have been observed, such as the reduced abundance of echinoderms (e.g., *Echinaster sepositus* and *Holothuria* spp.) (Fernández-Torquemada et al., 2013) and changes in the community composition of soft-bottom benthic communities (e.g., Polychaeta and Amphipoda) that affect their diversity, abundance, and richness (De-la-Ossa-Carretero et al., 2016c, 2016a; Del-Pilar-Ruso et al., 2015).

Recent studies highlighted the adverse effects of brine discharge on the photosynthetic rate and oxidative stress of macroalgae (*Ectocarpus* sp. and *Dictyota kunthii*) transplanted in the discharge area of an SWRO in La Chimba (Antofagasta, Chile) exposed to salinities that were >7 % higher than the natural salinity (34.4 psu) (Muñoz et al., 2023a, 2023b). A recent study on Chilean seagrass (*Zostera chilensis*) under experimental laboratory conditions showed that exposure to salinities that were >8 % higher than the natural salinity (34 psu) negatively affected its photosynthetic rate and increased its oxidative stress (Blanco-Murillo et al., 2023).

Scientific studies on brine discharge dispersion have been conducted mainly in the Mediterranean Sea, the Arabian Gulf, and Australia, where desalination capacity is extensively developed (Kress et al., 2020). However, scientific knowledge is lacking in some regions where desalination is under continuous development, such as the South America Pacific coast (Eke et al., 2020; Sola et al., 2021). Thus, this study aims to analyze the dispersion of saline plumes from the brine discharge of SWRO plants with different production capacities along the South America Pacific coast, using Chile as a case study. This study includes (a) estimates of the areas affected by saline plumes from the desalination plants, (b) a calculation of the salinity increment in the study area, and (c) the development of an underwater conductivity, temperature, and depth (CTD) survey exploring saline plume dispersion in the near field of brine discharge outfalls.

2. Materials and methods

2.1. Case studies

2.1.1. Aguas Antofagasta desalination plant

Aguas Antofagasta's SWRO plant is in La Chimba, Antofagasta Region, Chile (Fig. 1). The plant started operating in 2003 and has a maximum desalinated water production capacity of approximately 84,600 m^3/day (980 L/s); therefore, its maximum brine discharge production capacity at a recovery rate of 45 % is approximately 103,400 m^3/day (Mezher et al., 2011). Its freshwater production is consistent over time and maintained at maximum capacity. The produced

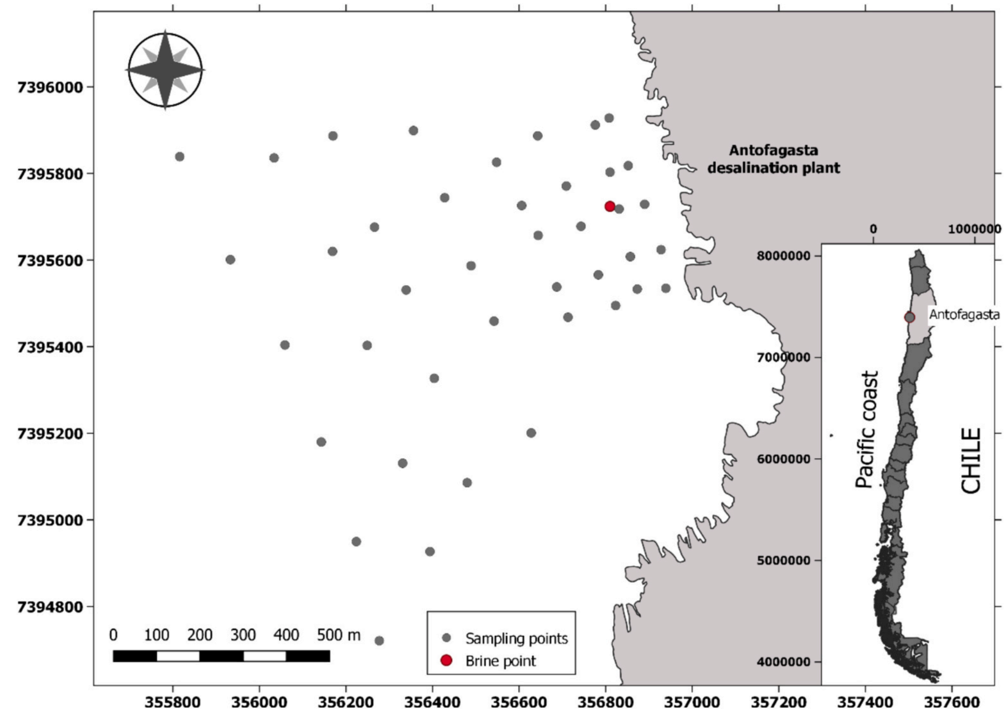

Fig. 1. Study area with sampling points of CTD survey conducted on Aguas Antofagasta's SWRO plant, Antofagasta Region.

desalinated water is mainly for human consumption.

Brine is discharged through a 266 m-long and submarine outfall from the coastline at a depth of 15 m through four L-shaped diffusers with a height of 40 cm and an angle of 90°, separated approximately every 5.5 m and oriented alternately to the north and south. The seawater at the intake is drawn in through a 350 m submarine pipeline at a depth of 15 m.

2.1.2. Minera Escondida desalination plant

Minera Escondida's SWRO plant, located in Coloso Port, Antofagasta Region, has the largest production capacity in Latin America (Fig. 2). The plant began operating in 2017 and has a maximum desalinated water production capacity of approximately 328,000 m^3/day (3800 L/s), which translates to a brine discharge production capacity of approximately 389,000 m^3/day at a recovery rate of 45 % (Mezher et al., 2011). The produced fresh water is consistent over time and is mainly used in the mining industry.

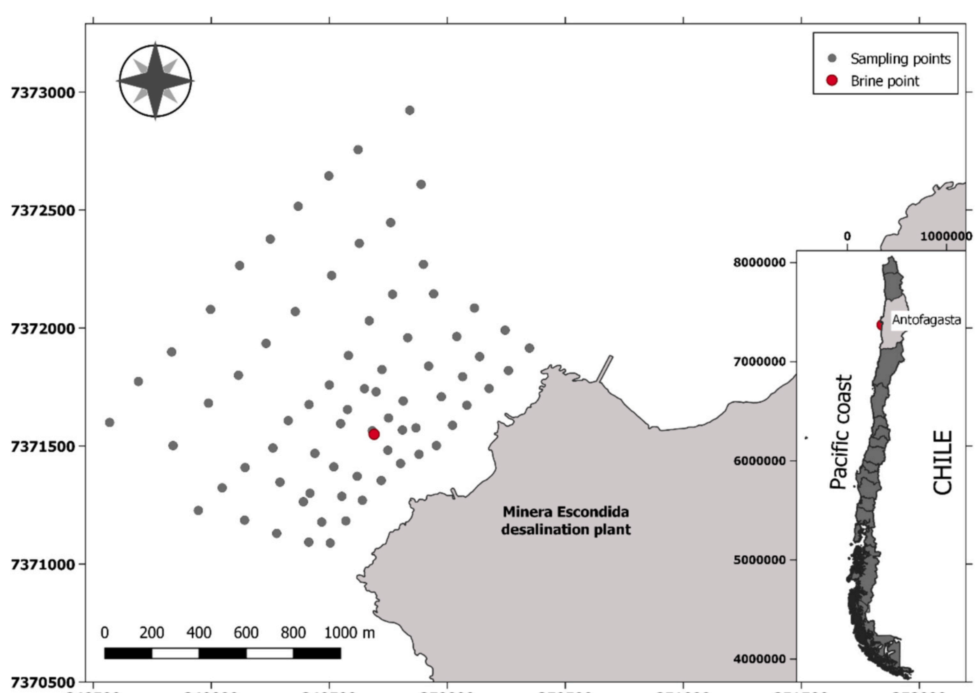

Fig. 2. Study area with sampling points of CTD survey conducted on Minera Escondida's SWRO plant, Antofagasta Region.

Its brine discharge is disposed through two parallel 400 m-long submarine outfalls from the coastline at a depth of 20 m and both through 12 diffusers with an angle of 30° installed along the last 77 m of each pipeline, separated every 7 m and oriented alternately to the north and south. The seawater at the intake is drawn in through a 580 m submarine pipeline at a depth of 26 m.

2.1.3. Candelaria desalination plant

The Candelaria desalination plant is located in the Bay of Caldera, Atacama Region (Fig. 3). The plant started operating in 2013 and has a maximum desalinated water production capacity of 43,200 m^3/day (500 L/s), which means the brine discharge production capacity is approximately 52,200 m^3/day at a recovery rate of 45 % (Mezher et al., 2011). The produced desalinated water is mainly used in the mining industry.

Brine is discharged through a 260 m-long submarine outfall from the coastline at a depth of 25 m through eight diffusers with a diameter of approximately 650 mm and an angle of 45° installed along the last 40 m of the pipeline, separated approximately every 5 m and oriented alternately to the north and south (Fig. 4). The seawater at the intake is drawn in through a 580 m submarine pipeline at a depth of 26 m.

2.2. Sampling and data processing

We performed an oceanographic survey at each desalination plant to assess the saline plume dispersion of its brine discharge. A grid of sampling points was designed at each desalination plant following a previous methodology (Fernández-Torquemada et al., 2009; Sola et al., 2020a), which enabled a thorough analysis of the dispersion pattern of the saline plume until its complete dilution. The extension of the studied area and the grid spacing between stations depended on the production of the desalination plant, the discharge type, and the receiving environment (bathymetry and hydrodynamic regimes). The grid spacing between sampling stations ranged from 50 m to 200 m. At each sampling station, continuous vertical profiling of salinity was conducted using a CTD device; salinity, temperature, and depth were measured every second until the bottom was reached. The CTD device was an *RBR Concerto*, which has a measurement range of 0–70 psu and a resolution of ±0.01 psu. All stations were positioned using a GPS handheld (*Garmin eTrex 20*; precision: ±5 m) based on UTM coordinates. The number of stations, ranging from 40 (Aguas Antofagasta) to 73 (Minera Escondida), was established depending on the plume size.

The surveys were conducted in the daytime on August 21, 2022, at Candelaria's SWRO plant, May 7, 2019, at Minera Escondida's SWRO plant, and May 4, 2019, at Aguas Antofagasta's SWRO plant. The CTD measurements were performed from a boat suitable for conducting scientific and/or professional work at sea. All surveys were conducted under calm sea conditions: waves below 0.5 m and wind speeds of <10 km/h; in order to avoid underestimating the maximum influence area of the brine discharges, since higher waves and currents result in a faster dilution of the discharges (Fernández-Torquemada et al., 2009; Loya-Fernández et al., 2012).

The salinity values were set to the seawater salinity measured in the last meter over the bottom for each sampling station due to the characteristics and thickness of the saline plume related to the seabed (Fernández-Torquemada et al., 2019). The saline plumes form a high-density plume that follows the bottom bathymetry. For that, we did not identify differences in surface salinity measurements at any SWRO plant evaluated, as observed in previous studies (Kress et al., 2020; Sola et al., 2020a). Further, at each station except those in Aguas Antofagasta's SWRO plant, the maximum and average salinities were defined for interpolation analysis. At Aguas Antofagasta's SWRO plant, only the average values were obtained because the values were very similar.

An underwater CTD survey was conducted in the daytime on August 27, 2022, at Candelaria's SWRO plant. This survey allowed us to study the saline plume dispersion in the near field of the outfall with improved accuracy and robustness (Loya-Fernández et al., 2018; Palomar et al., 2012). For this purpose, an additional 42-point grid was defined with a 30 m extension on each side of the outfall and a 20 m extension following the maximum-slope line from the last diffuser (Fig. 3). At each sampling station, salinity was measured by a scuba diver for 1 min at the bottom using a CTD device. For each station, the maximum and average salinities were defined for interpolation analysis.

The salinity increment over that of the reference seawater (natural

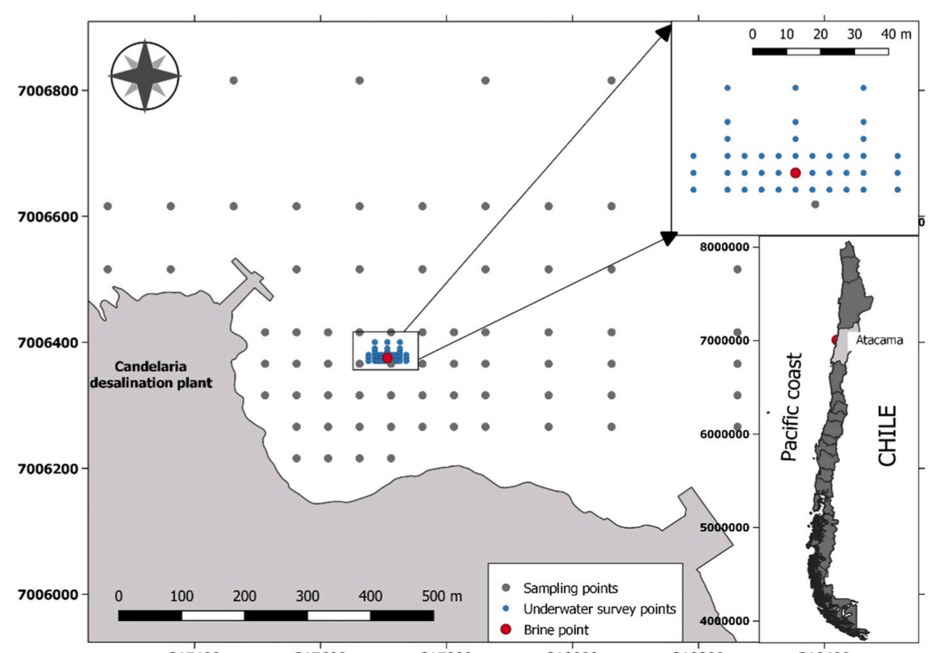

Fig. 3. Study area with sampling points of CTD surveys conducted on Candelaria's SWRO plant, Atacama Region. The dark gray sampling points indicate the boat CTD survey, and the blue points refer to the underwater CTD survey. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

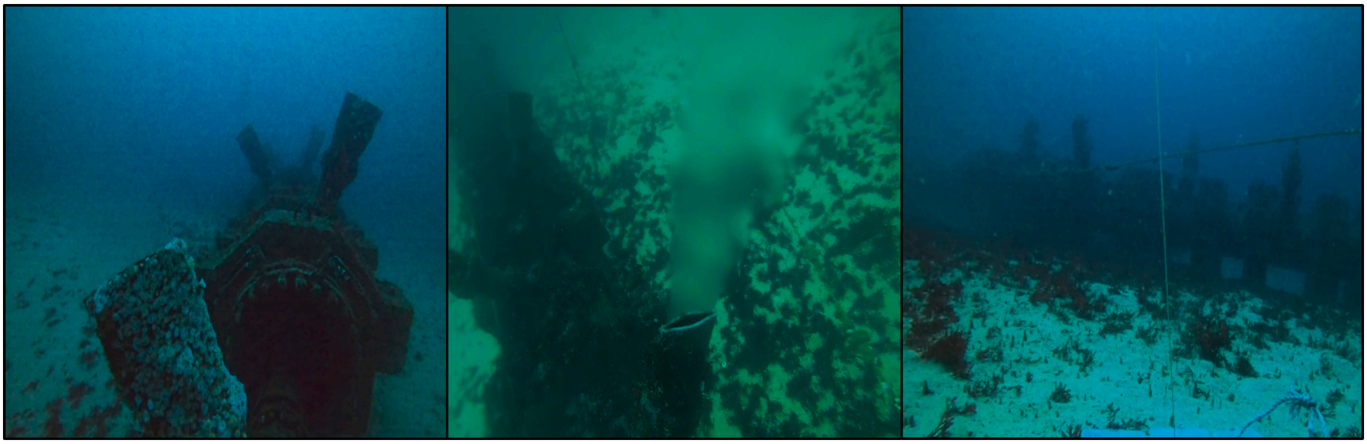

Fig. 4. Brine discharge outfall from Candelaria desalination plant.

conditions, not affected by saline plumes) was calculated as a percentage of the reference for each data point. Natural salinity values were measured using the CTD device >5 km from the brine discharge point of each SWRO plant; the average values were 34.4 psu for Minera Escondida and 34.45 psu for Aguas Antofagasta and Candelaria.

2.3. Statistical analysis and spatial representation

The salinity data obtained from each survey were analyzed via kriging spatial interpolation to obtain a real representation of the saline plume in the space. In the kriging method, the sampled data points were used to estimate salinity values over a continuous spatial area. The applied model has been validated in previous works (Fernández-Torquemada et al., 2009; Sola et al., 2020a). Kriging interpolation and model cross-validation were conducted using the Geostatistical Analyst extension in the software ArcGIS© Pro version 3.0.3. The representation of spatial maps and the measurement of affected areas were performed using the software QGIS version 3.10.

3. Results

3.1. Brine discharge dispersion from desalination plants

The saline plume from Minera Escondida's brine discharge showed

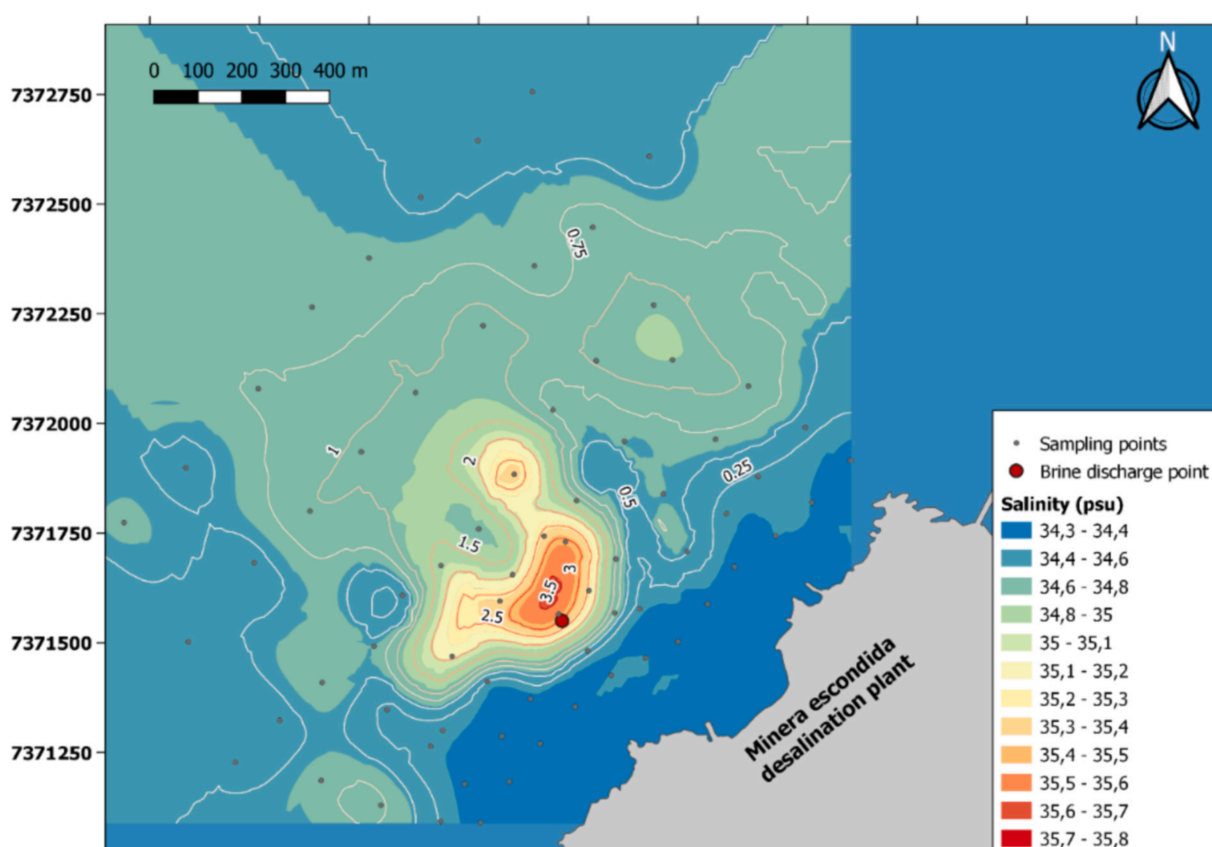

Fig. 5. Spatial representation of saline plume dispersion from Minera Escondida desalination plant. The isolines indicate the percentage of salinity above the natural salinity. This map was created using average salinity values from the survey performed on May 7, 2019.

the largest brine influence area among the case studies analyzed, showing a dispersion pattern whose line of maximum depth was in the northwest direction. The maximum salinity measured was 35.52 psu, which was >3.26 % higher than the natural salinity (Fig. 5). Salinity increments of above 1 % extended to over 500 m from the discharge point, although the maximum salinity was reduced to <35 psu (1.5 % higher than the natural salinity) within 150 m of the discharge point.

Fig. 6 shows the saline plume dispersion of Minera Escondida's SWRO plant, including the maximum salinity values regarding the natural environmental conditions. The maximum salinity measured was 35.7 psu, which was >3.78 % higher than the natural salinity. Saline plumes with salinity increments of above 1 % reached >1 km northward from the brine discharge point.

In the dispersion pattern of the saline plume from the Aguas Antofagasta desalination plant, the line of maximum depth was in the west direction from the brine discharge location. The maximum salinity measured was 35.85 psu, which was >4.06 % of the natural salinity (Fig. 7). Salinity increments of above 1 % extended to >600 m from the discharge point.

The saline plume from Candelaria's SWRO plant showed an extension area of approximately 100 m from the discharge outfall, and the line of maximum depth in its dispersion pattern was in the north direction (Fig. 8). The underwater survey results showed salinity values of above 56 psu from the outfall diffusers, but these were drastically reduced to below 36 psu in the first 5 m from the discharge point of each diffuser. The maximum salinity measured was 35.6 psu, corresponding to >3.34 % of the natural salinity, at 10 m from the discharge point. However, salinity was reduced to below 35 psu in <30 m (1.5 % over the natural salinity) from the discharge point.

Fig. 9 shows the saline plume dispersion of Candelaria's desalination plant, including the maximum salinity values regarding the natural environmental conditions. The maximum salinity measured through the underwater survey was 35.85 psu, which was >4.06 % of the natural salinity, at 10 m from the discharge point. The salinity increment in this area was reduced by <1 % within 50 m of the discharge point.

3.2. Salinity excess over natural conditions

The brine dispersion areas of the three desalination plants showed maximum salinity increments of below 5 % (Table 1). The maximum salinity increment was measured in Aguas Antofagasta, which was 4.06 % (35.85 psu) and reached approximately 23 m from the brine discharge point. This was followed by the affected area at the Candelaria desalination plant, which showed a salinity increment of 3.34 % (35.6 psu) but spread to only 10 m from the discharge point. Finally, Minera Escondida's SWRO plant had a salinity increment of 3.26 % (35.52 psu) up to approximately 17 m from the discharge point.

The brine dispersion from Minera Escondida showed the largest affected area; the salinity increment was ≥3 %, covering approximately 20 km^2 and reaching 178 m from the discharge point. On the contrary, the affected area of Candelaria's brine discharge had a salinity increment of ≥3 %, covering approximately 0.01 km^2 and extending only to 20 m from the discharge point. Likewise, the saline plume from the Aguas Antofagasta SWRO plant affected an area of approximately 18 km^2 and reached 80 m from the discharge point.

In the Candelaria and Aguas Antofagasta SWRO plants, the areas with salinity increments of ≥2 % ranged from 1 km^2 to 109 km^2 and extended to 20 and 509 m, respectively. In the Candelaria and Minera Escondida SWRO plants, the saline plume areas with salinity increments of >1 % ranged from 4 km^2 to 380 km^2 and extended to 45 and 750 m, respectively.

4. Discussion

Desalination is a major method for addressing the water scarcity and increased water demand in some regions worldwide (Eke et al., 2020). However, in some countries, such as the USA and Chile, environmental concerns hinder the development of desalination projects, especially the potential environmental impacts of brine discharge on coastal ecosystems (Heck et al., 2018; Sola et al., 2021). Moreover, most existing studies on the potential impact and management of brine discharge were

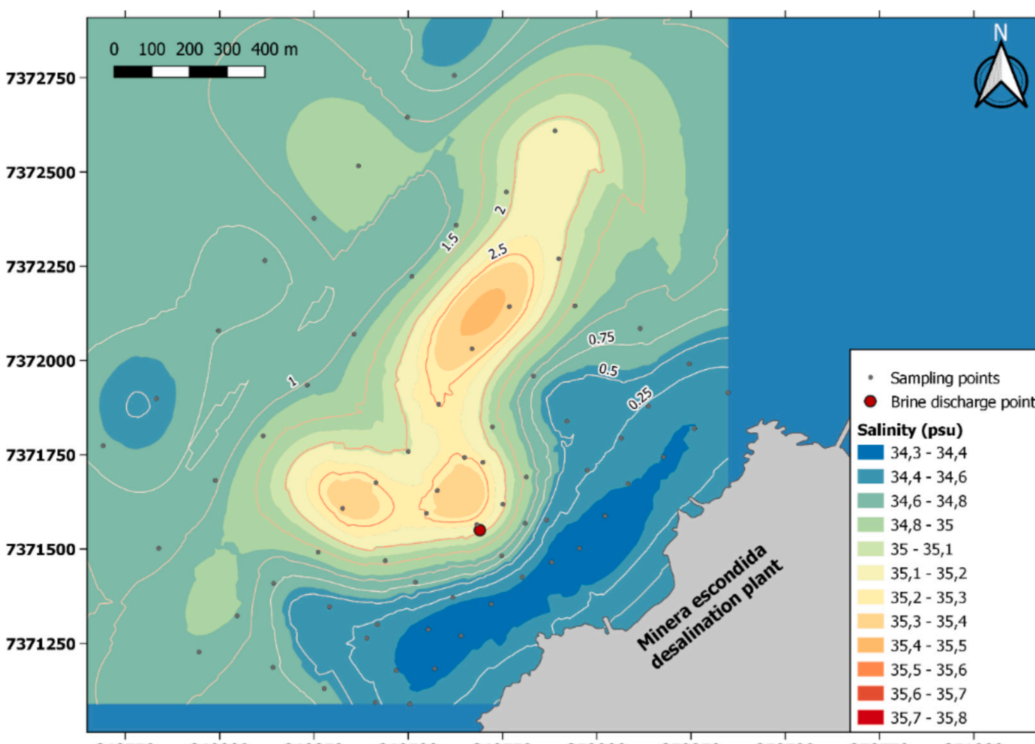

Fig. 6. Spatial representation of saline plume dispersion from Minera Escondida desalination plant. The isolines indicate the percentage of salinity above the natural salinity. This map was created using maximum salinity values from the survey performed on May 7, 2019.

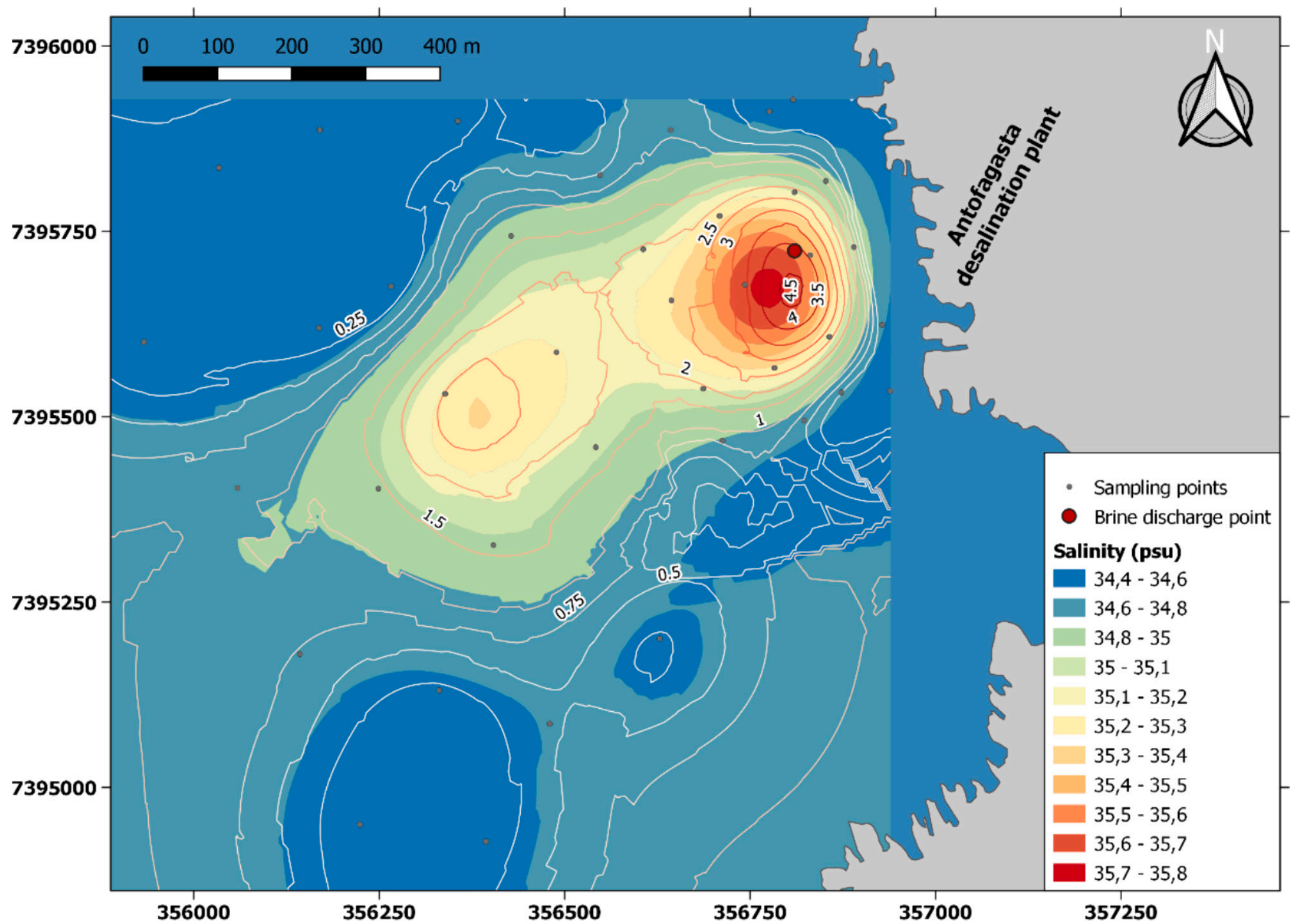

Fig. 7. Spatial representation of saline plume dispersion from Aguas Antofagasta desalination plant. The isolines indicate the percentage of salinity above the natural salinity. This map was created using average salinity values from the survey performed on May 4, 2019.

conducted in Mediterranean coastal areas, so their findings cannot be extrapolated to the oceanographic and ecosystem characteristics of the South America Pacific coast. The current paper presents the first scientific results characterizing the behavior and affected area of brine discharge from three SWRO plants, which use submarine outfalls as their disposal method, located along the South America Pacific coast region.

Among the case studies evaluated, the brine discharge from the Minera Escondida SWRO plant showed the largest affected area (Table 1), mainly due to its higher production capacity. Nevertheless, the Minera Escondida and Aguas Antofagasta SWRO plants showed similar affected areas with salinity increments of >1 %, reaching 750 and 650 m, respectively, despite the production capacity of the former being approximately four times that of the latter. This may be justified because the Aguas Antofagasta SWRO has only four diffusers and has lower efficiency than newer desalination plants that use new diffusers (e.g., Venturi diffusers, diffusers with reduced discharge nozzles) or larger numbers of diffusers (Kelaher et al., 2020; Portillo et al., 2013). Moreover, the Aguas Antofagasta plant's diffusers have an inclination angle of 90° to the Y axis, so their efficiency of brine discharge dilution is lower than that of new diffusers, whose inclination angles are approximately 45° (Fernández-Torquemada et al., 2019; Kress et al., 2020; Portillo et al., 2014). This has been observed in other desalination plants monitored in the Mediterranean region: the brine discharge area significantly enlarges due to increases in production capacity during seasonal fluctuations, but the saline plume dispersion area is significantly reduced using effective mitigation measures (Fernández-Torquemada et al., 2019; Sola et al., 2020a, 2020b).

In the case of the Candelaria SWRO plant, our results indicated that the saline plume dispersion area was limited. The salinity increment was <1 %, which reached a radius of <100 m from the discharge point. This may be justified, as the maximum production capacity of the plant is 43,200 m^3/day (500 L/s). Moreover, the plant was operating below its maximum capacity during the survey. It also has eight efficient diffusers and a steep seabed slope, enabling rapid dilution in the receiving marine environment.

In general, our results indicated that the salinity increment (over the natural salinity, 34.4 psu) in the brine-discharge-affected areas of the desalination plants evaluated was below 5 % within a radius of <100 m from the discharge points. Moreover, the effluents were rapidly diluted upon contact with the receiving marine environment. The maximum salinity values ranged from 3.26 % to 4.06 % (35.23–35.85 psu), showing a maximum salinity increment of 1.6 psu. According to the obtained results, these salinity increments have reduced potential environmental effects on coastal ecosystems over 50 m from the discharge point, where the salinity of a saline plume is drastically reduced (Muñoz et al., 2023a).

In addition, the saline plume dispersion of the studied SWRO plants showed faster dilution than in SWRO plants in other regions with similar production characteristics and brine discharge disposal method, where saline plumes reach several hundreds of meters from discharge points (Kress et al., 2020; Sola et al., 2020b). For example, at the Ashqelon desalination plant (Israel; 329,000 m^3/day), salt plumes were observed up to 3 km from the outfall point, and the maximum salinity increment was 10 %; at Palmachim desalination plant (Israel), the maximum salinity increment was 12.8 %, and a salinity increment of 1 % was observed over an area of up to 4.4 km (Kress et al., 2020). In Spain, at the San Pedro del Pinatar desalination plants, with a production capacity of 134,000 m^3/day, a salinity increment of 1 % was observed over a 2–3

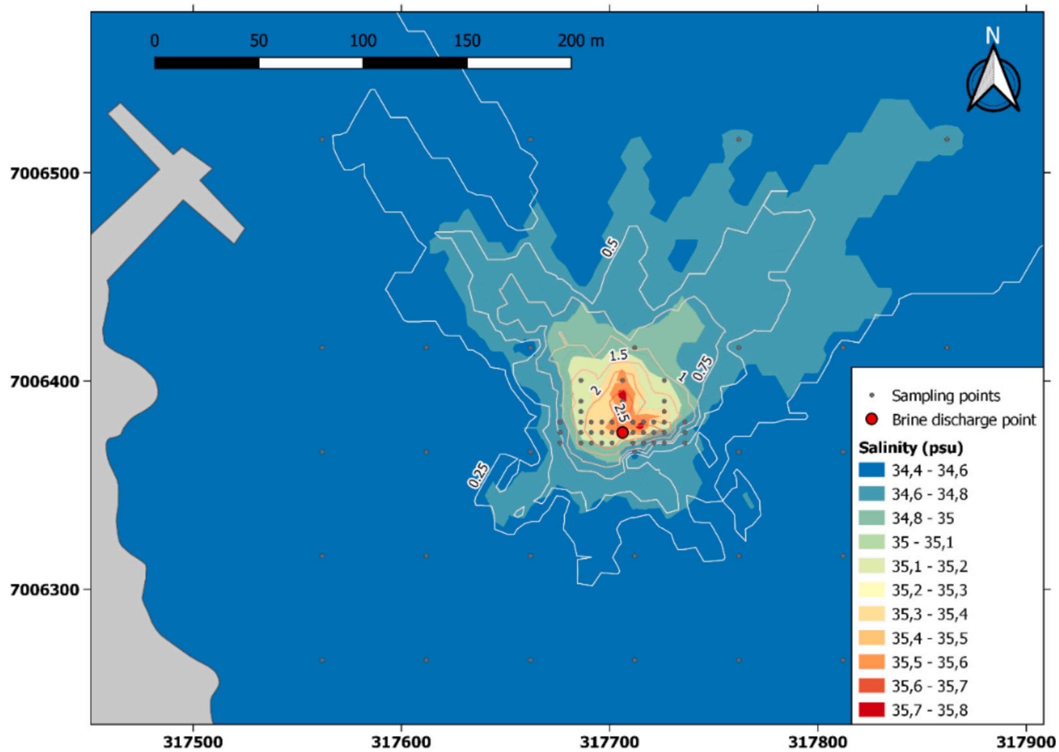

Fig. 8. Spatial representation of saline plume dispersion from Candelaria desalination plant. The isolines indicate the percentage of salinity above the natural salinity. This map was created using salinity values from the surveys performed on August 21 and 27, 2022.

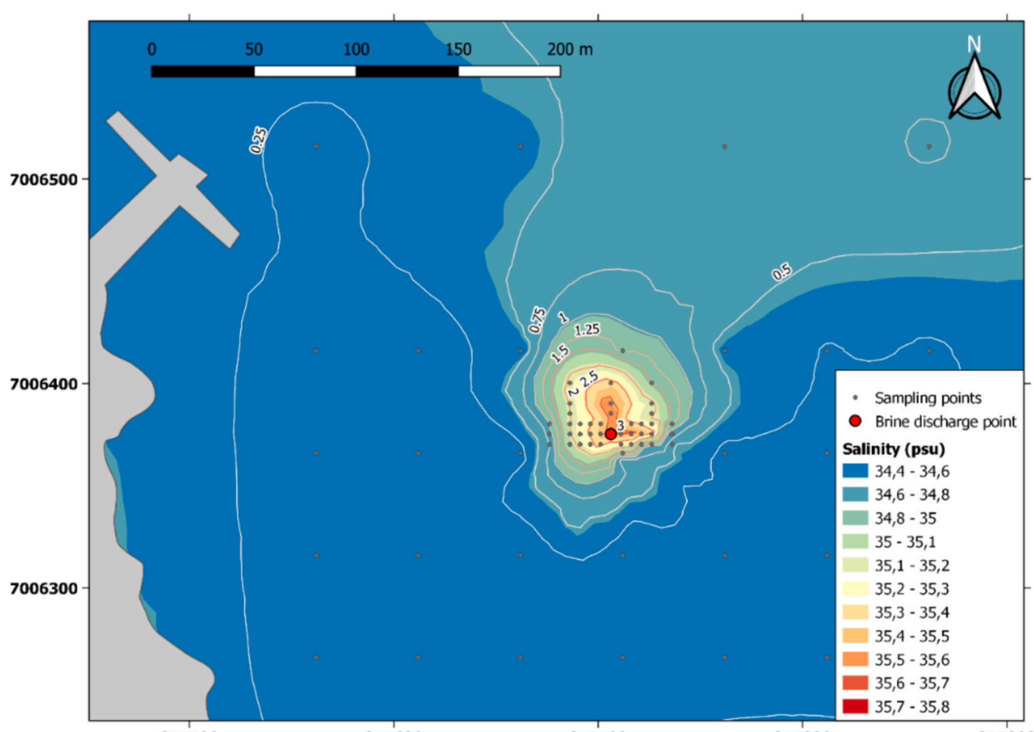

Fig. 9. Spatial representation of saline plume dispersion from Candelaria's SWRO plant. The isolines indicate the percentage of salinity above the natural salinity. This map was created using maximum salinity values from the surveys performed on August 21 and 27, 2022.

km area, and the maximum salinity increment measured was 15 %; at the Alicante desalination plants, which use a predilution system with seawater and have a total production capacity of 130,000 m^3/day, a salinity increment of 1 % was observed over an area exceeding 1 km (Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2009; Sola et al., 2020b). At the Mostaganem desalination plant (Algeria), which has a production capacity of 200,000 m^3/day and uses an outfall with an alternating diffuser system, the maximum salinity increment was 9 %,

Table 1
Identification of areas with excess salinity and their maximum distances reached for all desalination plants.

Area of excess salinity (km^2)							Maximum excess salinity	
SWRO plant	≥1 %	Distance (m)	≥2 %	Distance (m)	≥3 %	Distance (m)	Excess (%)	Distance (m)
Minera Escondida	380.42	750.0	93.95	352.0	20.18	178.00	3.26	17.0
Aguas Antofagasta	368.98	650.0	108.92	509.0	17.69	80.00	4.06	23.0
Candelaria	4.22	45.0	1.00	30.0	0.01	20.00	3.34	10.0

and salinity increments of above 1 % extended to >600 m (Belatoui et al., 2017).

Chile's coastline is characterized by strong currents and hydrodynamism, lower natural salinity than other regions (34.4 psu average natural salinity vs. 37.5 psu in the Mediterranean or 40 psu in the Red Sea), and particular oceanographic and geomorphological dynamics (e.g., seabed with a steep slope and a high depth); according to our results, the combination of the abovementioned factors and diffuser use results in the rapid dilution of brine discharge, even without predilution with seawater (Muñoz et al., 2023a; Navarro Barrio et al., 2021). The seas in the Mediterranean or Arabian Gulf regions have limited openings to the ocean and hence low currents. Likewise, coastal areas are shallow, and long distances are required to reach depths of over 20 m (Fernández-Torquemada et al., 2009; Sharifinia et al., 2019; Sola et al., 2020b). However, this study could be extended to further explore the particular oceanographic and geomorphological dynamics of Chile's coastline and how they specifically influence the dispersion of brine discharges.

In this study, an underwater CTD survey was performed to study with high accuracy the behavior of the saline plume dispersion every 5 m from the discharge point. The results suggested that salinity from the point of discharge (50–56 psu) was drastically reduced to below 36 psu at 5 m. Additionally, these results can help to enhance the robustness and understanding of the predictions of near-field mixing zone models (e.g., CORMIX and UM3) to be developed on the northern coast of Chile (Loya-Fernández et al., 2018, 2012; Palomar et al., 2012).

Some countries on the South America Pacific coast, such as Chile, have no specific environmental laws regulating the salinity increments in saline-plume-affected areas with respect to the distance from the discharge point (Sola et al., 2019a). Spain, for example, has strict environmental regulations; when seagrasses of high ecosystem relevance are identified in an area affected by brine discharge, salinity should not exceed approximately 2.5 % (5 %) of the natural salinity in 25 % of observations at the lower limit of detection for *P. oceanica* (*C. nodosa*), or approximately 6.5 % (9 %) in 5 % of observations, respectively (Navarro Barrio et al., 2021; Sánchez-Lizaso et al., 2008); in Western Australia, the salinity increment in a saline plume area cannot exceed 5 % within a distance of 100 m from the discharge point (Jenkins et al., 2012); in California, the salinity increment should not exceed 2 psu (6 % increase) within 100 m from the discharge point (Petersen et al., 2019).

Nevertheless, our results show that the studied desalination plants under hydrodynamic conditions studied comply with global environmental guidelines regarding permissible salinity increments; specifically, the brine discharge of the evaluated plants is diluted rapidly in the marine environment in the near field (Jenkins et al., 2012). In addition, our results coincide with the results obtained recently in (Santana-Anticoy and Sola, 2024), which evaluates the brine discharge dispersion from the Nueva Atacama SWRO plant located in the north of Chile (close to the Candelaria SWRO plant evaluated in this study), showing the increase in salinity over the natural salinity in the brine-discharge-affected area was <4 % in a radius of <50 m from the discharge point. Also, our results comply with the recently published results by (Pereira et al., 2024), showing a fast dilution of the brine discharge from the Nueva Atacama SWRO plant using a near-field mixing zone model under different modelling conditions (e.g. currents, hydrodynamic conditions, diffusers configuration, bathymetry, among others).

However, based on our experience and analysis results, projects should include the following components for sustainable long-term desalination operation: (i) A specific environmental regulation regarding the maximum salinity increment in an affected area should be established. It may adopt a globally permissible standard (e.g., the salinity increment cannot exceed 5 % within a distance of 100 m from the discharge point) (Jenkins et al., 2012). However, it should be based on scientific results that evaluate the specific tolerance according to the characteristics of the ecosystems present in the study area, and be flexible enough to incorporate modifications according to the latest scientific knowledge. (ii) A rigorous environmental assessment process should be implemented in cooperation between public-private sector with the scientific sector and/or academia. This ensures the adoption of the best scientifically tested measures for minimizing the impacts of brine discharge on marine ecosystems (e.g., diffusers and/or predilution of discharge using seawater or other substances), such measures must be tailored to the type and size of each desalination plant and the hydrogeological conditions in the discharge area to accelerate the mixing of the discharge with the marine environment (Fernández-Torquemada et al., 2019; Gude, 2016; Sola et al., 2020b, 2020a). (iii) A rigorous environmental monitoring plan should be implemented. It should fulfill the appropriate requirements for ensuring the sustainable long-term operation of desalination plants in marine ecosystems (Petersen et al., 2018; Sola et al., 2019b). The requirements established by existing projects are highly heterogeneous, and not all projects involve a rigorous characterization of saline plumes for adequate knowledge of areas affected by brine discharge (Sola et al., 2019a).

5. Conclusions

Our results indicated that the increase in salinity over the natural salinity of the sea (34.4 psu) in the brine-discharge-affected area of the three evaluated desalination plants was <5 % in a radius of <100 m from the discharge points. Moreover, their brine discharge was rapidly diluted upon contact with the receiving marine environment. The area's strong oceanographic dynamics, low salinity (compared with other regions globally), and coastal geomorphology may facilitate such rapid dilution on the South Pacific coast of Chile compared to Mediterranean or Arabian Gulf regions. Considering the expected development of desalination, specific environmental regulations should be implemented in countries without environmental regulations to establish maximum permissible salinity increments in brine-discharge-affected areas. Furthermore, collaboration between public-private sector with the scientific sector during the environmental assessment of projects should be emphasized to implement the most appropriate prevention and mitigation measures during environmental assessment process. This will ensure the execution of the best mitigation measures and sustainable practices in new desalination projects, prevent socio-environmental conflicts, and ensure the use of desalination as a sustainable long-term solution to water scarcity.

CRediT authorship contribution statement

Iván Sola: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Adoración Carratalá:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Jeniffer Pereira-**

Rojas: Investigation, Conceptualization. **María José Díaz:** Writing – review & editing, Conceptualization. **Fernanda Rodríguez-Rojas:** Writing – review & editing, Conceptualization. **José Luis Sánchez-Lizaso:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Claudio A. Sáez:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ivan Sola reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors thank all those who have collaborated during the field works realized. We would like to thank the Universidad de Antofagasta team for their logistical support in the Antofagasta field studies. We would like to thank D.J. for their support during the Caldera survey.

Funding

This work was funded by a grant from European Union-Next Generation EU (MARSALAS21-30). I. Sola was also funded by the ANID project FONDECYT #3240401. M.J. Díaz was funded by the ANID project FONDECYT Postdoctoral 2024 #3240391. F. Rodríguez-Rojas was financed by the ANID project FONDECYT #11220425. C.A. Sáez was financed by the ANID project FONDECYT #1240365. C.A. Sáez and I. Sola were also financed by project ANID InES I+D 2021 (INID210013).

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