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Multi-criteria analysis for sustainable and cost-effective development of desalination plants in Chile

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In Chile, there is an increasing demand for freshwater supply for human consumption, agriculture, and industrial activities. In this sense, the country is highly threatened by climate change, which is drastically affecting the availability of water resources in the north-central region due to desertification processes. Therefore, seawater reverse osmosis (SWRO) desalination is becoming one of the most feasible alternatives to address current and future challenges regarding water scarcity in the country. This investigation aims to evaluate potential locations for a sustainable and cost-effective installation of desalination projects; the latter, under a multi-criteria and geographic information system (GIS)-model. The model was tested in the highly water scarcity-threatened Valparaiso Region, Chile, as a case study. The model was developed integrating economic and socio-environmental criteria involved in the development and/or construction of desalination projects. The results of the multi-criteria analysis show that the Valparaıso Region presents optimal areas for developing SWRO projects. Both the northern and central areas of the Region show appropriate locations for installing SWRO plants and their freshwater distribution lines, ensuring short- and long-term water supply, especially for agriculture and population consumption. The results obtained in this study could be extrapolated as a tool to assess the desalination projects development in other world regions to make future desalination projects more viable and sustainable for addressing global water demands.

KEYWORDS

sustainable desalination, desalination development, multi-criteria analysis, seawater reverse osmosis, Chile

1 Introduction

Chile is currently highly threatened by climate change, with a drastic reduction in precipitation, increased evaporation, frequency of droughts, and average temperatures, which is already seriously affecting the availability of water resources; indeed, a situation that will worsen in the next few years (Valdés-Pineda et al., 2014; Garreaud et al., 2019). Scientific models estimate a drastic situation for the period 2030 - 2060 for the central-northern region, projecting a reduction of up to 50% of water availability, that will cause serious socio-economic consequences, especially in productive activities such as agriculture and also human consumption (Garreaud et al., 2017).

In this context of water scarcity, there is an urgent necessity to complement traditional water resources with new alternatives. Considering Chile's geography, with 6400 km of coastline and an average width of 180 km, seawater desalination represents one of the best alternatives to solve current and future challenges regarding water scarcity (Sola et al., 2019a; Herrera-León et al., 2022).

The development of desalination projects is determined by many factors, such as financing, environmental requirements, politics, cost of desalinated water, public acceptance, among others. However, there are two main factors that represent a socio-economic barrier or increase in the development time of desalination projects in many countries (Sola et al., 2021). On the one hand, the development of a desalination project can cause impacts on the environment, mainly associated with the impact of brine discharge on marine ecosystems; also, the construction of the desalination plant and their water distribution line represent stages of eventual impacts (Missimer and Maliva, 2018; Berenguel-Felices et al., 2020; Sola et al., 2020b). In spite of the latter, the effects of brine discharges are usually the most important potential impact regarding desalination development (Heck et al., 2018; Sola et al., 2021). Brine effluents are characterized by a salinity concentration that can double the salinity of the seawater body; this excess salinity also implies higher density (Mezher et al., 2011; Panagopoulos et al., 2019). Therefore, the discharges have been observed to mainly affect the benthic communities present in the affected area, mainly sessile communities or those with a low mobility capacity to escape from the high salinity influenced zone (Petersen et al., 2018; Sharifinia et al., 2019; Sola et al., 2020b; Muñoz et al., 2023). However, scientific experiences have demonstrated that it is possible to achieve long-term sustainable desalination when properly corrective and preventive measures are adopted (Sola et al., 2020a). These include: the implementation of a rigorous environmental assessment process; the adoption of scientifically tested measures to minimize the impacts of brine discharges, such as the use of diffusers and/or dilution of the discharge with seawater or other sources; and/or the implementation of a rigorous Environmental Monitoring Plan (EMP) that implements the appropriate requirements to ensure low impacts on marine ecosystems (Sola et al., 2019a, 2019b).

On the other hand, the increase of costs of producing desalinated water compared to freshwater from natural sources potentially represents an important obstacle for desalination development in certain countries (Al-Karaghouli and Kazmerski, 2013; Sola et al., 2021). However, there are numerous successful experiences worldwide demonstrating that it is possible to a achieve a cost-effective use of desalinated water, even for agriculture and human consumption (Eke et al., 2020). For example, Spain is an international example in the use of desalination for agriculture, being the largest producer of desalinated water in the world, representing more than 20% of desalinated water production for agricultural consumption. The availability of freshwater for the agricultural sector has ensured the prosperity of an economic activity that represents a 9.7% of the country's total economic contribution (Zarzo et al., 2013; AEDyR, 2018; Pulido-Bosch et al., 2019; Alvez et al., 2020).

Desalination for agriculture has also increased in other areas of the world, such as Kuwait, with 13% of the total desalinated water for these purposes, Italy with 1.5%, the United States with 1.3%, Bahrain with 0.4% and Qatar with 0.1%. Although in other countries the production of desalinated water for agriculture represents a low percentage of production, the use of desalination for agriculture is projected to steadily increase worldwide, including in South America (DesalData, 2021).

The development of desalination projects has increased considerably in many regions of the world, although this development has mainly been related to developed countries with higher economic potential and/or financing, such as Saudi Arabia, Spain, Israel, the United Arab Emirates, China, among others. For that, the desalinated water production is mainly concentrated in the Middle East, representing more than 40% of the world's installed production capacity. The economic costs and/or socio-environmental barriers remain a challenge to the development of desalination projects in some regions of the world (Sola et al., 2021). However, if these aspects are addressed, it is expected that other regions such as South America, will increase the number of desalination projects in order to address water demand (Eke et al., 2020; Sola et al., 2021).

In the case of Chile, there is no integrated a water strategy for the efficient and structured development of desalination projects. Further, more than 85% of desalinated water production capacity is destined for mining (Sola et al., 2019a). Therefore, it is crucial the implementation of tools and strategies for making feasible the development of projects reducing the economic costs of desalinated water and being environmentally sustainable, in order to address the water demand for human consumption and agricultural activities with lower economic capacity than other industrial activities (e.g. mining).

The aim of this paper is to assess through a based multi-criteria Geographic Information System (GIS) model the potential locations for the sustainable and cost-effective desalination development, especially considering as final users agriculture and human consumption. The model has been applied in Chile, using the Valparaiso Region as a case study. For that, the goal is to identify the best zoning criteria and geographic alternatives for SWRO plants, in order to reduce the production costs of desalinated water, social conflicts, and minimizing potential environmental impacts. This study includes: i) the development of an extrapolable methodology for the installation of desalination plants and their water distribution lines; ii) the identification of the most optimal areas for the installation of desalinations plants in Valparaiso Region.

2 Materials and methods

2.1 Study area

The Valparaíso Region is located in the central-northern area of Chile (Figure 1). It is one of the regions most affected by the reduction of water resources, due to the consequences of climate change and the increasing water demand, mainly for agriculture and human consumption, which represents 80% and 12%, respectively, of the total water final users; also, is the second region most populated in Chile (Ministerio de Obras Públicas, 2017a; Garreaud et al., 2019). Indeed, the number of water scarcity decrees in the region has increased by to over 60 in the last decade, which include more than 25 affected cities or towns (DGA, 2022).

The agricultural sector in the region represents 3.5% of the total cropping area in Chile, covering approximately 150,000 hectares. Within this area, the main production activities are forestry (38%), fruit (34%), forage (11%), vegetables (7%), and vineyards (5%); moreover, the region represents 19% of the total fruit production in the country (Garreaud et al., 2017; Herrera-León et al., 2022).

2.2 Requirements factors for multi-criteria analysis for desalination

The analysis was carried out after an evaluation of the main economic and socio-environmental factors that may affect the development and/or construction of desalination plants and their respective freshwater distribution lines (Ibrahim et al., 2018; Sola et al., 2021). These criteria were divided into two groups: excluding criteria and evaluated criteria. Excluding criteria were attributed to areas that should be strictly avoided. This included: i) marine protected areas to avoid negative brine discharge impacts on marine sensitive organisms and ecosystems; ii) land protected areas (e.g. wetlands, estuaries) to evade environmental associated impacts related with construction and distribution lines; iii) areas with urban-industrial activities where land use is spatially saturated or with high concentration of polluting activities; iv) tsunami inundation risk areas in order to avoid medium and long-term potential flooding, important in the context of Chilean permanent earthquake events.

The criteria evaluated included: i) the proximity of SWROs to the coastline, in order to reduce the economic costs of brine discharge pumping and seawater intake (C); ii) elevation, prioritizing areas with low grounds, to reduce the economic costs related with brine discharge pumping, seawater intake and distribution of freshwater inland (E); iii) evaluation of potential freshwater demand for agriculture and human consumption (A;H); iv) the proximity of SWROs to appropriate roads, to reduce the economic costs associated with new associated infrastructure (R); v) the elude the proximity of SWROs to locations that may potentially create social conflict, such as fishermen ports and sites of anthropological value (S).

A review of the information and data published related to the factors included was carried out based on the data compiled in the Geospatial Data Infrastructure (*Infraestructura de Datos Geoespaciales*; *IDE)* in 2021 (https://www.ide.cl/).

The factors considered were evaluated using a semi-quantitative scale, where 1 represented the lowest degree and 5 the highest degree for the geospatial area assessed (Table 1).

In addition, to assess the importance between criteria, we calculated a weighting coefficient (Q) that was defined using a committee of experts using a semi-quantitative scale, where 1

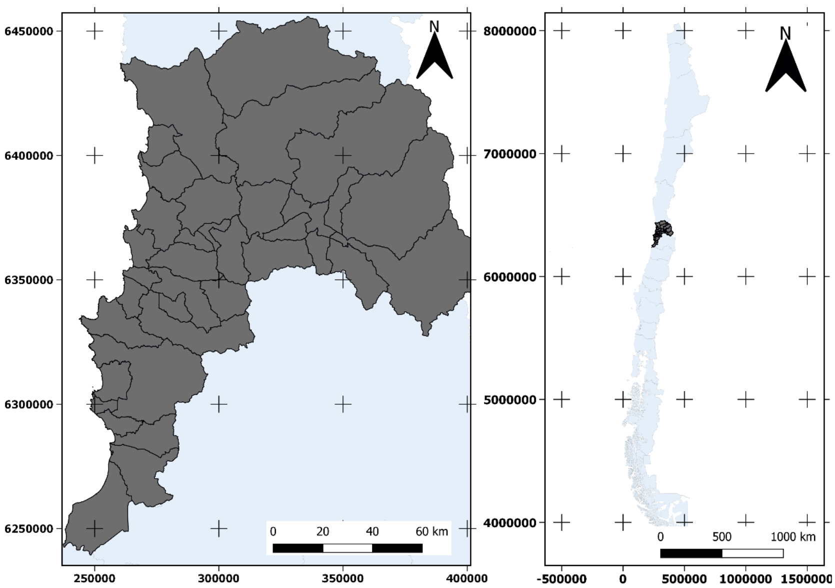

FIGURE 1
Location of Valparaiso Region among the 16 regions of Chile. This region was used as a case study for multi-criteria analysis.

TABLE 1 Semi-quantitative scale used for criteria evaluated.

Criteria evaluated	Score 5	4	3	2	1
Proximity of SWROs to the coastline (C)	0 – 0.5 km	0.5 - 1 km	1 - 2 km	2 - 4 km	> 4 km
Elevation (E)	0 – 0.1 km	0.1 – 0.2 km	0.2 – 0.4 km	0.4 – 0.8 km	> 0.8 km
Proximity to freshwater demands for agriculture (A)	0 - 5 km	5 - 10 km	10 - 20 km	20 - 50 km	> 50 km
Proximity to freshwater demands for human consumption (H)	0 - 5 km	5 - 10 km	10 - 20 km	20 - 50 km	> 50 km
Proximity of SWROs to the road infrastructure (R)	0 – 0.5 km	0.5 - 1 km	1 - 2 km	2 - 4 km	> 4 km
Proximity of SWROs to social conflict areas (S)	> 0.6 km	0.6 – 0.45 km	0.45 – 0.3 km	0.3 – 0.15 km	0 – 0.15 km

represented a lowest importance and 5 the highest relevance for each factor under the perception of the surveyed (Table 2). This allowed us to compare the experts' assessments based on the different criteria considered. The committee of experts included members of the International Desalination Association (IDA), academics, and researchers around the world with strong backgrounds in desalination (DesalData, 2021; Sola et al., 2021). Finally, the median measure was used to compare the results obtained from the surveys.

Finally, the multi-criteria analysis (Ceberio and Modave, 2006; Taherdoost, 2023) was estimated using Equation (1) as follows:

$$\text{Multi} - \text{criteria analysis}_i = \frac{\sum_i((C_i * Q_i) + (E_i * Q_i) + (A_i * Q_i) + (H_i * Q_i) + (R_i * Q_i) + (S_i * Q_i))}{\sum_i(C_i + E_i + A_i + H_i + R_i + S_i)}$$

where i is the evaluation for the weighting coefficient (Qi) and each criteria considered for the multi-criteria analysis. The following criteria were considered for the analysis: proximity of SWROs to the coastline (C), elevation (E), proximity to freshwater demand for agriculture (A), proximity to freshwater demand for human consumption (H), proximity of SWROs to road infrastructure (R), proximity of SWROs to potential social conflict areas (S).

The results analyzed were presented in three zones within the Valparaiso Region, the northern, central and southern zones of the Region. The multi-criteria analysis and the spatial representation were conducted using the QGIS© v.3.10.12 software through the geospatial data compiled (Ceberio and Modave, 2006; Taherdoost, 2023). Values higher than 4 upon the multi-criteria analysis represent optimal areas for desalination projects and their distribution lines.

TABLE 2 Semi-quantitative scale used to calculate the weighting coefficient (Qi) for each criteria assessed.

Score	Semi-quantitative scale for criteria evaluation
1	Represents a very low relevant criteria
2	Represents a slightly relevant criteria
3	Represents a more relevant criteria
4	Represents a strongly relevant criteria
5	Represents an extremely relevant criteria

3 Results

3.1 Weighting coefficient of criteria evaluated

The results obtained showed that the criteria that most affect the development of desalination projects and their water distribution in Chile are the proximity of the plant to the coast, the elevation where the project and the water distribution are installed and expected to operate, and the proximity to the largest water consumers. On the other hand, the least relevant factor was the proximity to road infrastructure (Table 3).

3.2 Optimal areas for installing desalination projects in the region

When applying our multi-criteria analysis and representing it on a GIS-based model, the results demonstrate that the northern zone of the Valparaíso Region near Papudo presents an optimal area to establish an industrial desalination plant; moreover, with appropriate conditions for a distribution land line inland through the cities of Cabildo and La Ligua (Figure 2). The identified most suitable area for installation of an industrial desalination project and freshwater distribution line considerate and avoid sites with risk of inundation, environmental and ecological value, and with

TABLE 3 Results obtained of semi-quantitative scale used for criteria evaluation results obtained from the different desalination experts.

Criteria evaluated	Weighting coefficient (1 - 5)
Proximity of SWROs to the coastline (C)	5
Elevation (E)	5
Proximity to freshwater demands for agriculture (A)	5
Proximity to freshwater demands for human consumption (H)	3
Proximity of SWROs to the road infrastructure (R)	1
Proximity of SWROs to social conflict areas (S)	3

The values presented indicate the median of the surveys obtained.

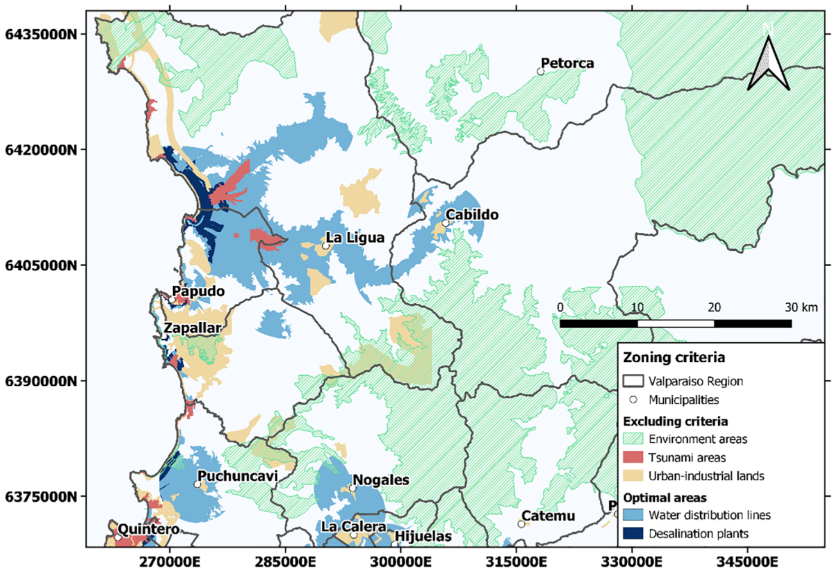

FIGURE 2
GIS-based results of the multi-criteria analysis to identify the most optimal areas for desalination plants and their respective freshwater distribution lines for the Valparaiso Region northern area.

prospects for generating social conflicts. Also, the coastal area of Puchuncaví appears appropriate for a desalination plant due to logistic features; however, its closeness to locations with high ecological value and population distribution, also in the path of a potential distribution line, diminishes it potential.

In addition, another suitable area for a desalination plant was observed in Concon, at the center of The Valparaiso Region (Figure 3). However, a minimum of 10 km north from the main urban and industrial pole located in the city, which is still in the suitable area, is suggested by the model in order to avoid social and environmental conflict. From the coastal area of Concon, there is also an appropriate zone for an inland distribution line, with a potential extension south-east towards the cities of Limache and Olmue, and also in direction north-east to through the cities of Quillota, La Cruz, La Calera and Hijuelas. With appropriate technological and logistical measures, a distribution line could be also guided to the main cities of Viña del Mar and Valparaíso.

Finally, the Valparaiso Region's southern zone has a suitable area located south of Santo Domingo locality, with a distribution line with multiple possibilities for a distribution line at least for 20 km inland (Figure 4). However, the surrounding towns are sparsely populated and there is an environmental protection area south of Santo Domingo that may constrain the distribution of freshwater south of the region in the long term.

4 Discussion

The high water demand and climate crisis scenario highlights the need for sustainable use of the desalination technology to complement traditional alternatives addressing water scarcity problems faced in Chile (Valdés-Pineda et al., 2014; Garreaud et al., 2019). The results of the multi-criteria analysis show that the Valparaíso Region presents different suitable areas in terms of economic and socio-environmental advantages for developing desalination projects and their distribution lines.

In the last decade, the development of desalination projects has increased significantly around the world, although this development has been linked to countries with high economic and/or financing potential; or with industries with high economic capacity which can sustain the higher costs of freshwater produced through desalination (Sola et al., 2021). Likewise, in the context of Chile, the mining industry has installed the majority of desalination capacity, representing more than 70% of total desalination capacity installed in the country (Sola et al., 2019a). However, our results demonstrate that certain areas in the context of the highly water scarcity-threatened Region of Valparaíso, are appropriate for the development of multipurpose desalination projects. The latter, with the capacity of significantly reducing economic costs, and decreasing the risks of socio-environmental conflicts; especially if considering the desalination industry as a viable solution for agricultural activities and human consumption (Zarzo et al., 2013). In addition, the Valparaíso Region is facing a significant freshwater shortage of 36.5 m^3/s, considering the agricultural expansion associated of new large irrigation projects, mining expansion projects, and the increase of population and industrial activity. Specifically, a deficit of around 15 m^3/s is expected for agricultural expansion, mainly attributed to the growing of fruit production such as avocado, citrus, vineyards or nuts, vegetables, cereals, among others (Ministerio de Obras Públicas, 2021, 2017b).

According the results obtained, both the northern and central areas of the Valparaíso Region have appropriate locations for installing SWRO projects that would ensure the short-term and long-term water availability for the region. Firstly, the coastal area of Concon has an appropriate area for installing a desalination project that could address the high-water demand of the large agricultural

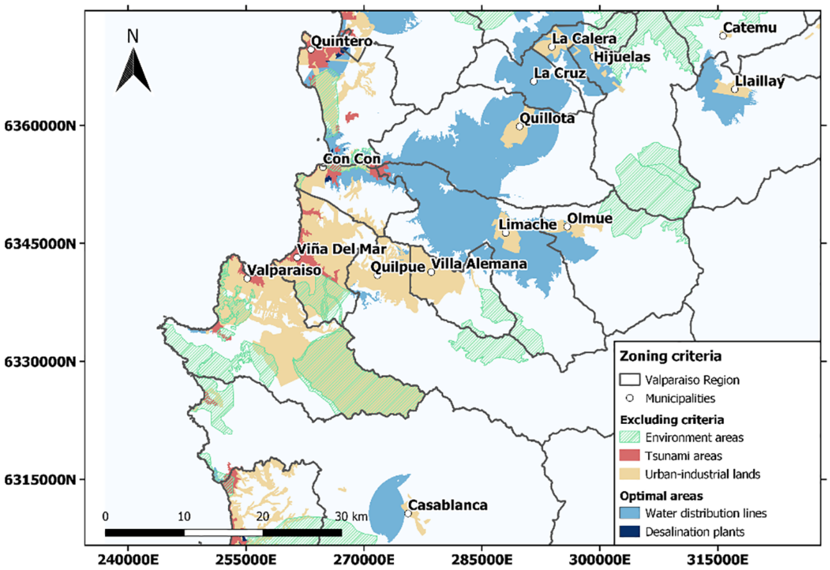

FIGURE 3
Results of the multi-criteria analysis to identify the most optimal areas for desalination plants and their respective freshwater distribution lines for the Valparaiso central area.

producers located around Limache, Quillota, La Calera, Hijuelas, La Cruz, Nogales; but also, it could be solved the water scarcity of the surrounding small villages. On the other hand, the coastal area of Papudo has also an appropriate area that could attend the severe water scarcity and high-water demand of the agricultural producers and freshwater consumption of La Ligua, Cabildo, Petorca and surrounding small villages. Specifically, these areas present at least a freshwater demand of more than 100,000 m^3/day (>1200 l/s) for human consumption and agricultural production (e.g. avocado, citrus, grapes, among others), highlighting the strong necessity to complement traditional water sources considering desalination alternative (Ministerio de Obras Públicas, 2021, 2017b).

Therefore, it is recommended the development of SWRO plants that would range from 100,000 to 300,000 m^3/day installed in the most suitable areas identified, aiming to mitigate the freshwater deficit of Valparaiso Region. In addition, our results are in accordance with the plan of Chilean Ministry of Public Works, which set out plans for two reverse osmosis plants of 1000 l/s in order to address the freshwater demand of Petorca and La Ligua. Their assessment indicated an estimated investment cost of around 75 - 80 million dollars, excluding

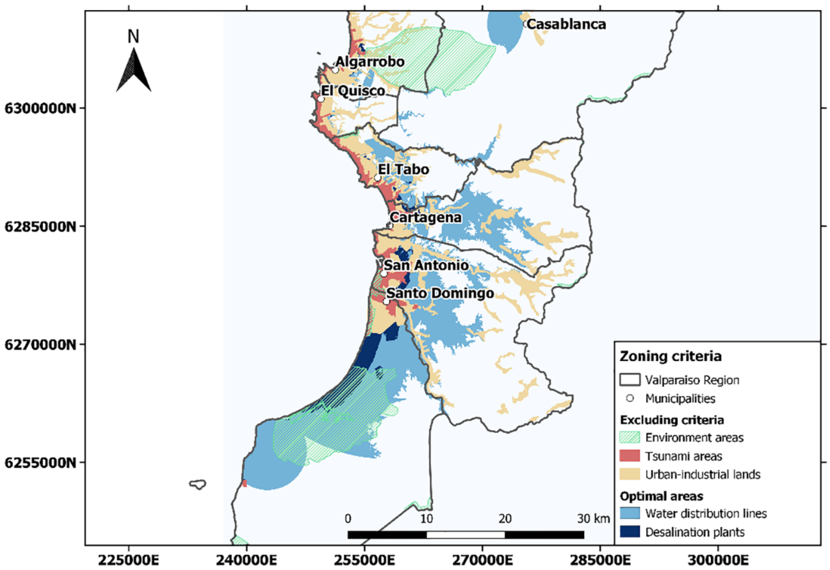

FIGURE 4
Results of the multi-criteria analysis to identify the most optimal areas for desalination plants and their respective freshwater distribution lines for the Valparaiso southern area.

freshwater transmission, for the construction for each plant, which would benefit agricultural and human consumers (Fragkou and Budds, 2020; Ministerio de Obras Públicas, 2017b).

However, in the case of southern area of the Region, our results suggest that the most appropriate strategy may be based on the adoption of smaller and even modular desalination plants with lower construction costs, and in accordance with the area' s characteristic; in order to attend local freshwater demands of small and medium-sized agricultural producers and surrounding small villages (Zarzo et al., 2013).

In the context of Chile, the desalination as a strategy for securing water would attend the freshwater shortages, and in turn would allow: i) minimizing the overexploitation of groundwater exploited by industrial farmers, and therefore, reducing saline intrusion in coastal groundwater; ii) avoiding socio-environmental conflicts between industries and the population in the compulsory repurchases or expropriation of water rights; iii) minimizing the pressure on existing water management models, which entail high political, economic, and social costs; iv) the creation of employment and local economic development, which may involve local population participation during the construction and/or operation phase of the implemented desalination projects; as well as the socio-economic development of the agricultural sector (Zarzo et al., 2013; Fragkou and Budds, 2020).

Furthermore, it is important the integration of renewable energies such as solar photovoltaic and wind technologies which are currently used as energy suppliers for desalination projects in other countries, for reducing energy costs in the long-term and aiding sustainable desalination development in Chile. However, currently the investment cost of using renewable energies for desalination is still very high, which considerably increases the cost of desalinated water produced in the short-term. Thus, with the aim of reducing short-term investment costs, the government should support through subsidies the use of renewable energies for the development of sustainable desalination projects; thus reducing capital costs and the consumption of fossil fuels (Shahzad et al., 2017; Panagopoulos et al., 2019; Sola et al., 2021).

On the other hand, it is important to consider that this analysis has integrated protected areas and areas of high environmental value to be avoided in the location criteria of SWRO plants; however, to minimize the effects of brine discharges on marine ecosystems even in non-protected areas, it should be carried out a proper management of brine discharges (Fernández-Torquemada et al., 2019; Sola et al., 2020b). In this regard, it should include: the implementation of a rigorous environmental assessment process assessing the preventive measures necessary for minimizing potential environmental impacts; the adoption of scientifically tested measures to minimize the impacts of brine discharges, such as the use of several diffusers and/or pre-dilution of discharges with seawater or other water sources; and the implementation of a rigorous environmental monitoring plan that implement the appropriate requirements to ensure the sustainable operation of desalination plants with marine ecosystems (Sola et al., 2019b, 2019a).

In spite of the results obtained, further exploration in this research is necessary to complement our results with the: i) assessment of the short and long-term specific freshwater demand of each area identified by the results of the multicriteria model, allowing to the formulation of desalination plant proposals aligned with the specific characteristics of each zone; ii) the estimation of the construction (CAPEX) and operation (OPEX) economic costs for supplying freshwater to the final users; iii) the study of appropriate financing models according the specific characteristics of each desalination project proposal; iv) the evaluation of technical performance items (e.g. feed water salinity tolerance, product water quality and reliability and maintainability).

Finally, this study has allowed the development of GIS-based multi-criteria model for managing freshwater resources upon desalination as a complement. The Valparaiso Region in Chile resulted an efficient case study to test the model, considering that one of its main purposes is to set desalination as an alternative for human consumption and agriculture, especially in countries with low-medium economic capacity. Thus, the multi-criteria model has proven to be a reliable tool that can be extrapolated to assess the development of desalination projects in other regions of Chile and the world. The experience gained through this investigation is highlighted as worth applying for future desalination projects globally, as its implications in terms of cost-effectiveness and social perception may surely also facilitate multipurpose desalination applications at different production scales.

5 Conclusions

The application of the multi-criteria analysis as a scientific-technical tool has permitted the identification of the most optimal areas for developing desalination projects with economic and socio-environmental considerations. These desalination projects should ensure a long-term water supply and security for the Valparaíso Region, especially for the agricultural producers located around La Cruz, La Ligua, Cabildo, Limache or Quillota; but also, to address the severe water shortages that are facing some surrounding towns. Finally, the results obtained from this analysis can be integrated in global strategies for desalination projects installation, promoting effective investment, environmentally sustainability, and therefore more fluid pre-installation legal requirements processing.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

IS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. DZ: Conceptualization, Resources, Writing – review & editing. JS: Conceptualization, Supervision, Writing – review & editing. CS: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing.

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Conflict of interest

Author DZ was employed by company Sacyr Water.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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