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Impact of seawater desalination and wastewater treatment on water stress levels and greenhouse gas emissions: The case of Chile

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Abstract

Many regions around the world are suffering from water stress, and desalinated water and recycled water are seen as alternatives for meeting the water demand. However, high energy consumption and associated greenhouse gas emissions are some of the main environmental impacts. This is notable for many arid and semi-arid countries where desalination and water recycling are considered options for ensuring water resources availability. This research presents the incorporation of the quantification of greenhouse gas emissions generated during the operation of desalination and wastewater treatment plants in the assessment of water stress levels using the water stress indicator adopted by the 2030 Agenda for Sustainable Development. Chile was chosen as a case study, as it is a country where there is a considerable difference between the availability of conventional water sources and the water demand, and the electrical grid is fed mainly by fossil fuels. The methodology proposed allows calculating the indirect greenhouse gas emissions due to electrical consumption for the operation of desalination and wastewater treatment plants, and the direct greenhouse gas emissions coming from biological processes used in wastewater treatment plants. The results showed that Chilean arid climate zones will not experience water stress in the future at the regional level, mainly because of the installation of several desalination plants by 2030. Meanwhile, recycled water from the urban sector will slightly contribute to the reduction in the level of water stress in almost all Chilean regions by 2030. Moreover, desalination and wastewater treatment plant will contribute only between 0.34% and 0.75 % of total greenhouse gas emitted in Chile by 2030. Therefore, the operation of these industrial systems for facing water scarcity problems in northern and central zones of Chile is a suitable alternative because it does not generate large environmental problems.

Keywords: Water Stress; Desalination; Wastewater; Greenhouse Gas; Chile

1. Introduction

Water scarcity has brought into focus the urgent need for development of strategies and actions to manage water resources effectively, as it is widely acknowledged that water is one of the major limiting factors in socioeconomic development (Tzanakakis et al., 2020; World Economic Forum, 2019; Liu, 2017; Kummu et al., 2016; Mekonnen et al., 2016; United Nations, 2011; Vairavamoorthy et al., 2008). In this context, the 2030 Agenda for Sustainable Development includes a specific goal (SDG 6) focused on ensuring the availability and sustainable management of water and sanitation for all (Hoekstra et al., 2017). Specifically, Target 6.4 of SDG 6 addresses water scarcity, aiming to substantially increase the water-use efficiency across all sectors, ensure the sustainable withdrawal and supply of freshwater, and substantially reduce the number of people suffering from water scarcity (Fehri et al., 2019; Vanham et al. 2018). Two main indicators are used to monitor progress in addressing this target: (1) indicator 6.4.1 aims to monitor changes in the water-use efficiency over time and is expressed in terms of the value per volume of water use, commonly in dollars per cubic meter (UNSD, 2021a), and (2) indicator 6.4.2 aims to monitor the level of water stress by accounting for water resources and withdrawal from all sectors in a particular region, country, or basin and is expressed in terms of a percentage (UNSD, 2021b). However, it is important to mention that the use of indicators for measuring the level of water stress in different regions at different scales is not a new method of assessment. Many indicators have been developed to facilitate the assessment of the status of water scarcity around the world since the late 1980s, and these are known as Water Stress Indicators (WSIs) (Damkjaer and Taylor, 2017)

Most existing WSIs estimate the ratio between the water use rate and the water availability rate (Liu et al., 2017), but other elements must be considered to carry out an effective assessment. Vanham et al. (2018) pointed out that there are seven essential elements that should be considered for the estimation of WSIs: 1) net and gross water withdrawal; 2) environmental flow requirements; 3) temporal disaggregation; 4) spatial disaggregation; 5) surface water, groundwater resources, and their interactions; 6) desalinated water and fossil groundwater; and 7) water recycling, water storage in reservoirs, and aquifer recharge management. Determining the net water withdrawal is important to determine how much water is being withdrawn from conventional water sources and never returned to same source (Vanham et al. 2018), while determination of the environmental flow requirements is essential for ensuring the minimum water flow rates and levels needed to maintain rivers and sustain aquatic ecosystems (United Nations Environment Program, 2009). Temporal and spatial disaggregation is essential for understanding water stress levels at different geographical scales and determining how these levels change through the years (Brunner et al., 2019; Fehri et al., 2019). To identify interactions between surface water and groundwater, it is essential to understand how the changing climate and land-use alterations affect water resources availability. This requires the use of hydrological models (Swain et al., 2020). The final elements that must be considered in water scarcity assessment—the use of desalinated water and fossil groundwater as alternative water sources as well as the implementation of strategies and technologies for water recycling, water storage in reservoirs, and aquifer recharge management—should be considered key activities for decreasing water scarcity; however, these elements have not been analyzed in detail in studies when WSIs are using to assess water stress levels (Vanham et al. 2018; Wada et al., 2011).

Considering that having secure and resilient water supply systems is becoming more challenging and that, at the same time, current economic development is leading to increased water demand. It is appropriate to consider nonconventional water sources, such as recycled water and desalinated water, as alternatives for dealing with water scarcity (Vanham et al., 2018; Gude, 2017; Wada et al., 2011). The use of recycled water and desalinated water could help to reduce the gap between water resources availability and demand as well as allowing the conservation of existing water resources, since the exploitation of inland water bodies, surface water resources, and groundwater needs to be reduced (Gude, 2017; Hardy et al., 2015). In fact, today, part of the water demand is currently being met by desalination plants, especially in regions where water is scarce. There are more than 15,000 desalination plants operating in 177 countries worldwide to produce over 1000 m^3/s of desalinated water (Jones et al., 2019). The dominant process used is reverse osmosis, which accounts for 84% of all operational desalination plants and produces approximately 700 m^3/s of desalinated water, representing 70% of the world's desalinated water (Jones et al., 2019). Therefore, desalinated water is a key nonconventional water source in regions where conventional water resources are scarce. For assessing water stress levels, desalinated water use must be subtracted from the water demand as this alleviates the demand that has to be met from the available conventional water sources. On the other hand, it is estimated that 359.4 billion m^3/year of wastewater is produced, with a global average of 49 million m^3/capita (Jones et al., 2021). The amount of reused wastewater globally has reached 40.7 m^3/year, representing about 11% of the total volume of wastewater produced (Jones et al., 2021). The activated sludge process is the main type of wastewater treatment in operation and is used to treat about 80% of urban wastewater in developed countries by removing organic and nitrogen compounds (Ghimire et al., 2021). Although it has been indicated that water recycling does not reduce water stress levels because it fosters that less water needs to be abstracted from a particular basin, country, or region, but at the same time the amount of water returning to the same place is smaller, which means that the estimated net water withdrawal for the basin or region under analysis does not change (Hoekstra et al., 2011). However, this statement must be reconsidered when recycled water comes from flows that are not returned to the same basin, country or region analyzed since this alternative helps in decreasing their water stress levels because the net water withdrawal would change. A clear example is the urban sectors located in coastal areas, where part of the water used is sent direct to the ocean after treatment and not to the same place from where it was abstracted. Therefore, recycled water coming from flows that are not returned to the same basin, country, or region, must be subtracted from the water demand for assessing water stress levels.

Based on antecedents mentioned, desalinated water and recycled water are considered as alternatives to reduce water scarcity; therefore, the energy consumption required for the operation of desalination and wastewater treatment plants must be considered in water stress assessment whether long-term sustainable alternatives want to be implemented, since the production of greenhouse gas emissions is one of the main environmental impacts generated by these industrial systems (Sabeen et al., 2018; Miller et al., 2015; Gupta and Singh, 2015). Greenhouse gases are emitted directly and indirectly from the operation of wastewater treatment and desalination plants (Nguyen et al., 2021; Mannina et al. 2016; Cornejo et al., 2014). Reverse osmosis and activated sludge are energy-intensive processes that can generate large amounts of greenhouses gas emissions indirectly during the power production based on fossil fuel combustion (Shemer and Semiat, 2017; Gude, 2016; Liu et al., 2015; Heihsel et al., 2019). The reverse osmosis system and pretreatment are the main energy consumers in reverse osmosis desalination plants, accounting for 71% and 11% of the total energy consumption, respectively (Voutchkov, 2018). Meanwhile, aeration of the activated sludge process is the main energy consumer in wastewater treatment plants, accounting for about 60% of the total energy consumption (Ghimire et al., 2021). In addition, direct greenhouse gas emissions occur mainly during the activated sludge process through biological processes, for example, carbon dioxide (CO_2) emissions from microbial respiration, and nitrous oxide (N_2O) from nitrification (Mannina et al. 2016). In the past, it was assumed that direct greenhouse gases emissions from water treatment plants are generally derived from biogenic and therefore not considered in the quantification (Eggleston et al., 2006). However, current research has indicated that wastewater contains an appreciable amount of non-biogenic (fossil) organic carbon that can be derived from the use of petroleum-based products, both domestically and commercially, which contribute to carbon dioxide emissions (Bao et al., 2015; Fent et al., 2006; Griffith et al., 2009). In this context, direct greenhouse gas emissions from wastewater treatment should be implemented in carbon footprint analysis to prevent underestimates (Kosse et al., 2018). In contrast, the direct greenhouse gas emissions produced from the reverse osmosis process is negligible compared with indirect emissions; thus, they are not quantified (Ihsanullah et al., 2021). Therefore, the use of water desalination and water recycling as alternatives for dealing with water scarcity is an environmental problem since greenhouses gases are emitted.

However, the impacts of seawater desalination and wastewater treatment plants on water stress levels and greenhouse gas emissions have not been presented in scientific literature to date; therefore, it is seen as an opportunity to provide a better understanding of the dependence on nonconventional water sources and the environmental impacts generated, aiming to determine long-term sustainable alternatives for facing water scarcity problems. In this context, the novelty of this research is to incorporate the quantification of greenhouse gas emissions generated during the operation of desalination and wastewater treatment plants in the assessment of water stress levels using the WSI adopted by the 2030 Agenda for Sustainable Development. Chile was chosen as the subject of this research because it has the following characteristics: (1) Chile has a variety of climates, resulting in large differences in the availability of conventional water resources as well as different water users across the country (Aguilera et al., 2019; Valdés-Pineda et al., 2014); (2) large amount of treated wastewater is sent direct to the ocean and not to the basin from where water is abstracted, particularly by users located in coastal areas; (3) the Chilean government has proposed new policies to promote the use of desalinated water and recycled water in the urban, industrial, and agriculture sectors (MOP, 2020); (4) water demand is growing in Chilean regions suffering from water scarcity, and desalination and wastewater treatment plants are seen as the best option for meeting water requirements (MOP, 2020); (5) Since 2018, eleven desalination plants have been operating at the industrial scale operating in Chile, producing over 5000 l/s of desalinated water. Moreover, there are ten desalination projects at different stages of evaluation, and the desalination capacity is predicted to increase by about 100% in the coming years (Herrera-León et al., 2019); (6) the Chilean electrical grid is mainly based on the combustion of fossil fuels, contributing to the generation of greenhouse gas emissions (Vega-Coloma and Zaror, 2018); and (7) several investigations focusing on current and future water scarcity at the local level in Chile have concluded that different basins are suffering from water stress (Bitran et al., 2014; Salinas et al., 2016; Urquiza and Billi, 2020; Muñoz et al, 2020). This paper is structured as follow: Section 2 presents the methodology that is divided into four stages to carry out the water stress assessment incorporating the quantification of greenhouse gas emission produced during the operation of desalination and wastewater treatment plants for the northern and central zones of Chile; Section 3 presents the results that are the values of the WSI and greenhouse gas emission resulting from the production of desalinated water and recycled water for the northern and central zones of Chile; and finally, Section 4 and Section 5 presents the discussions of the results obtained and the main conclusions of this research, respectively.

2. Methodology

This section is divided into four stages: First, the study area is characterized; second, the method of WSI assessment is presented; third, the method of quantification of greenhouse gas emissions generated by the operations of desalination and wastewater treatment plants is presented; and finally, the data collection required to assess the WSI and quantify the greenhouse gas emissions in the years 2015 and 2030 are presented. In the latest stage, a sensitivity analysis is also presented for understanding how different values of the main parameters affects the production of greenhouse gas emission from desalination and wastewater treatment plants.

2.1 Study area characterization

Chile is administratively divided into sixteen regions, which are indicated with Roman numerals in Figure 1. The Roman numerals were assigned in ascending order from north to south. However, the Roman numeral order was broken in 2007 due to the creation of three new administrative regions: Arica and Parinacota Region (XV), Los Ríos Region (XIV), and Ñuble Region (XVI). In addition, the Santiago Metropolitan Region located in the center of the country and home to the country's capital, Santiago de Chile, was excluded from this naming scheme, because it was assigned RM. The area of study was the northern and central zones of Chile, which are divided into nine administrative regions. Figure 1 shows these administrative regions, and Table 1 shows the main characteristics of each in terms of the surface area, population, main water users, number of basins, mean annual rainfall, and number of desalination and wastewater treatment plants operating at the industrial scale.

The northern zone comprises five administrative regions. For simplicity, they have been named after their respective capital cities: Arica, Iquique, Antofagasta, Copiapó, and La Serena. The northern zone has a total surface area of 300,904 km^2 and 2,207,914 inhabitants, which corresponds to 12.56% of the total Chilean population (INE, 2018). The central zone comprises four administrative regions that have also been named after their respective capital cities: Valparaíso, Santiago, Rancagua, and Talca. The total surface area of the central zone is 78,482 km^2, and the population is 10,888,215, which corresponds to 61.96% of the total Chilean population (INE, 2018). The northern zone has an arid or semi-arid climate with an extremely low level of precipitation, high temperatures, and a mean annual rainfall of 87 mm/year (DGA, 2016). This zone has 48 basins (DGA, 2018) from which water has been withdrawn for decades for human and industrial activities (Scheihing and Tröger, 2018; Houston and Hart, 2004). In addition, this zone has thirteen desalination plants based on reverse osmosis technology that operate at the industrial level for the treatment of seawater as well as forty-nine wastewater treatment plants whose main process is activated sludge. Mining industry is one of the main industries in northern Chile and is dedicated to the extraction and processing of copper, molybdenum, lithium, gold, silver, and other minerals (Cisternas and Gálvez, 2014). The second major industry is agriculture (DGA, 2016).

The central zone of Chile has a Mediterranean climate with a mean annual rainfall of 943 mm/year (William, 2017; DGA, 2016), which is concentrated between the months of May and September (Valdés-Pineda et al., 2014). Since 2010, this zone has suffered from an uninterrupted sequence of dry years, with an average rainfall deficit of 20-40%, resulting in a significant drought (Garreaud et al., 2020). This zone has 20 basins (DGA, 2018), and water is mainly used in agriculture to produce a large variety of fruits, vegetables, and flowers (Aguilera et al., 2019). In addition, this zone has only one reverse osmosis desalination plant in operation. It has one hundred and twenty-three wastewater treatment plants based mainly on the activated sludge process. It is worth mentioning that the southern and austral zones of Chile were not considered in this case study because they have abundant water resources and water availability exceeds water demand (Valdés-Pineda et al., 2014). On the other hand, in the northern and central zones, water resources are limited, scarce, or even non-existent, leading to the exploitation and overexploitation of some conventional water sources to satisfy the water requirements of different users. Therefore, the water demand is greater than the water resources availability (DGA, 2016).

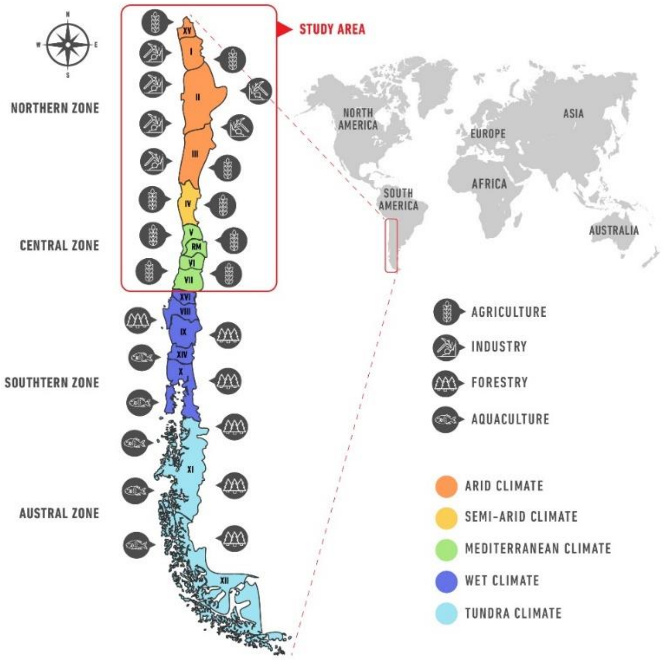

Figure 1: Administrative regions, main water users, and climates in Chile. The climate information was extracted from Rioseco and Tesser (2013).

Table 1: Main characteristics of each administrative region located in the northern and central zones of Chile.

Administrative region (Roman numeral/capital cities)	Surface area [km^2] (DGA, 2016)	Population (INE, 2018)	Main water users (DGA, 2016)	Number of basins (DGA, 2016)	Mean annual rainfall [mm/year] (DGA, 2016)	Number of desalination plants (Valenzuela et al., 2018)	Number of wastewater treatment plants (SISS, 2019)
XV/Arica	16,873	226,068	Agriculture	5	132	1	1
I/Iquique	42,226	330,558	Mining and agriculture	5	77	0	7
II/Antofagasta	126,049	607,534	Mining	10	45	7	9
III/Copiapó	75,176	286,168	Mining and agriculture	11	82	3	9
IV/La Serena	40,580	757,586	Agriculture	10	222	2	23
V/Valparaiso	16,396	1,815,902	Agriculture	8	434	1	34
RM/Santiago	15,403	7,112,808	Agriculture	2	650	0	34
VI/Rancagua	16,387	914,555	Agriculture	2	898	0	24
VII/Talca	30,296	1,044,950	Agriculture	5	1,377	0	31

2.2 Water stress indicator assessment

According to FAO (2018), the WSI adopted in the 2030 Agenda for Sustainable Development for monitoring the level of water stress in a particular region, country, or basin is expressed in Equation (1). Equation (2) is a variation of Equation (1) that is presented to highlight the main elements analyzed in this research, which are the use of recycled water and desalinated water as alternatives for water facing water scarcity problems. Figure 2 shows the main elements considering in the quantification of the WSI, and it is presented aiming to provide the reader a better understanding of the relationships between the elements of the system under analysis. The net water withdrawal was estimated as the sum of gross water withdrawal from conventional water sources by users minus the quantity of reclaimed water that is returned to the same conventional water sources after treatment to reach quality standards, assigned as reclaimed water 1 in Figure 2. As mentioned above, it is important to recycle water from the flow assigned as reclaimed water 2 in Figure 2, since this water flow is lost and its recycling can help to decrease water stress levels. Recycled water, both assigned as recycled water 1 and recycled water 2 in Figure 2, were estimated as the sum of treated wastewater that is sent directly to agricultural and industrial users for nonpotable applications. Desalinated water was calculated as the sum of water produced from seawater to produce water that meets quality standards for urban and industrial users. Water resources availability was estimated as the sum of water generated from precipitation minus water that undergoes natural evapotranspiration, and environmental flow requirements represent the quantity of water required to sustain aquatic ecosystems aiming to preserve nature and protect the environment (see Figure 2). The quantification of environmental flow requirements is extremely variable, since, as a first step, it is necessary to decide what aspect of an aquatic ecosystem or ecosystem service will be protected (Vanham et al., 2018). The main methods used for quantification are hydrological, hydraulic-habitat, and holistic; however, method selection depends on the needs and resources of the study area (Pastor et al., 2014; Sood et al., 2017). FAO (2018) computed the environmental flow requirements as a percentage of the available water resources that is obtained with the information available of the mean annual runoff. In this context, Pastor et al. (2014) proposed that the environmental flow requirement is between 25% and 46% of the mean annual runoff reported. All elements of the WSI are given in cubic meters per second, and the level of water stress was determined considering the values of the WSI defined by the UNSD (2021b), as shown in Table 2.

$$\text{WSI (\%)} = \frac{\text{water use}}{\text{water resources} - \text{environmental flow requirements}} * 100 \qquad (1)$$

$$\text{WSI (\%)} = \frac{\text{net water withdrawal} - \text{recycled water} - \text{desalinated water}}{\text{water resources availability} - \text{environmental flow requirements}} * 100 \qquad (2)$$

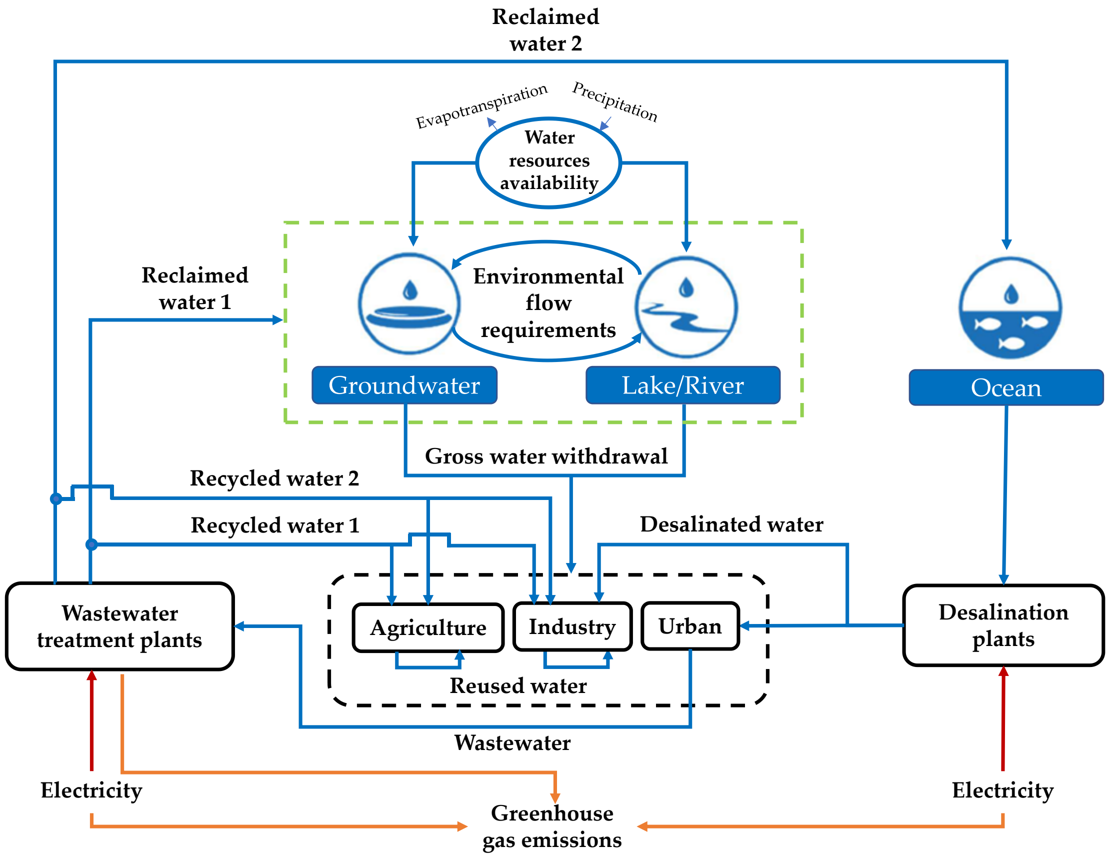

Figure 2: Schematic representation of the main elements of water stress indicator.

Table 2. Different levels of water stress based on the water stress indicator (UNSD, 2021b).

Values	Level of water stress
$\mathbf{WSI \geq 100\%}$	Critical
$\mathbf{75\% \leq WSI < 100\%}$	High
$\mathbf{50\% \leq WSI < 75\%}$	Medium
$\mathbf{25\% \leq WSI < 50\%}$	Low
$\mathbf{WSI < 25\%}$	No stress

2.3 Greenhouse gas emissions generated by the operation of desalination and wastewater treatment plants

Figure 2 shows conceptually that desalination and wastewater treatment plants require electricity for their operation, which results in greenhouse gas being emitted indirectly to the environment (Gude, 2016; Lazarova et al., 2012). Moreover, a considerable amount of direct greenhouse gas emissions is generated from biological processes used in wastewater treatment plants (Mannina et al. 2016). The amount of electricity used annually for the operation of a desalination and wastewater treatment plant is a function of its capacity and the unitary electrical energy consumption required (Gude, 2016; Cornejo et al., 2014). This amount of electricity is necessary to maintain the operation of the water treatment plants continuously, but it does not consider the electricity needed to convey the water produced to users located far away (Herrera-León et al., 2018). The electricity required for water conveyance was not considered in this research. To estimate greenhouse gas emissions, it is necessary to know the emission factor of the area under study, which depends on the resources feeding the electrical grid (Foster and Bedrosyan, 2014). Therefore, to quantify the amount of greenhouse gas emissions generated indirectly through electricity consumption by desalination plants, Equation (3) is presented. In this equation, β represents the unitary greenhouse gas emissions generated by the electrical grid according to the study area, while α represents the unitary electrical energy consumption of desalination plants, and Q represents the capacity of the desalination plants. It is worth mentioning that direct greenhouse gas emissions from desalination plants were not quantified in this research, because they are negligible compared with indirect emissions (Ihsanullah et al., 2021). In the same context, Equation (4) presents the amount of greenhouse gases emitted indirectly through the operation of wastewater treatment plants and greenhouse gases emitted directly through biological processes used in wastewater treatment plants, where β represents the unitary greenhouse gas emissions of the electrical grid according to the study area, α^* represents the unitary electrical energy consumption of wastewater treatment plants, γ represents the unitary greenhouse gas emissions produced from biological processes, and Q^* represents the wastewater treatment plants' capacity.

$$\mathrm{GHG_{desal}} = \beta \left[\frac{\mathrm{kg\ CO_{2eq}}}{\mathrm{kWh}}\right] \cdot \alpha \left[\frac{\mathrm{kWh}}{\mathrm{m^3}}\right] \cdot \mathrm{Q} \left[\frac{\mathrm{m^3}}{\mathrm{h}}\right] \tag{3}$$

$$\mathrm{GHG_{WWTP}} = \beta \left[\frac{\mathrm{kg\ CO_{2eq}}}{\mathrm{kWh}}\right] \cdot \alpha^* \left[\frac{\mathrm{kWh}}{\mathrm{m^3}}\right] \cdot \mathrm{Q}^* \left[\frac{\mathrm{m^3}}{\mathrm{h}}\right] + \gamma \left[\frac{\mathrm{kg\ CO_{2eq}}}{\mathrm{m^3}}\right] \cdot \mathrm{Q}^* \left[\frac{\mathrm{m^3}}{\mathrm{h}}\right] \tag{4}$$

2.4 Data Collection and Sensitivity Analysis

The data required for the assessment of the WSI are usually collected from national institutions dealing with water issues and national ministries related to water resources, agriculture, or the environment in the area under study (FAO, 2018). In general, the data are mainly published in national statistical yearbooks, national water resources, and irrigation master plans, as well as in other reports, such as publications from national and international research centers. In the Chilean context, the WSI was calculated for the years 2015 and 2030 by collecting data mainly from reports published by the General Water Directorate (DGA), which is a regulatory body that operates under the Chilean Ministry of Public Works. As mentioned above, the net water withdrawal was estimated as the sum of gross water withdrawal from conventional water sources by users minus the quantity of reclaimed water returned to the same conventional sources after treatment. Gross water withdrawal values in 2015 and 2030 were gathered from the report published by the DGA (DGA, 2017). It is worth mentioning that these values represent the water consumption of each user located in basins belonging to the analyzed Chilean administrative region shown in Table 1. Data for water resources in 2015 and 2030 were obtained from a report published by the DGA that recorded the mean annual runoff values for each basin from 1985 to 2015 and the projected values for 2030 (DGA, 2018). The environmental flow requirements in 2015 and 2030 were calculated as 20% of the available water and represented by the mean annual runoff of the basins located in the Chilean administrative region under analysis. This percentage was based on the regulatory framework established by the Ministry of the Environment in Chile (MMA, 2015). It should be noted that the environmental flow requirements in Chile is lower than the environmental flow requirements indicated previously, which are between 25% and 46% of the mean annual runoff (Pastor et al., 2014). This is because the value of each country is based on natural and social conditions, level of development, population density, availability of non-conventional water sources and climatic conditions (FAO, 2018). Data on desalinated water produced by seawater desalination facilities in 2015 and 2030 were obtained from a report detailing the desalination plants in operation and those undergoing evaluation in Chile (Valenzuela, 2018). Meanwhile, the amounts of reclaimed water returned to the same conventional water source, reclaimed water returned to the ocean, and recycled water for 2015 were gathered from a report published by the Chilean Ministry of Public Works (MOP, 2020). The amounts of reclaimed water returned to the same water source, reclaimed water returned to the ocean, and recycled water for 2030 were quantified with consideration of the goals established by the Sanitation Sector Agenda 2030 in Chile. These goals are that at least 30% of reclaimed water discharged to the ocean and 20% of reclaimed water discharged to conventional water sources will be available for direct recycling by different users by 2030, mainly in the agricultural and industrial sectors (SISS, 2019). This means that 20% and 30% of the flows assigned as reclaimed water 1 and reclaimed water 2 will be recycled, respectively, as shown in Figure 2. In addition, it is important to highlight that, in this study, only recycled water from the urban sector was considered, and water recycled from the agriculture and industrial sectors was not considered due to data not being available. The industrial sector reuses water in its facilities by applying water-saving solutions and efficient technology (Cisternas and Gálvez, 2018; Ghorbani and Kuan, 2017). However, this reused water is not considered to be recycled, since it never leaves the industrial facility; therefore, the reuse of water is reflected in a reduction in water withdrawal, rather than an increase in the amount of recycled water.

In this study, greenhouse gas emissions were computed considering that the reverse osmosis process is used in desalination plants to produce water from seawater to meet the quality standards required for the urban and industrial sectors. Meanwhile, the activated sludge process is used in wastewater treatment plants to treat wastewater from the urban sector aiming to produce water that meets the quality standards required for irrigation and other nonpotable applications. In addition, it is important to mention that the anaerobic digestion of sludge was not considered in this study; therefore, methane emissions occurring in this biological process were not calculated. The operation of both industrial systems is mainly affected by the feed water characteristics, plant capacity, and plant performance (Voutchkov, 2018; Ghimire et al., 2021). Therefore, instead of using specific values to estimate greenhouse gas emissions using equations (3) and (4), a local sensitivity analysis considering the assumptions of linearity is incorporated to assess how the variability of the equation's parameters affects the behavior of both water treatment plants. A sensitivity analysis seeks to determine how different values of an independent variable affect a specific dependent variable under a given set of assumptions. In this context and based on data reported in the scientific literature, the sensitivity analysis considered minimum and maximum values for each parameter since any value obtained for greenhouse gas emissions from desalination and wastewater treatment plants can be computed by the arithmetic mean of two values within this range. The unitary electrical energy consumption of a reverse osmosis plant (α) has been shown to vary between 2.5 and 4.0 kWh/m^3 (Zarzo and Prats, 2018). The unitary electrical energy consumption of an activated sludge process (α^*) varies between 0.3 and 0.65 kWh/m^3 (Gikas, 2017), while the unitary greenhouse gas emissions from the biological processes of the activated sludge process (γ) varies between 0.14 and 0.94 kg CO_2-eq/m^3 (Mannina et al., 2020), including biogenic and non-biogenic sources of direct CO_2 emissions. Considering the decline in greenhouse gas emissions in recent years in Chile, the unitary greenhouse gas emissions factor of the electrical grid (β) was 0.8 kg $CO_{2\text{-eq}}$/kWh in 2015 and is projected to be 0.3 kg $CO_{2\text{-eq}}$/kWh in 2030 (Molinos-Senante and González, 2019).

3. Results

3.1 Water stress indicator for the northern and central zones of Chile

The variation in net water withdrawal, water resources availability, environmental flow requirements, recycled water, desalinated water, and the WSI for the northern and central zones of Chile for the years 2015 and 2030 are presented in Figure 3 and Figure 4, respectively.

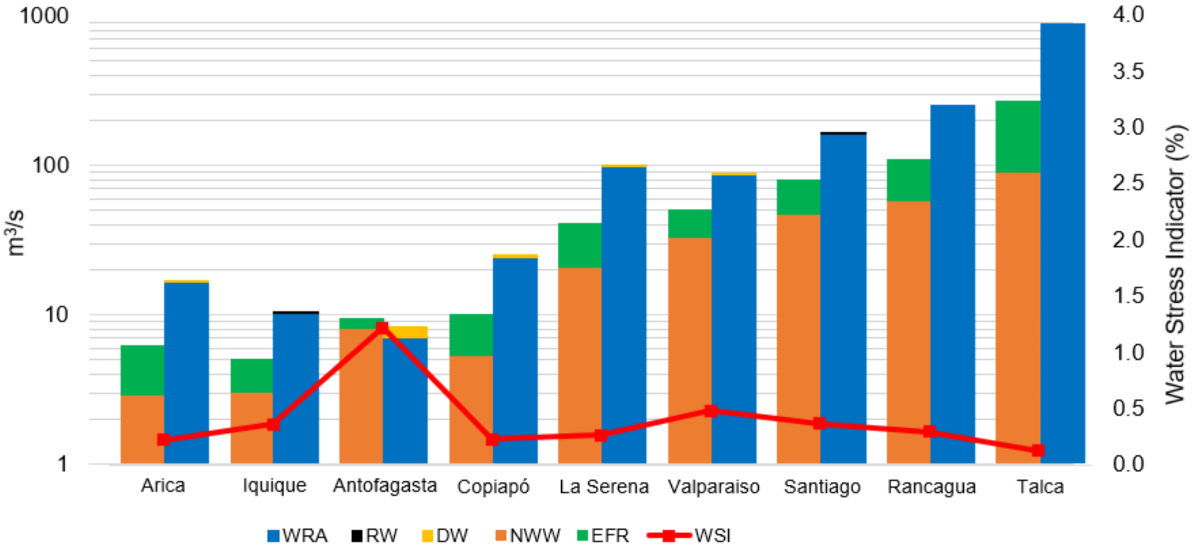

Figure 3: Values of WRA, RW, DW, NWW, EFR and WSI for the northern and central zones of Chile in 2015 (**WRA**: water resources availability (m^3/s); **RW**: recycled water (m^3/s); **DW**: desalinated water (m^3/s); **NWW**: net water withdrawal (m^3/s); **EFR**: environmental flow requirements (m^3/s); **WSI**: water stress indicator (%)).

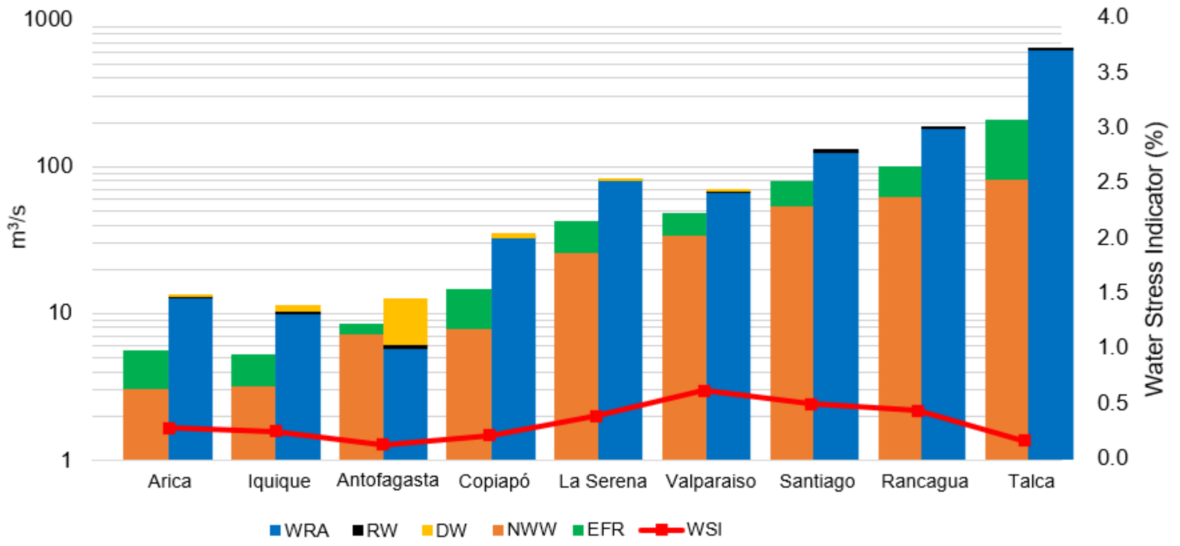

Figure 4: Values of WRA, RW, DW, NWW, EFR and WSI for the northern and central zones of Chile in 2030 (**WRA**: water resources availability (m^3/s); **RW**: recycled water (m^3/s); **DW**: desalinated water (m^3/s); **NWW**: net water withdrawal (m^3/s); **EFR**: environmental flow requirements (m^3/s); **WSI**: water stress indicator (%)).

3.2 Greenhouse gas emissions resulting from the production of desalinated water and recycled water for the northern and central zones of Chile

The magnitudes of direct and indirect greenhouse gas emissions in Chile resulting from the production of desalinated water and recycled water are presented in Table 3 and Table 4, respectively. These tables show the capacity of desalination and wastewater treatment plants based on reverse osmosis and activated sludge processes, respectively, as well as the greenhouse gases emitted by the operation of these industrial systems in the Chilean administrative regions analyzed in 2015 and 2030.

Table 3. Desalinated water and greenhouse gas emissions produced in the northern and central zones of Chile in 2015 and 2030.

Administrative region	**2015**					**2030**				
	Desalinated water capacity (m^3/s)	Indirect GHG emissions [tCO_2-eq/year]		Direct GHG emissions [tCO_2-eq/year]		Desalinated water capacity (m^3/s)	Indirect GHG emissions [tCO_2-eq/year]		Direct GHG emissions [tCO_2-eq/year]	
		Min	Max	Min	Max		Min	Max	Min	Max
Arica	0.01	631	1,009	-	-	0.01	237	378	-	-
Iquique	0.00	0	0	-	-	0.95	22,422	35,875	-	-
Antofagasta	1.27	80,328	128,526	-	-	6.28	148,525	237,640	-	-
Copiapó	0.98	61,558	98,493	-	-	2.28	53,927	86,282	-	-
La Serena	0.16	10,293	16,469	-	-	0.84	19,943	31,909	-	-
Valparaiso	0.09	5,803	9,284	-	-	0.89	21,098	33,756	-	-

Santiago	0.00	0.00	0.00	-	-	0.00	0.00	0.00	-	-
Rancagua	0.00	0.00	0.00	-	-	0.00	0.00	0.00	-	-
Talca	0.00	0.00	0.00	-	-	0.00	0.00	0.00	-	-
Total	2.51	158,613	253,782	-	-	11.25	266,151	425,842	-	-

Table 4. Recycled water and greenhouses gas emissions produced in the northern and central zones of Chile in 2015 and 2030.

Administrative region	2015					2030				
	Recycled water capacity (m^3/s)	Indirect GHG emissions [tCO_2-eq/year]		Direct GHG emissions [tCO_2-eq/year]		Recycled water capacity (m^3/s)	Indirect GHG emissions [tCO_2-eq/year]		Direct GHG emissions [tCO_2-eq/year]	
		Min	Max	Min	Max		Min	Max	Min	Max
Arica	0.00	0	0	0	0	0.23	657	1,423	1,022	6,860
Iquique	0.12	914	1,981	533	3,581	0.37	1,050	2,275	1,634	10,968
Antofagasta	0.09	692	1,499	404	2,710	0.43	1,221	2,646	1,900	12,757
Copiapó	0.04	319	691	186	1,249	0.15	424	919	660	4,432
La Serena	0.01	41	90	24	162	0.44	1,235	2,676	1,921	12,901
Valparaiso	0.00	0	0	0	0	0.97	2,766	5,992	4,302	28,886
Santiago	0.25	1,870	4,051	1,091	7,323	4.72	13,396	29,024	20,838	139,911
Rancagua	0.00	0	0	0	0	0.47	1,329	2,880	2,068	13,882
Talca	0.00	0	0	0	0	0.18	511	1,107	795	5,336
Total	0.51	3,836	8,312	2,238	15,026	7.96	22,589	48,944	35,139	235,935

4. Discussion

Based on the results obtained, most of the Chilean administrative regions under analysis presented low or no water stress in 2015, except for Antofagasta. As shown in Figure 3, the net water withdrawal and environmental flow requirement in Antofagasta were higher than the water resources availability and the amounts of desalinated water and recycled water. Therefore, this Chilean administrative region reached a critical water level status according to standards declared by the UNSD (2021b). However, it was estimated that Antofagasta will radically change its status to a no water stress level by 2030 mainly by the installation of reverse osmosis plants, as shown in Figure 4. Which means that at regional scale there is enough water available to supply regional water demand. The most greatly affected Chilean administrative region in that year will be Valparaíso, which is predicted to have a medium water stress status. This situation will happen due to an expected decline of water resources availability in central Chile, an area that has suffered from an uninterrupted sequence of dry years since 2010 with annual rainfall deficits ranging from 25 to 45% (Garreaud et al., 2020). All other Chilean administrative regions are predicted to have low, or no water stress levels in 2030. It is important to highlight that considering the amount of water available and the net water withdrawal, there are large differences between the northern and central zones of Chile. For instance, the water resources availability in Iquique was 10.09 m^3/s in 2015, whereas in Santiago it was 161.13 m^3/s. Similarly, the net water withdrawal in Copiapó was 7.86 m^3/s in 2030, whereas in Talca, it was 82.28 m^3/s. This situation is repeated when any administrative region located in the northern zone is compared with other located in the central zone (see Figures 3 and 4).

4.1 The impact of desalination and wastewater treatment plants in reducing water stress levels in the northern and central zones of Chile

Seawater desalination based on the reverse osmosis process will play a fundamental role in reducing the pressure on conventional water resources in some Chilean administrative regions by 2030. In fact, desalination plants operating in 2015 produced a total of 2.51 m^3/s of desalinated water, and future projects will increase this capacity by 328% to reach a total of 11.25 m^3/s, as shown in Table 3. Desalinated water production is concentrated in the northern zone of Chile, and it will provide strong support to decrease water stress levels in the Chilean administrative regions of Iquique, Antofagasta, and Copiapó (see Figure 4). At the regional scale, these administrative regions are not predicted to suffer from water stress in 2030, which is outstanding considering that they are located in the most arid desert on Earth. However, it is important to highlight that the amount of desalinated water produced in this area is lower than the net water withdrawal of any Chilean administrative region; therefore, it will be not possible to meet the water demand with desalinated water only. Moreover, the net water withdrawal in the northern zone of Chile is considerably lower than that in the central zone as was previously mentioned. Thus, a small amount of desalinated water will be used to decrease water stress levels considerably in the northern Chilean regions. In this context, it is expected that two desalination plants will be operating in Arica and Iquique, producing a total of 0.96 m^3/s of desalinated water. Twelve desalination plants will be operating in Antofagasta by 2030, producing a total of 6.28 m^3/s of desalinated water, which will mainly be used to satisfy the water requirements of the industrial and urban sectors (see Table 3). Moreover, it is expected that ten desalination plants will be installed in Copiapó and La Serena, producing a total of 3.12 m^3/s of desalinated water in an attempt to meet a portion of the regional water demands. Additionally, it is planned that the first seawater desalination plant financed by the Chilean government will be installed in Copiapó. This will be a milestone in the history of desalination in Chile since the government will install and operate a desalination plant as part of its strategy to reach a low level of water stress in Chile. Therefore, desalination plants will play a fundamental role in addressing the problem of water scarcity in northern

Chile. In fact, if the desalination projects under evaluation are installed in the northern zone of Chile, desalination plants will supply a total of 10.36 m^3/s of desalinated water, accounting around 22% of the total water supply in this zone by 2030. The situation is different for the central zone, since, from Valparaíso to Talca, the installation of only two desalination plants is planned, and these will supply a total of 0.89 m^3/s of desalinated water, accounting for 0.35% of the total water supply in this zone by 2030.

Wastewater treatment plants based on the activated sludge process will contribute slightly to a reduction in the level of water stress by 2030, as the amount of recycled water is predicted to be less than 0.50 m^3/s in almost all the Chilean administrative regions analyzed, excluding Santiago and Valparaiso where are located the bigger urban areas in Chile (see Table 4). However, the total amount of recycled water produced from the urban sector is predicted to increase from 0.51 m^3/s in 2015 to 7.96 m^3/s in 2030. This will be an important resource that could help to decrease water stress levels. In this context, recycled water is predicted to account for 2.65% of the total water supply in the northern and central zones of Chile by 2030. The future increase in recycled water is predicted because at least 30% of reclaimed water discharged to the ocean and 20% of reclaimed water discharged to conventional water sources should be available for direct recycling by different users, mainly in the agricultural and industrial sectors, as established by the Sectoral Agenda for Sanitation 2030 in Chile (SISS, 2019). But it is important to pointed out that recycled water coming from water flows previously sent direct to ocean, it is the only amount of water recycling that contributes to reduce water stress levels as mentioned in previous sections. In this context, Valparaíso is an administrative region that is predicted to produce a large amount of recycled water (0.97 m^3/s) by 2030, accounting for 12% of all recycled water in both zones analyzed, as shown in Table 4. The increase in recycled water is predicted to occur because, in 2015, a portion of the reclaimed water from the urban sector was discharged into the ocean, and this will be recovered for recycling by 2030. However, Santiago is predicted to have the largest amount of recycled water (4.72 m^3/s) among the administrative regions in Chile by 2030, accounting for 59.30 % of all recycled water in both zones analyzed, and this will satisfy a portion of the water demand (see Table 4). This situation is reasonable if we consider that 40.5% of the Chilean population resides in this region; therefore, the urban sector consumes a significant amount of water. Nevertheless, it is important to pointed out that water recycling in not helping to decrease water stress levels in Santiago. This is because Santiago sends all reclaimed water to the same source from where water used was abstracted, and not the ocean or other region. To boost water recycling, the Sectoral Agenda for Sanitation 2030 in Chile is implementing a new law to regulate the wastewater collection and disposal service in an attempt to improve the efficiency of the use of water resources.

4.2 Quantification of greenhouse gas emissions generated by the operations of desalination and wastewater treatment plants in the northern and central zones of Chile

In the Chilean context, the amounts of desalinated water and recycled water produced are predicted to increase from 3.02 m^3/s in 2015 to 19.21 m^3/s in 2030, increasing the availability of nonconventional water resources by 536%. This will help to address the problem of water scarcity, because it will be possible to meet a portion of the water demand in the future with desalinated water and recycled water that previously was sent to the ocean and not to the same place where water was abstracted. However, this situation will lead to an increase in greenhouse gas emissions due to the operation of desalination and wastewater treatment plants based on the reverse osmosis and activated sludge processes, respectively. As mentioned above, indirect production of greenhouse gas emissions from desalination and wastewater treatment plants occurs due to the electrical consumption required to maintain the continuous operation of both industrial systems; meanwhile, the direct production of greenhouse gas emissions from wastewater treatment plants occurs due to biological processes. Regarding the activated sludge process using in wastewater treatment plants considering in this research, CO_2 emissions from microbial respiration and N_2O produced from nitrification and denitrification are the main compounds associated with the direct production of greenhouse gas emissions in this type of industrial systems. It is worth mentioning that the indirect production of greenhouse emissions is strongly affected by the characteristics of the electrical grid, where electricity is generated to maintain continuously operating water treatment plants. It well known that an electrical grid fed mainly by fossil fuels generates more greenhouse gases than an electrical grid fed by renewable energy sources. In this context, the Chilean government has promoted the use of renewable energy sources to feed its electrical grid in recent years, resulting in a decline of greenhouse gases emitted per kilowatt-hour of electricity produced. Thus, unitary greenhouse gas emissions factors (β) of 0.8 kg $CO_{2\text{-eq}}$/kWh in 2015 and 0.3 kg $CO_{2\text{-eq}}$/kWh in 2030 were considered, as was mentioned in the methodology section. This clearly affected the calculation of greenhouse gas emissions produced during the operation of reverse osmosis and activated sludge processes.

Taking into consideration the unitary greenhouse emission factors (β), as well as the minimum and maximum values reported in the literature for the unitary electrical energy consumption of the reverse osmosis process (α), the unitary electrical energy consumption of the activated sludge process (α^*), and the unitary greenhouse gas emissions produced from the biological processes involved in the activated sludge process (γ), the total amount of greenhouse gases emitted by the operation of the reverse osmosis and activated sludge processes was found to vary between 164,687 and 277,120 tCO_2-eq/year in 2015, and this is predicted to increase to 323,879 to 710,721 tCO_2-eq/year by 2030. For both years, the main amount of greenhouse gas emissions was emitted indirectly due to the operation of the reverse osmosis process. This industrial system consumes more electricity than wastewater treatment plants and the desalinated water capacity is larger than the recycled water capacity in Chile (see Table 3 and Table 4). In this context, the Chilean administrative regions that will generate new larger greenhouse gas emissions in 2030 because the operation of desalination and wastewater treatment plants predicted to be Iquique, Antofagasta, and Copiapó. Moreover, Santiago and Valparaiso are predicted to contribute to new greenhouse gas emissions due to significant increases in the recycled water capacity of the urban sector aiming to produce water that meets the quality standards for irrigation and other nonpotable applications. This situation shows how the increasing use of nonconventional water sources can solve local problems due to water scarcity but, simultaneously, it could worsen global problems by increasing the direct and indirect generation of greenhouse gas emissions by the operation of desalination and wastewater treatment plants. However, comparing the direct and indirect generation of greenhouse gas emissions by the operation of desalination and wastewater treatment plants in 2030 with the national greenhouse gas emissions committed for the same year in Chile that is 95,000,000 tCO_2-eq/year (Chilean Government, 2020), the emissions generated by the operation of both industrial systems represent only between 0.34 and 0.75 % of total greenhouse gas emitted by the country analyzed. Therefore, considering the installation and operation of desalination and wastewater treatment plants for facing water scarcity problems in northern and central zones of Chile is a suitable alternative because it does not generate large environmental problems at national level. However, this situation should be analyzed in other regions since the characteristics of the electrical grid and water industrial systems are different.

The variation of direct greenhouse gas emissions depends on the feed water characteristics, plant capacity, and plant performance in wastewater treatment plants. Meanwhile, the indirect greenhouse gas emissions in desalination and wastewater treatment plants depend on the characteristics of the electrical grids, which is proportional to the value of the unitary greenhouse gas emissions factor reported by national energy agencies. For reverse osmosis process, the pretreatment and reverse osmosis systems are the main energy consumers resulting in indirect greenhouse gas emissions; while in the activated sludge process, the aeration system is the main energy consumer. In this context, it is reported in scientific literature that the reverse osmosis process requires about 2.5–4 kWh/m^3 of the desalinated water produced, and the electricity consumption depends on the feed water salinity, the recovery ratio, the efficiency of the pumps, the plant size, and the efficiency of energy recovery systems. In contrast, the activated sludge process consumes approximately 0.3–0.65 kWh/m^3 of the treated wastewater produced, depending on the effluent quality, plant size, and water treatment train configuration. Therefore, to reduce the energy consumption in the reverse osmosis process, the implementation of efficient high-pressure pumps, the improvement of membrane technology through the development of highly permeable membranes and low fouling composites, and the implementation of energy recovery devices are recommended (Ihsanullah et al., 2021). Meanwhile, to reduce energy consumption during the activated sludge process, the implementation of automated aeration control through the integration of appropriate sensors and blowers with variable speed drivers in the aeration system is recommended (Eslamian, 2016). In addition, based on the results obtained, efforts should continue to be focused on the direction of using renewable energies to meet the energy demands totally or partially of desalination and water treatment plants aiming to reduce the indirect emission of greenhouse gases (Abdelkareem et al., 2018; Maktabifard et al., 2018; Gude, 2017).

5. Conclusions

This paper presented the incorporation of the quantification of greenhouse gas emissions generated during the operation of desalination and wastewater treatment plants in the assessment of water scarcity in Chile using the WSI adopted by the 2030 Agenda for Sustainable Development. In 2015, low levels of water stress were reported for almost all Chilean administrative regions analyzed, except for Antofagasta, which presented a critical water stress level in that year. Paradoxically, in 2030, Iquique, Antofagasta, and Copiapó, i.e., the administrative regions located in the arid climate zone, are predicted to experience no water stress at the regional level. To reach this goal, twenty-six desalination plants based on the reverse osmosis process are expected to be operating in Chile by 2030, and most of them will be installed in the northern zone of Chile. Therefore, seawater desalination will play a significant role in reducing water stress. On the other hand, wastewater treatment plants based on the activated sludge process will have a minor contribution to a reduction in the level of water stress by 2030, as the amount of recycled water from the urban sector is predicted to be low in almost all Chilean administrative regions analyzed, excluding Santiago and Valparaiso, which are predicted to account for 59% and 12% of all recycled water produced, respectively, to meet a portion of the water demand. It is important to pointed out that the increase in recycled water in Valparaiso will occur because, in 2015, a portion of the reclaimed water from the urban sector was discharged into the ocean, and this will be recovered for its recycling by 2030. In contrast, the situation is different in Santiago because all reclaimed water will be sent to the same source from where water used was abstracted, and not the ocean or other region. Therefore, water recycling in not helping to decrease water stress levels in this administrative region. Although it is predicted that desalinated water and recycled water will help to reduce the water scarcity, this may become an environmental issue due to greenhouse gas emissions. The total amount of greenhouse gases emitted through the operation of reverse osmosis and activated sludge processes varied between 164,687 and 277,120 tCO_2-eq/year in 2015 and is predicted to rise to 323,879–710,721 tCO_2-eq/year by 2030 due to increases in the desalinated water and recycled water capacities, as these processes involve greater electricity consumption. In this context, the main Chilean administrative regions that are predicted to be impacted by greenhouse gas emissions are Iquique, Antofagasta, and Copiapó due to the installation of new desalination plants to meet the requirement for water with the necessary quality standards for the urban and industrial sectors. Santiago and Valparaiso are also predicted to be affected due to a significant increase in water recycled from the urban sector in 2030, which will produce water that meets the quality standards for irrigation and other nonpotable applications aiming to reduce water scarcity. This situation shows how the increasing use of nonconventional water sources can solve local problems due to water scarcity but, simultaneously, it could worsen global problems by increasing the direct and indirect generation of greenhouse gas emissions by the operation of desalination and wastewater treatment plants. However, it was also estimated that desalination and wastewater treatment plant will contribute only between 0.34% and 0.75 % of total greenhouse gas emitted in the country by 2030. Therefore, the installation and operation of desalination and wastewater treatment plants for facing water scarcity problems in northern and central zones of Chile is a suitable alternative because it does not generate large environmental problems at national level.

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