

# Chapter 3

## Water Quality: Trends and Challenges



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**Abstract** The complex dynamics of the interactions between natural factors (geology, hydrology, biogeochemistry) and human factors (mining, agriculture, urban space, infrastructure) underlie a diverse range of challenges related to water quality throughout Chile. Water quality in Northern Chile is characterized by high local concentrations of dissolved salts, metals, and metalloids in surface and groundwater. Salts and metals show decreasing concentrations towards Central Chile due to higher water discharge; yet still local enrichments are observed in some tributaries (notably copper). Reservoirs and lakes in Central Chile show mesotrophic and eutrophic conditions with chronic episodes of algal blooms and fish kills from the high influx of nutrients linked mainly to diffuse pollution from agriculture and urban wastewater discharges without tertiary treatment. Water quality in Southern Chile is characterized in general by low dissolved salts concentrations and oligotrophic to oligo-mesotrophic conditions, with local exceptions in streams and bodies of water that receive industrial and treated urban wastewater discharges or that are used for fish farming. Several challenges to water policy arise when considering water quality issues: (i) integrated management approach to water quality; (ii) a more comprehensive and dense monitoring network; (iii) protection and improvement of the trophic state of Chilean lakes and reservoirs; (iv) promote the use of more sustainable treatment alternatives like enhanced natural attenuation and constructed wetlands.

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## 3.1 Introduction

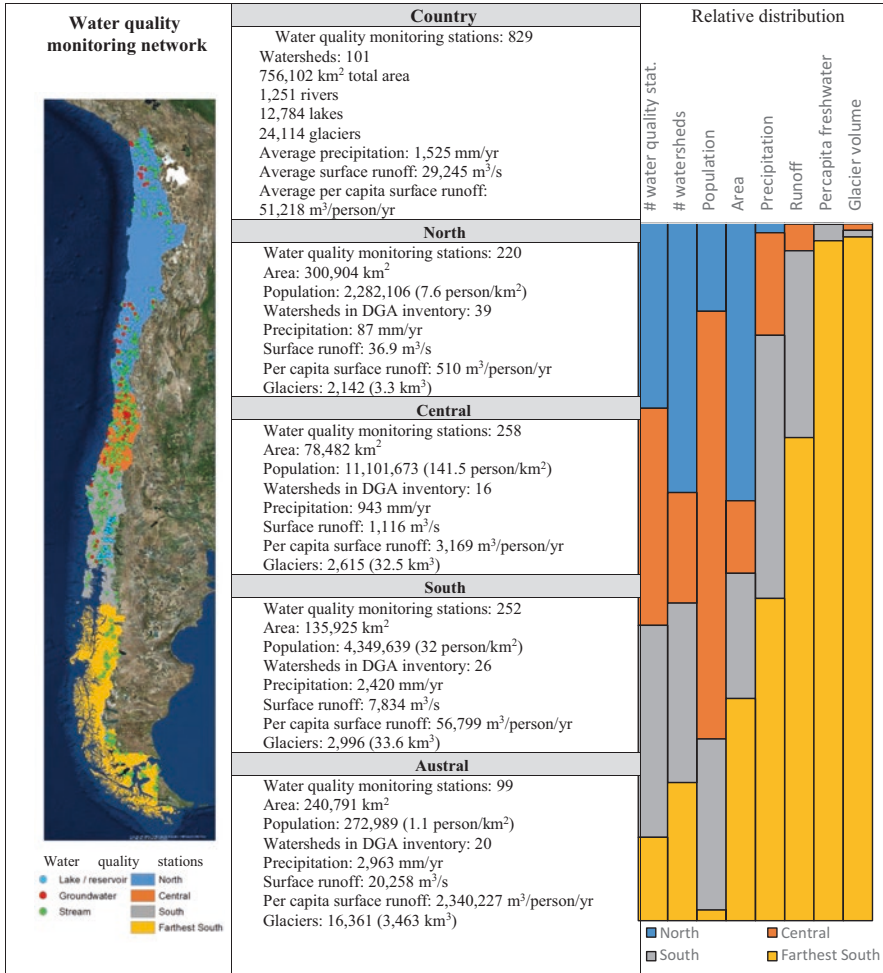
Water quality is assessed by a set of physicochemical and biological characteristics of water in relation to an intended use, such as human consumption, irrigation, supporting natural ecosystems, and recreation. Water quality parameters are controlled by the complex interaction of natural and human factors across the territory, which, in the case of Chile, reflects a wide variety of hydrological and geochemical settings interacting with a range of socioeconomic activities, notably mining, agriculture, aquaculture, forestry, hydroelectricity, urban soil use, and the operation of urban sanitary infrastructure. These activities thrive on sufficient and safe water, yet they also impact water quantity and quality, shaping a formidable challenge for water policy, particularly for the sustainable use of water resources and the protection of ecosystems.

Much has been advanced in characterizing and understanding water quality in Chile, notably since the early work by Klohn (1972) that presents a first description of water quality in Northern Chile up to the recent atlas published by the Chilean water agency—DGA (Dirección General de Aguas 2016) that provides an overview based on the DGA's national monitoring network. Despite considerable advances in water quality monitoring and a growing number of works revealing how geochemical and hydrologic processes control water quality, advances in decision and public policy making are still hampered by insufficient data and integrated processes understanding. To that extent, this chapter aims to: (i) provide a synopsis of key parameters determining the quality of continental waters (i.e., surface and groundwater) across different Chilean regions using datasets from the government and scientific studies; (ii) discuss case studies that portray the complex interaction between natural and anthropogenic factors controlling water quality; and (iii) summarize the trends and challenges in water quality for Chilean water policy, with emphasis in areas of mineral enrichment and aridity, urban areas, and pristine environments.

## 3.2 Water Quality Across Chilean Regions

### 3.2.1 *The Water Quality Monitoring Network in the Context of the Chilean Hydrography, Hydrology, and Geochemistry*

A striking characteristic of the Chilean hydrography and hydrology is the variety of climatic conditions ranging from those of the hyper arid Atacama Desert in Northern Chile to those of the rainy cool oceanic climate. The DGA inventory includes 101 watersheds with 1,251 rivers, 12,784 lakes, and 24,114 glaciers (Dirección General de Aguas 2016). Chilean water resources may be divided for descriptive purposes in four regions according to its hydrographic and hydrologic traits: North, Center,



**Fig. 3.1** Water quality monitoring stations and Chilean continental waters at a glance (Authors elaboration based Dirección General de Aguas (2016))

South, and Austral. The DGA monitoring network for water quality includes 829 stations, for streams, for groundwater, and for lakes and reservoirs. For each site, 1–12 samples per year are taken, depending on operational definitions and constraints (typically 3 for streams and groundwater and 2 for lakes and reservoirs). Figure 3.1 shows the distribution of water quality monitoring stations at the national level and for each region, including some basic statistics for each region. In 2014, about 39% of the 101 watersheds in the DGA inventory were not actively monitored, 19% had only 1 water quality monitoring station, and only 19% had 10 or more water quality monitoring stations (Dirección General de Aguas 2014).

The distribution of monitoring stations concentrates on areas of water scarcity, higher population density, and areas of human activity. Its distribution in surface water streams aims to depict water quality upstream and downstream from potential anthropogenic “pressures” (activities that may impact water quality), thus it could

**Table 3.1** Parameters measured in surface waters by the national water quality monitoring network operated by the DGA. The parameters measured in the laboratory include their detection limit as of 2014

Parameters measured in the field			
Temperature, pH, electrical conductivity, and dissolved oxygen (O <sub>2</sub> )			
Parameters measured in the laboratory			
Analyte	Detection limit (mg/L)	Analyte	Detection limit (mg/L)
Ag	0.01	K	0.2
Al	0.3	Mn	0.02
As	0.001	Mg	0.1
B	1.0	N	0.01
Ca	0.4	Na	0.2 at 589 (nm); 12.0 at 330 (nm)
Cd	0.01	Mo	0.05
Cl <sup>-</sup>	1.0	Ni	0.02
Co	0.01	Pb	0.05
COD	1 (lakes); 3.0 (other types)	PO <sub>4</sub> <sup>3-</sup>	0.012 (lakes); 0.003 (other types)
Cr	0.01	Se	0.001
Cu	0.02	SO <sub>4</sub> <sup>2-</sup>	3.0
Fe	0.02	Zn	0.01
Hg	0.001		

Source: Dirección General de Aguas (2014)

help contrast a “natural state” and a possible impacted condition. Nevertheless, in many Andean watersheds it is difficult to establish a “natural state”, since a high natural enrichment may occur and human interventions may be located in the upper sections, especially for metals and dissolved salts in mining areas in Northern and Central Chile. In such cases, careful geochemical studies involving the analysis of geochemical tracers and models are needed to discriminate between the natural background and human pollution.

Table 3.1 shows the parameters considered in the national water quality monitoring network for streams and groundwater. It includes parameters that are measured in the field (temperature, pH, electrical conductivity, and dissolved oxygen) and those measured in the DGA laboratory (ISO17025 accredited): a wide range of metals, anions, nutrients (nitrogen, phosphate), and one aggregate organic parameter (chemical oxygen demand, COD). Table 3.1 also shows the detection limits in place in 2014 for those parameters measured in the DGA laboratory (Dirección General de Aguas 2014). Depending on the intended water use, this list of parameters may be insufficient for assessing the water quality of streams and groundwater. In some cases, the detection limit of the measurement may be larger than the value against it will be compared to.

The DGA monitoring network is not the only source that reports measurements of water quality parameters. Other sources of water quality information include:

- (a) *Secondary water quality standards surveillance plans*: just recently, several watersheds and lentic waters have in place secondary water quality standards (known as NSCA by its Spanish acronym). This framework includes a surveillance plan for a predefined set of parameters, locations and monitoring fre-

quency. The current secondary standards in place are for the following watersheds: Serrano, Maipo, Biobío, and Valdivia, and for the Villarrica and Llanquihue lakes. For the following watersheds, secondary water quality standards are being prepared<sup>1</sup>: Aconcagua, Mataquito, Elqui, Rapel, and Huasco.

- (b) *Environmental impact assessment platform*: the Chilean law 19.300 Bases for the Environment enacts the Environmental Impact Assessment System (known as SEIA by its Spanish acronym) which requires that a range of new investment projects or modifications conduct an environmental impact assessment. When activities entering the SEIA have the potential to impact water, they are required to consider a water quality baseline and a water quality surveillance program. Such information is available through the SEIA and the Superintendence of the Environment (known as SMA by its Spanish acronym) platforms.
- (c) *Superintendence of Sanitary Services (known as SISS by its Spanish acronym)*: all water companies that provide drinking water and wastewater treatment according to the Chilean concession system are required to comply with drinking water and treated wastewater discharge standards. Although not available through a web platform, specific data may be requested via the transparency law that compels the public service agencies to respond to public data requests.

Despite the high costs of not having a complete water quality monitoring network, Chile still does not have an integrative water quality clearinghouse that takes advantage of different monitoring programs from miscellaneous data sources. Furthermore, the approach to water quality is mostly statistical, without systematically supporting conceptual and quantitative models helping to frame data interpretation. An improved approach for water quality monitoring and data management should be coherent with an integrated watershed management approach.

### 3.2.2 *Water Quality Trends for Streams, Groundwater and Lakes in Selected Watersheds*

The DGA water quality database contains more than 50 years of water quality measurements across the country and over 1 million reported values for 63 watersheds (out of 101). Here, we provide a broad overview of the spatial trends for 21 selected watersheds and key water quality parameters for each type of water source (i.e. streams, groundwater and lakes). The selection of watersheds considered area, population, and/or geographic representativeness. For each monitoring station within the 21 selected watersheds, we discarded entries reported anomalously by the DGA and entries dated before 1980. We also discarded for each station data series the extreme outliers, defined as values lower than  $Q_1 - 3 * IQ$  or greater than  $Q_3 + 3 * IQ$ , where  $Q_i$  refers to the  $i^{\text{th}}$  quartile and the interquartile range  $IQ = Q_3 - Q_1$ . Only

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<sup>1</sup>Information retrieved from the Ministry of the Environment public expedient <http://planesynormas.mma.gob.cl> on 06/20/17.

sampling stations with 10 or more values were considered in the statistics. For lakes, a database previously distilled by DGA was used.

Figures 3.2, 3.3, and 3.4 show the water quality snapshot of key parameters for streams (pH, EC, COD, As, B,  $\text{NO}_3^-$ ), groundwater (pH, EC,  $\text{Cl}^-$ , As, B,  $\text{NO}_3^-$ ), and lakes (pH, EC, COD,  $\text{NO}_3^-$ , total P, chlorophyll a) throughout Chile, respectively. Boxplots were used to provide a graphical representation of the variability of each parameter within the watershed. It is important to emphasize that the aim of these figures is to render a broad view at the country level, and not to reveal specific site or temporal trends. A few studies have looked into the DGA database to study specific sites, processes and trends (e.g., Pizarro et al. 2010a, b).

### 3.2.2.1 Streams

Streams pH values fluctuate in general between 6.5 and 8.5 with two watersheds in Northern Chile showing remarkable low pH values: the Lluta River and the Elqui River watersheds, both related to tributaries seriously impacted by acid drainage (Galleguillos et al. 2008; Oyarzun et al. 2012; Leiva et al. 2014; Ribeiro et al. 2014; Guerra et al. 2016a, b; Abarca et al. 2017; Arce et al. 2017; Flores et al. 2017). The pH value<sup>2</sup> indicates how acidic (pH < 7) or alkaline (pH > 7) is the water. It is a central parameter that controls the bioavailability of nutrients and the toxicity and mobility of metals, impacting the extent of aquatic life and transport of contaminants.

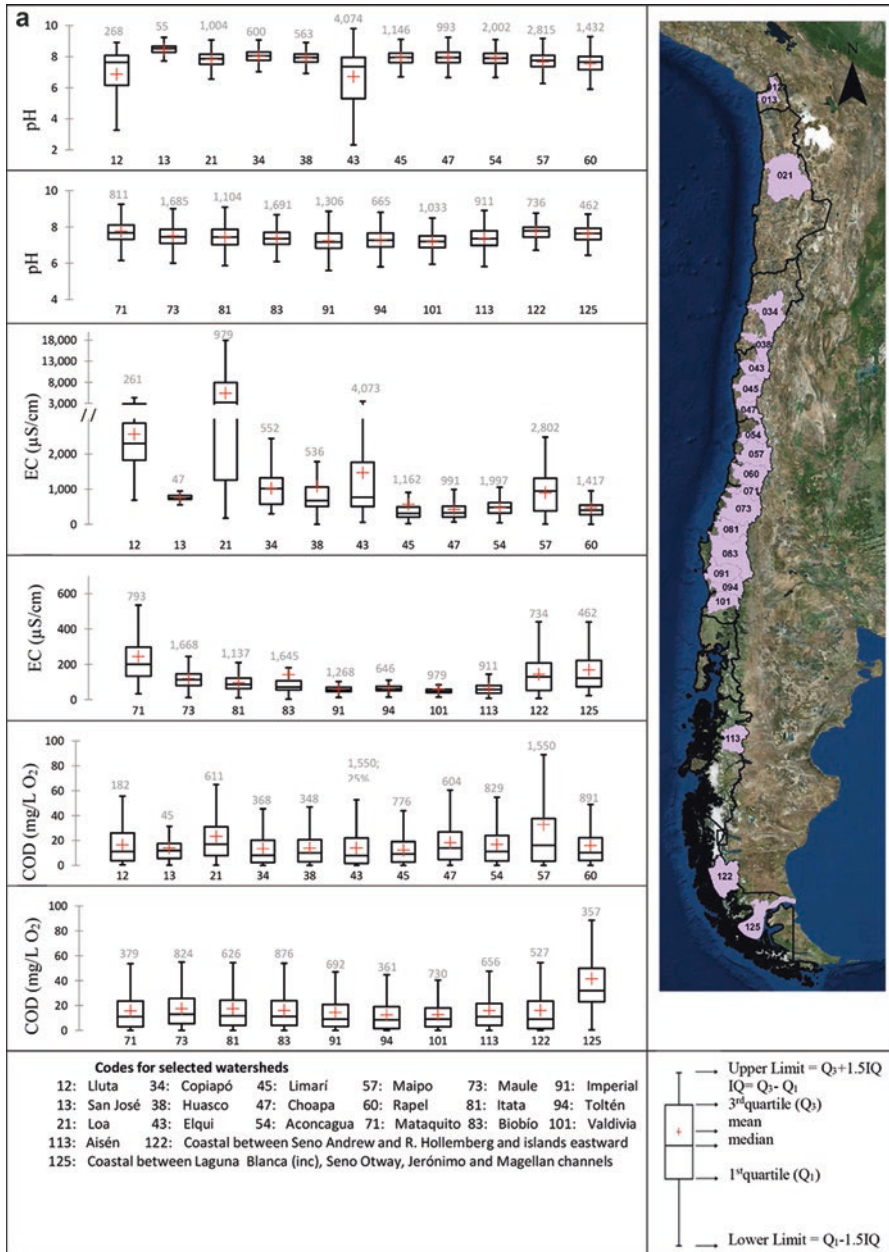
Electrical conductivity accounts for the dissolved salts concentrations. High EC may restrict water for irrigation purposes and as drinking water sources. Besides acid drainage, high EC may be linked to geothermal sources, exchanges with groundwater (i.e. return flows from irrigation), high evaporation and poor dilution in arid climates. Thus, high EC values are observed preferentially in watersheds in Northern Chile with extreme values above 15 mS/cm<sup>3</sup> (e.g., Loa River watershed) associated to geothermal springs. El Tatio geothermal field is a world attraction that contributes elevated dissolved salts and arsenic concentrations to the drainage network downstream via the Salado River (Bugueño et al. 2014). El Tatio geothermal field is not a case of acid drainage, as pH values of the springs are circumneutral to alkaline. Groundwater further contributes alkaline, saline and arsenic-rich waters to the lower Loa River watershed.

High boron concentrations are also observed in the Lluta and Loa watersheds (Fig. 3.2). Boron is a well-known phytotoxic. Thus, poor water quality due to boron enrichment may become a serious threat to agricultural development in the impacted watersheds.

Further south, local metal enrichment and saline conditions that become diluted downstream by favorable hydrological conditions may be found in the Aconcagua (Gaete et al. 2007), Maipo (Yerba Loca-Mapocho system (Segura et al. 2006; Montecinos et al. 2016; Pasten et al. 2015), Rapel (Pizarro et al. 2010b; Pizarro et al.

<sup>2</sup>pH is a logarithmic measure of the effective concentration of hydrogen ions (pH = - log {H+}).

<sup>3</sup>mS/cm = milliSiemens/centimeter = deciSiemens/meter = dS/m.



**Fig. 3.2** Overview of water quality in Chilean streams across 21 watersheds. Two scales are used to highlight different ranges across watersheds. (a) pH, electrical conductivity (EC), and chemical oxygen demand (COD), (b) Arsenic (As), boron (B), and nitrate ( $NO_3^-$ ) (Authors elaboration using raw data from DGA database)

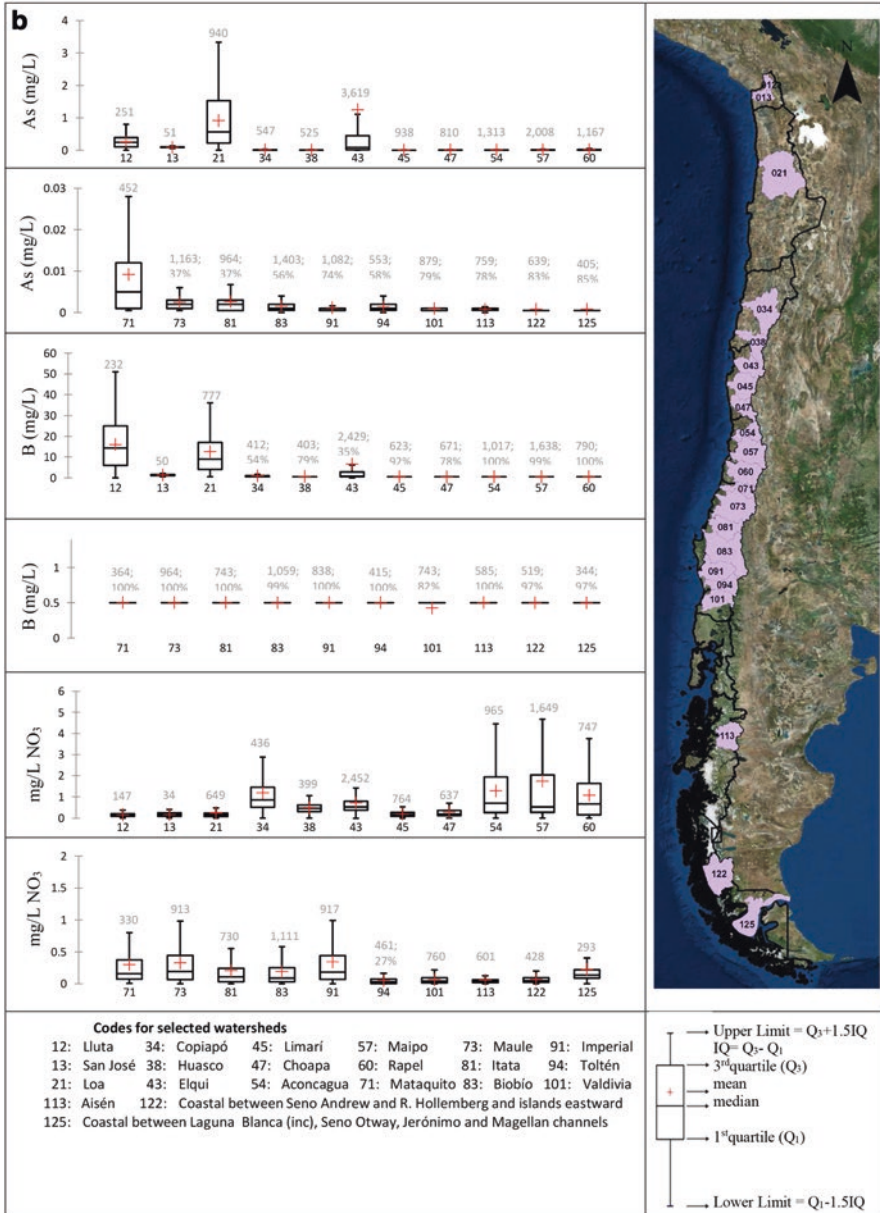
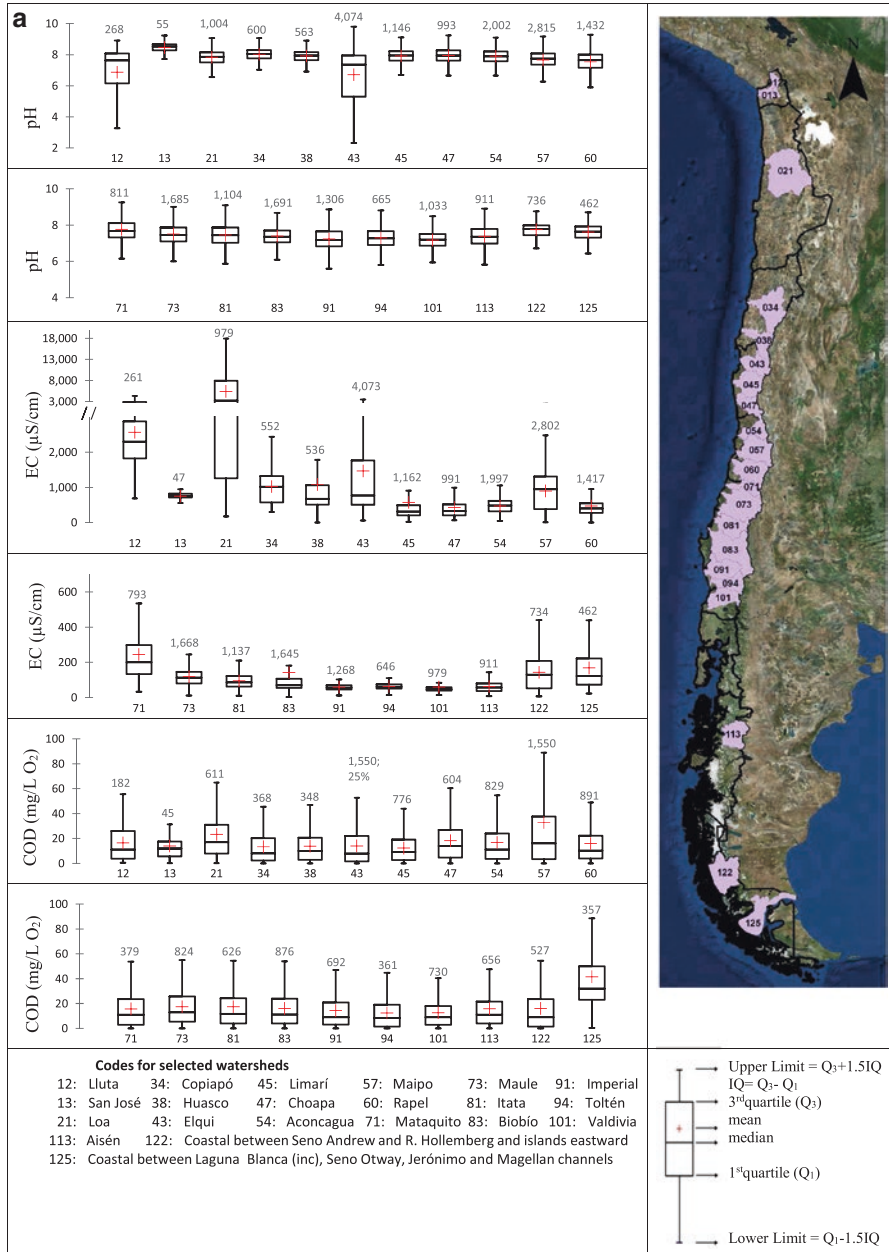


Fig. 3.2 (continued)





**Fig. 3.3** Overview of water quality in Chilean groundwater across 21 watersheds. Two scales are used to highlight different ranges across watersheds. **(a)** pH, electrical conductivity (EC), and chloride ( $Cl^-$ ), **(b)** Arsenic (As), boron (B), and nitrate ( $NO_3^-$ ) (Authors elaboration using raw data from DGA database)

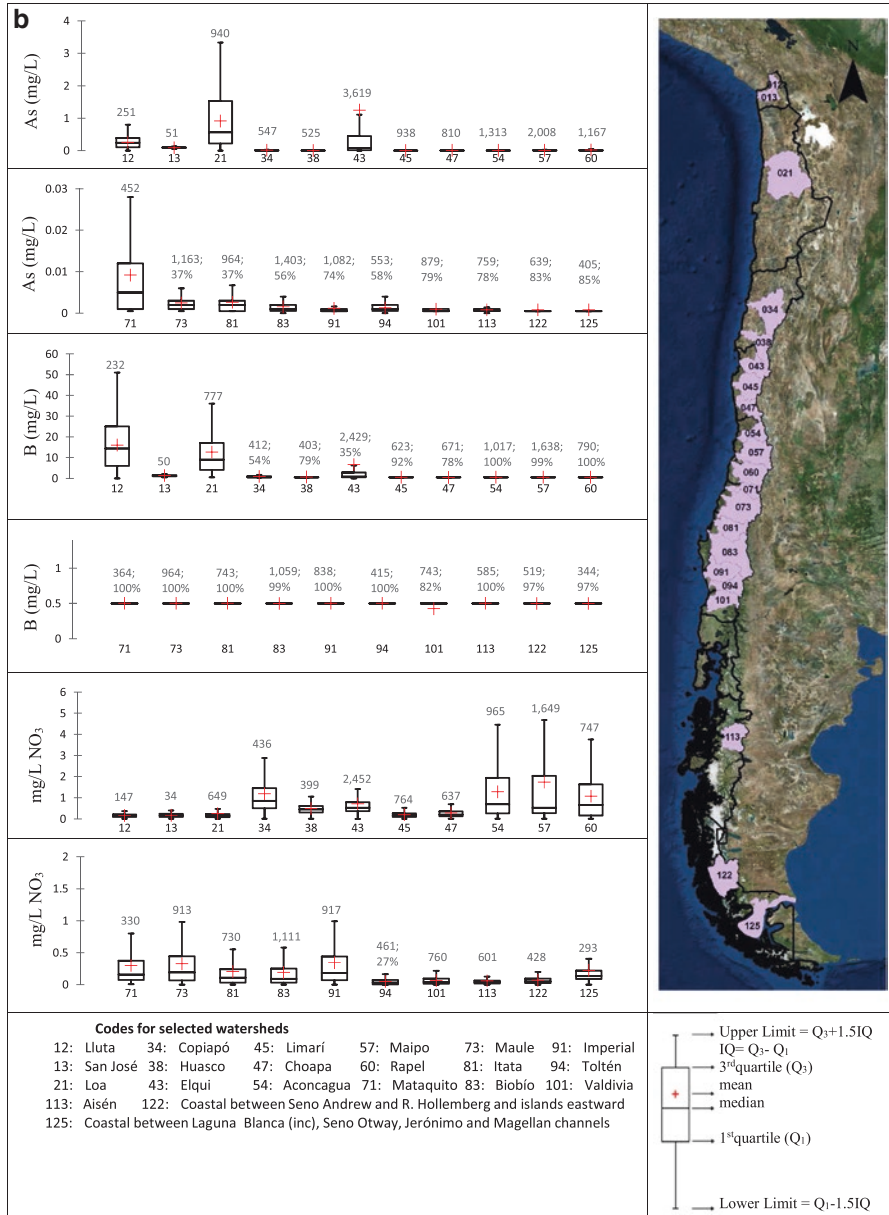
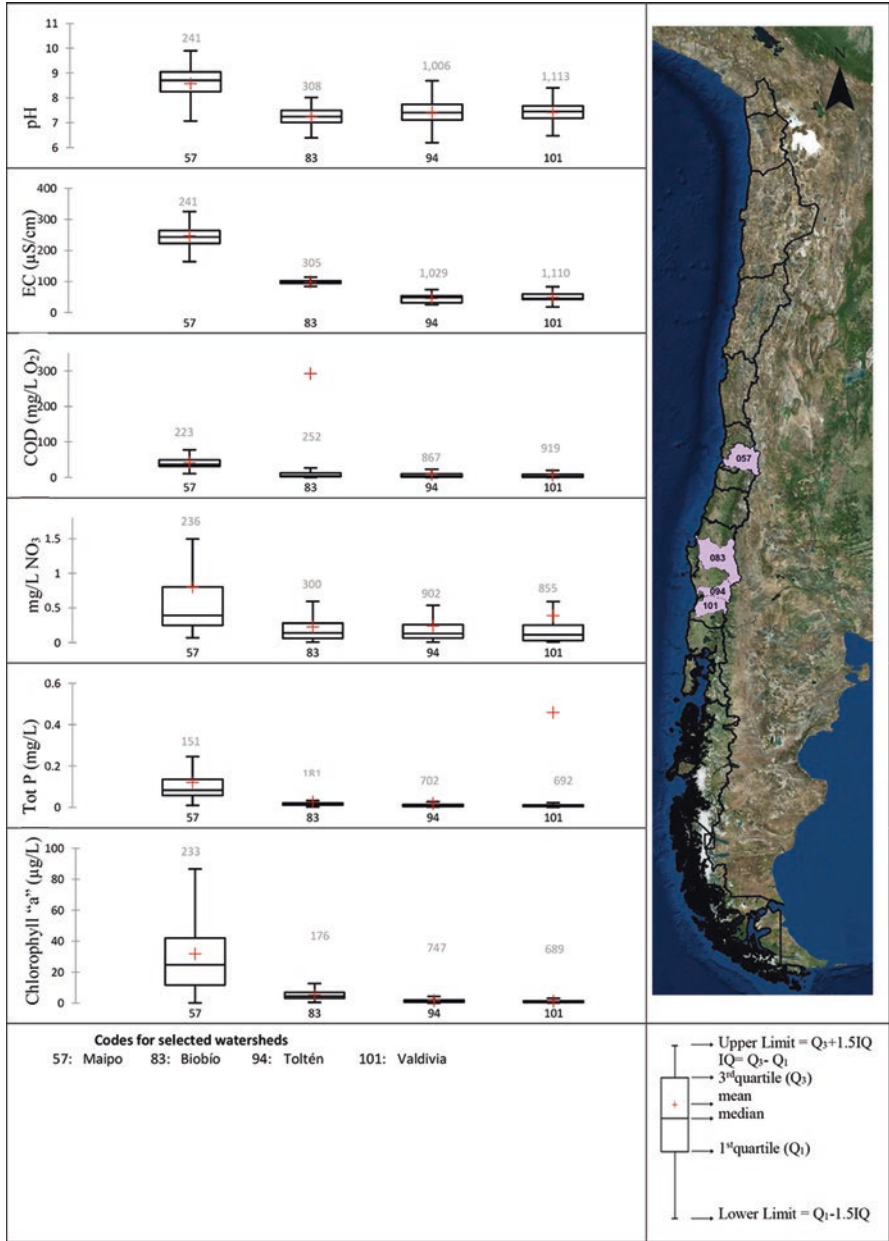


Fig. 3.3 (continued)



**Fig. 3.4** Overview of water quality in Chilean lakes across 4 watersheds. Two scales are used to highlight different ranges across watersheds. (Authors elaboration using processed data from DGA)

2003), and Mataquito watersheds (Tapia et al. 2009). Despite these, watersheds in Central Chile show lower metal concentrations and salinities compared to those in Northern Chile. However, the concentrations are still quite high and pose a serious challenge to drinking water production and to irrigation. Furthermore, it is expected that the biggest mining developments in Chile will occur in Central Chile, thus understanding and monitoring metal enriched systems in this area is a high priority.

Nitrate enrichment in surface waters is observed in three Northern Chile watersheds (Copiapó, Huasco, Elqui) but the highest concentrations are observed in three Central Chile watersheds (Aconcagua, Maipo and Rapel). Although in a lower range, five watersheds in Southern Chile (Mataquito, Maule, Itata, Biobío, and Imperial) show some nitrate enrichment when compared to other watersheds further south (Toltén, Valdivia, Aisén and the coastal watersheds in the Farthest South region). Nitrate enrichment is generally associated to diffuse pollution from agricultural practices, a relationship that has been demonstrated in Chile (Ribbe et al. 2008).

With respect to COD, the highest values are found in two watersheds (Maipo and the Southernmost coastal area) with two different origins. The first is associated to the urban environment (likely raw and treated wastewater discharges during the considered timeframe) and the second is likely associated to livestock production (mainly bovine). Since COD quantifies the concentration of oxygen required to oxidize organic matter, COD indicates the presence of substances that will lead to consumption or even depletion of dissolved oxygen, such as those present in human and animal waste.

*The Lluta River Watershed: A Model for the Interaction Between Natural and Anthropogenic Controls of Water Quality*

In the case of the Lluta river watershed, the Azufre River drains an area with legacy elemental sulfur mining that ceased operation in the 1960s and that did not consider a proper mine closure program. Common pH values in the Azufre River are around 2, which means that the concentration of  $H^+$  ions is 100.000 times that of neutral pH. Acid drainage that generates low pH values seriously impairs water uses like freshwater ecosystem services, drinking water sources and irrigation. It promotes highly reactive conditions that lead to the dissolution of geomaterials, increased dissolved heavy metals (notably arsenic), and with concurrent increased dissolved salts (notably sulfate). Pollutants from acid drainage are persistent and propagate through the drainage network. Natural attenuation processes mitigating dissolved toxic metal concentrations occur at river confluences receiving acid drainage (Guerra et al. 2016a; Abarca et al. 2017; Arce et al. 2017) and in wetlands where bacteria favor the immobilization of arsenic (e.g., Leiva et al. 2014). Shifts in metal speciation (the chemical form of a metal, for example dissolved vs particulate chemical species) are key to understand the toxicity and mobility of metals. In the case of the Lluta River, the performance of water infrastructure strongly depends on water quality (e.g., Rios et al. 2011).

(continued)

The Colpitas River in the Lluta watershed also shows high salinities associated to the Colpitas geothermal springs (known as “borateras” due to their high boron content) (Ramila et al. 2015). The high boron concentrations in the Lluta watershed have a strong negative effect on agriculture as it is a well-known phytotoxic and it restricts agriculture to salts and boron tolerant species like corn. A striking contrast may be observed when comparing to the neighbor San José watershed, where water rights and property value are about four times those in the Lluta River watershed.

The dependence of water quality from hydrological conditions in Andean watersheds seriously challenges water quality monitoring strategies as intra daily variations induced by snow melt can trigger dramatic changes in metal concentrations (Guerra et al. 2016b). The Chironta reservoir currently considered for irrigation and flooding control in the Lluta River valley will be a natural settling basin for arsenic rich particles and it will likely become an arsenic repository if preventive measures are not considered in its design and operation. The accumulation of metal rich sediments in reservoirs and lakes occurs in other metal-impacted watersheds like the Elqui River watershed (Galleguillos et al. 2008).

### 3.2.2.2 Groundwater

The variations of pH values in groundwater show a narrower and more uniform range throughout the country, even in watersheds impacted by acid drainage (Fig. 3.3). This is likely due to the buffering effect by the porous material in contact with groundwater. Watersheds in Northern Chile exhibit lower pH and broader ranges likely due to lower alkalinity and buffering capacity.

Electrical conductivity follows in general the trend of EC in surface waters, which is also shown in the chloride concentrations. Watersheds with high evaporation and agricultural practices exhibit the highest conductivities (e.g. Lluta, San José, Loa, Copiapó, Huasco). South from the Elqui River, EC is notably lower, with higher values in the Elqui, Limarí, Choapa and Maipo watersheds.

Nitrate and dissolved salts in groundwater may arise from a combination of natural geological formations in Northern Chile, while in Central and Southern Chile this may be associated locally with urban pollution and more broadly with agricultural practices (e.g., Fernandez et al. 2017; Yevenes et al. 2016; Fuentes et al. 2014; Arumi et al. 2005; Donoso et al. 1999).

### 3.2.2.3 Lakes and Reservoirs

Two issues have become important for Chilean lakes and reservoirs: eutrophication and metal enrichment in sediments. While the limited lake monitoring network focusses on assessing the trophic state through the measurement of nitrogen forms,

phosphorus and chlorophyll a in the water column, it does not include systematic measurements of sediments. As shown in Fig. 3.4, nutrients and chlorophyll “a” levels are notably higher in Central Chile -Rapel reservoir and Aculeo Lake-, reflecting the trophic state of these water bodies as detailed in the following section.

### **Eutrophication**

Eutrophication refers to the enrichment of an ecosystem with nutrients, typically nitrogen or phosphorous compounds. This phenomenon may occur naturally, but it is often enhanced by anthropogenic activities due to point and nonpoint pollution sources. Point sources include municipal and industrial wastewater discharges, whereas nonpoint sources include agricultural and urban runoff. Since nonpoint sources are diffuse and much more difficult to monitor and regulate, appropriate control of this phenomenon is a challenge. The relative contribution of point and nonpoint pollution sources varies substantially, depending on land use and local human population densities (Smith et al. 1999). The main consequence of the elevated nutrient levels is the occurrence of algal blooms, a rapid increase of the population of phytoplankton algae in a water body. Main effects of the excessive presence of algae include aesthetic effects and limited sunlight availability required for photosynthetic organisms, due to the increase in turbidity in the water column.

Eutrophication is one of the main water quality threats in the world and Chile is not an exception. Lakes and reservoirs throughout the country have been classified according to their trophic state using the definition of Smith et al. (1999). The definition of the trophic state of lakes is based on total nitrogen (TN), total phosphorus (TP), chlorophyll a, and Secchi disk transparency. Waters having poor nutrient supplies are defined as oligotrophic, whereas those having relatively large nutrient supplies are defined as eutrophic. Waters having intermediate levels are defined as mesotrophic. Some examples of Chilean lakes and reservoirs having different trophic states are El Yeso reservoir (oligotrophic), the Aculeo Lake (mesotrophic), the Peñuelas reservoir (hyper-eutrophic) and the Rapel reservoir (mesoeutrophic) (Ministerio de Obras Públicas 2014). The Rapel reservoir is known for its algal blooms, and the link between the operation of the hydropower plant and the water quality of the reservoir has been recently studied (Guzmán 2013; Ibarra et al. 2015; Rossel and de la Fuente 2015; Carpentier et al. 2017). These studies showed that the inclusion of environmental constraints in the operation of the hydropower plant such as the definition of minimum instream flow or maximum ramping rate of the turbine outflow, reduces both hydrological and thermal alteration of the river downstream. However, these environmental constraints also strengthen stratification, which may produce anoxic conditions thus aggravating water quality issues.

### **Metals in Sediments**

The chemical composition of sediments has not been traditionally measured in monitoring campaigns as part of water quality assessments. Nevertheless, sediments play an important role in controlling the contaminant fluxes in waters. Ample evidence is available showing the enrichment of lakes and reservoirs with metals in Andean watersheds (Contreras et al. 2015; Galleguillos et al. 2008; Pizarro et al. 2009; Pizarro et al. 2006). Furthermore, the analysis of sediment cores may provide

a historic registry of the metal dynamics in lakes and reservoirs. This is a central issue for reservoirs with metal enrichment as interactions between the metal and nutrient cycles may be observed. Events causing anoxic conditions may mobilize metals from oxidized sediments to the solid phase, notably by the microbial reduction of manganese and iron oxides.

### **3.3 Water Quality Challenges with Implications to Water Policy**

#### ***3.3.1 Integration of Water Quality Monitoring with Conceptual and Quantitative Models for Decision Making and Public Policy: Addressing Water Quality Conflicts in a Context of Climate Change***

Water quality is at the center of water conflicts and sustainability agendas. Access to sanitation and safe and sufficient water is the obvious starting issue. However, the interdependencies of socio-environmental systems also prompts the need for public policy and decision making in issues related to water quality and food, ecosystem services, natural patrimony, and environmental justice.

A prime example of this challenge is the collision between mining, agriculture and cities that compete for soil and water in Central Chile. The largest copper reserves, considered currently in the expansion programs of mining companies, are located in Central Andes, right on the upper section of the most populated watershed in the country (Maipo), the main sources of water for urban and agricultural use for the Metropolitan and Valparaíso regions. Insufficient knowledge of the long term dynamics of metals from natural sources and acid drainage sources, and the uncertain fate of the glaciers potentially impacted by mining in a context of global change, challenge the sustainability of mining development in Central Chile.

A major caveat of the current state of the art in managing water quality in Chile is the lack of an integrated approach that articulates water monitoring (quantity and quality) with working conceptual and quantitative models. An integrated understanding of the dynamics of the interactions between watersheds and human pressures could provide a robust science-based approach for public policy and decision-making in issues involving water quality. Figure 3.5 shows the location of key human pressures, including mining, industry, and urban effluents. Feedback between conceptual models, quantitative models, and monitoring would drive continuous improvement, where local communities, industries, government agencies, and research institutions should play a fundamental role, as it is suggested in Fig. 3.6. The development of secondary water quality standards for priority watersheds and lakes sets a perfect stage for assembling integrated quantitative and conceptual models with surveillance plans.



**Data sources:**

- a) Industrial and chemical sites from the registry of emissions and transfer of contaminants (Registro de Emisiones y Transferencia de Contaminantes, RETC);
- b) Mine tailings sites obtained from the Chilean Geology and Mining Agency database (Servicio Nacional de Geología y Minería, SERNAGEOMIN);
- c) Treated wastewater effluents were obtained from the Superintendencia de Servicios Sanitarios, SISS).

Fig. 3.5 Overview of key anthropogenic pressures for water quality





**Fig. 3.6** Towards a science-based approach for public policy and decision making in water quality. Feedback between conceptual models, quantitative models, and monitoring drives continuous improvement and feeds public policy and decision making. Private stakeholders, government agencies, and research institutions actively participate (Authors elaboration)

### 3.3.2 A more Comprehensive and Dense Monitoring Network

The approach proposed in Fig. 3.6 requires a strong monitoring network. Some important parameters and information should be systematically considered for future enhancements of the monitoring network, based on international practice and also on specific issues that are relevant for the Chilean case:

- (a) *Total alkalinity*: it is a general parameter that provides a measurement of the sensitivity of waters to acidification and it is measured by many water monitoring agencies in other countries (e.g., United States Geological Survey, USGS). The characteristic enrichment with metallic sulfides of the Andean geology in

Northern and Central Chile makes Chile's waters prone to acidification due to mixing with acid drainage. Although acid drainage may originate from natural sources, active and legacy-mining operations may strongly enhance its production. This threat to water quality is supported by ample evidence in Chile (Flores et al. 2017; Guerra et al. 2016a; Ribeiro et al. 2014; Oyarzun et al. 2012; Parra et al. 2011; Dold and Fontbote 2002).

- (b) *Chemical speciation and total vs. dissolved metals*: the mobility and toxicity of metals is controlled primarily by their chemical speciation. Dissolved metals (operationally defined as the fraction that passes a  $0.45 \mu\text{m}^4$  pore size membrane) are more mobile and toxic than particle-bound metals. Particle bound metals may settle and form contaminant repositories in reservoirs or become part of the fine river sediments depending on the kinetic turbulent energy available for their transport (e.g., Contreras et al. 2015; Tapia et al. 2014; Sepulveda et al. 2009; Pizarro et al. 2006). Furthermore, the reactivity of metals controls their potential impact on natural ecosystems: metals that are loosely bound to solids may be transferred to the dissolved phase, becoming more toxic and mobile. Metals that are loosely adsorbed to oxides or precipitated as carbonates may be released to the water when low pH or anoxic conditions prevail, while metals associated to silicates or forming crystalline sulfides are less likely to dissolve in the short term. Therefore, it is important to consider a systematic approach to metal speciation, starting from the distinction between total and dissolved metals (Guerra et al. 2016a; Abarca et al. 2017; Arce et al. 2017). Again, the Andean metal enrichment in Northern and Central Chile makes it relevant to start considering metal speciation to assess the trends in water quality and the processes that control it.
- (c) *Turbidity*: it is associated with suspended inorganics (e.g., clay, silt), organics (e.g., plant litter decomposition by-products) and organisms (e.g. algae, bacteria). This indicator is commonly used in many countries to evaluate the environmental health of water bodies (it is also a basic parameter measured by the USGS). Beyond giving a complementary measure of the suspended solids with respect to total suspended solids (TSS), turbidity is a key parameter for the quality of fish habitats; it is relevant for recreational uses of water; it helps reveal hydrological (e.g., erosion) and pollution processes (e.g., acid drainage, eutrophication); and it is important as a quality measurement for industrial and drinking water sources. Thus, turbidity is an easy-to-measure general water quality parameter that should be systematically measured within the surface water quality monitoring network. This parameter is measured in lakes but not in streams neither groundwater.
- (d) *Nutrients*: phosphorus (e.g., total P and orthophosphate) and nitrogen forms (e.g., nitrate, nitrite, ammonia nitrogen) are limiting nutrients for photosynthetic biomass growth, thus increased values of nitrogen and phosphorous indicate a deterioration of water quality, leading to algal blooms, anoxia, and fish kills typically in lakes and reservoirs. The Chilean monitoring network includes

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<sup>4</sup>  $1 \mu\text{m} = 1 \text{ micrometer} = 1 \times 10^{-6} \text{ m}$ .

sampling and analyses of nutrients for lakes and reservoirs, and the surface water quality network measures nitrogen forms only. It is important to monitor systematically nitrogen forms in streams because it helps track and control nutrient sources within each watershed. Agricultural diffuse pollution and treated wastewater effluents are prime suspects for nutrient discharges. This information is critical to argue for more stringent standards for treated wastewater discharge. A lower standard for nutrients in treated effluents will likely lead to an upgrade of wastewater treatment plants to include biological nutrient removal, as it is the practice in developed countries.

- (e) Sediment chemistry: sediments in rivers and lakes can help reveal the dynamics of natural and anthropogenic contaminants. Sediments may also behave as sources or repositories of contaminants, a process that may be driven by the chemistry of the water column. This aspect is extremely important in mining-impacted areas. Very few studies are available that provide measurements of sediment chemistry, while sediment composition is not systematically monitored by the DGA.
- (f) Emerging contaminants and agrochemicals: Chilean nitrates are known to co-occur with perchlorate, an endocrine disruptor when it is found in trace levels in drinking water (Calderon et al. 2014; Bohlke et al. 2009; Gibbs et al. 2004; Urbansky et al. 2000). Evaluating perchlorate occurrence in groundwater used as source for drinking water production is important since it is not very reactive in groundwater. Traditional groundwater treatment technologies used in Chile do not remove perchlorate significantly. Other emerging contaminants for surface waters include disinfection by products from wastewater treatment, personal care products, hormones and pharmaceuticals. Last but not least, the monitoring of agrochemicals in groundwater and surface waters should be strengthened to unravel the real extension of this type of pollution.

### ***3.3.3 Protecting and Improving the Trophic State of Chilean Lakes and Reservoirs***

In recent years, Chile has been developing water quality guidelines for watershed and lakes management (NSCA). Relevant examples are those guidelines for the Villarrica Lake and the Llanquihue Lake. In the first case, the objective is to avoid the accelerated increase of the trophic state of the Villarrica (Ministerio del Medio Ambiente 2013), while in the second case the objective is to keep the water quality status of the lake, contributing to maintain the current oligotrophic condition of the Llanquihue (Ministerio del Medio Ambiente 2010). This is a big step in preserving aquatic ecosystems and preventing changes in their water quality, especially because these lakes are also important tourist attractions.

Other oligotrophic lakes in Central-Southern Chile are also threatened due to tourism activity. Recently, a decrease in temperature and conductivity, alongside an

increase in N and P levels were reported in ten lakes in that region, over a period of 18 years. Those lakes include Llanquihue, Villarrica, Caburgua, Calafquén and Riñihue. This decrease in the water quality of the lakes may be explained by a combination of land use change due to urban areas expansion, deforestation, exotic plantations, and regional climate change such as decreased rainfall and rapid melting of glaciers- (Pizarro et al. 2016). Evidence for eutrophication in oligotrophic lakes in Central Chile has also been identified (von Gunten et al. 2009). This is a concern since these lakes are located in remote high-elevation basins (2680–3250 m altitude), where direct anthropogenic effects are not observed, and one of the lakes -Laguna Negra- is part of the drinking water system for Santiago. Use of hydrodynamic and water quality models such as those used in the Rapel reservoir and Riñihue lake (Campos et al. 2001) may be useful to simulate these and/or other water bodies at risk under different scenarios.

To avoid excessive nutrient discharge and thus eutrophication of receiving water bodies, nutrient removal in wastewater treatment plants is required. This is a common practice in countries such as USA, Italy and Australia. In Chile, only 5% of the wastewater treatment plants include biological nitrogen and phosphorous removal, and 2.5% include chemical phosphorous removal (Baraňao and Tapia 2004). More efforts should be made regarding this matter so important to aquatic ecosystems health, especially for those lakes and reservoirs whose trophic state may be directly affected by wastewater discharges.

### ***3.3.4 Enhanced Natural Attenuation and Constructed Wetlands as Sustainable Treatment Alternatives***

On-site infiltration ponds and wetlands are examples of natural wastewater treatment systems. In these systems, the removal mechanisms depend on their natural components and thus do not rely on an external energy source for treatment purposes. Pond systems are the oldest and most applied technology. Facultative ponds represent 3% of the wastewater treatment systems in Chile, where the treated effluents are discharged in rivers such as Limarí and Elqui in Northern Chile (SISS 2017b). Nevertheless, the effectiveness of pond treatments should be critically assessed considering their operational flexibility, space requirements, and capacity to adapt to different inflow conditions.

Natural wetlands have been found to improve water quality due to the interaction between vegetation, water and soil. Various physical, chemical and biological processes occur in different wetland compartments. Wetland soils filter and retain solids, also capturing dissolved pollutants. Vegetation growth requirements fosters nutrients uptake. Vegetation may also accumulate metals and metalloids in roots and shoots due to active and passive mechanisms. Decaying organic matter from vegetation is used as a source of organic carbon for microorganisms. Despite that wetlands often provide optimal conditions for different types of microorganisms to thrive,

pathogens are commonly eliminated due to predation, natural die-off, and UV radiation. Plant roots provide surface for biofilms to attach. Roots also transfer oxygen to the rhizosphere, where aerobic and anaerobic zones may be found. This micro environment favors the formation of iron plaque on the roots surface, making this surface highly reactive and thus a sink for pollutants. Combinations of these processes explain the effect of wetlands on water quality parameters such as total suspended solids (TSS), TN, TP, dissolved oxygen (DO), COD, and also on pathogens, and metal and metalloids concentration and speciation.

The Ministry of Environment (Ministerio del Medio Ambiente, MMA) has defined ecosystem services as “the direct and indirect contribution of ecosystems to human wellbeing” (Ministerio del Medio Ambiente 2017). Wetland ecosystems provide us with services worth trillions of US dollars at a worldwide scale (RAMSAR 2017). These services include water purification, recreation and tourism, flood control, reservoirs of biodiversity and climate change mitigation and adaptation. Considering the importance of wetlands, the MMA developed a National Inventory of Wetlands which is now available, aiming to support conservation and protection plans (Centro de Ecología Aplicada 2011).

Constructed wetlands are engineered systems that mimic natural wetlands for wastewater treatment or other purposes. Around 99.8% of the wastewater collected and generated by the urban population in Chile receives treatment in wastewater treatment facilities (SISS 2017a), being the urban sewage coverage 96.8%. However, many rural zones have no access to sewage or treatment facilities. Therefore, on-site, low-cost, easy to maintain treatment systems such as constructed wetlands have potential to be implemented. Some of these systems have recently being implemented in Chile for black and grey<sup>5</sup> water treatment in various locations at domiciliary and small community scale. Some examples include a wetland system to serve 12 houses in Pucón, and another wetland system at a public square in San Pedro de Atacama. A notable application is a horizontal subsurface flow constructed wetland pilot system in Hualqui, Biobío Region, which treats municipal wastewater from a treatment plant that serves a rural community of 20,000 inhabitants (Casas Ledón et al. 2017). Areas of research at the laboratory level include different local applications such as treatment of sewage (Burgos et al. 2017), swine wastewater (Plaza de los Reyes and Vidal 2015) and arsenic and metal-contaminated water (Lizama Allende et al. 2014). This evidence suggests that constructed wetlands may be a sustainable option for water treatment, with further efforts required to evaluate their performance depending on water quality requirements and local conditions. Plans for future implementations of constructed wetlands include a wetland that aims to repair environmental damage associated to industrial wastewater discharges of a pulp mill in Santuario de la Naturaleza Carlos Anwandter (SNCA), Valdivia. This wetland will receive the treated effluent from Valdivia wastewater treatment plant after tertiary treatment and before it is discharged to the Cruces River. The

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<sup>5</sup>Black water refers to wastewater and sewage from toilets, whereas grey water refers to wastewater from baths, sinks, washing machines and other kitchen appliances.

design includes plant species representative of the Cruces River wetland, such as *Typha angustifolia* (narrowleaf cattail) and *Scirpus californicus* (bulrush).

The National Forestry Corporation (CONAF) is responsible for the oversight of 9 RAMSAR sites (out of 13 total RAMSAR sites in Chile), including SNCA. Recently, a handbook for monitoring wetlands included in the National System of Wild Protected Areas of the State (SNASPE) was developed (Zamorano, et al. 2016). The aim of the handbook is to strengthen the institutional monitoring capacities of these wetlands so as to contribute to their effective conservation. Given the role of wetlands in water quality control, biodiversity and provision of ecosystem services, their protection is required, especially considering the current and future scenarios regarding water resources availability and quality. Currently, a legislative project by the MMA that creates the Biodiversity and Protected Areas Service is still under evaluation. This project stems from the lack of specific regulation for protecting wetlands, since the declaration of a site in the RAMSAR category does not imply an official protection category at a national level (Ministerio del Medio Ambiente 2014), unless the wetlands are included in the SNASPE, which is the case of 7 out of the 9 RAMSAR sites under the administration of CONAF (CONAF 2010).

### 3.4 Conclusions and Implications for Water Policy

Water quality of Chilean waters varies widely due to the different climate conditions and the complex interactions between natural and human factors. Main issues include elevated salinity and concentrations of metals and metalloids in Northern and Central Chile and eutrophication primarily in Central Chile. The natural presence of copper and arsenic from geological sources in addition to anthropogenic activities explain heavy metals enrichment. Wastewater treatment coverage in urban areas is close to 100% but only 5% includes nutrient removal and 29% of the generated wastewater is discharged in Chilean coast by marine outfalls<sup>6</sup>.

An integrated approach that articulates water monitoring (quantity and quality) with working conceptual and quantitative models of water quality is needed. Understanding the patterns of the dynamic interactions between Chilean watersheds and human pressures will provide a robust science-based approach for public policy and decision-making in issues involving water quality management.

A compelling policy that assures the access to thorough and reliable water quality data is necessary. This will likely be achieved by (1) strengthening the coverage (spatial representativeness, water quality parameters), density, and sampling frequency of the national water monitoring network, (2) coordinating the efforts of water stakeholders (public, industry, NGOs) in water quality monitoring and protection; and (3)

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<sup>6</sup>Information retrieved from SISS webpage <http://www.siss.gob.cl/577/w3-article-11091.html> on 09/29/17.

supporting the role of research institutions in elucidating the complexity of water quality interactions in socioenvironmental systems.

Although progress has been made in priority watersheds and lakes by NSCA, current institutions and policies will not necessarily ensure that the target water quality standards are maintained (Melo and Pérez 2018). Future public policies aiming for the protection of water resources and aquatic ecosystems need to be consistent with relevant regulations and institutions, as highlighted in other chapters of this book. In addition, further efforts to target main water quality issues, for example by promoting sustainable water treatment alternatives, are required to move forward in the successful implementation of these policies.

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