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Unlocking the fog: assessing fog collection potential and need as a complementary water resource in arid urban lands–the Alto Hospicio, Chile case

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Water scarcity is a rising issue in fast-growing cities in arid lands, where demand outpaces supply. This leads to non-renewable water systems and exacerbates social inequalities. This is the case for Alto Hospicio (AH), located in the northern Chilean Atacama Desert. Regarding its water availability, the main source of drinking water comes from underground aquifers, last recharged about 10,000 years ago. Nevertheless, atmospheric water such as fog, is present in this territory and offers an alternative, though its potential in large urban areas remains unexplored. This study assesses the fog water collection potential in AH and its surroundings using two methods: *in-situ* data collection using Standard Fog Collectors (SFCs) and the AMARU model, which estimates fog collection in space and time. This research concludes that fog water collection is feasible in the northeast and southeast areas surrounding the city, where fog collection rates reach up to 10 L m^{-2} day^{-1}. Fog water has the potential to serve as an effective alternative water source for populations lacking access to drinking water from a public water source, and for activities such as irrigation of urban green spaces, human consumption, and hydroponic farming. Key recommendations for policymakers include incorporating atmospheric water into local city policies, promoting further research on estimating the fog water potential in the AH metropolitan zone, and rethinking water management strategies from nonconventional resources.

KEYWORDS

fog collection, arid cities, alternative freshwater resource, Alto Hospicio, complementary urban water supply

1 Introduction

Water stress is a rising issue affecting several countries where the populations regularly consume almost all their available water supply (World Economic Forum, 2019; Kuzma et al., 2023). Especially fast-growing cities in arid lands face increasing water scarcity due to unsustainable technological advancements and its reliance on finite water resources. Urbanization has contributed to desertification and health issues associated with the urban heat island effect (ARUP, 2018). This concern is a present reality in various regions, with Chile being a poignant case study. The country has been struggling with water stress for the past decade, affecting around 8 million inhabitants due to megadrought (Garreaud et al., 2020), urban growth, and the outdated water code written in its Constitution, which heavily favors privatization (Bartlett, 2022). Without urgent actions towards sustainable water management, Chile will have to assume a significant depletion of water and recurring shortages by 2050 (Bartlett, 2022; Kuzma et al., 2023; Simon et al., 2023; Yang, 2022).

Along with other nations, Chile necessitates context-specific solutions to achieve water security. These solutions depend on assessing the current provision of their freshwater supply in relation to available alternative resources and climatic conditions (Reitano, 2011). The geographical distribution of freshwater resources in Chile is highly unequal (Aitken et al., 2016). While southern Chile has a temperate climate with regular rainfall, the northern region has a semi-arid to hyperarid climate with areas experiencing extremely low to zero precipitation (Herrera-León et al., 2022). The latter is where the Atacama Desert lies, and where water stress is mostly felt due to limited natural resources, decreasing rainfall in the Andes, and the expansion of urban areas (Santoro et al., 2018; Scheihing, 2018; Escenarios Hídricos, 2030, 2019). In the Tarapacá region, which is the main province of the Atacama Desert, the major water users are the mining and agriculture sector, mainly overexploiting groundwater (Suárez et al., 2021). The current extraction rates for these industries as well as for urban purposes, are unsustainable (Santoro et al., 2018; Herrera-León et al., 2022). This situation disproportionally affects the most socio-economic vulnerable populations, such as in Alto Hospicio (AH). The city emerged as a satellite center of Tarapacá's capital Iquique, housing the population lacking economic means. These informal settlements have aided in the development of AH, but the rapid and unplanned way in which the city has expanded resulted in a lack of infrastructure and pressure on the water distribution network (Figueroa and Fuentes, 2009; Imilán et al., 2020; Municipalidad Alto Hospicio, 2022). The main source of potable water comes from underground aquifer located inland, at the foot of the Andes (Aguas del Altiplano, 2017). These were lastly recharged between 17,000 and 10,000 years ago, when the Atacama Desert still received some rainfall, making the water a non-renewable resource due to the current rate of extraction and the rising demand. This is also referred to as water mining as it is a non-renewable resource (Santoro et al., 2018). In December 2023, Iquique and Alto Hospicio constitute as a Metropolitan Area of Chile. Within this framework, a key benefit will be the more strategic deployment of public resources, including drinking water infrastructure and supply sources assessment (Gobierno Regional Tarapaca, 2023).

Cities are densely populated settlements with over 50,000 inhabitants, concentrating people, infrastructure, and activities within closely spaced buildings, impervious surfaces, and managed outdoor spaces (Bechtel et al., 2015; Dijkstra et al., 2021). Urbanization, more than climate change (Vörösmarty et al., 2000; Punia et al., 2022), is intensifying the demand of water often exceeding the capacity of traditional resources, demanding the exploration of complementary nonconventional resources such as fog to support sustainable developments (UN Water, 2020). In this context of fast-growing water demand, fog, referred to as "camanchaca", is a viable water resource along the northern coast of Chile (Cereceda and Schemenauer, 1991; Cereceda et al., 1992; Schuetze et al., 2013). The word "camanchaca" comes from the local native language Aymara, meaning "darkness" (Escobar and García, 2017). This term refers to the close association the ancient civilizations already had with the presence fog (Verbrugghe and Khan, 2024). The coastal fog results from the interaction between strong subsidence given by the pacific anticyclone and the cool ocean surface temperature (Espinoza et al., 2024). This interaction sustains a strong inversion layer, which produces a cloud layer of ~200 m thick at approximately 500 m ASL (Lobos-Roco et al., 2024). This fog-cloud is seasonal, varying in both height and presence. During winter and spring, the clouds are at 500–700 m ASL with higher presence (40%), while in summer, its prevalence decreases significantly (<5%) and its height shifts to 1,000–1,200 m ASL. This cloud layer is advected inland producing advective fog (del Río et al., 2021). Therefore, the region experiences periods where a thick layer of stratocumulus reaches land (Muñoz et al., 2011; del Río et al., 2018; Espinoza et al., 2024). Aside from advective fog accounting for ~76% of the events, orographic and radiative fog are also present, accounting for ~22% and ~2% respectively (Keim-Vera et al., 2024). Through a simple design comprising a mesh that intercepts droplets, fog collectors serve as an alternative for various rural communities along the globe (Cereceda, 2000; Klemm et al., 2012). Extensive reviews of types of fog collectors, related social aspects, and fog collection projects supplying communities for agricultural or domestic activities, or for reforestation purposes are available (Klemm et al., 2012; Domen et al., 2014; Fessehaye et al., 2014; Qadir et al., 2021; Farnum, 2022; Schemenauer et al., 2022; Albornoz et al., 2023; Verbrugghe and Khan, 2023a, 2023b). However, fog collection in or for urban areas remains underexplored.

This study explores the feasibility of using fog as an alternative water resource in arid urban settlements, using AH as a study case. We selected AH due to its dependence on a non-renewable water source, its proximity to fog-loaded regions, and its significant social challenges such as the lack of urban green spaces and fresh vegetable production. The paper is structured as follows. Section 2 presents the socio-hydrological context of Chile and AH, from the perspective of water challenges in arid environments. Afterwards, we shortly describe existing fog collection projects. Section 3 outlines the methodology for assessing the fog water collection potential in the city and surrounding areas. Section 4 describes the results, including the water needs of AH and fog water collection zones. Section 5 provides a discussion on potential uses of fog water in the city, such as irrigation of public urban green spaces, supply for populations lacking access to potable water, and hydroponic agriculture. Finally, Section 6 presents conclusions, exploring the natural potential of fog water collection in the surroundings of AH, highlighting the need of increasing the assessment of fog water collection potential to refine model calibration, and suggesting a preliminary set of guidelines for policymakers to consider integrating fog water as a complementary resource.

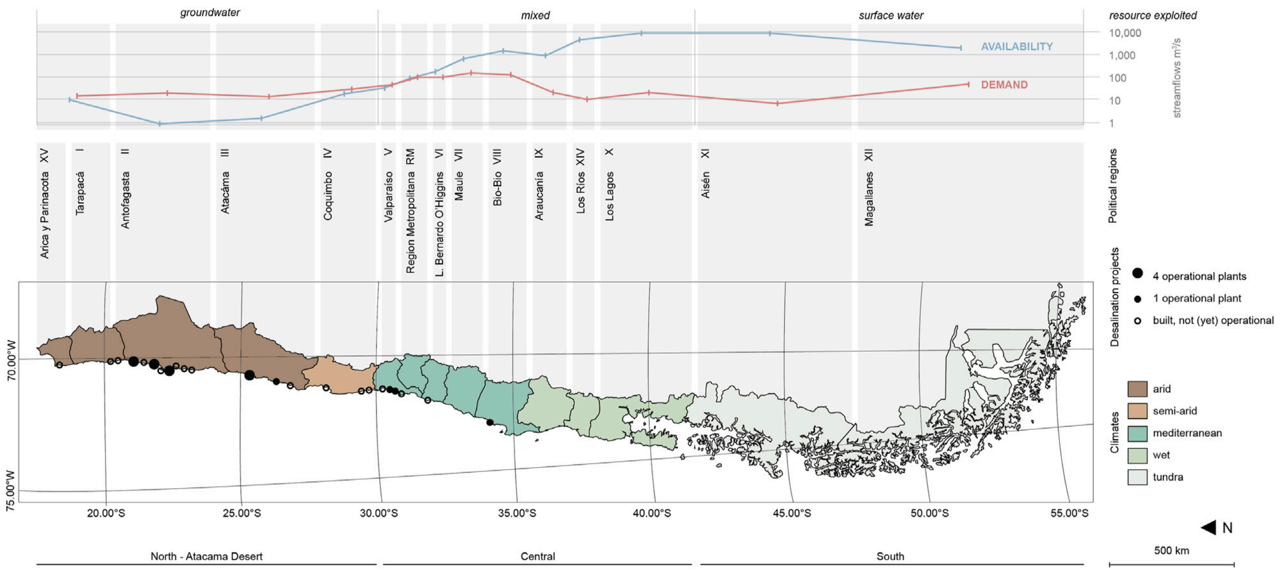

FIGURE 1
Exploited water resources, edited from (Superintendencia de Servicios Sanitarios, 2023); streamflow availability and demand, edited from (Valdés-Pineda et al., 2014); and desalination projects, edited from (ACADES, 2016); across Chile's varying climatic regions, edited from (Herrera-León et al., 2022).

2 Socio-hydrological context of Chile and Alto Hospicio

2.1 Water challenges in Chile

Chile has an average annual runoff availability of 53,952 m^3 per inhabitant. However, the distribution of freshwater resources is highly uneven (Aitken et al., 2016). The northern regions are arid, while the south has abundant rainfall. This variation is attributed to the country's long latitudinal span of 6,400 km, stretching from 17°30′S and 56°30′S, as illustrated on the map in Figure 1. The northern regions' natural deficit results in yearly water availabilities of less than 1,000 m^3 per inhabitant while the south's availability overpasses 10,000 m^3 per inhabitant (Valdés-Pineda et al., 2014). Chile is supplied with 42% of surface water, 56.6% of groundwater and 1.5% of seawater (Superintendencia de Servicios Sanitarios, 2023). As seen on the graph in Figure 1, the southern regions exploit the abundantly available surface water originating from streamflow. In the central regions, streamflow quantities and demand are similar. Therefore, freshwater originates from both available surface water and groundwater sources (Valdés-Pineda et al., 2014). Although all urban wastewater is treated in the nation, only 5.5% is treated for direct reuse. Of the remainder, 21.3% is disposed of into the sea, and 73.1% is discharged into continental water bodies (Superintendencia de Servicios Sanitarios, 2023). The Sectoral Agenda for Sanitation 2030 is implementing a new law to facilitate water recycling to sustain the urban growth and increase resilience (Superintendencia de Servicios Sanitarios, 2020; Herrera-León et al., 2022). The increasing demand of water in the Atacama Desert, aside from urban growth, is driven by the water intensive mining activities. This increasing economic development and freshwater use are directly related. However, water demand highly surpasses the little amount of available streamflow, necessitating reliance on groundwater to meet all needs, but the overexploitation of groundwater is depleting the resource at an alarming rate (Valdés-Pineda et al., 2014). Reverse osmosis is therefore becoming more common to increase water security, particularly in the Antofagasta and Atacama region (as illustrated in Figure 1) where copper and lithium are extracted, which are extremely water intensive (Sola et al., 2019). Around 80% of all desalination plants in Chile are for mining purposes (ACADES, 2016).

Over the past decades, almost half of all socio-environmental conflicts in Chile were directly related to water issues, primarily linked to droughts and the depletion of aquifers, as well as inadequate water management and governance (Escenarios Hídricos, 2030, 2019). The country's Water Code, enacted in 1981, has long prioritized privatization. While there have been some reforms in recent years, these changes have not been sufficient to address the inequalities affecting those outside extractive industries nor the challenges induced by climate change (Julio et al., 2024). Nonetheless, according to the yearly assessment of the SISS, 99.94% of urban residents have access to potable water, with 97.5% connected to the distribution network (Superintendencia de Servicios Sanitarios, 2023). Although Chile's urban water infrastructure has been successful in coverage and access, climate change poses significant challenges to future water management (Madeira, 2022). The deficiency and decreasing quality of freshwater requires resilience strategies. This imposes mitigation and adaptation strategies across supply, demand, infrastructure, and urban planning, which results in higher water tariffs due to the significant investments needed (Molinos-Senante, 2018). To balance cost and reliance, nonconventional water supplies are a viable solution. Such self-sufficient and sustainable sources include rainwater collection, water reuse and recycling, and in arid environments where the situation is most critical, fog and dew harvesting (Rygaard et al., 2011; ARUP, 2018).

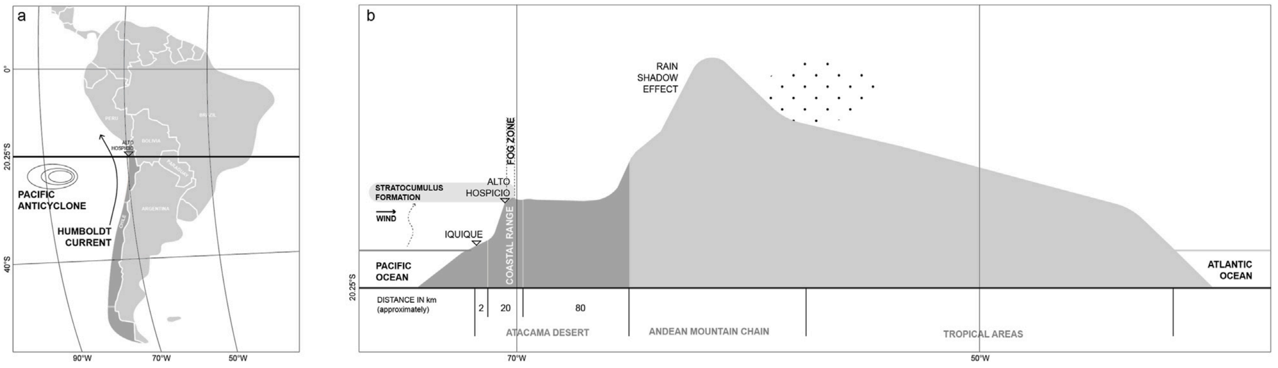

FIGURE 2
Extreme aridity in South America and fog formation potential through geo-climatic factors. **(A)** The Humboldt current and the pacific anticyclone along the Chilean coastline. **(B)** Simplified cross section from the Pacific to the Atlantic Ocean, illustrating the rain shadow effect from the tropics and fog formation in the region of Alto Hospicio, based on (Azua-Bustos et al., 2022).

2.2 Case study: Alto Hospicio (AH)

AH is located in the Tarapacá region of the Chilean Atacama Desert, 9 km east from Iquique, on a plateau of the coastal mountain range, about 500 m ASL. The city occupies a total surface of 574.6 km^2 and a total length of 11 km from north to south. On the west, it borders the cliff overlooking Iquique, while the other three sides are surrounded by hills exceeding 1,000 m ASL (Ilustre Municipalidad de Alto Hospicio, 2022). AH is located within the hyperarid region of the Atacama Desert, which comprises of a (semi-) arid to hyperarid continental strip along the southern Peruvian and northern Chilean coastline (Lobos-Roco et al., 2024). The extreme aridity is characterized by an annual average precipitation of less than 1 mm, as recorded by the weather station at the Diego Aracena airport (Mikulane et al., 2022). The desert is framed by the Andean Cordillera on the east and borders the Pacific Ocean on the west (Azua-Bustos et al., 2022). According to the Koppen-Geiger classification system, this area has a cold desert climate, annotated by BWk, which implies that the mean annual temperature is lower than 18°C, and high rates of evaporation over precipitation are present (Peel et al., 2007). There are numerous factors that cause extreme aridity, depicted in Figure 2. The Pacific anticyclone, a high-pressure area, forms atmospheric stability that prevents the passage of frontal systems originated from the south. Humid masses coming from the Amazon Basin are obstructed due to the Andean Mountain chain, referred to as the rain shadow effect. The Humboldt current at the barrier of the ocean and the continent displaces cold waters from south to north, reducing sea water temperatures and thus, evaporation (Schween et al., 2020; Azua-Bustos et al., 2022). The high permanent presence of this marine atmospheric moisture results in the formation of fog and dew in the coastal and adjacent inland valleys of the continent. As shown in Figure 2B, the northern Chilean coastline consists of a narrow littoral plain followed by a steep cliff called the coastal mountain range with peaks of 1,300 m ASL. Warm air masses above the cold ocean form low, and extended stratocumulus clouds are advected by the wind from the east towards the continent, leading to advective fog touching the coastal mountain range at heights ranging from 500 to 1,300 m ASL (Lobos-Roco et al., 2024). Therefore, a more precise classification for the fog-loaded Chilean coastal region of the Atacama Desert according to Koppen-Geiger is BWn, with n referring to fog (nebel in German), meaning a "coastal desert with abundant cloudiness" (Cereceda et al., 2008). This non-rainfall resource is essential for biodiversity. Up to 10 km inland, concentrated vegetated island with endemic flora called "fog oases" in Chile are found. They serve as an excellent indicator for fog presence (del Río et al., 2018; Mikulane et al., 2022).

2.3 Sociodemographic factors and urban expansion of Alto Hospicio

AH's emergence is closely related to its role as a peripheral area to Iquique. Initially in the 1980s, it developed as a destination for impoverished groups who settled through informal settlements. Over time, it attracted urban migrants due to both its low land values and its proximity to Iquique's thriving economic opportunities in mining and trade around the ZOFRI free trade zone (Fernández Labbé, 2023). From the 1990s, government housing policies massively promoted the development of subsidized housing projects, further expanding AH despite its initial lack of infrastructure and services (Mansilla Quiñones et al., 2020). By 2002, the commune had grown to 50,000 residents and in 2004, it officially became a municipality (Figueroa and Fuentes, 2009; Ilustre Municipalidad de Alto Hospicio, 2020). In December 2023, Iquique and AH formed a metropolitan area. A "Metropolitan Area" is a territorial extension formed by two (or more) municipalities in the same region with shared urban infrastructures and services, and together exceeding 250,000 inhabitants. This allows for shared public policies and investments led by the municipalities and the Regional Government of Tarapacá (Ministerio del Interior y Seguridad Pública, 2023). AH and Iquique are home to three-quarters of the total population living in the Tarapacá region, with AH containing around 113,000 inhabitants in 2017, according to the national Chilean census "INE". The population was projected to

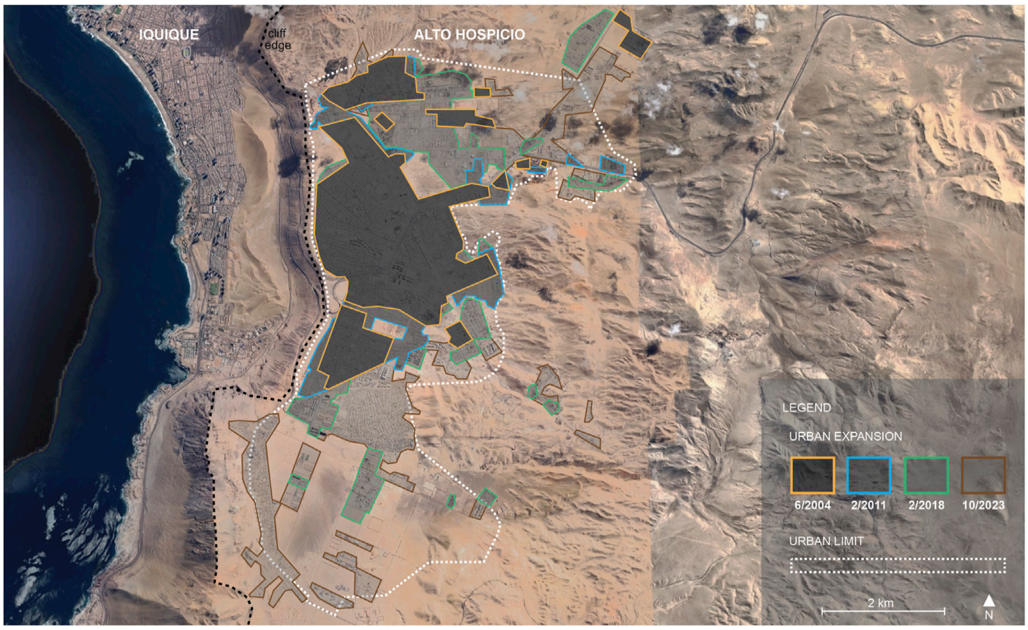

FIGURE 3
Urban expansion of Alto Hospicio (AH) from 2004 to 2023 using Google Earth Pro images from 2004 (orange), 2011 (blue), 2018 (green), and 2023 (brown).

reach 143,300 by 2024, and around 178,800 by 2035. From 2014 to 2019 the numbers of foreigners tripled accounting for 18.4% of the inhabitants of AH in 2021 (Jara-Labarthé et al., 2021; Biblioteca del Congreso Nacional de Chile, 2023; Gobierno Regional Tarapaca, 2023). Moreover, the arrival of migrants after 2020 furthered the development of a nonformal housing market of irregular plots until today. According to the National Migration Service, about 24,000 visas were granted in the commune in 2020 and 2021 (Fernández Labbé, 2023). The urban expansion from 2004 to 2023 is demonstrated in Figure 3.

Informal settlements are part of the expansion of AH. A study by TECHO-Chile and CES in 2022–2023, identified 63 informal settlements in the form of encampments in the Tarapacá region, with 46 located in AH, housing 10,079 families in precarious conditions. The highest concentration is in the El Boro sector (northeast AH). In contrast, Iquique has 11 encampments. Notably, only 1.6% of these settlements are formally connected to the water distribution network, 75.4% receive water via trucks, while the remainder relies on punctures to the public network (TECHO-Chile, and CES, 2023). These settlements along with the further urbanization and influx of migrants created complex social issues exacerbated by the lack of services, which generates a strong dependence on Iquique. Additionally, the population suffers from a lack of quality public spaces, and despite of the existence of infrastructures, it is of low quality. According to the National Socioeconomic Survey (CASEN) in 2015, 23.3% of AH's inhabitants experienced multidimensional poverty (Mansilla Quiñones et al., 2020). Although more recent statistics for AH are unavailable, CASEN reported that multidimensional poverty in the Tarapacá region was 19.4% in 2015, rising to 24.3% in 2017, and slightly decreasing to 23.8% in 2022 (Observatorio Social, 2022). Nationally, the multidimensional poverty also decreased from 20.3% in 2020 to 16.9% in 2022, largely due to government support (UChile, 2023). Nonetheless, AH's poverty is reflected in its average income compared to the nation and its neighboring city Iquique. In 2022, the average national income was $USD 760, with Tarapacá averaging $USD 747, Iquique at $USD 877, and AH at $USD 560 (Durán and Kremerman, 2023). In 2023, the national number rose to $USD 837 and Tarapacá to $USD 820 (INE, 2024).

2.4 Fog collection as an alternative water resource

Fog is a cloud that touches the ground comprised of water particles of 1–40 microns, locally decreasing visibility to less than 1 km. The presence of mountains, its orientation, and wind are important to efficiently harvest fog water (Schemenauer et al., 2022). Fog formation is found along the arid western coast of Africa, the Canary Islands, the Arabian Peninsula, the coasts bordering the Pacific Ocean, and in semi-arid tropical highlands where rain is seasonal such as in Guatemala, Colombia and the Philippines (Molina et al., 2008; Balaguer et al., 2011; Suau and Zappulla, 2015; Schemenauer et al., 2016; Zamani et al., 2021).

Fog harvesting is a passive, low-cost, and low-maintenance approach to obtain fresh water. A mesh suspended vertically toward the predominant fog-loaded wind intercepts droplets whereon they coalesce and fall into a gutter. The most widely implemented and installed collectors are Large Fog Collectors (LFC) with a fog harvesting surface of ten by four (variable) meters. The most used interception surface is a double layer of polyethylene, widely known as the raschel mesh. It is a low-cost product also used as a shade cloth in nurseries and greenhouses (Schemenauer et al., 2022). Most countries that have implemented fog collectors and evaluated its harvesting potential are developing countries (Chile, Bolivia, Peru, Ecuador, Colombia, South Africa, Namibia, Eritrea, central Tanzania, Oman, Yemen, Saudi Arabia, and Morocco) (Fessehaye et al., 2014; Correggiari et al., 2017; Ait el kadi et al., 2024). In the 1980s, a pioneering project was set up in El Tofo, in the Coquimbo region in Chile. Which began as a research project for reforestation purposes, expanded to providing potable water with 100 LFCs (or "atrapanieblas" in Spanish) to 300 inhabitants down the slope. During the fog season, which is approximately from June to November in the region, the village received up to 15,000 L of water per day. Prior to this emblematic project, the town of Chungungo relied on water delivered by trucks ("camiones aljibe" in Spanish) receiving only 10,000 L per week (Fessehaye et al., 2014; Correggiari et al., 2017). The pilot project was seen as a success in terms of research and validation, but after 1 decade, the collectors were degraded due to storms, and lack of maintenance and funding (Edwards et al., 2001; Dale, 2003). Recently, researchers in the Atacama Desert have successfully utilized fog water for hydroponic food production in greenhouse structures in Falda Verde, Chile, enabling the soilless cultivation of lettuce, strawberry, basil, and mint (Albornoz et al., 2023, 2024). While these are among the successful projects for rural areas showing their potential, to date, there is only one known fog water collection project in an urban context. This project, located in the Villa María del Triunfo sector of Lima, Peru, supplies water to 250 households in slums. Nevertheless, the use of fog as a hydric resource has been carried out under the perspective of domestic uses in rural settlements (Fessehaye et al., 2014; Correggiari et al., 2017; Verbrugghe and Khan, 2023b). Many other projects underline the effectiveness of fog water collection in rural settings, demonstrating its potential as a reliable supply capable of delivering significant quantities of water (Klemm et al., 2012).

3 Methodology

To assess the fog water potential for the urban area of AH, we use *in-situ* observations with fog collection data over a year. In addition, we use a numerical model suggested by Lobos-Roco et al. (2025), the Advective fog Model for Arid and semi-arid Regions Under climate change (AMARU), to quantify the areas and potential fog water harvesting volumes in space and time.

3.1 *In-situ* fog water collection

Fog water collection is measured using the Standard Fog Collector (SFC) proposed by Schemenauer and Cereceda (1994). This device comprises one square meter of double raschel 35%-shade mesh standing at 2 m from the ground. The mesh is connected to a galvanized metal channel at its bottom edge to conduct the collected water into a pluviometer that registers the fog water volumes every 10 min (Schemenauer and Cereceda, 1994). Two SFCs were installed in the urban area and surrounding elevations (Figure 4; Table 1-a), from which the one located at the higher elevation (High SR) includes an all-in-one meteorological station registering data every 10 min. Fog collection measurements were conducted for the first time in AH over a 1-year period, from October 2023 to October 2024. Table 1 summarizes the spatial setting and data type gathered through these *in-situ* measurements.

3.2 Numerical modeling AMARU

To numerically quantify the fog water potential in the metropolitan area of Iquique and AH, we use the AMARU model (Lobos-Roco et al., 2025). Using available routine meteorological data, this model estimates the amount of fog water that can potentially be harvested using SFCs. While detailed information about the model is provided in Lobos-Roco et al. (2025), we describe key modeling details of how the results for AH were obtained. The AMARU model is defined by the following main equation:

$$\int_{t0}^{t1} W_{h(z)} = \left(r_{l(z)} u_x \eta\right) dt$$

where W_h corresponds to the modeled fog water harvested at z level, r_l is the adiabatic liquid water content (in g m^{-3}), u_x is the perpendicular-to-the collector wind speed (in m s^{-1}) and η is an empirical dimensionless coefficient of efficiency. The model is integrated into a predefined period of time (t_0 to t_1), at every hour, which can later be integrated into monthly and annual water collection rates, expressed in L m^{-2} per day. The model's objective is to estimate the adiabatic liquid water content (r_l) in the atmosphere's vertical column (z). This r_l is obtained using data from two meteorological stations (Table 1-b) positioned along a topographic gradient. Once the liquid water content is obtained, we use wind speed measurements from the same stations and use an η of 25% (Riverda, 2011; Carvajal et al., 2020). The result is a vertical column of water harvesting potential ($W_{h(z)}$). The final step is to combine this vertical column with two remote-sensing satellite products. The first is a digital elevation model at a 30m-spatial resolution, where fog collection height range and flux direction are established. The second is the fog and low clouds (FLC) spatial extension at 2 km resolution, obtained from the GOES satellite following the methodology suggested by Espinoza et al. (2024). In this way, the model displays the distribution of the most probable areas for potential fog collection. The water volumes are integrated into average monthly daily rates.

The model runs with hourly data from 2018 from two meteorological stations: Diego Aracena Airport and the fog oasis of Alto Patache (Table 1). The model has been validated using SFC observations from Alto Patache, a fog oasis 65 km south from Iquique. The comparison showed that the model underestimates observations by 10% (0.5 L m^{-2} day^{-1}). In addition to this validation, we have compared modeling results with the observations in AH from the low SR and high SR SFCs. Both low SR data and the model show null fog collection. High SR station shows rates of <0.2 L m^{-2} day^{-1}, while the model shows <1 L m^{-2} day^{-1}.

4 Results

4.1 Water supply in Alto Hospicio: current situation and emerging needs

The Tarapacá region is comprised of two provinces, Iquique and Tamarugal, with the latter located inland. AH is supplied with

FIGURE 4
Standard fog collectors (SFC) at high SR (left) and low SR (right).

TABLE 1 Spatial setting and data type gathered through (a) fog collection measurements and (b) model inputs.

	Station	Coordinate	Altitude	Recording time	Variables
a	Low Santa Rosa (Low SR)	20.27 S–70.08 W	572 m ASL	Sept-2023/Oct-2024	Fog collection
	High Santa Rosa (High SR)	20.29 S–70.07 W	683 m ASL	Oct-2023/Oct-2024	Fog collection, precipitation, air temperature, solar radiation, relative humidity, wind speed and wind direction
b	Diego Aracena Airport	20.53 S–70.17 W	48 m ASL	Jan/Dec 2018	Precipitation, air temperature, solar radiation, relative humidity, wind speed and wind direction
	Alto Patache	20.82 S–70.15 W	850 m ASL	Jan/Dec 2018	Fog collection, precipitation, air temperature, solar radiation, relative humidity, wind speed and wind direction

potable water from underground drillings located in the Pampa del Tamarugal basin through 72 km of ductile iron pipes (Figure 5). These underground drillings are located at the aquifers El Carmelo (EC) and the "Canchones–Cumiñalla" (Ca–Cu) system (Aguas del Altiplano, 2018a; Aguas del Altiplano, 2018b), which are non-renewable water resources (Santoro et al., 2018).

The Ca–Cu production system consists of a group of 18 drillings, each with an average depth of 110 m. The water is elevated and transported to several water tanks until reaching the "Santa Rosa" water storage tanks in the southeast sector of AH. The water is stored in two tanks of 10,000 and one of 5,000 m^3 and distributes water to most sectors in the city. The north of the city called El Boro is supplied from the "El Boro" tank measuring 800 m^3, with water originating from the "Santa Rosa" tanks. The water is distributed to the city through a network of feeders and matrices with a total length of more than 151 km, whose diameter fluctuates between 75 and 250 mm. The surplus is transported to the "Alto Hospicio" tanks, which supplies Iquique and consists of two tanks of 5,000 and 2,000 m^3. These also receive water transported from the EC system, which also supplies Pozo Almonte inland (Aguas del Altiplano, 2023a; Aguas del Altiplano, 2023b).

Until 2019, wastewater was collected and treated at a plant consisting of four aeriated lagoons in the El Boro sector. A portion of this treated water was used to irrigate nearby olive groves, while the remainder was discharged to Iquique (Aguas del Altiplano, 2018a; Aguas del Altiplano, 2023b). However, the treatment plant was eventually closed due to persistent odor issues affecting local residents. Although initially located away from the center of AH, the area had become increasingly populated after 2011 (Agenda Sustenable, 2020). Currently, wastewater is transported to Iquique, where it undergoes preliminary treatment through screening to remove debris, passing through coarse and fine screens, as well as a sand trap, before being disposed of into the Pacific Ocean (Aguas del Altiplano, 2018b).

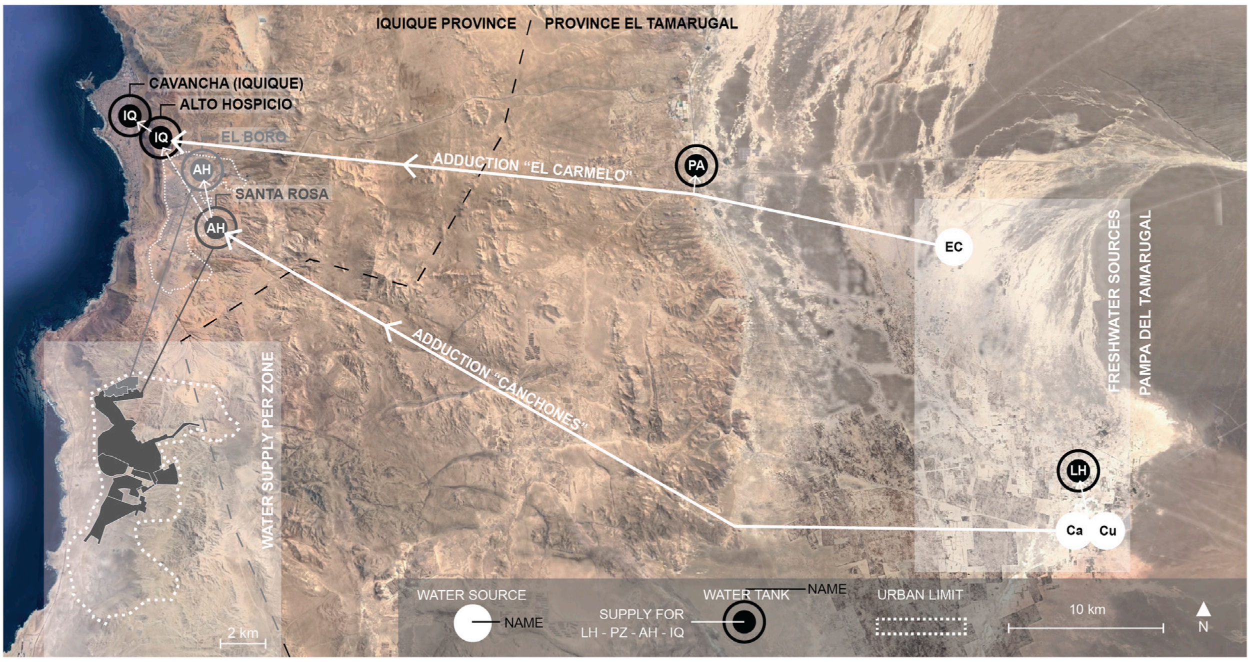

FIGURE 5
Water sources for the urban area of Alto Hospicio (AH), from groundwater drillings Canchones (Ca) and Cumiñalla (Cu), which also supply La Huayca (LH), and for Iquique (IQ) from El Carmelo (EC), which also supplies Pozo Almonte (PA). Based on information from Aguas del Altiplano (2023a), Aguas del Altiplano (2023b).

Regarding drinking water consumption, AH was projected to use 159.55 L day^{-1} per inhabitant in 2023. This implied a daily consumption volume of 17,112 m^3 for approximately 107,256 inhabitants. Aside from population growth by 2037 (144,426 inhabitants), numbers indicate that the consumption will increase to 164.08 L day^{-1} per inhabitant, resulting in a daily volume of 23,697 m^3 (Aguas del Altiplano, 2023b). While the current water distribution network reaches 100% of the population officially living in AH (Aguas del Altiplano, 2023b; Superintendencia de Servicios Sanitarios, 2023), new informal settlements such as camps and land grabs may not be included. The city's expansion in 2023 has extended beyond its urban limits (Figure 3) partly due to the COVID-19 pandemic, which displaced many immigrants from South America to Chile (Imilán et al., 2020; Alvarado Peterson and Rojo-Mendoza, 2023).

4.2 Fog water collection potential in Alto Hospicio

Our assessment of fog water collection potential indicates that the surroundings of AH, encompassing an area of about 100 km^2, demonstrate harvesting rates ranging between 0.2 and ~5 L m^{-2} day^{-1} on an annual average, according to the AMARU model. However, this potential is confined to the mountainous regions at elevations of 700–1,000 m ASL outside AH's urban limits. In the following subsections, we describe our assessment through *in-situ* observations and modeling results in detail.

4.2.1 *In-situ* fog water collection data

Figure 6 shows the total fog water collected monthly at the High SR station. The data from this site shows very low potential since the SFC is right at the bottom of the stratocumulus cloud base (Figure 8), where fog is less dense. Despite this low rate, the data provides information on the seasonal cycle of fog presence. The fog season starts in May and lasts until October, peaking in June with a rate of 2.5 L m^{-2} month^{-1}. This seasonal variation highlights that the fog collection season is concentrated within 6 months from winter to spring.

To better understand the atmospheric conditions that produce fog at the High SR site, Figure 7A shows the diurnal cycle of key meteorological conditions measured in 2024. Fog is collected mainly during the night and early morning (00:00 to 09:00 local time), with a peak rate of 140 mL m^{-2} per 10 min, which coincides with the lowest temperature of ~10°C and highest relative humidity of ~100% (Figure 7C). During the late morning and afternoon, temperature increases up to 23°C due to the increases in solar radiation (600 W m^{-2}), dissipating clouds since relative humidity drops to 70%. The thermal and moisture regime shows that the location of High SR is in a transition zone between the ocean-influenced coast and the absolute desert (annual precipitation ~0.8 mm, Figure 7B). This is because the temperature oscillates ~15°C during the day, and minimum relative humidity is still high (70%). Fog is collected under a very low wind speed, <1 m s^{-1}, with a clear SE direction (Figure 7D), corresponding to the typical coastal circulation from the south but altered by topography. This very low wind speed might be responsible for the low fog collection rates, since the High SR site stands over a small valley.

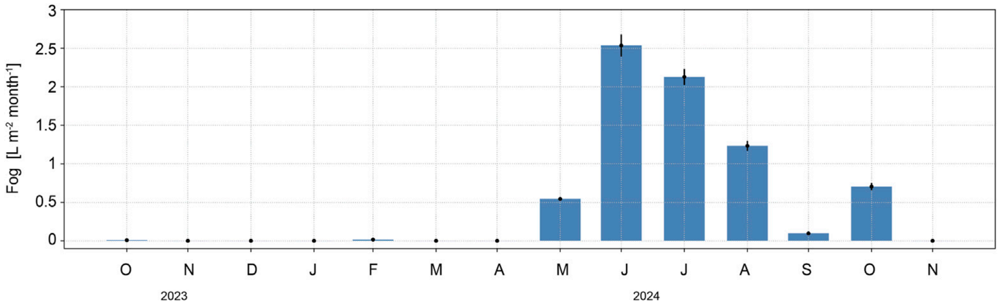

FIGURE 6
Total fog harvested per month in High SR site between October 2023 and October 2024.

4.2.2 Modeling results

To complement the *in-situ* data, Figure 8 shows an annual average daily rate of fog water collection around AH. According to our model, we observe an amphitheater-shaped area surrounding AH with potential fog water collection rates between 0.2 and 4.9 L m^{-2} day^{-1}. This amphitheater covers an area of around 100 km^{2} with the highest collection potential concentrated in the northern region. This area has mountains with heights ranging from 700 to 1,100 m ASL, facing southward. These characteristics align perfectly with the height at which stratocumulus forms and the direction of its advection (prevailing wind direction from southwest to southeast). The areas with more fog water collection potential are between 800 and 900 m ASL. The areas on the east and west of AH show moderate fog collection potential, which is where the High SR observational point is located. Here, the fog water collected (Figure 6), which is <0.1 L m^{-2} day^{-1}, aligns with the modelled rates of <0.2 L m^{-2} day^{-1}. Finally, additional areas in the south of AH have fog collection potential; however, these are located far from the city and situated at higher altitudes exceeding 800 m ASL.

Figure 9 shows the monthly average of daily fog water collection rates estimated by the AMARU model with meteorological data from 2018. Our model results show a well-marked monthly variability and seasonal cycle, consistent with the *in-situ* observations, validating the model's performance. Furthermore, the model indicates the absence of fog at Low SR. Figure 9A shows that in March, a few places in the east of the city show low fog water potential of ~0.2 L m^{-2} day^{-1}, numerically visualized in the graph (Figure 9B). In June, the areas of fog water potential expand across the northern, eastern, and southern regions. In areas closest to the city, fog water collection rates increase to 2 L m^{-2} day^{-1} during this period. The peak season is between August and September, when fog water collection potential reaches ~10 L m^{-2} day^{-1} across the northern, eastern, and southern regions of the study area (Figure 9B). In November, the fog water potential decreases to 3–5 L m^{-2} day^{-1} and to zero in December.

The sampled areas, displayed with yellow squares in Figure 9A, have the highest water potential and are less than 1 km from AH's urban limits, representing potential places to develop fog water collection projects.

5 Discussion

The findings of this study suggest that fog water collection, mostly in the surroundings of AH, has potential considering its geographical and atmospheric conditions. Preliminarily analysis identifies the northeast and southeast areas, located less than 1 km from the urban limits, as having the highest fog water potential, making them theoretically promising sites for large-scale fog water collection projects. Fog collection in AH offers a potential complementary water resource for various needs in the city. According to local government records, the city currently addresses the following water demands: 1) water for human consumption, which is supplied to the population living in slums, 2) water for irrigating common urban green spaces, and 3) local production of fresh food. The discussion assesses the viability of fog water collection to meet these demands.

5.1 Water for human consumption

As of 2019, the Ministry of Housing and Urban Development's Cadastre reported a total of 30 slums outside the urban fringe of AH, housing a total of 3,519 households and 10,301 people. These slums are primarily located in the northern part of the city (see Figure 3). These residents rely on water deliveries via trucks provided by the local government of AH. According to the 2023 Public Account, 300,000 L of water per week were delivered. Regarding the estimated municipal expenditure to meet this water demand, it is projected to be $USD 451 per week, or $USD 23,482 annually, based on the average cost of 1 m^{3} of potable water in AH in 2023, as mentioned above. Besides, for the population living in slums located inside the urban fringe, the local government issues over 36,000 "water vouchers" per month to more than 10,000 families. The water voucher program is a national public policy for families that allocate at least 5% of their monthly income to potable water and sewage services. The government subsidizes a portion or percentage of the monthly payment for up to a maximum of 13 m^{3} of potable water and sewage services for permanent residents of both urban and rural areas across the country. According to the data, the local government of AH financed approximately 5,616,000 m^{3} of drinking water in 2023 (Ilustre Municipalidad de Alto Hospicio, 2023).

The proximity of locations with significant fog collection potential, situated just outside the urban limits, presents a promising opportunity for the installation of large-scale fog collectors, pending further refinement of the data. Theoretically and considering that these locations have a modelled annual average

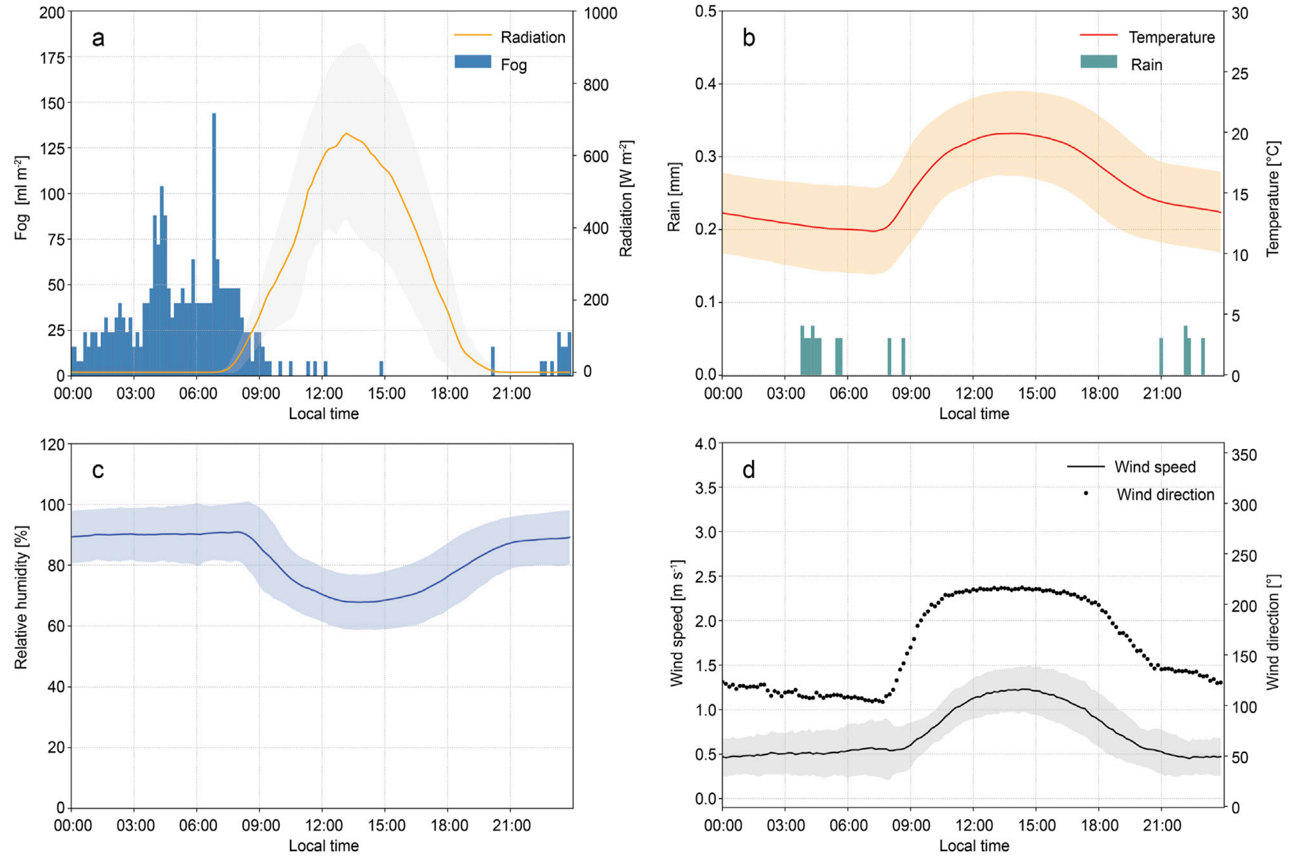

FIGURE 7
Annual averaged diurnal cycle of **(A)** fog collection and shortwave radiation, **(B)** 2-m air temperature and precipitation, **(C)** relative humidity, and **(D)** wind speed and direction, observed from October 2023 and October 2024 at High SR.

rate of (Figure 8) of 2.5 L m^{-2} day^{-1}, 17,000 m^2 of mesh is needed to meet the weekly water demand of 300,000 L for the urban slums. Distribution could be managed through piping infrastructures or continued delivery by trucks. Important to convey is that given the seasonal variability of fog formation and the rapid peri-urban population growth, fog water is most suitable as a complementary supply. Implementing large storage systems or ponds is necessary to ensure continuity to bridge the seasonal gap. However, during the fog-scarce periods, alternative water sources, such as trucks, may still be necessary.

5.2 Irrigation of urban green spaces

The United Nations' New Urban Agenda (2017) highlighted several challenges faced by contemporary cities, including the lack, reduction, and unequal access to natural habitats and green spaces, which are recognized as multifunctional areas that improve people's health and wellbeing. Green spaces play a fundamental role from an environmental and social perspective. They increase urban biodiversity, reduce contributions to climate change and the urban heat island effect, encourage physical activity, reduce anger, anxiety, depression and stress, improve visual comfort, and increase community connectedness, food security, and social cohesion (Reeve et al., 2015; Ahuja, 2016; Kellert, 2016; Terkenli et al., 2020; Carter et al., 2021; Cree and Robb, 2021; Roe and McCay, 2021). However, water demands for maintaining green spaces in general, are highly dependent on the regional water system (Nouri et al., 2012; 2019; Reyes-Paecke et al., 2019). The hyperarid environment of AH complicates efforts to green the city through precipitation (Sarricolea et al., 2017; del Río et al., 2018). According to data from the Ministry of the Environment (2016), within the context of the “Development of a Digital Climate Database for Chile: Baseline (1980–2010) and Projections to 2050” project (Ministerio del Medio Ambiente [MMA], 2016), AH receives a maximum precipitation of 3 mm, impeding sustainable implementation and maintenance of urban green spaces. Furthermore, society is becoming increasingly aware that continued stress on surface and groundwater sources, commonly exploited in arid climates, is not sustainable (Newman et al., 2017). Aside from local water scarcity, the pressure on the conventional water distribution infrastructure and its availability is increased by industries and population growth (Dirección General De Aguas, 2017; Salinas et al., 2016). Given these factors, the availability of an alternative and reliable water source for maintaining green infrastructure in desert cities—within the broader context of greening urban environments, as outlined in the New Urban Agenda (United Nations, 2017)—is crucial to ensure the sustainable development of cities and communities.

Regarding budgetary limitations for implementing greening initiatives and maintenance, AH is recognized as one of the most

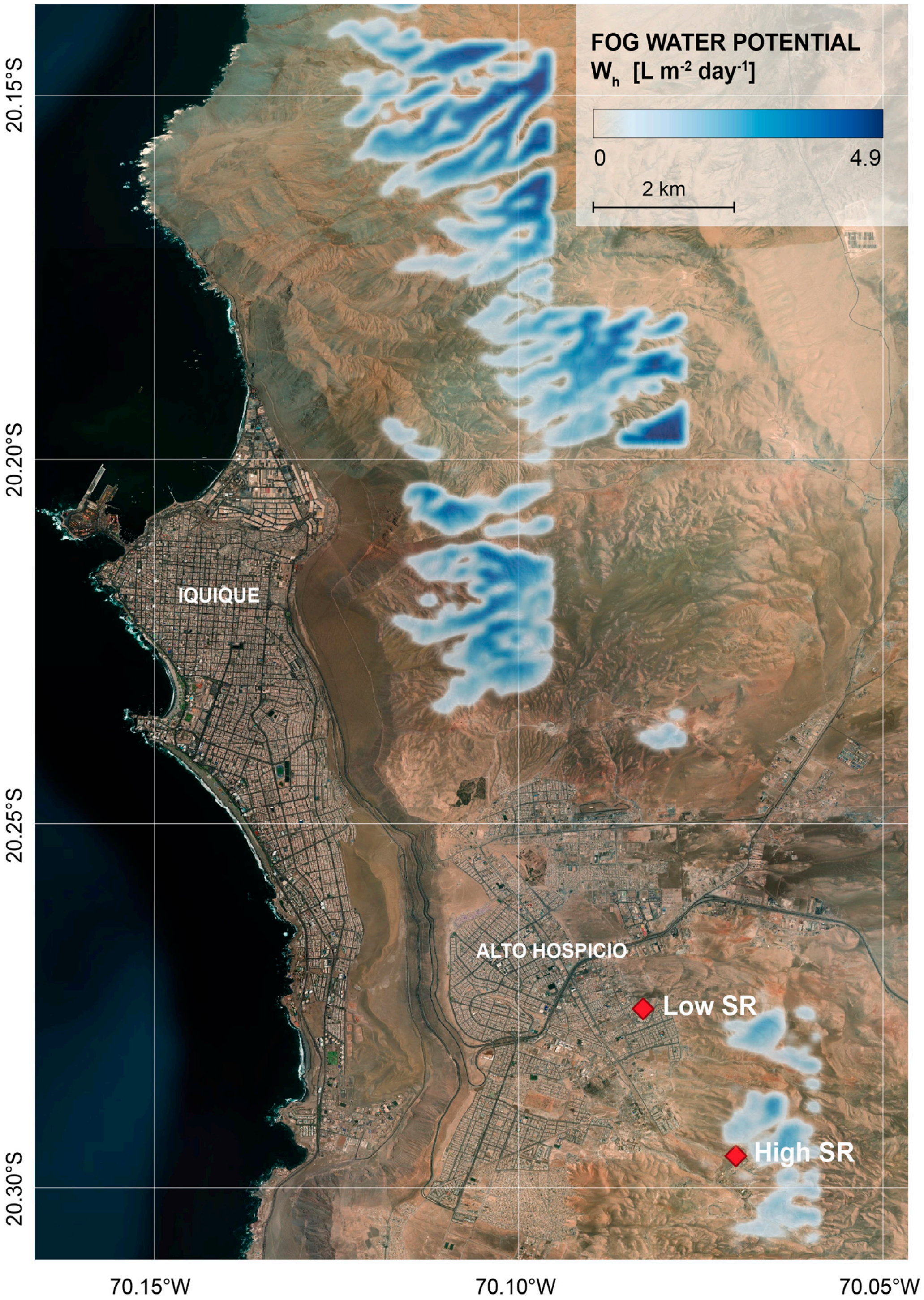

FIGURE 8
Fog water potential (Wh) in the surroundings of Alto Hospicio. Solid blue colors show annual averaged daily rates and red dots show the location of the two observational points.

affected local governments in Chile by inequalities. It presents a dependence of the Common Municipal Fund on its own income of 70% in the year 2020, concentrating only 0.3% of the communal budgets with respect to the national total. Besides, it presents a low quality of urban life according to some national indexes from the last 10 years (Centro de Inteligencia Territorial de la Universidad Adolfo Ibáñez, 2017; Orellana et al., 2021). Regarding other statistics that characterize AH, the northern and especially the southern edges show low values of social welfare with respect to investments in infrastructure with higher values of daily thermal amplitude, which

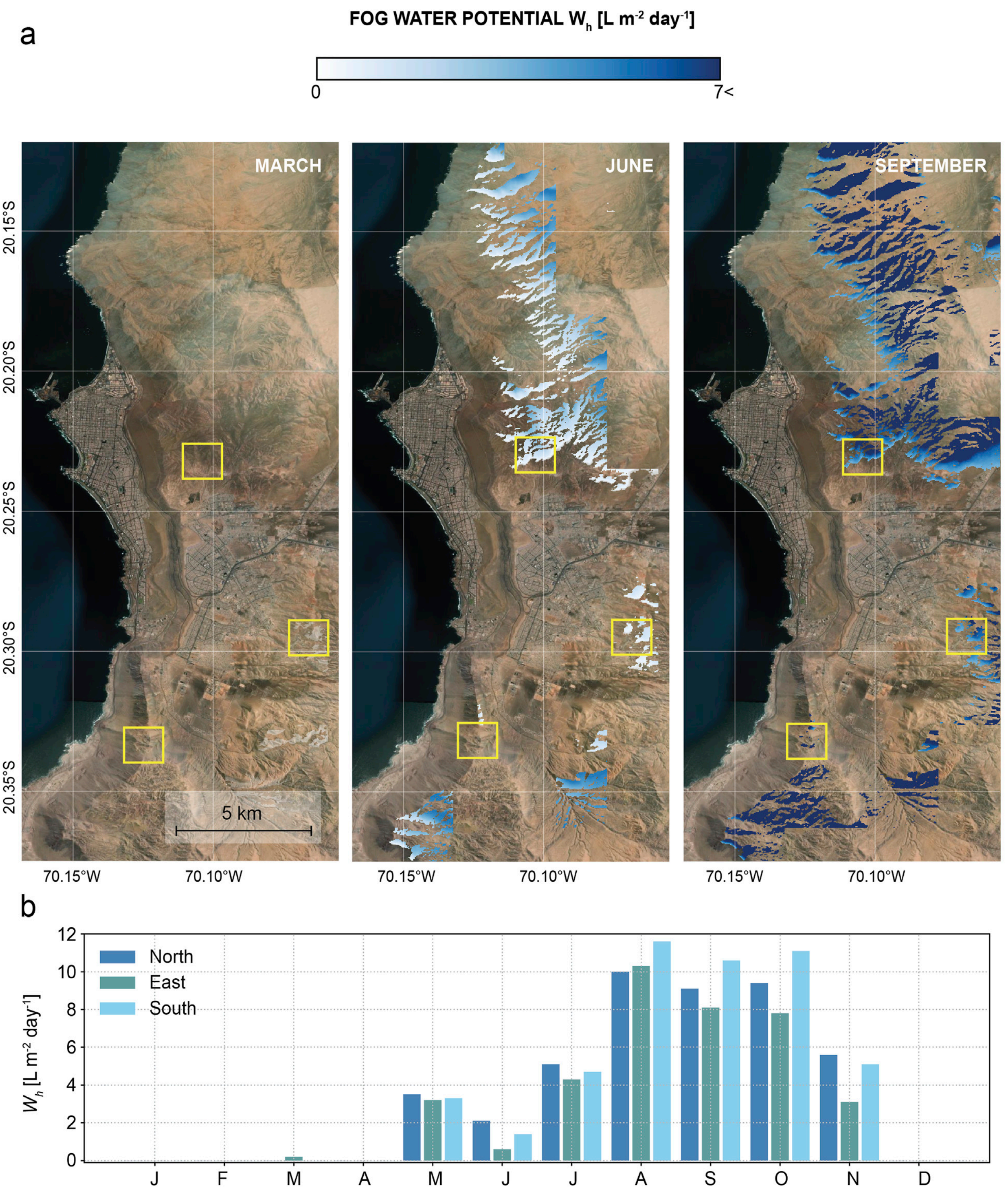

FIGURE 9
(A) Fog water potential W_h obtained from the AMARU model in 2018. The yellow squares indicate the closets (<1 km) areas with high fog water potential around AH. **(B)** Monthly cycle of daily rates of fog water collection in the North, East and South sampled areas of AH.

reflects the need for more green areas or infrastructure; scarce or almost no presence of green areas; low accessibility to public services; and low proportion of health facilities. In its "Public Account 2023" document, which summarizes all administrative actions, the local government reports that it is responsible for irrigating the city's public urban green spaces. Green spaces in AH covered a total area of 25 ha in 2022, and now exceeds 30 ha, with more than 100,000 L of potable water delivered to several watering committees for irrigation.

Using fog water for irrigation arises as a potentially practical and sustainable solution. To meet the annual water demand of 100,000 L, around 110 m^2 of mesh would be needed, based on the same annual average rate of 2.5 L m^{-2} day^{-1}. The collected water does not require extensive treatment, making it particularly suitable for non-potable uses such as urban green infrastructure. Municipalities could establish systems where fog water is collected in nearby areas with high collection potential and transported via water trucks or piped directly into storage facilities within the city. This approach would allow the integration of fog water into existing irrigation systems, reducing reliance on treated water for non-potable purposes.

5.3 Local production of fresh food

Between the 1950s and 1980s, AH was primarily a horticultural hub supplying Iquique. However, the rapid population growth after the 1980s, marked by land seizures and the development of housing projects, replaced its earlier role (Municipalidad Alto Hospicio, 2022). The World Health Organization recommends a daily intake of around 400 g of fresh fruit and/or vegetables per person (Wallace et al., 2020). To meet this, northern Chile relies on import from central Chile or neighboring countries, which results in high prices unaffordable for low-income inhabitants such as from AH (Albornoz et al., 2023). Local food production would be an alternative for supplying the community, but the hyperarid environment of AH restricts water availability and the implementation of agricultural production. This is exacerbated by the poor quality of the soils due to high levels of salinity, limiting the number of crops that can thrive under these conditions (Villanueva et al., 2003). Therefore, soilless production arises as a viable alternative for vegetable production. This technique uses either hydroponic systems or substrate-based production in containers, with its main advantage being that it requires significantly less water than traditional soil-based agriculture (Pomoni et al., 2023). Our findings indicate that fog water is not available during the whole year, however, the implementation of hydroponic systems including storage tanks or even, using the same hydroponic system as a reservoir, would allow for vegetable production throughout the year. The quality of fog water is remarkably good for this strategy, since it presents a very low content of dissolved solids suitable for direct use into hydroponic systems and storage (Albornoz et al., 2024).

Hydroponic agriculture demands an average of 0.5 L day^{-1} per square meter of ground surface cover with crops (Albornoz et al., 2023). This makes fog water particularly valuable, as even low amounts of captured water can sustain crop growth. In 1 m^2 of hydroponic lettuce, around 25 to 35 plants can fit, yielding between 3.0 and 4.0 kg of fresh produce in a 30-day period. With an average collection rate of 2.5 L m^2 day^{-1}, almost 5 m^2 of hydroponic lettuce (or any other leafy green crop) could be supported, yielding between 15 and 20 kg of fresh vegetables for local consumption in AH. Integrating fog water for activities within the city requires transporting the collected water into urban areas, incurring costs associated with piping infrastructure or transportation. In contrast, using fog water for local food production is more practical, as it can be collected, used, and stored directly at the source. This makes local food production a particularly promising application with low associated water infrastructure costs, and even more interesting for AH, where local fresh food production is almost inexistent.

6 Conclusion

Many fog collection projects underline the effectiveness of fog water collection in rural settings, demonstrating its potential as a reliable supply capable of delivering significant quantities of water. The global challenge of freshwater scarcity mostly poses socioeconomic and environmental challenges for rapidly growing arid cities, where fog collection is underexplored. This gap demonstrated the need for further research to evaluate the potential and scalability of fog water collection in larger human settlements such as cities (more than 50,000 inhabitants) or towns (population between 2,000 and 5,000 inhabitants). The preliminary observations and the AMARU model validate the potential of fog as a complementary supply for various purposes in AH.

Future research should first further evaluate the fog collection potential using SFCs to confirm the modeling results. Due to our observations' extremely low collection rates at High and Low SR, the AMARU model ran and calibrated using data from nearby (65 km south) Alto Patache fog oases (Table 1-b), which brings uncertainty to the modeling results. This uncertainty is based on the fact that we assume that Alto Patache fog conditions are similar in AH surroundings, which can lead to over-, or underestimations. Nonetheless, to deal with this uncertainty, we have corrected the modeling using the fog and low cloud frequency obtained from the GOES satellite. This frequency is lower in AH than in Alto Patache; consequently, our modeled fog collection rates decreased to more realistic values. Despite our correction, new data in or around AH over a period of minimum 1 year in locations with higher collection potentials should be collected to calibrate the model correctly. The next step is to assess the needs for fog water uses. On a broader scale, it is beneficial to assess the impacts of fog collection projects on the urban metabolism, as well as the sustainability and socio-economic benefits. Particularly for water security and environmental justice in marginalized communities of growing urban and peri-urban areas. Lastly is the water quality of fog in urban environments. While findings from Albornoz et al. (2024) indicate low contents of dissolved solids in another region of Chile, the chemistry of fog is a direct function of the air quality (Kaseke and Wang, 2018). Acting as atmospheric scrubbers, it is recommended to assess the fog water quality from SFCs in the surrounding metropolitan region of Iquique and AH.

From a national policy perspective, incorporating nonconventional resources such as fog water collection into water management strategies has the potential to alleviate pressure on overexploited and finite resources. This integration could be achieved by incentivizing investments in fog collection infrastructures, offering financial support for pilot projects, and establishing guidelines of fog water systems. This could include standards for their design and maintenance. Additionally, spreading awareness campaigns are crucial in promoting the benefits of fog water collection. A collaborative approach involving researchers, urban planners, key stakeholders, and communities could ensure its acceptance and alignment with broader sustainability goals. This study aims to inspire researchers and policymakers to explore the urban potential of fog collection in regions with similar arid, but fog-loaded conditions. By showcasing its potential and applications, the findings encourage replications in built-up and populated areas already experiencing or at risk of water stress, promoting the use of a nonconventional resources. Ultimately, fog water collection as part of urban water management in arid regions addressees immediate resource challenges in harmony with nature and represents a transformative step towards equitable and sustainable cities in the face of global water scarcity.

Data availability statement

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

Author contributions

VC: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Validation, Visualization, Writing–original draft, Writing–review and editing. NV: Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing–original draft, Writing–review and editing. FL-R: Data curation, Formal Analysis, Investigation, Methodology, Writing–review and editing. CR: Writing–review and editing. FA: Writing–review and editing. AZK: Supervision, Writing–review and editing.

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Conflict of interest

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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