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Evaluation of surface water quality in basins of the Chilean Altiplano-Puna and implications for water treatment and monitoring

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Abstract Water quality characterization and assessment are key to protecting human health and ecosystems, especially in arid areas such as northern Chile, where water resources are scarce and rich in pollutants. The objective of this study was to review and assess available official water quality data in the Chilean Altiplano-Puna basins for a 10-year period (2008–2018), including water treatment systems. Within the 43,600 km^2 of Chilean Altiplano-Puna territory, only 16 official water quality monitoring stations had up-to-date data, and the sampling frequency was less than 3 per year. Most of the water samples collected at the evaluated stations exceeded the drinking and irrigation water Chilean standards for arsenic, boron, and electrical conductivity. Moreover, the characteristics of the Altiplano-Puna affect water quality inside and beyond the area, limiting water usage throughout the Altiplano-Puna basins. Drinking water treatment plants exist in urban and rural settlements; however, the drinking water supply in rural locations is limited due to the lack of adequate treatment and continuity of service. Wastewater treatment plants operate in some urban locations but rarely exist in rural locations. Limited data impede the proper assessment of water quality and thus the evaluation of

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the need for treatment systems. As such, the implementation of public policies that prioritize water with appropriate quantity and quality for local communities and ecosystems is imperative.

Keywords Water quality network · Arsenic · Boron · Drinking water · Water treatment systems · Northern Chile

Introduction

The natural and anthropic features of the Altiplano-Puna (AP) Plateau constitute a unique environment. This region, located in the Central Andes between 15° and 28° S, encompasses areas of Bolivia, Peru, Argentina, and Chile (Fig. 1). It is limited to the east by the Eastern Cordillera and to the west by the Western Cordillera, an active volcanic arc (Grosse et al., 2018). The AP has an average altitude of nearly 3800 m.a.s.l. and is the second largest plateau after the Tibet Plateau (Lamb et al., 1997).

The Chilean AP Plateau contains valuable ecosystems. Among these, wetlands (vegas, bofedales, and wet grasslands) present a unique species richness with high levels of endemism, constituting areas of biodiversity concentration in the region (Ahumada et al., 2011). These fragile ecosystems are refuge and breeding areas for many species experiencing conservation problems (e.g., *Phoenicopterus chilensis*, *Rhea pennata tarapacensis*, *Vicugna vicugna*, *Lama guanicoe*, *Lagidium viscacia*) (CEA, 2015) and play a vital role in the development of their basins (Ahumada et al., 2011). In the Chilean AP and its surroundings, many areas have been declared under protection by the State of Chile and by international organizations (Table S1 and Figs. S1 to S6, Supplementary Information). National protected areas include national parks, national reserves, natural monuments, nature sanctuaries, and protected national properties (Ministerio del Medio Ambiente, 2020b). Additionally, some areas have been declared priority sites for the National and/or Regional Biodiversity Strategy (Ministerio del Medio Ambiente, 2020b). International protected areas include various Ramsar

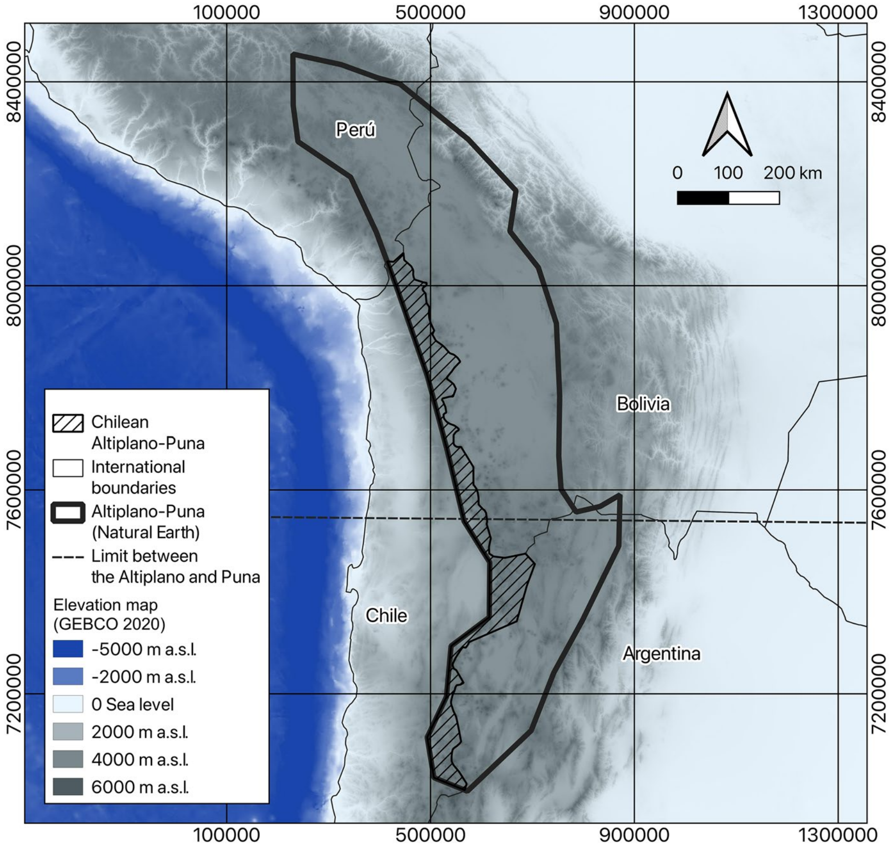


Fig. 1 Location of the Altiplano-Puna and its elevation map in meters. DEM obtained from GEBCO (2020). The limit from Natural Earth is shown in black (1:50 physical vector, version 4.1.0). The Chilean Altiplano-Puna corresponds to the hatched area. Inspiration for this figure comes from Fig. 1 in Tapia et al. (2019)

sites and the Lauca Biosphere Reserve (Ministerio del Medio Ambiente, 2020a).

The Chilean AP is also home to 1988 people (Tapia et al., 2019) belonging to four ethnic groups. Aymara people inhabit the Arica y Parinacota and Tarapacá Regions. The Quechua people live in the Tarapacá and Antofagasta Regions. The Likan Antai (atacameños) people inhabit the Region of Antofagasta, and Colla people live in the Region of Atacama (Molina, 2012). Within the AP area, indigenous communities mainly perform grazing activities (llamas, alpacas, sheep, and goats), taking advantage of the extensive wetlands (Castro-Lucic, 2002) and agriculture (Molina, 2012).

Northern Chile is one of the most arid areas in the world, which makes water availability a main concern for policymakers (Meseguer-Ruiz et al., 2019). Despite this aridity, rainfall increases considerably toward the AP and Andean mountains, providing the water resources needed for the development of cities, mining, and agricultural activities (Sarricolea et al., 2017b). Therefore, surface and groundwater quantity and quality from the AP plateau region are not only relevant for the activities developed within the plateau but also have a significant impact downstream in its basins.

To protect ecosystems and the health of inhabitants, water quality monitoring and assessment are essential. Furthermore, water quality is a limiting factor to public health and economic development (Alexakis, 2020). Water quality deterioration around the world is caused by geological processes, agrochemicals, mineral ore weathering, the overexploitation of natural resources and industrial and mining activities (Alexakis, 2020). Water quality assessment is also important in places where natural conditions, such as the geological characteristics of the region, determine water chemistry, for example, in India, where arsenic is present in excess (Jain et al., 2018). This assessment is particularly important in isolated and rural areas where the treatment of water sources is basic or absent, for example, in Minas Gerais, southeastern Brazil, where rural communities only filter spring water for their use (de Oliveira et al., 2022).

The water quality index (WQI) is a useful tool to grant a system with a certain classification; however, different WQI models can have significantly different results even when applied to the same area (Alexakis, 2020) and may not give a representative value when there are limited available data. Therefore, a holistic approach that assesses water quality along with socioeconomic activities and the unique characteristics of a system is critical (Bekas et al., 2021; de Oliveira et al., 2022).

Extreme aridity and the presence of salars, hydrothermal water sources, and volcanic formations explain the naturally poor water quality of the AP. Although various studies have reported the presence of arsenic, boron and other pollutants in the AP (e.g., Pincetti-Zúniga et al., 2022; Romero et al., 2003; Tapia et al., 2019), to our knowledge, data from the existing Chilean water quality network in that area have not been fully analyzed. Data from this network, unlike specific studies, could provide valuable information on historical water quality trends and interseasonal variability for an important number of parameters. These data may also shed light on the compliance of water quality standards according to the current and potential uses of the water bodies and thus the treatment or protection requirements to comply with the corresponding standards.

Human activities such as cattle raising and agriculture require water quality that meet their requirements. In addition, the COVID-19 pandemic has required constant washing of hands to prevent contagion, creating more attention on drinking water availability and quality.

The aim of this research work is to evaluate the water quality of the Chilean AP, identifying the inhabitants and activities affected by it and the currently available water treatment systems. For this evaluation, we evaluated water sources in the study area comparing to the Chilean standards of drinking water and irrigation water.

Materials and methods

The methodology applied in this study included (a) characterization of the Chilean basins that are located within the AP, identifying the main water uses in these basins, (b) analysis of available data from the Chilean water quality network, compared to drinking water and irrigation water Chilean standards, (c) review of available literature from the water quality of different water bodies in the basins, and (d) compilation of the available information on the drinking water and wastewater treatment systems currently present in the basins.

Study area description

The study area corresponds to the 14 basins that are part of the Chilean AP. These include naturally endorheic basins contained in the AP (Tapia et al., 2019), preandean and andean exhorreic basins, and endorheic basins of intermediate elevations — according to the official definition of Chilean basins (DGA, 2013, 2014) — that are born at the AP and/or receive natural recharge from the Andean Range located at the AP. The names of these basins, hereafter "AP basins," are Altiplánicas, Río Lluta, Río San José, Costeras Río San José-Quebrada Camarones, Quebrada Río Camarones, Costeras Río Camarones-Pampa del Tamarugal, Pampa del Tamarugal, Fronterizas Salar Michincha-Río Loa, Río Loa, Fronterizas Salares Atacama-Socompa,

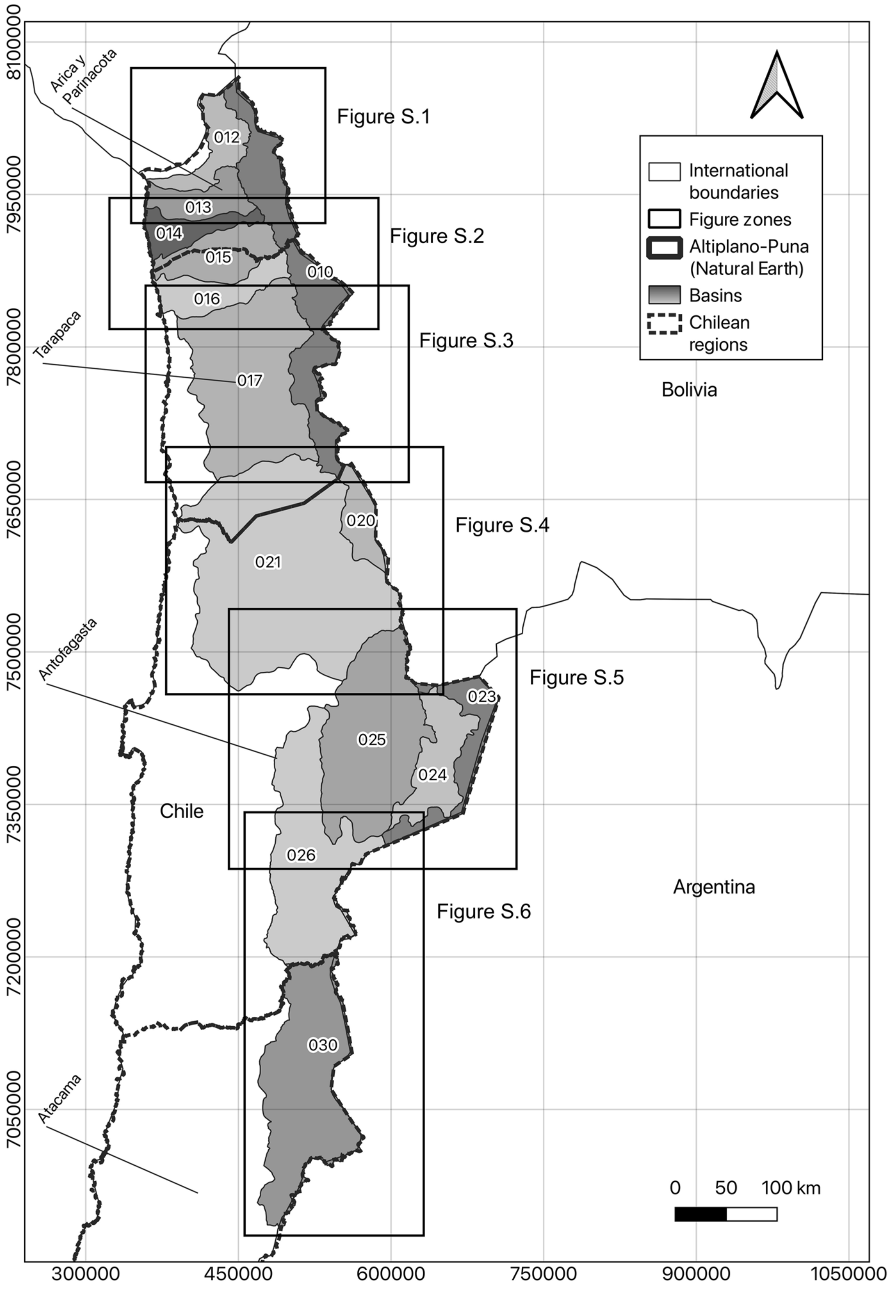


Fig. 2 Chilean basins and regions in the AP. The basin ID number corresponds to that assigned by DGA (2014)

Endorreica entre Fronterizas y Salar Atacama, Salar de Atacama, Endorreicas Salar Atacama-Vertiente Pacífico, and Endorreicas entre Frontera y Vertiente del Pacífico (DGA, 2014).

In northern Chile, the AP is located between 17° and 27° S in the Regions of Arica y Parinacota, Tarapacá, Antofagasta and Atacama (Figs. 1 and 2). According to our estimation based on the limit from Natural Earth, the Chilean AP surface is 43,594 km^2, which corresponds to 13% of the total AP surface.

The Chilean AP presents a tundra with a dry winter climate (Sarricolea et al., 2017a). It has low mean annual temperatures (2 °C; Araya-Osses et al. (2020)), low atmospheric humidity and high solar radiation (Aceituno, 1996). The mean annual precipitation varies between 400 and 50 mm, decreasing spatially toward the southwest (Sarricolea et al., 2017b). Rainfall is largely concentrated in the austral summer months (70% occurs from December to February), in a phenomenon known in Chile as "invierno boliviano." Nevertheless, it exhibits significant fluctuations on the intraseasonal and interannual timescales. These later fluctuations are related, in part, to the El Niño Southern Oscillation (ENSO) phenomenon (Garreaud et al., 2003).

Table S2 (see Supplementary Information) presents key aspects of the AP basins, including hydrographic descriptions, populations, and water uses.

Collection of water quality data

The main Chilean water quality data repository is managed by the General Water Directorate (Dirección General de Aguas, DGA by its Spanish acronym), which is part of the Ministry of Public Works (Ministerio de Obras Públicas, MOP by its Spanish acronym). The DGA collects data from 829 water quality monitoring stations throughout the Chilean continental territory (DGA, 2016a). These data form part of an online open public repository where reports can be obtained from as far back as 1960 (DGA, 2020). The parameters currently measured by the DGA, relevant to this study, are indicated in the Supplementary Information (Tables S5 to S15).

The analyses corresponding to these measurements were performed in the Environmental Laboratory of the DGA. Information on the analytical methods, current limits of detection, and equipment employed was provided directly by this laboratory and is shown in Table S19.

To identify and analyze the main pollutants in the Chilean AP, the following methodology was applied: first, the DGA water quality monitoring stations located within the AP were identified. Then, historical measurements from December 1, 2008, to November 30, 2018, from the DGA repository were obtained. This period was selected because it covered a full ten-year period at the moment the data were processed. Overall, 16 water quality stations presented data within the 10-year period. Their names, assigned ID and DGA code are included in Tables S17 and S18 (Supplementary Information), whereas their locations are shown in Figs. S1 to S6. All the stations, except for DGA-09 (Pozo JICA G), correspond to surface water.

Water quality assessment

To classify water quality, mathematical approaches such as water quality indices (WQI) can be used (Alexakis, 2020). The DGA developed a water quality index for groundwater (DGA, 2009); however, the DGA has recently used an indicator recommended by the ONU: SDG indicator 6.3.2, "proportion of water bodies with good ambient quality," for surface water and groundwater. Depending on the water body, basic parameters and their thresholds were defined: dissolved oxygen for rivers and lakes; electrical conductivity for rivers, lakes, and aquifers; nitrite + nitrate for rivers and lakes; nitrate for aquifers; orthophosphate for rivers and lakes; and pH for rivers, lakes and aquifers. The thresholds were set based on three priorities: (1) ambient water quality standards, (2) percentiles of DGA data between 2007 and 2014, and (3) water quality standards such as irrigation. If (1) is not available, (2) must be employed, and if DGA data are missing, (3) must be employed. If the measurements present an 80% compliance or above, the evaluation is "good quality," whereas if the compliance is below 80%, the evaluation is "not good quality" (DGA, 2019). The calculated values for these indicators can be checked online for selected monitoring stations and basins (DGA, 2022).

As a comparison, the CCME-WQI considers five classifications depending on the obtained value: excellent, good, fair, marginal, and poor and includes at least four water quality parameters. The mathematical formulation of this index includes three parameters: F1 represents the number of variables whose objectives are not met, F2 represents the percentage of tests that do not meet their objectives (failed tests), and F3 represents the amount by which failed tests do not meet their objectives. This WQI was formulated by Canadian jurisdiction to protect aquatic life and assess water quality by applying guidelines (Bilgin, 2018).

Given the lack of ambient water quality standards in the AP basins and the notable presence of nonconventional pollutants such as arsenic and boron, the water quality assessment was performed based on the primary water quality standards in Chile. As such, the use of water quality indices was not considered for this study. One of their limitations is that they do not highlight the parameters that exceed threshold values but provide a value for global water quality classification (Espejo et al., 2012).

The primary water quality standards in Chile considered for this study are (i) drinking water, regulated by NCh409/1:2005 "Agua potable—Parte 1: Requisitos" (Drinking water – Part 1: Requirements) (Instituto Nacional de Normalización, 2005) -hereafter, NCh409- and (ii) irrigation water, regulated by NCh1333:1978 Mod.1987 "Requisitos de calidad del agua para diferentes usos" (Water quality requirements for different uses) (Instituto Nacional de Normalización, 1987) -hereafter, NCh1333. The NCh1333 standard also regulates esthetic use, recreational use, and water destined for aquatic life. The thresholds for drinking and irrigation water are presented in the Supplementary Information (Tables S5 to S15). None of the AP basins has ambient water quality standards. Furthermore, only five out of the 101 basins defined by the DGA currently have ambient water quality standards (Pastén et al., 2021).

Data analysis

Since this study is focused on the comparison with Chilean regulation, the percentage of the number of measurements that exceeded the water quality thresholds established by NCh409 and by NCh1333 at each water quality station was calculated. Figures 3 and 4 present the percentage of exceedance for those parameters where a water sample exceeded the corresponding limit at two or more DGA stations, at least once. Detailed results are shown in the Supplementary Information (Tables S17 and S18).

The analysis performed in this study is based on the number of times a certain parameter exceeded the limit, instead of the comparison between the median or average value of the parameter and the corresponding limit. This is because the first approach is more relevant for water consumption or any other use. Other researchers, such as Galindo et al. (2007) and Pincetti-Zúniga et al. (2022), have also used this approach. Galindo et al. (2007) compared water quality throughout an Argentinian basin with Argentina regulations by calculating the percentage of samples exceeding the reference levels for human drinking water, irrigation, and cattle consumption. More recently, Pincetti-Zúniga et al. (2022) assessed water quality from the Arica y Parinacota Region (in Chile) by reporting the number of samples that exceeded NCh409 and NCh1333 for monitored parameters.

Statistical parameters were also calculated for most measured parameters: median value, standard deviation, total number of measurements, 5 and 95 percentile values; they are presented in the Supplementary Information (Tables S5 to S15). The calculation of the statistical parameters could not be made for some parameters because the detection limit was above thresholds or because the parameter was not measured by the DGA. This is also indicated in the Supplementary Information (Tables S5 to S15). In this case, the corresponding measurement was not included for the calculation of the percentage of exceedance of the associated water quality parameter.

Construction of maps

To provide an overview of the spatial distribution of water quality in water bodies in the Chilean AP region, scientific literature and local government reports (in Spanish, available online) were extensively reviewed. Salars and brackish lagoons or lakes (TDS > 10 g/L) were not included because these waters could not be used for consumptive uses. Figures 5, 6, and 7 were constructed to show the reported values for the key water quality parameters according to our review: arsenic, boron, sulfate, electrical conductivity and pH. These figures also include the median values calculated for these parameters as described in the "Collection of water quality data" section. All data used are shown in the Supplementary Information (Tables S5 to S15, Table S20).

Figures S1 to S6 were constructed to visualize the key natural and anthropogenic components identified in the 14 basins. These figures are presented from north to south, as shown in Fig. 2.

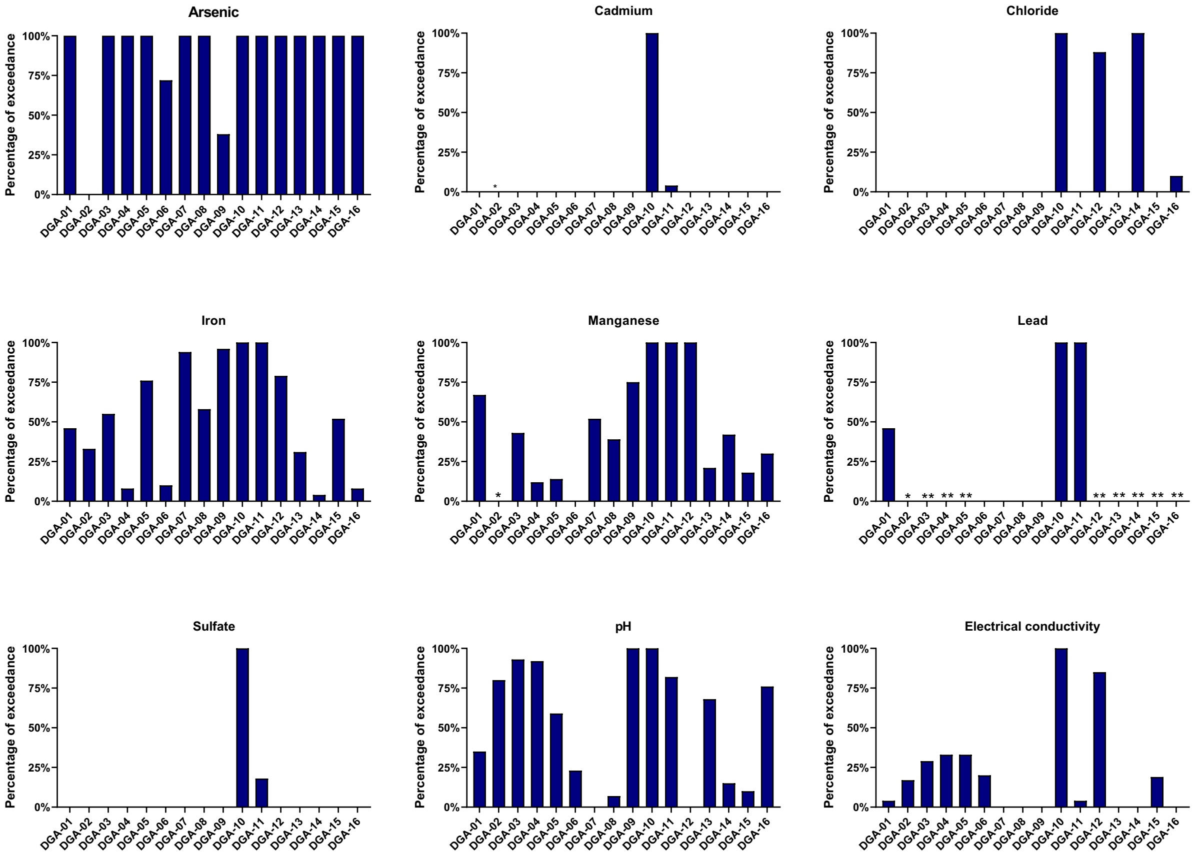


Fig. 3 Percentage of samples that exceeded the Chilean drinking water standard NCh409 at the selected DGA monitoring stations during the period under analysis (15 surface water stations and 1 groundwater station). The presented parameters correspond to those where water samples at two or more stations exceeded the standard limit, at least on one occasion. *: Data not available. **: The analytical method`s detection limit exceeded or equaled the standard value

The distribution and levels of the main water pollutants within Chilean AP basins, along with their key components, are shown to allow a better understanding of the water usage and water treatment systems within these basins.

Information on drinking water and wastewater treatment systems

The description of drinking water and wastewater treatment systems was requested via the Transparency Law (Law n° 20,285), which compels public services agencies to respond to public data requests. The agencies were the Superintendence of Sanitary Services in 2019 (SISS by its Spanish acronym) and the Direction of Hydraulics Works (DOH by its Spanish acronym) in 2020 regarding urban and rural systems, respectively. A database directly from the national DOH office (updated to 2019) was also received. To clarify and update the description of the rural systems, the corresponding regional DOH offices (Arica y Parinacota, Tarapacá and Antofagasta) were contacted.

Results and discussion

Comparison of AP water quality data with Chilean standards

Water quality in the Chilean AP region is poor, exceeding the NCh409 and NCh1333 limits multiple times. At all DGA monitoring stations, at least four parameters exceeded NCh409, and at least three parameters exceeded NCh1333 (Table S17 and S18). The most

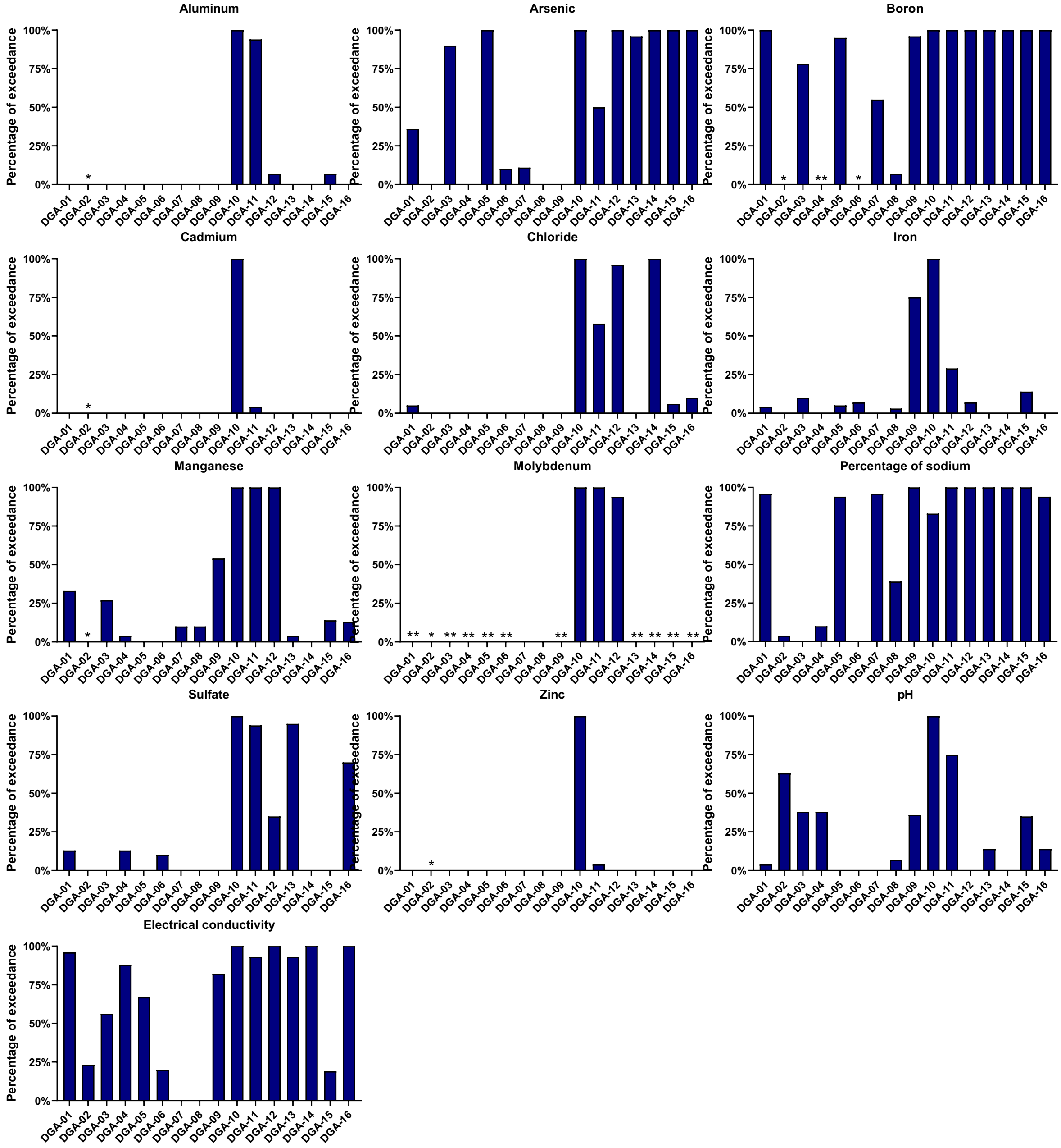


Fig. 4 Percentage of samples that exceeded the Chilean irrigation water standard NCh1333 at the selected DGA monitoring stations during the analysis period (15 surface water stations and 1 groundwater station). The presented parameters correspond to those where water samples at two or more stations exceeded the standard limit, at least on one occasion. *: Data not available. **: The analytical method`s detection limit exceeded or equaled the standard value

critical ones were arsenic, boron, iron, manganese, percentage of sodium, sulfate, pH, and electrical conductivity (EC). Nevertheless, chloride, cadmium, lead, aluminum, molybdenum, and zinc also exceeded NCh409 and/or NCh1333 in some cases (Figs. 3 and 4). Arsenic was the parameter with the highest exceedance: only at 2 out of the 16 DGA stations, less than 29% of the reported concentrations was below the NCh409 limit (0.01 mg/L).

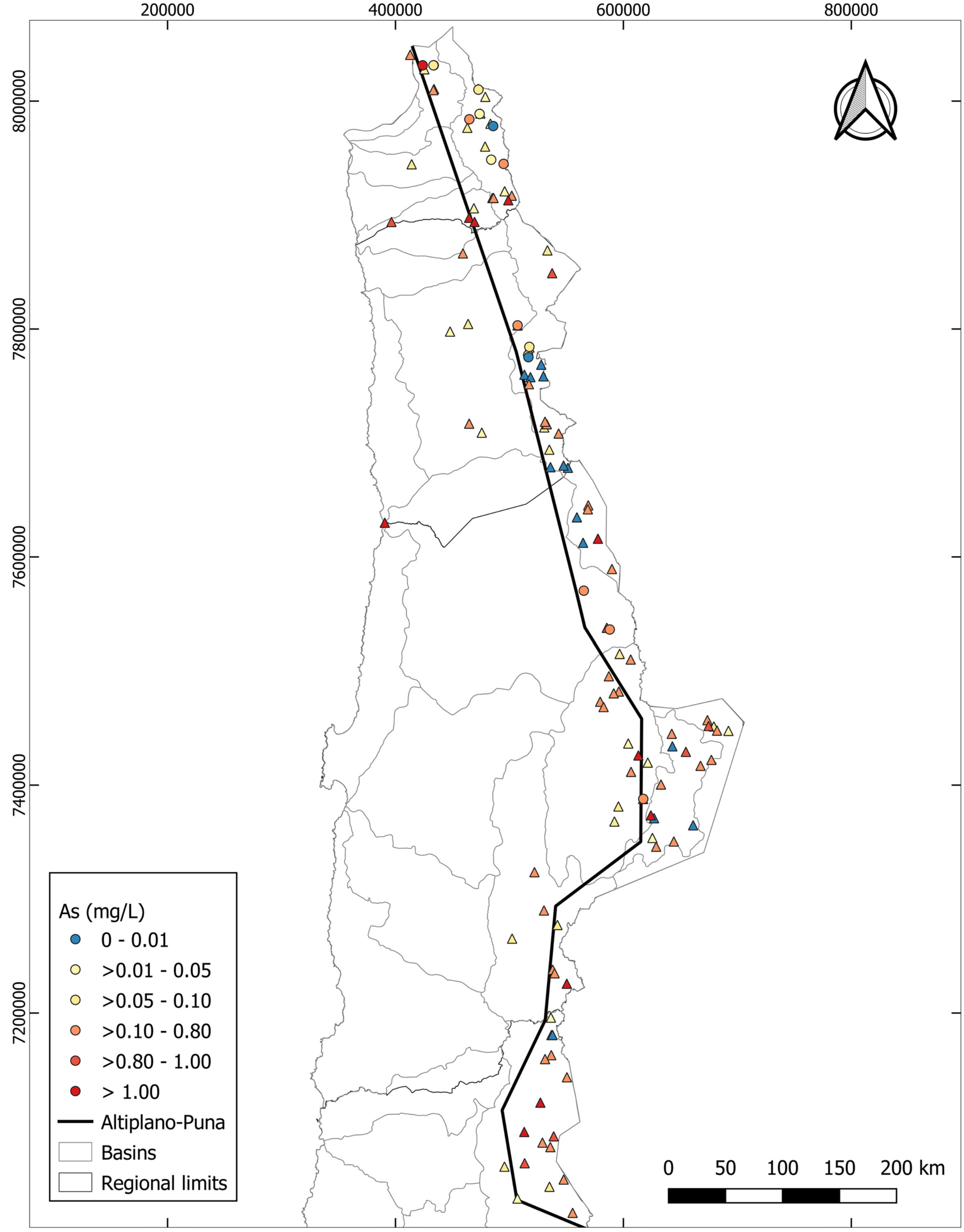


Fig. 5 Arsenic (**a**) and boron (**b**) concentrations in the studied basins. Circles correspond to the median value of the DGA dataset calculated in this study (15 surface water stations and 1 groundwater station), whereas triangles correspond to data reported in the literature

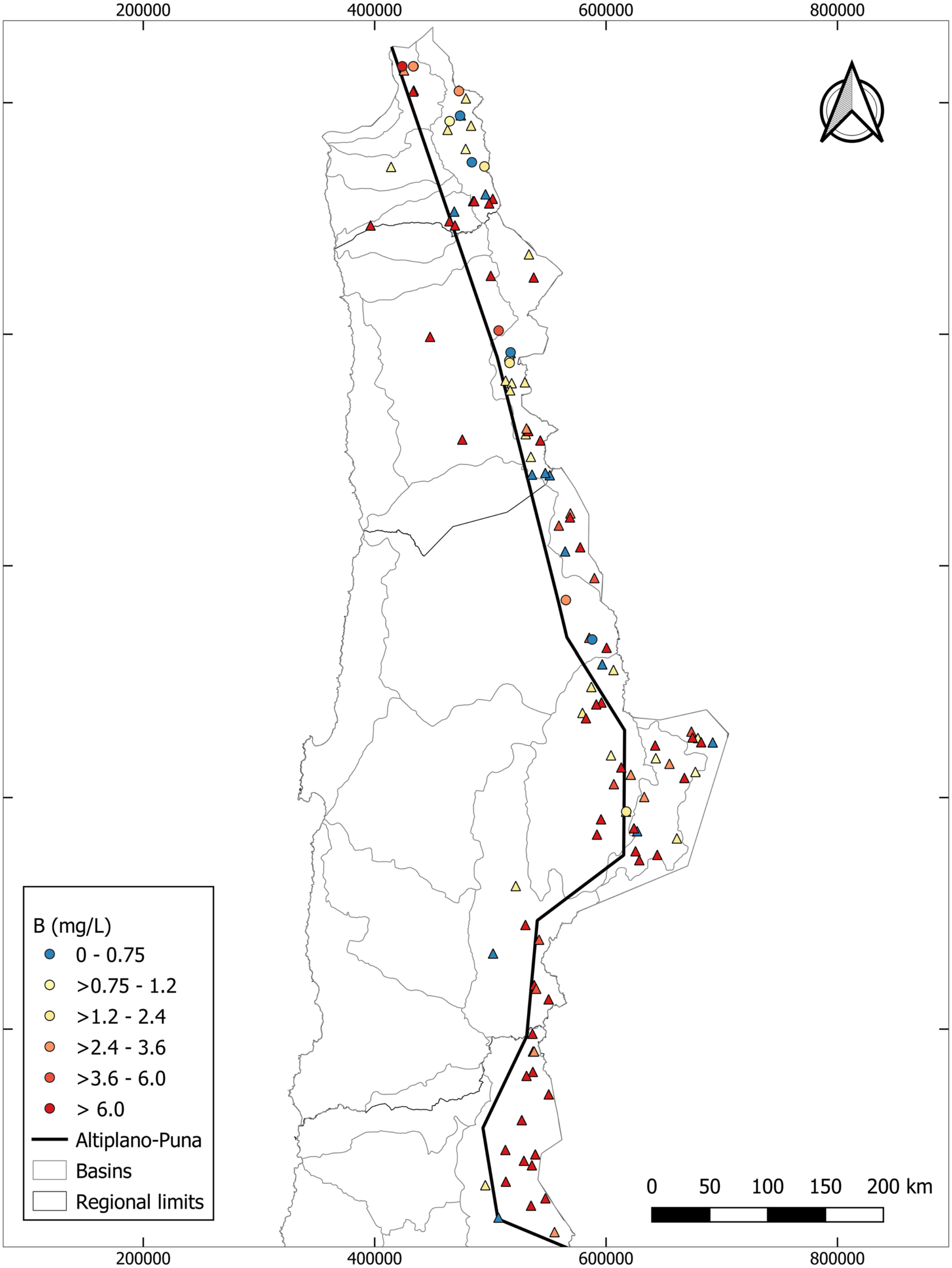


Fig. 5 (continued)

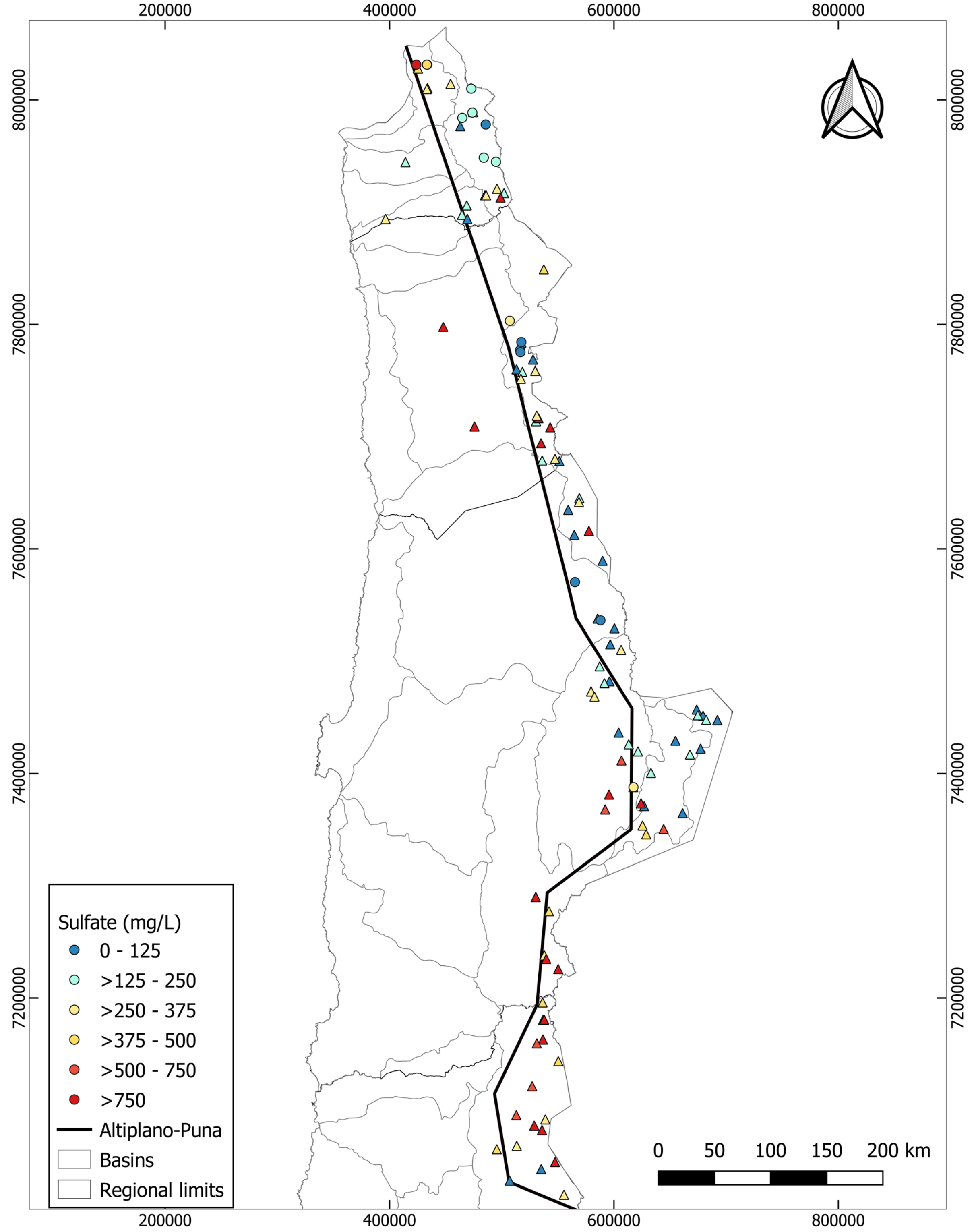
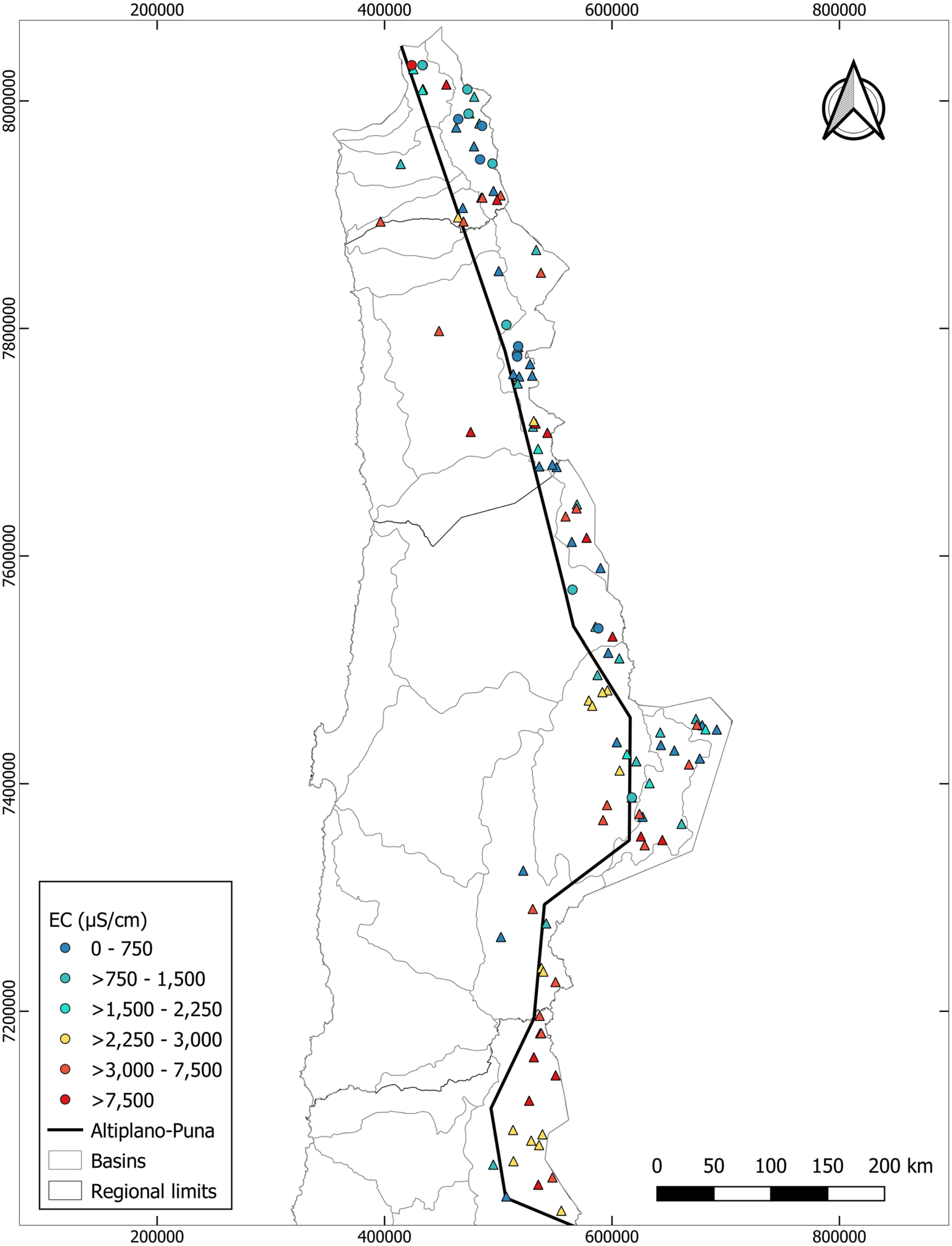


Fig. 6 Sulfate (**a**) and electrical conductivity (**b**) levels in the studied basins. Circles correspond to the median value of the DGA dataset calculated in this study (15 surface water stations and 1 groundwater station), whereas triangles correspond to data reported in the literature



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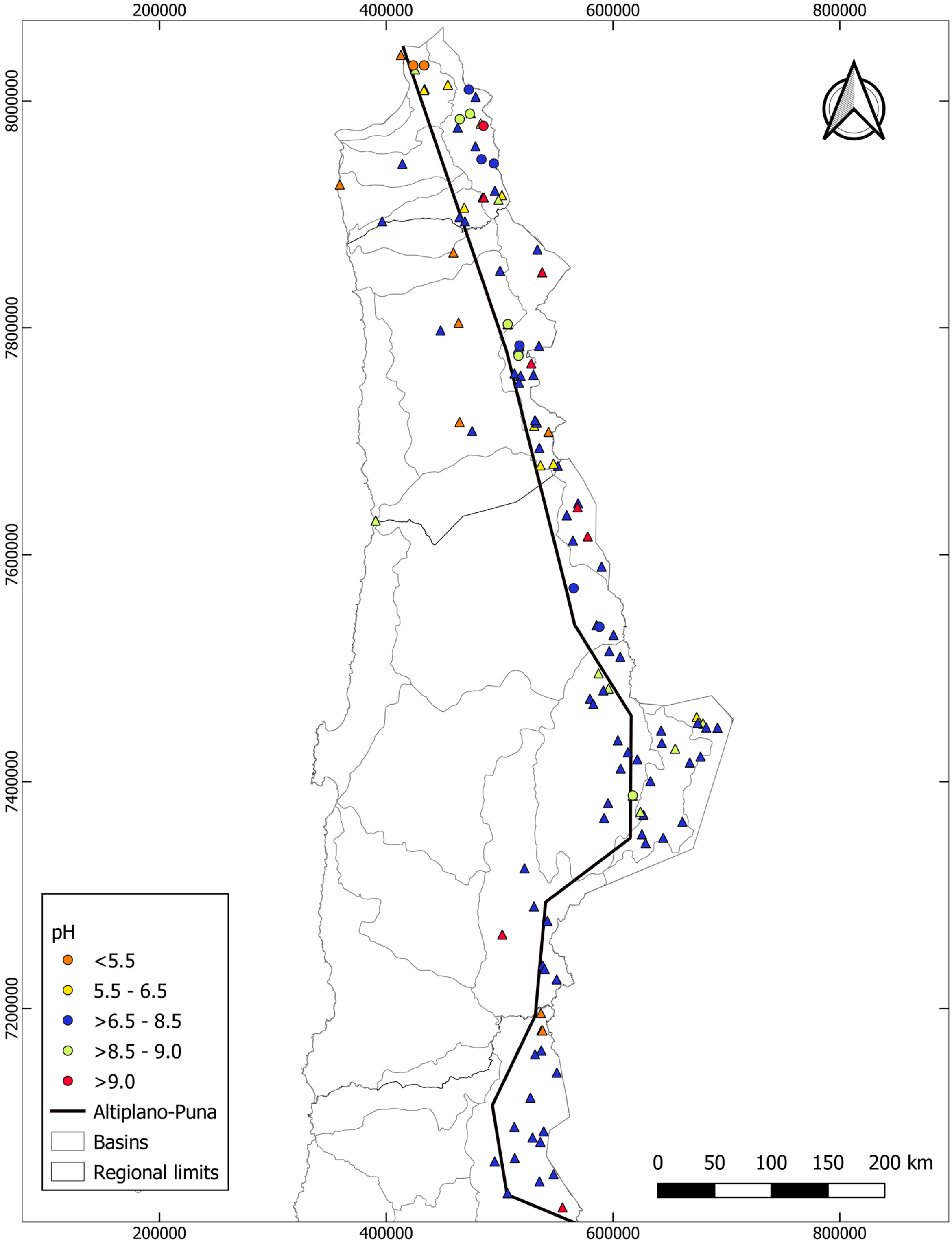

Fig. 7 pH values in the studied basins. Circles correspond to the median value of the DGA dataset calculated in this study (15 surface water stations and 1 groundwater station), whereas triangles correspond to data reported in the literature

National water quality network

Water quality monitoring networks are important for the assessment of surface waters and aquifers to manage water resources for different purposes (Lictevout et al., 2014). Water quality monitoring networks must consider an adequate number of sampling sites, frequency of sampling and analyses, and measured chemical parameters (Khalil et al., 2010). The number of water quality stations in the AP presented a low territorial coverage: the AP counted 16 stations with water quality data between December 1, 2008, and November 30, 2018. This is equivalent to an estimated water quality station density of 1 station per 2500 km^2 of territory. Moreover, there are entire basins, such as basins 023, 024, 026, and 030, with no water quality monitoring stations. The water quality station density of AP is low compared to the estimated Chilean average density index of 1 station per 1000 km^2 of territory (829 stations throughout 756,102 km^2 of Chilean continental territory) (DGA, 2016a). The latter is already lower than the European standard of 1 water quality station per 270 km^2 (EEA, 2016).

Additionally, the sampling and analysis frequency was also low: the maximum number of measurements throughout the 10-year period of analysis was 31 measurements of pH, copper and manganese at the "Río Guallatire en desembocadura Río Loa" station; same number for copper, iron, manganese and EC at the "Río Piga en Collacagua" station (Supplementary Information). This is equivalent to an average frequency of 3 measurements per year, which is lower than recommended frequencies that range from 4 to 26 per year (EEA, 2016; Nguyen et al., 2019). For the type of chemical parameters measured, there are several parameters included in the standards that were not monitored (in NCh409: ammonia, cyanide, fluoride, nitrite; as such the nitrate + nitrite ratio could not be calculated; TDS; they were estimated using EC (Supplementary Information); in NCh1333: barium, beryllium, cyanide, fluoride, lithium, and vanadium). Fluoride was measured in 2022 by DGA at surface water stations. Although it is currently suspended due to a lack of personnel, the DGA aims to implement these measurements (Fredes, 2022). Phosphate, although not included in any of these standards, is a relevant parameter for ecosystems and agriculture and was only measured sporadically. Bicarbonate (HCO_3^-) has not been measured by the DGA since 2006 (Lictevout et al., 2014), despite its relevance to characterizing the lakes and salars of the AP (Risacher et al., 2003). However, the DGA has developed a document for the implementation of the analysis of alkalinity using a field test kit, which is being executed in the Maipo basin and it is expected to apply it in other regions (San Miguel, 2022). The detection limits of the analytical techniques to measure lead, chromium and mercury were higher than the threshold established in NCh409. The same situation occurred for molybdenum and mercury in NCh1333. Therefore, it was not possible to compare these parameters with the corresponding thresholds according to these standards.

This traditional approach to assessing water quality based on the comparison of measured parameters with existing local normative often allows the proper identification of contamination sources and may be necessary for checking compliance (Debels et al., 2005). In this case, the performed assessment indicated that in all water sources from the AP basins, at least one parameter exceeded both standards.

Factors determining water quality

The Chilean AP presents a wide spectrum of water quality (Figs. 5, 6, and 7). Although arsenic, boron, iron, manganese, percentage of sodium, and sulfate would be recognized as pollutants for surpassing Chilean water quality standards, AP waters are of natural origin, and the presence of these is mainly owed to the volcanic formations, hydrothermal waters, salars and evaporitic salts, part of the natural AP environment (Risacher et al., 2003; Tapia et al., 2021). Anthropogenic activities that may also affect water quality are associated with the mining industry. Worldwide, anthropogenic sources such as exploited iron ore and other mineral deposits and environmental liabilities such as mine tailings generate acid mine drainage and/or acid rock drainage (Abarca et al., 2017; Alexakis et al., 2021; Carrillo-González et al., 2022; Fan et al., 2022; Guerra et al., 2016). Although most of the Chilean mining activities are concentrated to the west, outside of the AP (Tapia et al., 2021), there are some copper mining operations in the area that exploit sulfide minerals (for example, in the 021 basin, Fig. S4) Fractured sulfide minerals as well as mine tailings trigger the formation of acid mine and acid rock drainage that may also affect water resources (Kidder et al., 2020).

Since this work is focused on DGA data and available literature, information on the effects of mining operations on the water quality of AP is not included in this work.

Sources of arsenic, boron, and other pollutants are mainly attributed to volcano-sedimentary formations and climatic characteristics (Alexakis et al., 2014; Küçüksümbül et al., 2021). The presence of arsenic in South America, especially in the AP, has been widely reported (e.g., Bundschuh et al., 2020; Tapia et al., 2019, 2021). In the Altiplánicas basin, this presence is due to the presence of volcanic complexes: Nevados de Pachayata, Parinacota, Choquelimpie (DGA, 2015; Dorador et al., 2003; Risacher et al., 1999). Similarly, in the Río San José basin, it is due to geological characteristics associated with volcanoes and hydrothermal sources, the presence of alteration zones, lithological changes, runoff and the effects of the topography (Espinoza, 2013; JICA, 1995). The presence of arsenic and boron in the Caritaya River, Río Camarones basin, is due to the contribution of the Amuyo lagoons, the ravines on the south side, and by the incorporation of chemical elements released from the leaching or dissolution of minerals in the lagoon area (CNR, 2014a). Geothermal fields have a strong influence on the Río Loa and Pampa del Tamarugal basins. In the upper part of the first one, the El Tatio geothermal field is the main source of arsenic, boron, and lithium, affecting the Salado River and the San Pedro River (Romero et al., 2003). The Puchildiza geothermal field, in the second one, originates from the Puchuldiza River, the main tributary of the Aroma River (Montenegro, 2008). These thermal waters are extremely high in arsenic, boron, and EC, and since the Aroma, Tarapacá, and Chacarilla streams contribute 80% of the recharge of the Pampa del Tamarugal aquifer, the groundwater quality of the Pampa del Tamarugal basin is highly influenced by the quality of those streams (Lictevout et al., 2013). In the AP area of the Salar de Atacama basin, the natural alteration of volcanic rocks and hydrothermalism would give rise to the presence of arsenic, boron, and sulfate (Alonso et al., 1996; Carmona et al., 2000). In addition, the main recharge area of the Salar de Atacama basin corresponds to the Andean range (Marazuela et al., 2019). Most creeks and rivers originate at the foot of their volcanoes and hills. Due to this influence, boron, arsenic, and sulfate (to a lesser extent) are present throughout most rivers and creeks (CNR, 2014b; DGA, 2004b; Risacher et al., 1999). Therefore, most water bodies in the villages, *ayllus*, and towns of the basin (Fig. S5) are affected by these problems. High rates of evaporation in this basin (due to high solar radiation and altitude) would further concentrate the solutes in this basin (DGA, 2004b).

Dry climate, high evaporation, and the lack of any dilution explain extreme concentration phenomena (Mohammadzadeh-Habili et al., 2021; Tomaz et al., 2020). However, in the case of the Loa River, this is only a partial explanation. Groundwater interacting with volcanic rocks with compositions analogous to those in the El Tatio geothermal field also has elevated arsenic, boron, and lithium, and its inflow into the Medium and Lower Loa may contribute to high levels of these pollutants in the river (Romero et al., 2003).

Mining activities significantly pollute rivers (Fan et al., 2022; Kumkrong et al., 2022). This is the case for the Río Lluta basin. The water quality of the Azufre River, a tributary of the Lluta River, is strongly influenced by the legacy of sulfur mining (sulfur tailings and waste rock deposits) located in the base of the Tacora Volcano and by hydrothermal springs that discharge into the river with high concentrations of heavy metals and metalloids (Leiva et al., 2014). This explains the very high arsenic, boron, iron, aluminum, zinc, and sulfate levels in the Azufre River (Guerra et al., 2016).

Water quality spatial distribution in the AP basins

Trace element mapping is tremendously useful to assess suitability for water use or treatment (Alexakis et al., 2021). The spatial distribution of arsenic, boron, sulfate, EC and pH in the Chilean AP and water bodies influenced by this area are presented in Figs. 5, 6, and 7. There are few data of other parameters that exceeded the drinking and irrigation water Chilean standards at the DGA stations (e.g., iron, manganese, cadmium, lead, aluminum, molybdenum and zinc); as such, these could not be included. Many water bodies in the basins are rich in arsenic, boron, and sulfate and present high EC. The most critical elements are arsenic and boron due to their detrimental effects, elevated concentrations and the concomitant exceedance of drinking and irrigation water Chilean standards.

Arsenic in the water bodies varies between 0.0 and 21 mg/L, with a median of 0.21 mg/L (Table S20), exceeding NCh1333 and NCh409 in most cases (Fig. 5a). Despite the marked arsenic presence, there are several water sources having < 0.01 mg As/L (blue dots in Fig. 5a; basins 010, 020, 024, and 030) or < 0.1 mg As/L (yellow dots in Fig. 5a; basins 010, 012, 013, 015, 017, 023, 025, 026, and 030), thus complying with NCh409 and NCh1333, respectively. The lowest arsenic concentrations were reported in springs and rivers (Risacher et al., 1999; Table S20). Arsenic concentration values in water and exposure found in Chile are among the highest in the world (Raju, 2022). As such, in Chile and many countries of the world, such as Mexico, Argentina, USA, Bangladesh, India, the issue of arsenic contamination and the associated human health risk has been well studied (Golfinopoulos et al., 2021). Table 1 shows reported arsenic concentrations worldwide.

Similarly, most water sources in the Chilean AP far exceed the NCh1333 boron standard (>0.75 mg/L; Fig. 5b). Boron concentrations in water bodies vary between 0.11 and 519 mg/L, with a median of 5.8 mg/L. The highest boron levels are present in springs and hydrothermal springs, with a maximum of 444 mg/L in the hydrothermal springs next to the Colpitas River (Table S20). The few water bodies with low boron concentrations correspond mainly to rivers and springs located in basins 010, 015, 020, 023, 024, 025, 026, and 030, with a minimum of 0.11 mg/L in the Ajatarma River (Table S20).

Sulfate in water bodies varies between 7.39 and 3720 mg/L, with a median of 272 mg/L (Table S20). Almost half of the reported concentrations did not exceed NCh1333 (<250 mg/L) (Fig. 6a), despite the elevated levels observed at some locations. Rivers and springs presented the lowest concentrations, although several creeks and groundwater also showed low sulfate concentrations (Table S20). Basins 026 and 030 presented high sulfate concentrations in most water bodies (Fig. 6a), for example, in the Azufre River = 3104 mg/L, although the highest concentration was reported in a spring = 3730 mg/L (Table S20).

The elevated EC values in water bodies reflect their pollutant enrichment. Water bodies presented a median EC of 2285 µS/cm (Table S20). Most AP waters exceed the NCh1333 classification "water with which generally no adverse effects will be observed" (<750 µS/cm, Table S16). As expected, EC and sulfate presented a similar spatial distribution within the AP basins (Fig. 6). Therefore, rivers and springs presented the lowest EC levels (Table S20), while basins 026 and 030 presented the highest EC values (Fig. 6b).

The pH values were generally within the drinking and irrigation water Chilean standards, in contrast to the previous parameters (Fig. 7). These values were within the range of 1.9–9.7, with a median of 7.97 (Table S20). Seventy percent of water bodies were within the acceptable range for NCh409 and 84% for NCh1333. pH is basic in most cases, and values higher than 8.5 have been reported in places such as Chungara Lake, Cotacotani Lake, and its surroundings (Dorador et al., 2003; Herrera et al., 2006; Márquez-García et al., 2009; Risacher et al., 1999). This increase in pH is due to calcite supersaturation (Risacher et al., 1999). The Coscaya River (017 basin) is another example (median value 8.63, Table S20) and has historically shown elevated pH values. This river is born in the Andes, and the presence of calcareous sedimentary formations in the area may explain these alkaline values (DGA, 2004a). Nevertheless, some water bodies present acidic pH values, such as the Azufre River (012 basin), which has an extremely low pH (<2), corresponding to the lowest reported value (Table S20).

Table 1 Arsenic concentrations in water sources in different countries

Country	Location	Water source	Concentration (mg/L)	Reference
Mexico	Comarca Lagunera	Groundwater	> 10–650	Bundschuh et al. (2020)
Argentina	Chaco-Pampean Plain	Groundwater	< 4–5300	Bundschuh et al. (2020)
Chile	Quebrada de Chacarilla	Groundwater	680	Lictevout et al. (2013)
Chile	Antofagasta	Groundwater	100–1000	Mukherjee et al. (2009)
Chile	El Tatio river	Surface water	21,000	Romero et al. (2003)
Chile	Loa river	Surface water	1800	Herrera et al. (2019)
Greece	Milos island	Groundwater	2955–5850	Golfinopoulos et al. (2021)
India	Barpeta	Groundwater	0.1–569	Jain et al. (2018)
Bangladesh	Bengal basin	Groundwater	< 0.5–4730	Mukherjee et al. (2009)
USA	Tulare basin	Groundwater	< 1–2600	Mukherjee et al. (2009)

Given the poor water quality of the Chilean AP water resources, it is necessary to guarantee access to water with adequate quality through water treatment infrastructure. Furthermore, the water quality of the AP has a strong influence on the water quality beyond this region, affecting water that is used for human consumption and for agriculture in the valleys (Valle de Lluta, Valle de Azapa) and even water quality in cities on the coast of Chile, such as Antofagasta and Arica. The features of AP determine water quality throughout northern Chile, which explains the existence and characteristics of the water treatment systems described as follows.

Drinking water and wastewater treatment systems in the AP basins

Chile has shown a positive evolution in the indicators of access to drinking water and sanitation associated with the United Nations Millennium Development Goals (MDG) between 1990 and 2015, achieving a remarkable performance in the context of Latin America and the Caribbean. This has provided socioeconomic development and benefits for human health and the environment (Pastén et al., 2019). However, these indicators correspond to the urban sector only. This section presents key aspects related to drinking water and wastewater treatment in both urban and rural sectors in the AP basins.

Drinking water

Urban sector In Chile, the SISS is the institution supervising the services of the water companies that provide drinking water and wastewater collection and treatment in the urban areas by concession. In 2018, urban drinking water coverage exceeded 99.9% (SISS, 2018). Drinking water treatment plants (DWTP) are divided by SISS into two types: DWTP that do not use reverse osmosis (Table 2) and reverse osmosis DWTP (Table 3). Within the AP, these plants are located in the main communes of the Río San José (013), Pampa del Tamarugal (017), and Río Loa (021) basins (Figs. S1, S3 and S4).

All DWTP include removal of arsenic, iron, and manganese (Tables 2 and 3), in agreement with what was observed in the water quality stations of the AP located upstream. Cerro Topater, which treats surface water, presents higher design parameters for arsenic and iron removal than the plants that treat groundwater, indicating that groundwater has lower arsenic and iron concentrations. Since only 1 out of the 16 DGA monitoring stations corresponds to groundwater (Pozo Jica G) and is located in the Altiplánicas basin (010), it was not possible to compare these design values with arsenic and iron levels in groundwater from these basins. The median and standard deviations for arsenic, iron, and manganese at this station are 0.0095 ± 0.013, 10.37 ± 6.61, and 0.23 ± 0.13 mg/L, respectively (Tables S5, S9 and S10).

Reverse osmosis DWTP, which are capable of producing very high-quality water, still pose some challenges. Most reverse osmosis membranes are not specific for boron rejection, although this parameter is not included in NCh409. Additionally, reverse osmosis plants present high percentages of brine reject that must be adequately handled. In this case, rejection percentages fluctuate between 22 and 40% (Table 3). Evaporation is not always a feasible option due to the elevated surface needed, not even considering that northern Chile has evaporation rates that range from 5 to 10 L/m^2 day (1 L/m^2 day = 1 mm/day) (De La Fuente & Niño 2010; Houston, 2006; Moreno et al., 2011).

Rural sector The Rural Potable Water program (APR, Agua Potable Rural, by its Spanish acronym) has provided rural water infrastructure to concentrated and semiconcentrated Chilean towns since 1964, allowing 88% of the population in these towns access these systems (Fuster et al., 2018). The infrastructure is managed by cooperatives or user committees, which operate the systems and invest in maintenance, expansion, and improvement (ibid). The objective of the Subdirectorate of Rural Potable Water is to supply drinking water to rural concentrated and semiconcentrated populations, executing the required investment and performing the corresponding assessment to the organizations responsible for the administration, operation and maintenance of the systems (MOP, 2020b).

The DOH, dependent on MOP, is responsible for the APR program. In addition, the Subdirectorate of Rural Potable Water manages and promotes the development of APR organizations, implementing actions based on the program; however, it does not have regulatory power over the APRs (Fuster & Donoso, 2018). Law n° 20,998 (Gobierno de Chile, 2016) regulates rural water services. Currently, the Subdirectorate of

Table 2 Description of DWTP that do not use reverse osmosis. Information presented in this table was provided by SISS

ID	Basin	Water company	Name	Water source	Design parameters				Treatment process			
					Q (L/s)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	Grit removal	Coagulation-flocculation	Sedimentation	Filtration
DWTP-01	013	Aguas del Altiplano S.A	Planta de adsorción Chuño	Groundwater	50	0.016	0.016	0.016	No	No	No	Yes
DWTP-02	013	Aguas del Altiplano S.A	PTAP Pago de Gómez	Groundwater	90	0.016	0.016	0.016	No	No	Yes	Yes
DWTP-03	017	Aguas del Altiplano S.A	Abatidora de arsénico La Tirana	Groundwater	7.6	0.039	0.01	0.05	No	Yes	Yes	Yes
DWTP-04	017	Aguas del Altiplano S.A	Abatidora de arsénico Huara	Groundwater	4	0.018	0.01	0.01	No	No	No	Yes
DWTP-05	017	Aguas del Altiplano S.A	PTAP El Carmelo	Groundwater	1000	0.016	0.03	0.03	No	No	No	Yes
DWTP-06	017	Aguas del Altiplano S.A	Planta de Filtros La Huayca	Groundwater	5	0.055	0.016	0.02	No	No	No	Yes
DWTP-07	017	Aguas del Altiplano S.A	Planta de adsorción Matilla	Groundwater	7.5	0.025	0	0.01	No	No	No	Yes
DWTP-08	021	Aguas Antofagasta S.A	P.F. Cerro Topater	Surface water	690	0.6	0.0099	0.2	No	Yes	Yes	Yes

Table 3 Description of reverse osmosis DWTP. Information presented in this table was provided by SISS

ID	Basin	Company	Name	Water source	Design parameters					Treatment processes	
					Q (L/s)	Rejected *Q* (%)	As (mg/L)	Mn (mg/L)	Fe (mg/L)	Sand filter	Cartridge filter
DWTP-09	013	Aguas del Altiplano S.A	Módulo Osmosis Inversa Planta Estadio	Brackish water	28	25	0.04	0.013	0.04	Yes	Yes
DWTP-10	013	Aguas del Altiplano S.A	PTAP Pago de Gomez OI	Brackish water	90	32	0.016	0.018	0.06	No	Yes
DWTP-11	017	Aguas del Altiplano S.A	Planta Sulfatos Huara	Brackish water	3.6	40	0.018	0.01	0.01	No	Yes
DWTP-12	017	Aguas del Altiplano S.A	Planta Sulfatos Pozo Almonte	Brackish water	10.7	22	0.007	0.01	0.01	No	Yes

Rural Health Services (SSR by its Spanish acronym) is responsible for carrying out sanitation and drinking water projects, and community management, among others (Fuster & Donoso, 2018). As per this new law, the SISS will be responsible for supervising the quality of the services provided by the APRs.

The population living in the rural areas of the AP basins is supplied by the APR program, approximately 34,948 people. Various APR systems include additional treatment for arsenic and other pollutants. Unfortunately, some of them were not in operation at the time the information was obtained (Tables S3 and S4).

The Altiplánicas basin (010) has seven APR systems for an estimated population of 1,767 inhabitants. At most of their water quality stations, the arsenic limit set by NCh409 was exceeded (Fig. 3). However, the Visviri APR is the only system that has advanced treatment (Table S3). In addition, APR systems are absent in several subbasins (Lago Chungará, Salar de Surire, Salar del Huasco, Entre Salares Huasco y Coposa, Salar de Coposa, and Salar de Michincha). In the Salar de Huasco basin, an indigenous community (Asociación indígena Aymara Laguna del Huasco) has water rights (MOP, 2020a); however, no APR systems are found despite the 100% arsenic exceedance in the Collacagua River (Table S17).

Several problems were identified in the APR systems in the 010 basin. The Caquena APR system (out of service, Table S3) uses a nearby spring as its water supply up to 2015. In 2015, the family that owned the corresponding water rights interrupted this supply to the system. Then, the inhabitants initiated conversations with authorities to search for new water sources (El Concordia, 2015; Soy Chile, 2015). However, no further information was found regarding this search or the future operation of the Caquena system. The Parinacota and Guallatire APR systems are both out of service. The inhabitants of Guallatire have demanded their basic necessities, including access to drinking water, to the local authorities (Gobernación de Parinacota, 2015). These three systems were still out of service up to November 2020 (Gobernación de Arica y Parinacota, 2021).

The Río Lluta basin (012) has five APR systems for an estimated 5427 people. The recently inaugurated Valle del Lluta system is the most extensive rural drinking water system in the country, supplying drinking water to 781 families in the following towns of the Lluta River Valley: Linderos, Santa Rosa, Poconchile, Puro Chile, Chacabuco, Estación El Rosario, Alberto Jordán, Santa

Lucía, Valle Hermoso, and El Morro (Gobernación de Arica, 2019). Since the rural drinking water demand in the Quebrada Río Camarones basin (015) is increasing, in 2019, the MOP presented a million-dollar public investment plan for the construction and improvement of APR systems in the Arica y Parinacota Region (DOH, 2019). In the town of Timar, over US$ 520,000 will be invested for the collection, impulsion, treatment, storage and distribution of drinking water (DOH, 2020b). The inhabitants of Timar have been waiting for several years for a water distribution service (DOH, 2020b). In addition, in this basin, an investment of US$ 1.5 million is projected for the improvement of the rural drinking water plant in the town of Cobija (DOH, 2019). These initiatives seek to improve the infrastructure of APR systems that were damaged by the "invierno boliviano" during the summer season of 2018–2019.

A particular treatment scenario is observed in the Chusmiza APR (017 basin). According to DOH (2018), the construction started in December 2018, and it seems that it is not yet ready given that the Regional DOH did not include it in the provided information (Table S4). Here, concentrations of fluoride in the inflow reached 2.6 mg/L (the limit of NCh409 is <1.5 mg/L). The water source is the Chusmiza thermal spring (DOH, 2018). This source requires a treatment process with specific adsorbents for fluoride, which have a short lifespan and thus require continuous replacement. This constant replenishment accelerates continuous maintenance and water quality analysis to ensure the quality of the treated water (E. Cisternas, personal communication, July 30, 2020). The high concentration of fluoride is a complex issue, considering that the DGA did not monitor this parameter during the investigated period in the AP. Therefore, fluoride levels may also be high in other water sources in the AP, emphasizing the need to improve the water quality monitoring network. Photographs of the Quillagua, Toconao, and Chusmiza treatment plants can be found in the Supplementary Information.

The Río Loa basin (021) has nine APR systems, which supply water to an estimated population of 5528 people. Flor del Alfalfa and Chunchuri systems do not require treatment since they are connected to the sanitary company network (Aguas Antofagasta), according to Article 52° bis of the General Law of Sanitary Services (Gobierno de Chile, 1988).

Recently, the MOP announced important improvements and maintenance of APRs in six locations of the Antofagasta Region (DOH, 2020a). This includes Chunchuri, Quillagua, and Chiu-Chiu (021 basin). In Chunchuri, the maintenance work was finished and was mainly associated with the water distribution system. In Quillagua, the main goal was to install a remineralization system for the treatment plant. This plant is from 2016 and includes reverse osmosis and ionic exchange technologies (Table S4). This system supplies water for approximately 110 families. In Chiu-Chiu, a new design project will be developed given the population growth. The new and definitive design project aims to achieve independence from the Lasana system, since it is currently a shared system between both towns (Table S4), using Linzor as a water source, which is a property of Codelco (Chilean mining company) (DOH, 2020a). According to the regional DOH, in Ayquina, there are issues with land property, which makes public investment difficult.

Three out of the four currently active APR systems in the Salar de Atacama basin (025) have reverse osmosis or ionic exchange treatment (Table S4). This is because arsenic concentrations in the corresponding sources exceed the NCh409 limit. In fact, most surface waters in this basin are not safe for human consumption due to high levels of arsenic (Queirolo et al., 2000; Risacher et al., 1999). Socaire uses Vertiente Nacimiento, which has poor water quality (CNR, 2017), resulting in an arsenic concentration of 0.168 mg/L (according to the last report of regional DOH). Toconao uses Vertiente Silapeti and Vertiente Vilaco, which present 0.056 mg As/L and 0.206 mg As/L, respectively, according to the last report of regional DOH. Additionally, although San Pedro de Atacama uses groundwater as a source, the arsenic concentration in the water source and in drinking water exceeded NCh409, which was 0.011 mg/L according to the last report of regional DOH. Notably, arsenic concentrations exceeding NCh409 have been previously reported in tap water from San Pedro de Atacama, Toconao, and Socaire (0.6 mg/L (Martínez et al., 2004), 0.02 mg/L (Martínez et al., 2004), and 0.28 mg/L (Diaz et al., 2015), respectively). The only APR system with an excellent water quality source (Vertiente Chaquisoque, which complies with NCh409 according to the last report of regional DOH) is Peine, which explains the absence of treatment (Table S4).

The San Pedro de Atacama APR supplies drinking water to this town and to a large part of the *ayllus* in the area (Figure S5) (DGA, 2016b). According to Molina (2019), the drinking water supply in

San Pedro de Atacama is in crisis due to the increase in the local population and number of tourists. It is also important to note that some villages, such as Machuca, Río Grande and Talabre, do not currently have a drinking water supply. Nevertheless, for the Río Grande system, built by the San Pedro de Atacama Municipality, the APR organization, and the regional DOH (Antofagasta) are currently working together to start operating the treatment plant so the community can use the system. In addition, this regional DOH is also working with the Talabre committee, which was incorporated into the APR program in 2020, with the goal of getting the treatment plant operational. This community is currently supplied with tank trucks. In addition, in the Region of Antofagasta, there are two rural systems that do not belong to the APR program since they were not built by the MOP: Camar and Machuca. They have been mentioned in DGA (2016b) and are currently registered in DOH as "Non-MOP APR." Camar uses Vertiente Pepina as a water source (DGA, 2016b).

Due to the intense precipitation events that occurred in the summer of 2019 ("invierno boliviano"), the arsenic removal system in the Toconao APR was damaged. Therefore, it had to cease operations, and drinking water had to be distributed by tank trucks. Raw water for domestic use is being supplied (Municipalidad San Pedro de Atacama, 2019). Despite this, the system has been reported to be active (Table S4). In addition, the Socaire APR stopped operating in 2019 due to the freezing of the water source and the potential sediment drag due to snow storms (Soy Calama, 2019). During part of that year, the community was supplied by tank trucks.

The MOP announcement for improving APR systems in the Region of Antofagasta also includes Socaire, Peine and Toconao (DOH, 2020a). For these systems, a public call for tender was opened in May 2020.

Information on APRs was difficult to obtain, inconsistent, and incomplete. For several systems, the water source name was not identified. Table S21 presents the APR systems in the 012 and 013 basins with no information on the water source. The results of the last water quality analyses were provided for only a few systems, although the APRs must monitor the drinking water quality to ensure compliance with the NCh409. According to Donoso et al. (2015), between 2013 and 2015, 84.2% of the total APRs at a national level monitored the bacteriological quality of the supplied drinking water; however, no information was available for the total of the systems in the Arica y Parinacota (24) and Antofagasta (10) Regions, while 95% of the total of systems in the Taparaca Region (20) did not perform this analysis.

Several issues affect the APR program, with a lack of management capacity being one of them (Fuster & Donoso, 2018). According to Blanco and Donoso (2016), several elements that could support an appropriate management of the APRs would be defined in the recently approved Regulation. The operation of treatment systems with high maintenance requirements is a key factor affecting the continuity of the systems in the AP basins. In this context, the poor water quality in certain areas creates pressures on the treatment systems, increases maintenance requirements and reduces the lifespan of the systems. For example, in the Quillagua APR, the water source is very high in arsenic, total dissolved solids and boron, reaching values of 0.45 mg/L, ~ 9000, and 30 mg/L, respectively (E. Cisternas, personal communication, July 30, 2020). The flow rate treated in this APR is 5 m^3/h, and these pollutants are removed by filtration processes and reverse osmosis complemented with reverse ion exchange units. This APR system requires more complex maintenance processes, requiring personnel with technical training (E. Cisternas, personal communication, July 30, 2020). Other APR systems, such as the APR located in Toconao (Table S4), require less complex treatment processes, with simple operating conditions and arsenic concentrations of 0.1 mg/L in the inflow and a treatment flow rate of 12 m^3/h. In this case, the implemented treatment plant is quite simple and was designed according to the better quality of the inflow, and it is an ideal treatment process for extreme areas without trained technical personnel (E. Cisternas, personal communication, July 30, 2020).

Special attention must be paid to the elevated levels of boron in drinking water sources, which can have a significant impact on human health. Since boron has shown various toxicities but also beneficial effects, the toxicity of boron still remains controversial (Xu et al., 2020). For example, exposure to 30 g of boric acid over short time periods can affect the kidney, liver, stomach, intestines and brain, eventually leading to death (ATSDR, 2012). On the other hand, boron is an essential trace element for plants and humans (Cortes et al., 2011), facilitating improvements in wound healing, osteoporosis and brain function (Khaliq et al., 2018). Boron is not included in NCh409, although the WHO recommends a maximum limit of 2.4 mg/L (World Health Organization, 2017). Recently, the revised EU Directive 2020/2184 set a parametric value of 1.5 mg/L, which increases to 2.4 mg/L where desalinated water is the main source or where geological conditions could cause elevated levels of boron in groundwater (Dettori et al., 2022). In South America, for example, this parameter is included in the drinking water standards of Uruguay (0.5 mg B/L, Administración de las Obras Sanitarias del Estado (2006)) and Peru (1.5 mg B/L, Ministerio de Salud (2011). Most APR systems in the AP basins do not remove boron; therefore, the inhabitants are constantly exposed to this pollutant. This also applies to the inhabitants of the urban sectors of the basins (the "Urban sector" section) since conventional water treatment systems do not remove boron (Tagliabue et al., 2014).

Wastewater

Urban sector According to SISS, Chilean sewerage coverage reached 97.1% in 2018. Wastewater treatment coverage corresponds to 99.98% of the population having sewerage. It must be noted that marine outfalls are included in the wastewater treatment coverage, with 11% of the 299 wastewater treatment systems operating in Chile up to December 2018 (SISS, 2018).

As shown in Table 4, there are few wastewater treatment plants (WWTP) in the urban sector of the AP basins. Wastewater generated in the city of Arica, in the Río San José basin (013), is discharged by a marine outfall; therefore, it was not included since it only provides primary treatment. It is important to highlight that all the wastewater generated in the Tarapacá Region (WWTP-01 to WWTP-04) is directly reused for irrigation purposes.

Rural sector

The current situation of rural sanitation at the national level is deficient, since only 9.45% of the APRs have a wastewater treatment system (Fuster & Donoso, 2018). With Law n° 20,998 fully in place, the SSR will be involved in sewerage and wastewater treatment in rural areas. According to their records up to December 2018 obtained via the Transparency Law, a few APR systems

Table 4 Description of WWTP in the AP basins. Information presented in this table was provided by SISS

ID	Basin	Company	Name	Treatment type	Design parameters					Receptor	Corresponding regulation
					Maximum daily flow (m^3/day)	DBO5 loading (kg/day)	TSS loading (kg/day)	TKN loading (kg/day)	TP loading (kg/day)		
WWTP-01	017	Aguas del Altiplano S.A	PTAS-Pozo Almonte	Aereated lagoon	1642	410.4	295.49	98.5	13.13	Irrigation	Irrigation
WWTP-02	017	Aguas del Altiplano S.A	PTAS-Huara	Aereated lagoon	388.8	75	73.5	20.25	3	Irrigation	Irrigation
WWTP-03	017	Aguas del Altiplano S.A	PTAS-La Tirana	Aereated lagoon	2108.16	1354	1326.92	365.58	54.16	Irrigation	Irrigation
WWTP-04	017	Aguas del Altiplano S.A	PTAS-Pica	Aereated lagoon	1296	324	233.28	77.76	14.26	Irrigation	Irrigation
WWTP-05	021	Tratacal S.A	PTAS-Calama	Activated sludge	31,845	8,497	6,798	1,699	340	River, no dilution	DS 90

have full connections to sewerage. They are San Miguel de Azapa, Belén, Chapiquiña, Putre, Socoroma, Tignamar, and Huaviña. Mamiña has 64% connectivity to sewerage. All these systems also have wastewater treatment, except for Huaviña. Information on treatment types and related parameters is still incomplete and being systematized by MOP, which is why it was not possible to obtain access to it. To improve the efficiency and sustainability of public investment, technologies able to provide solutions for drinking water supply and wastewater collection and treatment for the rural sector have been proposed and evaluated (SUBDERE, 2018). With the new attributions of the SSR regarding rural sanitation, it is expected that these or other solutions will be implemented in the long term.

Conclusions

The natural characteristics of the AP determine the poor quality of the water originated, which moves downstream by natural recharge and contributing surface streams. As such, the AP affects the quality of water resources in and beyond this area, limiting their usage throughout the Chilean AP basins, including valleys and settlements toward the coast.

There is insufficient information to fully assess the water quality of the Chilean AP and thus the need for treatment systems or other required actions such as conservation strategies in the case of protected ecosystems. Although available measurements at DGA stations only allowed the evaluation of some pollutants included in the drinking water and/or irrigation standards, efforts are being made by DGA to include relevant water quality parameters. Additionally, it is important to consider the difficulty of obtaining access to the monitoring stations due to the altitude and irregular terrain of the AP, which is a limitation for expanding the monitoring network.

Arsenic and boron are the most critical pollutants. Arsenic is well recognized for its high toxicity and generally exceeded NCh409 (drinking water standard), as at 75% of the DGA stations, all measurements were above 0.01 mg/L. Boron generally exceeded NCh1333 (irrigation standard), as at 81.3% of the DGA stations, more than 54% of the reported measurements were above 0.75 mg/L. Throughout the AP basins, the high levels of boron limit crop yield and diversification of cultures, and they may also have adverse effects on human health.

Even though several drinking water supply systems exist in the AP basins, in rural locations the drinking water supply is inadequate due to the lack of required treatment and continuity of service. Initial investment in drinking water treatment plants is insufficient given the reported operation issues. Rural drinking water treatment plants must be self-standing systems capable of operating with minimum operator intervention. This is even more critical when considering the required advanced treatment, the extreme climatic conditions, and the negative effects of "invierno boliviano." Additionally, the lack of frequent water quality monitoring in water supplied by APR systems impedes verification of the compliance of NCh409, threatening the health of the inhabitants. The absence of sanitation and wastewater treatment is also a health threat, and a diffuse pollution source that may affect the APR groundwater sources. Wastewater treatment and reuse can provide a source for irrigation and other domestic uses. Like the case of drinking water treatment systems, conventional wastewater treatment systems are often abandoned in rural communities. To avoid this, treatment solutions according to the local conditions, e.g., with minimum operation and maintenance requirements, must be considered and evaluated prior to their implementation.

Public policies prioritizing safe water for rural communities that rely on this resource for their subsistence and the protection of the AP unique ecosystems must be implemented. Since the drinking water demand is relatively small compared to other consumptive water uses, the provision of safe water for domestic use must be the first one to be ensured. Ambient water quality guidelines or similar instruments must be put in place to protect aquatic ecosystems, not only in the AP but throughout the country.

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Data availability All data analyzed in this study are included in this published article and its supplementary information files.

Declarations

Competing interests The authors declare no competing interests.

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