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DESALINATED DRINKING WATER PROVISION IN WATER-STRESSED REGIONS

CHALLENGES OF CONSUMER-PERCEPTION AND ENVIRONMENTAL IMPACT

THE CASE OF ANTOFAGASTA, CHILE

Tesis presentada como parte de los requisitos para optar al grado de Magíster en Gestión y Planificación Ambiental

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ABSTRACT

Desalination is increasingly popular for ensuring potable water in water-stressed areas, but it is also associated with negative water quality perceptions, environmental impacts, and high energy demands. Additionally, the abundance of desalinated water supply often offsets former water-use efficiency strategies, encouraging water-demanding economic activities in water-stressed regions. Through the systematic assessment of the city of Antofagasta (Chile) using the City Blueprint Approach (CBA), this work aims to identify the main barriers, opportunities and transferable lessons that can enhance governance capacity towards the successful implementation of desalination as a water scarcity mitigation strategy. It is found that social-environmental challenges of a city such as heat risk, education rate, water scarcity and water quality limit good water management which faces issues regarding wastewater treatment, stormwater management and water system leakages. The evaluation of the capacity to govern desalinisation issues (namely consumer-perception, residue pollution and high energy demands) showed that in particular awareness about desalinisation-related challenges, agents of change and financial viability were limiting conditions. On the other hand, the city's ability for continuous learning, its ambitions for the water sector and implementing capacity were evaluated as being well-developed. The root cause of negative consumer perception issues is the historic arsenic contamination of drinking water and low organoleptic parameters standards. An improved monitoring of the latter is key to overcome this. Awareness about the impact of desalinisation residuals is low and requires better environmental standards. Impacts of brine discharge on marine ecosystems should be reduced through the appropriate selection of the discharge location and the use of dispersion devices. Lastly, energy demand should be reduced by energy recovery devices and the transition to renewable sources, including ocean energy. Based on these findings a priority ladder of water management principles in relation to the implementation of desalination is proposed to ensure a sustainable water provision in water-scarce regions: 1) expansion of network to ensure full access to drinking water 2) reduction of water consumption 3) application of fit-for-purpose reuse of treated wastewater and 4) desalination as a last resort to fulfill the remaining water demand.

Key words: Desalinisation – Water scarcity – Consumer perception – Water management - Water conservation

1. INTRODUCTION

Of the many factors that have been seen to play a role in current climate change, freshwater security has placed itself within the top of the list (Koop and van Leeuwen 2017). As a result of changing consumption patterns, increasing demand and water pollution, stresses exerted on the worlds water resources as well as on cities' water supply and treatment are increasing (Dawoud and Al Mulla 2012). By 2025, freshwater demand is expected to increase up to 50% in developing countries (UNESCO 2012). This increase is going to lead to demand competition, resulting in an estimated 40% supply shortage by 2030 (McKinsey and Company 2009). The inclusion of drinking water supply, sanitation, and hygiene in the Sustainable Development Goals of the United Nattions (Essex et al. 2010), demonstrates that the world community recognizes the importance of these three variables for development and health interventions. To maintain the habitability of urban regions, these must anticipate and adapt to increasing water stress and potential supply shortage (Ruth et al. 2007). Desalination of seawater, most popularly through reverse osmosis (RO), is increasingly applied to meet rising water demands (Roberts at al. 2010). A desalination plant (Image 1) uses membranes to remove excess salt and other minerals from saline water to obtain fresh water suitable for irrigation and human consumption. At present, desalinisation is most frequently applied in the Arabian Gulf, Mediterranean Sea, Red sea and the coastal waters of California, China, and Australia (Dawoud 2012). Although operational costs are high, desalination plants are able to provide a constant supply of high-quality drinking water from the abundant brackish and saline water resources (Dawout 2012). Globally, 15,900 desalination plants are in operation which produce 95 million m^3/day of potable water. This number is rapidly increasing as the need for freshwater supplies grow, technologies improve, and unit costs are reduced (Construvo 2010; Jones et al. 2019).

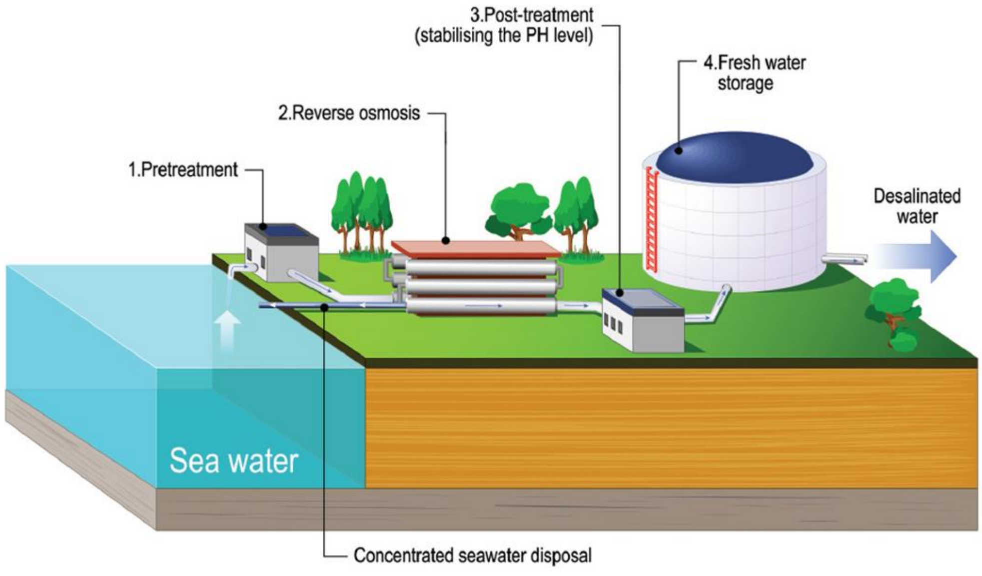

Image 1: Reverse Osmosis desalination plant (International Filtration News, 2019)

As guidance for the drinking water quality standards, most desalination plants use the World Health Organization’s Guidelines for Drinking Water Quality (GDWQ; WHO 2011). These present the concentrations of a broad spectrum of contaminants, including inorganic and synthetic organic chemicals, disinfection by-products, microbial indicators, and radionuclides that ensure a safe provision of drinking water for consumers (Construvo 2010). Beyond health-related aspects, aesthetic factors (or organoleptic parameters) such as taste, odour and turbidity, attributed to the presence of organic and inorganic contaminants and bacterial growth, are crucial in ensuring consumer satisfaction (Construvo 2010; Shoram and Hawari 2017). Past experiences with poor water quality associated with a long-standing mistrust of water providers can create a particular mode of water scarcity, in literature called “perceptual scarcity” (Fragkou and McEvoy 2016). Thus, a positive attitude toward the public agencies and private companies regulating the sector are crucial for water service perception also when desalination plants are introduced (Haddad 2018).

The process of desalinisation is associated with negative environmental impacts due to the chemical discharges into the marine environment (Dawout and Al Mulla 2012; Meerganza 2005; Lattemann and Hopner 2008; Petersen et al. 2018). If desalination discharge, or brine, is released to poorly flushed environments, the salinity and temperature of receiving waters increases substantially (Dawout 2012; Qdais 2008). Brine, which has a higher density than seawater, spreads over the sea floor in shallow coastal waters unless it is dissipated, affecting benthic organisms and seagrass beds. A thermal effect can in turn affect water quality processes and result in lower dissolved oxygen concentrations. Long-term exposure to unfavourable conditions can have a long-lasting impact on the species composition (Dawout and Al Mulla 2012). Furthermore, a number of residue contaminants can be released into receiving waters, such as sediments, heavy metals, hydrocarbons, chlorine, biocides, anti-fouling compounds, and reaction (by-) products, from diverse processes such as construction, corrosion, pre-treatment, chlorination and cleaning (Dawout and Al Mulla 2012; Hoepner and Lettemann 2003; Roberts at. 2010). This presents the potential for acute and chronic toxicity (Construvo 2010).

Desalination is further linked with a significant energy demand (Østergaard 2014). It has been estimated that a Reverse Osmosis (RO) plant requires between 0.5 - 4kWh/ m^3 which can vary depending on input salinity, temperature and the technology used (Li et al. 2018; Goh et al. 2017). This corresponds to about five times as much energy as used by traditional drinking water processes (Jacobsen 2012).

In short, desalination faces three recurring challenges; 1) water quality perception issues 2) environmental pollution of the residue of the desalinisation process 3) decreased incentive to conserve water while energy demands of the process are high. The manner in which a city uses available freshwater and how it adapts to increasing pressures on water as a scarce resource is greatly determined by the way that water is managed, and in turn how the water sector is governed. Water management is about achieving goals in a practical and efficient way with the available means. As such, interlinkages between water quality, sanitation, infrastructure and environmental factors such as climate change can be essential. Water governance is about identifying, adhering and prioritizing values and converting these values into goals, targets and policies that water managers work with (OECD 2015). Across the globe, cities experience a shift from traditional public responsibility towards a diversification of governance modes where responsibilities are shared between different public and private actors across multiple-governance levels (e.g. Lange et al. 2013; Mees 2016). Beyond the ability of particular institutions to govern water challenges, the joint capacity of different organisations involved is key and depends on a set of enabling conditions (Koop et al. 2017). Although today an efficient water use is recognized as being of high importance by many cities experiencing water scarcity, water governance is not always well embedded into the climate adaptation efforts.

The lack of understanding of the enabling conditions for a successful implementation and governance of desalination in arid regions is identified here as a knowledge gap. Hence, the aim of this research is to obtain a comprehensive, empirically-based understanding of the critical points of improvements for the urban management and governance of supplying (desalinised) drinking water in water stressed regions, by identifying the main barriers and assessing the capacity of stakeholders and authorities to govern desalinised water provision in the case of Antofagasta, Chile. This rapidly growing mining region is supplied by the largest desalinisation plant in Latin America. The findings of this investigation therefore can reinforce our current understanding of the water sector in Antofagasta, and assist decision processes in the efforts of mitigating water scarcity in arid regions worldwide. For the purpose of this study the definition of the water sector consists of sanitary activities (drinking water supply, wastewater collection, treatment, disposal) but also the overall management of the natural resource.

The following section describes the Analytical Framework, Section 3 provides a case study description of the city of Antofagasta, while section 4 provides the main results. In section 5 a discussion reflecting on the governance of desalinisation worldwide is provided based on key findings in the Antofagasta case study and avenues for future research are offered. Section 6 ends with the conclusions.

2. ANALYTICAL FRAMEWORK

In order to understand the key barriers for the provision of desalinised drinking water, the City Blueprint Framework is applied in the city of Antofagasta, Chile. This framework provides a holistic overview of urban water management, through a standardized and reproducible assessment method that identifies overarching lessons for supplying desalinised drinking water in water scarce regions. The framework consists of three complementary assessments (Koop and Van Leeuwen 2015; Koop et al. 2017):

1. The Trends and Pressures Framework (TPF)
2. The City Blueprint performance Framework (CBF)
3. Governance Capacity Framework (GCF)

In this study, the TPF and CBF are first applied in order to obtain a holistic understanding of the current status of integrated urban water management in Antofagasta. Next, the GCF provides a more in-depth analysis of how well stakeholders and authorities are able to govern the challenges related to the provision of desalinised water in the water scarce region of Antofagasta. The principal indicator and scoring methodology are provided for the Trends and Pressures Framework (Supplementary material A), City Blueprint Framework (Supplementary material B) and Governance Capacity Framework (Supplementary material C).

The TPF consist of 24 descriptive indicators that provide a broad overview of the main environmental, social and financial aspects that may influence urban water management in cities. The indicators are scored on a scale of 0 to 10 points, where a higher score indicates a higher urban pressure. The arithmetic mean of the indicators is the Trends and Pressure Index. The CBF consists of 24 indicators that provide a comprehensive overview of the integrated water resources management performance cities. The indicators are divided over seven broad categories: 1) basic water services, 2) water quality, 3) wastewater treatment, 4 water infrastructure, 5) solid waste, 6) climate adaptation, 7) Plans and actions. The output consists of two parts; a spider web presenting the scores of all indicators, and the geometric mean of the 24 indicators, which is called the Blue City Index. The GCF consists of three dimensions; knowing, wanting and enabling. The framework is used to assess governance capacity and provide insights into where the most effective improvements can be (Koop et al. 2017). As depicted in Table 1, nine governance conditions are spread over these dimensions that consist of a total of 27 governance indicators to assess the governance capacity of a city. A set of predetermined questions (Supplementary material C) corresponding to each indicator is used to conduct semi-structured interviews with various stakeholders of the water sector under study.

Table 1 Water Governance Capacity Framework (GCF; Koop et al. 2017)

Dimension	Condition	Indicator
Knowing	**1 Awareness**	1.1 Community knowledge 1.2 Local sense of urgency 1.3 Behavioural internalization
	2 Useful knowledge	2.1 Information availability 2.2 Information transparency 2.3 Knowledge cohesion
	3 Continuous learning	3.1 Smart monitoring 3.2 Evaluation 3.3 Cross-stakeholder learning
Wanting	**4 Stakeholder engagement process**	4.1 Stakeholder inclusiveness 4.2 Protection of core values 4.3 Progress and variety of options
	5 Management ambition	5.1 Ambitious and realistic goals 5.2 Discourse embedding 5.3 Management cohesion
	6 Agents of change	6.1 Entrepreneurial agents 6.2 Collaborative agents 6.3 Visionary agents
Enabling	**7 Multi-level network potential**	7.1 Room to manoeuvre 7.2 Clear division of responsibilities 7.3 Authority
	8 Financial viability	8.1 Affordability 8.2 Consumer willingness-to-pay 8.3 Financial continuation
	9 Implementing capacity	9.1 Policy instruments 9.2 Statutory compliance 9.3 Preparedness

3. CASE STUDY & METHODOLOGY

In efforts of providing freshwater to growing populations and supporting the economy's pivotal mining industries in a context of prolonged drought, the Chilean State has adopted a technologically-oriented mitigation approach, proposing the construction of desalination plants along the Chilean coastline. Particular attention has been given to the northern regions of the country, characterized by arid climates and the predominance of water intensive industries. The region of Antofagasta, and the region's homonymous capital city with a population of 398,000 is a key example of the implementation of a water desalination plant to combat water scarcity on a large urban scale. Thus the city of Antofagasta has been chosen as a representative case for this study.

The main source of fresh water in this city has historically been the Loa River, whose waters were transported over 300 km of pipes that cross the Atacama Desert before being received. Due to their high levels of mineral pollution, intensive treatment methods have to be applied. Furthermore, this source has not been able to satisfy the growing demand of the city. In 2003, the largest drinking water desalination plant in Latin America, "Planta Desaladora Norte" (Previously called La Chimba), was installed in Antofagasta with the goal of providing 100% of the city's drinking water (Flores 2016). The plant currently produces 1,056 litres per second and supplies over 83% of the urban population (Barnett 2020). Located within one of the driest regions in the world, this desalination plant has generated positive impacts for Antofagasta, reducing contamination as well as improving the continuity of service for the citizens. However, there is mistrust for the direct consumption of water, primarily motivated by a strong communal memory of historically high arsenic contamination and inadequate water quality norms in the region. Studies such as those of Fragkou (2016) indicate that 73% of citizens who consume desalinated water are not satisfied with the water supply, and 82% believe that consuming water directly is harmful to their health, resulting in strong preference for bottled water. With regards to environmental impacts there is insufficient consensus regarding the influence that the plant has on the marine biota - fishermen argue that marine life has decreased (Barnett 2020), while others argue it has not (On site visit Aguas Andinas). The plant has no independent energy sources and is currently running on the central national energy system, which in turn is 63% based on fossil fuels (Agencia de Sostenibilidad Energetica 2019).

In Chile, the national and regional governments mandate the normative and legislative contexts, and the management of water in corresponding jurisdictions is subcontracted by private companies (in this case the Colombian company Aguas Antofagasta) and recollection of wastewater (in this case the Chilean private-public company ECONSA). All relevant actors of the water sector are summarized in Table 2. The stakeholders with high influence and the most interest (Key Players) were identified as Econssa, Aguas Antofagasta, the Municipality of Antofagasta, the General Directive of Water (DGA) of the

Ministry of Public Works and CREO alliance. The stakeholders with a high interest but low influence (Subjects) are neighbouring communities, the University of Antofagasta, the Catholic University of the North and other scientific communities.

Table 2 Relevant actors of the water sector in Antofagasta.

Governance Level	**Urban Water Governance Stakeholder**	**Societal Layer**	**Description of task in water governance sector**
Supranational	Empresas Públicas de Medellín (EP)	Market	A Colombian company dedicated to the water and electricity sector. Currently owner of Aguas Antofagasta
National	Ministry of Public Works (Ministerio de Obras Publicas - MOP)	State	Responsible for the provision and administration of infrastructural works and connectivity, public buildings and optimal use of water resources. The Superintendence of Sanitary Services and the General Directive of Water are under its jurisdiction.
	General Directive of Water (Direccion General del Agua – DGA)	State	The Water Division of the Ministry of Public Works of the Government of Chile responsible for planning and managing the region's water cycle. They revise and release permits for all water distribution schemes
	Superintendence of Sanitary Services (SISS)	State	A public institution responsible for ensuring sanitary sector operational compliance and water quality of drinking water
	ECONSSA	State / Market	Semi-state company that overlooks concession contracts between sanitary companies and the State. Contracted by the City Council, responsible for the collection, treatment and disposal of wastewater
Regional	Antofagasta Regional Government (GORE Antofagasta)	State	The public institution that provides direct services to citizens and provides technical, economic and technological support to the municipalities on a regional scale.

Municipal	Municipality of Antofagasta	State	The local governing body responsible for all municipal affairs.
	Aguas Antofagasta	Market	Private sanitary company responsible for the supply of drinking water to the city of Antofagasta
	Neighbourhood Communities	Civil Society	Citizen organizations aiming to serve as a platform of local organization and communication between civil society and authorities
	Catholic University of the North (UCN) / CEITSAZA	Scientific community	Private University located in Antofagasta. Eighth oldest university in Chile. Within this CEITSAZA; Investigation centre of water Innovation and technology
	University of Antofagasta / CREA	Scientific community	Public University located in Antofagasta. Within this CREA; Regional Centre for Environmental Studies and Education
	CREO Antofagasta	Scientific community / Market	Public/Private initiative alliance funded predominantly by the mining sector that aims to project and facilitate a sustainable urban development of Antofagasta for 2035.

The data necessary for the three frameworks in this research was collected in two principal manners: desk research and on-site data collection. In the months of March - June of 2019, information was obtained from scientific literature and official policy documents, from which a preliminary scoring of each indicator was made. Next, 20 semi-structured interviews were conducted with diverse stakeholders of the water sector in the city and its surroundings in June-July 2019. The Trends and Pressures Framework and the City Blueprint Framework (supplementary information 1 & 2) include merely quantitative scores that were mainly scored through desk research and interviewees either verified or provided additional information to improve the accuracy of the scores. Although the Governance Capacity Framework relied on policy analysis and literature, more emphasize was on the interviewees. These interviews were face-to-face semi-structured and lasted for about one hour. The pre-defined questions (see Supplementary information C) and the interviewee expertise were the starting points of tailored questions to adequately score the indicators. Professionals with different backgrounds and responsibilities were selected to reduce the risk of bias. A total of 20 stakeholders was selected for an interview and represented the organizations Aguas Antofagasta, Antofagasta Municipality, Superintendent of Sanitary Services, ECONSSA, General Directive of Water (DGA) of the Ministry of Public Works, Directive of Hydraulic Works (DOH) of the Ministry of Public Works, CREO Antofagasta, Chamber of Deputies of Chile, University of Antofagasta, CEITSAZA, Neighbourhood Community Las Rocas, Neighbourhood Community Sector Centro, and citizens. A coding system is applied in this paper to consistently refer to these anonymized interviews. The results were processed using a standardized methodology of the framework as presented in the supplementary material.

4. RESULTS

The TPF and CBF key findings are discussed first in order to obtain a holistic understanding of the current status of the integrated urban water management in Antofagasta (sections 4.1 and 4.2). Next, the GCF provides a more in-depth analysis of how well stakeholders and authorities are able to govern the challenges related to the provision of desalinised water in the water scarce region of Antofagasta (section 4.3).

4.1 Trends and Pressures Framework

A total of 24 descriptive indicators within the social, environmental, financial and governance categories have been used in the Trends and Pressures Framework to evaluate the context which Antofagasta faces **(Figure 1)**. The key indicators of concern for Antofagasta are urban heat risk, citizen education rate, regional water scarcity and water quality. Heat risk is of great concern because the combined number of tropical nights and hot days in a year is above 77 (Villarroel and Paola 2013) and the city has a percentage of green/blue urban area of only 0.003%. Education rate is evaluated as a concern based on a primary education rate of 93% (The World Bank 2016). The indicator water scarcity, also evaluated as a concern, shows that 99% of total renewable freshwater resources are extracted in the region. Furthermore, it is calculated that the extracted groundwater represents 391% of the annual groundwater recharge of the region (DGA 2016). These numbers indicate that the vast majority of surface waters is consumed, and groundwater reservoirs are decreasing drastically. Water quality is also considered a concern, as 59% of the regional water is considered to have less than good ecological status (EPI 2010). The factors concerning political instability, unemployment rate and inflation rate have been scored as a medium concern, while burden of disease and economic pressures are considered a low concern. It is worth mentioning that although there are currently no concerns with respect to political instability and economic pressures, recent social uprising in the country can influence these indicators in the near future.

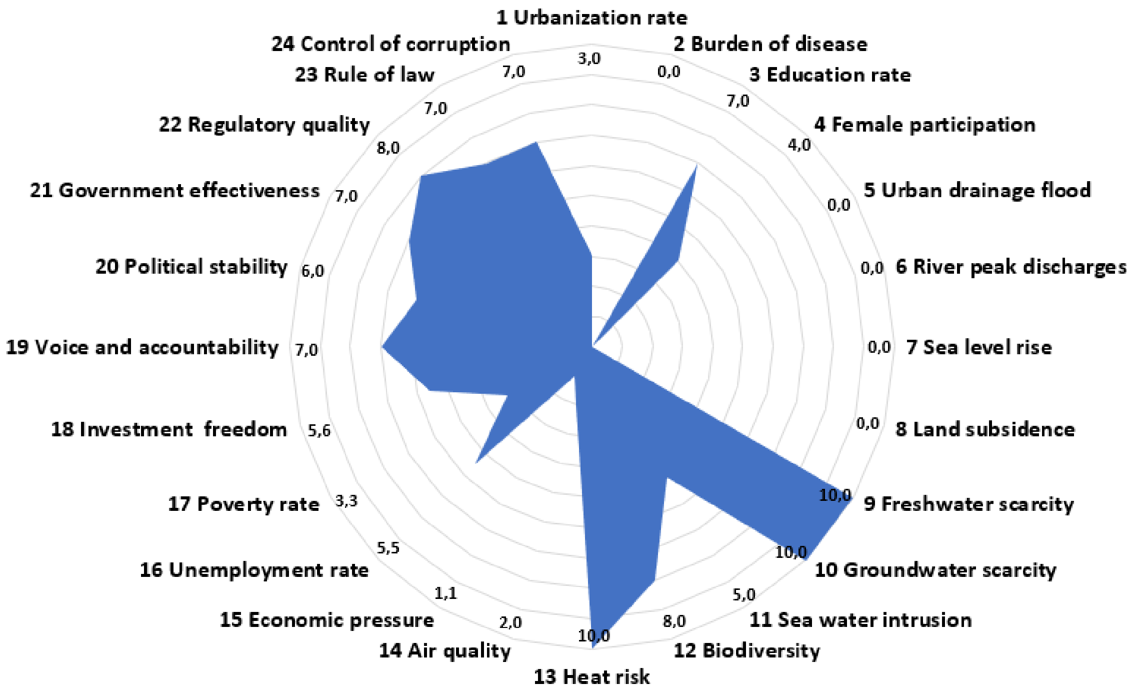

Figure 1 Trends and Pressures Framework results of the city of Antofagasta, Chile. Indicators score between 0 (low) and 10 (high; supplementary information B).

4.2 City Blueprint Framework

The City Blueprint Performance of Antofagasta **(Figure 2)** shows important strengths and weaknesses of the city's Integrated Water Resources Management (IWRM). Access to drinking water and sanitation (indicators 1-3) score high. Also, the operation cost recovery (indicator 14) is high, indicating financing of water services. Drinking water consumption (indicator 23) relatively low and thus scores high. The lowest scoring indicators relate to the treatment of wastewater and solid waste (indicators 5, 7-10, 16, 17) leading to environmental pollution. Because stormwater is not separated (indicator 11), it cannot be used for non-potable water purposes. Notably, water system leakages are over 30% (indicator 13) leading to the spilling of not only water but also energy that is necessary for the desalinisation process. Based on the holistic assessment of water management, environmental pollution and spilling of water and energy is high in Antofagasta. Interestingly, the drinking water quality (number of samples complying with local standards) is high. Water quality perception issues are therefore much more related to organoleptic parameters (colour, smell, taste and turbidity) and the collective memory of historic contamination.

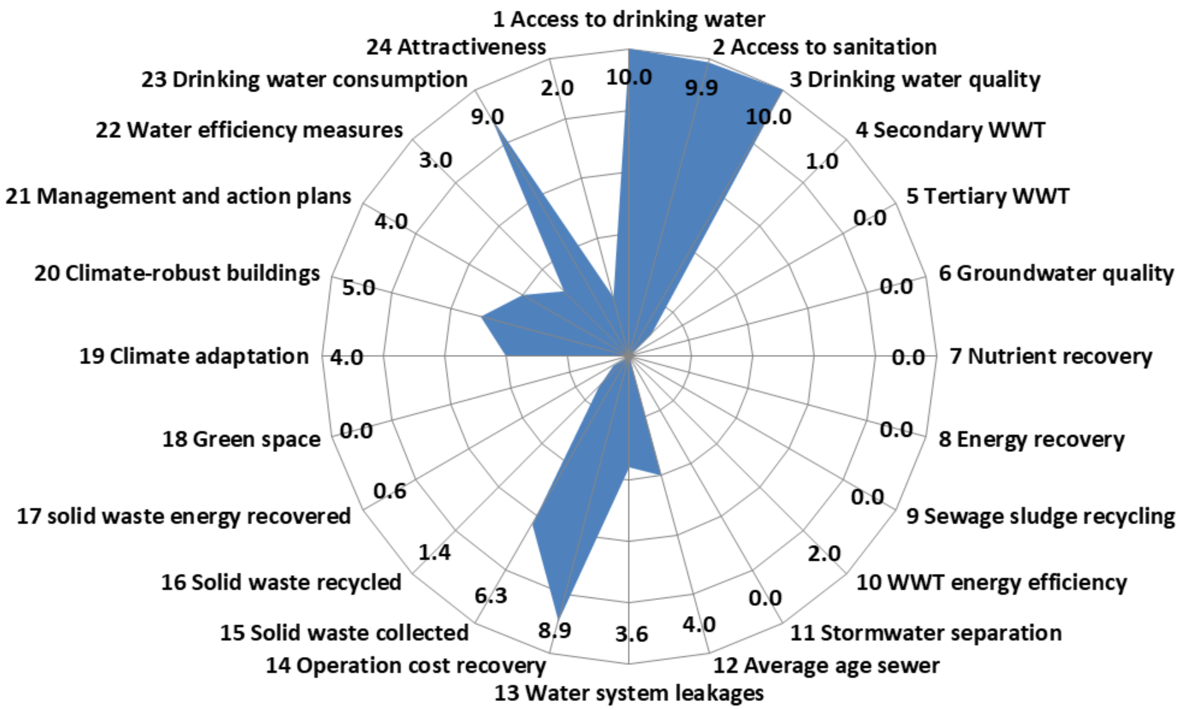

Figure 2 City Blueprint Framework results of the city of Antofagasta, Chile. Indicators score between 0 (low) and 10 (high; supplementary information B). This holistic water management assessment shows that, amongst others, wastewater treatment and water system leakages perform poorly.

4.3 Governance Capacity Framework

Figure 3 and **Figure 4** summarize Antofagasta's governance capacity to address water scarcity by desalination. Overall, water scarcity and the steep increase in water demand as well as the environmental impact of desalinization are generally not perceived as urgent and little effort has been made by any stakeholder to promote ecological conservation (indicators 1.2 and 1.3). The window of opportunity for entrepreneurial agents (indicator 6.1) to innovate is limited. Furthermore, the division of responsibilities, management fragmentation and poor evaluation of existing policy and management practices are important points for improvements (e.g. indicators 2.3, 5.3, 6.1 and 7.2). On the other hand, existing goals are both ambitious and realistic (indicator 5.1) and there is a strong consensus that adaptation is crucial for the development of the region (indicator 5.2).

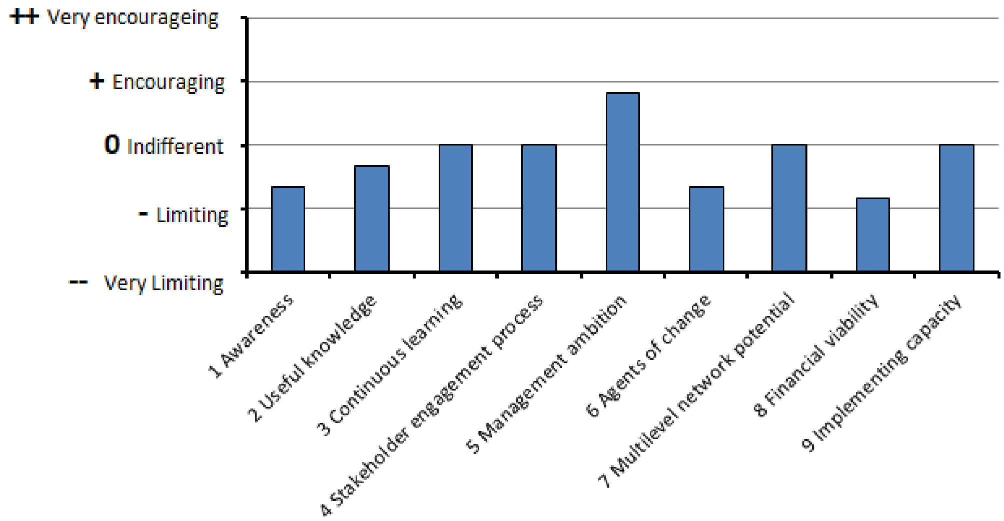

Figure 3 Governance Capacity of Antofagasta, with regards to the desalinised drinking water supply, by condition. Each condition is the average of the corresponding three indicators, as shown in Figure 3.

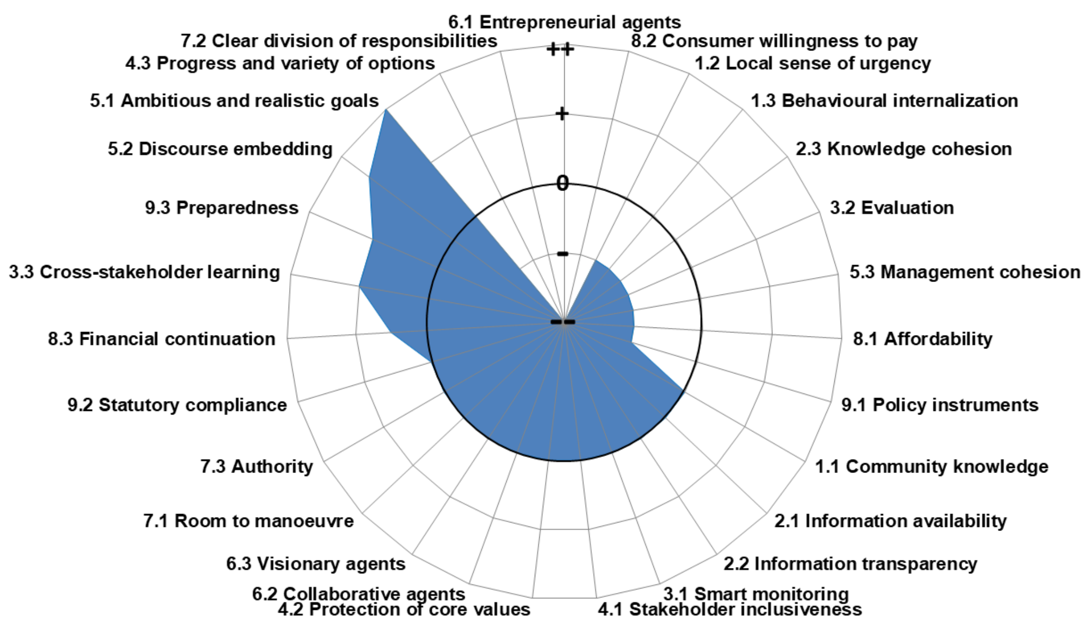

Figure 4 Governance Capacity of Antofagasta with regards to the desalinised drinking water supply, by indicator. The 27 indicators are ranked clockwise from most limiting (--) to most encouraging (++) in terms of the overall governance capacity.

Condition 1: Awareness

The region of Antofagasta has a history of extremely dry conditions (NE004; NE006; NE007;NE009, NE013 and NE01), yet citizen knowledge regarding water stress implications or possible mitigation actions is low (indicator 1.1; NE003; NE004; NE010; NE014; NE015 and NE017). There is distrust in the quality of tap water due to the collective memory of historic levels of contaminants (ex. Arsenic) (NE002; NE005; Aguas Antofagasta, nd), which extends to mistrust and misinformation regarding the current quality of desalinated water (NE003). The water supply security provided by the plant diminishes perception of water scarcity or water conservation as relevant issues (indicator 2.2; NE002;NE013; NE015 and NE017). Furthermore, there is no awareness of the resources that go into desalination, or its impacts on the ecosystem (NE002; NE004; NE008 and NE015), and consequently no sense of urgency regarding environmental degradation (NE013). There is little or no effort to enhance water conservation behaviours (indicator 1.3; NE002; NE009 and NE015), resulting in an average domestic water consumption of 180 litres/person/day (NE003;NE005; NE009). Only a minority of citizens, some independent initiatives and the public sector seek promotion of sustainable practices (NE002; NE005 and NE015).

Condition 2: Useful knowledge

Comprehensible information about the sanitary company (i.e., Aguas Antofagasta's) activities are shared on social media (NE003; NE007; NE008; NE011; NE014; NE017 and NE019). Accurate technical information of water production, treatment and operation of the desalination plant is available (NE017) and national studies such as Water Scenarios (Escenarios Hídricos) by Foundation Chile (Fundación Chile) provide reliable knowledge (NE006; NE009; NE012 and NE015). Information is limited with respect to a holistic understanding of the available water resources, their utilization, and ecological conditions (indicator 2.1; NE004; NE014 and NE017). For example, because of the insufficient capacity of the DGA, auditing and documentation of water rights and their exploitation is weak, often not up to date (NE019). Existing information regarding the region's water resources and their use is accessible (indicator 2.2; NE010; NE014 and NE017), mostly online, though often not easily comprehensible to non-experts (NE002, NE003; NE006; NE007; NE009; NE011 and NE015) which results in an inequality of access to knowledge (NE019). A simple example is that of the units of the data published; water permits production volumes are given in L/s, yet volume charged to consumers is given in m^3, making it difficult to visualize or relate (NE003).

Condition 3: Smart monitoring

Monitoring capacity (indicator 3.1) is particularly limited and outdated within the public sphere (NE002 and NE016), attributed to scarce resources. The regional DGA currently employs only four people, who are responsible for monitoring over 200 locations stretched over 126,050 km^2 (NE005; BCN,nd). Consequently, efforts focus on water rights use auditing, with little capacity left for further data analysis. The private sector has higher capacity for monitoring internal processes (NE002 and NE016). Evaluation of policy and implementation (indicator 3.2) is also inflexible within the public sector, while the private is seen to adapt faster. On a national level revision of norms within the public administration is a lengthy process, taking over five years (NE003; NE006; NE008 and NE009). The legal base for water management, the Water Code adopted in 1981, was modified in 2005 after 13 years of discussion in the Parliament. It allows for private ownership of water rights as well as their free transferring – a framework under constant dispute, receiving opposition from those who believe the water resource should be safeguarded by the State. This division of opinion plays an important role in the discontinuity of evolving norms (NE016). Furthermore, large scale desalination is a new phenomenon that is not treated appropriately by the law, in aspects of operation as well as the treatment of discharge waters (NE013). Water quality parameters of drinking was such as Boron and the Langelier Index (indicator of the saturation of water with respect to calcium carbonate) and regulation of discharge are absent (NE09 and NE013). Cross-stakeholder learning (indicator 3.3) is a positive indicator, since strong efforts for discussion between sectors can be observed at the local level (NE006; NE013; NE014 and NE016). Collaborations between local universities, the municipality, CREO, Aguas Antofagasta, Superintendent of Sanitary Services, the Ministry of Public Works, and the DGA have resulted in numerous educational programmes, seminars, work tables and training sessions with the aim to improve public knowledge, share expertise and target particular issues (NE002; NE008; NE012-NE014; NE016 and NE017).

Condition 4: Stakeholder engagement process

Communication between Aguas Antofagasta and citizens is adequate with respect to the quality and continuity of the water supply, having improved information availability and consultation channels (e.g. WhatsApp, Twitter and emergency number) in recent years (NE010; NE016 and NE019). However, the level of stakeholder participation in the decision-making process (indicator 4.1) is low, mostly informative, or consultative, untimely with little binding (NE004; NE006; NE008; NE011; NE014 and NE019). There is a strong centralization within both the public and the private sector (NE005; NE006; NE014-NE017 and NE019). With regards to the protection of core values (indicator 4.2) the principal aim of the sanitary sector is health and wellbeing of citizens. In recent years within the concessionary area of the sanitary company this is satisfied. On a national level however some question the capacity of the law to ensure access to water; the historic privatization of the resource has resulted in water being traded on the free market, with powerful entities being able to purchase abundant water property rights. In a region where water resources are so scarce, this is believed to be an important root of power and wealth imbalance of the region. Thus, it can be perceived that the system of private ownership of water rights, while aiming to optimize the resource's use, is unable to fully protect the values of local communities and the needs of those with limited economic resources (NE011). Procedures within the water sector, such as water property right applications and marine concessions are clear with standardised guidelines, but lengthy, unintuitive and inflexible (NE003; NE009; NE012; NE013 and NE019).

Condition 5: Ambitious and realistic goals

The goals of the water sector of Antofagasta are considered very ambitious and realistic (indicator 5.1). With unique initiatives such as The Antofagasta Recycled Water System (*SARA)* by CREO the city is developing treatment and reuse of municipal wastewater for green public areas (NE012; NE013 and NE019). Another ambitious and realistic idea, yet being developed is a centralized regional interconnected water network of pipelines (similar to an electricity grid), where fresh water from the mountains as well as desalinated water can be distributed across the region through a integrated network (NE003; NE004; NE006; NE011; NE017 and NE018). However, it is important to mention that particularly neighbourhood communities feel that the sanitary service still fails to meet basic expectations (NE008), and ambitions are unsynchronized with the reality of mistrust in tap water (NE011). The indicator discourse embedding (indicator 5.2) is evaluated low since the political and normative spheres do not reflect the need for particular legislation for the northern regions of the country. Only in 2005 the national water quality law NCh 409 was modified to restrict Arsenic concentrations to 0.01 PPM, despite the previously high values (Aguas Antofagasta, nd). In line with the above, management cohesion (indicator 5.3) is also scored as a limiting indicator. The Water Code, the environmental system and primary norms are centralized, the same across the whole country and do not consider the significant regional differences in geographical characteristics, technical capacities and financial resources (NE003-NE006; NE013; NE016; NE018 and NE019). A regional application of norms is lacking.

Condition 6: Agents of change

Our results depict that there are numerous opportunities for funding and support for both public and private initiatives of entrepreneurial activities (indicator 6.1; NE004; NE006 and NE015). The water utility Aguas Antofagasta offers problem-solving programmes for university students (NE003), Espacio Atacama local co-work, run by the My North Foundation (Fundacion Mi Norte) offers an “incubator” system for small and medium enterprises (NE006). The municipality offers community development programmes to guide incentives (NE012). The National Fund for Regional Development (CORFO) offers financial support for entrepreneurial incentives. Despite all the above, practically no entrepreneurial activity is present within the water sector (NE003; NE007; NE017 and NE019). The only active initiative known is Aquaservax (supported by Antofaemprende) which offers consumption reduction devices for domestic use (NE019). As cause, some perceive the opportunities as weak, short term or lacking technical support (NE006; NE014 and NE019). Others mention normative barriers or economies of scale as barrier for smaller businesses (NE017). The extent to which stakeholders are able to build trust-collaborations and connect business (indicator 6.2) is scored as indifferent. Work tables and committees conducted between diverse actors provide frequent opportunities for interaction (NE013 and NE014) and there is adequate trust and disposition for collaboration between the main stakeholders (NE004 and NE016). An example is the incentive CREO, which aims to construct participatory long-term strategic city planning (NE016). Nonetheless, some identify a lack of a common goal for the actors of the water sector (NE004). Finally, the extent to which actors are able to effectively push forwards long-term strategies (indicator 6.3) is also scored indifferent. Within the public sector the Superintendent of Sanitary Services formulates "development plans" with outlook for 15 years and the first five years being binding (NE016). DGA develops the "Strategic Plan for the Management of Hydraulic Resources" (NE012). However, the projections of these efforts are perceived as insufficient considering the complexity of the local environment (NE010). There is a sense of regional resentment towards the central government, a feeling that the region's resources are being exploited for short-term national economic wealth (NE010 and NE012). A long-term unified strategy or vision for sustainable water management does not exist (NE004 and NE010), and overall application of strategic planning is sectorial and fragmented (NE016).

Condition 7: Multi-level network potential

It is evaluated that the room to manoeuvre (indicator 7.1) is indifferent, due to inflexible national norms and long-lasting procedures for getting permits limit the possibilities for action (NE003 and NE007), particularly for the drinking water provision and sanitary sector (NE004). For example, a new law (10.795-33) currently in senate seeks to discourage sanitary services from doing non-regulated services, such as selling treated water for recycling (NE004). The division of responsibilities (indicator 7.2) is considered a limitation. Studies by Akhmouch (2012) and DGA and World Bank (2016) highlight that Chile has one of the highest levels of fragmentation of responsibilities when it comes to water-related competences, with over 40 authorities involved in the sector (NE019). Mapping these, it can be observed that there are areas of overlap as well as gaps (NE004, NE005; OECD 2012). Basic responsibilities of the sanitary sector are clearly and strictly formulated (NE003; NE006; NE012 and NE019) between the water utility Aguas and ECONSA (SEMBCORP) (NE002; NE013; NE010 and NE016). This separation is a reflection of the historic separation of concessions in the sanitary service, and results in a dilution of long-term responsibilities between the two companies (NE016). Public Administrations, namely Superintendent of Sanitary Services, DGA and the municipality monitor compliance, assign property rights and manage aspects of urbanistic planning respectively (NE003; NE005; NE017 and NE009). These institutions however can have uncoordinated or overlapping incentives which lead to inefficient allocation of funds (NE006 and NE017). It is identified that the legitimate forms of power and authority are rather restricted for addressing sustainable production and use of desalinised drinking water (indicator 7.3; NE006; NE019; DGA and World Bank 2016).

Condition 8: Financial viability

Affordability for basic water services is limited (indicator 8.1). Full coverage of sanitary service is available to Aguas Antofagasta's operational area (NE007; NE011; NE013 and NE016), however large outskirts of the city, mostly composed of immigrant neighbourhoods are not connected (NE006; NE008; NE009; NE011 and NE017). Furthermore, Antofagasta has one of the most expensive tap water tariffs in the country (NE003; NE005; NE011; NE013; NE015 and NE016). Antofagasta's inhabitants pay \$1,500 CLP/m^3 (\$1.94 USD/ m^3)[1] for the water service (Aguas Antofagasta, 2018) which can triple during the summer period, as a result of the gradual increase in the tap water tariff during the period of December to March for households who consume over a calculated average of the population. Climate adaptation measures such as water collectors or filters are scarce and not accessible (NE008). The state has responded to this by implementing subsidies for most vulnerable families (NE007 and NE014). It must be noted that the price of tap water is calculated based on a "model" company that does not consider the costs of desalination (NE003 and NE004). Consumer's willingness to pay (indicator 8.2) is rather low. There is a lack of understanding and mistrust in the calculation of the tariffs and generally resentment towards the sanitary sector, mostly based on the historic levels of contamination of Arsenic, service interruptions, bad odours during the implementation of the desalination plant. As a result, citizens would not be willing to pay more (NE004; NE008; NE011 and NE015). The consumer has high expectations of tap water but limited understanding of what the service entails or what their responsibilities are (NE004 and NE015). Finally, financial continuation (indicator 8.3) is considered indifferent. Private companies, particularly Aguas Antofagasta and mining companies have stable financial resources for innovation (NE004; NE007; NE017 and NE019). However, due to the private actor's diverse objectives their financial allocation can be fragmented (NE016). Furthermore, some perceive that necessary investments are postponed unless crucial (NE019). This can be evidenced by the low reposition rate of pipeline network of 0.6%/year (NE019), in other words the pipeline system gets repositioned only after 167 years. This suggests that sanitary companies can benefit from their activities without clear obligation of investing in appropriate infrastructure. Basic activities of the DGA, such as flow measurement involve constant and predictable costs and are done continuously (NE005). The public administration however has insufficient and discontinuous funds for improving infrastructure, maintenance, follow up of projects or overall innovation (NE006; NE012; NE014; NE016-NE019; DGA and the World Bank 2016).

Condition 9: Implementing Capacity

Policy instruments (indicator 9.1) are used scarcely to stimulate desired behaviour with regards to water conservation. On a citizen level the only policy instrument used is a

[1] *Conversion to date Jul 26, 2020 18:14 UTC. 1 USD = 774.2 CLP

gradual increase in the tap water tariff during the period of December to March for households who consume over a calculated average of the population (NE003; NE005 and NE006). There is disagreement on whether this is successful; some claiming it pushes for reduction in consumption (NE013) and others believing that it is unrealistic and harmful, as citizens' consumption is by need higher in summer (NE008). Municipal subsidies for water bills for the most vulnerable families are an important and helpful instrument (NE003; NE005 and NE008). On a commercial and industrial level there are no particular norms to stimulate efficient use of the resource (NE013; NE016 and NE019), which can be seen in the pipeline network leakages of 32% (NE019). Furthermore, a penalty for not using one's water rights (and even the risk of losing it) aims to encourage optimal economic use of water resources (Bravo et al. 2014). With regards to statutory compliance (indicator 9.2), existing legislation is complied with (NE002; NE004 and NE017). Particularly the water utility Aguas Antofagasta and the industrial sector are perceived to have high compliance with regards to water quality, as a result of the firm monitoring of the Superintendent of Sanitary Services (NE002-NE004; NE007; NE009 and NE013) – observing a compliance level of 99.4% with national drinking water quality criteria . Yet, some legislation is still weak or unclear, for example with regards to treatment and deposition of residual water, in which compliance is still poor (NE007; NE013 and NE017). Finally, the level of preparedness for gradual or sudden events (indicator 9.3) is evaluated as positive, mostly attributed to the well-coordinated division of roles for scenarios of emergencies, resulting from the vast experience that Chile has with natural disasters (NE005 and NE006). Some vulnerabilities remain nevertheless; Antofagasta is very vulnerable to precipitation as there is no infrastructure for rainwater drainage, and recently rain events are occurring more frequently (NE002; NE003; NE005 and NE014). The city is one of the few in the country that operate a dual provision system (desalinated and continental water) that can complement or substitute each other (NE003; NE005; NE007 and NE012). In case of failure of both, in theory the city has existing reservoirs that enable continued water provision for 36 hours. However, this back-up water reservoir is not always full or readily available (NE009). The desalination plant itself faces a major challenge of securing energy independence, as currently it is entirely dependent on the national system (NE013) and chlorine storage as it is dependent on frequent importation to the plant (NE009). Expanding the operational area of the sanitary system, renovating pipelines, reducing air/water contamination, creating contingency plans and regional water interconnection are perceived as the next challenges to tackle (NE004; NE010; NE012 and NE014).

5. DISCUSSION

The principal barriers identified for the effective implementation and governance of a desalinated water system are quality perception and trust of consumers, a lack of awareness and action in response to environmental impacts and the water-energy nexus. Recent literature and opportunities for these challenges are discussed below.

5.1 Perception and trust

Antofagasta has a high compliance with national drinking water quality criteria regarding chemicals and metals, turbidity and presence of microorganisms, organoleptic parameters (colour, smell, taste and turbidity) and presence of bacteria (SISS 2019). With regards to chemicals and metals, national legislation is predominantly in line with international guideline of the WHO of safe drinking water quality (WHO 2017). With regards to turbidity, total dissolved solids (TDS), and organoleptic parameters however, significant differences are found between the Chilean legislation and the WHO recommendations. For example, the WHO states that TDS concentration greater than 1000 mg/l become significantly unbearable to consumers, while at present, the Chilean norm allows for up to 1500mg/l. The recommendation for turbidity is < 0.1 NTU, however the national limit is 2.0 NTU. The recommendation for Sulphates (odour) is 250 mg/l, and the national limit is 500 mg/l. Thus, despite meeting the criteria to assure a healthy drinking water supply, organoleptic parameters exceed international standards of taste, colour and odour – which can in part explain the strong citizen rejection. Until the 1990s health-related quality parameters were widely accepted as the sole indicator of drinking water standards. However, today the public plays an increasingly important role in determining acceptable levels of drinking water properties and safety (De Franca 2010). Water organoleptic parameters, particularly taste, is paramount for quality perception, service satisfaction, willingness to pay and the selection of water sources including desalinised water (De Franca 2010; Gorden 2000). The importance of these parameters should not be underestimated on the basis of lacking health implications. Water testing must include measurements of physicochemical properties, biofilm presence and organoleptic parameters (Shomar and Hawari 2017). Furthermore, qualitative research on water organoleptics suggests that people prefer what they are used to, and frequent changes in quality, such as the gradual expansion of the desalinated supply throughout Antofagasta, are inversely associated with quality acceptability and water risk judgments (Syme & Williams 1993). Foreseeable changes in organoleptics, for instance owing to upgrades in the water distribution or treatment system must be anticipated and communicated.

In addition to organoleptic parameters, consumer perception of water quality and acceptance result from a complex interaction of numerous additional factors. These include trust in water suppliers and regulators, risk perception, attitudes towards water chemicals, prior experience and information reception (Miguel de Franca 2010; Nancarrow et al. 2010;

Johnson 2003; Baker 1998). Trust in companies, organizations or governmental institutions is linked to the perception of water quality and risk and thus acceptability (Poortinga and Pidgeon 2003; Johnson 2003), although the causal order of this relationship is not clear (De Franca 2010; Syme & Williams 1993; Bratanova et al. 2013). A lack of trust in water companies motivated by the scepticism that these actors are motivated principally by their financial benefits, as is observed in Antofagasta, is a common phenomenon (De Franca, 2010). Factors that can improve the relationship are perceptions of care, value similarity, competence, integrity, cooperation and openness and a sense of fairness and equitability within the water provision system (Nancarrow et al. 2010). Particularly a large portion of consumers express that the presence of chemical pollutants in drinking water is a principal concern (De Franca 2010). A higher perception of risk has also been related to the perception of prior negative outcomes resulting from the system (Nancarrow et al. 2010). These experiences can provide the basis for the interpretation of new information and can have a strong effect on perceptions of water quality and acceptability (De Franca 2010). The collective memory of Arsenic contamination of drinking water in Antofagasta, and the significant health impacts this had on the population is, therefore, a key factor in understanding consumer mistrust and behaviour in this region.

It is widely considered that coherent and accessible information must be available to all citizens. Nonetheless some argue that the effect of scientific and technical information alone on public perception can be limited (De Franca 2010). A statistical experiment by Johnson (2003) on 494 residents of New Jersey found that reading water quality reports did not shift customers' evaluations of water quality and utility performance from the evaluations of those in the control group, who did not see a report. The recommendation is not against the provision of such reports, but rather highlights the challenge of effective communication, the limitations of scientific reporting, and the need to complement information channels. For example, interpersonal sources of information, consisting of family members and friends are believed to also have a strong influence on perceptions, often overlooked in the drinking water context (Park et al. 2001). Thus, as a transferable lesson, education at the school, community and other levels aiming to promote understanding of drinking water issues should be transversal across generations (De Franca 2010).

5.2 Environmental impact

The environmental impacts of desalinization are generally not perceived as urgent in Antofagasta, and little effort has been made by any stakeholder to promote ecological conservation. This could be a result of the lacking consensus on the degree of environmental impact produced by the desalination plant, and simply other priorities. Although technological advances have resulted in the development of new and efficient desalination processes, the costly handling of brine, the hypersaline concentrate discharge associated with negative environmental impacts, remains a principal challenge worldwide (Jones et al. 2019). On average, for every 1m^3 of desalinated water, 1.5m^3 reject brine is produced as by-product

(Jones et al. 2019). In regions where uncertainties remain with regards to the extent of the impact of brine, the precautionary principle of environmental sciences must be applied.

Traditionally a limited number of discharge methods has been used to dispose of brine, including deep well injection; land disposal evaporation ponds; and mechanical/thermal evaporation (Dawout and Al Mulla 2012; Jones et al. 2019; Afrasiabi & Shahbazali 2011). Nonetheless, these methods are associated with considerable practical and economical challenges (Dawout and Al Mulla 2012). Subsequently, in coastal areas the most common method is direct discharge into the ocean (Purnama et al. 2003), as is the case in Antofagasta. A principal factor of consideration to reduce the extent of this ecological impact is the location of the discharge site (Roberts et al. 2010). Dispersion is believed to occur faster in deeper waters where currents tend to be stronger (Purnama 2003). Subsequently, exposed, open-sea are characteristics desired for discharge locations (Roberts et al. 2010). Dilution can be further enhanced by the release of brine through multiport, submerged pressure driven diffusers (Ahmad and Baddour 2014). Lastly, a simple method to reduce brine salinity is mixing brine with alternative water sources of a lower salinity, such as treated wastewater or even seawater before its return to the ocean. The implementation of multiport diffusers and dilution of brine with wastewater seams technologically most feasible for Antofagasta. In parallel, efforts should focus on treating, using or diminishing the volume of brine disposed to surface water (Jones et al. 2019). Afrasiabi & Shahbazali (2011) discuss various advanced technological processes being studied for the treatment of brine, such as Forward Osmosis, Vacuum Membrane Distillation and Direct Contact Membrane Distillation. Though more complex, using the above methods in combination with Reverse Osmosis a recovery rate of 89 - 98% can be achieved. Yet other methods seek to recover salts and nutrients from brine, producing commercial products and thus aiming to make treatment economically interesting (Perez-Gomez et al. 2012; Pramanik et al. 2017; El-Naas et al. 2010; Dawoud and Al Mulla 2012). The ultimate aim of these methods is zero liquid discharge (ZLD; Xevgenos et al. 2016).

5.3 Water - Energy nexus

The issue of energy demand was not perceived as a high concern in Antofagasta either, however literature suggests that the water-energy nexus is becoming key to providing both water and energy sustainability as the security of both is becoming fundamentally linked (Goh et al. 2017; Shahzad et al. 2017; Hamiche et al. 2016). The reduction of costs and carbon footprint of desalination lies in the improvement of energy efficiencies through recovering/reusing waste energy and the application of renewable energy (Li et al. 2018; Goh et al. 2017). With regards to energy efficiency, energy saving measures such as variable frequency controls for high pressure pumps are essential. Energy recovery devices can be used to exploit rejected brine pressure, with potential to recover up to 50% of energy consumed (Goh et al. 2017). Such a device is implemented in Antofagasta, though recovery rate is believed to reach only 30% (On site visit 2019). Local, regional or national binding standards should be imposed for the implementation of energy saving and energy recovery devices on all desalination plants installed.

The use of renewable energy alternatives to supply the high energy demands of desalination is essential for mitigating environmental impacts (Xevgenos et al. 2016). This can be achieved through multiple levels of governance simultaneously. For a desalination system connected to the national electrical line, such as the case of Antofagasta, the national distribution of energy sources is most relevant. For such a scenario, policies on the national level must be developed to promote the transition to clean energy production and the decarbonisation of the network. Simultaneously, available alternatives of renewable energy should be produced and utilized on a local or regional scale to enhance security of drinking water provision. To promote this national or regional binding guidelines or norms for the share of renewable energy used for desalination can be introduced.

An interesting yet less developed alternative is to use the ocean as a source of energy, presenting some advantages particularly for desalination plants. Most desalination plants are located in proximity to the ocean, reducing costs of transport. Ocean energy supply is predictable and constant and is the densest among renewable energy sources (Li et al. 2017). Additionally, some of the forms of ocean energy can be directly integrated with desalination processes and infrastructural installations, as such presenting potential for “Hybrid desalination” (Goh et al. 2017; Xevgenos et al. 2016). Such systems can theoretically decrease specific energy consumption of a seawater RO system by 40–58% while also contributing to the reduction of brine discharged back to the ocean. The potential of ocean energy in combination with desalination plants to ensure water-energy nexus is undoubtedly very promising. However, such installations are yet mostly in the form of pilot, involving considerable investment costs and challenges of scaling. Integration of this technology is likely to become feasible in the next decades (Li et al. 2018), but its infrastructural implications should be considered for long-term planning.

6. CONCLUSIONS

Desalination is a promising method to meet rising water demands in arid regions where freshwater sources are no longer sufficient. Nonetheless, it is associated with important limitations that can challenge water governance, namely issues of water quality perception, environmental pollution, and high energy demands. This study on Latin America´s largest desalination plant for human consumption in the Chilean city of Antofagasta, sheds light on these drawbacks and identifies transferable lessons that can enhance governance capacity under desalinated water provision in urban hubs. Results indicate that the relevant authorities and water sanitary companies must implement more strict limits on organoleptic parameters to overcome negative perception of water quality. Trust of consumers must be improved by strengthening the relationship between consumers, operators, and regulators through transparent and intelligible communication. Regarding the environmental impacts of desalinization, these are generally neither well known, nor perceived as urgent, thus little effort has been made to promote solutions to environmental pollution and energy consumption associated with the function of desalination plants. Following the precautionary principle of environmental sciences, if there is uncertainty about the potential negative impact of brine discharge to the marine environment, mitigation measures must be taken. Based on these findings it is recommended that appropriate ecological monitoring and the implementation of multiport diffusers and brine treatment methods, along the use of (or transition to) renewable energy sources is necessary for diminishing ecological impact of brine discharge and GHG emissions associated with the high energy demand of desalination.

Finally, it is observed than an important drawback stemming from the implementation of desalinization is that it can lead to a perceived abundance and comfort within the supply network, offsetting prior efforts for water-use efficiency in water stressed regions. An integrated and coordinated approach seems crucial for ensuring sustainable and equitable water provision. Thus, extrapolating to the urban water sector and based on the limitations observed in Antofagasta, a priority ladder of water management principles in relation to the implementation of desalination is proposed for the correct and efficient response to increasing water scarcity in arid regions.

1. **Ensure access to drinking water for all**: The expansion of the service network must be anticipated in line with the growth of cities and local urban planning.
2. **Enhance water conservation**: Consumption rates must be reduced both by enhancing domestic water conservation and by reducing system inefficiencies of pipeline leakages.
3. **Exploit the often-untapped potential of wastewater reuse**: Under water stress conditions, fit-for-purpose water reuse must be implemented, recognizing that wastewater is a largely untapped resource that has much potential to alleviate water stress. For this, a legislative framework is required that applies quality criteria per use category independently of the water's origin.

4. **Desalinate to address the remaining water deficit**: When the above measures have been taken and water scarcity remains an issue, the implementation of desalination becomes the next logical step for meeting water demand.

It is expected that these guidelines can be useful to stakeholders and enhance desalinated water provision in cities around the globe, as desalination is emerging as a key technology in guaranteeing water security for urban citizens.

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