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Current situation and major challenges of desalination in Chile

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ABSTRACT

Northern regions of Chile are suffering a significant water scarcity, which has been exacerbated during the last decades mainly by the intensive metals and minerals production, and the continuous population growth in the zones affected. This article presents the current situation in the field of desalination in Chile aiming to identify the current and future desalination capacity, the major technical difficulties, environmental issues, and economic aspects faced by the desalination industry in the country. The current situation is presented by making an inventory of the industrial scale and by reviewing the scientific literature on the subject published until 2018. It was identified that eleven desalination plants at the industrial scale are operating in Chile, producing a total of 5,868 l/s of desalinated water. Also, there are ten desalination projects in different stages of evaluation, which will increase the desalination capacity by 116.5% to reach a total of 12,706 l/s in the coming years. Moreover, the major challenges identified were the harmful algal bloom events, the disposal of desalination concentrate, and the high energy consumption by water supply systems. Potential solutions were identified to address these challenges and proposed as future directions in this investigation.

Keywords: Desalination; Chile; Present; Challenges; Future

1. Introduction

The current problem of water scarcity in some regions results from the limited availability of conventional water resources and the ineffective management of water resources [1]. The problem of water scarcity has been exacerbated over the last decade by the increasing water demand in these regions boosted by the constant population growth and economic development. In this context, saline water has become one of the most important non-conventional water resources. In fact, the use of desalination technologies for water production has increased significantly in the last decade [2]. The total installed production capacity of desalinated water worldwide increased from 51.6 million m^3/d in 2008 to 92.5 million m^3/d in 2017 [3]. The proliferation of desalination plants has concentrated in some countries making them the world leaders in the application of desalination technologies. Some of these countries are the United States [4], Spain [5,6], and the countries of the Middle East and North African regions [7–9].

Nevertheless, fast progressing desalination technologies have brought the installation of desalination plants beyond the country's leaders in this subject. For instance, desalination

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is playing a fundamental role to face the problem of water scarcity in northern Chile. This area of the South American region is located in the driest desert on Earth – the Atacama Desert – where the distribution of natural resources is paradoxical. The conventional water resources are very limited or even non-existent [10], but the presence of mineral resources in this area is impressive. The Atacama Desert holds one of the major global reserves of copper, molybdenum, lithium, and natural nitrates, among other valuable commodities [11]. In this context, the continuous growth of the extraction of minerals and metals in Chile generates significant economic benefits for the country, but it also increases the pressure on water resources. This problem causes a conflict between the mining sector, other manufacturing sectors, and local communities [12].

Fig. 1a shows the distribution of water across administrative regions in Chile (represented by roman numerals), where it is possible to observe that water scarcity suffered by the northern regions of the country is evident. The most affected regions are Antofagasta and Atacama, where water demand exceeds water supply by 22.1 and 14.8 m^3/s respectively. Remarkably, the overall average water runoff availability in the Antofagasta region is ca. 52 m^3/inhabitant/y as shown in Fig. 1b which is very close to the limit of the minimum water requirement estimated for human health, economic and social development that is 49.3 m^3/inhabitant/y [13]. Moreover, the demand for water will continue increasing in these regions because they have the highest concentration of mines operating in Chile and several new mining projects are in the companies' portfolio that will materialize

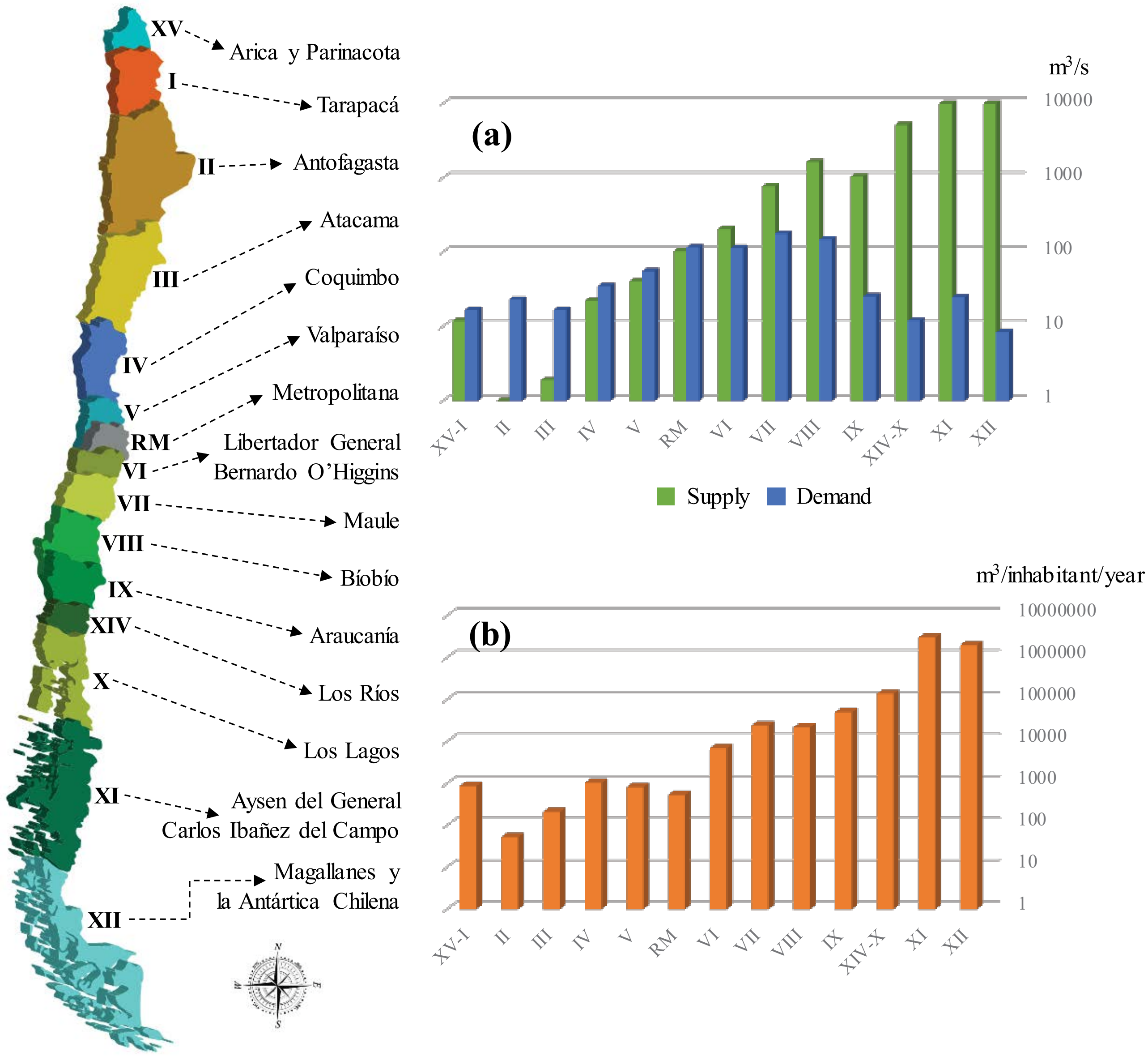

Fig. 1. Water resources in Chile - (a) Water distribution by regions and (b) average water runoff availability by regions (adapted from [14]).

in the coming years. Therefore, desalination is seen as one of the best alternatives to meet the future water demand of these regions.

Chile was chosen as the subject of this investigation because it has the following characteristics:

- The Chilean government has proposed new policies to promote the use of desalinated water in the urban, mining and agriculture sectors of the country.
- Water demand is growing in the Chilean regions suffering from water scarcity and desalination is seen as the best option to meet these requirements.
- Chile has the largest desalination system operating in South America.

This article presents the current situation of desalination in Chile aiming to identify the major technical difficulties, environmental issues and economic aspects related to this subject. The methodology used in this article focuses on the analysis and review of literature related to the applications and investigations of desalination technologies in Chile until 2018. This article is structured as follows: Section 2 presents the current situation regarding desalination in Chile from an industrial and scientific perspective, section 3 discusses the major challenges and potential future directions of the desalination in Chile based on the antecedents described in the previous section, and section 4 ends with concluding remarks.

2. Current situation of the desalination in Chile

The desalination history in Chile began in the late 19th century [15], but it is in the last decade when the installation of desalination plants in the country has increased remarkably. The following two subsections present an overview of the desalination plants at industrial scale operating and pending approval in Chile, and a literature review of the investigations focused on desalination carried out until 2018.

2.1. Overview of industrial scale desalination plants in Chile

Table 1 briefly describes desalination plants in operation and pending approval (under evaluation) in Chile that produces more than 10 l/s of desalinated water, and the location of these projects is shown in Fig. 2. Based on this information, there are currently eleven desalination plants at the industrial scale operating in Chile and ten desalination projects in different stages of evaluation. Desalination plants that are already in operation produce in total 5,868 l/s of desalinated water and future projects will increase this capacity by 116.5% to reach a total of 12,706 l/s. We need to bear in mind that most of the desalination plants work

Table 1
Desalination plants over 10 l/s operating and pending approval in Chile

Desalination plant	Design capacity (l/s)	Owner	Sector	Status	Region
Arica	412	Aguas del Altiplano	Urban	In operation	Arica y Parinacota
Quebrada Blanca	865	Teck	Mining (copper)	Under evaluation	Tarapacá
Tocopilla	100	Aguas Antofagasta	Urban	Under evaluation	Antofagasta
RT Sulfuros	1,950	Codelco-Chile	Mining (copper)	Under evaluation	Antofagasta
Antucoya	50	Antofagasta Minerals	Mining (copper)	In operation	Antofagasta
Michilla	75	Mejillones Municipality	Urban	In operation	Antofagasta
Sierra Gorda	63	KGHM	Mining (copper)	In operation	Antofagasta
Muelle Esperanza	38	Antofagasta Minerals	Mining (copper)	Under evaluation	Antofagasta
Spence	1,000	BHP Billiton	Mining (copper)	Under evaluation	Antofagasta
Distrito Centinela	173	Antofagasta Minerals	Mining (copper)	In operation	Antofagasta
Distrito Centinela 2	140	Antofagasta Minerals	Mining (copper)	Under evaluation	Antofagasta
La Chimba	850	Aguas Antofagasta	Urban	In operation	Antofagasta
Sur Antofagasta	1,000	Aguas Antofagasta	Urban	Under evaluation	Antofagasta
El Coloso	525	BHP Billiton	Mining (copper)	In operation	Antofagasta
El Coloso (expansion)	2,500	BHP Billiton	Mining (copper)	In operation	Antofagasta
Mantoverde	120	Mantos Copper	Mining (copper)	In operation	Atacama
Aguas CAP	600	CAP	Mining (steel)	In operation	Atacama
Atacama	1,200	Econssa Chile	Urban	Under evaluation	Atacama
Candelaria	500	Lunding Mining	Mining (copper)	In operation	Atacama
Bahia Caldera	95	Seven Seas Water Chile	Urban	Under evaluation	Atacama
Dominga	450	Andes Iron	Mining (steel)	Under evaluation	Coquimbo

Adapted from [17].

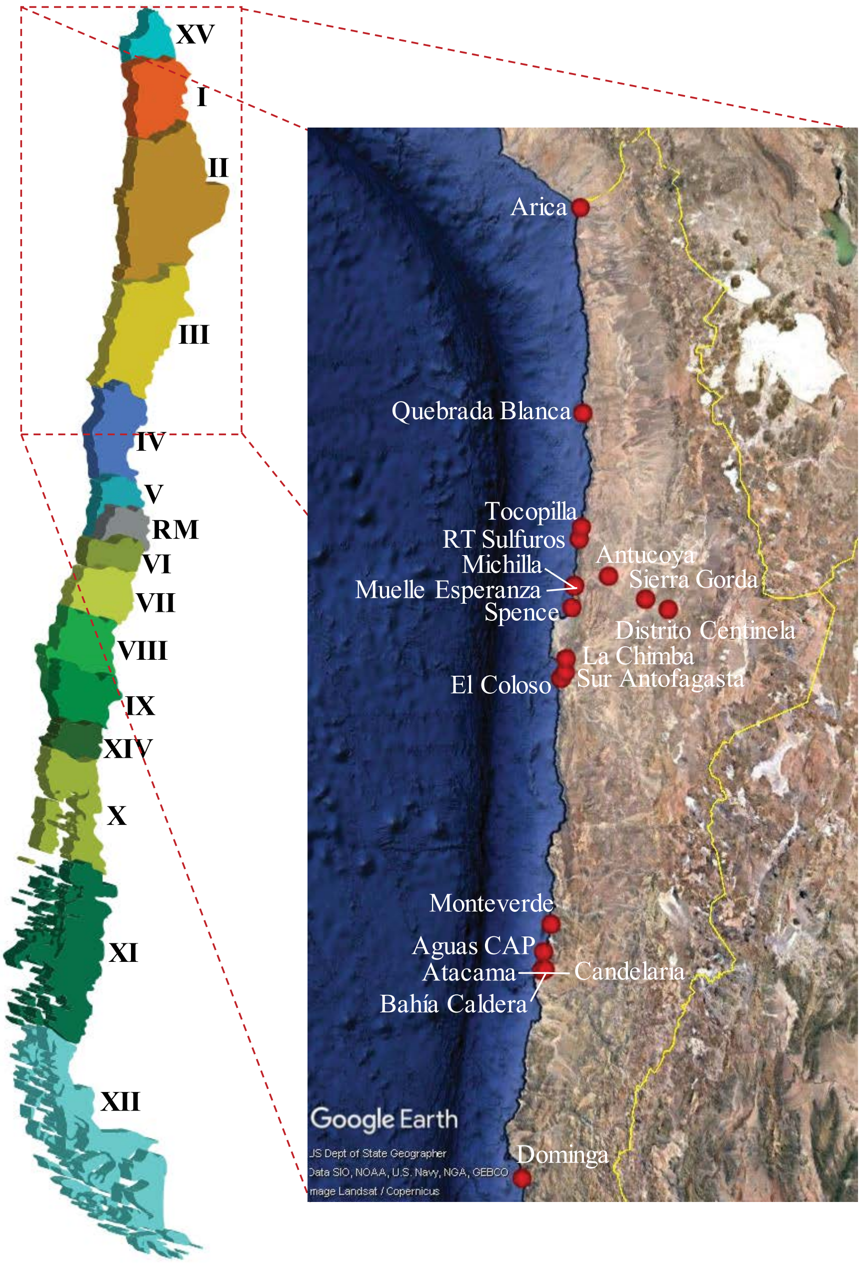

Fig. 2. Location of desalination plants over 10 l/s operating and pending approval in Chile (adapted from [17]).

to satisfy the water demand of the Chilean mining sector. Indeed, 70% of total future capacity will be used to meet the demand of the mining sector for water [16], and the remaining 30% will be used by the urban sector. It is also worth to mention that all desalination plants summarized in Table 1 are based on reverse osmosis technology for the treatment of seawater, and the only exception is the desalination plant *Arica* that treats water coming from a river.

In this part, we provide a general description based on the antecedents given by [18] about the desalination plants in Chile (Table 1). The desalination plant *Arica* is the oldest one operating in Chile, it was launched in 1998 to satisfy part of the water requirements of the urban sector in the region. Initially, it produced 200 l/s, but nowadays it delivers 412 l/s of desalinated water. Desalination plant *Quebrada Blanca* is part of a mining project that will process copper-molybdenum sulfide ores, which has been recently approved by the Chilean government. Desalinated water will be used for human consumption and in other health and industrial services. Desalination plant *Dominga* is part of a mining project that will produce copper and iron concentrate. The desalination plant will produce 450 l/s of desalinated water and it will be the first plant located in the Coquimbo region (Fig. 2).

Antofagasta region has the highest concentrations of desalination projects among all Chilean regions as shown in

Fig. 2. In this context, desalination plant *Tocopilla* will satisfy 100% of the water requirements of a city with a population of ca. 23,000 inhabitants. The initial capacity of the plant will be 75 l/s and soon it will increase to 100 l/s of desalinated water. Desalination plant *RT Sulfuros* will supply the water required by a new mining project that will process copper sulfide ores, and is part of the state-owned company, Codelco-Chile. In the first stage of the mining project, desalination plants will produce 630 l/s and their output is expected to increase to 1,950 l/s of desalinated water. It is the first desalination plant owned by the Chilean government. The desalinated water supply system will comprise a desalination plant based on reverse osmosis technology, four pumping stations, and a 48 inch 160 km long pipeline to convey water to the mining plant located at 3,000 m above sea level. The built-own-operate-transfer business model will be used by the Chilean company as a strategy to materialize the project in collaboration with a private company. The project will involve a total investment estimated at 1,000 million US$.

The company Antofagasta Minerals has got four desalination projects in the region - two in operation and two under evaluation. All projects are connected to the same water distribution system aiming to satisfy the water demand of different mining projects of this company. Desalination plant *Distrito Centinela* is located near one of its mining facilities, and it delivers 173 l/s of desalinated water mainly used for human consumption. Desalination plant *Antucoya* produces 50 l/s of desalinated water and it was installed with the same objective in mind as the previous plant but to meet the water demand of another mining project. Desalination plant *Distrito Centinela 2* will provide 140 l/s of desalinated water, also mainly for human consumption, and it is part of a new mining project of the company. Desalination plant *Muelle Esperanza* belongs to the same new mining project but it will be located at the company's dock, and it is the smallest desalination plant included in this study as it produces only 38 l/s of desalinated water. Desalination plant *Michilla* was donated to the Municipality of Mejillones by the Antofagasta Minerals company to meet the water demand of a fishing village of ca. 250 inhabitants.

Desalination plant *Sierra Gorda* uses water coming from a thermoelectric plant in a mining project that processes copper-molybdenum sulfide ores. The mining project uses seawater directly in their processes, hence the desalination plant supplies water mainly for human consumption. Desalination plant *Spence* will produce 1,000 l/s of desalinated water aiming to satisfy the water requirements of a new mining project under the same name. Desalination plant *La Chimba* started its operations in 2003 and nowadays it produces 850 l/s of desalinated water to satisfy part of the water requirements of the Antofagasta city that has ca. 400,000 inhabitants. Desalination plant *Sur Antofagasta* will cover the remaining water demand of the same city, which will make the city the first South American urban center that will meet 100% of its population demand for water using seawater. One of the most significant technical challenges that these desalination plants must face is harmful algal blooms events that are recurrent at the Antofagasta coast. The same city hosts the largest desalination system operating in South America, desalination plant *El Coloso*, which supplies water to the largest copper mine in the world. After its expansion, the desalination plant is capable to produce a maximum of 3,025 l/s of desalinated water which is significant since it represents 60% of the total current desalinated water output in Chile. The costs of this expansion were estimated at 3,500 million US$.

Atacama region has three desalination plants in operation and two more projects are pending approval as shown in Table 1. Desalination plant *Mantoverde* produces 120 l/s of desalinated water used to satisfy 80% of the water demand of a copper mine plant. Desalination plant *Aguas CAP* was designed to produce 600 l/s of desalinated water aiming to satisfy the entire demand for water posed by the mining company CAP, to partly meet the demand of a small community in the neighborhood and to supply water for the irrigation of different crops in the area. Desalination plant *Candelaria* started its operations in 2013 and currently produces 500 l/s of desalinated water. Desalination plants which are currently evaluated, and their approval is pending are the *Atacama* and *Bahía Caldera*, both projects designed to meet almost all water demand of the urban sector of the Atacama region.

2.2. Desalination in Chile: literature review

A systematic content analysis approach based on scientific literature was used to provide relevant information on the progress of desalination in Chile. The content analysis method is a qualitative study that allows analyzing text data. It is defined according to Hsieh and Shannon [19] as a "research method for the subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns". The main goal of this method is to provide new insights and a better understanding of this specific subject we have selected for our study. According to Fink [20], the systematic process of the content analysis method consists of fourth steps: (1) definition of search criteria, (2) material collection, (3) material analysis, and (4) material description. The first step guides the searches of the subject under study and the main criteria for literature analysis include keywords, publication language, type of documents and years of publication. In the second step, we need to collect the material from scientific literature databases. The third step is the analysis and selection of the material against the previously defined criteria and find out whether they are related to the subject under study. Material outside of this scope must be excluded from the analysis. Finally, the goal of the fourth step is to describe in detail the collected material.

The systematic content analysis approach developed in this investigation was conducted in line with the steps proposed by Fink [20]. The words "desal" and "Chile" were used to search titles, abstracts or keywords of articles and reviews written in English over the period 1974–2018 and indexed in Scopus scientific database. As a result of this search, thirty-seven publications were collected. After their analysis, we selected nineteen publications shown in Table 2. Eleven of these publications focus on desalination applications in the mining sector, five publications in the urban sector, and three publications that come from aquaculture and agriculture sectors. A detailed description of them is presented below.

Table 2
Scientific articles and scientific reviews of desalination in Chile

Title	Main information	Sector	References
El Coloso (Chile) reverse osmosis plant	This paper presents the technical aspects of the first years of operation of the desalination plant El Coloso.	Mining	[21]
Delivering sustainable water supply in the Atacama Desert	This paper describes a desalinated water supply project designed to meet water demand of the highest operating copper mine in the world.	Mining	[22]
Northern Chile and Peru: a hotspot for desalination	This paper discusses the background of some desalination projects located in Chile and Peru from a business perspective.	Mining	[23]
Seawater desalination off the Chilean coast for water supply to the mining industry	This paper discusses the use of an ultrafiltration membrane system as a pretreatment in two desalination plants located in the Atacama Desert.	Mining	[24]
Simultaneous design of desalination plants and distribution water network	This paper presents a methodology for designing desalination plants and water distribution networks simultaneously.	Mining	[25]
Optimization approach to designing water supply systems in non-coastal areas suffering from water scarcity	This paper presents a novel optimization approach to designing water supply systems in areas suffering from water scarcity considering economic and technical aspects.	Mining	[26]
Use of seawater in mining	This paper reviews several aspects of the use of seawater in mining with an emphasis on Chile.	Mining	[27]
Biomineralization of calcium and magnesium crystals from seawater by halotolerant bacteria isolated from Atacama Salar (Chile)	This paper evaluates a biodesalination process of seawater to remove calcium and magnesium ions to improve the quality of water for industrial purposes.	Mining	[28]
Use of discharged brine from reverse osmosis plant in heap leaching: opportunity for caliche mining industry	This paper evaluates the feasibility of the use of brine coming from desalination plants for the leaching of caliche minerals to recover nitrate and iodine.	Mining	[29]
CSP + PV hybrid solar plants for power and water cogeneration in northern Chile	This paper analyses techno-economic feasibility of a polygeneration system based on a solar power system, a photovoltaic system and a multi-effect distillation plant to produce water and electricity.	Mining	[30]
Solar polygeneration for electricity production and desalination: case studies in Venezuela and northern Chile	This paper analyses techno-economic feasibility of a polygeneration system based on parabolic trough solar collectors coupled with a multi-effect distillation plant to produce water and electricity.	Urban	[31]
Preliminary evaluation of the use of vacuum membrane distillation for the production of drinking water in Arica (Chile)	This paper evaluates the feasibility of a desalination system based on vacuum multi-effect membrane distillation for supplying drinking water.	Urban	[32]
Seawater desalination by combined nanofiltration and ionic exchange	This paper evaluates two seawater desalination systems based on nanofiltration membrane and ion exchange process for supplying drinking water.	Urban	[33]

Removal of boron from water through soluble polymer based on N-methyl-D-glucamine and regenerated-cellulose membrane	This paper evaluates a separation method based on a water-soluble polymer coupled to polymer-enhanced ultrafiltration to remove boron from water available in Northern Chile.	Urban	[34]
Solar stills of inclined evaporating cloth	This paper evaluates a desalination system based on a natural freezing process to supply drinking water in the Atacama Desert.	Urban	[35]
Separation of nitrite and nitrate from water in aquaculture by nanofiltration membrane	This paper evaluates the separation of nitrogen compounds by a nanofiltration system designed to provide water of adequate quality for fish production.	Aquaculture	[36]
Ammonia, nitrite and nitrate separation from sweet water by nanofiltration	This paper evaluates the separation of nitrogen compounds by a nanofiltration system aiming to provide water of adequate quality for fish production.	Aquaculture	[37]
Water desalination by natural freezing	This paper evaluates a desalination system based on a natural freezing process to supply water for crops irrigation in greenhouses in the Atacama Desert.	Agriculture	[38]
Integrated water resource management and energy requirements for water supply in the Copiapó River basin, Chile	This paper develops an integrated water resources management model to assess the water-energy nexus in a basin located in the Atacama region	Mining-urban	[39]

Petry et al. [21] presented technical aspects of the initial years of operation of the *El Coloso* desalination plant. The plant was put into operation in 2006 and supplied 525 l/s of desalinated water to a copper mine which wanted to increase its production capacity. Researchers pointed out that one of the most significant challenges of the *El Coloso* plant was to establish a pretreatment stage that would be able to control the harmful algal bloom events that occur often at the northern coast of Chile. To achieve this goal, a conventional dissolved air flotation process followed by two-stages of pressurized dual media filters were installed as a pretreatment to *El Coloso*. Spenceley et al. [22] examined the Escondida Water Supply (EWS) project that was focused on the expansion of the *El Coloso* desalination plant. This new desalinated water supply system was launched in 2018 and the main purpose for its functioning is to add 2,500 l/s of desalinated water to the current production to help in increasing copper production of the mining company. The EWS transformed to *El Coloso* in the biggest desalination plant operating in South America with a maximum production capacity of ca. 3,000 l/s of desalinated water. The EWS project consists of a desalination plant based on reverse osmosis technology and four high-pressure pumping stations to transport the water produced by more than 180 km from the ocean to the mine located at 3,200 meters above sea level. Due to the size and technical complexity of this engineering project, the Global Water Intelligence Organization awarded *El Coloso* with the title of the Industrial Desalination Plant of the Year at the Global Water Summit Awards 2017.

Dixon [23] discussed the background of some desalination projects located in Chile and Peru from a business perspective. This study analyzes management strategies applied in these projects, the timing for their execution and the positions of the different stakeholders about them. An interesting topic that was highlighted in this study is the option to establish a sharing water supply system between water users, such as the neighboring mines or municipal water supply utilities. This option is seen as a potential opportunity from an economic perspective since these projects require a large financial investment. Knops et al. [24] presented the experiences from using an ultrafiltration membrane system as a pretreatment in two desalination plants located in the Atacama Desert. This pretreatment was proposed considering that the Chilean coast has high algae concentration as was previously mentioned, which reduces the performance of the desalination plants. The first desalination plant provides desalinated water to a thermal power plant that supplies electricity to cities and to the mining sector in the Antofagasta region. The second desalination plant provides water to a mining company processing copper ores operating in the Atacama region. The main results of this study demonstrated that the ultrafiltration membrane system is an effective and low-cost pretreatment for both desalination plants evaluated.

Herrera et al. [25] and Herrera-León et al. [26] presented novel optimization approaches to design water supply systems in non-coastal areas suffering from water scarcity considering economic and technical aspects of the project. Antofagasta region was used as a case study in both investigations aiming to validate the applicability of the methods proposed. The main results showed that proposed optimization approaches are useful tools for determining solutions to real-scale problems. Moreover, the investigations highlighted the relevance of water conveyance for water supply systems when the user is located at long distances and high altitudes of the water source. In this context, the costs and energy involved in water conveyance may exceed the costs and energy-related to the desalination process. Cisternas and Gálvez [27] reviewed several aspects of the use of seawater in the mining sector with an emphasis on Chile. They examined mainly the consumption of seawater and its projection in the Chilean mining industry, management aspects of the use of seawater, and negative and positive effects of the use of seawater in metal and non-metallic mining industry. One of the main findings of this investigation was that not all chemicals and biological compounds present in seawater are harmful to Chilean mining operations. Therefore, a complete elimination of all of them using desalination processes is not strictly required. In this context, Arias et al. [28] proposed a partial desalination treatment based on biodesalination process to remove calcium and magnesium ions aiming to improve the quality of water used for mining and industrial purposes. The biodesalination process uses ureolytic halotolerant bacteria living in the Atacama Desert for precipitating calcium and magnesium crystals from seawater. Experimental results demonstrated that the selected bacteria could reduce the concentration of calcium and magnesium in seawater by 95% and 8% respectively. However, the researchers pointed out that further studies are needed to optimize the biodesalination process for its potential application at the industrial scale. Ordóñez et al. [29] evaluated the feasibility of using the desalination concentrate as a bleaching agent of caliche ores to recover nitrate and iodine compounds. A column leaching was used to perform several experiments, and the main results indicated that the use of irrigation rates between 4 and 8 $L/h/m^2$ allows obtaining high recovery rates of nitrate and iodine compounds. The desalination concentrate is produced as a waste in desalination plants and its disposal generates negative impacts into the marine environment. Therefore, the strategy proposed by Ordóñez et al. [29] could not only generate economic revenues, but also significant environmental benefits.

Valenzuela et al. [30] analyzed the techno-economic feasibility of a polygeneration system based on concentrating solar power (CSP) system, a photovoltaic (PV) system, and multi-effect distillation (MED) plant. This system aim to produce water and electricity mainly to supply the mining sector. The polygeneration system proposed was modeled to analyze the effects of the CSP + PV plant operation, and how the variation of the system parameters can influence the operation of the MED plant integration. The simulation was carried out considering several operation options that lead to different system configurations. The main results showed that the optimum configuration will depend strongly on the type of the main product of the polygeneration systems the owner wants to achieve. Mata-Torres et al. [31] analyzed the techno-economic feasibility of a polygeneration system based on parabolic trough solar collectors coupled with a MED plant to produce water and electricity for the urban sector. The main result showed that the polygeneration system is a feasible alternative from a technical and economic perspective, and it could provide electricity and water to more than 85,000 inhabitants. These results were obtained under specific conditions; therefore, for other cases, the feasibility of the system must be evaluated according to local conditions since the costs depend mainly on them.

Andrés-Mañas et al. [32] evaluated the feasibility of a desalination system based on vacuum multi-effect membrane distillation for supplying drinking water to a rural area of the Arica y Parinacota Region. The desalination plant has a nominal production of 60 l/h, and the heat required for the desalination process is provided by a hybrid system composed of a solar field and diesel generation system. This system works alternatively depending on the availability of solar radiation in the area. The main results showed that to supply drinking water for over one year, you need a stationary solar thermal collector with a total area of 70.5 m^2. Such a collector will generate about 49% of the total heat required for 1 d of operation of a desalination system. Bórquez and Ferrer [33] evaluated two seawater desalination systems based on nanofiltration (NF) membranes and ion exchange process for supplying drinking water. The first desalination system consists of two stages of the NF membrane in series, while the second option in one stage of the NF membrane and one stage of the ionic exchange process in series. Experimental results showed that using both methods we could obtain drinking water that meets the standards for drinking water set in Chile. However, the two-stage process involving the NF membrane and the ionic exchange process was the best configuration for supplying drinking water because it requires lower energy consumption compared to two stages of the NF membrane. Sánchez et al. [34] evaluated a separation method to remove boron from water available in northern Chilean regions, via sorption-desorption cycles using a water-soluble polymer based on N-methyl-D-glucamine coupled to polymer-enhanced ultrafiltration. The presence of boron in water is detrimental to water consumption and crop irrigation. Experimental results showed that the proposed system was able to remove boron from water coming from Northern Chile. Frick and von Sommerfeld [35] evaluated a desalination system based on a natural freezing process to supply drinking water in the Atacama Desert. The desalination system consists of various solar stills with the inclined evaporating surface. The main results demonstrated that the proposed system can provide drinking water and could be an economical solution for several localities in the northern regions of Chile.

Hurtado et al. [36] and Cancino-Madariaga et al. [37] evaluated experimentally the separation of nitrogen compounds by an NF membranes system aiming to ensure adequate water quality for fish production in a recirculation aquaculture system. Experimental results in both studies show that the NF membrane system can reject nitrogen compounds, but its separation performance depends strongly on nitrogen concentration, water quality, and system configuration. Fournier et al. [38] evaluated a desalination system based on a natural freezing process to supply water for crop irrigation in greenhouses in the Atacama Desert. The desalination system was proposed to this area since salt water can freeze in ambient temperatures above 0°C. The main results showed that the proposed system was able to produce nine liters of water per square meter of melting ice. Therefore, this method could be an economically viable alternative for supplying water for crop irrigation in small rural areas.

Suárez et al. [39] developed an integrated water resources management model to assess the water-energy nexus in a basin located in the Atacama region. The model evaluated different management scenarios including seawater desalination as an option to increase water availability. The main result showed that if water consumption is reduced by 30%, 70 GWh of additional energy would be required over the next 30 years to supply energy to the desalination system to reduce water stress in the area. This could be achieved by using solar energy; however, to reach this goal, decision-makers from the Chilean government as well as water and energy companies should be engaged in the process.

3. Major challenges and potential future directions of desalination in Chile

Based on the aforementioned antecedents, the desalination industry is playing a fundamental role to face the problem of water scarcity in the northern regions of Chile. Most of the desalination plants supply water to the Chilean mining sector. Indeed, 70% of the total future desalination capacity in Chile will meet the water demand of this productive sector. This situation highlights the strong relationship between desalination and mining in Chile. Also, the installation of desalination plants producing potable water has also been considered as an option to partly meet the demand for water posed by the urban sector. Therefore, we may legitimately expect that the application of desalination technologies will continue to expand in the future in Chile. However, this fast growth also produces some technical, environmental, and economic challenges to the country that are discussed below.

Since almost all desalination plants in Chile are treating seawater, one of the current technical challenges facing the desalination industry in Chile is the occurrence of harmful algal bloom in its coasts [40]. This phenomenon can cause irreversible damages to the reverse osmosis membranes surface affecting the operation of desalination plants. Moreover, algal bloom events can cause health problems to the population since they could change the physical, chemical and biological characteristics of water organisms [41]. Several technologies can be used as pre-treatment systems in desalination plants to reduce the organic load present in seawater during an algal bloom event, such as sedimentation, dissolved air flotation, granular media filtration, and ultrafiltration membranes [42]. Another alternative to face the algal bloom problem is to install subsurface intake systems that improve the quality of feed water. This type of system uses the natural geological properties of sediments and rocks for filtering the feed water by straining and biodegrading organic matter and other particulates [43,44]. In general terms, this natural phenomenon is difficult to predict; hence, adequate strategies should be put in place at an operational level to be prepared to face these harmful events.

An environmental challenge comes from the potential damages generated by the disposal of desalination concentrate. It could generate local impacts on marine benthic communities located close to the desalination plant discharge points, increasing the salinity of water bodies, and discharging some harmful chemical additives industry as was in the pre-treatment processes and maintenance activities of desalination plants [45]. To face this situation, new strategies should be tested to manage this waste in the specific context of Chile. An interesting option is the use of desalination concentrate in the non-metallic mining industry as was proposed by Ordóñez et al. [29]. This option was investigated in depth in the last years [46–49]. However, another interesting alternative could be the recovery of critical materials from desalination concentrate. These strategic materials can be utilized in different technological applications, which open up new business opportunities [50]. However, the real benefits and risks of these opportunities must be evaluated from a technical and economic perspective in future investigations.

The complex topography of Chilean mine's location leads to several technical and economic challenges that must be faced in the design and operation stages of the water supply system. As was indicated in the previous section by Herrera et al. [25] and Herrera-León et al. [26], appropriate approaches considering the simultaneous design of desalination plants and water transport systems should be considered to analyze and evaluate the tradeoffs between technical and economic factors involved. In this context, Herrera-León et al. [51] have proposed an optimization approach to designing water supply systems for mines operating in Chile. The proposed approach can determine – from a technical and economic perspective – the optimal topology of the system, optimal locations, and sizes of the desalination plants, pumping stations, and pipelines. According to scholars, the problem of water scarcity is also a problem of energy consumption since desalinated water supply systems are highly energy-intensive. Moreover, this problem may translate into negative environmental impacts related to greenhouse gas emissions because in Chile energy comes mainly from the combustion of fossil fuels. To face this problem, northern Chilean regions offer an excellent opportunity to use solar energy technologies since they have one of the highest solar radiation on Earth [52].

It has been demonstrated that solar energy technologies are a feasible option to diminish environmental impacts generated by the intensive energy consumption of the Chilean mining industry [53,54]. Taking this opportunity into consideration and having in mind the water scarcity problem existing in northern Chilean regions, the development of polygeneration systems that integrate solar energy and desalination technologies to supply energy and water is seen as an interesting option. However, more cooperation between the energy sector and the water sector is necessary to carry out such projects. Also, a significant technical challenge for the solar industry lies in the development of renewable energy systems capable to supply energy continuously all day long. In this context, energy storage technologies are key elements [55].

The Chilean mining industry does not require high-quality water which desalination plants produce. Therefore, a disruptive solution for mining companies is to use seawater in their operations to avoid the installation of desalination plants and the costs associated with them. Some mining companies in Chile are already using seawater in their operations [27,56]; however, this option also generates some operational problems. For instance, the presence of calcium and magnesium ions in seawater reduces the recovery yield in the copper-molybdenum mining industry [57,58]. To face this problem, partial desalination treatment of seawater has been proposed. Arias et al. [28] proposed a partial desalination treatment based on the use of halotolerant bacteria isolated from the salt lakes located at the Atacama Desert to remove calcium and magnesium salts. With the same goal in mind, Jeldres et al. [59] and Cruz et al. [60] proposed a partial desalination treatment using a mixture of chemical reagents. However, further investigations must be carried out to evaluate the technical and economic feasibility of these partial desalination treatment techniques at the pilot and industrial levels. Another problem related to the use of seawater is its high density compared to desalinated water that increases the power needed to transport the water from the coast to the mountains over 1,000 meters above sea level, where ore processing plants are commonly located in Chile. Moreover, the corrosive nature of seawater would demand to use of high-quality material for piping and equipment. These factors, among others, such as the location of industrial facilities, the type of ore deposits, the cost of electricity, and environmental regulations must be evaluated to decide whether to use desalinated water or seawater directly in mining operations.

Besides the abovementioned challenges, the use of desalination plants for agriculture purposes would generate economic and social benefits for the country. Chile is a developing country, and consequently, its population and the standard of living are growing. This generates more pressure on the food security of the country [61]. Therefore, the use of desalinated water for crop irrigation is seen as a promising alternative to meet the future demand for food. The use of desalinated water in the agricultural sector has several advantages, which include the continuous and stable supply of water and irrigation with high-quality water that allows obtaining high-quality agricultural products [2]. However, one of the major limitations is the cost of desalinated water production higher than conventional water supplies [62]. Despite this situation, nowadays some arid and semi-arid countries, including Spain [63], Israel [64], and Australia [65] are using desalinated water for crop irrigation. To reduce the risks of using desalinated water for crop irrigation in Chile, desalination technologies should be evaluated in the future according to local characteristics where these systems will be installed.

4. Concluding remarks

This article presents the current situation and major challenges of desalination in Chile. The current production capacity of desalinated water in northern Chile has increased notably in the last decades due to the rapid development of the mining sector and the constant growth of the population. Nowadays, eleven desalination plants over 10 l/s are operating in Chile and the installation of ten desalination plants is expected in the future. The major challenges identified in the specialist literature include harmful algal bloom events affecting the technical performance of desalination plants, the disposal of desalination concentrate producing environmental impacts in the local marine ecosystems, and the high energy consumption by water supply systems, which results in the emission of greenhouse gases. Potential solutions have been identified to face these problems, such as the development of partial desalination treatment techniques for the Chilean mining sector, the use of desalination concentrate for promoting business opportunities, and the use of solar energy technologies, among other solutions. However, more cooperation and integration between the private, public and academic sectors is needed for these solutions to materialize.

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