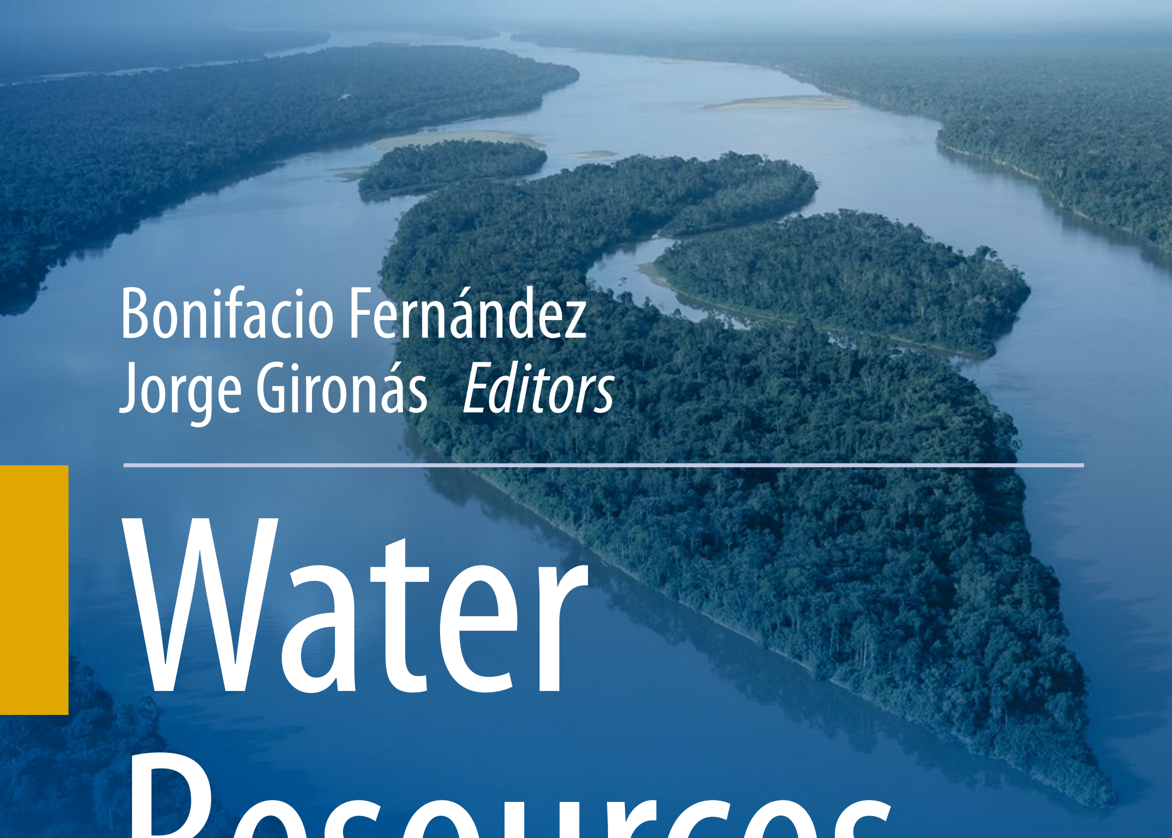
World Water Resources



Bonifacio Fernández
Jorge Gironás *Editors*

Water Resources of Chile

Springer

World Water Resources

Volume 8

Series Editor

V.P. Singh, Department of Biological and Agricultural Engineering,
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This series aims to publish books, monographs and contributed volumes on water resources of the world, with particular focus per volume on water resources of a particular country or region. With the freshwater supplies becoming an increasingly important and scarce commodity, it is important to have under one cover up to date literature published on water resources and their management, e.g. lessons learnt or details from one river basin may be quite useful for other basins. Also, it is important that national and international river basins are managed, keeping each country's interest and environment in mind. The need for dialog is being heightened by climate change and global warming. It is hoped that the Series will make a contribution to this dialog. The volumes in the series ideally would follow a "Three Part" approach as outlined below:

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Readership

Readers would be university researchers, governmental agencies, NGOs, research institutes, and industry. It is also envisaged that conservation groups and those interested in water resources management would find some of the books of great interest. Comments or suggestions for future volumes are welcomed.

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To our families and to the Chilean community of scientists, researchers, and professionals who have dedicated their lives to study, preserve, and wisely use our most precious resource.

Preface

Water is the most critical resource for the sustainable development and management of a country, its society, economy, territory, and the environment. Understanding and characterizing water resources, their space and temporal dynamics and occurrence, as well as their uses, is thus essential. Several views, approaches, disciplines, tools, and data sources are needed in such task; unfortunately, a single reference integrating all this is rarely available. This void is what motivates this book.

Water Resources in Chile attempts for a complete characterization of the status of the hydrologic research and practice in Chile, as well as the up-to-date situation about water research, uses, threats, and challenges. The book corresponds to a major effort involving leading researchers and practitioners with a large expertise and background in hydrology and water resources in the country. After Chap. 1, which presents a brief country profile, there are 21 more chapters addressing a wide variety of subjects. Chapters 2, 3, 4, 5, 6, 7, 8, 9, and 10 cover different topics related to hydrology and sources of fresh water. Chapters in this section deal with climate and weather, precipitation, hydrometeorological regimes, surface and groundwater resources, snow processes and glaciers, floods and droughts, water quality, and the recently developed general water balance for the country. Chapter 11 introduces the policy framework of water resources and river basin management in Chile, while Chaps. 12, 13, 14, 15, 16, and 17 describe the agricultural, domestic, mining, hydroelectric, forestry, and environmental water uses in the country. Finally, Chap. 18, 19, 20, 21, and 22 address several issues of interest for water management, including economic and legal aspects of water in Chile, the impact of climate change and land-use changes in water resources, an analysis of current research in water-related issues, and a closing chapter dedicated to the challenges with which the country must cope to ensure a sustainable water use in the future.

We, the invited Editors as well as all the authors, are pleased to contribute with this book to the Springer series "World Water Resources". We believe the Chilean case will be of interest for the international community, due to the wild disparities in the country's geography and climate, the frequent occurrence of water-related extreme events, the highly relevant role of snowmelt and groundwater, the variety of water uses and stakeholders, the particular social and legal framework, and the overall status of a country aiming to become a developed nation, with many fundamental social issues yet to be resolved.

Santiago, Chile Bonifacio Fernández and Jorge Gironás

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We would like to thank the Pontificia Universidad Católica de Chile, and in particular our colleagues and the staff members of the Departamento de Ingeniería Hidráulica y Ambiental, place in which we have developed our academic career. Finally, we want to kindly thank all the authors involved in this book, as well as the Springer Editorial team and Dr. Vijay P. Singh, Editor-in–Chief of the World Water Resources series.

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Chapter 1
Country Profile

Jorge Gironás, Bonifacio Fernández, and José Saldías

Abstract Chile, the country for which this book was prepared, is located on the southwestern region of South America, between the Pacific Ocean and the Andes. This profile briefly describes the main features of the country, including its geographical and climatic attributes, as well as general aspects about its administration, demography and economy. Finally, water resources availability, uses, and some challenges are introduced.

Keywords Chile · Geography · Climate · Weather · Demography · Economy · Water resources

1.1 Introduction

Continental Chile is a long, narrow strip located on the southwestern region of South America, between the Pacific Ocean to the west and the Andes to the east (Fig. 1.1). The country borders with Argentina, Perú and Bolivia, and is

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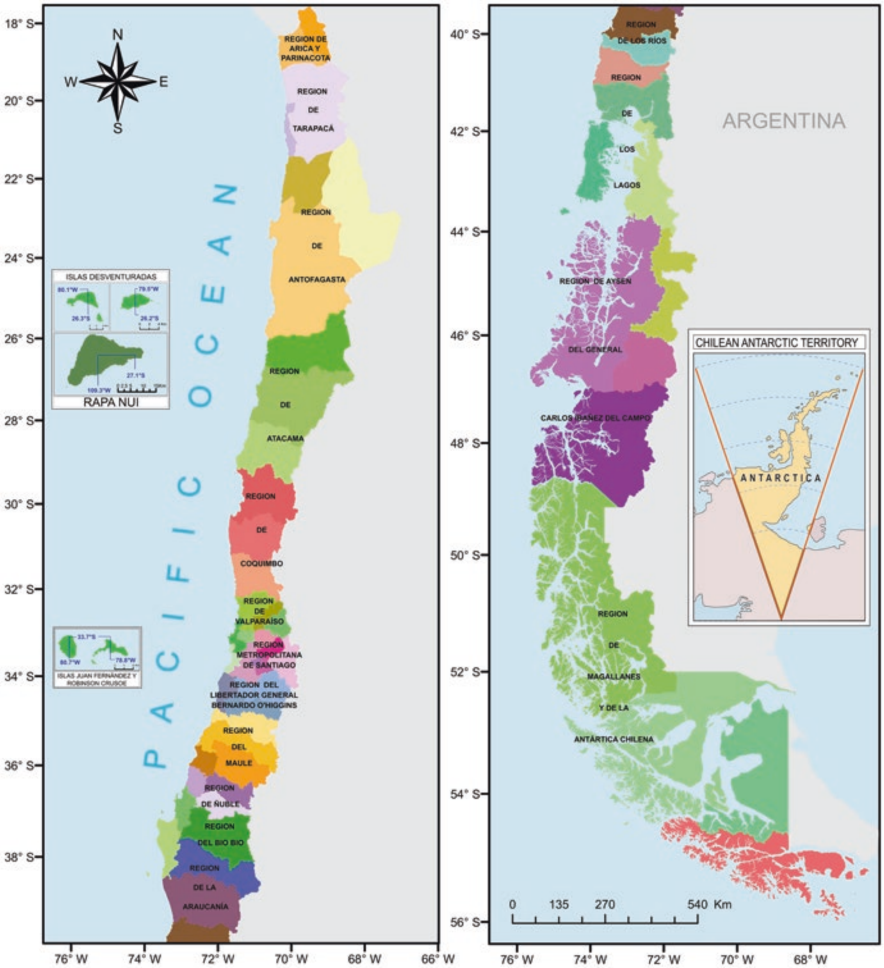

Fig. 1.1 Official administrative map of Chile, in Spanish, as developed by the Instituto Geográfico Militar (IGM, https://www.igm.cl/div/tabs_descarga.php). The 16 Regions and their 56 provinces are shown

administratively divided in 16 regions, 56 provinces and 346 communes. Chilean territory also includes the Juan Fernández archipelago, the Salas y Gómez island, the Desventuradas islands, and Easter island in the Pacific Ocean. A section of Antarctica called Chilean Antarctic Territory is also claimed to be part of Chile.

Continental Chile abides within latitudes 17°'29'57 S and 56°'32'12 S enclosing a surface area of ~756,700 km^2 (World Bank 2017). With an estimated length of 4,300 km, an average width of 180 km (Johnson and Carmagnani 2020) and a strong topographical gradient imposed by the Andes, Chile possess a very unique geographical configuration featuring a wide variety of climates, geomorphology, geology, soil and vegetation. Furthermore, the Pacific Ocean, the Humboldt Current and the Pacific

Anticyclone have all an important effect in the climate. This contextual richness produces a diverse hydrological and hydrogeological setup, in which a large diversity of residential, industrial, environmental and agricultural uses, among others, occur. Thus, the study, modeling, monitoring, recording, sustainable exploitation, and preservation of water resources become a key and continues challenge for the country.

1.2 Demographics and Economy

According to the 2017 national census (INE 2018), the total population of the country is 17,574,003 habitants. Most inhabitants reside clustered in central Chie, specifically on the Metropolitan region where roughly 40% of the population lives. In terms of age composition, trends of age-group distributions reflect a progressive maturing of the country's population, with 11.4% of the population being older than 65 years (INE 2018). Currently, the life expectancy is ~80 years. Improvements in health care conditions and lifestyle modernization (Johnson and Carmagnani 2020), as well as a drop in the fertility rate up to 1.67 children per woman (World Bank 2017), explain this life expectancy and age distribution.

Chile is a highly urbanized country, with 87.8% of the population living in urban areas. Furthermore, 12.8% of the population consider themselves indigenous people (INE 2018). Despite having 11.1 years of formal education in average, Chile has shown significant progress education-wise, with 29.8% of populace achieving higher education and a 96.9% literacy (INE 2018). Nevertheless, more efforts are needed to bring high-quality education to all the social sectors in the country, particularly those with low-incomes.

The Chilean economy is based on the exploitation of agricultural, fishing, forest, and mining resources, while many manufactured products must be imported (Johnson and Carmagnani 2020). Since 2010, the country is a full member of the Organization for Economic Cooperation and Development (OECD). The primary economic sector constitutes 21% of the gross domestic product (GDP) showcasing the mining industry as the main contributor, followed by livestock and agriculture. The industrial sector features manufacture, supply and construction, and generates 30.5% of the added value. Finally, the service sector adds the remaining 48.5% of the GDP through industrial and personal services, commerce, transport and communications (MEFT 2014). Overall, Manufacture, commerce and the financial and insurance industry together embrace more than 50% of the national GDP.

1.3 Geography and Climate

On the west continental border, lies the junction of the Nazca, South American and Antarctic tectonic plates. The slip process between the plates generates strong subduction earthquakes, and eventually, tsunamis. Furthermore, the dehydration of the subdued rock under the continental plate melts its surroundings in the earth's crust, developing a large area of volcanic activity on The Andes mountain range (SERNAGEOMIN 2015). This massive formation extends throughout continental territory, with elevations up to ~7,000 m altitude in central Chile. Parallel to the Andes, the Coastal Mountain Range also runs from north to south; this range is an area of high tectonic activity thermo-regulated by the Pacific Ocean (Pereira-Claren et al. 2019). Both ranges have a significant role in driving the relief, natural vegetation, soils and the different manifestation of the water resources (DGA 2016). Most of the population lives in the central valley located between the two mountain ranges, region in which the majority of the agriculture activity also takes place.

1.4 Water Resource

The central agency controlling the study, monitoring, and use of water resources in the country is the Dirección General de Aguas (DGA), which belongs to the Ministerio de Obras Públicas. DGA (2016) divides the country in 101 River basins. There are 1,251 rivers, 12,784 lakes and lagoons, and 24,114 glaciers. Average annual precipitation over the territory and the corresponding runoff are estimated to be 1,525 and 1,220 mm/year, respectively (DGA 2016). Overall, Chile is a privileged country in terms of water resources. The average annual runoff per capita is ~51,218 m^3/person/year, value well above 1,000 m^3/person/year, the limit that typically defines water scarcity (Falkenmark et al. 1989). Nevertheless, because precipitation tend to increase with latitude, and population concentrates in the central zone, water scarcity prevails from the Metropolitan Region to the North, with an average water availability of 500 m^3/person/year. On the other hand, such availability exceeds 7,000 m^3/person/year from Santiago to the South (DGA 2016).

As many other countries in the world, Chile is vulnerable to climate change. As an example, climate change has been shown to explain in a significant fraction the national decline in rainfall during the last 10 years, period known as the Megadrought (CR2 2015). Furthermore, recent flood events (e.g. Vicuña et al. 2013; Wilcox et al. 2016) have risen the questions of whether the magnitude and frequency of these extreme events can be partially attributed to climate change, and how predicted trends and uncertainty could be incorporated in design, management and adaptation in general (Chadwick et al. 2019). While there are continuous efforts to give water access to the different users, the mega drought and overall scarcity reveal startling flaws when water is not enough for everyone (CR2 2015; Molinos-Senante and Donoso 2016; EE.HH. 2018; Muñoz et al. 2020). Hence, the state, stakeholders and research centers have been continuously promoting the assessment of water resources, and the characterization of the current situation in order to define proper water management policies (EE.HH. 2019). Much more work is needed to ensure future basic supply for the population and nourish a healthy and sustainable economy.

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Chapter 2
Climate and Weather in Chile

Patricio Aceituno, Juan Pablo Boisier, René Garreaud, Roberto Rondanelli, and José A. Rutllant

Abstract Main physical mechanisms controlling weather and climate in the continental domain of Chile are addressed in this chapter, with particular emphasis on those that are more pertinent to the precipitation regime. In particular, most relevant factors that modulate the rainfall variability, from the intraseasonal time-scale to long-term changes, are discussed in relation with the characteristics of the large-scale atmospheric circulation and different modes in the functioning of the ocean-atmosphere system, and the anthropogenic forcing of climate change.

Keywords Climate · Weather · Precipitation · Rainfall variability · Atmospheric circulation · Ocean-atmosphere system · Climate change

2.1 Introduction

Main physical mechanisms controlling weather and climate in the continental portion of Chile are discussed in this chapter, with particular emphasis on those that are more pertinent to the precipitation regime. Following the presentation in Sect. 2.2 of

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the large-scale factors influencing climate in this part of the world, including the Pacific Ocean and topography, the characteristics of precipitation episodes and associated mechanisms are addressed in Sect. 2.3. A description of rainfall variability from intraseasonal to interdecadal time scales is presented in Sect. 2.4, while a discussion about the role of coastal low-level stratus clouds along the arid and semi-arid coast of northern Chile as an alternative source of water resource is included in Sect. 2.5.

2.2 Large Scale Factors Controlling Weather and Climate in Chile

The semi-permanent subtropical anticyclone over the Southeast Pacific (SEP) and the westerly wind regime at mid-latitudes are the most relevant large scale atmospheric factors controlling weather and climate in the continental territory of Chile (Fig. 2.1), spanning from around 19°S to 56°S along the western margin of South America (Fuenzalida 1971).

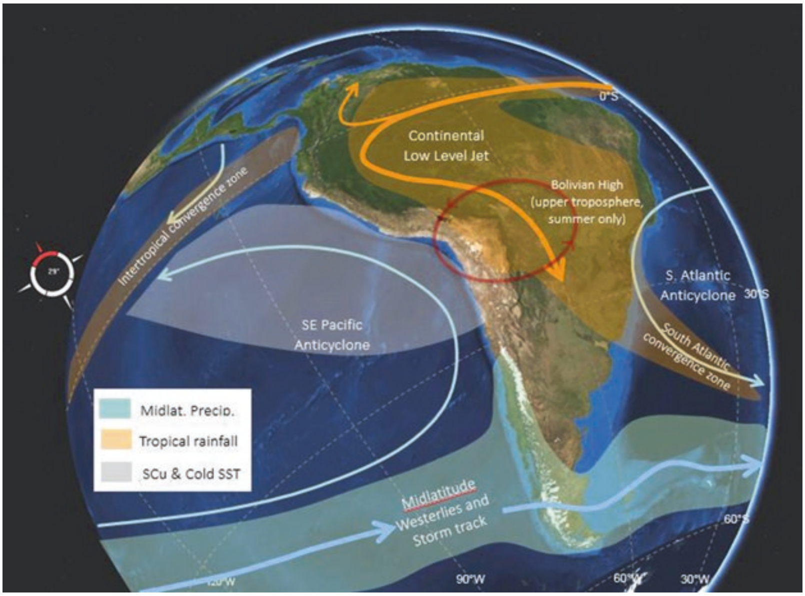

Fig. 2.1 Large scale circulation patterns affecting the hydroclimate of Chile. The cyan and orange curves indicate the circulation near the surface. The red curve indicates the circulation induced by the Bolivian high in the upper troposphere (10 km above sea level, ASL), only evident in austral summer. Cyan and orange shades indicate rainfall produced by extratropical and tropical systems, respectively. Note the effect of the Andes cordillera in extending northward the effect of extratropical storms. The gray shade indicates the typical location of the stratocumulus (low cloud) deck over the SE Pacific

Frontal systems rooted in cyclonic disturbances drifting in the mid-latitude westerly wind belt account for most of the precipitation in south-central Chile, but are restricted by the SEP anticyclone (see Sect. 2.3.2 of this chapter) thus creating a marked north-south precipitation gradient, with annual mean values ranging from less than 10 mm in the hyper-arid north to about 100–1000 mm in the central part, and to more than 3000 mm in the humid southern part of the country (Fig. 2.2a). The southward (northward) displacement of the subtropical anticyclone/westerly wind belt is ultimately forced by the annual cycle of radiative forcing that also controls the annual cycle of air temperature with relative warm (cold) conditions during austral summer (winter) and a marked seasonality in the rainfall regime over the central portion of the country (30°S–40°S) where precipitation episodes concentrate during winter (June–July–August, Fig. 2.2b).

The cold Pacific northward Humbold current exerts a strong homogenizing effect on the temperature regime along the coast, explaining a meridional gradient that is significantly weaker than that observed on the average for same latitudes at the hemispherical scale. Furthermore, the strong temperature inversion layer separating the relatively cold and humid atmospheric boundary layer from the relatively warmer air mass subsiding above, impose an upper limit to the vertical development of the stratus cloud deck stretching over a large oceanic region within the domain of the SEP subtropical anticyclone.

Topography plays a significant role in shaping the characteristics of weather and climate in Chile. Apart from the barrier effect of the Andes, that isolates the Chilean territory from the influence of continental air masses, particularly in the northern and central portion of the country, the topography modulates the regional and local spatial distribution of rainfall. Forced uplift of air masses on the windward side of the mountains enhances rainfall intensity while subsidence on the leeside reduces it.

Although separated by the formidable Andes cordillera, conditions over the interior of the continent also influence the Chilean climate and weather, especially during austral summer (January–February–March) over the Altiplano region in the central Andes (15–22°S) as explained in Sect. 2.3.1. Summer rainfall episodes linked to continental processes can also occur down to 35°S but limited to the upper parts of the Andes cordillera (Viale and Garreaud 2014).

2.3 Precipitation Episodes and Associated Mechanisms

No matter where we look along continental Chile, the yearly rainfall accumulation is the result of well-defined precipitation events lasting a few days. As reviewed in this section, the number, nature and seasonality of these events varies greatly with latitude. Precipitation in the northern highlands (Altiplano region) is mostly caused by convective storms that develop preferentially in the afternoon and evening during austral summer (December–January–February) in connection with the South American Monsoon at tropical latitudes (e.g. Vera et al. 2006). Central and southern Chile are mostly affected by cold fronts rooted in

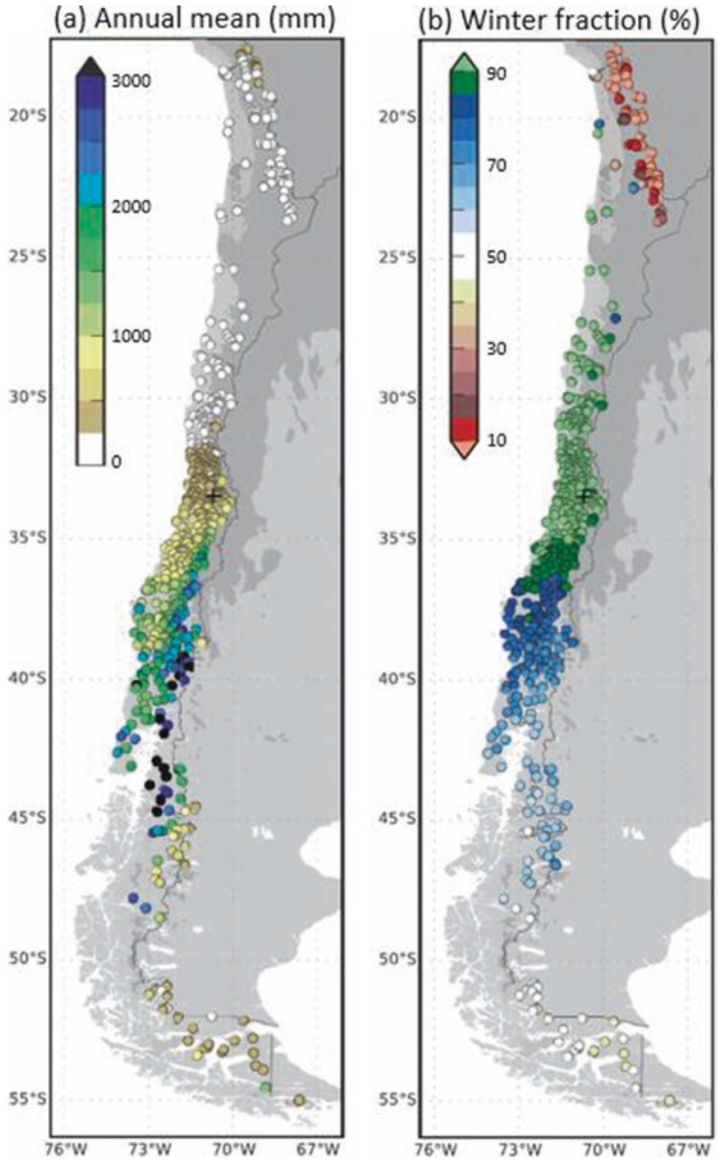

Fig. 2.2 Where and when does it rain along Chile? (**a**) Mean annual precipitation (mm) in local observational sites. (**b**) The contribution (%) of rainfall during the austral winter semester (April–September) to annual totals in each site. (Data source: National Weather Service (DMC) and National Water Agency (DGA). Adapted from Boisier et al. 2018)

midlatitude cyclones, more prevalent during winter months, although cut off lows and zonal atmospheric rivers (stationary fronts) can also deliver substantial rainfall throughout the year. The annual fraction of rainy days increases from less than

10% at 30°S to nearly 75% at 45°S (Viale and Garreaud 2015). Farther south the lack of local records along the coast difficult this assessment, but one may speculate an increased fraction of rainy days and a decrease in the seasonality of the rainfall regime.

2.3.1 Rainfall Events in the Altiplano Region

The Altiplano is a high level plateau (ground level at about 3800 m ASL) extending along the central Andes from about 15–23°S, whose climate has been described by Aceituno (1996) and Garreaud et al. (2003), among others. During most of the year, the central Andes are exposed to westerly winds in the middle and upper troposphere that bring dry air, hindering rainfall in the Altiplano. During the austral summer, however, an upper level anticyclone develops over the central part of the continent (the so called Bolivian High), in response to heating over the central part of the continent (Lenters and Cook 1997), leading to weak easterly winds atop of the central Andes. When the easterlies are strong enough, moist air sourced in the Amazon basin and Bolivian lowlands is entrained into the plateau, feeding precipitation events that can last several days interrupted by dry periods of similar duration (Garreaud 1999; Garreaud and Aceituno 2001), as shown in Fig. 2.3a for the location of Chungará. Rainy events are not truly continuous; given their convective nature, intense precipitation (rain, snow and hail), accompanied by lighting, most often occurs during evening but convection subdues during night and is typically absent in the morning hours.

Satellite imagery in Fig. 2.3b illustrates the mesoscale structure of the convective activity, with distinct cores of about 50 km in the horizontal dimension. Convection can be widespread over the Altiplano but it hardly encompasses the western slope of the Andes (near the Chilean border) where very arid conditions prevail. Yet, summer precipitation over the Altiplano is the only source of groundwater and supply for the springs in the upper part of the Atacama Desert (Houston and Hartley 2003). There is also a marked north-south gradient in precipitation over the Altiplano, with highest values around the Titicaca lake (about 700 mm/year) and minimum over the Salar de Uyuni (<100 mm/year).

2.3.2 Extratropical Systems in Central and Southern Chile

To the south of the dry-diagonal that crosses the west coast of South America between 23°S and 27°S, systems of extratropical origin are responsibly for most of the precipitation in central and southern Chile. Here, most of the precipitation is caused by deep stratiform clouds that develop along cold fronts arching equatorward, as the one shown in Fig. 2.4. The fronts are in turn rooted in surface cyclones

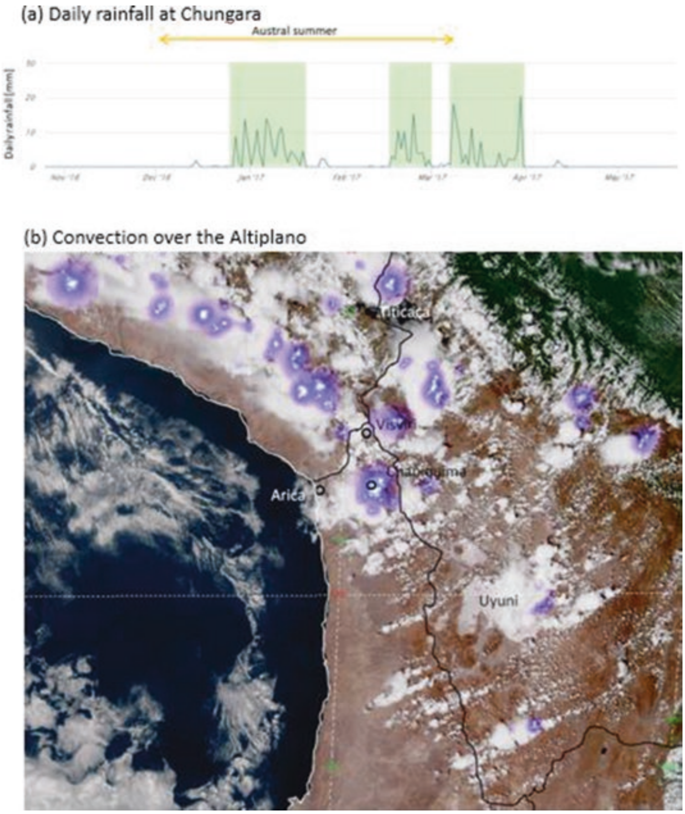

Fig. 2.3 Temporal and spatial characteristics of the summer rainfall over the Altiplano region (northern Chile). (**a**) Time series of the daily rainfall at Chungará station (18.3°S, 69.1°W, 4570 m ASL) between Dec. 2016 and May 2017. (Data source: National Water Agency (DGA). The green bars encompass 1–2 week long wet periods.) (**b**) Visible satellite image (from GOES 16) for January 29, 2019 at 17:15 local time. The purple-blue shading represents high density of lightning, indicative of the convective nature of the clouds

drifting eastward in the midlatitudes in connection with upper level troughs. On average the latitudinal position of the storm tracks reaches its northernmost position (45°–50°S) in austral winter, producing precipitation in central and southern Chile. By the contrary, the storm track moves southward (50°–55°S) during summer that, together with the expansion of the subtropical anticyclone over the SE Pacific, restrict the precipitation to southern and austral Chile during this season.

Low-level northwesterly flow ahead of a cold front transports warm air with high water vapor content from the subtropical Pacific southward to the west coast of South America. Part of this warm, moist stream ascends over the cold front causing clouds and precipitation over the open ocean but the most significant ascent -and hence precipitation- occurs when the moist-laden air masses approach the impressive Chilean topography. This forced ascent has several consequences. First, it

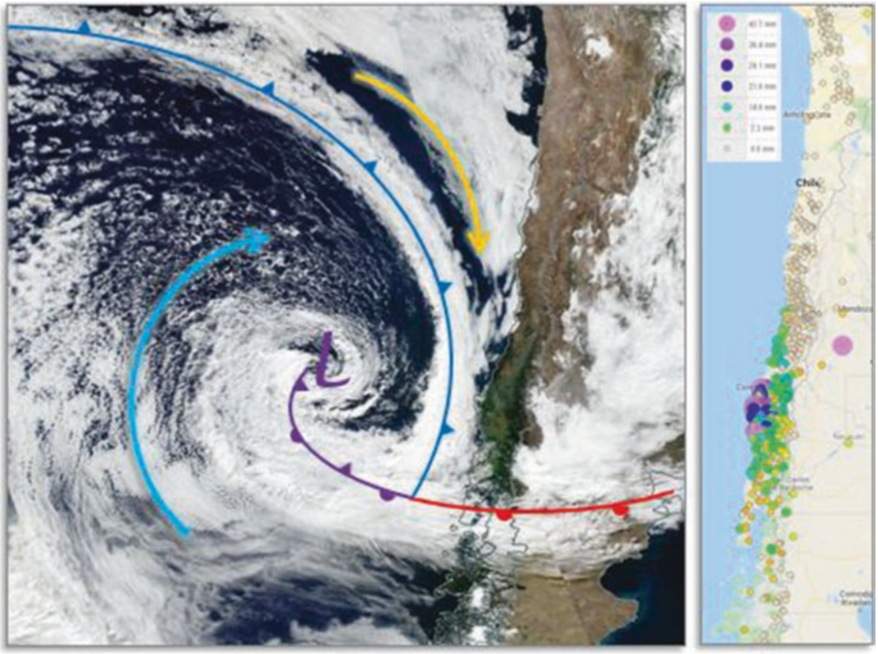

Fig. 2.4 An extratropical storm approaching southern Chile. The left panel is a visible image from the MODIS sensor aboard of the AQUA Satellite for May 5th 2018, at 15:45 UTC. The blue, red and purple lines indicate the location of the cold, warm and occluded fronts, respectively. The light-blue and yellow arrows indicate the low-level flow around the surface depression (low pressure), whose center is identified by the letter L. The right panel shows the station-based total precipitation caused by this system (accumulated rainfall from 4 to 6 of May, 2018). (Data source: National Weather Service (DMC) and National Water Agency (DGA))

produces west-east precipitation gradients at several scales. Between 33°S and 40°S, there is a precipitation maximum along the coast on the windward side of the coastal range and a minimum in the central valley (Falvey and Garreaud 2007; Garreaud et al. 2016). Figure 2.5 illustrates this rainfall contrast for central Chile and the Nahuelbuta mountains in the coast of the Biobío region at about 38°S. To the east of the central valley, precipitation increases by a factor 2–4 over the western slope of the Andes (the Andean amplification is difficult to determine because of the lack of high altitude precipitation records and it also varies significantly among storms), and sharply decreases to the east of the continental divide (Viale and Núñez 2011; Viale and Garreaud 2015). The upstream precipitation enhancement and downstream rain shadow across the southern Andes cordillera creates one of the most extreme precipitation gradients on earth (Smith and Evans 2007), with annual accumulation changing from >3000 to <300 mm within 200 km in the east-west direction across the Patagonia region.

The second consequence of the coastal range and the Andes along central Chile is the blocking of impinging (zonal) flow leading to the formation of a terrain

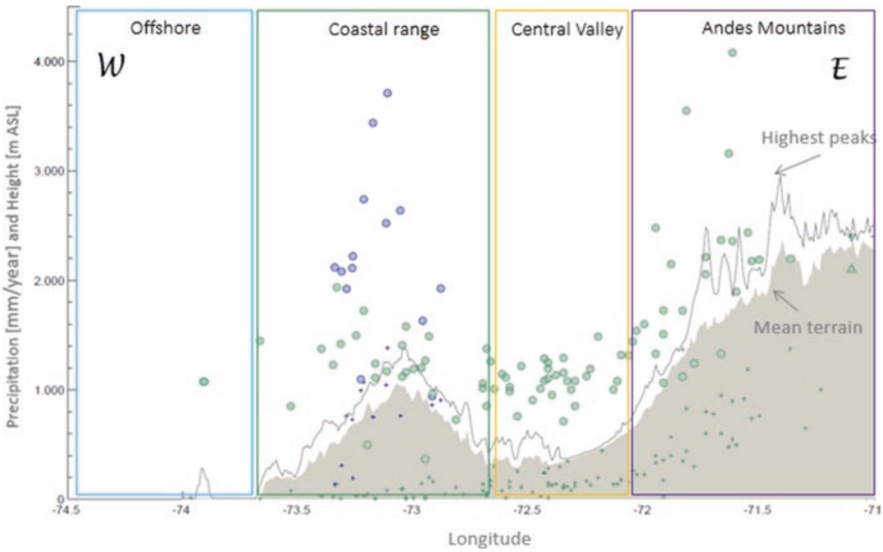

Fig. 2.5 Impact of the topography on precipitation. Circles indicate the mean annual precipitation (MAP) considering all stations between 36.5°S and 38.5°S along a west-east transect (roughly perpendicular to the coastal range and the Andes). Crosses indicate the elevation of these stations (note the absence of high elevation stations in the Andes). The terrain profile is indicated by the mean and maximum height in that range of latitudes. The green circles are MAP from DMC and DGA stations. The blue circles over the coastal range are MAP estimates based on a network of stations installed during AFEX (Garreaud et al. 2017)

parallel, northerly jet (Barrett et al. 2009). During the approach of a cold front, this northerly jet can be very strong, enhancing convergence and rainfall over the Biobio region (36–38°S) but retarding the advance of the front toward central Chile (Barrett et al. 2009). Depending on their speed, air parcels above ~2 km can surpass the Andes and deliver precipitation, so that storm-accumulated precipitation at any given latitude is significantly dictated by the strength of the mid-level westerly flow impinging upon the Andes. The correlation between the intensity of this flow and rainfall amount improves slightly if one considers the zonal moisture transport (Falvey and Garreaud 2007) and is also found on longer time scales: the strongest the westerly winds averaged over a season or year, the largest the cumulative precipitation in that period (Garreaud 2007; Garreaud et al. 2013).

In most storms (at least two third of the events) precipitation over the central valley begins almost simultaneously with the arrival of the cold front and the bulk of the rainfall accumulation occurs under cold conditions (post-frontal precipitation), with a freezing level altitude around 2200 m (Garreaud 2013). This level is well below the Andes crest height at subtropical latitudes (>5000 m ASL) so that a substantial portion of the winter precipitation builds up a seasonal snow pack that eventually melts during the next spring-summer season (Cortés et al. 2011). Indeed, many cold fronts arriving to central Chile during winter produce a minor concurrent increase in the flow of the rivers draining the Andes cordillera. A few winter storms, however, feature warm conditions (air temperature doesn't drop during the precipitation period) causing the freezing level to remain as high as 4000 m ASL, increasing the pluvial area up to a factor 4 relative to average conditions (Garreaud 2013). Warm winter storms have caused some of the most devastating landslides and flooding in the recent past and will be described in connection with zonal atmospheric rivers.

2.3.3 Atmospheric Rivers

The increasing availability of high resolution images of spatial distribution of water vapor and precipitable water (column integrated water vapor content) from meteorological satellites allows the detection of relatively long, narrow regions in the atmosphere, identified as atmospheric rivers (ARs), that transport water vapor outside of the tropics in a concentrated and highly efficient way (for an updated review see Ralph et al. 2017). These features are relevant to the rainfall regime in Chile because those making landfall along the coast favor the occurrence of intense rainfall. Recent surveys of ARs (Guan and Waliser 2015; Viale et al. 2018) indicate that 20–40 ARs make landfall in the coast of central-southern Chile per year (maximum at 40–50°S), one of the largest frequency worldwide, explaining about half of the annual rainfall and extreme precipitation events. Atmospheric rivers are mostly a wintertime phenomenon in central Chile, but they can occur year-round to the south of 40°S.

Most cold fronts described in Sect. 2.3.1 feature an AR ahead of them. ARs can also occur ahead of stationary fronts extending thousands of kilometers across the South Pacific with a zonal (East-West) direction and little displacement in the cross-front (north-south) direction. When a zonal AR landfalls, substantial prefrontal precipitation (up to 100 mm) can accumulate at the coast, inland valleys and the western slope of the Andes over periods of 24–72 h without a decrease in air temperature and freezing levels. As commented before, such situation renders AR/Warm storms into a significant hydrometeorological hazards, such as the 3-May-1993 landslide in Santiago, with a toll of more than 80 fatalities (Garreaud and Rutllant 1996) and the 16-Dec-2017 flooding of the Santa Lucía village in northern Patagonia, with a toll of more than 20 fatalities (Viale 2017). This later case helps to describe the characteristics of a zonal, quasi-stationary AR as depicted in Fig. 2.6. The AR extended more than 3000 km from the central Pacific to South America, and was located just below the axis of the wind maxima that contributed to the exceptional AR length. The upper level flow is mostly zonal, with a hint of a ridge aloft, quite different from the circulation observed most often in winter storms over central Chile (Fig. 2.4) featuring a deep trough aloft and northwesterly flow. Since, in this case there is weak synoptic-scale forcing for upward motion, precipitation (in excess of 80 mm/day) was largely generated by the forced ascent over the Andes of the narrow string of moist air defining the atmospheric river.

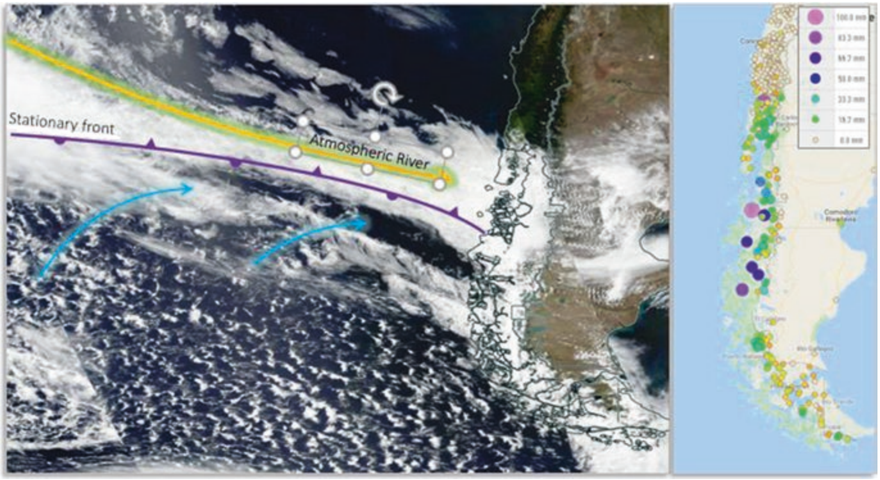

Fig. 2.6 An Atmospheric River (AR) landfalling in southern Chile. The left panel is a visible image from the MODIS sensor aboard of the AQUA Satellite for December 16, 2017, at 15:45 UTC. The purple line indicate the location of a stationary front. The light-blue and yellow arrows indicate the low-level flow at each side of the front. The AR is the stream to the north of the front transporting large amounts of water vapor that cause precipitation when it encounters topography. The right panel shows the station-based total precipitation caused by this AR (accumulated rainfall from 15 to 17 of December, 2017). (Data source: National Weather Service (DMC) and National Water Agency (DGA))

2.3.4 Cut-Off Lows

Cut-off lows (COLs) (Palmen 1949) were only recently recognized as potentially relevant for precipitation in Chile, especially in the northern portion of the country (Pizarro and Montecinos 2000; Fuenzalida et al. 2005). Cut-off lows are synoptic scale systems that owe their existence mostly to breaking of the extratropical synoptic scale waves (Ndarana and Waugh 2010). As an upper level trough amplifies towards subtropical latitudes, a cyclonic anomaly becomes disconnected (cut-off) from the high latitude westerly wind regime (see Fig. 2.7). An upper level cyclone is then shed northward reaching even subtropical latitudes along the Chilean coast where it often moves erratically for several days until dissipation or crossing the Andes. The relatively cold mid-tropospheric conditions associated with this system explain the Spanish names given to this phenomenon ("núcleo frío en altura", upper tropospheric cold core and "gota fría", cold drop).

A cut-off low is primarily an upper tropospheric phenomenon with circulation and thermodynamic features most evident in the upper levels of the troposphere and surface manifestations hardly present. Nevertheless, COLs are relevant for weather conditions in Chile as they are responsible for a significant fraction of total precipitation in the Northern-Central portion of the country (Barahona 2013). The spatial distribution of precipitation and the fraction of annual rainfall attributed to COLs

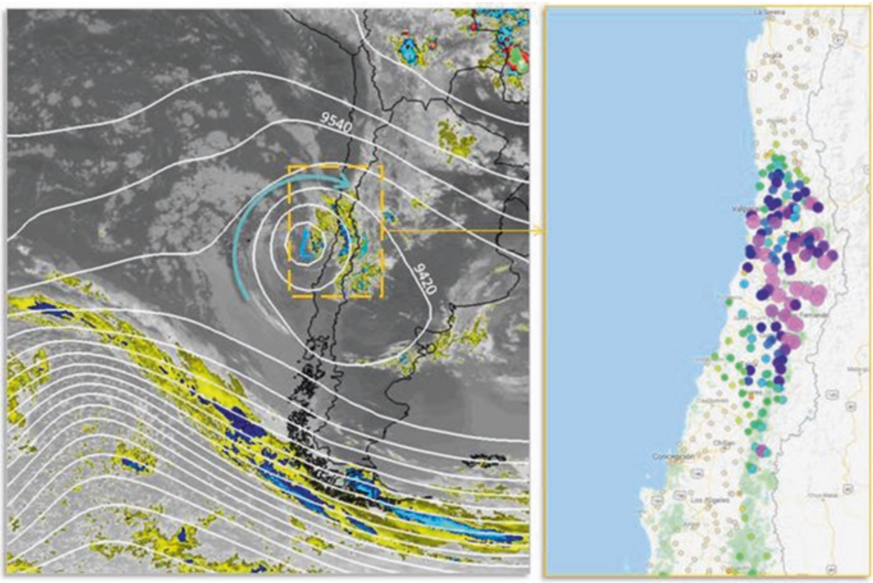

Fig. 2.7 A Cutoff low over central Chile. The left panel is an infrared image from the GOES-12 for March 7, 2008, at about 8 AM. Dark gray areas are cloud free, light gray areas indicate low and midlevel clouds, while yellow and blue areas indicate clouds with high tops, presumably precipitating. Superimpose on this image are the 300 hPa geopotential height contours (every 60 m) showing a cutoff low with its center (L) just offshore central Chile. The right panel shows the station-based total precipitation caused by this COL (accumulated rainfall from 6 to 8 of March 2008). (Data source: National Weather Service (DMC) and National Water Agency (DGA))

are shown in Fig. 2.8 for the period 1979–2014. The contribution of these systems to annual rainfall varies between 0 and 50 mm in the semi-arid region to the north of 32°S while the maximum contribution occurs at about 36°S (with nearly 200 mm/year). Farther north the percentage of annual rainfall associated to COLs can reach 30% or more, although statistics become less reliable with fewer cases detected as one moves into the hyperarid Atacama Desert. In Central Chile, from about 30°S to 38°S, the percentage of annual rainfall due to COLs varies between 10 and 15%.

Besides the impact on annual precipitation, COLs can generate extreme precipitation events, the most recent and noteworthy being the Atacama flooding episode in March 2015 (Barrett et al. 2016; Bozkurt et al. 2016; Rondanelli et al. 2019), one of the worst hydrometeorological disasters in the history of the country in terms of losses of life and infrastructure. Flooding during this storm resulted from the accumulation of up to 100 mm during 3 days over an otherwise arid region, with rainfall intensities in excess of 10 mm/h at some stations.

The relatively cold air associated to COLs induces a decrease in the static stability in mid to lower levels of the troposphere as well as a cyclonic circulation consistent with the field of temperature anomalies. Given that most of these disturbances originate over the cold water of the Southeast Pacific, convective instability is not

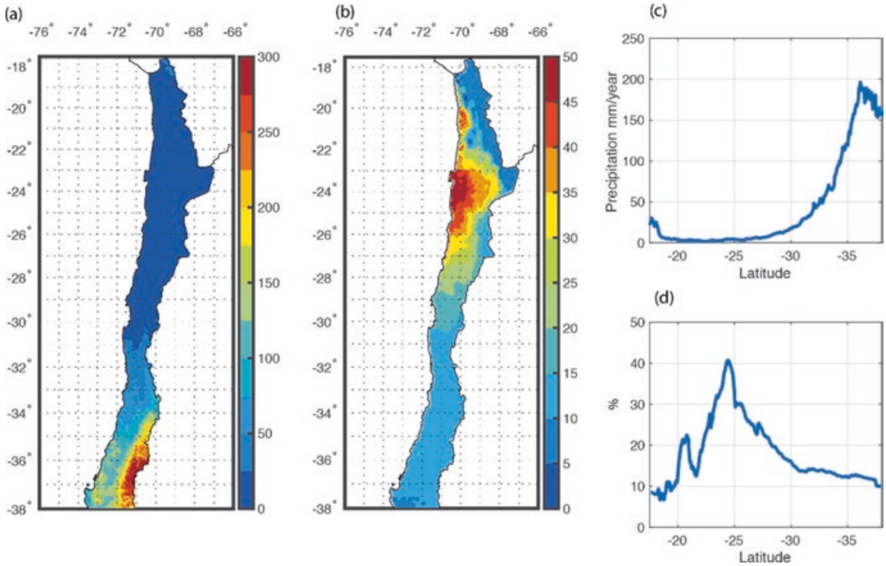

Fig. 2.8 Distribution of annual precipitation due to cut-off lows: (**a**) spatial distribution and (**c**) latitudinal distribution from CR2MET daily rainfall product for the period 1979 to 2014 (Boisier et al. 2018), using the cut-off low database developed by Barahona (2016); (**b**) spatial distribution and (**d**) latitudinal distribution of the percentage of annual precipitation due to cut-off lows

frequently released over the ocean and consequently dry air masses ascending in the leading edge of the cut-off low explain the relative absence of precipitation over the ocean off the chilean coast (Garreaud and Fuenzalida 2007; Barahona 2016). Given that a fundamental mechanism for the dissipation of the cut-off low is the heating due to the release of latent heat by water vapor condensation, the cold ocean and the blocking effect of the Andes cordillera act as a "protection" to the release of convective instability and further dissipation of the cut-off low. This might explain the maxima in the frequency of cut-off lows near the Chilean coast (Fuenzalida et al. 2005; Garreaud and Fuenzalida 2007; Barahona 2016).

Different mechanisms control the occurrence of rainfall episodes associated to a cut-off low as it approaches the South American continent, with pre-existing positive sea surface temperature anomalies and larger than average water vapor in the region off the coast of Chile and Peru favoring their occurrence (Fuentes 2014; Bozkurt et al. 2016). In some cases, when water vapor is available from the eastern side of the Andes, deep convection is triggered mostly over the mountains due to the release of conditional instability associated to the forced uplift, usually accompanied by precipitation and thunderstorms. In other cases, when relatively warm conditions prevail, precipitation might concentrate over the coastal region, thereby reversing the typical positive gradient of precipitation with altitude (Scaff et al. 2017).

Cut-off lows are therefore highly relevant for the occurrence of rainfall episodes in Chile, not as much for the total amount of annual precipitation explained by these systems but rather by the potentially large and localized rainfall intensities and therefore a low spatial predictability of their occurrence, both features arising from the convectively unstable nature of these systems.

2.4 Intraseasonal to Decadal Scale Precipitation Variability

As described in the previous section, the extratropical and oceanic nature of precipitation in most of the Chilean territory is coherent with a marked seasonality and a typical return period (weekly) of rainfall events in winter. Yet, superimposed to the synoptic time scale, there is a myriad of climate variability modes within the Pacific basin that modulates precipitation in Chile within the year (intraseasonal) and in longer time scales (interannual to decadal).

The intraseasonal climate variability in the Southern Hemisphere has been the subject of a large body of research, notably boosted by the increased availability of global weather maps and re-analyses since the 1990s. Beyond the variable observed or method applied, the examination of low-frequency variability of extratropical circulation leads to a coherent picture. The Southern Annular Mode (SAM) and the Pacific–South American (PSA) patterns of variability emerge as the leading intraseasonal modes in this region (e.g., Sinclair et al. 1997; Thompson and Wallace 2000; Mo and Paegle 2001). The SAM (also known as Antarctic Oscillation or high-latitude mode) characterizes a zonally, quasi-symmetric structure in atmospheric fields, measuring the strength of the polar vortex. The PSA patterns refer to stationary wave trains of particularly large amplitude in the south Pacific. The nature of these modes is discussed later.

Figure 2.9 illustrates the influence of intraseasonal circulation variability on precipitation, based on a principal component analysis applied on monthly sea-level pressure (SLP) anomalies in southern extratropical latitudes (20–90°S) for the austral winter semester (April–September). The three leading modes correspond closely to the SAM and PSA modes number 1 and 2 described in former studies (e.g. Sinclair et al. 1997). The first mode measures the co-occurrence of pressure levels below and above normal at mid and high latitudes, respectively, which correspond to the negative SAM phase after a usual definition of this phenomenon (e.g., Marshall 2003). The second mode characterizes high-pressure anomalies around the Amundsen Sea, while the third mode exhibits a wave-like pattern with SLP anomalies of different sign along the Antarctic Circle.

Figure 2.9 also illustrates how the circulation patterns modulate precipitation across the southern Pacific (reanalysis estimate) and in central-southern Chile (observations-based). Within the extratropics, anomalously dry conditions prevail on the equatorward side of the centers of high SLP; a response that can be viewed as the direct – blocking – effect of persistent anticyclones on the westerly flow and baroclinic eddies. In turn, positive precipitation anomalies are found near the centers of negative SLP anomalies. In this way, the first mode (SAM) leads to a band of positive precipitation anomaly at 35–45°S, affecting most of central-southern regions of Chile (Fig. 2.9a; see also Gillett et al. 2006). This effect is consistent with

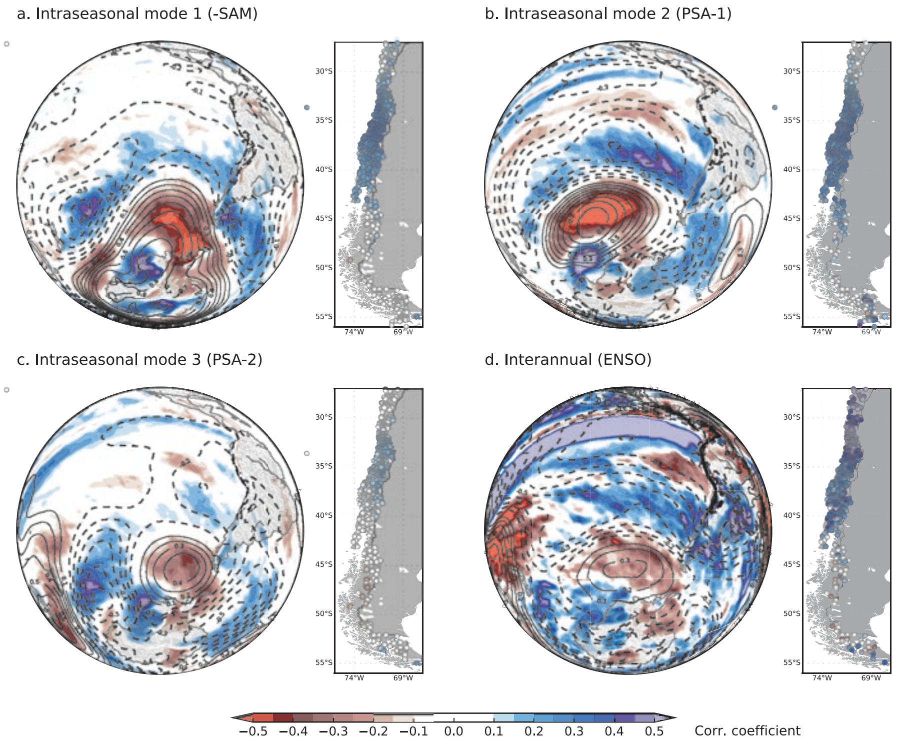

Fig. 2.9 Modes of low frequency variability. (**a–c**) Pearson's correlation coefficient of the three leading components of monthly sea-level pressure (SLP) anomalies during austral winter (April–September) in the region 20–90°S with SLP (continuous (broken) lines denoting positive (negative) correlation) and precipitation (colored areas). Correlations in panel (**d**) are obtained between the winter mean multivariate ENSO index (MEI) and SLP/precipitation. Results illustrated in hemispheric maps (left panels) are computed with ERA-Interim reanalysis data (Dee et al. 2011), while details in central and southern Chile (right) are based on observations at stations belonging to the National Weather Service (DMC) and National Water Agency (DGA)

the increased meridional pressure gradient at mid-latitudes and the equatorward location of the storm track during a negative SAM phase (Sinclair et al. 1997; Rao et al. 2003). A similar precipitation pattern is observed in the SE Pacific with the PSA-1 mode, leading to wetter conditions in central and south-central Chile (Fig. 2.9b). In this analysis, the PSA-2 mode comprises an anticyclonic anomaly near the southern tip of South America. Consequently, dry conditions should prevail during the positive phase of this mode in austral Chile, although the limited records in Patagonia do not reflect this effect clearly (Fig. 2.9c). Due to the same mechanism described previously, this mode associates also with positive rainfall anomalies further north in central Chile.

Although the nature of PSA modes is not fully understood (O'Kane et al. 2016), they are frequently linked to standing Rossby waves in the atmosphere, triggered by deep convection in the tropics (Mo and Higgins 1998; Renwick and Revell 1999;

Mo and Paegle 2001). The PSA patterns represent then teleconnections through which a tropical disturbance may affect weather in remote regions. Particularly, this mechanism explains the SE Pacific circulation and South American climate response to some well-known tropical phenomena, notably the Madden-Julian Oscillation (MJO) and El Niño/Southern Oscillation (ENSO) (Aceituno 1988; Karoly 1989; Renwick and Revell 1999; Grimm et al. 2000; Mo and Paegle 2001; Renwick 2005; Barrett et al. 2011; Álvarez et al. 2016).

During the warm ENSO phase (positive MEI Index; El Niño years) there is a tendency for above normal precipitation in central Chile in austral winter and spring. Later in the latter season, these positive rainfall anomalies shift to south-central Chile, while farther south dry anomalies prevail in the austral summer (Rutllant and Fuenzalida 1991; Montecinos and Aceituno 2003). The wetter than normal conditions in central Chile are a regional manifestation of large-scale circulation and precipitation anomalies, as shown in Fig. 2.9d. El Niño leads to anticyclonic circulation anomalies over the Amundsen-Bellingshausen Sea. The stationary and quasi-barotropic nature of these high-pressure systems blocks the westerlies and associated polar-front jet stream, diverting the storm track toward subtropical latitudes (Rutllant and Fuenzalida 1991; Marqués and Rao 1999), where the weakened SE Pacific subtropical anticyclone (SEPSA) favors the development of cyclonic circulation anomalies. The linear, contemporaneous (no lag) relationship between SST anomalies in the tropical Pacific (Niño3.4 index) and central Chile rainfall fluctuated between 0.6 and 0.7 during most of the twenty-first century, enough to consider its use for intraseasonal prediction (Montecinos and Aceituno 2003). During the first decades of the present century, however, the strength of the negative correlation reduced significantly for reasons yet unclear (Garreaud et al. 2019).

ENSO further impacts the rainfall over the South American Altiplano. The weaker than average subtropical jet during La Niña summers (December–January–February) foster advection of moist air from the interior of the continent towards the central Andes (see Sect. 2.3.1) thus increasing rainfall (Garreaud and Aceituno 2001). On the contrary, during El Niño summers stronger than average westerlies in the subtropics restrict rainfall over the Altiplano.

The mechanisms explaining rainfall variability at inter-annual time scales in connection with the ENSO cycle (2 to 7 years) is closely related to intraseasonal phenomena and the occurrence of PSA modes (Fig. 2.9). In particular, when the convective phase of the MJO (30–90 day cycles) transits eastward along the equatorial Pacific from the western side (La Niña-like) to the central Pacific (El Niño-like), a concomitant strengthening and weakening of the SE Pacific subtropical anticyclone is observed. In the later stage, the enhanced convection around the date line triggers a PSA teleconnection (e.g. Álvarez et al. 2016). Therefore, both ENSO and MJO can act constructively to generate circulation anomalies in central Chile that favor the occurrence of intense precipitation episodes (Donald et al. 2006; Juliá et al. 2012; Barrett et al. 2011; Rondanelli et al. 2019).

Given the strong influence of oceanic and atmospheric conditions in the equatorial and South Pacific regions on climate in Chile, its behavior exhibits a decadal-scale variability connected to known ENSO-like, low frequency cycles (e.g., Garreaud and Battisti 1999; Dong and Dai 2015). Following the same mechanisms established for ENSO, warm phases of the Pacific Decadal Oscillation (PDO) or Interdecadal Pacific Oscillation (roughly the same phenomenon) are associated with wetter than normal conditions in central Chile, notably during the 1930s and 1980s. Particular attention has been paid to climate effects of a relatively rapid transition from a negative to a positive PDO phase in the mid-1970s (e.g. Quintana and Aceituno 2012; Jacques-Coper and Garreaud 2015). Moreover, a particularly strong rainfall decline in central Chile since the early 1980s, related to a gradual turn back to a cold PDO phase, has accentuated the effects of a secular drying trend in Chile (Boisier et al. 2016).

2.5 Long-Term Changes in Precipitation

According to what most climate models project for the next decades under carbon-intensive global socioeconomic scenarios, the western coast of southern South America would be one of the regions of the planet strongly affected by precipitation loss (Collins et al. 2013; Schewe et al. 2014; Jiménez-Cisneros et al. 2014). This drying trend, as those modelled in other subtropical regions in the globe (southern Spain and northwestern Africa, south Africa, southwestern Australia), is associated with hemispheric-scale perturbations frequently interpreted as a poleward shift of general circulation patterns, including the expansion of the subtropical dry regimes under influence of descending Hadley Cell branch (Cai et al. 2012). At higher latitudes, an intensification of the circumpolar vortex alike the positive phase of the SAM – shown by both climate models and historical reconstructions (e.g. Gillett et al. 2013) – produces a poleward shift of the region of maximum westerly flow, with dryer/wetter conditions northward/southward from the edge of the mid-latitude storm track. As a result of these large-scale perturbations, current models simulate a particularly strong drying pattern across the SE Pacific, directly heading central-southern Chile (Fig. 2.10), where precipitation may decline by 40% toward the end of the twenty-first century (Polade et al. 2017).

Consistent with the modelled climate response to anthropogenic forcing, observational records indicate a long-term precipitation reduction along the southwest coast of South America (e.g., Aceituno et al. 1993; Minetti et al. 2003; Haylock et al. 2006; Quintana and Aceituno 2012; Cai et al. 2012; Purich et al. 2013), which is particularly significant in central Chile since the end of 1970s. The causes of this trend seem both natural – with the PDO as key driver – and anthropogenic, the latter accounting for about one third of the total signal (Boisier et al. 2016). Further research showed that in addition to the increasing greenhouse gas (GHG) concentration in the atmosphere, changes in atmospheric circulation associated with the stratospheric ozone depletion have very likely contributed to the strong precipitation decline observed in the southern portion of the country during summer (Boisier et al. 2018), a seasonal signature well reproduced in climate model simulations (Fig. 2.10).

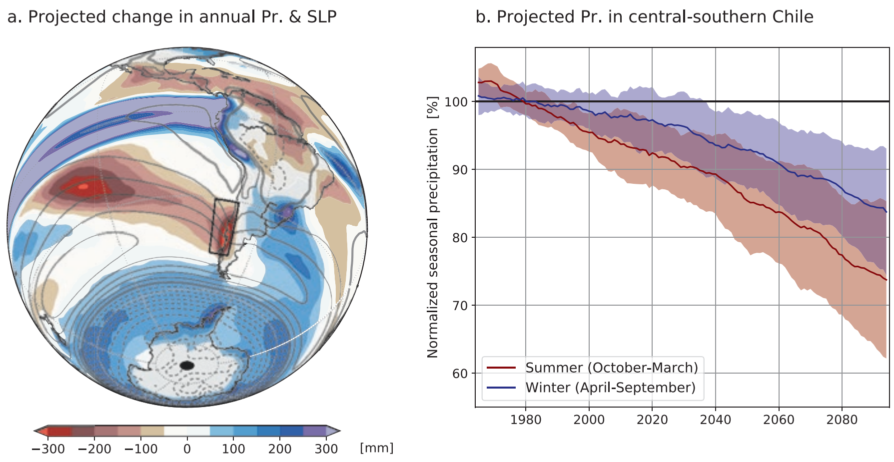

Fig. 2.10 Future climate scenarios: (**a**) Projected multi-model mean change in annual precipitation (colors) and in sea-level pressure (solid and dashed contours indicate positive and negatives differences, drawn every 0.5 hPa) toward the end of the twenty-first century (2060–2099 minus 1960–1999). (**b**) Multi-model mean ± 1 standard deviation of seasonal summer and winter precipitation in central-southern Chile (see domain in panel (**a**)). All results are based on the full-forced historical and rcp8.5 simulations from 34 climate models participating in Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2011)

Since about 2010, the unfortunate combination of a secular drying trend and natural climate variability has resulted in a decade-long rainfall deficit in central Chile. In addition to the multiple impacts driven by reduced water availability, this so-called mega-drought has been accompanied by an above normal frequency of heat waves and more intense fire seasons (Garreaud et al. 2017). The persistence and intensity of this dry period (mean rainfall deficit of ~25%) expose a sharp picture of the hydroclimatic conditions that a large region in Chile could face as the norm around the mid-twenty-first century if no strong mitigation measures against fossil-fuel emissions are adopted globally (Fig. 2.10).

Further details on climate scenarios and regional-scale hydrological projections for Chile are included in Chap. 19. Nevertheless, a source of considerable uncertainty in future climate scenarios is the unknown functioning of ENSO in a warmer world, given the high relevance of this mode in the interannual variability of the hydroclimate of central-south Chile.

2.6 Other Processes Relevant to Water Resources

The search for sustainable human development in subtropical arid climates in Chile calls for the prospection of non-conventional water resources. Present projections for climate evolution in these areas under different GHG emission scenarios anticipate a decreasing trend in annual precipitation (e.g. Schulz et al. 2011) and inland warming, both contributing to increase aridity indices. Small coastal communities along northern Chile could benefit from cloud-water collection in areas where highly-persistent coastal low-clouds (i.e. stratocumulus clouds: Sc) are intercepted by coastal orography. A key aspect when assessing the potential of this freshwater resource is the projection of the future evolution and seasonal variability of Sc frequency, cloud base and top heights, liquid water content and drop-size distribution (e.g Klemm et al. 2012). Besides the necessary research on these physical climate issues, improved designs of water collecting devices are of utmost importance both in terms of efficiency and adequate structures to withstand episodic high-wind storms.

Early experiences in Chile were developed at the Universidad Católica del Norte (Antofagasta) (e.g. Lleal i Galceran 1987, and references therein). In the late 1980s, the *Camanchacas Chile* International Project was carried on at El Tofo, north of La Serena, aimed at studying the collection efficiency of low-cost rectangular meshes. Ultimately, the idea was to supply fresh-water to Chungungo, a nearby fishermen village (Schemenauer et al. 1988; Fuenzalida et al. 1989). Ongoing monitoring and research initiatives are taking place at Fray Jorge relict forest (e.g. Garreaud et al. 2008), at Alto Patache, Iquique (e.g. Muñoz-Schick et al. 2001) and Talinay (e.g. Rutllant et al. 2017). Results from these experiments have permitted the recognition of episodic strong water collection events in connection with the rear edge of coastal lows with northwesterly winds (advective *camanchacas*), and other more frequent, albeit less intense, orographic lifting events of the moist marine boundary layer air under southerly winds (orographic *camanchacas*) (e.g. Cereceda et al. 2002).

A simple calculation provides an order of magnitude of this fresh water resource. Consider a fog-collection mesh with surface area A (m^2) and a cloud with liquid water content L ($l\ m^{-3}$), moving across the mesh with speed U ($m\ s^{-1}$) perpendicular to it. Then the cloud volume crossing the mesh in 1 s is UA ($m^3\ s^{-1}$), and the collected water would be $\alpha\ UAL$ ($l\ m^{-2}\ s^{-1}$), where the collecting efficiency α (typically 10%) depends on the cloud droplet size distribution, mesh material and framework. Since characteristic collected water volumes range between 2 and 12 lt m^{-2} day^{-1} and assuming 8 days of water collection per month during 6 months, mean annual collected water volume would be around 250 l for a 1 m^2 mesh.

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Chapter 3
Precipitation, Temperature and Evaporation

Lina Castro and Jorge Gironás

Abstract In this chapter, spatial and temporal patterns of temperature, precipitation and potential evapotranspiration along Chile are shown and analyzed in detail. Data obtained from gridded maps provided by the Centro de Ciencia del Clima y la Resiliencia (CR2), as well as 874 precipitation stations and 376 thermometric stations belonging to the Dirección General de Aguas (DGA), and Dirección Meteorológica de Chile (DMC) are used for this purpose. On the other hand, potential evapotranspiration was estimated using the Thornthwaite method. The Mann Kendall (MK) statistical test of trend with a 5% of significance level was used for the identification of temporal trends in temperature and precipitation.

Keywords Precipitation · Temperature · Evaporation · Evapotranspiration · Data · Weather stations · Spatial distribution · Long term patterns · Temporal trends

3.1 Introduction

The evaluation of long-term meteorological variables as temperature, precipitation and evapotranspiration, is essential for water resources planning and management, as well as for other activities such as crops management and irrigation, hydropower generation and drinking water supply. This evaluation has become even more

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relevant considering recent changes in climate due to the increment in greenhouse gases concentrations in the atmosphere, with increasing temperatures and decreasing precipitations in Chile's middle latitudes (Vicuña et al. 2011, 2013).

Air temperature is one of the main data for the observation of water balance and the input for hydrological and agrometeorological models. This variable is needed for calculating net radiation and evapotranspiration, and in the agricultural field it is a piece of information that allows the estimation of a crop's phenological stage. In snowmelt-driven basins, air temperature helps estimate the zero-degree isotherm and then differentiate the area with a liquid or solid contribution, which is a condition to assess the accumulation and later melt at snowmelt time.

Precipitation is the main meteorological forcing, as it is heavily involved in hydrological processes such as infiltration, runoff, and snow accumulation. Therefore, it is an indispensable component of water balance for the management of water and agricultural resources. This variable's spatial and temporal variability and its randomness makes it a continuous object of study, especially in countries where the observation network is scarce or nonexistent. The variable's distribution and magnitude condition hydrological systems' responses, so it causes uncertainty for the management and design of hydraulic structures. The estimation of precipitation at a spatial level is complex, and that complexity grows as the temporal resolution increases. In basins with complex topography, knowing precipitation's spatiotemporal variability is a challenge, even more so considering the climate change conditions that have affected natural variability.

Potential evapotranspiration (PET) is one of the indicators of water demand of a referential crop's surface; consequently, PET enables the quantification of water use in any type of crop. PET is quantified and becomes the input for water resource planning (based on the calculation of water balance), crop yield prediction, the climate characterization in different zones, irrigation management, and for the planning and use of land according to water availability, especially in agricultural grounds located in arid and semiarid zones, where the dry season coincides with that of the highest requirements for crops (Sánchez and Carvacho 2006; Sánchez Martínez and Carvacho Bart 2011).

In this chapter, spatial patterns of temperature, precipitation and potential evapotranspiration along Chile are shown and analyzed using data obtained from gridded maps and meteorological stations. On the other hand, there are other processes in nature, which do not produce cyclical variations in the components of the climate system but rather constant increases or decreases, defining long-term trends. One of these processes is global warming, recognized as a sustained increase in surface temperature of the order of 0.2 °C per decade over the last 30 years (Hansen et al. 2010). Thus, this document presents temperature and precipitation trends using time series with both sources of information. The data observed in weather stations are extreme temperatures and daily accumulated precipitation. The potential evapotranspiration was estimated using the Thornthwaite method for which it is required the mean temperature and the daylight coefficient (Thornthwaite 1948). For the calculation of the temporal trend of temperature and precipitation, it is used the Mann Kendall (MK) statistical test of trend (Kendall 1955; Mann 1945) with a 5%

of significance level, and an estimator of the slope of that trend. The MK test is one of the most widely used nonparametric tests to detect significant trends in time series (Vicuña et al. 2013), giving positive values for increasing trends, and negative values for decreasing trends. The magnitude of that linear trend is evaluated using the nonparametric slope estimator Thiel – Sen (TS estimator) (Sen 1968).

The records of precipitation and temperature come from databases of the Directorate General for Water (DGA) and the Chilean Weather Service Agency (DMC), vector maps from the (DGA) and grid maps from the Centre for Climate and Resilience Research (CR2). DGA and DMC count on 874 precipitation stations and 376 thermometric stations located in diverse points of the Chilean territory. Most of those stations are located in the central valley and in the center-south region of the country, with low density in the north and south, as well as in the Andes (Fig. 3.1). On the other hand, the length of the records of this institutions are not uniform and present a high percentage of missing data, just 343 precipitation stations and 82 thermometric stations count on records of 30 years or more (Fig. 3.2).

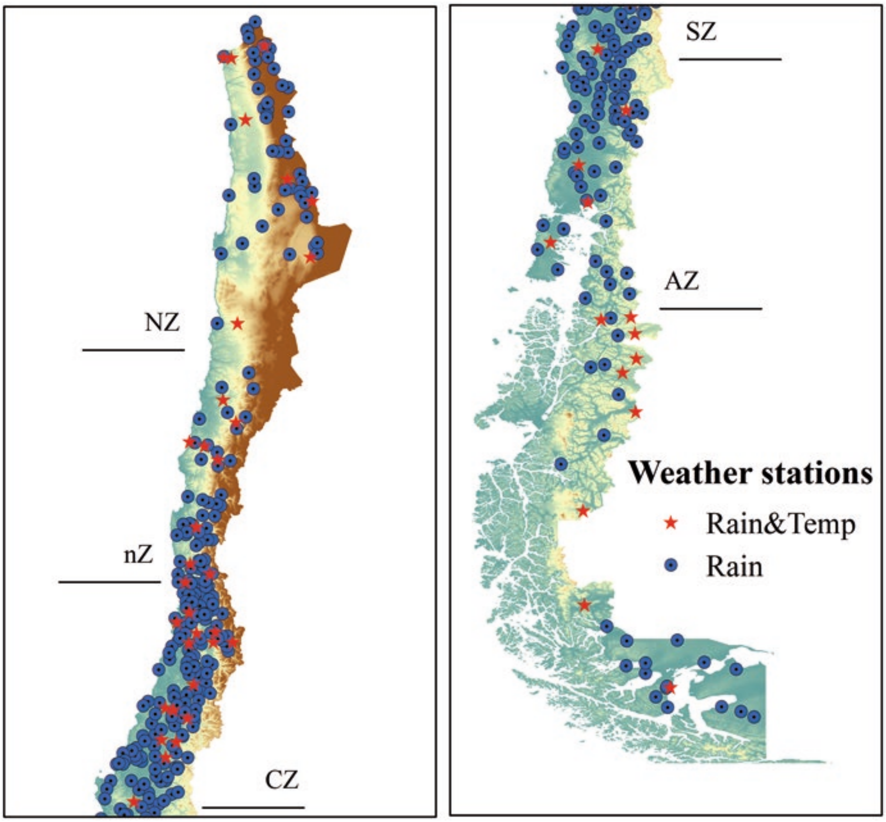

Fig. 3.1 Weather stations from DGA and DMC: Rain and temperature gauges. The gray and dotted gray lines are the natural zones

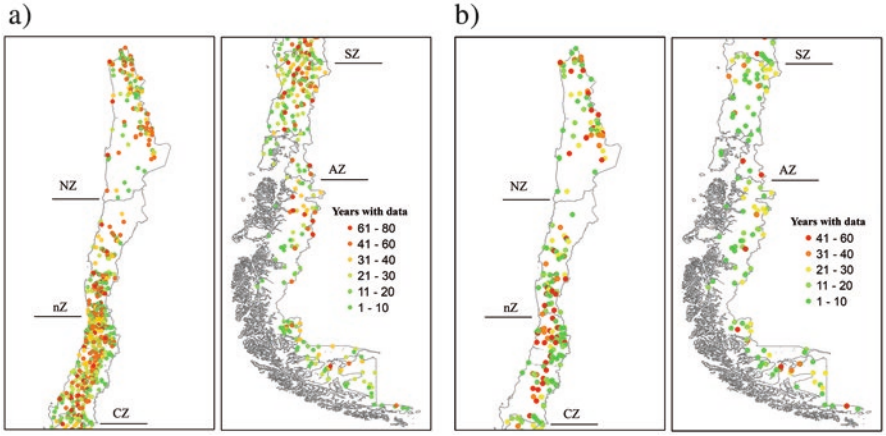

Fig. 3.2 Recording period for (**a**) rainfall and (**b**) thermometric stations

The density, spatial and temporal coverage of the monitoring stations is not enough to generate spatial patterns or generate maps of temporal trend at country level. Although DGA and DMC counts on 874 precipitation stations and 376 thermometric stations, just a part of them counts on enough data to perform space-time analysis generalized for all of Chile (Fig. 3.2). Additionally, DGA counts on annual mean precipitation and temperature vector maps that were generated in the water balance of Chile with data comprehended between 1951 and 1980 (DGA 1987).

Given the scarcity of meteorological stations any method of spatial interpolation will be subject to high uncertainty, and therefore the CR2 Gridded Products (CR2MET) generated in the framework of the "National Water Balance Update" was used as additional information (DGA 2017). These products were made from local observations, re-analysis data (ERA – Interim) and satellite images (MODIS LST), and a methodology of spatial interpolation developed for this project. In the DGA report (DGA 2017) it is shown how temporal correlations, between the product CR2MET and the observations, were above 0.7 at the center-south zone of the country, decaying towards the more distant regions and with low density of meteorological stations. However, this new source of information delivers a valuable set of specialized maps of the extreme daily temperatures and the daily precipitation, available in a rectangular grid of 0.05° latitude-longitude, for a period of time 1979–2016.

Recognizing the importance of the observations in the monitoring stations of DGA y DMC, and with the purpose of coinciding in the analyzed period of time in both sources of information (local and grided), records of 38 years between 1979 y 2016 were downloaded. The maps, tables and figures generated in the spatial and temporal analysis of the meteorological variables, were made in monthly, seasonal (autumn – winter: April to September, spring – summer: October to March) and annual (January to December) scale. Additionally, considering that Chile is a country that crosses all the climatic zones from north to south, the analysis are also summarized in special units called Natural Zones: (a) Big North – NZ (18–26°S): from Arica to Antofagasta; (b) Little North – nZ (26–32°S): from Atacama to Coquimbo; (c) Central Zone – CZ (32–37°S): from Aconcagua to Bio Bio; (d) South Zone – SZ (37–45°S): from Araucanía to Los Lagos Region; and (e) Austral Zone – AZ (45–56°S): from Aysen to Magallanes (Fig. 3.1).

3.2 Temperature

Continental Chile extends throughout a wide latitudinal range, from 18°S to 56°S, from west side of Andes Mountains to the Pacific Ocean, covering a wide range of climatic regimes that go from extreme aridity in the north, passing through Mediterranean climate in the center-south of the country, until the south with precipitation the whole year. The factors that influence thermal differences the most are: latitude, which affects the caloric intake in surface; the height above the sea level, which is represented by two mountain chains (Coastal Mountain Range and Andes Mountains) that influence in the wind and in the sea air access to the central depression; the atmospheric circulation, with presence of low and high pressures, nature and amount of cloudiness, wind, etc.; and the maritime influence, which modifies favorably the temperature, with less cold winters and cooler summers on the coast, and the Humbolt Current that mainly regulates the temperatures of the north zone.

The El Niño-Southern Oscillation (ENSO) and the associated sea surface temperature (SST) anomalies of the adjacent ocean, greatly influence the temperature along Chile, especially in the north and center-south of the country. The magnitude of ENSO-related SST anomalies and associated near-surface temperature departures decrease southward from their largest values in the tropics (Garreaud 2009; Montecinos et al. 2003). Garreaud (2009) affirm the overall pattern is that El Niño episodes are associated with (a) below average rainfall over tropical South America, (b) above average precipitation over subtropical South America, and (c) warmer than normal air temperature at tropical and subtropical latitudes. Generally opposite conditions prevail during La Niña episodes. In the austral zone of Chile, there is no clear sign of influence of the ENSO in the temperature or precipitation. In contrast, the Southern Annual Mode (SAM), an atmospheric mode of circulation characterized by pressure anomalies of one sign centered in the Antarctic and anomalies of opposite sign on a circumpolar band at about 40–50°S, appears to modulate the air temperature over the southern tip of South America (Garreaud 2009; Gillett et al. 2006).

This section shows the spatial patterns of temperatures throughout Chile. The source of data used to generate the maps is: extreme temperatures observed in meteorological stations with 30 years or more (minimum recording period of 1986–2016), CR2MET gridded maps, and a map of the average annual temperature generated by the DGA for the national water balance (DGA 1987). The resulting maps are shown at monthly, seasonal (spring-summer, fall – winter) and annual scales. Section 3.2.1

presents the spatial pattern of extreme temperatures calculated with local observations and CR2MET products, Section 3.2.2 presents an analysis of the temporal trends of the temperature series with the two data sources, and Section 3.2.3 presents the potential evapotranspiration calculated with the observed mean temperatures, with the CR2MET gridded maps and the actual evapotranspiration obtained in the Water Balance for Chile (DGA 1987).

3.2.1 Temperature Long Term Pattern

To analyze the observed data, we used 57 of the 376 thermometric stations; the others were discarded because they had a record period below 30 years and missing data above 20%. Mean annual records were synthesized in a boxplot per natural zone for data observed in stations and those obtained with CR2MET in the pixels coinciding with the stations (Fig. 3.3). In both cases, Tmin and Tmax have similar ranges of variation and means. Observed records show Tmin variations between −7 °C and 20 °C at an annual scale, with a variation range between −16 °C and 24 °C at a monthly scale (not shown in the figure). The Tmin has a wide range of variation between 5 °C and 17 °C in the ZN with a mean of 14 °C, whereas the variation range of the other zones is not higher than 3°. In the nZ the mean is around 10 °C, in the CZ 8 °C, in the SZ 6 °C, and in the AZ, 3 °C. The annual mean

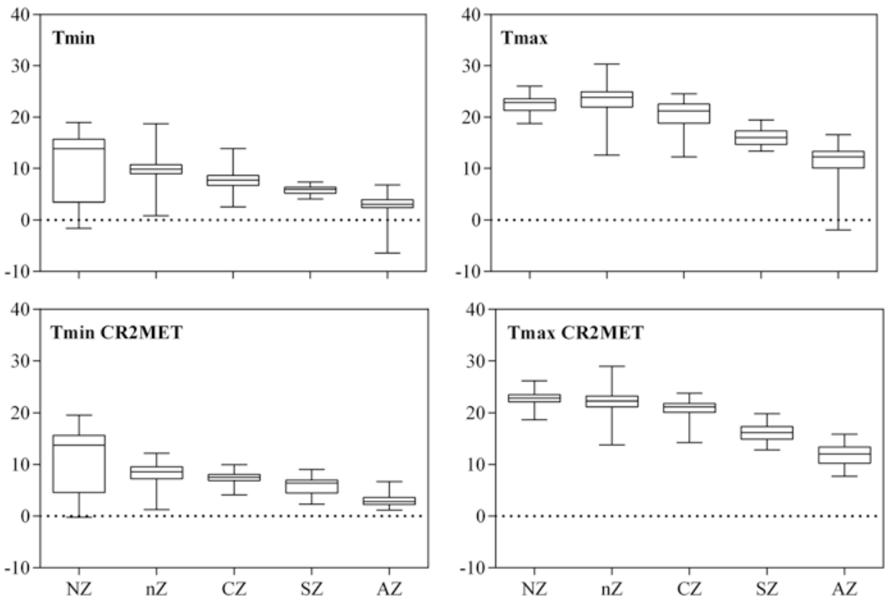

Fig. 3.3 Minimum and maximum annual average temperature by natural zone obtained from the meteorological stations (first row) and the CR2MET (second row) for the period 1979–2016

maximum temperature varies from −2 °C to 31 °C in the case of the observed records, with a narrow variation range per natural zone. The ZN shows a 23 °C, mean for the Tmax, which is similar to that obtained in the Zn (24 °C), decreasing to 21 °C for the ZC, to 16 °C for the ZS and to 12 °C in the ZA. The most influential factors for thermal differences are the following: relief – through the altitudinal decrease in the Andes, and the impeded access of sea breeze towards to central depression; the solar declination angle, which generates less radiation at a higher latitude (Fuenzalida et al. 2006); and lastly, the regulating effect of marine waters in coastal areas. The minimum temperature's variation range observed in the ZN reflects the daily thermal amplitude resulting from a great atmospheric transfer. The latter occurs especially at night, when there is a great heat loss due to nocturnal radiation from the surface to the atmosphere and which brings about an abrupt cooling of the surface (Henríquez 2013).

Figure 3.4 shows the spatial variation of the extreme annual mean temperatures (Tmin, Tmax) and the mean temperature (T2m) obtained from CR2MET and the DGA's-generated map in 1987. The figures show how temperatures vary in latitude, decreasing from north to south and longitudinally due to elevation. Additionally, Fig. 3.3 shows the variation ranges of extreme temperatures observed and obtained with the CR2MET per natural zones, and for the points that coincide in both data sources. These temperatures show, at least in terms of variation range and means, a high coincidence. The Tmin – CR2MET throughout the Chilean territory shows a

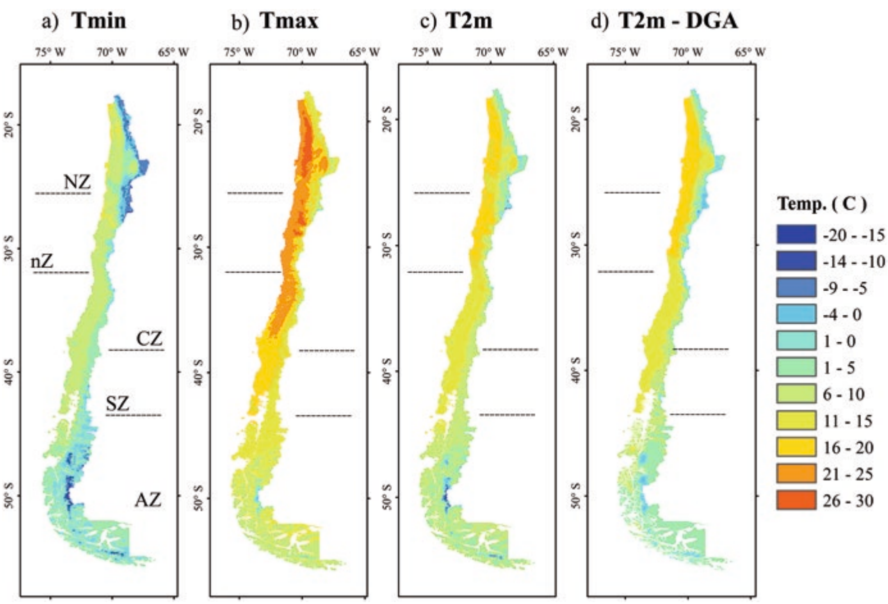

Fig. 3.4 Spatial distribution of mean temperature at annual temporal scale for (**a**) Minimum temperature, (**b**) Maximum temperature, (**c**) mean temperature with CR2MET data, and (**d**) mean temperature with DGA (1987)

variation from −20 °C to 17 °C (Fig. 3.4a), with minimum temperatures in the north in Chilean plateau of the Andes, and also in the country's austral zone in the Pascua and Baker river basins, in the Patagonian mountains. The Tmax – CR2MET (Fig. 3.4b) shows a variation range from −8 °C to 30 °C throughout the Chilean territory, where predominant temperatures are above 15 °C from the SZ (The Rivers Region) to the NZ, except for the high zones of the Andes in the north, where temperatures are below 15 °C and reach a Tmax of −8 °C. The temperatures obtained with the CR2MET (Tmax, Tmin, T2m) in Chilean plateau at north of the Andes are characteristic of the tundra climate, present in dry and always cold zones in the north. The minimum temperatures in the south of the country in the Magallanes Region are characteristic of a cold high-altitude climate with temperatures below 0 ° C throughout the year, with preferably solid precipitations. On the other hand, the maximum temperatures occur in the intermediate depression of the NZ and nZ, characteristic of desert climates, with very warm summers and daily thermal oscillations that can reach 35 °C. In contrast, the temperatures along the coast are always spring-like, with variations from 6° to 25 °C. The analysis of coinciding points (weather station – pixel, Fig. 3.3) in the CR2MET show a variation range of Tmin and Tmax respectively between 0 °C and 20 °C / 18 and 26 °C for the NZ, between 1 °C and 12 °C / 14 and 29 °C for the nZ zone, between 4 °C and 10 °C / 14 and 24 °C for the CZ, between 2 °C and 9 °C / 13 and 20 °C for the SZ, and between 1 °C and 7 °C / 8 and 16 °C in the AZ. The variation and mean ranges are similar to that of weather stations, where the most noticeable differences are the inferior extremes of extreme temperatures, with recorded minimum temperatures reaching −10 °C and − 2 °C for the Tmin and Tmax, respectively.

In regard to T2m, both data sources show a high spatial matching in a considerable part of Chilean territory, despite different methodologies used in interpolation and period of records used to obtain them (DGA: 1951–1980, CR2MET: 1979–2016). Both in T2m-CR2MET (Fig. 3.4c) and T2m-DGA (Fig. 3.4d), the temperature variation is in the range between −10 °C and 20 °C. In both graphics the differences in the plateau at the north of the country and at the austral zone stand out, in addition to an increment of the temperatures in the Andes Mountains along the country. Vicuña et al. (2013), Stolpe and Undurraga (2016) and Burger et al. (2018) agree that there is a significant tendency to temperature increase in several zones of Chilean territory, being noticeable in the Andes, which in turn helps to explain the negative mass balance of snow and glaciers recorded in the region. As with the extreme temperatures, the range of variation and median by natural zones coincide in both data sources. The T2m is between 12 °C and 23 °C in the NZ, between 14 °C and 17 °C in the NZ, between 12 °C and 16 °C in the CZ, between 10 °C and 13 °C in the SZ and between 4 °C and 9 °C in the AZ.

Figure 3.5 shows the mean temperature, for Tmin, Tmax and T2m with CR2MET data, for the spring – summer season (October–March), or growing season. The ranges of variation of Tmin – CR2MET are around −20 °C, in certain zones at the south and north of the country, to 20 °C in NZ, although most part of the country is distributed between 6 °C and 15 °C. The Tmax – CR2MET is in the range of −9 °C

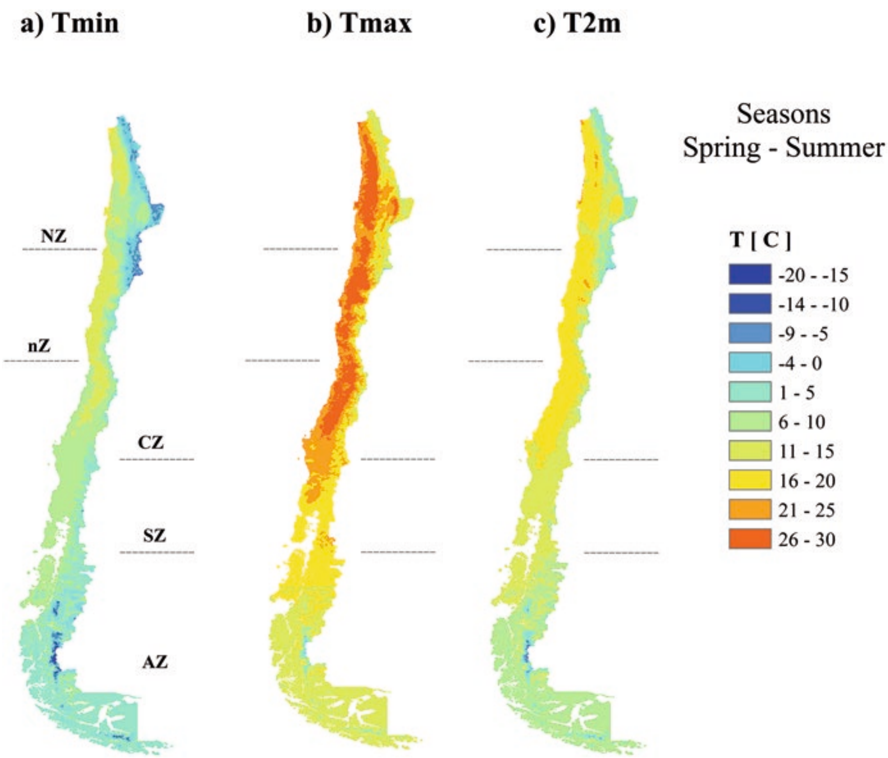

Fig. 3.5 Spatial distribution of mean temperature in Spring and Summer seasons for (**a**) Minimum temperature, (**b**) Maximum temperature and (**c**) mean temperature using CR2MET

to 30 °C, with maximum temperatures that go above 20 °C from the north of the Araucanía Region in SZ to NZ in the coast and intermediate depression. It can be seen in Fig. 3.5a and b that higher thermal oscillations in spring – summer occur in the intermediate depression and in the plateau, with minimum temperatures below 0 °C and maximums that can reach 20 °C. The minimum oscillations occur in SZ and AZ, with minimums close to 0° y maximums that do not exceed 30 °C. T2m – CR2MET varies between −13 °C and 21 °C, with temperatures above 16 °C from Central Zone to Big North, excepting the plateau that keeps temperatures between 1 °C and 10 °C in the growing season.

Figure 3.6 shows a monthly variation obtained with T2m – CR2MET products throughout the year in the studied period. The T2m-CR2MET behavior varies as seasons of the year show up: high temperatures from November to March, spring – summer, and low temperatures from April to October, autumn – winter. NZ and nZ of the country keep temperatures above 10 °C, with permanent maximums in the valley of Tarapacá region. Colder temperatures are present in Magallanes region in the Austral Zone of the country, specifically in the Patagonian mountain range, where it can be seen mean T2m below zero degrees centigrade almost all year

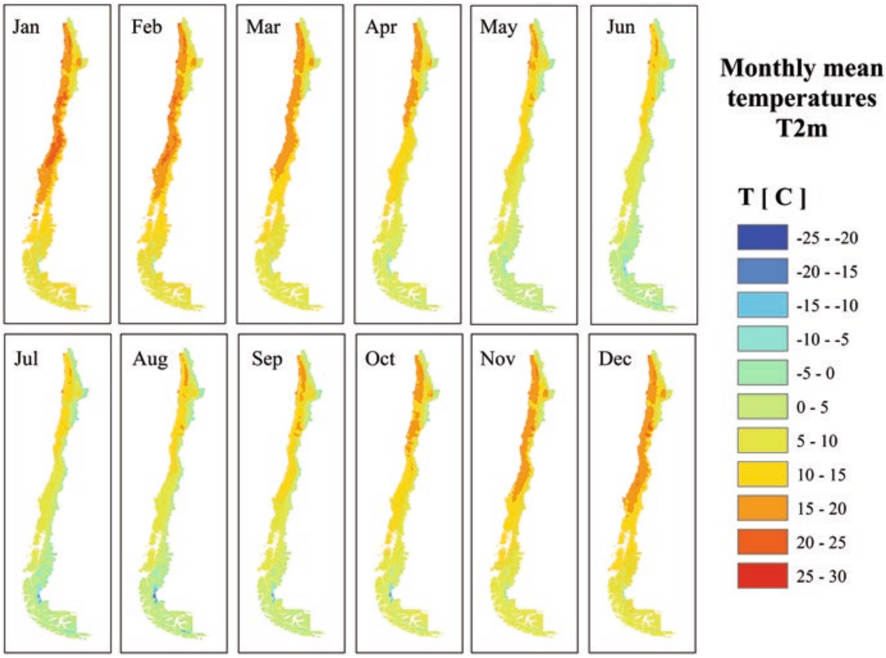

Fig. 3.6 Monthly mean temperatures with T2m – CR2MET data

excepting the months of December and January when they rise to 5 °C. In center-south zone of the country the temperatures oscillate between 10 °C and 30 °C in the central valley, less extreme temperatures in the coast that do not exceed 25 °C on average, and cold weather of height towards the Mountain Range which temperatures vary from −10 °C to 10 °C on average.

3.2.2 Temperature Trend Analysis

The detection of change in the long term of climatic variables over the Chilean territory is one of the first efforts that must be made before developing effective actions of mitigation and adaptation for the potential climate change and for the future analysis of water balances under a changing climate (Kukal and Irmak 2016). Several authors in recent years have taken charge of evaluation of temporal trends in meteorological variables in Chile (Burger et al. 2018; Meseguer Ruiz et al. 2017; Schulz et al. 2012; Stolpe and Undurraga 2016; Vicuña et al. 2011, 2013). Therefore, it is not objective of this chapter to make a trend analysis, but to show the trend at country using the new database CR2MET (Alvarez-Garreton et al. 2018; DGA 2017), the observed data in ground stations and compare this with the results of several studies carried out in Chile. This section involves the calculation of the

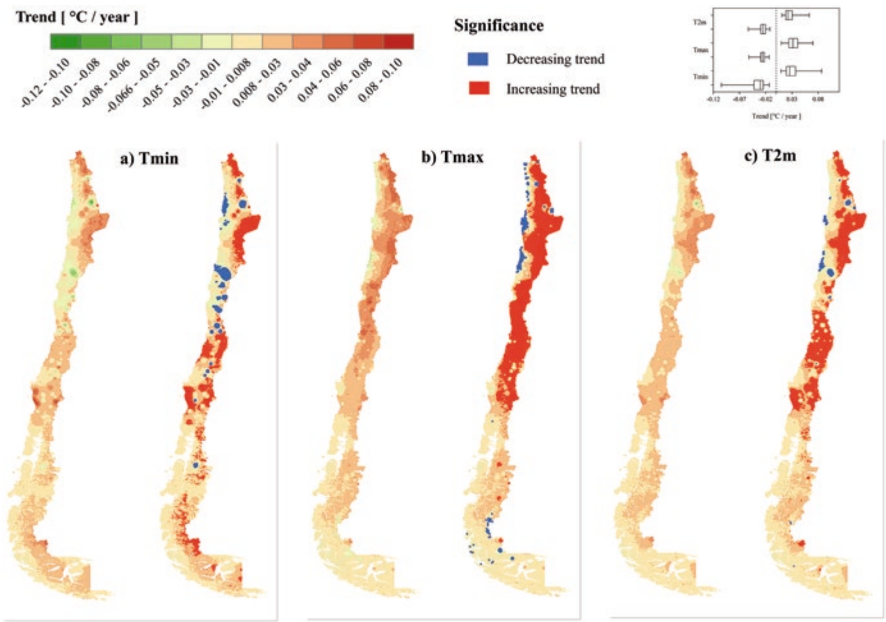

Fig. 3.7 Trend values in °C/year. Trend in colors indicate the observed trend is statistically significant at 95% confidence level of extreme and mean temperatures, (**a**) Tmin, (**b**) Tmax, (**c**) T2m. Top panel, trend values only for those cells with significant trend

Mann – Kendall test and the Theil-Sen slope estimator for the maximum and minimum temperature, and the mapping of that trend for the period 1979–2016.

Figure 3.7 was built using the monthly products of the CR2MET and adding them at an annual scale. As a result, it was obtained a temporal series of 38 years of records spatially distributed over all Chile. The value of the trend in [°C/year] was calculated with the Thiel-Sen estimator, after the calculation of the statistician Mann-Kendal, following the methodology proposed by Valdes-Pineda et al. (2016) and Kukal and Irmak (2016). There are highlighted in red those pixels with significant trend (with $\alpha = 0.05$) to increase and in blue those pixels with significant trend to decrease of temperature. In the upper right part of the figure, it is shown a diagram of boxes that summarizes the temperature variation for those pixels with a significant tendency to increase the temperature (right side) and decrease the temperature (left side). Figure 3.7 shows that the trend in general is to increase the temperatures especially in center south zone of the country and in Andes to the north. The estimated trend for Tmin varies from +0.01 to +0.09 °C/year, for Tmax there are noted trends from +0.01 to +0.07 °C/year, and for T2m there are noted trends from +0.01 to 0.06 °C/year with a median around +0.03 °C/year. The zones with tendency to temperature decrease the are few in relation to those that show trend to increase. However, it draws attention to see how the trend to decrease the temperature occurs in the north coast of the country with values

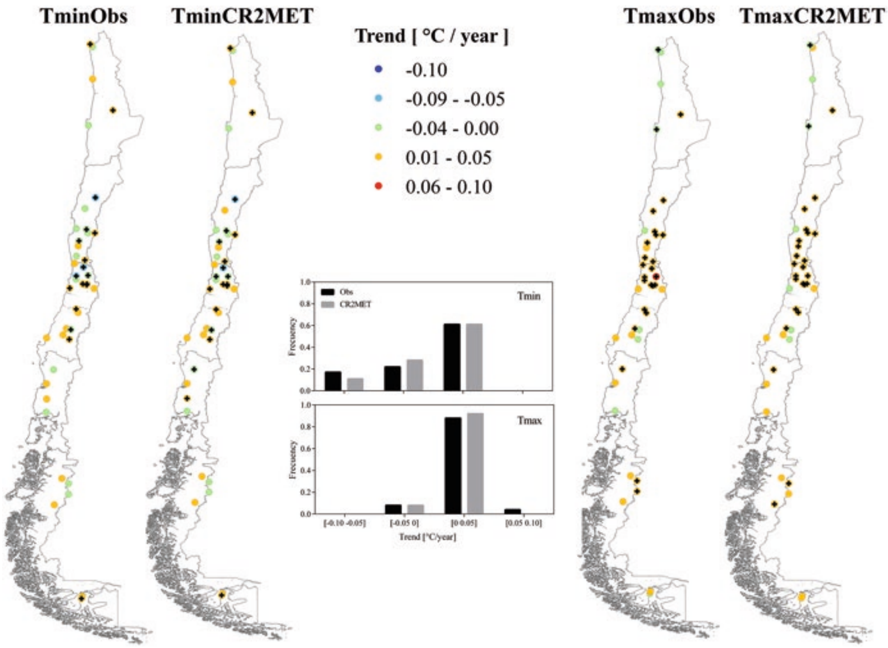

Fig. 3.8 Trend [°C/year] in minimum and maximum temperatures using local observations and CR2MET for the same locations, using last a 38 year of records (1979–2016). Significant trends are marked with a cross

from −0.10° to −0.01 °C, being higher for the Tmin than for the other temperatures.

Although the CR2MET products are a valuable source for the spatiotemporal analysis of meteorological variables throughout the Chilean territory, one should be skeptical about the results of a trend analysis for products generated from multiple sources. For this reason, we chose those CR2MET pixels that coincided with the location of thermometric stations (coinciding pixels). For each of these pixels, we calculated the trend and significance, and then compared that with the estimations from the data observed for the same period of time. Figure 3.8 shows the calculated trend for 47 thermometric stations that fulfil a similar period to that used in the CR2MET and the aforementioned criteria. The local data trend varies between −0.05° and +0.06 °C/year for the Tmax and it varies between −0.09° and + 0.05 °C/year for the Tmin, a range that is similar to that estimated with CR2MET data. The trend is significant for the two sources of data in more than 40% of the thermometric stations throughout the country, especially in the center-south zone. For those stations with significance (shown in the figure with black crosses), the Tmin shows an upward trend in 60% of them, while the Tmax shows an increase by more than 90% with the majority of values being between 0.02° and 0.05 °C/year (see Fig. 3.8's histograms).

In Chile's center-south zone, temperature temporal trend analyses have been carried out (Burger et al. 2018; Vicuña et al. 2013; Stolpe and Undurraga 2016; Garreaud 2011; Falvey and Garreaud 2009), and these agree on the fact that trends in the extreme temperatures are positive and significant for the central valley and the Andes in fall, spring, and summer. In northern Chile, Schulz et al. (2012) and Meseguer Ruiz et al. (2017) have also found intensified dryness, a long-term positive trend, with a clear increase of minimum temperatures in the central valley, and a slight tendency for Tmax to decrease in the coastal zone, which are results coinciding with those found with the CR2MET database. Carrasco et al. (2008) evaluated temperature from radiosondes throughout Chile, showing significant trends for the studied period 1958–2006 from Antofagasta to the central zone (Quintero/Santo Domingo) with values of 0.22 +/− 0.01 °C per decade for Antofagasta, and 0.15+/− 0.1 °C per decade for Quintero and Santo Domingo throughout the year. On the other hand, in Puerto Montt (south zone), the significant change occurred only in summer season and reached 0.14 °C per decade.

3.2.3 Potential and Real Evapotranspiration

While evaporative flows are an essential element in water balance, they represent a variable that is difficult to measure (DGA 2017). The atmosphere's evaporating power is affected by multiple meteorological factors, such as solar radiation, air temperature, relative humidity as a measure of the environment's evaporative capacity, and wind's speed. However, in addition these factors, evaporative flows depend on vegetation characteristics, its density and stage of growth, soil properties, and the humidity content (Sánchez Martínez and Carvacho Bart 2011). Potential evotranspiration (PET) refers to the maximum water quantity that a soil's surface covered in vegetation is able to transfer, considering that vegetation grows in optimal conditions, without water supply limitations and depending only on the atmospheric conditions at the moment of estimation (Sánchez Martínez and Carvacho Bart 2011). PET can be regarded as equivalent to the concept of evotranspiration of reference (ETo) (Mckenney and Rosenberg 1993), which is estimated for a grass crop growing with all the water at its disposal and free of diseases (Allen et al. 2006). To know PET or ETo's magnitude several methods have been developed that are based on aerodynamic theoretical considerations, energy balances, and empirical, semi-empirical and combined formulations. The theoretical ones have been focused on estimating potential evaporation while the others have mostly focused on PET. Among the physics-based methods, both empirical and semi-empirical, in Chile those most well-known and used are Penman's equation (Penman 1948, 1963), Turc's method (Turc 1961), Blaney–Cridle (Blaney 1959), and Thornthwaite's method (Thornthwaite 1948).

In Chile, irrigation projects require the estimation of water demand. Although to do so we need to estimate PET, guidelines do not enforce the use of an alternative. Penman's method is the most reliable; even though it uses few variables (temperature, relative humidity, and solar radiation) it has not been extensively applied since neither HR nor solar radiation are frequently measured variables in the territory. Similarly, Turc's method requires average temperature, global radiation, and relative humidity. Blaney – Criddle and Thornthwaite's methods only require average temperature and the hours of daylight coefficient. Given the data availability throughout the country, we decided to apply Thornthwaite's method (TM) using as input the monthly mean temperatures obtained from CR2MET products and the estimated hours of daylight coefficients according to each pixel's geographical coordinates and Earth's solar distribution theory (Bras 1990).

If the estimation of the potential evapotranspiration requires knowing the variables that interfere in it, the estimation of the real evapotranspiration (RET) is the result of a water balance evaluation. Nowadays, an update of the national water balance (DGA 2017) is being done, where one of the expected results is the real evapotranspiration rate at different temporal scales. However, the results are not available, so in this section it will be shown the real evapotranspiration estimated in the Water Balance of 1987 (DGA 1987). It should be noted that the RET map of the DGA was obtained from partial studies of the time and it refers to real evapotranspiration of natural surfaces and of crops. The RET map of 1987 is available at the DGA in vector form (shape), but was rasterized for comparison purposes.

Figure 3.9a shows the annual accumulated PET obtained from Thornthwaite's method (TM) with CR2MET's multiannual monthly mean temperatures and hours of daylight rates. Figure 3.9b is the RET obtained from the water balance of 1951–1980 in shape format and rasterized to the same scale as that of CR2MET. Once the TM is applied, PET is directly proportional to the theoretical sunshine hours and the monthly mean temperature, which is reflected in Fig. 3.9a. The figure shows that from north to south there is a decrease of evaporative potential, with maximum values of up to 900 mm/year in the intermediate depression of the Atacama's region, Antofagasta and Tarapacá, where there is the greatest amount of radiation and the highest temperatures. The spatial variation is also observed from west to east as a result of mean temperature variation, which is lower as the Andes ascend (Fig. 3.3). In fact, the lowest PETs occur in the north of the country in the plateau zone of Andes and the Patagonian mountains in the south. In the NZ and the nZ, PET shows means with values near to 700 mm/year (Figs. 3.10 and 3.11a), with monthly variations that depend on the degree of insolation received throughout the year and that have a monthly variability range wider than that observed in the CZ and SZ (Figs. 3.10 and 3.11d, e). The NZ has an annual variation range that goes from 0 to 900 mm/year (Fig. 3.9a), with maximum ranges in the central valley and coast, and minimum ranges in the altiplane and mountain zones. The NZ has an evaporative potential throughout the year with values ranging from 10 mm/month as minimum in July to 85 mm/month in January. In nZ there are fewer areas below 200 mm/year and most values concentrate between 690 and 750 mm/year, with a monthly variation from 10 mm/month in July to nearly 100 mm/month in January. The CZ has a spatial variation ranging with a minimum of 230 to 750 mm/year, a mean of nearly 700 mm/year, and a lower annual and monthly range. That zone's monthly PET ranges from 10 mm/month in June to 122 mm/month in January. The SZ shows a

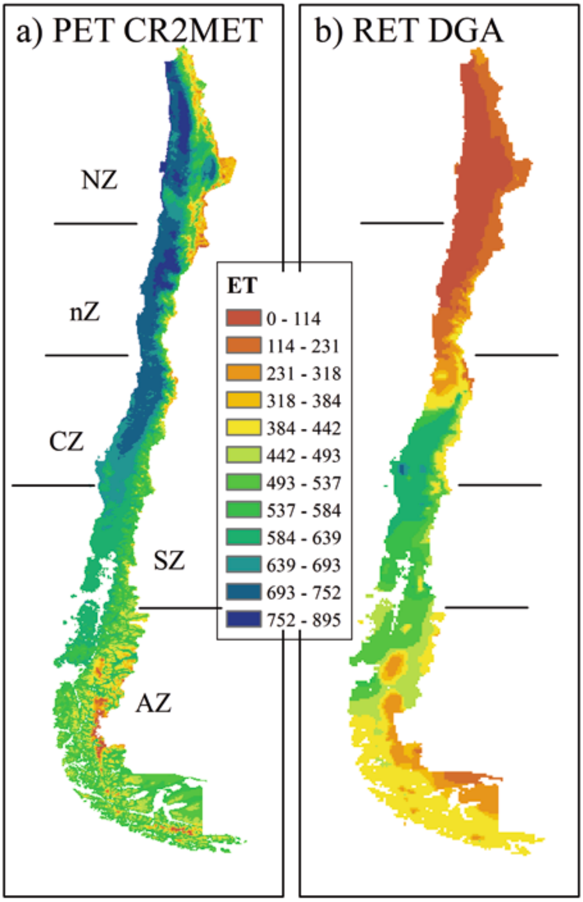

Fig. 3.9 Potential evapotranspiration [mm/year] with CR2MET data and actual evapotranspiration obtained by the DGA (1987)

spatial variation that ranges from 320 mm/year to nearly 700 mm/year, a mean of 600 mm/year, and a narrow annual and monthly range. Monthly, it has minimum and maximum values of 10 and 95 mm/month respectively. The AZ shows a special variation with values within the range of 0 and 640 mm/year, with most values being within the range of 440 to 490 mm/year. At a monthly level, it has minimums of zero PET for June and July, reaching 95 mm/month in January.

According to the DGA study (DGA 1987) (Fig. 3.9b), north zone of the country presents a REP with maximums of 114 mm/year in the intermediate depression and a RET in the range between 114 and 231 mm/year in the Andes Mountains. In NZ and nZ the ET rate exceeds the precipitation rate, a hyper-arid, arid and semiarid systems condition, so RET generated in the zone is not obtained only by low precipitations in the zone but also by evaporation of underground layers (Hernández-López et al. 2016; Johnson et al. 2010; Montecino et al. 2016). In Chile's center-south zone the RET rate is higher with values that can reach approximately 600 mm/year, exceeding the low rainfall that occurs during the year. The center-south zone, or

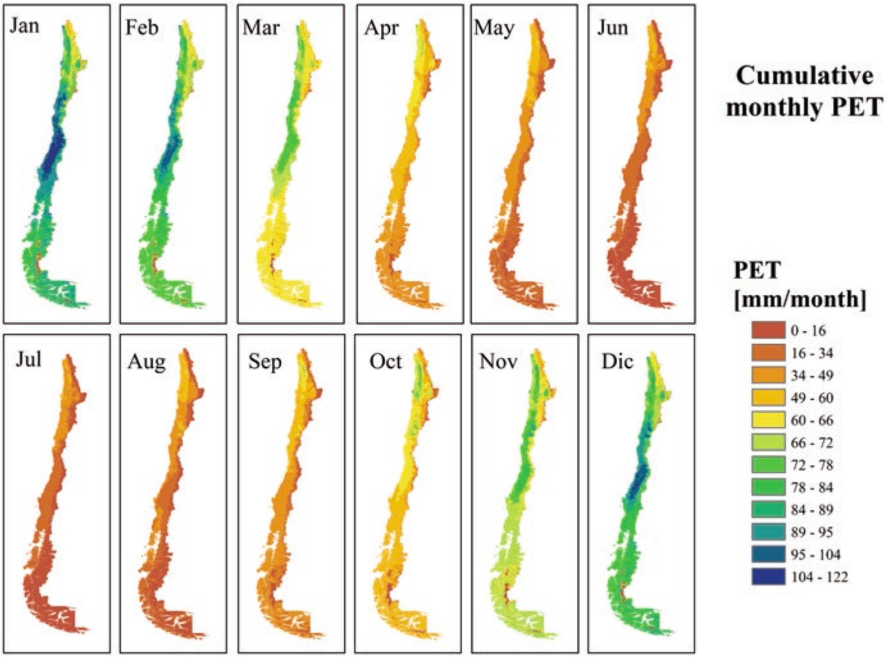

Fig. 3.10 Monthly potential evapotranspiration [mm/month] from CR2MET data

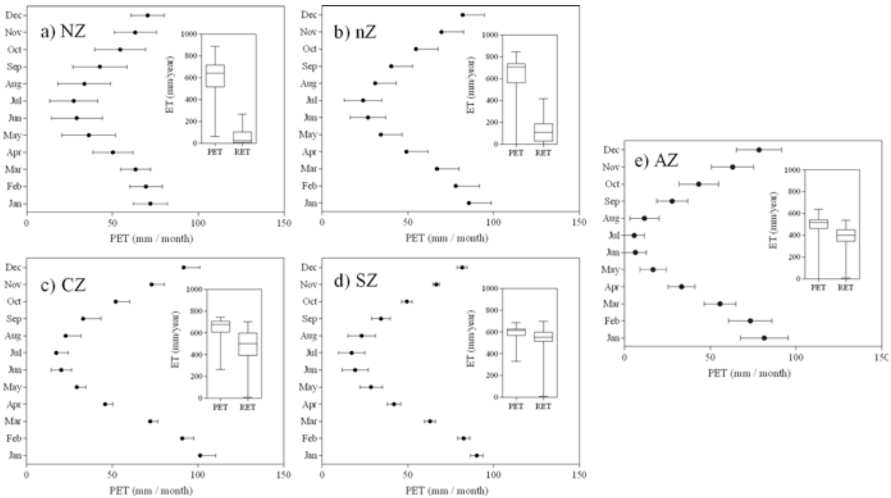

Fig. 3.11 Annual potential evapotranspiration (PET) and real evapotranspiration (PET) (plots inside), and monthly potential evapotranspiration for natural zones. (**a**) NZ. (**b**) nZ. (**c**) CZ. (**d**) SZ. (**e**) AZ

Mediterranean area, presents a high power of evaporation from the atmosphere in the spring-summer periods with values that can reach 122 mm/month. This zone is described by Little et al. (2009) as a semi-arid zone, which is subject to a significant deficit of water, a critical situation in the dry period spring-summer (Olivera-Guerra et al. 2014). It should be noted that this zone is mainly agricultural, and given these RET rates, the water needs for crops exceed a precipitation that basically focuses during the 3 months of winter. In south zone real evapotranspiration is low, the Aysén presents RET that do not exceed 600 mm/year, and in Magallanes region this value does not reach 400 mm/year. Water availability in those zones is plentiful and agricultural crops are incipient.

3.3 Precipitation

Throughout Chile annual precipitation regimes are distinguished, which can be characterized by natural zones. In north of the country (NZ) precipitations are low, concentrated in summer in the plateau zone (heights over 3000 m), but an extreme aridity dominates in lower elevations from extreme north of the country to 27°S. In the plateau, precipitation in summer responds to an excess of latent heat in the atmosphere due to the radiation reflected by the ground that generates a vertical instability in the air and convection (Sarricolea and Romero 2015), the presence of dynamic forcing to lift the air plots near to surface and enough water vapor near the surface (from the South American Monsoon). In nZ, limited by the Atacama Desert to the north and Coquimbo at south, the Andes rises to more than 5000 masl. The above causes strong spatial variations in the annual mean precipitation between the central valley and the mountain range. Precipitation is mainly produced by the passing of extratropical cold fronts during the months of winter, with more than 80% of annual total between May and August (Vicuña et al. 2011). During the passing of cold fronts, the zero isotherm is located around 2500 masl allowing snow accumulation in a considerable part of basins during winter, which turns into the main contribution of flow in that zone during spring and summer. In CZ, there are well defined periods of rainfall, a winter period, and a summer period with an amount of precipitation significantly lower that increases from north to south (Garreaud et al. 2003). The climate of the zone is Mediterranean, with frontal precipitations concentrated between April to September, where storms exhibit a high variability in spatial distribution and intensity given the topographic complexity in the Andes mountains and the coastal range (Falvey and Garreaud 2007). In inter-annual time scales annual precipitation in central Chile shows a range between 100 and 700 mm in Santiago, with wet (dry) years that have a well-documented association with the phases of El Niño (La Niña) Southern Oscillation (Falvey and Garreaud 2007; Montecinos and Aceituno 2003; Montecinos et al. 2000). South and austral region, is characterized by abundant precipitations all year reaching over 4000 mm/year accumulated to the west of Andes mountains and abundant precipitations throughout the coast increasing to the south. In austral zone, the western Patagonia presents a hyper wet mild weather with isotherms to the 1000 masl, a modest seasonal cycle and precipitations reaching 8000 mm/year (DGA 1987). These high accumulations are produced by the orographic rainfall increase, contributing water to vast forests, numerous glaciers, mighty rivers, and to the northern and southern Patagonia ice-fields and to the Darwin mountain range icefield (Garreaud 2009).

The following sections present spatial patterns estimated with the CR2MET products, the annual mean precipitation given by the DGA (1987), the amount of days with rainfall and the observed trend, and lastly the estimation of temporal trends using grid products and local observations.

3.3.1 Long Term Patterns

For the analysis of the observed data, 244 of the 874 rainfall stations were used, the others stations were discarded because they had less than 30 years of recording period or missing data over 20%. Figure 3.12 shows a box diagram with all the annual rainfall for each natural area for both the data recorded at stations and those obtained from CR2MET in the pixels coinciding with the rain gauges. The median of the two data sources is quite similar, with multiannual average rainfall of 110 mm/year in the NZ and nZ of which 72% of the records were below 100 mm/year for the NZ and below 73% for nZ; CZ has a median of 630 mm/year with 80% of annual records below 1200 mm/year; in SZ the median is 1680 mm/year with 78% of annual records between 1000 and 2500 mm/year; and a median of 530 mm/year in AZ with 72% of annual records with rainfall below 1000 mm/year.

Figure 3.13 shows the spatial representation of the mean annual accumulated precipitation provided by the DGA built with rainfall observations for the period 1951-1980 (P.DGA) (DGA 1987) (Fig. 3.13a), the mean precipitation for the period 1979–2016 obtained with the products CR2MET (P.CR2) (DGA 2017) (Fig. 3.13b), and the mean precipitation for the period autumn – winter using CR2MET (P.Wet. CR2) (Fig. 3.13c). In general, it can be seen that there is similarity in the spatial distribution and magnitude of annual precipitation in throughout country (Fig. 3.13a

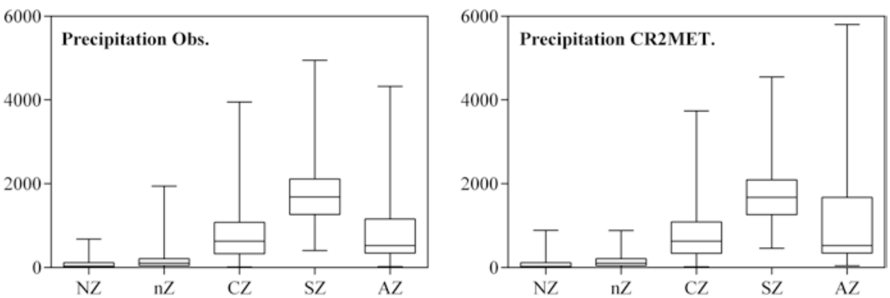

Fig. 3.12 Average annual precipitation by natural zone obtained from weather stations and CR2MET for the period 1979–2016

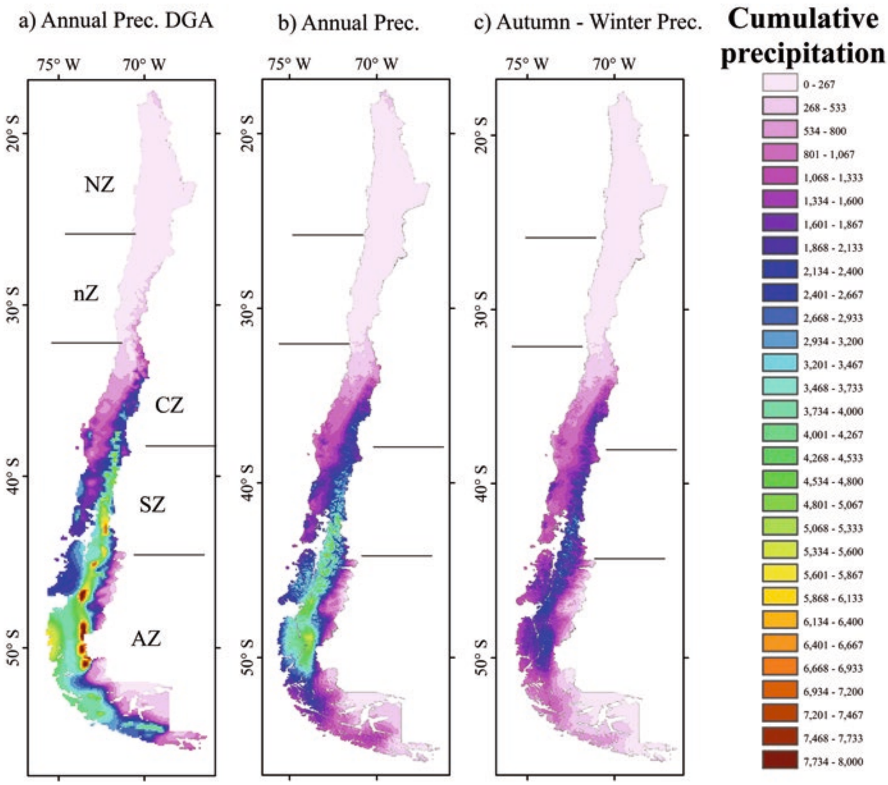

Fig. 3.13 Annual precipitation (**a**) DGA, (**b**) CR2MET, (**c**) autumn – winter precipitation CR2MET

and b), especially in the central-southern zone where the density of stations is higher. It is important to note that the annual precipitation of the DGA presents values that can reach 8000 mm/year at Aysén region and Magallanes Region, especially in the Patagonian, while the CR2MET product reaches a maximum of 6000 mm/year. This change may be the cause of the change in the methodology of spatial interpolation, the recording period used in both sources, and the source of the information basis for its construction. The general pattern in Fig. 3.13a and b shows that precipitation increases from north to south and from west to east on the western slopes of the Andes, the latter due to the orographic effect explained in the introductory part of this section.

Figure 3.13 shows that in the northern zone (NZ, nZ) the annual total precipitation in the mid-depression is extremely scarce, with hyper-arid zones in which precipitation does not reach 1 mm/year (Houston 2006); in the nZ, this amount increases towards the mountains with values averaging 10 mm/month (Fig. 3.15a). During the austral summer, precipitation events occur in the plateau called “Bolivian winter” or South American monsoon, which causes annual precipitation in the mountains (Figs. 3.13a, b, 3.14 and 3.15a) reaching 300 mm/year above 3000 msnm, and a

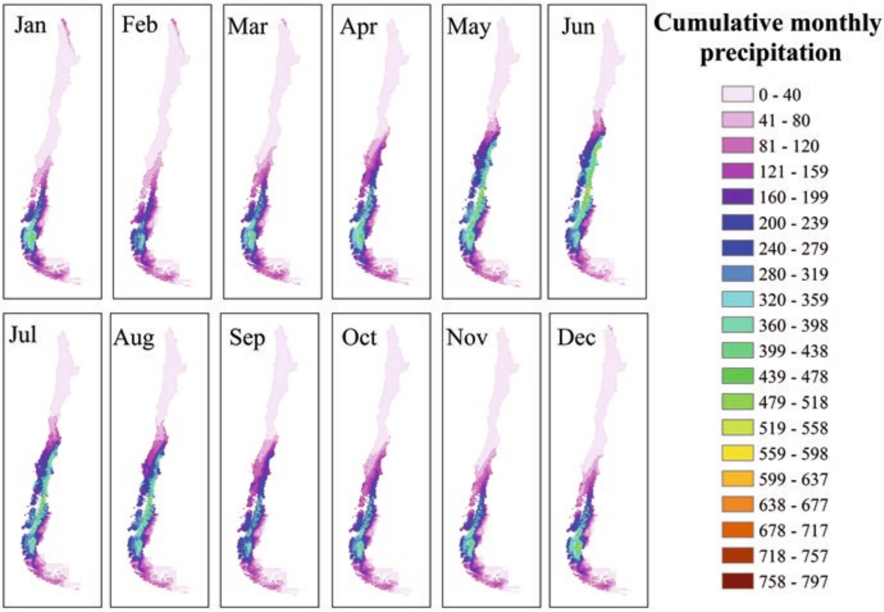

Fig. 3.14 Monthly precipitation [mm/month] using CR2MET products (1979–2016)

rapid descend to 20 mm/año at 2300 msnm (Valdés-Pineda et al. 2016; Mendonça 2017). Despite this, in inferior elevations what dominates is an extreme aridity from the northern limit to 27°S (Fuenzalida et al. 2006). Figures 3.14 and 3.15a show the monthly accumulated precipitation in the NZ, providing evidence that the Bolivian winter occurs mainly at the end of spring and during the whole summer, while it concentrates up to 90% of a whole year's precipitation.

Center – south zone shows an annual precipitation cycle (Figs. 3.13, 3.14, and 3.15c, d) that presents higher accumulation in winter season (April – September), being higher for south zone compared to center zone. Lowest values of precipitation are presented in winter summer with substantial decreases in February. Annual accumulation in these zones of the country vary from 400 mm/year to values over 4000 mm/year, being higher towards western side of Andes Mountains. In fact, the windward slopes of the Andes between 32°S and 35°S can experience up to twice the precipitation observed over the western lowlands (Falvey and Garreaud 2007; Valdes-Pineda et al. 2016).

The southern zone is characterized by abundant rainfall throughout the year, reaching an accumulated rainfall of over 4000 mm/year, but on the eastern slope the amounts decrease by an order of magnitude (Fuenzalida et al. 2006) (Figs. 3.13, 3.14, and 3.15e). South of Los Lagos region (Puelo river basin) and the central depression of Aysén region (Aysén, Baker and Pascua river basins), are the areas receiving the greatest rain and snow contributions all year, although they decline to the south with a value of 1200 mm/year at Cape Horn.

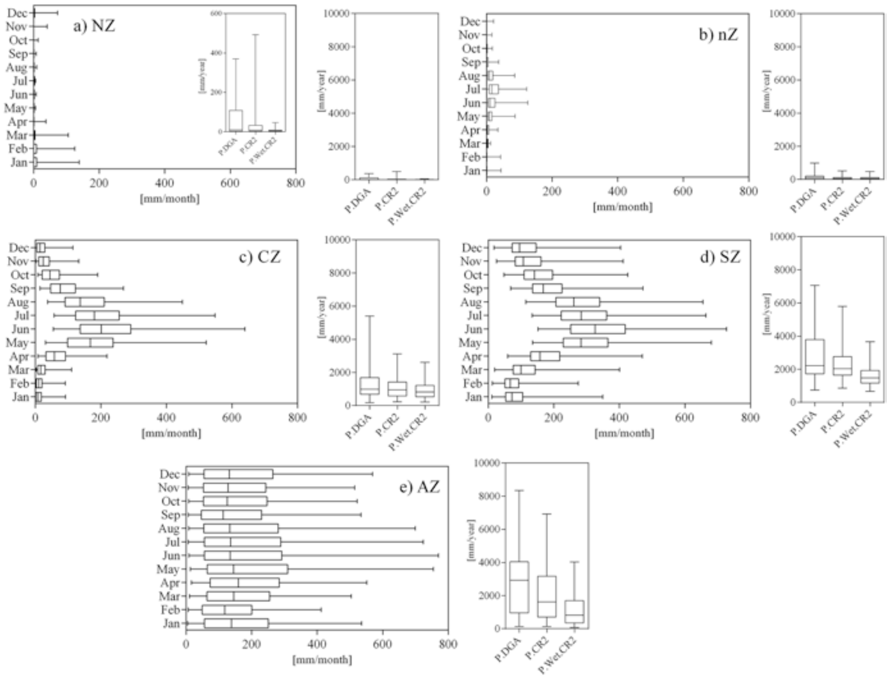

Fig. 3.15 Box and whisper plot with monthly cumulative precipitation for each natural zone using CR2MET. Box diagram of the multiannual accumulated average precipitation obtained from the DGA map (P.DGA), and CR2MET, on an annual basis (P.CR2) and for the autumn-winter period (P.Wet.CR2). (**a**) NZ. (**b**) nZ. (**c**) CZ. (**d**) SZ. (**e**) AZ

3.3.2 Frequency and Trend of Rainy Days

The spatial pattern observed in the previous section is reinforced with the number of rainy days by the year shown and analyzed in this section, which consider those days that have at least 0.2 mm/precipitation day. Figure 3.16a, b show the rainy days mean in 219 precipitation stations with complete daily records (10% maximum of missing data per year) for the period 1979–2016. Similar to precipitation, the number of rainy days increases from north to south with mean values ranging from 2 days/year in the north of Chile to 226 days/year in the SZ and AZ. In the NZ and nZ, the number of rainy days in the coast and intermediate depression has means of 6 and 11 days/year respectively, whereas in the mountains and plateau rainy days reach a maximum of 60 days/year (Fig. 3.16b). The CZ, SZ, AZ are the zones with the highest variation ranges in precipitation occurrences. La CZ has a mean of 44 days/year, a minimum of 4 days/year and a maximum of 120 days/year. The SZ and the AZ are the zones with the highest amount of humid days with a mean of 194 days/year, a maximum of 226 days/year and a minimum of 97 days/year.

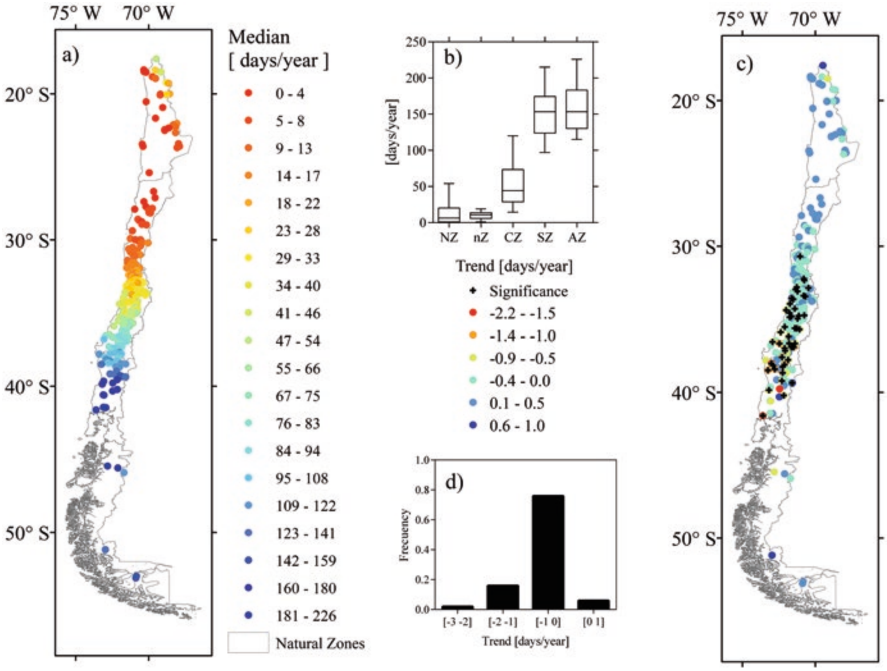

Fig. 3.16 (**a**) Frequency of rainy days in [days/year] using local observation in period 1979–2016, (**b**) box and whispers box for each natural zones with median values for station, (**c**) trend of rainy days in [days/year], (**d**) histogram of significance trends

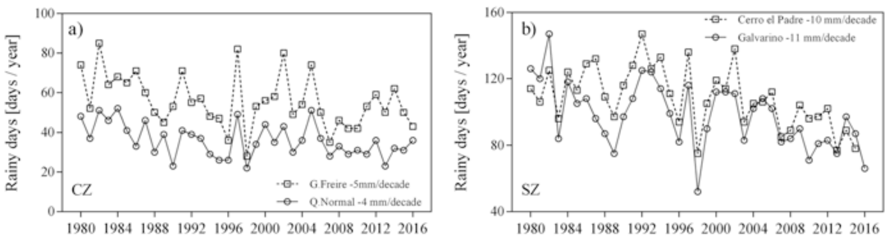

Fig. 3.17 Time series of the number of days per year at two representative stations for (**a**) CS and (**b**) SZ

In the last 10 years, there has been a decrease both in magnitude and occurrence of precipitation throughout the country. The temporal trend of rainy days per year was calculated using the MK and the TS estimator. To do this, we used the temporal series of daily accumulated precipitation of 219 stations, estimating for each of these the number of rainy days per year for the period 1979–2016. Figure 3.16c shows the TS estimator in each station and the significance obtained with MK (crosses), and Fig. 3.16d shows a histogram with the trend for stations with statistical significance ($\alpha = 0.05$). The country's center-south zone is the one showing a significant trend of a decreasing precipitation occurrence, with nearly 80% of stations with a reduction of 0.5 days/year or 5 days/decade, which in the analyzed period (1979–2016) implies a 15-to-20 day decrease in a zone with a rainy day average of 44 days/year (CZ). An example of this is illustrated in Fig. 3.17, showing the time series of two stations in the CZ and SZ. The two figures show that in the last 10 years there has been an average decrease of 8 to 10 days/year for Q.Normal and G.Freire respectively in the CZ, and an average decrease in the SZ of 22 to 24 days/year for the Galvarino and Cerro el Padre stations, which represents double the trend estimated with the TS estimator.

3.3.3 Precipitation Trends

The variability (including interannual and interdecade changes) of Chile's climate results from the superposition of large scale phenomena; those with the greatest influence in the spatial distribution of precipitation are the Antarctic Oscillation (AAO), the Pacific's Decade Oscillation (PDO), and El Niño South Oscillation (ENSO) (Figueroa 2014; Quintana and Aceituno 2012). The AAO consists of an oscillation in which atmospheric pressure in polar and mid-latitudes oscillates between positive and negative periods, and it is considered an important driver of precipitation variability in the country's center-south. The positive phase is associated to higher pressures as well as stable and dry conditions, while the negative phase is characterized by low pressure systems that can increment storms or rains. The PDO represents the temperature variability pattern in the Pacific Ocean with alternations between 20 to 30 years in the cold or warm phase. The cold phase is associated with La Niña, that is, cold waters and intense trade winds, whereas the warm phase is associated with El Niño, that is, warmer waters and moderate trade winds. The South's Oscillation (SO) or ENSO is a global phenomenon of ocean-atmospheric interaction in the Pacific Ocean, with a strong inter-annual effect in the north and center of Chile. According to Quintana and Aceituno (2006, 2012) the debilitation of the PDO's positive phase in the 1990s and the intensity of the subtropical anticyclone in the South Pacific are the factors responsible for the conditions favoring the precipitation decrease in the north, center, and south of Chile in recent years. Nevertheless, the authors suggest that the significant decrease trends respond not only to natural climate variability, as the SOI and POD rates do not show an evolution consistent with other periods of time. Boisier et al. (2016) demonstrate that at least in Chile's central zone, the anthropogenic forcing is indeed a key factor behind the persistence of the current drought in Chile, even when that forcing is not the main factor explaining the negative precipitation trend. Regarding future climate scenarios, it is likely that this precipitation decrease trend continues, which has already been reflected in most global and regional climate models used to evaluate the impact of climate change.

Precipitation is the most important climatic variable affecting availability of water resources, and therefore in recent years multiple assessments of precipitation trends throughout the country have been made to know what changes have occurred and whether these changes respond to natural climate variability or are the result of relevant constant and/or monotonic variation due to climate change (Espinoza and Martín-Vide 2014; Garreaud 2011; Meseguer-Ruiz et al. 2018; Sarricolea et al. 2017, 2019; Valdes-Pineda et al. 2016; Vicuña et al. 2013). Most part of the evaluations have focused in center – south zone of the country because of the agricultural and economic importance of this sector. Few others have focused in the north where despite being a hyper-arid zone, the low precipitation of the plateau is fundamental to develop cities and the limited agricultural and livestock production. Thus, using CR2MET products and taking advantage of spatial continuity and the record period (1979–2016), the Mann Kendall and TS estimator was used to determine the annual time series trend for every pixel and the significance. Similarly, the same statistics were calculated using 244 rainfall stations with a registration period similar to that used by CR2MET.

Figure 3.18a, b show the TS estimator statistics using the CR2MET data and the statistical significance obtained with MK highlighted in colors or those grids where there is a statistically significant increase or decrease (α = 0.05). Figure 3.18a shows that most of the Chilean territory from north to south has negative trends: the NZ, nZ and SZ with most trends in the range −0.01 to −10 mm/year, the CZ and SZ with

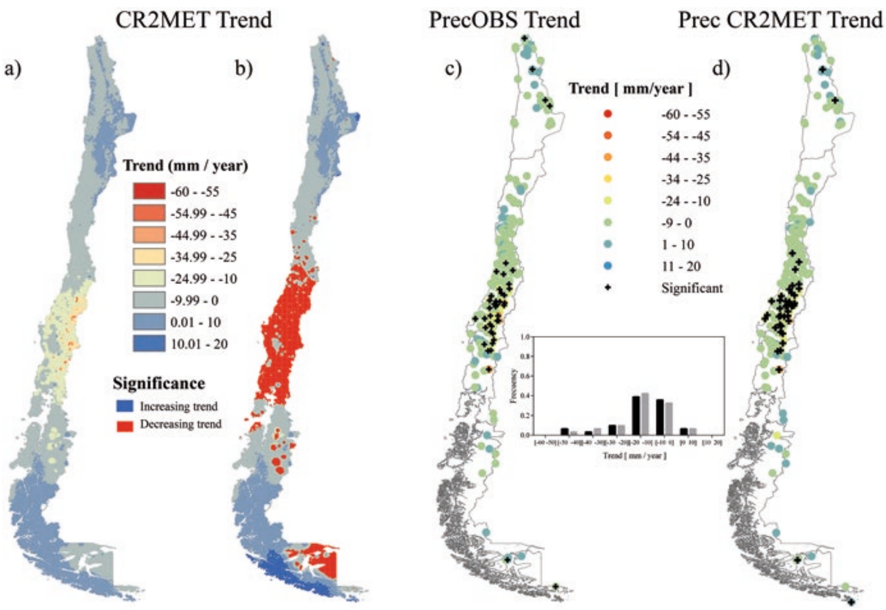

Fig. 3.18 (**a**) TS estimator [mm/year] with CR2MET data, (**b**) cells with significant tendency to increase (red dots) and decrease (blue dots) the annual precipitation. Trend at (**c**) ground stations and (**d**) CR2MET in coincident cells. The significant tendency in black crosses

more drastic and statistically significant trends within the range of −10.1 to −25 mm/year. The AZ shows positive trends [0.01–10 mm/year] that are significant only in a third of the area and similar to the negative trends in the range of −0.01 to −10 mm/year. In order to verify if the trends calculated with the CR2MET are comparable to the records observed, the TS estimator was calculated in 244 rain weather stations for the period 1979 to 2016, and compared with what was obtained in CR2MET's coinciding pixels (Fig. 3.18c and d respectively). The two data sources produced quite similar results in magnitude and the trend's significance, coinciding in 95% of evaluated stations.

Of the 244 precipitation stations analyzed, 209 show a negative trend with values reaching −44 mm/year, with 96% of them within the range of −0.04 to −20 mm/year; that trend is significant mainly in the center-south zone of the country. The regions with the most drastic decreases are those located south of the Metropolitan Region, the seventh, eighth, and ninth, with several stations with significant trends of −25 a −35 mm/year. This is consistent with the findings of Garreaud (2011), Vicuña et al. (2013) and Boisier et al. (2016) which report decreases in the Maule Region (seventh region) of 94 mm/decade, or Chile's central zone with decreases above 80 mm/decade.

At a spatial level, using the CR2MET data, a generally non-significant increase in precipitation is observed in the intermediate depression. In the other hand, in the Andean salt flats, in the NZ and nZ, is shown a significant decrease (CR2MET and OBS) in the plateau with a maximum decrease in a pair of stations of −1.9 and −2.12 mm/year (−20 mm/decade) (Fig. 3.18c). This result is coincident with those shown by Sarricolea et al. (2017) and Meseguer-Ruiz et al. (2018) who found significant decreasing trends for these two stations with values up to 44 mm/decade. The coastal desert, although showing a decreasing trend, is not significant.

In the AZ, the trend in the Aysén region is to decrease the precipitation rate with values that do not exceed −2 mm/year in precipitation stations and, at spatial level using CR2MET, the zone is mostly in the range of −0.01 to −10 mm/year. In the AZ, the Patagonian mountain range in the Magallanes Region shows a significant positive trend. In this regard, Carrasco et al. (2008) also found evidence from radiosonde measurements (1973–2006) of increased precipitation, but without statistical significance to show that this increase is due to global warming at the time of the authors' analysis. Garreaud (2011) refers to a precipitation trend map whose results are consistent with those observed in Fig. 3.18b, c, showing positive trends above even 50 mm/decade in the AZ. Boisier et al. (2016) found evidence of moderate positive trends in Patagonia (~50°S) using climate model simulations.

3.4 Extreme Events

The extreme hydrometeorological phenomena have occurred mostly in the country's center-south zone, which concentrates nearly 70% of the population (Rojas et al. 2014). These events have taken place between latitudes 32° and 35°S, a

Mediterranean zone or a windward extratropical sector, with storms concentrating in winter season as a result of frontal systems associated with mid-latitude cyclones (Falvey and Garreaud 2007; Viale et al. 2018). The influence of the Andes in the precipitation pattern extends for hundreds of kilometers, with a sharp, complex topography, narrow valleys, and steep slopes, which not only cause an increase in the precipitation magnitude (which can go from 1-to-3-time increase to that recorded in the valley), but also establishes the perfect scenario for hydrometeorological disasters.

The extreme episodes that have occurred in central Chile have lasted from 12 to 36 h and have been mostly associated to cold, postfrontal cases (~60% of events); however, a sizable number of these events are associated with warm conditions (30%) and little temperature change (Garreaud and Rutllant 1996; Garreaud 2013). Several authors (Garreaud 2013; Rojas et al. 2014; Viale and Nuñez 2011; Viale et al. 2018) have argued that the majority of those extreme episodes are associated with atmospherical rivers impinging on the subtropical Andes prior to the arrival of the cold fronts. In the case of cold fronts, atmospherical rivers dictate rain's intensity towards the interior, characterized by widespread rainfall throughout Chile (Falvey and Garreaud 2007). On the other hand, more than 80% of the warm events correspond to atmospheric rivers that not only arrive with a considerable amount of humidity, but also with warm conditions that cause an increase of the zero-degree isotherm; in turn, the latter increases the contributing area and causes violent floods. One of the most remembered warm events in central Chile occurred in May, 1993. The precipitation associated with the cold front reached an accumulated precipitation between May 2 and 3 that did not go above 20 mm but had a temperature over 10 °C the day of maximum streamflow. As a result, there was an increase of rain area between 3 and 4 higher than normal in the central zone's Andean basins. The isotherm reached 4000 m when in the central zone the snowline normally is between 1500 and 2900 m (Garreaud and Rutllant 1996).

Northern Chile, a narrow strip of land between the subtropical southeastern Pacific and the Andes (18°–26°S), features extremely dry conditions and aridity. This climate is the result of the stability and extension of the subsidence associated with the subtropical anticyclone, the cold waters in the ocean's eastern border, and the Andean slope perpendicular to the coast (Garreaud and Rutllant 1996; Bozkurt et al. 2016). Winter's occasional rains are not above 6 mm annually in the central valley, and the precipitation in the western Andes (elevations >3000 m) receives precipitation during the austral summer (from 10 to 100 mm/year). In turn, this precipitation increases during the cold phase of El Niño South Oscillation (ENOS) and makes the northern and central rivers of the Atacama Desert cause floods in the summer season (Rojas et al. 2014). However, despite the extreme aridity, the Atacama region has had significantly higher precipitations events throughout its history; in the last decade there have been 3 of these events in less than 5 years.

Several authors (Aceituno et al. 2009; Vargas et al. 2000; Bozkurt et al. 2016; Vargas Easton et al. 2018) have documented events since the end of the 1800 to 2018 whose main cause has been associated to ENSO's warm phases, such as the event that occurred in July, 1877; February, 1972; May, 1985; July, 1987; June, 1997, among others. This adds to events with neutral ENSO such as that occurring in June, 1991 and July, 2011. The precipitation events in the austral summer or of a convective character occur in the December–February trimester and March–May with storms that are fed by the humidity coming from the east side of the Andes. Of the events classified as catastrophic due to the loss of human lives, economic losses, and magnitude of accumulated precipitation, we can highlight the storm occurring from June 16 to 18, 1991, which had daily accumulated precipitations of nearly 40 mm and a maximum of 57 mm in 24 h; such precipitations caused rises and overflows in the Copiapó, Vallenar, and Huasco rivers. Similarly, the storm occurring in June 11 to 12, 1997 in Copiapó had accumulated precipitations of 148.7 mm and a maximum of 87.4 mm in 24 h, which caused a detrital flow and mud in the city of Copiapó and claimed the lives of 7 people. The storm on March, 24 to 26, 2015, which has been classified as the greatest rain disaster in 80 years, had an accumulated precipitation of nearly 70 mm but maximum temperatures of 22.1 °C, bringing about an elevated isotherm rain area. This event caused the overflow of the Copiapó and Salado rivers and 31 deaths, 16 missing persons, and 16,588 homeless people. The event occurred between May 10 and 11 with accumulated precipitations of approximately 120 mm in the Manflas station (at 1410 m); it caused landslides and overflows in the Copiapó and Salado rivers, and once again left more than 1,000 people homeless while both regions were considered catastrophe zones. In the most recent event, on January 27, 2020, the same zones were affected; the accumulated precipitation did not go above 16 mm during the two-hour storm, but it caused the overflow of the Salado and Copiapó rivers and affected once again the towns of Chañaral and Tierra Amarilla together with blocked roads, more than 3000 homeless people, 2 deaths, and 2 missing persons.

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Chapter 4
Surface Water Resources

Eduardo C. Varas and Eduardo V. Varas

Abstract This chapter presents three main topics: river basins and streamflows, lakes and reservoirs, and wetlands. Because they vary significantly, surface water resources and the corresponding river basins are grouped in 4 zones: arid and semi-arid zone, central zone, southern zone and Patagonia. River flows in each zone are not homogeneous and vary gradually, as differences in climate, vegetation, topography and other factors that influence flow are present. To give a quantitative picture of surface runoff, a total of 86 gaging stations distributed across these zones have been selected. Flow data have been collected from the National Bank of water resources information. To present an overall idea of surface water resources using a relatively small number of data tables, an approach based on annual flow volumes and monthly percentage distribution of this annual volume was used. On the other hand, lakes and reservoirs and wetlands are presented in a single section since most natural lakes are in the southern regions of the country and wetlands are located in all latitudes.

Keywords Water resources · River basins · Streamflow · Lakes · Reservoirs · Wetlands · Spatial distribution · Temporal variability

4.1 Introduction

Chile is a long and narrow stretch of land, having an approximate length of 4300 km and a maximum width of 180 km. It extends from 17° to 55° southern latitude. The eastern boundary is the Cordillera de los Andes and the western boundary is the Pacific Ocean. Consequently Chile's climate has significant variations both in latitude and longitude. Annual rainfall is almost nil in the northern and can reach

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7000 mm in the southern areas. River flows are sometimes due mainly to rainfall and in other cases rivers have a mixed regime due to snow melting and rainfall in the lower altitudes. Rivers in the north have ephemeral flow during the year and some do not reach the ocean and in the south they have large perennial flows discharging into the ocean. The Directorate General for Water recognizes 101 watersheds with a total area of 756,102 km^2, 1251 rivers, 12,784 lagoons and lakes and 24,114 glaciers. Water resources are used for agricultural demand (82%), industrial needs (7%), mining (3%) and municipal water (8%) (Directorate General for Water, Ministry of Public Works, Water Atlas, Chile).

Consequently, surface water resources vary significantly and hence they will be presented classifying river resources in four zones: arid and semi-arid zone (Arica and Parinacota, Tarapaca, Antofagasta, Atacama and Coquimbo Regions); central zone (Valparaiso, Metropolitan, Libertador B. O'Higgins, Maule and Bio-Bio regions); southern zone (Araucanía, Los Ríos and Los Lagos Regions); and Patagonia (C. Ibañez Aysen and Magallanes Regions). River flows in each zone are not homogeneous and vary gradually since differences in climate, vegetation, topography and other factors which influence flow are present.

In order to give a quantitative picture of surface runoff, a total of 86 gaging stations have been selected distributed in each of the four zones. Flow data has been collected from the National Bank of water resources information (Ministry of Public Works, Directorate General for Water, National Bank of Water) and basic statistics have been calculated. To present an overall idea of surface water resources using a relatively small number of data tables an approach based on annual flow volumes and monthly percentage distribution of this annual volume was used. Summaries of annual flow volumes are given in detail for each zone and monthly values have been synthesized as a fraction of annual volumes. However, some representative gaging stations are presented in each zone at a monthly scale. Graphs and tabulated values of monthly percentiles representative of streamflows in each zone are presented. This information can be used to formulate synthetic hydrologic series using Montecarlo simulation methods or to estimate preliminary monthly values of streamflow at hydrologically similar locations.

This chapter presents three main topics: river basins and streamflow, lakes and reservoirs and wetlands. River basins will present river flows classified in four zones as mentioned previously. On the other hand, lakes and reservoirs and wetlands will be presented as one section since most natural lakes are in the southern regions of the country and wetlands are present in all latitudes. In order to give a quantitative picture of surface runoff, a total of 86 gaging stations have been selected distributed in each of the four zones. For each zone gaging records have been analyzed in a monthly scale. Summaries of annual flow volumes are given in detail for each zone and monthly values have been synthesized as a fraction of annual volumes. Also some representative gaging stations are presented in each zone at a monthly scale. Flow data has been collected from the National Bank of water resources information (Ministry of Public Works, Directorate General for Water, National Bank of Water).

4.2 River Basins

4.2.1 Arid and Semi-Arid Zone

The arid and semi-arid zone has 41 watersheds with a total area of 300,904 km^2, a population of 2,280,000 habitants and a population density of 7.6 habitants/km^2. Average annual precipitation is 87 mm/year and a total annual flow 36.9 m^3/s. This zone has 2142 glaciers with a total estimated volume of 3.3 km^3. It is one of the driest regions of the world, represented by the Atacama Desert with a total area of 180,000 km^2. This zone has a total of 718,406 Has of national parks and protected areas, such as Llullaillaco, Isluga, Pampa del Tamarugal, Lauca and Fray Jorge (Directorate General for Water, Ministry of Public Works, Water Atlas, Chile).

This zone has few rivers with perennial flow, some smaller creeks discharge into the sea and others are ephemeral. All of them have a significant importance in the development of the region and in the conservation and survival of aquatic life. Important rivers of this zone are Lluta, Lauca, Loa, Elqui, Limarí and Choapa Rivers.

4.2.1.1 Watersheds

Lluta River watershed with an area of 3378 km^2 is located in Tarapacá Region and lies 18°–18°30′ southern Latitude and 70°20′- 69°22′ longitude. Lluta River is 147 km long and receives waters from Azufre River and Caracarani, Colpitas and Socoroma creeks. Lluta has a perennial flow and is considered a pre-Andean watershed which discharges its water into the ocean.

The highlands of the Tarapacá Region (Altiplano) have higher precipitation and present snow fields on the slopes of the volcanoes. The largest rivers are the Lauca and the Caquena. Both rivers do not discharge in the sea. Lauca is a perennial river and its resources are used mainly on irrigation. Larger flows exist in December through March due to the increase in precipitation in what is known as the Bolivian winter. Chungara Lake and Parinacota volcano located in this region are well known natural beauties.

Parinacota wetland receives the Desaguadero river and several springs to form the Lauca River. The wetland area is 28 km^2 and is located west of Cotacotani lake at an elevation of 4350 m. Lauca watershed in Chilean territory is 2350 km^2 and the river flow in a southern direction until Chapiquiña hills and then flows west into Bolivia to die in Coipasa Salar.

Loa river watershed is located in the Antofagasta Region. Principal towns in this area are Quillagua, Calama, Campamento Enaex, Chiuchiu, Chuquicamata, Lasana, Conchi y Lequena. The watershed has an area of 33,570 km^2 and is located inside 21°00′ y 22°58’ S latitude and 70°05′ y 68°00’ W longitude. Loa is the longest river in Chile. Loa’s regime is pluvial and floods are due to high intensity rainfalls occurring in summer months. The river is formed in the slopes of Miño volcano at an altitude of 5651 m. Flows in a southern direction occupying a deep canyon for

105 km where the river receives its first tributary San Pedro river. After flowing for another 45 km Loa receives its second tributary the Salado River. After receiving the Salado the river turns towards the west and flows for 23 km into a valley widening and reaches Calama to irrigate approximately 100 has, to form the largest oasis if this zone. Downstream of the irrigated area the river recovers a deep canyon with almost vertical slopes. Reaching Chacance 123 km downstream the Salado River, Loa receives San Salvador river and changes direction to flow north. It flows north for 80 km and reaches Quillagua, last irrigated area. Downstream Quillagua Loa rivers turns west, receives a last tributary Quebrada Amarga and continues flowing to reach the ocean at Caleta Huelen. Loa surface water resources supply municipal water, industry, copper mines, and irrigation for Lasana, Chiuchiu, Calama and Quillagua (Directorate General for Water 2005).

The three main tributaries of River Loa are the San Pedro River, the Salado River and the San Salvador River. The San Pedro is an ephemeral stream so its contribution is not significant, although it drains an area of 1087 km^2. Salado River is formed by many springs close to El Tatio volcano at an elevation of 4200 m. The Salado receives as tributaries the Toconce, Hojalar and Caspana. The Salado length is 80 km and its basin area is 2210 km^2. The San Salvador is formed by the contribution of several ephemeral creeks and by the Quebrada Opache. It flows for a distance of 56 km to reach Chacance and discharge into Loa River. Its basin area is 619 km^2.

Elqui River is located in Coquimbo Region. The watershed has an area of 9826 km^2 and its limits are 29°35′ and 30°20’ S latitude. The river is formed 2 km upstream of Rivadavia, due to the confluence of Turbio and Claro Rivers. It flows in westerly for 75 km to reach La Serena, receiving several tributaries in this reach which are normally dry except in periods of rain in very wet years. Turbio River forms 43 km upstream of Rivadavia at an elevation of 1370 m by the confluence of Toro and Laguna Rivers. Its watershed has an area of 4196 km^2. The Claro River is also formed in the Cordillera and its only tributary is Cochiguaz River. Its drainage area is 1512 km^2, and flows in a southern direction for 65 km) (Directorate General for Water 2004).

Limarí River watershed is located in Coquimbo Region, and it lies between the valleys of Elqui River and Choapa River. It has an area of 11,800 km^2. The main tributaries of Limarí are Grande and Hurtado Rivers. Both tributaries are formed in the Cordillera de los Andes at an elevation of 4500 m and they have a large basin with snow precipitation. The Recoleta reservoir is located in the Hurtado River and has a capacity of 100 million m^3. Grande River has several large tributaries Rapel, Mostazal and Huatulame Rivers. Huatulame is regulated by the Cogotí reservoir with a capacity of 150 million m^3. Limarí River is formed by the confluence of the Huatulame and Grande Rivers. The Limarí is regulated by Paloma reservoir located at the confluence of both rivers and has a maximum volume of 750 million m^3. This reservoir is 4 km upstream of the city of Ovalle. The Limarí has a total length of 60 km and discharges in the ocean in Punta Limarí. The valley of the Limarí between Ovalle and the ocean is wide and has lateral terraces with fertile agricultural land (Directorate General for Water 2004). Choapa watershed is also in Coquimbo

Region and has an area of 8100 km^2. The Choapa is formed by the confluence of Totoral, Leiva and Del Valle Rivers and runs for 140 km to discharge its waters in the ocean. In the Cordillera de los Andes Choapa receives the Cuncumén and Chalinga Rivers. Once it reaches the valley the Choapa receives the Illapel River and later discharges its water to the sea in Caleta Huentelauquén (Directorate General for Water 2004).

4.2.1.2 River Stream Flows

Table 4.1 presents the principal statistics of annual flow volumes of 13 gaging stations in the arid and semi-arid zone. Annual flow volumes are shown as the sum of mean monthly flows in each gaging station expressed as m^3/s. To express annual flow in cubic meters figures should be multiplied by the number of seconds in 1 month ($24 \times 3600 \times 30$).

The specific productivity per unit watershed area for this zone is in the range of 3 and 150 l/s/km^2 with an average value of 32 l/s/km^2. The probability of specific productivity being in the range of 7 and 68 l/s/km^2 is 0.75. Specific productivity increases towards the southern part of the zone. In the north sector only the main river courses discharge water in the ocean, many small creeks and rivers discharge their water into salares or depressions. In this zone annual flow volumes tend to be significantly serial correlated.

Figure 4.1 shows a distribution curves for monthly flows in term of annual volumes. This gives a preliminary estimate of monthly mean flows in terms of annual flow volumes. Distribution curves for 90%, 50% and 15% percentiles are shown with corresponding tabulated values.

Figure 4.2 shows distribution curves for the median specific productivity calculated with the data of 98 flow gaging stations selected in this chapter. Mean median annual specific productivity increases from 20 l/s/km^2 in the arid and semi-arid zone to 400 l/s/km^2 in the center zone, to 765 l/s/km^2 in the southern zone and 542 l/s/km^2 in Patagonia zone.

Table 4.2 presents mean monthly flows (m^3/s) for four representative gaging stations. The table shows the average flow, the coefficient of variation and the 90% percentile, the median and 15% percentile for each month in each gaging station.

4.2.2 Central Zone

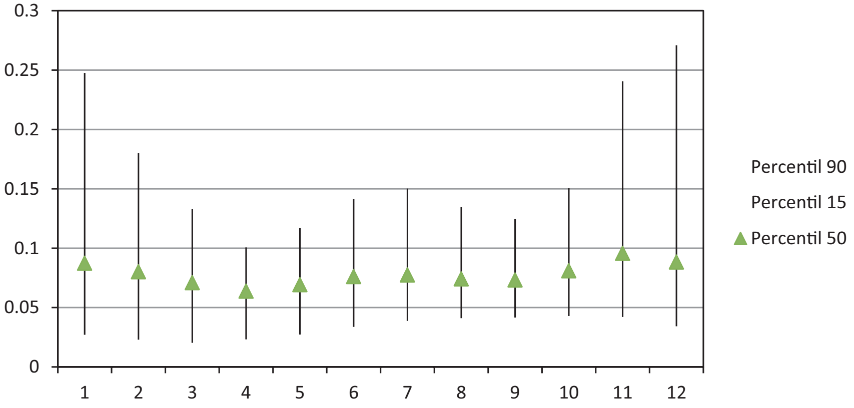
4.2.2.1 Watersheds

The center zone has a mediterrenean climate and 15 watersheds with a total area of 78,482 km^2, a population of 11,101,673 habitants which represent 62% of Chilean population and a population density of 141.5 habitants/km^2. Average annual precipitation is 943 mm/year and a total annual flow 1116 m^3/s. This zone has 2615

Table 4.1 Principal statistics of annual flow for 13 gaging stations in the arid and semi-arid zone

Gaging station	Basin area (km^2)	Data	Average (m^3/s)	St. Dev (m^3/s)	Min. (m^3/s)	Max (m^3/s).	Skew	Kurtosis	Correlation coef.	90% (m^3/s)	50% (m^3/s)	15% (m^3/s)	Sp. Prod (l/s/km^2)
Tarapacá Creek at Sibaya	620	28	2.26	2.20	0.09	9.83	1.98	4.32	0.64	5.62	1.49	0.68	3.65
Tarapacá Creek at Mocha	580	4	3.14	3.10	0.57	7.35	1.08	0.01	0.81	6.23	2.33	0.79	5.41
Camarones River at Conanoxa	1926	47	4.93	3.49	0.31	14.60	1.14	0.98	0.45	9.36	4.02	1.41	2.56
Cancosa River at El Tambo	100	24	2.35	0.83	0.54	3.67	−0.30	−0.52	0.60	3.36	2.35	1.58	23.50
Choapa River at Puente negro	3725	79	140.45	128.30	3.46	585.02	1.45	1.90	0.84	333.54	108.90	25.94	37.70
Choapa at Salamanca	2253	69	90.54	81.68	3.32	313.15	1.26	0.08	0.86	205.06	60.40	16.71	40.19
Claro River at Rivadavia	1502	84	44.62	32.89	4.26	143.49	1.18	0.83	0.74	93.55	34.03	15.39	29.71
Codpa River at Cala-Cala	50	36	1.42	0.91	0.09	3.36	0.57	−0.53	0.10	2.68	1.33	0.51	28.40
Elqui river at El Almendral	6681	73	106.27	77.82	5.42	429.00	1.67	3.35	0.61	214.19	80.48	44.24	15.91
Grande River at Paloma 1	6210	71	83.54	87.30	1.52	437.73	1.75	3.65	0.84	198.41	45.97	11.87	13.45
Grande River at Puntilla de San Juan	3512	76	100.04	101.67	8.12	456.60	1.91	3.86	0.90	213.26	68.74	20.45	28.49
Hurtado river at Angostura de Pangue	1772	100	35.02	35.76	3.21	194.69	2.35	6.11	0.79	69.68	24.04	9.64	19.76
Illapel river at Huintil	928	79	35.31	29.94	4.29	133.30	1.35	1.47	0.79	76.05	25.44	8.47	38.05
Isluga river at Bocatoma	120	21	5.35	1.21	3.22	7.45	0.26	−0.81	0.15	7.24	4.99	4.31	44.58

Limarí river at Panamericana	11,261	60	101.25	168.46	0.88	883.56	2.77	8.53	0.82	251.35	26.95	9.17	8.99
Lluta river at Alcerreca	1108	51	18.76	9.09	1.17	43.66	0.24	0.11	−0.10	30.30	18.93	9.23	16.93
Lluta river at Panamericana	2305	31	14.82	11.65	1.82	49.96	1.40	2.05	−0.05	29.09	12.99	3.97	6.43
Salado river at confluence Loa river	2378	28	24.81	22.03	1.17	78.71	0.79	−0.09	0.91	47.67	24.10	4.67	10.43
San Pedro river at Cuchabrachi	933	66	8.84	4.34	0.71	24.16	1.20	2.83	0.54	14.23	8.07	5.14	9.47
San Pedro river at Parshall #1	1060	45	11.37	3.51	0.74	16.81	−1.65	3.17	0.75	16.63	12.27	9.17	10.73
San Pedro river at San Pedro	1417	61	9.60	4.31	0.74	16.81	−0.53	−0.85	0.88	14.41	11.13	4.93	6.77
San Salvador river at Loa confluence	1609	17	6.41	10.92	0.26	43.17	2.92	8.66	0.98	13.48	2.50	1.14	3.98
Turbio river at Varillar	4148	104	89.13	70.85	8.54	534.59	2.93	14.36	0.62	160.41	65.94	36.90	21.49
Loa river at sea	32,820	29	2.95	2.15	0.48	9.97	2.00	4.15	0.08	1.69	2.46	5.16	0.09



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percentile 90	0.25	0.18	0.13	0.10	0.12	0.14	0.15	0.13	0.12	0.15	0.24	0.27
Percentile15	0.03	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.03
Percentile 50	0.09	0.08	0.07	0.06	0.07	0.08	0.08	0.07	0.07	0.08	0.10	0.09

Fig. 4.1 Distribution curves for monthly flows in terms of annual flow percentages in arid and semi-arid zone

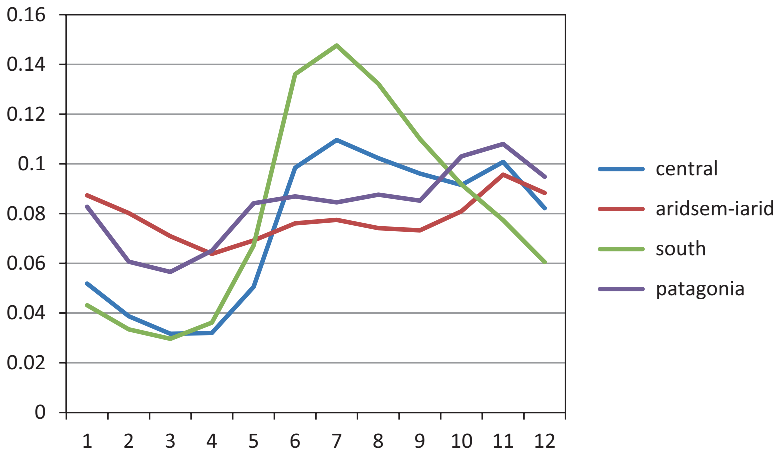


Fig. 4.2 Variation of 50% percentile in the four zones

glaciers with a total estimated volume of 32.5 km^3. It has 531 lakes and lagoons with a total surface area of 190 km^2, principal natural lakes are Maule Lake, Cauquenes Lake and Peñuelas Lake. This zone has a total of 76,324 Has of national parks and protected areas, such as Parque La Campana, Rio Clarillo, Lago Peñuelas, Rio Cipreses and Alto del Lircay.

Table 4.2 Statistics of mean monthly flows in representative gaging stations in the arid and semi-arid zone

Station		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Camaronesin Conanoxa	Average	0.8	1.0	1.0	0.4	0.4	0.5	0.4	0.3	0.3	0.2	0.2	0.3
	cv	0.9	1.0	1.2	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3
	Percentiles 90%	2.1	2.8	1.8	0.8	0.8	0.9	0.6	0.6	0.5	0.5	0.4	0.6
	50%	0.4	0.6	0.6	0.3	0.4	0.5	0.4	0.3	0.2	0.2	0.2	0.2
	15%	0.1	0.1	0.2	0.1	0.2	0.2	0.3	0.2	0.1	0.1	0.0	0.1
Choapa in Pte. Negro	Average	10.1	4.5	3.4	4.0	6.7	12.2	14.9	12.9	13.4	16.7	27.4	23.6
	cv	1.7	1.7	1.5	1.2	1.5	1.1	1.2	1.0	1.3	1.0	0.9	1.3
	Percentiles 90%	27.4	9.2	6.5	8.5	10.9	18.0	23.1	20.5	23.4	29.3	55.6	66.7
	50%	1.9	0.8	1.0	1.5	3.0	6.1	7.8	7.7	6.2	10.0	18.1	7.4
	15%	0.5	0.3	0.3	0.4	0.9	2.0	3.7	2.9	1.8	2.3	3.3	1.0
Limarí in Panamericana	Average	7.2	3.9	2.7	3.4	5.3	8.1	15.9	12.8	10.5	9.4	14.7	15.5
	cv	2.8	2.2	2.1	1.9	1.9	1.3	3.3	2.3	2.0	2.4	2.5	2.7
	Percentiles 90%	20.1	14.3	5.6	6.9	9.7	20.9	18.5	27.3	36.5	25.6	30.4	60.0
	50%	0.9	0.8	0.8	1.3	1.9	3.6	4.2	2.9	2.0	1.5	1.5	1.2
	15%	0.3	0.2	0.2	0.2	0.3	1.0	1.7	0.8	0.5	0.5	0.5	0.3
Elqui in Almendral	Average	12.4	9.9	8.0	7.9	8.7	8.7	8.9	7.8	7.9	8.9	10.7	13.5
	cv	1.4	1.1	0.8	0.7	0.8	0.7	0.7	0.8	0.8	1.0	1.1	1.4
	Percentiles 90%	23.8	18.4	14.7	14.1	14.5	13.6	12.8	11.7	10.5	14.6	19.3	24.9
	50%	5.8	6.0	6.0	5.6	5.4	5.7	6.3	5.7	6.1	6.2	6.1	5.8
	15%	3.3	3.3	3.2	3.1	3.4	3.4	3.6	3.6	3.1	3.3	3.5	3.4

Table 4.3 General characteristics of principal watersheds in the central zone

Basin	Latitude S	Latitude S	Longitude W	Longitude W	Area (km^2)	River length (km)
Aconcagua	32°40′	33°05′	71°10′	70°10′	7340	177
Maipo	32°55′	34°15′	71° 43′	69° 46′	15,274	250
Rapel	33° 53	35°01′	71°90′	70°10′	13,767	310
Mataquito	35°07′	35°10′	72°15′	70°50′	6332	220
Maule	35°15′	36°10′	72°40′	70°50′	21,054	250
Itata	36°12′	37° 16′	73° 10′	71° 00′	11,327	140
Bio-Bio	36°80′	38°30′	73°12′	71°18′	24,371	380

Principal cities are Santiago, Valparaiso, Concepción and Talcahuano. Main watersheds are Aconcagua, Maipo, Rapel, Mataquito, Maule, Itata and Bio-Bio. Rivers in the central zone are perennial, have their source in the Cordillera de los Andes and discharge their waters into the ocean. Table 4.3 shows the approximate limits of each watershed, its area and the length of the main river system. Mean area of the 6 watershed is 15,000 km^2. Topography in this zone presents four distinctive features the Cordillera de los Andes in the east with elevations in the order of 4000 m to 6000 m, a central valley with agricultural, forestry and industrial developments, the mountains of the coastal range with elevations of 500 m to 800 m and the coastal area in the Pacific Ocean. The climate is temperate, most of the rainfall occurs in winter and summers are dry and warm. At elevations above 2500 m precipitation is mostly snow.

Rivers have perennial flows generally supercritical with a mixed regime due to snowmelt contribution in the spring and summer months and precipitation contribution in rainy winters. Usually there are high flows in spring and summer an also high flows in winter due to rainfall.

Aconcagua watershed is located in the Valparaiso Region and in the southern part of the arid and semi-arid zone. Its area is 7340 km^2 and the main river flows in an east-west direction. Aconcagua receives its most significant tributaries in the Cordillera, which originate in areas of important elevations like Juncal (6110 m); Alto de los Leones o Cabeza de León (5400 m.) and Aconcagua (7021 m.) mountains. The Aconcagua River is formed at an elevation of 1430 m by the confluence of the Juncal and Blanco Rivers. The Juncal originates at the Juncal Norte glacier and receives also several small creeks of glacier origin. Blanco River is formed at the foot of La Copa and Altar mountains and its biggest tributary is Los Leones River formed in glaciers located at the Alto Los Leones (5400 m) mountain (Directorate General for Water 2004).

Maipo basin is located in Metropolitan Region. The river source is springs in the slope of Maipo volcano at an elevation of 5.523 m in the Andes Mountains, runs through the Cordillera and the central valley and discharges in the ocean near Tejas Verdes. Principal tributaries in the Andes are Volcan, Yeso and Colorado Rivers. Mean streamflow when the Maipo reaches the central valley is about 115 m^3/s. In the middle reach Maipo River receives the Mapocho River and in the lower reach receives several small creeks. Maipo has a mixed regime having important snowmelt contribution in the upper reaches and winter rainfall contributions in the lower reaches. Water resources irrigate 136,000 Has in the spring and summer months mostly for vineyards and fruit crops. Municipal water for Santiago and industrial supply are important consumers. Maipo basin has also hydroelectric generation plants with an installed capacity of 300 MW. The upper basin has also mining operations and recreational use. The area is important for environmental issues due to the existence of biodiversity and endemic species.

Rapel watershed is located in Libertador B. O'Higgins Region. Rapel River is regulated in its lower reach by a reservoir with a capacity of 680 million m^3 for electricity generation and recreational uses. Rapel is formed by the confluence of Cachapoal and Tinguiririca Rivers immediately upstream of Rapel reservoir. Cachapoal River has a watershed of 6370 km^2 and is formed with contributions of Pico Barroco and Los Piuquenes glaciers. In the Cordillera receives several tributaries Las Leñas, Cortaderal, Los Cipreses, Pangal, Coya and Claro. The source of Tinguiririca River is in the Cordillera de los Andes by the confluence of the Damas and Azufre Rivers.

Mataquito River is formed by the confluence of the Teno and Lontue Rivers. It has a mean annual flow of 150 m^3/s. It discharges in the ocean south of Laguna Vichuquén. Mataquito water resources are used mainly for irrigation of 100,000 has. Mataquito originates by the confluence of the Teno and Lontue Rivers close to the city of Curicó. It runs through a wide valley in westerly direction for 95 km until it discharges into the ocean. The Teno River main tributary of Mataquito originates in Teno Lake at an elevation of 3000 m. The Teno is formed by the confluence of the Nacimiento and Malo Rivers. Its main tributary in the valley reach is Claro River. The Lontué has a basin of 2510 km^2 and originates by the confluence of the Colorado and Los Patos. Its total length is 126 km (Directorate General for Water 2004).

Maule River is located in Maule Region and has a mean annual flow of 460 m^3/s. It originates in the Cordillera de las Andes by the confluence of Puelche, Cipreses, Claro and Melado Rivers. In the valley reach receives the Loncomilla River. It discharges its water in the ocean at the city of Constitución after running for 250 km. Maule water resources are used for irrigation and hydroelectric power generation at Cipreses (101 MW), Isla (68 MW), Curillinque (89 MW), Loma Alta (40 MW), Pehuenche (500 MW), Machicura (90 MW) and Colbun (400 MW). In the valley reach the Maule receives the Claro and Loncomilla tributaries.

Itata watershed is located in the Ñuble Region. The river has two main tributaries, the Ñuble and Diguillin Rivers. Topography is characterized by small rounded hills, small slopes and terraces with flat valleys with large areas like the Itata valley. The river source is close to Cholguan railroad station where the Itata receives two tributaries, the Cholguan and Huepil rivers. The river flows for 85 km before reaching the confluence with Ñuble River. After crossing the coastal mountains the Itata discharges into the sea. The Cholguan river origin is the slope of Calas hill and flows 59 km to get to the confluence with the Huepil, whose source is in the foot of the Andes. The Diguillin is formed at the foot of the Chillan volcano which is 3.211 m high. The main tributary of the Itata is the Ñuble with a basin of 5097 km^2. After flowing for 155 km the Ñuble joins the Itata in the place called Confluencia (Directorate General for Water 2004).

Bio-Bio watershed is located in Ñuble and Bio-Bio Regions. The Andes Mountains in this zone have elevation of ~3300 m and presents several volcanoes Callaqui (3164 m), Antuco (2979 m), Copahue (2965 m). The central valley is open and wide with agricultural, forestry and cattle activities. The Bio-Bio River is long and is probably the river with the largest mean annual flow. The Bio-Bio origin is the Galletue Lake and Icalma Lake. The river in the first reach has several small tributaries Lonquimay, Rahue and Ránquil. Leaving the mountain region it receives the Vergara River and later the Laja River. The Bio-Bio section in the valley is wide and when it reaches the sea in Concepción has a section width of 2000 m. Mean annual flow is 350 m^3/s (Directorate General for Water 2004).

4.2.2.2 River Stream Flows

Table 4.4 presents the principal statistics of annual flow volumes of 30 gaging stations in central zone. Annual flow volumes are shown as the sum of mean monthly flows in each gaging station expressed as m^3/s. To express annual flow in cubic meters figures should be multiplied by the number of seconds in 1 month ($24 \times 3600 \times 30$).

The specific productivity per unit watershed area for this zone is in the range of 115 and 900 $l/s/km^2$ with an average value of 422 $l/s/km^2$. The probability of specific productivity being in the range of 194 and 730 $l/s/km^2$ is 0.75. Specific productivity is several times larger than in the semi-arid zone and also increases towards the southern part of the zone.

Figure 4.3 shows a distribution curves for monthly flows in term of annual volumes, allowing to have a preliminary estimate of monthly mean flows in terms of annual flow volumes. Distribution curves for 90%, 50% and 15% percentiles are shown with corresponding tabulated values.

This zone is more homogeneous than the arid zone even though the rainfall also increases with latitude. Specific productivity has a coefficient of variation of 0.5 significantly lower than the preceding zone. Rivers originate in the upper Andes and cross the central valley and the coastal mountains to reach the sea.

Table 4.5 presents mean monthly flows for four representative gaging stations. The table shows the average flow, the coefficient of variation and the 90% percentile, the median and 15% percentile for each month in each gaging station.

Table 4.4 Principal statistics of annual flow for 30 gaging stations in the central zone

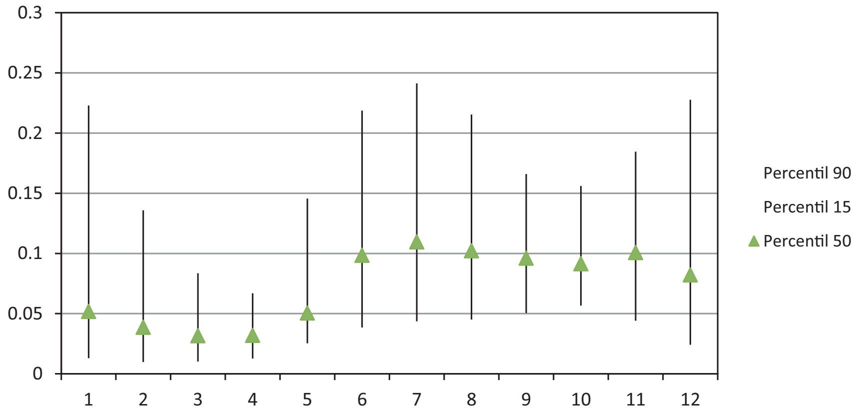
Gaging station	Basin area (km^2)	Data	Average (m^3/s)	St. Dev (m^3/s)	Min. (m^3/s)	Max. (m^3/s)	Skew	Kurtosis	Correlation coef.	90% (m^3/s)	50% (m^3/s)	15% (m^3/s)	Sp. Prod (l/s/km^2)
Aconcagua river at Chacabuquito	2400	82	380.68	141.21	137.52	765.61	0.71	0.50	0.74	563.51	366.52	242.87	158.62
Blanco river at Río Blanco	382	65	54.62	54.62	9.88	223.47	0.20	−0.93	0.77	162.03	98.04	28.32	142.98
Putaendo river at Resguardo Los Patos	927	79	89.36	54.63	15.92	250.94	1.08	1.04	0.81	160.34	81.30	35.57	96.40
Maipo river at El Manzano	4968	72	1227.60	399.98	234.71	2592.01	0.54	0.91	0.65	1750.33	1242.09	831.52	247.10
Maipo river at las Melosas	1488	31	317.86	139.47	66.91	719.96	0.66	0.96	0.61	447.01	326.85	447.01	213.62
Itata river at Cholguán	852	92	509.34	152.77	115.08	855.92	−0.02	0.06	0.35	719.63	513.38	356.86	597.82
Chillán river at Esperanza	224	56	184.91	53.18	71.65	325.93	0.09	−0.39	0.46	249.12	183.22	134.76	825.49
Diguillín river longitudinal	1232	57	497.14	268.98	18.90	1170.92	0.18	−0.58	0.35	853.21	497.30	200.77	403.52
Itata river at Cerro Negro	3329	29	1350.72	607.71	247.72	3110.95	0.70	1.51	0.17	1974.74	1347.42	742.45	405.74
Itata river at balsa Nueva Aldea	4731	62	1451.57	623.89	255.61	3093.59	0.33	−0.20	0.28	2223.87	1381.29	753.10	306.82
Polcura river at Central El Toro discharge	800	14	364.01	122.20	166.03	592.01	0.04	−0.10	0.70	509.27	374.90	237.50	455.01
Laja river at Tucapel	2680	75	1565.82	620.73	18.00	3083.50	−0.05	0.35	0.56	2298.36	1573.65	983.91	584.26

(continued)

Table 4.4 (continued)

Gaging station	Basin area (km²)	Data	Average (m³/s)	St. Dev (m³/s)	Min. (m³/s)	Max. (m³/s)	Skew	Kurtosis	Correlation coef.	90% (m³/s)	50% (m³/s)	15% (m³/s)	Sp. Prod (l/s/km²)
Bio-Bio river at Rucalhue	7044	79	5127.72	1579.66	595.56	8449.33	−0.50	0.01	0.58	6879.72	5310.88	3618.43	727.96
Bio-Bio river at Desembocadura	21,217	42	10509.82	4360.00	265.69	16688.52	−0.63	−0.35	0.53	15456.26	11403.09	5826.17	495.35
Vergara en Tijeral	2470	50	581.67	252.11	12.60	1049.71	−0.28	−0.36	0.34	894.27	571.72	316.91	235.49
Malleco river at Collipulli	428	74	389.32	362.25	6.08	2650.42	4.31	22.39	0.28	507.04	323.60	207.16	909.63
Cachapoal en Termas de Cauquenes	2522	16	364.29	241.38	86.15	813.62	0.91	−0.65	0.71	726.78	277.97	161.53	144.44
Cachapoal river at Puente Arqueado (CA)	6481	16	836.40	455.69	334.80	1675.78	0.79	−0.81	0.54	1547.85	641.72	436.53	129.05
Tinguiririca river at Bajo Los Bríones	3700	85	531.48	195.36	29.45	1063.42	0.03	0.30	0.53	783.88	537.68	343.92	143.64
Tinguiririca river at Los Olmos (CA)	3545	16	620.97	256.40	289.01	1229.57	1.48	1.91	0.64	987.70	548.26	467.37	175.17
Teno river after confluence with Claro	1188	71	632.43	218.53	132.03	1138.58	0.06	−0.63	0.85	930.90	612.36	416.74	532.35
Colorado river at junta con Palos	942	70	479.13	178.21	25.11	997.86	−0.08	0.38	0.76	682.02	487.64	336.09	508.63
Palos at confluence with Colorado	514	55	298.45	104.55	14.36	525.25	−0.19	0.00	0.72	428.46	291.48	207.94	580.64
Claro river at Talca	2596	39	901.88	385.90	53.25	1610.37	−0.14	−0.62	0.32	1427.55	916.32	498.52	347.41

Melado river at Lancha DGA	2148	27	1106.21	500.52	115.87	2091.42	−0.01	−0.31	0.28	1702.28	1055.44	573.30	515.00
Maule river at Colbún	5619	28	2552.24	1171.44	314.91	4491.19	−0.42	−0.35	0.32	3971.39	2643.96	1357.38	454.22
Longaví river at longitudinal	810	22	439.65	240.99	19.31	799.52	0.00	−1.18	0.46	771.01	500.89	175.82	542.78
Perquilauquén river at Quella	1995	55	649.20	275.39	148.77	1210.35	0.19	−0.67	0.27	1042.52	611.14	360.73	325.41
Ñuble river at San Fabián	1709	53	1257.98	429.14	341.49	2316.35	−0.17	−0.06	0.58	1692.63	1347.13	793.67	736.09
Mapocho river at Los Almendros	620	68	71.22	38.57	1.97	181.26	0.91	0.95	0.92	119.70	63.40	37.19	114.87
Volcán river at Queltehues	523	97	100.70	5664.00	18.84	340.01	1.22	2.84	0.55	175.31	88.10	44.90	192.54



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percentile 90	0.22	0.14	0.08	0.07	0.15	0.22	0.24	0.22	0.17	0.16	0.18	0.23
Percentile 15	0.01	0.01	0.01	0.01	0.03	0.04	0.04	0.05	0.05	0.06	0.04	0.02
Percentile 50	0.05	0.04	0.03	0.03	0.05	0.10	0.11	0.10	0.10	0.09	0.10	0.08

Fig. 4.3 Distribution curves for monthly flows in terms of annual flow percentages in central zone

4.2.3 Southern Zone

4.2.3.1 Watersheds

The southern zone has a rainy climate and 21 watersheds with a total area of 135,925 km^2, a population of 4,349,639 habitants which represent24% of Chilean population and a population density of 32 habitants/km^2. Average annual precipitation is 2420 mm/year and a total annual flow 7834 m^3/s. This zone has 2996 glaciers with a total estimated volume of 33 km^3. It has 1345 lakes and lagoons, principal natural lakes are Laja Lake, Llanquihue Lake (80.5 km^2), Ranco Lake (429.9 km^2), Villarrica Lake (174.7 km^2). This zone has 33 national parks and protected areas with a total of 1,313,048. Main exponents are Laja Lake, Conguillio, Puyehue, Vicente Perez Rosales, Corcovado, Palena Lake, Alto Bio-Bio, and Llanquihue (Directorate General for Water, 2016 Water Atlas). This zone is characterized by the presence of natural lakes and rivers with large permanent flows of a mixed regime due to snowmelt in the upper watershed and abundant rainfall in the lower areas. Natural lakes regulate river flows allowing hydro-electric developments which use the difference in elevation between the mountains and the plains. The area is also well known as a tourist destination because of its volcanoes, lakes and rivers. Main watersheds are the Imperial, Tolten, Valdivia, Bueno, Maullin, Petrohue, Puelo and Yelcho.

Imperial watershed is located in the Araucania Region and has an area of 12,763 km^2. Its upper watershed includes the Tolhuaca volcano (2780 m), Llaima volcano (3124 m) and the Cordillera Nevada. Tolten watershed is also in the

Table 4.5 Statistics of mean monthly flows (m^3/s) in representative gaging stations in the central zone

Station		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Aconcagua in Chacabuquito	Average	61.4	39.2	24.3	15.8	13.4	14.0	14.5	15.9	20.2	31.7	57.6	76.6
	cv	0.7	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.4	0.5	0.6
	Percentiles 90%	124.9	63.7	35.7	20.3	18.8	23.5	23.5	25.4	34.1	50.9	93.4	148.4
	50%	44.8	31.4	20.8	13.8	11.8	11.7	13.0	13.8	17.7	29.0	55.6	59.3
	15%	29.4	23.1	15.8	10.5	8.9	8.5	8.2	8.6	11.2	17.5	32.8	33.2
Maipo in El Manzano	Average	195.4	141.1	98.4	69.7	61.8	58.4	58.7	59.2	67.9	95.5	152.9	202.6
	cv	0.5	0.5	0.4	0.4	0.6	0.3	0.4	0.4	0.3	0.3	0.3	0.5
	Percentiles 90%	352.4	215.3	142.7	104.0	80.2	83.0	89.0	87.1	98.9	142.6	229.9	337.0
	50%	165.8	122.6	85.6	65.6	55.2	57.1	52.8	57.3	63.6	89.9	139.5	177.2
	15%	108.5	90.1	66.1	49.1	41.7	40.5	38.1	39.5	46.5	65.3	102.2	123.4
Tinguiririca in Bajo Los Briones	Average	92.7	60.4	36.6	23.5	25.5	32.5	35.5	34.2	35.0	48.0	78.4	101.5
	cv	0.4	0.3	0.3	0.5	0.6	0.7	0.7	0.6	0.4	0.3	0.3	0.4
	Percentiles 90%	129.3	81.6	46.1	35.0	43.0	56.0	67.5	58.1	50.1	67.4	104.6	147.0
	50%	85.2	55.6	32.6	19.3	19.7	23.4	25.8	27.2	32.6	45.9	73.3	82.5
	15%	55.6	39.9	25.3	14.9	12.5	14.0	15.9	16.8	22.7	34.4	57.8	63.1
Bio-Bio in desembocadura	Average	359.6	257.5	255.9	375.9	978.8	1694.6	1883.3	1619.7	1439.7	1238.1	1002.3	659.2
	cv	0.4	0.4	0.3	0.4	0.7	0.5	0.4	0.4	0.3	0.4	0.4	0.4
	Percentiles 90%	522.5	397.2	323.5	613.1	1925.3	2892.3	3004.2	2445.7	2145.8	1688.5	1563.0	998.0
	50%	354.3	239.0	244.9	326.9	799.2	1646.9	1868.9	1526.9	1330.5	1194.4	918.7	623.8
	15%	242.5	187.3	208.1	233.6	355.3	937.9	1045.4	1031.9	860.7	947.3	674.2	342.5

Araucania Region has an area of 8.398 km^2 and its origin is Villarrica Lake. Tolten main tributary is Allipen River. The Valdivia watershed is in the Region de los Lagos and has an area of 10.275 km^2. Its two main tributaries are the Cruces and Calle-Calle Rivers. In the upper reach the Valdivia receives the contribution of Calafquen, Panguipulli and Riñihue Lakes.

The Río Bueno watershed is in Region de los Lagos, has an area of 15,367 km^2, and includes the Ranco, Puyehue and Rupanco lakes. The Maullin watershed is located in the Los Lagos Region, has an area of 3972 km^2. The river is 85 km long and has a mean annual flow of 100 m^3/s. The river source is Llanquihue Lake and its regime is pluvial. The Petrohue River is 36 km long and originates is the Todos los Santos Lake, and the basin area is 2640 km^2. Its regime is pluvial and is well known for the Saltos del Petrohue and recreational facilities.

The Puelo River source is the Puelo Lake, runs for 120 km and discharges in the Seno del Reloncaví. Mean annual flow is 670 m^3/s and its resources are used for hydroelectricity. Yelcho source is Lago Yelcho. Its main tributaries are Futalelfu, Correntoso, Enredadera Cascada, Ensenada, and Malito Rivers. Runs for 246 km and discharges in the Corcovado Gulf. The basin area is 11,000 km^2 and has a pluvial regime with an annual mean flow of 360 m^3/s.

4.2.3.2 River Stream Flows

Table 4.6 presents the principal statistics of annual flow volumes of 14 gaging stations in the southern zone. Annual flow volumes are shown as the sum of mean monthly flows in each gaging station expressed as m^3/s. To express annual flow in cubic meters figures should be multiplied by the number of seconds in 1 month ($24 \times 3600 \times 30$).

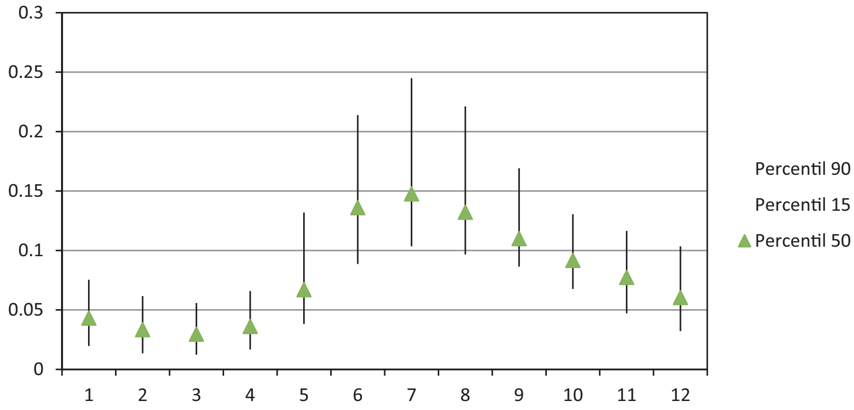
The specific productivity per unit of watershed area for this zone ranges between 208 and 1351 $l/s/km^2$, with an average of 801 $l/s/km^2$. The probability of specific productivity being in the range of 504 and 1185 $l/s/km^2$ is 0.75. Specific productivity is several times larger than in the semi-arid zone and also increases towards the south of the zone.

Figure 4.4 shows a distribution curve for monthly flows in term of annual volumes, to have a preliminary estimate of monthly mean flows in terms of annual flow volumes. Distribution curves for 90%, 50% and 15% percentiles are shown with corresponding tabulated values.

This zone is more homogeneous than the arid zone even though the rainfall also increases with latitude. Specific productivity has a coefficient of variation of 0.38 significantly lower than the preceding zone. Rivers originate in the upper Andes and flow crossing the central valley and the coastal mountains to reach the sea. The length of the main rivers is in the order of 200 or 300 km. Table 4.7 presents mean monthly flows for four representative gaging stations. The table shows the average flow, the coefficient of variation and the 90% percentile, the median and 15% percentile for each month in each gaging station.

Table 4.6 Principal statistics of annual flow for 14 gaging stations in the southern zone

Gaging station	Basin area (km^2)	Data	Average (m^3/s)	St. Dev (m^3/s)	Minimum (m^3/s)	Maximum (m^3/s)	Skew	Kurtosis	Correla tion coef.	90% (m^3/s)	50% (m^3/s)	15% (m^3/s)	Sp. Prod (l/s/km^2)
Fui river at Desague Lago Pirihueico	1466	33	985.08	318.31	367.50	1779.15	0.40	0.24	0.58	1393.43	941.21	706.92	671.95
San Pedro river at Desague Lago Riñihue	4228	37	4177.41	909.66	2223.49	6079.39	0.02	−0.38	0.60	5320.74	4081.96	3327.34	988.03
Cruces river at Rucaco	1740	49	992.66	255.59	399.71	1389.08	−0.43	−0.64	0.36	1297.87	1014.61	701.25	570.49
Río Rahue river at Cancura	1818	19	1581.17	627.21	998.11	2709.42	0.84	−0.84	0.74	2572.84	1378.66	1065.50	869.73
Río Maullín river at Llanquihue	1646	18	974.56	107.38	823.56	1180.68	0.16	−0.90	0.36	1100.94	989.53	851.14	592.08
Río Bueno river at Bueno	3714	36	4364.40	1142.92	960.47	6993.79	−0.44	1.56	0.39	5728.32	4376.56	3471.79	1175.12
Pilmaiquen river at San Pablo	2680	59	2034.44	370.03	1138.40	2631.35	−0.57	−0.34	0.40	2408.38	2113.61	1629.99	759.12
Chol-Chol river at Chol-Chol	3778	67	1493.11	448.78	83.22	2482.87	−0.49	0.65	0.27	2007.08	1511.34	1094.98	395.21
Cautin river atRari-Ruca	1365	89	1194.45	368.03	407.26	2415.70	0.95	1.40	0.51	1611.11	1134.62	860.38	875.05
Quepe river at Quepe	1654	59	344.50	340.74	20.38	1533.14	−1.15	1.32	0.30	1274.57	1005.88	724.32	208.28
Allipen river at Los Laureles	1503	72	1625.66	374.08	862.35	2739.85	0.22	0.07	0.56	2116.27	1599.25	1242.43	1081.61
Donguil river at Gorbea	701	56	355.93	108.31	54.14	538.48	−0.61	0.11	0.25	495.27	375.35	260.03	507.75
Río Tolten river at Coipue	3264	35	3460.22	1406.23	346.00	6600.49	−0.33	0.28	0.52	5030.25	3540.67	2234.62	1060.12
Trancura river at confluenceLlafenco river	1215	48	1266.94	329.34	355.71	1847.30	−0.51	−0.16	0.44	1661.23	1312.83	943.82	1042.75



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percentile 90	0.08	0.06	0.06	0.07	0.13	0.21	0.24	0.22	0.17	0.13	0.12	0.10
Percentile 15	0.02	0.01	0.01	0.02	0.04	0.09	0.10	0.10	0.09	0.07	0.05	0.03
Percentile 50	0.04	0.03	0.03	0.04	0.07	0.14	0.15	0.13	0.11	0.09	0.08	0.06

Fig. 4.4 Distribution curves for monthly flows in terms of annual flow percentages in southern zone

4.2.4 Patagonia Zone

4.2.4.1 Watersheds

The typical climate of this zone is temperate maritime cold with abundant rainfall. Mean annual precipitation is in the order of 3000 m. The larger precipitation is in winter although it is not rare to expect precipitation in summer. In this zone you can find the Magellan forest with native species such as coigue, canelo, cypress and arrayán. You can also find typical Chilean fauna such as puma and huemul.

The Patagonia zone has also a rainy climate and 22 watersheds with a total area of 240,791 km^2, a population of 272,989 habitants which represent 1.5% of Chilean population and a population density of 1.1 habitants/km^2. Average annual precipitation is 2963 mm/year and a total annual flow 20,258 m^3/s. This zone has 16,361 glaciers with a total estimated volume of 3463 km^3. It has 10,363 lakes and lagoons with a total surface area of 7030 km^2. Some of this water bodies are partly in Argentina. Larger natural lakes are General Carrera Lake (1850 km^2), Cochrane Lake (182.8 km^2), Toro Lake (191.7 km^2). This zone has a total area of national parks, national monuments and protected areas of 8,924,447. Main exponents are National Parks O'Higgins, San Rafael Lagoon, Torres del Paine, Cabo de Hornos, National Reserve areas Alacalufes and Las Guaitecas (Directorate General for Water, Ministry of Public Works, Water Atlas, Chile). Principal rivers are the Baker, Palena, Simpson, Mañiguales, Ibañez, Pascua and Cisnes. Table 4.8 shows some characteristics of these watersheds.

Baker watershed is the second largest in Chile and the one that has the largest flow. It is regulated by General Carrera Lake which is the second largest of South America. Baker has a mixed flow regime, a great potential for hydro-electric

Table 4.7 Statistics of mean monthly flows /m^3/s) in representative gaging stations in the southern zone

STATION		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bueno river in Bueno	Prom	287.8	228.6	196.1	221.0	327.1	522.7	629.9	545.7	456.9	411.1	378.0	356.4
	cv	0.3	0.3	0.3	0.4	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3
	Percentiles 90%	342.5	251.0	220.9	231.6	352.1	591.7	820.1	578.9	608.7	467.8	482.3	439.1
	50%	269.4	197.3	181.6	188.0	268.9	450.6	564.7	453.5	456.2	367.7	378.9	316.0
	15%	165.1	170.9	144.5	152.7	209.2	323.4	388.1	373.8	342.8	305.3	279.4	238.5
Cautin in Rariruca	Prom	56.8	46.8	41.4	49.2	106.5	165.9	167.7	156.0	135.9	119.2	102.7	84.1
	cv	0.3	0.3	0.3	0.5	0.7	0.5	0.4	0.5	0.4	0.3	0.3	0.4
	Percentiles 90%	75.9	64.9	55.7	71.9	185.2	226.0	233.5	191.9	162.1	161.9	137.8	115.7
	50%	54.3	43.8	39.3	43.8	74.8	144.7	147.4	131.8	116.8	109.9	95.0	77.4
	15%	38.5	34.3	30.6	31.7	43.7	90.0	93.5	96.3	93.5	78.5	64.7	50.6
Pilmaiquén in San Pablo	Prom	107.9	86.6	83.8	108.0	176.6	268.7	283.2	266.6	212.4	176.8	160.5	142.2
	cv	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.3	0.2	0.3	0.3	0.4
	Percentiles 90%	147.1	115.2	110.4	182.5	264.7	362.3	390.6	353.8	280.4	228.7	223.1	192.2
	50%	96.7	78.7	74.1	94.2	156.6	268.4	272.8	263.8	220.5	167.5	146.0	115.2
	15%	69.6	62.4	59.1	69.7	89.4	169.8	181.2	189.5	171.4	126.8	116.4	95.7
Cruces in Rucaco	Prom	22.2	15.9	14.6	23.9	78.2	171.4	201.4	176.0	123.8	86.9	56.5	37.3
	cv	0.4	0.3	0.3	0.7	0.8	0.5	0.4	0.4	0.3	0.5	0.5	0.5
	Percentiles 90%	34.8	21.9	20.5	41.1	163.0	277.7	327.6	261.2	168.1	135.7	92.9	61.8
	50%	21.1	15.4	14.5	17.8	60.9	166.1	193.5	160.6	115.7	75.6	46.1	32.1
	15%	14.5	10.1	9.9	12.7	27.0	94.3	111.2	110.3	88.8	49.2	31.8	21.8

Table 4.8 General characteristics of principal watersheds of the Patagonia Zone

Watershed	Origin	Area (km^2)	River length (km)	Mean flow (m^3/s)
Baker	Bertrand Lake	26,726	170	870
Palena	Palena Lake	12,887	240	700
Pascua	O'Higgins Lake	14,760	62	650
Cisnes		5,196	160	700
Aysen	Several lakes	11,674	170	628

development and is well known for recreational purposes. Baker river watershed has a great potential for its singularity, environmental characteristics of its flora and fauna, and recreational activities. Tributaries of Baker River are Chacabuco, Cochrane, Del Salto, Colonia, Los Ñadis, Ventisquero and Vargas.

Palena River has a pluvial regime and its watershed area is partially in Chilean territory. The Aysén River exhibits a mixed flow regime. Principal tributaries are Simpson River which drains the southern part of the watershed and Mañiguales which drains the north area. It discharges in the sea in the Aysen fiord. It has a mean annual flow of 630 m^3/s. Aysen watershed has 13 beautiful natural lakes.

Pascua River is the most torrential river in Patagonia. It has several rapids in the vicinity of Chico Lake. Downstream of the junction with the Quiroz River several wide meanders are formed as well as wetlands and swamps. Pascua has potential for hydro development, although there is a concern of ecologist groups.

4.2.4.2 River Stream Flows

Table 4.9 presents the principal statistics of annual flow volumes of 29 gaging stations in the southern zone. Annual flow volumes are shown as the sum of mean monthly flows in each gaging station expressed as m^3/s. To express annual flow in cubic meters figures should be multiplied by the number of seconds in 1 month ($24 \times 3600 \times 30$).

The specific productivity per unit watershed area for this zone is in the range of 94 and 5780 1/s/km^2 with an average value of 1250 l/s/km^2. The probability of specific productivity being in the range of 175 and 3150 l/s/km^2 is 0,75. Figure 4.5 shows a distribution curves for monthly flows in term of annual volumes, in other to be able to have a preliminary estimate of monthly mean flows in terms of annual flow volumes. Distribution curves for 90%, 50% and 15% percentiles are shown with corresponding tabulated values.

This zone is more homogeneous than the arid and central zones even though the rainfall also increases with latitude. Specific productivity has a coefficient of variation of 1,25. Rivers originate in the upper Andes and flow crossing the central valley and the coastal mountains to reach the sea. The length of the main rivers is in the order of 200 or 300 km.

Table 4.10 presents mean monthly flows for four representative gaging stations. The table shows the average flow, the coefficient of variation and the 90% percentile, the median and 15% percentile for each month in each location.

Table 4.9 Principal statistics of annual flow for 29 gaging stations in Patagonia zone

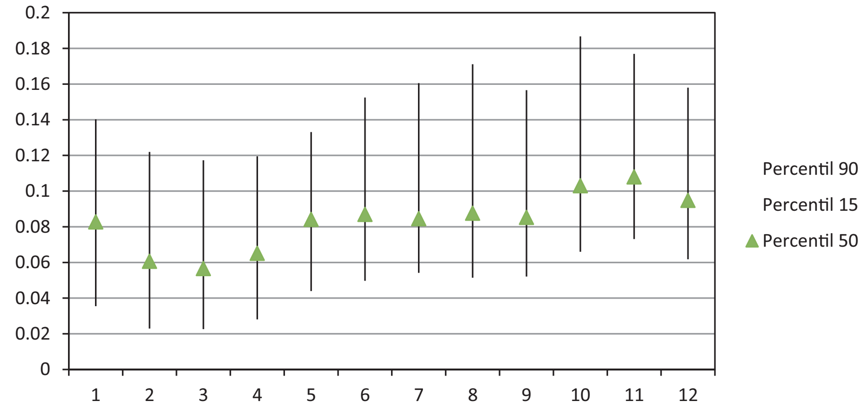
Gaging station	Basin area (km^2)	Data	Average (m^3/s)	St. Dev (m^3/s)	Minimum (m^3/s)	Maximum (m^3/s)	Skew	Kurtosis	Correla tion coef.	90% (m^3/s)	50% (m^3/s)	15% (m^3/s)	Sp. Prod ($l/s/km^2$)
Manso river before confluence Puelo river	3513	17	2271.10	608.40	1151.85	3453.15	−0.12	−0.09	0.51	2947.49	2289.60	1637.65	646.48
Puelo river at Tagua-Tagua Lake	8449	11	6077.11	1249.98	4081.69	7758.51	−0.23	−1.61	0.28	7246.73	6586.78	4915.74	719.27
R Puelo river at Carrera Basilio	8000	15	7329.58	1553.93	3484.73	9745.05	−0.97	1.52	0.40	8834.54	7868.59	5751.60	916.20
futaleufú river at La Frontera	7610	17	3672.50	952.54	1810.14	4974.79	−0.70	−0.21	0.70	4635.35	3901.38	2730.46	482.59
Espolón river at Espolón Lake	475	17	597.96	135.58	316.71	776.95	−0.95	0.13	0.23	740.51	634.35	450.90	1258.86
Petrohué river at Todos Los Santos Lake	2210	8	2986.05	990.15	960.38	4068.08	−1.35	1.83	0.73	3822.01	3360.01	2270.33	1351.15
Palena at confluence with Rosselot river	9000	19	9394.67	1931.05	4331.51	11620.81	−1.35	1.47	0.46	11189.69	10039.31	7750.35	1043.85
Tigre river at La Frontera	312	17	162.91	60.00	19.36	240.33	−1.11	0.68	0.64	214.49	181.13	103.37	522.15
Mayer river at desembocadura		30	1228.13	372.39	386.04	2221.00	−0.12	1.19	0.28	1614.14	1288.88	836.50	
Pascua river at O'Higgins Lake		14	6364.20	1884.26	876.75	8630.55	−2.07	5.46	−0.17	7668.43	6542.78	5952.83	
Pascua river at confluence Quetru river		14	7400.35	2188.68	1779.06	9652.58	−1.69	2.50	−0.58	9051.16	8377.38	5607.03	
Blanco riverat confluence Aysériver	1250	20	2901.85	707.71	635.22	3614.01	−1.93	4.83	0.11	3511.87	3049.51	2560.67	2321.48

(continued)

Table 4.9 (continued)

Gaging station	Basin area (km^2)	Data	Average (m^3/s)	St. Dev (m^3/s)	Minimum (m^3/s)	Maximum (m^3/s)	Skew	Kurtosis	Correla tion coef.	90% (m^3/s)	50% (m^3/s)	15% (m^3/s)	Sp. Prod ($l/s/km^2$)
Blanco Chico river atconfluence Río Oscuro	53	34	28.45	12.05	2.73	46.21	−0.53	−0.61	0.48	42.08	28.08	16.87	536.79
Blanco river at confluence Huemules	350	23	114.55	32.72	42.06	176.72	−0.33	−0.07	0.28	145.95	120.30	87.36	327.29
Blanco river at Caro Lake	0	32	981.66	239.44	412.78	1483.84	−0.55	0.12	0.17	1201.23	1030.93	682.48	
Claro river at Piscicultura	0	22	60.45	24.83	7.61	87.45	−1.02	−0.17	0.57	84.19	67.85	31.70	
Emperador Guillermo river at confluenceMañiguales	700	38	195.61	54.01	59.95	334.98	−0.01	1.04	0.43	255.34	199.66	150.38	279.44
Huemules at Cerro Galera	890	29	92.33	25.81	27.84	127.37	−0.70	−0.07	0.62	123.17	97.91	59.43	103.74
Mañiguales river at confluence Simpson	4058	36	1705.64	603.74	94.02	2870.58	−1.14	1.40	0.01	2273.52	1828.23	1114.51	420.32
Pollux at confluence Simpson	450	9	42.11	25.48	2.84	73.91	−0.21	−1.19	−0.33	71.40	39.27	14.79	93.58
Simpson juconfluence Mañiguales river	3676	15	359.40	555.91	32.23	1564.08	1.67	1.04	0.94	1366.19	99.08	50.54	97.77
Ñireguao river at Villa Mañiguales	2000	38	382.66	110.13	109.57	662.20	−0.08	0.23	0.33	498.22	376.23	276.25	191.33
Simpson at Coyhaique	3022	37	529.41	187.44	37.88	815.80	−0.81	0.48	0.38	730.72	549.12	332.28	175.19
Baker river atd Bertrand Lake	0	15	6640.41	922.76	4849.65	7854.56	−0.68	−0.37	0.28	7699.16	6849.12	5647.28	

Baker river at angostura Chacabuco	0	15	7929.19	1302.99	5771.57	9667.69	−0.39	−1.18	0.33	9376.10	8185.83	6331.28	
Ibañez river at desembocadura	2483	36	1623.39	305.30	714.35	2282.59	−0.51	1.58	0.21	1997.37	1595.54	1406.95	653.80
Cochrane river at Cochrane	0	27	175.34	68.31	35.82	300.65	−0.16	−0.53	0.86	258.35	179.43	117.70	
Río Murta river at Desembocadura	0	33	1042.16	179.26	584.86	1443.70	−0.31	1.05	−0.07	1227.83	1063.68	905.33	
El Baño river at Chile Chico	0	23	13.67	8.23	1.06	31.36	0.92	1.09	0.45	24.11	12.53	8.51	
Baker bajo Ñadis	0	14	10391.07	2090.73	4795.28	13173.47	−1.54	3.21	0.19	12283.96	10836.65	8529.24	



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percentile 90	0.14	0.12	0.12	0.12	0.13	0.15	0.16	0.17	0.16	0.19	0.18	0.16
Percentile 15	0.04	0.02	0.02	0.03	0.04	0.05	0.05	0.05	0.05	0.07	0.07	0.06
Percentile 50	0.08	0.06	0.06	0.07	0.08	0.09	0.08	0.09	0.09	0.10	0.11	0.09

Fig. 4.5 Distribution curves for monthly flows in terms of annual flow percentages in Patagonia zone

4.3 Lakes and Reservoirs

4.3.1 Lakes

Chile has 33 major lakes as classified by the listing of lakes and lagoons (Ministry of Public Works, Directorate General for Water, Public Lakes Inventory). Most of them are in the Los Ríos and Los Lagos Regions. These natural lakes provide regulation for surface water resources and are the source of several important rivers. They are used for recreational purposes and provide water for irrigation, municipal and industrial uses and also are valuable assets for recreational purposes, Mast of these lakes are surrounded by mountains and volcanoes being beautiful natural sceneries specially in southern regions. Table 4.11 shows a listing of major lakes as recorded by the Public inventory of lakes. There are also many smaller lakes and lagoons which also are used as repository of water resources and are important to sustain aquatic fauna and are natural habitat for wild fauna and ecosystems.

4.3.2 Reservoirs

Man-made reservoirs are key elements for regulating river flow and thus provide more confidence in the availability of essential resource for hydroelectricity, irrigation, water supply for municipal use, industrial activities and mining. Most of these

Table 4.10 Statistics of mean monthly flows (m^3/s) in representative gaging stations in the Patagonia zone

Station		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rio Mayer in Desembocadura	Average	184.0	174.3	147.5	118.7	103.3	64.1	57.1	59.8	61.5	111.6	145.3	169.0
	cv	0.5	0.6	0.5	0.5	0.3	0.4	0.4	0.4	0.6	0.5	0.4	0.4
	Percentiles 90%	220.9	222.7	211.6	175.1	160.6	97.8	82.4	94.4	83.0	156.2	190.1	229.4
	50%	183.8	170.4	132.6	104.8	104.9	56.7	54.9	52.5	59.3	109.2	142.2	156.8
	15%	154.8	149.6	100.9	82.0	54.4	38.5	35.7	34.0	41.2	67.0	102.0	129.8
Rio Mañihuales before jta Simpson	Average	126.8	86.0	101.7	122.6	175.6	201.9	218.8	207.9	186.9	224.4	218.5	184.3
	cv	0.5	0.6	1.0	0.5	0.5	0.4	0.5	0.6	0.4	0.3	0.3	0.4
	Percentiles 90%	208.3	159.3	170.3	190.0	293.4	306.7	365.8	330.0	272.0	312.8	319.9	289.8
	50%	117.8	72.1	71.4	131.2	175.5	196.0	210.8	176.7	163.9	202.3	210.5	174.8
	15%	64.6	43.4	42.1	55.4	87.5	104.7	100.5	130.9	130.5	166.7	143.2	112.7
Rio baker in desague Bertrand Lake	Average	662.8	702.3	695.4	647.5	634.4	585.2	533.7	474.9	437.1	430.6	475.7	558.1
	cv	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.1
	Percentiles 90%	744.0	814.5	801.6	786.5	753.7	680.9	638.2	564.8	504.9	493.6	553.8	627.3
	50%	661.2	687.1	691.5	653.0	640.5	621.0	548.7	482.4	465.6	424.3	486.4	565.2
	15%	587.2	622.9	609.3	573.0	522.5	514.2	480.2	410.5	358.0	375.0	394.1	479.4
Rio Ibañez in Desembocadura	Average	205.2	167.0	146.4	131.1	142.9	103.6	98.4	93.2	87.2	145.1	190.3	234.5
	cv	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.3	0.4	0.3	0.3
	Percentiles 90%	273.1	226.9	196.9	199.8	207.9	163.2	153.6	153.7	132.2	238.8	246.0	329.0
	50%	199.0	156.0	134.0	124.1	132.7	94.7	94.1	84.0	81.5	133.6	185.4	232.2
	15%	140.9	135.7	105.7	80.3	80.5	54.5	48.8	46.8	56.5	97.5	149.8	189.1

Table 4.11 Major natural lakes

Name	Region	Latitude S	Longitude W	Elevation (m)	Lake area (km^2)
VERDE LAGOON	III	26G 53M	68G 28M	0	16
LANALHUE LAGOON	VIII	37G 55M	73G 18M	23	31
LLEULLEU LAGOON	VIII	38G 09M	73G 20M	15	41
BUDI LAKE	IX	38G 52M	73G 18M	18	56
CABURGA LAKE	IX	39G 08M	71G 46M	470	51
VILLARRICA LAKE	IX	39G 15M	72G 05M	205	177
CALAFQUEN LAKE	XIV	39G 31M	72G 10M	200	119
PANGUIPULLI LAKE	XIV	39G 43M	72G 13M	135	111
RINIHUE LAKE	XIV	39G 50M	72G 19M	105	84
PIRIHUEICO LAKE	XIV	39G 56M	71G 48M	570	34
RANCO LAKE	XIV	40G 25M	72G 42M	70	442
MAIHUE LAKE	XIV	40G 16M	72G 03M	85	49
PUYEHUE LAKE	XIV	40G 39M	72G 29M	180	156
RUPANCO LAKE	X	40G 49M	72G 30M	118	223
LLANQUIHUE LAKE	X	41G 08M	72G 49M	50	850
TODOS LOS SANTOS LAKE	X	41G 06M	72G 16M	189	183
CHAPO LAKE	X	41G 28M	72G 30M	235	54
CUCAO LAGOON	X	42G 39M	74G 05M	40	9
HUILLINCO LAKE	X	42G 40M	73G 57M	5	18
YELCHO LAKE	X	43G 19M	72G 18M	45	116
ROSSELOT LAKE	XI	44G 08M	72G 19M	60	33
YULTON LAKE	XI	45G 06M	72G 55M	470	59
ELIZALDE LAKE	XI	45G 46M	72G 19M	0	26
DEL SALTO LAKE	XI	46G 08M	74G 32M	0	18
GENERAL CARRERA LAKE	XI	46G 30M	72G 00M	0	1840
PRESIDENTE RIOS LAKE	XI	46G 29M	74G 26M	0	313
CAMILO HENRIQUEZ LAKE	XI	46G 24M	75G 12M	0	8
ELENA LAKE	XI	46G 35M	74G 40M	0	45
MANUEL RODRIGUEZ LAKE	XI	46G 27M	75G 15M	0	11
SAN RAFAEL LAGOON	XI	46G 41M	73G 58M	0	122
BERTRAND LAKE	XI	46G 57M	72G 51M	0	68
COCHRANE LAKE	XI	47G 10M	72G 14M	0	320

reservoirs are located in the arid and semi-arid zones, the central region and the north part of the southern zone. Mining operation in the north of Chile are also using desalting techniques to use sea water directly in mine operations or to replace soft water use of coastal cities and trade them for water resources in mountain areas. Table 4.12 shows a list of major reservoirs constructed by the Government and

Table 4.12 Reservoirs

Region	Name	Capacity (million m^3)	Year	Use
V	Peñuelas	95	1900	Municipal water supply
III	Lagunas de Huasco	14	1911	Irrigation
V	Lliu-Lliu	2	1925	Irrigation
IX	Huelehueico	5	1930	Irrigation
V	Pitama	2	1932	Irrigation
V	Lo Orozco	6	1932	Irrigation
V	Purisima	2	1931	Irrigation
V	Lo Ovalle	14	1932	Irrigation
V	Perales de Tapihue	11	1932	Irrigation
V	Cerrillos de Leyda	3	1932	Irrigation
VI	Lolol	6	1932	Irrigation
RM	Huechun	14	1932	Irrigation
IV	Colimo	10	1933	Irrigation
IV	Recoleta	97	1934	Irrigation
XV	Caritaya	42	1935	Irrigation
IV	La Laguna	40	1937	Irrigation
III	Lautaro	27	1939	Irrigation
IV	Cogoti	138	1939	Irrigation
VII	Bullileo	60	1948	Irrigation
VII	Tutuven	13	1951	Irrigation
VII	El Planchón	73	1952	Irrigation
VIII	Laguna de Laja(*)	890	1954	Hydro-electricity
VII	Laguna del Maule (*)	850	1957	Hydro-electricity
XV	Laguna Cotacotani	21	1962	Irrigation
RM	Rungue	2	1964	Irrigation
IV	La Paloma	755	1967	Irrigation
RM	El Yeso	256	1967	Municipal water supply
VII	Digua	220	1968	Irrigation
VIII	Coihueco	29	1972	Irrigation
II	Conchi	22	1975	Irrigation
VI	Los Cristales	9	1976	Irrigation
V	Aromos	35	1987	Municipal water supply
VI	Convento Viejo I	27	1994	Irrigation
III	Santa Juana	170	1995	Irrigation
IV	Puclaro	200	1999	Irrigation
IV	Corrales	50	2000	Irrigation
IV	El Bato	25	2009	Irrigation
VI	Convento Viejo II	240	2008	Irrigation
VII	Ancoa	80	2011	Irrigation
Vi	Rapel	695	1968	Hydro-electricity
VII	Colbün	1544	1985	Hydro-electricity
VIII	Ralco	1174	2004	Hydro-electricity
VIII	Pangue	83	1996	Hydro-electricity

private companies which represent a total capacity of 8.808 million cubic meters (Directorate General for Water 2010).

The government has a construction program that should increase the total capacity to approximately 9.000 million cubic meters by the year 2018.

4.4 Wetlands

As mentioned Chile has a wide range in climate and geomorphology, consequently there are areas which are unique in terms of their environmental conditions. In Chile we can find protected areas in estuaries, lagoons, wetlands, deserts, salty lagoons, salares, lakes, and mountains. These environments are habitat for fishes, reptiles, birds and many other unique species, hence biodiversity of wetlands is a valuable asset in terms of environmental and social issues.

Chile signed in 1981 the RAMSAR Convention agreement and hence acquired a compromise to designate wetlands to be included in RAMSAR list of internationally important wetlands and to generate laws and policies that comply with the protection and conservation of national wetlands. Wetlands are defined as ecosystems which produce benefits and services fundamental for life on Earth. They provide water, food, and resources, recharge groundwater, control floods and represent a habitat for many species of flora and fauna (Ministry of Environment 2018).

RAMSAR sites are not formally protected areas, but they are officially protected by the government in case of environmental impact studies. Chile has 13 RAMSAR sites which represent a total of 361,760 has. These sites are not necessarily included in the list of protected areas according to Chilean legislation. Protected areas are defined as national monuments, national parks, national reserve areas and nature sanctuaries. Table 4.13 presents the list of declared RAMSAR sites and the proportion of the sites which are included in the classification defined by Chilean legislation. Consequently only 22% (80,201 has) of the RAMSAR sites areas are included in what the national legislation considers to be national protected areas and some RAMSAR sites are not included in the National System of Protected Areas (SNAP). Protected areas are shown in Table 4.14.

The National Plan for Wetland Protection 2018–2022 is a governmental initiative to contribute to maintain wetlands and preserve biodiversity. The National Biodiversity Strategy (2017–2023) which was approved in 2018 established five strategic lines of action. The five objectives were: promote sustainable use of biodiversity for human welfare and to reduce the threat to ecosystems and species; create public conscience, knowledge and social participation to defend biodiversity as benefit for humanity; develop a robust institutions and equality in the distribution of biodiversity benefits; include biodiversity in government policies, plans and programs of the public and private sectors, and protect and recover biodiversity and services in ecosystems.

This Plan was formulated to avoid the loss and degradation of wetland ecosystems. The objectives of this plan are to protect biodiversity and services of

Table 4.13 Intersection of RAMSAR sites and protected areas. (National Plan of Wetlands Conservation 2018–2022, Ministry of Environment 2018)

RAMSAR sites		Protected areas				
	has	Nature monuments	National parks	National reserves	Nature sanctuaries	RAMSAR percent areas
Laguna de aguas calientes IV	15,529		334.9			2%
Bahia Lomas	58,946					0%
Humedal El Yali	520			154.1		30%
Parque andino Juncal	13,706					0%
Laguna conchali	34				34	100%
Lag Negro Francisco-Santa rosa	62,460		50,076			80%
Salar de Pujsa	17,397			5567		32%
Rio Cruces	4877				3588	74%
Salar de Surire	15,858			82.6		52%
Salar de Tara	96,438			6030		6%
Salar de Huasco	6000				6000	100%
Salinas Huentelauquen	2772					0%
Sistema Hidrologico Soncor	67,133			248.9		0%

Table 4.14 List of National System of Protected Areas (SNAP) according to the National Plan of Wetlands Conservation 2018–2022, Ministry of Environment 2018

Region	Areas (has)
Magallanes y Antártica Chilena	3,425,323
Los Lagos	250,923
Los Ríos	129,976
Aysén del General Carlos Ibáñez del Campo	374,722
La Araucanía	70,560
Biobío	54,333
Maule	42,067
Antofagasta	38,753
Arica y Parinacota	29,120
Aysén del General Carlos Ibáñez del Campo	374,722
Libertador General Bernardo O'Higgins	20,377
Atacama	18,745
Coquimbo	17,888
Metropolitana de Santiago	13,889
Tarapacá	13,315
Valparaíso	7272

ecosystems in priority wetlands, to define protected areas which warrants their conservation and management in the long run; to identify with available information the priority areas that the National System of protected Areas (SNAP) should protect in the short run at regionally and national scales, and to manage the requests to create protected areas and present them to the Council of Ministers for Sustainability.

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Chapter 5
Groundwater Resources

Francisco Suárez, Sarah Leray, and Pedro Sanzana

Abstract This chapter presents the status of groundwater resources in Chile focusing on two relevant aspects. First, the geological and climatic aspects that shape the country's hydrogeological configuration. These, in turn, provide the context for the hydrogeological configuration within the country. Then, based on the official information provided by the *Dirección General de Aguas*, DGA, a quantification of groundwater resources in the different hydrogeological administrative units is presented. To illustrate the different typologies of aquifer encountered in the country, some examples of relevant hydrogeological basins are described. Through these examples, we also display different problems that are foreseen in terms of groundwater knowledge, overexploitation, restricted areas, water quality, and climate change, among other factors. Finally, based on the information found, future challenges related to groundwater resources are presented.

Keywords Groundwater · Geology · Hydrogeology · Aquifer · Overexploitation · Restricted areas

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5.1 Introduction

Chile covers an area of 756,626 km^2, with a unique geographical configuration in the world. Its longitudinal extension, north to south, reaches more than 4,300 km whereas its lateral extension is on average only 180 km. Thus, the great variability of climate, soil and vegetation covers, topography and geology, conforms the hydrological and hydrogeological setup of the country. Despite this contextual richness, the hydrogeological knowledge is far from being exhaustive and remains to be more thoroughly and more extendedly acquired. Nor are fully assessed the sustainable conditions for exploitation and protection.

The groundwater systems studied so far are typically located in northern Chile. There, groundwater is an important water source because surface waters are scarce. Water demand comes mostly for mining and agricultural purposes. But given that groundwater recharge is small, or even inexistent, and that there are natural water quality issues, critical states of exploitation have been already reached.

In central Chile, where population is located in dense urban areas, groundwater has been traditionally perceived as a valuable resource, for its high quality and its continuous productivity. Highly transmissive alluvial basins located in the close vicinity of population settlements have thus been significantly exploited, conjointly with surface water resources. Even when precipitation provides a greater recharge to the aquifers, densely populated urban centers are constantly demanding more water. In general, most of the hydrogeological units are decreed as in a state of restriction, and in few cases critical states of exploitation have been reached.

Going south of Chile, in more humid locations where both surface waters and groundwater are abundant and have excellent quality, population diminishes considerably and thus agriculture, which is supplied with surface resources, is the main water user. In the Patagonian region, although precipitation is small (~400 mm/year), there are no relevant water conflicts because the population is scarce.

This chapter presents the status of groundwater resources in Chile focusing on two relevant aspects. First, the geological and climatic aspects that shape the country's hydrogeological configuration. Then, based on the official information provided by DGA, a quantification of groundwater resources in the different hydrogeological administrative units is presented. To illustrate the different typologies of aquifer in the country, some examples of relevant hydrogeological basins are described. Through these examples, we display as well different problems that are foreseen in terms of groundwater knowledge, overexploitation, restricted areas, water quality, and climate change, among others. Finally, based on the information found, future challenges related to groundwater resources are presented.

5.2 Hydrogeological Context

5.2.1 Chilean Landscapes and Drivers for Groundwater Occurrence

In this section, we describe the geology of Chile, one of the main drivers for groundwater occurrence. Applied to groundwater, this description is not as exhaustive as would be in a geology book. In this respect, locations within the country that do not have a hydrogeological interest are not addressed in this chapter, e.g., the Chilean Antarctic region. Intimately linked to the geological history, the topography, another key driver for groundwater occurrence, is also included in this description. Finally, a brief presentation of the climatic conditions and its variability completes this description. For a detailed overview of a climatic description and/or precipitation and evapotranspiration patterns the reader is referred to Chaps. 2 and 3 of this book, whereas a more detailed description of the different basins is provided in Chap. 4. Altogether, Chilean geology, topography, and climate help in getting a contextual understanding of groundwater in the different regions throughout the country.

Chile, located in the western margin of South America, belongs almost entirely to the South American plate, except in southernmost Patagonia, where it is part of the Scotia Plate (Bird 2003). To the west, the Nazca plate subducts beneath the South American plate, while south of 45°S the Antarctic plate subducts below both the South American and Scotia Plate (Fig. 5.1a). Subduction has been a continuous process along western South American margin since the late Proterozoic (around 600 Ma), except during the Late Permian and the Triassic (around 250–200 Ma) where a very slow, or no subduction has been proposed (Charrier et al. 2007; Mpodozis et al. 1989), although recent studies have questioned this paradigm (del Rey et al. 2016). Thus, current Chile's geological, structural and morphological features are mainly controlled by the interaction between the subducted slabs and the overriding South American Plate (Gansser 1973; Jordán et al. 1983; Kley et al. 1999). Five morphotectonic units have been recognized in the country, they are from north to south (Fig. 5.1a): (1) the Main Cordillera (the Andes); (2) the Central Depression; (3) the Coastal Zone; (4) the Patagonian Cordillera; and (5) the Andean Foreland (Hervé et al. 2007; Charrier et al. 2007).

Igneous rocks crop out in the Main and Coastal Zones, but their maximum expression is in the Patagonian Cordillera, where the Patagonian Batholith dominates (Fig. 5.1b; Sernageomin 2003; Hervé et al. 2007). These rocks correspond mainly to granitoids, gabbros and diorites and are the evidence of magmatic activity in the country at least since the Ordivician (around 470 Ma; Sernageomin 2003). Metamorphic rocks are mainly restricted to the Coastal Zone (around 35° to 47°S) and in the eastern flank of the Patagonian Cordillera (around 47° to 55° S), although some outcrops are also found in the northern part of the Main Cordillera (Fig. 5.1b; Sernageomin 2003; Hervé et al. 2007). In the Coastal Zone, they comprise mainly metagreywacke, andalusite schist, blueschist, greenschist and an alternation of meta-sandstones and metapelites (Hervé et al. 2013); in the Patagonia Cordillera,

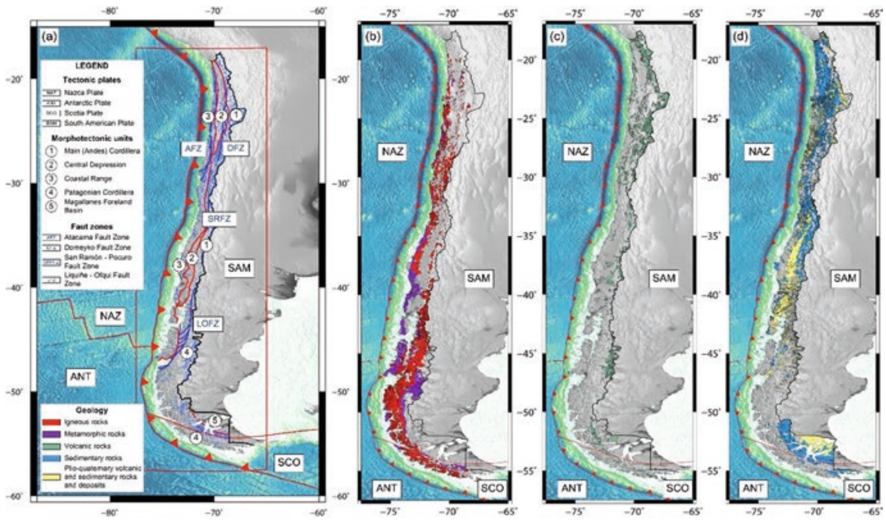

Fig. 5.1 (**a**) Geodynamic context and morpho-structural units. Modified from Scheuber and Andriessen (1990), Arriagada et al. (2000), Charrier et al. (2007, 2015), Farías et al. (2010), Díaz et al. (2014), Cembrano et al. (1996), Rosenau et al. (2006), Alvarez-Marron et al. (1993), Klepeis (1994), Poblete et al. (2014), Pankhurst and Hervé (2007). Plate limits from Bird (2003). (**b**) Igneous and metamorphic rocks. (**c**) Volcanic rocks. (**d**) Sedimentary rocks and Plio-quaternary volcanic and sedimentary rocks and deposits. (Modified from Sernageomin 2003)

they comprise metapelitic schist, amphibolites, metabasites, marble and gneisses among others (Calderón et al. 2007; Hervé et al. 2007, 2008). Volcanic rocks are the surface expression of magmatic processes. They crop out mainly in the northern part of the Coastal Zone, and almost uninterruptedly in the main Cordillera between 17° and approximately 47°S, while in the Patagonian Cordillera they form a curved ribbon that represent the vestiges of an ancient ocean (Fig. 5.1c; Dalziel et al. 1974; Calderón et al. 2007; Poblete et al. 2016). Lithologies cover a wide range of types, among them basalts, andesites, rhyolites, and pyroclastic rocks. Sedimentary rocks are mainly found north of 40°S and to the west of the Patagonian Cordillera, south of 50°S (Fig. 5.1d). In the north, both marine and continental sedimentary are found, while in southernmost Chile, they correspond mainly to marine sedimentary rocks (Sernageomin 2003; Charrier et al. 2007). Quaternary deposits are mainly exposed in the central depression and in the Andean foreland region, in southernmost Chile (Fig. 5.1d), while Pliocene-Quaternary volcanic rocks are restricted to the main cordillera.

Several fault zones have been recognized in the country related to the development of the Andes and major shear zones. Relevant fault systems from north to south include (Fig. 5.1a): the Atacama, the Cordillera de Domeyko, the San Ramon-Pocuro and the Liquiñe-Ofqui. The Atacama fault system, in the north, and the Liquiñe-Ofqui fault system in the south are both a set of shear faults. The Atacama fault zone recorded a sinistral sense of shear (Scheuber and Andriessen 1990), while dextral shear deformation has been documented in the Liquiñe-Ofqui fault zone (Cembrano et al. 1996; Arancibia et al. 1999). On the other hand, the Cordillera de Domeyko (north) and San Ramón-Pocuro (center) fault systems, located in the western part of the Main Cordillera, are a set of thrust faults with minor lateral displacement (Arriagada et al. 2000; Díaz et al. 2014).

Topography and climate are intimately linked. In fact, the development of a cordillera through time can drastically change the atmospheric pattern in a region (Ehlers and Poulsen 2009). Regarding the topography, the elevation of the Andean Cordillera diminishes from north, with elevations higher than 5,000 m a.s.l., to south, with elevations less than 1,500 m a.s.l. Nevertheless, all along the country, the Andes Cordillera acts as an active barrier for the trades and westerlies winds, creating important rain shadows. In the north of Chile (18°S – 27°S), the three main physiographical features, i.e., the Andes Cordillera, the Central Depression and the Coastal Range, are well established (Fig. 5.1a). The Andes Mountains have elevations that can reach ~6,000 m a.s.l and very steep gradients, up to 30%, while the Altiplano Puna presents elevations of more than 3,500 m a.s.l., and small gradients. The Central Depression, which presents elevations between 700 and 1,400 m a.s.l. and relatively small gradients (up to 1–2%), is well developed and contains Tertiary and Quaternary material that comes from the Andes Mountains. This filling forms the pampas that are bounded at the west by the Coastal Range, which presents elevations between 2,000 and 3,000 m a.s.l., and promotes formation of salt flats. The Coastal Range falls abruptly to the Pacific Ocean.

The climate is the main pedogenic factor in the north of Chile. The arid and hyper-arid conditions result in soils with almost no vegetation and organic matter, where xerophyte vegetation is the dominant species. The Coastal Range is under the permanent influence of the Pacific anticyclone, and thus precipitation is almost inexistent. However, a dense fog, referred to as "camanchaca", is abundant in a small coastal fringe and allows the development of weak vegetation located in the slopes of the ravines. In the Central Depression, the arid climate is severe, with a mean annual temperature of 18 °C, precipitation of less than 10 mm/year, potential evapotranspiration of almost 2,000 mm/year, and very clear skies (Alvarez-Garreton et al. 2018; Garreaud et al. 2009). Vegetation is represented by phreatophytes, by Tamarugos that are fed by groundwater, and other species towards the pre-Andean elevations (Latorre et al. 2003). At higher elevations, steppe climates with summer precipitation are present. Summer precipitation in the Andean plateau has a convective nature and can reach local values of 400 mm/year. The predominant altiplanic vegetation is the Andean steppe, with llaretales appearing above 4,000 m a.s.l. (Latorre et al. 2007).

The Central Depression disappears between 27°S and 33°S (Fig. 5.1a). An internal mountainous landscape dominates the region and is crossed by transverse valleys that are the result of water erosion from the Andes Mountains (Charrier et al. 2007). On the west side there is a coastal region that has large plains of marine abrasion, separated by erosion from the interior, and with the development of dunes (Casanova et al. 2013; Murray-130 Wallace and Woodroffe 2014). Here, the desert climate presents an increase in the winter rainfall, passing to a dry steppe climate and also resulting in aridisols. In this region, agriculture is possible with irrigation. The rivers of the transverse valleys are perennial because of the mountainous precipitation that creates thin irrigation areas and phreatophyte vegetation. The coastal vegetation is comprised by shrubs, cacti and an herbaceous cover due to the high humidity.

The three main physiographical features reappear between 33°S (Santiago) and 42°S (Puerto Montt) (Fig. 5.1a). The elevations of the Andes Mountains decrease towards the south from ~7,000 m a.s.l. near Santiago to ~2,000 m a.s.l. near Concepción (latitude 37°S). The Central Depression constitutes the main area of accumulation of Quaternary sediments, which corresponds to fluvial, fluvio-glacial and glacial deposits (Fig. 5.1d, Charrier et al. 2007). It has elevations ranging between 300 and 500 m a.s.l. and presents a wavy shape towards the south and relatively small longitudinal gradients. The Coastal Range, which has elevations of ~2,000 m a.s.l. in front of Santiago, decreases to less than 1,000 m a.s.l. near 34°S and even disappears in some locations. On its western side, different terrace levels are developed. Between 32°S and 38°S, there is a region with a Mediterranean climate. Precipitation falls primarily during the cold winter season, whereas the summer is dry. Precipitation increases and potential evapotranspiration decreases towards the south. Because the Andes Mountain has a greater height and width towards the south, there are more water reserves stored as snow compared to the north (Mernild et al. 2017). The Central Depression is comprised of fertile soils, well suited for agriculture, located in the floodplain banks of rivers (Casanova et al. 2013). A humid and temperate climate is observed between 38°S and 42°S. Precipitation also increases towards the south due to frontal perturbations moving along the region as a result of a weak influence of the Pacific anticyclone at these latitudes. In the Central Depression, humid soils have been formed from ashes and volcanic lava. These soils, which are intensively used for agricultural purposes, typically have poor drainage. Nonetheless, the topographical conditions allow surface runoff.

At latitudes between 42°S and 47°S the east-west structure of the country is maintained, although partly submerged (Fig. 5.1). The Coastal Range corresponds to the islands and archipelagos, the Central Depression is completely under the sea and the Andes Mountains reach elevations of no more than 2,000 m a.s.l. The complex system of channels and fjords is the result of the strong action of the last glaciation period (Boyd et al. 2008; Hulton et al. 2002). Towards the south of the 47°S parallel, the Coastal Range and the Central Depression disappear, and the Andes Mountain is divided into a western archipelago and an eastern mountain region, which in some locations surpasses 3,000 m a.s.l. and it has wide extensions covered by glaciers. The glacial activity from the Quaternary formed deep fjords, stripped away the soils and leaving bare the bedrock.

To the south of the 52°S parallel, Chile extends towards the east of the Andes Mountain, covering the Andean Foreland (Fig. 5.1). As surface waters are dominant in the south of the country, groundwater is scarcely used in these regions. In the Pacific side, weather is cold and annual precipitation rates exceed 3,000 mm, whereas in the eastern side annual precipitation averages 300 mm. Where precipitation is large, the soils are rich in organic matter. Because intrusive rocks outcrop in the Patagonian coast (Fig. 5.1b), soils only form at lowest elevations.

5.2.2 *Hydrogeological Settings*

In general, the Chilean aquifers identified so far are found in unconsolidated Quaternary deposits, such as volcanoclastic, fluvial, fluvioglacial, alluvial, lacustrine, laharic and aeolian sediments. These deposits fill the valleys bounded by Tertiary, Mesozoic and Paleozoic impermeable formations. Typically, these high-yield aquifers are unconfined or semi-unconfined with static levels relatively shallow (<50 m); and with heterogeneous soil particle distributions. The developed aquifers are much more productive than those known in non-Quaternary formations, such as in volcanic Tertiary or consolidated sedimentary Tertiary. However, little is known about the secondary porosity of these reservoirs, which in some cases can be significantly productive (Guihéneuf et al. 2014; Leray et al. 2013; Ruelleu et al. 2010; Scibek et al. 2016).

In response to the flow patterns that are observed in the South American continent, Chile has been divided into three hydrogeological provinces (DGA 1986; Fig. 5.2): *Highlands* (“Altiplánica”), *Coastal Basins* (“Cuencas Costeras”), and *Central Basins* (“Andina Vertiente Pacífico”). The *Highlands* province constitutes a large endorheic zone that also covers Perú, Bolivia and Argentina. Within the Chilean territory, the drainage system is mostly shared with Bolivia (between 18°S and 20°S). Towards the south, a network of small endorheic basins exists with no apparent surface connection with neighboring countries. The *Central Basins* province extends along the country, with extremely heterogeneous hydrogeological characteristics. The *Coastal Basins* province covers all the catchments that do not drain the Andes Mountains.

5.2.2.1 The *Highlands* Province (“Altiplanica”)

The *Highlands* province is basically found at elevations higher than 3,500 m a.s.l. Given the presence of fractured volcanic rocks and endorheic basins, complex groundwater systems have been encountered so far (Corenthal et al. 2016; Ortiz et al. 2014; Vásquez et al. 2013). Salt flats are formed at the lowest points of these basins, and evaporation is the main water outlet (Hernández-López et al. 2014, 2016; Johnson et al. 2010). The hydrogeological potential of the *Highlands* province is intimately linked to the climate and to the lithology of the zone. Convective summer precipitation events that occur over a Tertiary-Quaternary volcanic cover, which has a secondary permeability, i.e., dominated by fractures, allows groundwater recharge and water flow towards lower elevation zones. These zones, generally comprised of unconsolidated Quaternary deposits, store water and allow their access through wells. The thickness of these deposits can be larger than 100 m and the well

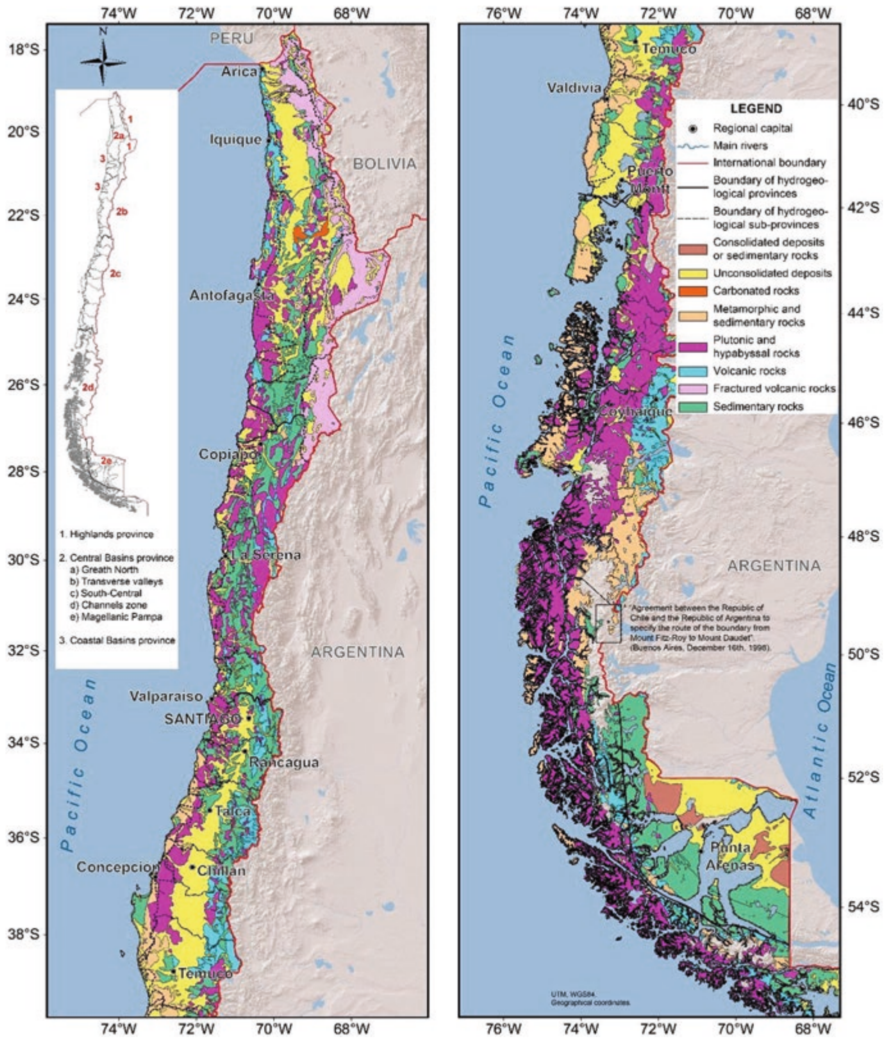

Fig. 5.2 Chilean hydrogeological map showing the different hydrogeological provinces and sub-provinces. (Modified from DGA 1986)

productivity is up to 2 m^3/s (Fig. 5.3; DGA 1986). Also, these groundwater resources have a good groundwater quality – with total dissolved solids (TDS) of about 500 mg/L, as long as the groundwater does not reach the salt flats in which evaporation concentrates the water (Marazuela et al. 2019). Frequent elements found in

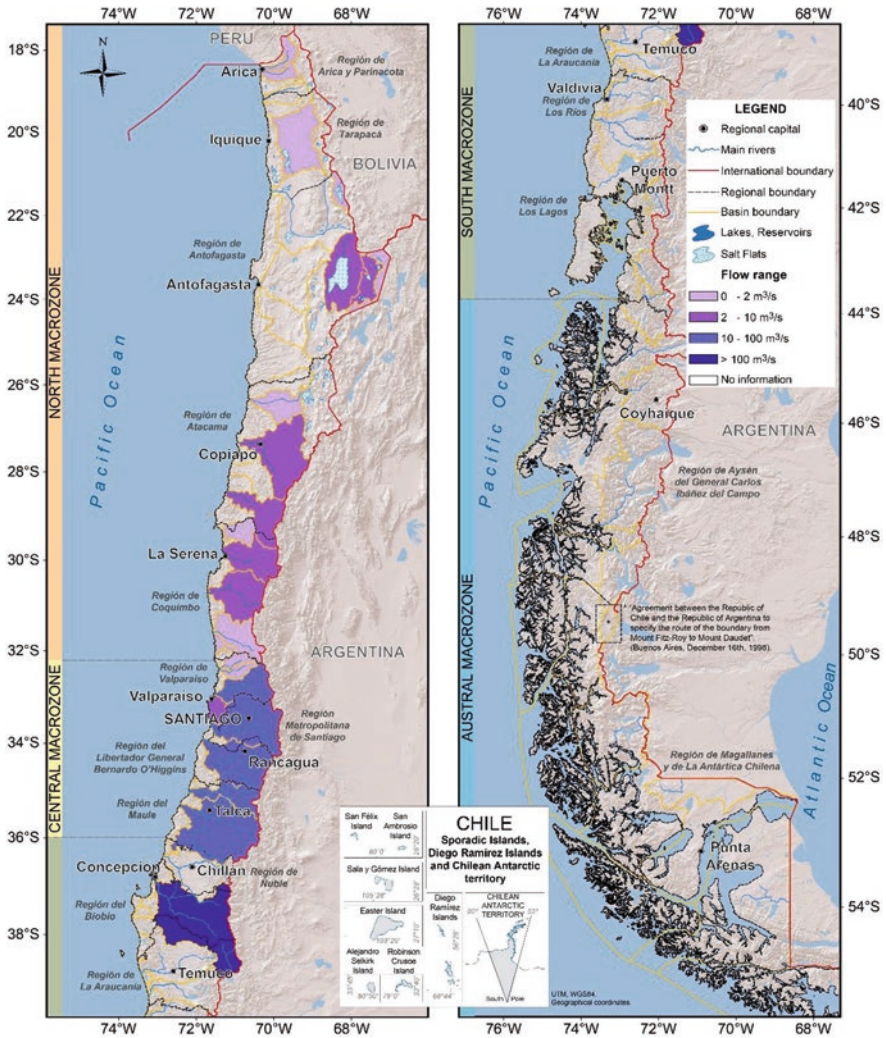

Fig. 5.3 Groundwater availability represented by well productivity (m³/s). (From Iniciativa Escenarios Hídricos 2030 2018)

both groundwater and surface waters are boron and arsenic, most likely due to the volcanic activity (Tapia et al. 2018). In general, the water required by the local communities of the *Highlands* is supplied by surface waters while groundwater is occasionally utilized in domestic uses. The main groundwater user in the *Highlands* aquifers is the mining industry, which takes advantage of the chemical elements dissolved in the brines of the salt flats.

5.2.2.2 The *Central Basins* Province ("Andina Vertiente Pacífico")

Because the *Central Basins* province extends along the entire country, which has extremely heterogeneous hydrogeological characteristics, this province is subdivided into five sub-provinces (DGA 1986; Fig. 5.2): (a) *Great North* ("Norte Grande"), (b) *Transverse Valleys* ("Valles Transversales"), (c) *South-Central* ("Central-Sur"), (d) *Channels Zone* ("Zona de los Canales"), and (e) *Magellanic Pampa* ("Pampa Magallánica"). These sub-provinces were defined according to criteria such as the existence of aquifer formations and their nature, and the characteristics of the recharge and discharge process (DGA 1986).

The *Great North* sub-province (Fig. 5.2) extends from the Perú-Chile international border until 27°S. Because it is a desert region with insignificant surface water, groundwater resources are of great interest for human activities (Aitken et al. 2016). This sub-province has three clearly defined sectors in terms of their aquifer nature (DGA 1986). The first sector, which is between 18°S and 19°S, has rivers oriented in the west-east direction that originate in the western slopes of the Andes Mountains, and drain to the Pacific Ocean. The aquifers are mainly comprised of Quaternary fluvial deposits from the scarce rivers of the region. These aquifers are typically unconfined, with thicknesses of 200 m or less, well productivities up to 2 m^3/s (Fig. 5.3), and recharge coming from the rivers of their basin (Taucare et al. 2015). Groundwater is mainly used for domestic and agricultural purposes. The second sector is mainly related to the Pampa del Tamarugal aquifer (between 19°S and 22°S), which is within a massive and heterogeneous deposit of Tertiary and Quaternary alluvial material in the Central Depression (Viguier et al. 2018). This aquifer has a variable thickness, with 100–300 m thick Quaternary alluvial deposits (see below for more details about this aquifer). The third sector is the Atacama Desert (between 22°S and 27°S), which, with the exception of the Loa river, is an arheic system.

The *Transverse Valleys* sub-province (Fig. 5.2) is located between 27°S and 33°S. The aquifers in this sub-province are located in fluvial Quaternary deposits. Their recharge comes mainly from the rivers and streams in the area (Strauch et al. 2009). These aquifers have thicknesses that vary between a couple of meters to approximately 200 m, with well productivities up to 10 m^3/s (Fig. 5.3). Groundwater quality is good near the river headwaters with approximately 500 mg/L of TDS. Downstream, groundwater quality diminishes by salinization, reaching TDS concentrations between 1,000 and 2,000 mg/L near the coast (DGA 1986). The water of these aquifers is mostly used for domestic and industrial uses, and for agricultural irrigation, in case surface waters are not able to meet the water demand.

The aquifers of the *South-Central* sub-province, which is located between 33°S and 42°S, are intimately linked to the Central Depression (Fig. 5.2). These aquifers are fed by rivers and streams, melt water and direct infiltration of precipitation

(Arumí et al. 2016; Muñoz et al. 2016). These aquifers are no longer restricted to the river course. Instead, these aquifers occupy wide sectors of the unconsolidated Quaternary deposits of the Central Depression. These deposits are very heterogeneous and are constituted by fluvial transport, and towards the south, by glacio-fluvial transport coming from the Andes Mountains. In these aquifers, groundwater flow is practically parallel to the surface flows in the east-west direction. Most of the aquifers are unconfined or semi-confined, although some confined units exist at local scales due to the presence of impermeable clay or volcanic deposits. The aquifers of this sub-province show variable thickness, ranging from a few meters near the mountain ranges to a couple of a hundred of meters in the middle of the Central Depression. Typically, near the Coastal Range, groundwater comes back to the surface. In this sub-province the well productivity is very high (>100 m^3/s, Fig. 5.3) and groundwater quality is excellent, with TDS concentrations of less than 500 mg/L (DGA 1986). In the north section of the *South-Central* sub-province, which is the area with the highest population density, groundwater is mostly exploited for potable and industrial uses, and as a supplement for irrigation. Towards the south, the climate is more wet and thus, its main use is for potable water. However, as population diminishes considerably towards the south, the importance of groundwater and its exploitation is reduced.

The *Channels Zone* sub-province extends between 42°S and 56°S (Fig. 5.2). Even if it is the rainiest region of the country, it is poor in terms of aquifers and hydrogeological studies because there are outcrops of metamorphic and plutonic rocks from the Paleozoic and Mesozoic. These rocks typically have an insignificant primary permeability. Few wells have been drilled in locations with small accumulation of glacio-fluvial unconsolidated Quaternary deposits. The waters from these aquifers have good quality and are used for domestic purposes (DGA 1986). Most of the unconsolidated deposits are present between 46°S and 47°S, in which Chile covers a small portion of the Patagonian steppe Pampas.

The *Magellanic Pampa* sub-province covers the Chilean regions that extends towards the east of the Andes Mountain (Fig. 5.2) where the surface drainage is primarily oriented towards the Pacific Ocean and the Strait of Magellan. The Pampa has Quaternary and Tertiary formations. The Quaternary formations that have been explored correspond to heterogeneous fluvio-glacial and fluvial deposits with permeable layers of small extension. Therefore, aquifer productivity is strongly restricted, and only a few wells show a high yield. Aquifers are relatively shallow and of good water quality, and their recharge is provided by the scarce precipitations of the steppe climate. Groundwater use in this sub-province is exploited primarily to supply water for domestic use and for the livestock. The explored Tertiary sandstone aquifers located around the Strait of Magellan and in Tierra del Fuego are more productive than those of the Pampas. These sandstone deposits are located at depths of 300–400 m. The recharge of these aquifers is located towards the south at higher elevations, so near the Strait of Magellan there are strong upwelling conditions. This groundwater has good water quality with TDS smaller than 700 mg/L (DGA 1986). Therefore, it is typically used for domestic and livestock purposes.

5.2.2.3 The *Coastal Basins* Province ("Cuencas Costeras")

The *Coastal Basins* province is directly related to the Coastal Range (Fig. 5.2), between the north of Chile and Puerto Montt (42°S). It is divided into two sub-provinces (DGA 1986): the *Arheic* and *Exorheic Coastal Basins*.

The *Arheic Coastal Basins* sub-province is located at the west of the *Great North* sub-province. It does not present any surface flow because of the total absence of water resources in the region. This sub-province is defined by ancient flow patterns and it does not present any hydrogeological interest. On the contrary, there are alluvial aquifers in the *Exorheic Coastal Basins* sub-province in front of the *Transverse valleys*. These aquifers are typically unconfined with thicknesses of less than 100 m. Groundwater exploitation is very limited and well productivity typically does not surpass 10 m^3/s (Fig. 5.3). Groundwater quality is regular, with TDS concentrations ranging between 500 and 1,000 mg/L (DGA 1986). These waters are mostly extracted for domestic use. The main sources of recharge in the hyper-arid Coastal Range of the Atacama Desert are coastal region rainfall (Herrera et al. 2018) and the fog that locally occurs. Nonetheless, there is a lack of studies that investigate this phenomenon in Chile (Aravena et al. 1989). The *Coastal Basins* located at the east of the *South-Central* sub-province also offer the possibility of groundwater exploitation. The aquifer thickness in these basins are typically thinner than those of the Central Depression, with thicknesses of less than 100 m. These aquifers are recharged by the precipitation that falls in the Coastal Range. The wells in these aquifers have productivities up to 1 m^3/s (Vargas 2017), and the water quality is good, with the exception of regions where saltwater intrusion occurs (DGA 1986). Therefore, small volumes of groundwater are pumped for domestic supply water.

5.2.2.4 Other Hydrogeological Provinces

As described above, in this chapter, emphasis is put in locations in which groundwater exploitation has been of interest and whose knowledge has been identified as critical. Nonetheless, various regions present or may present a hydrogeological interest. Most parts of Southern Chile for instance, because of the favorable climatic context, are of significant groundwater resource when exploited. But because of the significant surface water, they have traditionally been poorly characterized and apparently little exploited, though further quantitative assessment is needed (Vargas 2017). The Pacific island also has a hydrogeological context that facilitates groundwater extraction. For instance, Eastern Island has very permeably volcanic soils in which infiltration can reach values of ~1,000 mm/year. Thus, surface runoff is very sporadic and the aquifers comprised by volcanic ashes and lava are extensive, with high productivities that easily exceed a few m^3/s. However, groundwater use is small because the few inhabitants in the island. In terms of water quality, it is excellent in the center of the island, but suffers from seawater intrusion near the coastline or in deep wells (DGA 1986).

5.3 Identified Groundwater Resources

This section presents data analyzed and provided by the DGA, which summarize the current knowledge of groundwater resources along the country. These data have the aim of providing information for water resources management. The DGA has defined four macrozones that group many regions with similar hydrographic, orographic and climatic attributes (Fig. 5.4).

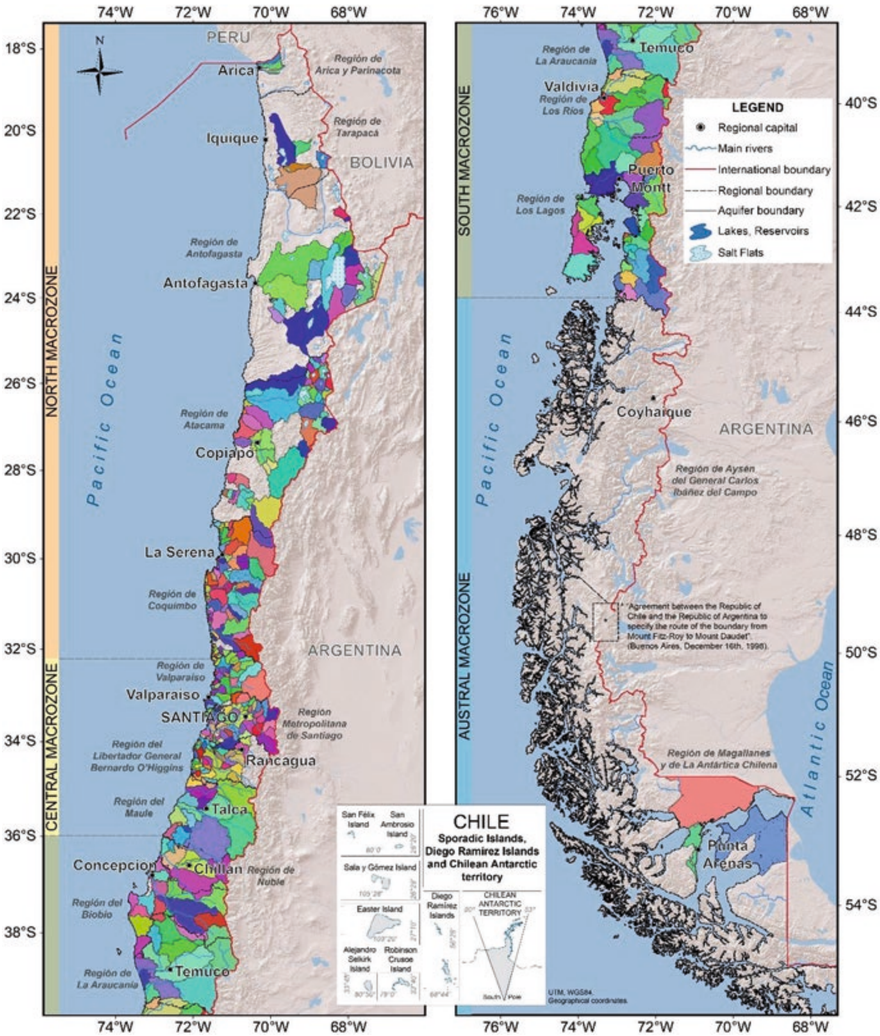

Fig. 5.4 Distribution of the aquifers defined by the DGA. The aquifers are displayed in different colors. Note that along the country there are aquifers that have not been investigated, which are not shown in this figure. (Modified from DGA (2016) with data updated on January 2019)

Most of the Chilean aquifers have been divided into administrative units called *Hydrogeological sectors of common use* ("Sectores Hidrogeológicos de Aprovechamiento Común" or SHAC). A single SHAC is defined as an aquifer or a part of it, which has spatial and temporal hydrological characteristics that allow a delineation for an individual hydrogeological assessment or management (DGA 2016). Hence, SHAC not necessarily resemble the topographical catchment. Table 5.1 shows that, until January 2019, the DGA has delimited a total of 137 aquifers (see Fig. 5.3) and 375 SHAC along the country. Most of the investigated aquifers and SHAC are located in the Central macrozone (between regions IV and VIII) and in the North macrozone in which agriculture and mining are the main water users. Note that in the austral macrozone few aquifers or SHAC have been investigated so far.

Table 5.1 also presents the volume of groundwater stored in the aquifers, expressed in m^3/year. In the Chilean legislation, there are five types of volumes that are used for groundwater management: (1) sustainable volume, which is the annual volume of water that enters the aquifer through precipitation, reservoir or lakes and/or from surface or other groundwater systems. This volume can be susceptible to constitute definitive groundwater rights; (2) provisional volume, which corresponds to the annual groundwater volume associated to provisional water rights in a SHAC that have restricted areas of exploitation; (3) available volume, which is the sum of the sustainable and provisional volumes, and that is possible to grant as definitive or provisional water rights; (4) committed volume, which is the annual volume of the groundwater rights already approved and of the water rights requested that are already processed; and (5) requested volume, which is the annual volume of water related to the water requests that are resolved or in process. The sustainable volume, which is related to aquifer recharge, is typically estimated using two approaches. The first one is through a hydrogeological numerical simulation, e.g., see DGA (2012), and the second approach is by applying Eq. (5.1) (DGA 2018):

$$R = A P_p C_i \tag{5.1}$$

where R (m^3/year) is the annual diffuse recharge of the aquifer, A (m^2) is the area of the basin, P_p (m/year) is the annual mean precipitation, and C_i (−) is a dimensionless infiltration coefficient, which is based on the geomorphology and/or land-use of the basin (DGA 2014). Note that Eq. (5.1) does not include lateral inflows into the aquifer. Hence, to estimate the sustainable volume, the annual volume of water that enter from other groundwater systems must be estimated independently.

In the North macrozone and in most of the Central macrozone, the committed and requested groundwater volumes are greater than the available volume (Table 5.1). Even more, in these geographical regions, the groundwater flows granted as water rights (Table 5.2) are also greater than both the sustainable and available groundwater volumes. Hence, if the existing water users pump their water rights at the maximum rate, the aquifers will be extremely overexploited and depleted. Although this situation does not occur in all the aquifers of these macrozones, there are some basins that are under tremendous and increasing water stress

Table 5.1 Number of aquifers, of Hydrogeological sectors of common use (SHAC) and groundwater volumes (sustainable, available, committed and requested) distributed by administrative regions and by macrozones (DGA 2016)

Macrozone	Region	Number of aquifers[a]	Number of SHAC[a]	Sustainable volume[b] (m^3/year)	Available volume[b] (m^3/year)	Committed volume[b] (m^3/year)	Requested volume[b] (m^3/year)
North	XV	3	4	39,735,360	56,607,120	161,126,520	185,882,911
	I	4	5	73,006,437	87,341,914	238,691,939	353,256,481
	II	8	20	271,548,715	198,661,135	272,166,527	103,349,210
	III	4	50	300,356,811	336,842,796	778,802,926	1,193,028,713
	IV	6	44	344,470,881	577,578,687	735,460,354	1,012,389,892
Central	V	8	70	432,424,786	663,167,392	1,648,581,519	1,376,036,757
	RM	5	44	1,435,978,534	2,838,024,159	3,669,865,445	5,552,260,009
	VI	11	48	636,973,588	1,633,969,405	1,472,766,281	1,895,056,322
	VII	14	16	2,676,544,227	3,048,716,331	1,400,266,026	1,683,986,789
South	VIII	20	20	2,258,269,344	2,258,269,344	583,354,705	828,238,730
	IX	12	12	2,676,091,811	2,676,091,811	433,266,414	477,590,671
	XIV	11	11	1,843,465,636	1,843,465,636	317,521,244	388,218,984
	X	31	31	3,085,499,264	3,085,499,264	529,410,498	592,375,206
Austral	XI	–	–	–	–	–	–
	XII	–	–	–	–	–	–
	Total	137	375	16,074,365,395	19,304,234,996	12,241,280,398	15,641,670,676

[a]Data updated on January 2019
[b]Data updated on August 2015

Table 5.2 Number of groundwater rights and of granted groundwater flow distributed by administrative regions and by macrozones (DGA 2016)

		Number of groundwater rights[a]			Granted groundwater flow[a]			
Macrozone	Region	Definitive	Provisional	Total (N°)	Definitive	Provisional	Total (L/s)	Total (m^3/year)
North	XV	558	7	565	3,491	36	3,527	111,227,472
	I	877	9	886	6,426	212	6,638	209,335,968
	II	545	17	562	14,123	181	14,304	451,090,944
	III	970	56	1,026	28,381	385	28,766	907,164,576
	IV	6,147	58	6,205	26,115	1,780	27,895	879,696,720
Central	V	8,496	119	8,615	65,220	910	66,130	2,085,475,680
	RM	6,391	156	6,547	116,950	6,560	123,510	3,895,011,360
	VI	5,951	185	6,136	53,980	4,401	58,381	1,841,103,216
	VII	3,240	0	3,240	54,515	0	54,515	1,719,185,040
South	VIII	5,951	0	5,951	29,220	0	29,220	921,481,920
	IX	3,476	0	3,476	18,110	0	18,110	571,116,960
	XIV	1,183	0	1,183	11,590	0	11,590	365,502,240
	X	2,526	0	2,526	23,598	0	23,598	744,186,528
Austral	XI	261	0	261	465	0	465	14,664,240
	XII	390	0	390	657	0	657	20,719,152
	Total	46,962	607	47,569	452,841	14,465	467,306	14,736,962,016

[a]Data updated on August 2015

due to constantly growing demands from the mining and agricultural sectors, and from urban development. Examples of these basins are the Copiapó River basin (Suárez et al. 2014), the Limarí and Petorca River basin (Budds 2018; Oyarzún et al. 2014), the Aconcagua River basin (DGA 2015), and the Maipo River basin (Steinbrügge et al. 2005), amongst others. As shown in Fig. 5.5, the historic trend of the piezometric level in wells of the North and Central macrozones shows that approximately 72% of the wells have a statistically significant negative trend, whereas only 11% of the wells exhibit a statistically significant positive trend

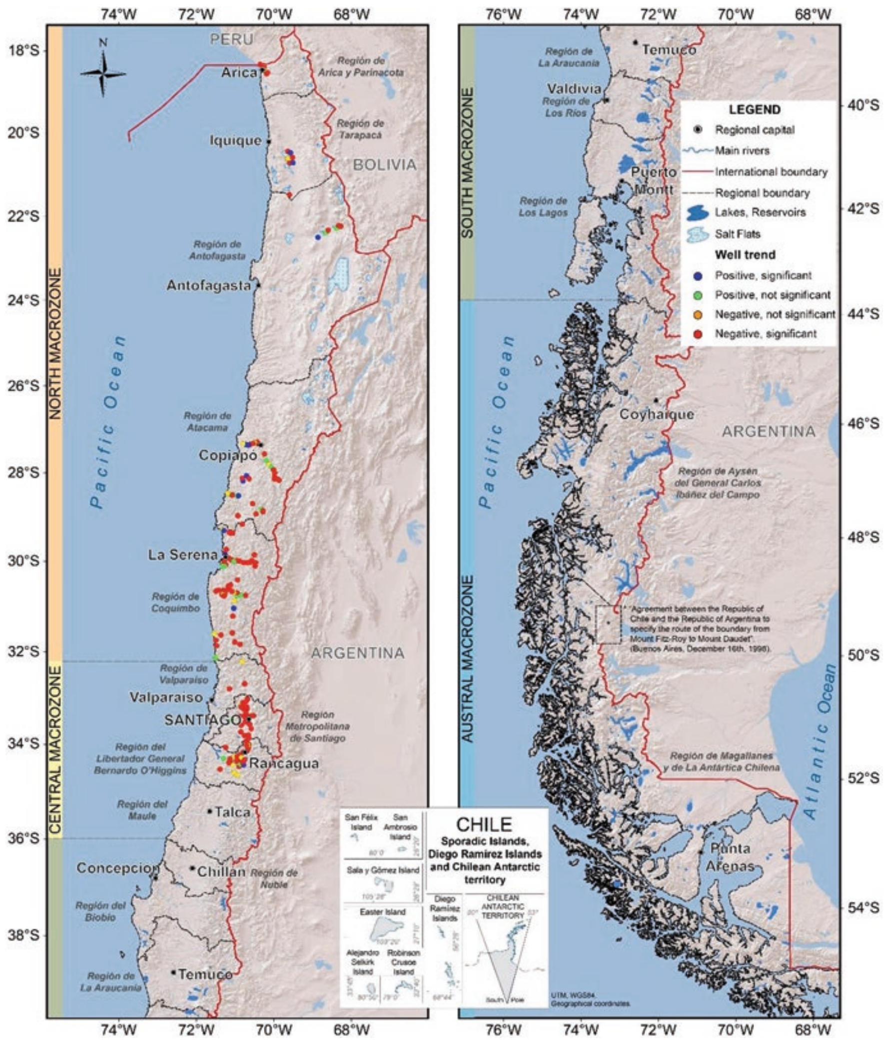

Fig. 5.5 Historic trend of piezometric level in wells, between 1960 and 2016. (From Iniciativa Escenarios Hídricos 2030 2018)

(Iniciativa Escenarios Hídricos 2030 2018). Given the current situation, the DGA aims to develop strategic plans of integrated water management in the SHAC along Chile (see Chap. 22 of this book).

In the southern part of the Central macrozone and in the South macrozone, granted water rights are generally smaller than the sustainable volume of the SHAC (see Tables 5.1 and 5.2). This situation is also likely to happen in the Austral macrozone. Therefore, sustainable exploitation of the aquifers can be achieved in these macrozones.

Since groundwater is a scarce and valuable resource, especially in the North and Central macrozones, mechanisms for its protection have been developed. On one hand, in locations where there is a serious risk of groundwater depletion or where sustainability is in danger, the DGA can declare an area subject to groundwater restriction. On the other hand, when the groundwater resource is completely compromised, and no additional water rights can be granted (both in a definite or provisional way), the DGA can declare an area subject to groundwater prohibition. Figure 5.6 presents zones of groundwater restriction or prohibition along the country. In the North macrozone, there are 64,943 km^2 in which there is groundwater restriction, whereas in the Central macrozone there are 32,362 km^2 for a total of more than 140 areas of restriction. Moreover, there are 11,052 km^2 of zones where groundwater extraction has been prohibited, distributed in six zones in the North and Central macrozones (Fig. 5.6). Also, the Chilean legislation prohibits exploitation of protected aquifers (~5,815 km^2 distributed in more than 200 aquifers) that feed wetlands in the Andean plateau, as they play an important role in sustaining unique ecosystems, Andean indigenous communities, as well as agricultural activities (Fig. 5.6). Furthermore, as in 1981 Chile subscribed an intergovernmental treaty with a framework for national action and international cooperation for wetlands conservation and prudent use of their resources, known as the Ramsar Convention (Gardner and Davidson 2011), there are protected sites, such as the Salar del Huasco (Suárez et al. 2020) or the Soncor system in the Salar de Atacama (Ortiz et al. 2014). In these sites, there is no authorization for groundwater exploitation nor for obtaining groundwater rights if there is not a favorable environmental assessment. Some of these wetlands are located near the international border, so they might be part of transboundary aquifers (e.g., Salar de Surire, Salar del Huasco, Salar de Tara), whereas other aquifers are being exploited by non-metallic mining and are considered for future development of lithium resources (Corenthal et al. 2016; Ortiz et al. 2014). In the South and Austral Macrozones, there are few zones where groundwater is restricted or prohibited because surface waters are dominant and thus, there is no stress for groundwater extraction yet.

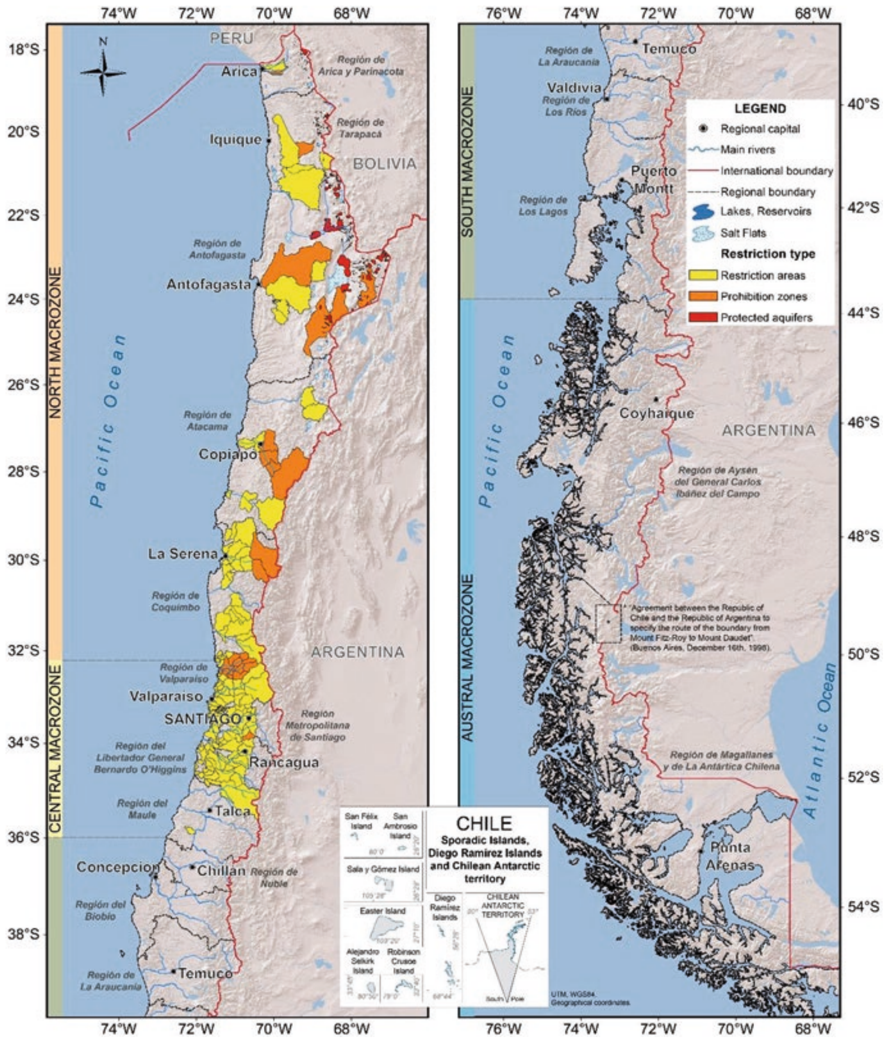

Fig. 5.6 Zones of groundwater restriction or prohibition along the country. (Modified from DGA (2016) with data updated on January 2019)

5.4 Illustrative Aquifers and Related Issues

5.4.1 Aquifers in the North of Chile

The major hydrogeological systems in the north occur in sedimentary basins. To illustrate the different typologies of the aquifers of northern Chile, three groundwater systems representative of the physiographical conditions of this region are selected.

5.4.1.1 Pampa del Tamarugal

The first representative hydrogeological system corresponds to the Pampa del Tamarugal aquifer, an endorheic system located in the *Central Basins* province (*Great North* sub-province), within the Central Depression. The Pampa del Tamarugal basin has an area of 17,353 km^2 and elevations that range between 800 and 1,100 m a.s.l. The Pampa del Tamarugal aquifer is one of the most important water resources of northern Chile. Precipitation mainly occurs during summer (December–March) on the western part of the basin at high elevations with values of ~180 mm/year. At elevations below 2,000 m a.s.l. mean annual precipitation is less than 10 mm/year, whereas at the lowlands it is almost nil (~1,000 m a.s.l.) On the other hand, potential evaporation ranges between 2,000 and 2,500 mm/year (Rojas and Dassargues 2007).

The Pampa del Tamarugal aquifer has a variable thickness than ranges between 300 and 700 m, from which 100–300 m corresponds to Quaternary alluvial deposits. The aquifer is unconfined and semi-confined with transmissivities generally lower than 10^{-2} m^2/s, and well productivities between 0.1 and 0.5 m^3/s. The water sources of this aquifer are mainly related to the ravines of the western slope of the Andes Mountains (Renner and Aguirre 2015). These waters infiltrate when they reach the pampa at the foothills of the western Andes Mountains. It is also thought that part of the recharge of the Pampa del Tamarugal aquifer comes from the Altiplanic ignimbrite aquifers, which may conduct water through fractures located at its basement (Viguier et al. 2019a, b, 2018). The recharge of the Pampa del Tamarugal aquifer is estimated to be ~1 m^3/s (Vargas 2017); whereas the discharge reaches values of ~4 m^3/s, which are used for water supply, agriculture and the mining industry (Samuel et al. 2020; Viguier et al. 2018). The current groundwater extraction combined with the natural discharge clearly exceeds recharge rates, even if there is an additional recharge from the Andes Range through deep fissures in basement rocks, which may reach maximum values of 2 m^3/s (Rojas et al. 2010). Since the sixties, the groundwater levels have fallen in many observation wells between 2 and 4 m (Renner and Aguirre 2015).

5.4.1.2 Salar de Atacama

The second representative groundwater system is the Salar de Atacama aquifer, which is in the *Highlands* province, but in a zone where a chain of depressions exists: the *intramountainous* basins (Renner and Aguirre 2015). The aquifers and streams of the Salar de Atacama watershed are of high significance because they contain vital water resources for the fragile ecosystems of the region (Ortiz et al. 2014). This aquifer also has the largest lithium deposits in the world. Consequently, it is of high relevance for the non-metallic mining (Corenthal et al. 2016). Moreover, the Salar de Atacama and Calama basins host ~90% of the groundwater resources of the Tarapacá region (HARZA 1978).

The Salar de Atacama basin is a tectonic endorheic basin limited to the west by the Domeyko Mountain Range (3,000 m a.s.l.) and to the east by the Andes Mountains (6,000 m a.s.l.) (Fig. 5.7). It has an extension of approximately 17,007 km^2 of which 3,200 km^2 corresponds to the salt flat itself located at an elevation of ~2,300 m a.s.l. (Fig. 5.6b). On the west side of the basin, it is thought that groundwater recharge is negligible, although there are few data to quantify aquifer recharge precisely (Amphos 21 2018). On the other hand, as shown in Fig. 5.6c, meteoric water infiltrates from elevated areas in the Andes Mountains, dissolving salts from volcanic-origin soils and transferring them towards lower areas. In these

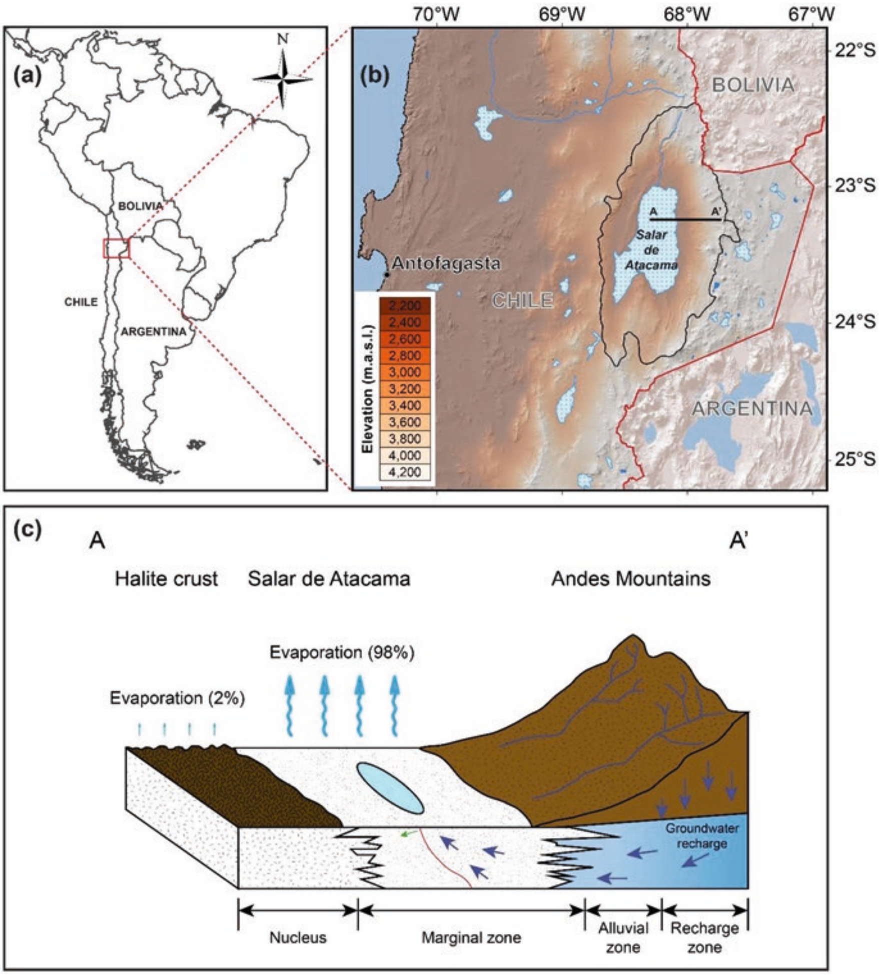

Fig. 5.7 (**a**) Geographic location of the Salar de Atacama; (**b**) relief image of the Salar de Atacama; and (**c**) Key topographic characteristics and conceptual model proposed by Vásquez et al. (2013) of flow recharge in the east side of the Salar de Atacama

areas is where the dissolved salts are concentrated due to evaporation leading to the formation of evaporites (Vásquez et al. 2013).

The climate in the region is arid to hyper-arid, and rainfall events mostly occur between December and March during the austral summer. The mean annual precipitation is of 10–25 mm/year in the center of the salt flat and increases up to ~300 mm/year towards the east of the basin, in the Andes Mountains (Renner and Aguirre 2015; Vásquez et al. 2013). Potential evaporation greatly exceeds precipitation, varying between 1,600 and 3,000 mm/year at the central part of the salt flat and the Andes Mountains, respectively (DGA 2009).

The groundwater flow system in the Salar de Atacama includes four hydrogeological zones (from east to west): the recharge zone, the alluvial zone, the marginal zone and the nucleus, as shown in Fig. 5.7c. Approximately 80% of the groundwater recharge comes from the rivers located at the north-eastern end of the basin (Renner and Aguirre 2015), although in the *intramountainous* basins groundwater recharge is typically provided by precipitation at high elevations within the Andes Mountain Range. In the Salar de Atacama, Amphos 21 (2018) estimated that approximately 5,670 L/s (~20% of rainfall) enters the salt flat as groundwater recharge, whereas between 5,050 and 6,300 L/s are evaporated into the atmosphere at lagoons and wetlands.

It is believed that the aquifer is a closed system and that the main water contribution is due to infiltration at elevated areas, i.e., in the Andes Mountains (Ortiz et al. 2014; Vásquez et al. 2013). Nonetheless, recent literature discusses that modern recharge within the Salar de Atacama basin does not balance reasonable estimates of modern or geologically averaged discharge (Corenthal et al. 2016) and that the hydrologic imbalance must be explained by a regional groundwater flow recharged from an area over four times greater than the topographic watershed.

Having hydrogeological basins that are larger than the topographic basins also has been suggested in other zones in the north of Chile. For instance, Jordan et al. (2015) showed that in the Loa hydrogeological system (located to the north of the Salar de Atacama basin), the groundwater catchment may double the size of the topographic basin. Moreover, the Loa catchment most likely extends way further from the Chile-Bolivia international border, making it a transboundary aquifer. The latter is important as transboundary waters present increased challenges to regional stability, as hydrologic needs can be overwhelmed by political factors (UNEP 2009). Moreover, many transboundary aquifers remain unknown or only partly recognized as an unconnected system (Unesco-IHP and UNEP, Unesco-IHP 2016). Therefore, managing international waters requires a more clearly defined role to be followed by the governments involved, as well as more scientific data, education and training.

Given that the DGA manages water resources under steady-state conditions, and that the Salar de Atacama basin is typically considered a closed basin (Amphos 21 2018), having a hydrogeological basin larger than the topographical basin also has implications in water resources allocation (Corenthal et al. 2016).

5.4.1.3 Copiapó River

The third hydrogeological system corresponds to the aquifer of the Copiapó River basin that is situated in the *Central Basins* province (*Transverse Valleys* sub-province). The Copiapó River basin has an area of 18,538 km^2 and is located in the Atacama region of Chile, between the 27°S and 29°S latitudes. It represents an example of an arid basin under tremendous and increasing water stress due to constantly growing demands from crop irrigation, urban water supply, mining industry and tourism (Hunter et al. 2015).

The climate of the region is arid, with an average annual precipitation over the basin of ~28 mm, but with large inter-annual variation due to El Niño and large spatial variation due to elevation change (Meza et al. 2015). Precipitation is positively correlated with altitude and strongly seasonal, with 80% of the rainfall occurring between May and August. The mean annual evaporation is ~1,500 mm/year at 350 m of altitude, and increases at a rate of 2,000 mm/km approximately (Suárez et al. 2014). The Copiapó River has a mixed hydrologic regime. Monthly average flows at the "Río Copiapó en La Puerta" and "Río Copiapó en Angostura" flow gauges range between 2.08 and 2.93 m^3/s and between 0.26 and 0.67 m^3/s, respectively. These two gauges record water inputs and outputs to the main close groundwater system (Meza et al. 2015).

The main aquifers of the basin are unconfined and composed by fluvial deposits. Therefore, these aquifers have relatively high storage coefficients (0.1–0.2) and transmissivity values (~10^{-3}–10^{-1} m^2/s) (Suárez et al. 2014). The groundwater recharge of the Copiapó River basin is caused by irrigation and infiltration of precipitation, especially at higher elevations. At the urban centers, potable water and sewage losses are important sources of groundwater recharge. On the other hand, discharge is dominated by groundwater pumping. Natural and artificial recharge was estimated to ~3.6 m^3/s with a consumption of 5 m^3/s, which turns out in a 40% deficit (Renner and Aguirre 2015). Hence, groundwater storage is being depleted, resulting in lower table levels, poorer water quality and larger amounts of energy required for pumping.

5.4.2 Aquifers in Central Chile

Contrarily to north of Chile, aquifers in Central Chile, from 32°S to 36°S (i.e., Aconcagua, Maipo-Mapocho and Rapel basins), benefit from much favourable climatic conditions and good recharge conditions. Major developed aquifers in Central Chile all share similar characteristics as they are mainly located in the Central depression where quaternary deposits accumulated (Fig. 5.8) forming sub-regional to regional systems, i.e., areas of 1,000–5,000 km^2.

First, unconsolidated deposits, though very variable between and within basins, are relatively thick. In the Santiago basin, following systematic geophysical estimations (González et al. 2018; Yáñez et al. 2015), basin thickness increases from the

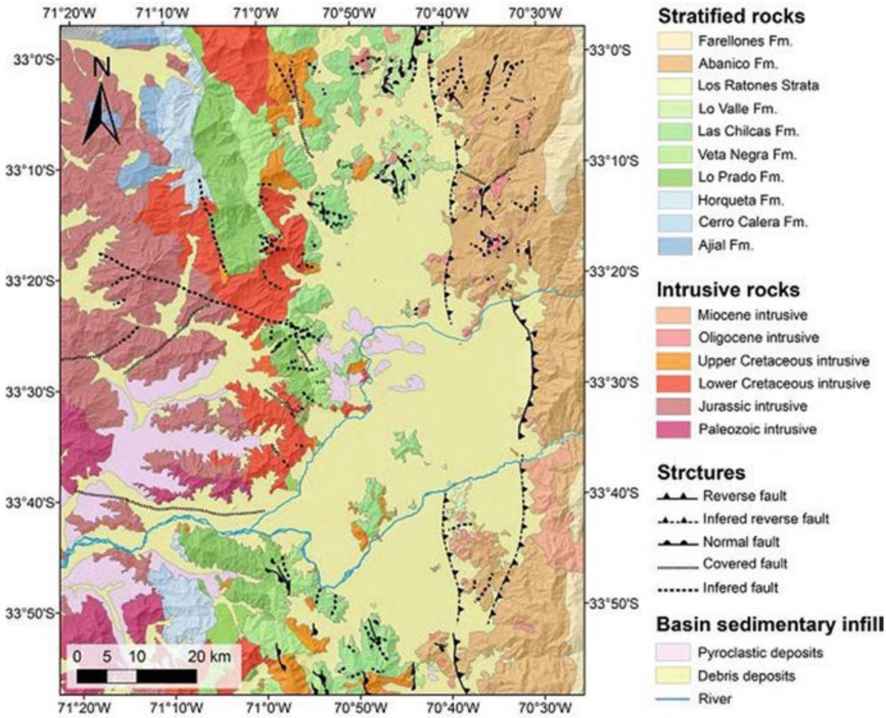

Fig. 5.8 Geological context of the Santiago basin. The identified aquifers are located in the basin sedimentary infill. (From Yáñez et al. 2015)

borders, i.e., the Piedmont and Coast Range margins, and can reach up to 500 m in the basin centre. Though variable, a value of 300 m is a fairly representative value. Based on wells information, the Aconcagua and Rapel basins are estimated to be at least 200 and 100 m thick, respectively. Second, an alternation of more or less permeable layers forms an unconsolidated stratified system of sand-gravel and clay. While the total number of aquifer layers may vary and are not fully characterized, it is estimated that about 2 or 3 confined aquifers underly an unconfined aquifer (DGA 2000, 2015). Finally, according to the hydraulic tests carried out in multiple wells, hydrodynamic characteristics typical of non-consolidated materials are found. The saturated hydraulic conductivity varies between 10^{-6} and 5×10^{-3} m/s and the storage coefficient between 0.002 and 0.12. Significant thickness and hydraulic conductivity result in excellent transmissivity and a very good response time to pumping. The stabilized drawdowns are hence very limited, of the order of 1 m, and the stabilization times less than 1 min, resulting in ideal conditions for exploitation and significant productivities ranging between 10 and 100 m^3/s (Fig. 5.3).

Beyond these common characteristics, the recharge conditions of these aquifers are not completely known. In particular, the role of the Andean Cordillera as a possible exporter of groundwater and its implication on the recharge conditions remains largely unknown. Nevertheless, a consequent effort has been made to characterize the different sources of recharge and to quantify their respective contributions. To this end, numerical models of these aquifers have been developed (DGA 2000, 2005, 2015) using the MODFLOW software (Harbaugh et al. 2017), which have contributed to understanding the hydrogeological functioning of the basins. They are now used as a reference for hydrogeological studies. For instance, the Santiago aquifer has been investigated using its hydrogeological model (DGA 2000), which shows that anthropic activity affects the functioning of the aquifer. On the one hand, groundwater recharge is caused by irrigation, precipitation at the mountain front and block, rivers and streams, and by water losses from the potable water piping network of the urban center. On the other hand, groundwater discharge occurs at multiple groundwater extraction points, some of them illegal and not clearly identified. Also, some lateral basins and rivers drain exfiltrating water that intercepts the surface, mainly upstream of the basin.

Central alluvial aquifers also share similar issues because of the important part of population that they harbor – more than 50% of Chilean people – and the significant human activity (industry, agriculture, mining) that takes place. The very high productivity of alluvial aquifers has greatly favored the economic development of these regions, but has also favored the overexploitation of aquifers as they are perceived as an infinite resource. In 2003, only 67% of the water rights granted could actually be extracted on a sustained basis in the Santiago basin (Muñoz et al. 2003). The drought of recent years has further strongly affected recharge with an increase in evapotranspiration and a decrease in rainfall (Garreaud et al. 2017), reaching 30% in some sectors, such as the Pirque sector in the south east of Santiago. The current state of the aquifers and piezometric level trends are particularly concerning (Iriarte et al. 2009). Some sectors, such as Maipu in the Santiago basin, have seen piezometric levels continuously decreasing by ~1.5 m per year over the past 10 years. Most of the water table is currently located more than 100 m deep. Such aquifers are then undergoing a significant hydric stress from both anthropic and natural forcing (Fig. 5.5), and a “restriction zone” has been declared for groundwater extraction in most of them (Fig. 5.6).

Additionally, the numerical models developed so far, which are the tools used for groundwater management, may be partially outdated and/or inadequate to model the evolution observed during the last decades and the current state. For instance, the hydrogeological model of the Santiago basin (DGA 2000) was developed for the period 1950–1998. This model has not been updated although it has been two decades since it was built. At the time of the model development, approximately 2,000 groundwater extraction points were accounted for, whereas nowadays extraction wells are at least three times more than those existing in 2000. Also, the groundwater recharge time series of this hydrogeological model was estimated until 1998. Consequently, to use this model the recharge time series must be assumed after 1998. The assumption typically made is that the groundwater recharge time series repeats in the future; therefore, water users and the water authority are obviously neglecting any impact of climate change on the basin. Climate change studies in the region have revealed that it is likely that temperature will increase, and precipitation will be reduced in the region, with the subsequent reduction in river flow (Migliavacca et al. 2015; Vicuña et al. 2018).

Besides, the effect of urbanization on groundwater systems is not well understood, as it depends on the geological and hydrogeological setting, and the adopted storm water management practices, among other factors. Commonly, it is recognized that urbanization decreases groundwater recharge due to higher imperviousness (Foster et al. 1994; Hutchinson and Woodside 2002; Waldron and Larsen 2015; WMO 2008). Nonetheless, human alterations such as deep groundwater supply and septic systems can change the expected effects of human development on the aquifer, and eventually increase groundwater recharge and runoff (Bhaskar et al. 2016). The rise in the recharge due to urbanization is stronger in catchments with a semi-arid climate (Foster and Chilton 2004) as they import larger water volumes from other regions. Figure 5.9 shows a compilation of data form cities around the world comparing recharge before and after urbanization (Garcia-Fresca and Sharp 2005). In the Santiago aquifer (SCL) a slight increase in groundwater recharge has been observed (883 mm/year–910 mm/year). This effect is mainly due to a larger irrigation of green areas and losses from the drinking water network. The sub-sector called the Mapocho Alto aquifer (MA) shows major changes due to the intensive use of vegetation (1045 mm/year–1153 mm/year), this sub-sector is one with the highest water consumption for urban irrigation in Santiago (Sanzana et al. 2019). Sanzana et al. (2019) also identified a significant local recharge associated with pipe leaks and inefficient urban irrigation in a sub-sector of Mapocho Alto. From the evaluation of different future scenarios, Sanzana et al. (2019) found that a sustainable water conservation scenario will decrease the current groundwater levels, while the median flow reduces from 408 to 389 l/s, and the low flow (Q95%) from 43 to 22 l/s.

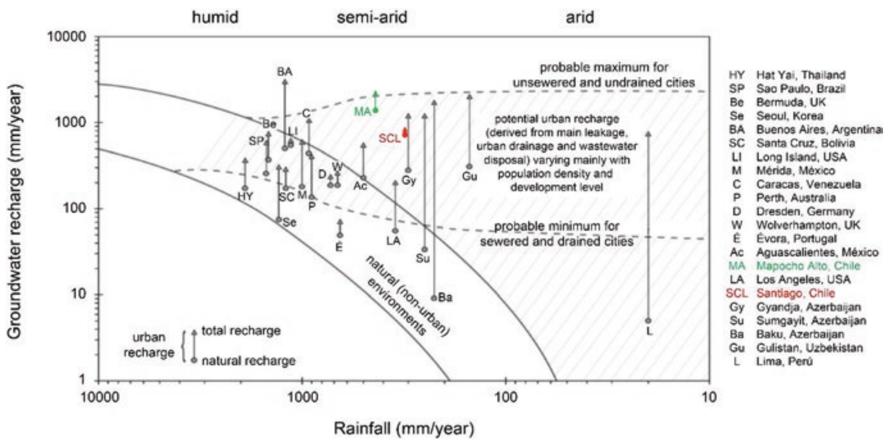

Fig. 5.9 Estimates of groundwater recharge in cities prior to (circle) and after (triangle) urbanization presented by Garcia-Fresca and Sharp (2005). The Santiago aquifer (SCL) and the aquifer sub-sector called Mapocho Alto (MA) are shown with an increase in recharge

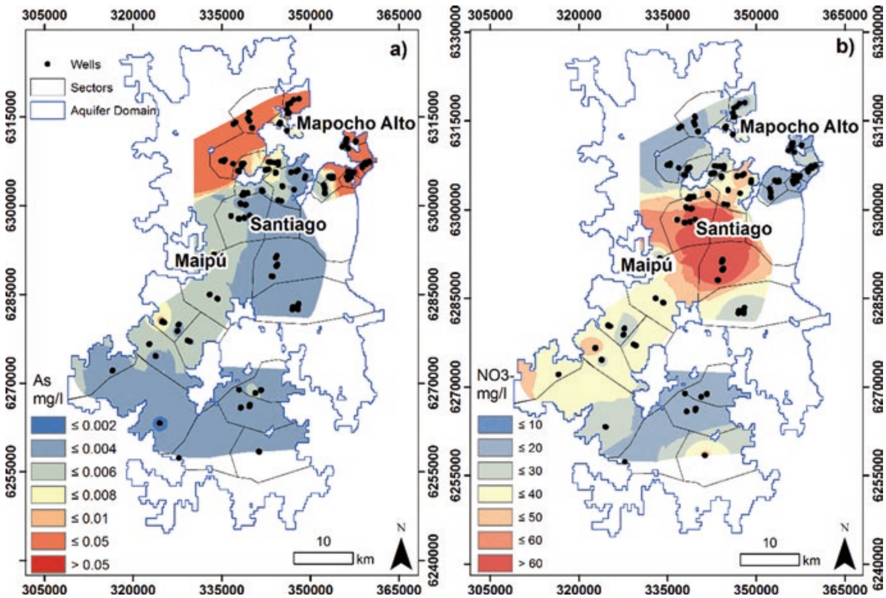

Fig. 5.10 Spatial distribution of the main contaminants found in the aquifer of Santiago: (**a**) arsenic; and (**b**) nitrate

Beyond groundwater quantity assessment and management, water quality is another relevant aspect of groundwater resource in Central aquifers. In the aquifer of Santiago (Maipo and Mapocho rivers), the water treatment companies ("Grupo Aguas" and "SMAPA") must report different groundwater quality parameters to the Superintendence of Sanitary Services ("Superintendencia de Servicios Sanitarios", SISS). According to this information, the most frequent groundwater quality parameters that surpass the drinking water norm (NCh409/1.Of2005) are arsenic and nitrate (SISS 2009). The Chilean water norm sets the maximum contaminant levels of arsenic and nitrate at 0.01 and 50 mg/l, respectively. Arsenic is mostly of natural origin due to rock leaching into the aquifer, whereas nitrate contamination has an anthropic origin and is related to the agroindustry, the paper industry, pesticides, and non-point source wastewater. The spatial distribution of arsenic and nitrate in the Santiago aquifer is presented in Fig. 5.10, which shows that high levels of arsenic are found in the northern sections of the aquifer, whereas the highest levels of nitrates occur in the southeast zone of the city of Santiago.

5.5 Perspectives and Future Challenges

Chile benefits from very varied hydrogeological contexts, depending on climatic, topographic and geological variability along its more than 4,000 km of land. Despite this contextual richness, the hydrogeological knowledge of the country remains limited. Because of the very high transmissivity of alluvial aquifers in Central Basins, e.g., the Santiago or Rancagua aquifers, few studies have intended to thoroughly characterize such systems, and address issues related to recharge conditions, residence times or flow patterns. Significant progress remains to be done to create a baseline of knowledge all over the country.

Having a baseline for the aquifers is critical as the pumping wells have been constantly increasing over the last few decades, creating a tremendous impact on groundwater resources. Regardless the region, exploited aquifers are highly stressed, both on water quantity and quality. Understanding the sources and nature of groundwater recharge underlies many societal, scientific questions, and even geopolitical issues for transboundary aquifers. In the north of Chile, constraining the processes that dominate the paleo and modern water balance of these sensitive aquifers is critical towards placing reliable and bounded sustainability (Corenthal et al. 2016).

In Central Chile, assessing the recharge conditions from the Andes Cordillera and the durability of groundwater resources appears critical to face increasing water demand and climatic uncertainty for the next decades. In such constraining ambient, groundwater systems that have been barely exploited historically are henceforth considered as a potential additional resource. This is the case of southern aquifers. Hence, elaborating a baseline of knowledge probably constitutes the main challenge for hydrogeology in Chile. This baseline comes conjointly with the development and constant update of numerical models, which have been mainly developed by the DGA and to some extent by the National Geology and Mining Service (Sernageomin). Both hydrogeological knowledge and numerical tool would allow to achieve a sustainable exploitation not only for developed aquifers, but also for aquifers expected to be developed for supporting water demand.

Hydrogeological knowledge and numerical models must be translated into tools for integrated water resources management that consider all the stakeholders. One promising tool to address this challenge is agent-based modeling, which can effectively engage stakeholders in the modeling process and improve decision making in hydrogeology (Castilla-Rho 2017). Hence, agent-based modeling, combined with numerical hydrogeological models, can help to promote strategic plans of water resources management in these areas.

Beyond a better understanding of Chilean aquifers, some efforts can be carried out to explore new resources. Because of practicality or necessity, hydrogeology in Chile focused mainly on relatively traditional systems, e.g., on homogeneous alluvial aquifers. However, more complex contexts have proved to be of interest in many site studies all over the globe. In this context, plutonic, volcanic and metamorphic rocks that sprinkle all along Chile, associated with active tectonic in the Coastal Range and in the Cordillera Piedmont (Moreno and Gibbons 2007), could be of interest for water resources. Even when being local kilometric structures, fractured aquifers can constitute an attractive alternative resource to satisfy water needs of local communities or scattered settlements (~10,000 inhabitants). Fractured aquifers can also be a less contaminated temporary resource, or an in-situ and easily-accessible resource for irrigation in agricultural settings (Lachassagne 2008).

Specifically, in the north up to Central Chile, where the sustainability of groundwater exploitation is hardly, or not, achieved, additional developments can be carried out to either sustain the groundwater resource or adapt to changing conditions. The interest in developing Managed Aquifer Recharge, and take the best advantage of the temporal availability of water, is increasing and a few projects are emerging (Bonilla Valverde et al. 2018; Cortez Salvo 2012). In zones where groundwater is suspected to be fossil and not sustainably recharged, a migration in water use towards seawater desalination is occurring (Chavez-Crooker et al. 2015), thus ensuring a better continuity of the resource.

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Chapter 6
Snow Cover and Glaciers

James McPhee, Shelley MacDonell, and Gino Casassa

Abstract The Andes Cordillera strongly determines Chile's biophysical conditions. Spanning the entire length of the country, this mountain range's interaction with the atmosphere dominates regional hydroclimates, from the high-plateau fed groundwater systems in the country's arid north, through the snow-dominated catchments in the Mediterranean central region, to the temperate rain-forests and glacial environments of Chile's Patagonia and Tierra del Fuego. This chapter offers an overview of the cryosphere (that is, pertaining to snow and ice) conditions in the country and their influence on hydrological systems. We cover aspects of the Chilean cryosphere's spatial distribution and temporal variability, physical characteristics and dynamics, and provide an overview of the most recent estimates of projected future conditions under climate change.

Keywords Snow · Glacier · Ice · Los Andes · Cryosphere · Spatial distribution · Temporal variability · Climate change

6.1 Introduction

Mountains play a relevant role as water sources for natural and socio-hydrological systems worldwide. Through enhanced precipitation, the accumulation of snow and ice in glaciers and seasonal snowpacks, groundwater storage and surface storage in

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lakes and wetlands in mountain regions, mountains modulate water exchange between the atmosphere and the land surface, generating hydrological conditions that have given rise to biodiversity hotspots and have sustained the livelihood of billions of people on all continents but Antarctica. The Andes Cordillera strongly determines Chile's biophysical conditions. Spanning the entire length of the country, this mountain range's interaction with the atmosphere dominates regional hydroclimates, from the high-plateau fed groundwater systems in the country's arid north, through the snow-dominated catchments in the Mediterranean central region, to the temperate rain-forests and glacial environments of Chile's Patagonia and Tierra del Fuego. This chapter offers an overview of the cryospheric (that is, pertaining to snow and ice) conditions in the country and their influence on hydrological systems. We cover aspects pertaining to the Chilean cryosphere's spatial distribution and temporal variability, physical characteristics and dynamics, and provide an overview of the most recent estimates of projected future conditions under climate change.

6.2 Physical Setting of the Chilean Andes

6.2.1 Climatology

As indicated in Chap. 2, the main factors that influence Chile's climate are the Pacific Ocean with its subtropical anticyclone and the Humboldt current, the westerly circulation, the presence of the Andes, and the summer occurrence of the Bolivian High in the Altiplano which causes precipitation events in the north. Seasonal changes are especially relevant in the north, central and southern Chile to latitude 47°S. There is a strong climate variability at intraseasonal, interannual and interdecadal time scales, linked to several modes including the tropical El Niño/Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO) and the Pacific Decadal Oscillation (PDO), also known as the Interdecadal Pacific Oscillation (IPO), and the Antarctic Oscillation (AO or AAO, also known as the Southern Annular Mode, SAM).

Long term warming of up to 0.15 °C/decade is especially relevant along the Andes (Falvey and Garreaud 2009; Burger et al. 2018), while a secular drought has been observed between 30°S and 33°S (Schulz et al. 2011), and also between 35°S and 43°S (Quintana and Aceituno 2012). Under future warming scenarios, a precipitation decline of up to 40% may occur under a pessimistic climate change scenario by the end of the century (Polade et al. 2017), due to a poleward shift of the subtropical anticyclone. South of about 47°S precipitation is predicted to increase due to an intensification of the circumpolar vortex (Gillet and Fyfe 2013).

6.2.2 *Orography and Tectonics*

The subduction of the Nazca and the Antarctic plates below the South American plate has resulted in the formation of the Andes Cordillera since the Jurassic (200 Ma), with a main uplift dating back to the Miocene (23 My ago) (Pankhurst and Hervé 2007). The Chilean Andes attain a maximum elevation of 6893 m at Ojos del Salado in the north (27.1°S), dropping to a maximum elevation of 4032 m at Mount San Valentín in the Patagonian Andes at 46.6°S. The North-South reduction in elevation of the Andes is due partly to a more active Nazca plate subduction velocity (8 cm/year) compared to the Antarctic plate (2 cm/year), with a present-day location of the Chile triple-junction at 46.7°S (Hervé et al. 2007). Another factor that contributes to reduce the southernmost Andes cordillera elevation is the water and glacial erosion driven by enhanced precipitation in the South due to the influence of the westerly air flow. The height of the cordillera, in combination with its climate conditions, controls the presence of snow and glaciers along a meridional gradient, with typical elevations above 5000 m in the north to sea level in southernmost Chile.

6.3 Snow Regimes and Snow Classification

6.3.1 *Arid and Semiarid Settings*

In its northernmost region, Chile's Andes Cordillera lies within the driest climate on Earth (See Chap. 2). The scant precipitation occurs over the High Plateau region (altiplano), and is concentrated during the summer months of December through March. Therefore, despite its very high elevation and corresponding low mean temperature, the high radiation loads in this region during the precipitating months of the year prevent the formation of a significant seasonal snowpack. Correspondingly, glaciers are all but absent in this region as well. This situation begins to change southward, such that the headwaters of the Copiapó River (27°–28,5° S) begin to show a more relevant presence of cryospheric forms. Here, the mountain range reaches elevations in excess of 5 km above sea level (asl), and mountain watersheds routinely show mean elevations in the order of 3500 m asl. Correspondingly, solid precipitation events during the winter months do result in somewhat persistent snowpacks, which last over ground in the order of weeks after each precipitation event (Fig. 6.1). Snow cover duration from MODIS imagery shows a mean of approximately 100 days at 4000 masl, and a minimum snow line elevation at 3500 m asl being reached usually towards the end of July. Snow on the ground in this region exists in conditions of very low relative humidity, low temperature, high solar radiation and strong winds. As such, turbulent fluxes play an important role in the energy balance of the snowpack: sensible cooling exercises strong control over the snow temperature and sublimation explains in excess of 50% of seasonal snow ablation

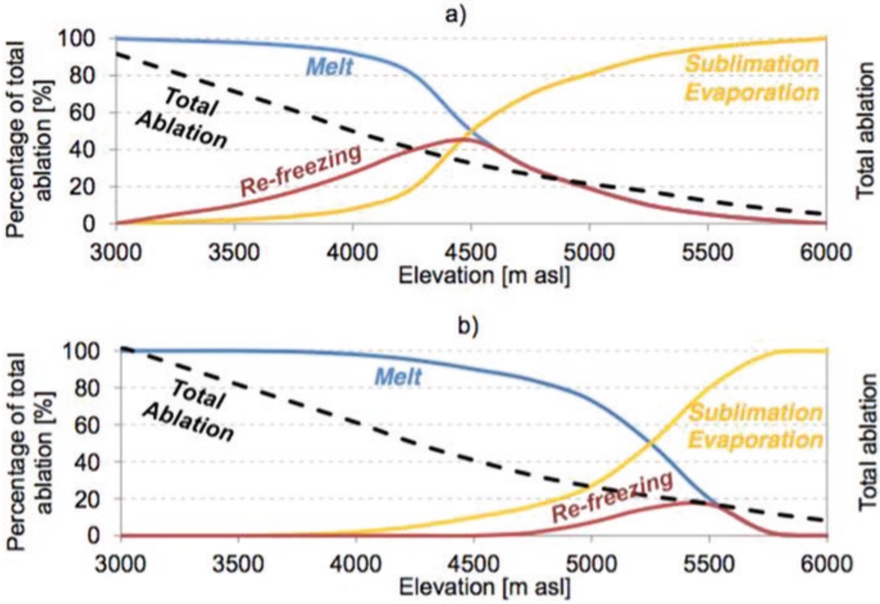

Fig. 6.1 Ablation and sublimation as a function of elevation. (Adapted from Ayala et al. 2017) (**a**) Early ablation season (**b**) Late ablation season

over large reaches of the mountain range (Favier et al. 2009; Gascoin et al. 2013; MacDonell et al. 2013; Schaffer et al. 2019). Chile's "Norte Chico" area, comprising mostly the Coquimbo and northern Valparaiso regions, is subject to arid to semi-arid conditions, and this usually favors shallow snowpacks, where turbulent fluxes make up for a significant fraction of the seasonal energy balance. Consequently, sublimation is also significant here as a component of the water balance, reaching up to 75% in some areas. Ayala et al. (2017) developed a conceptual model based on numerical analysis (Fig. 6.1) finding that sublimation as a fraction of ablation becomes more significant with elevation, due to the associated increase in wind speed and decrease in air relative humidity. The elevational range in which the relative contribution of melt and sublimation to ablation is determined also changes seasonally. Early in the ablation season, sublimation is dominant at a broader range, down to 4500 masl. Later in the season, melt conditions appear at higher elevations dominating over sublimation up to elevations around 5500 masl. It is also noteworthy how refreezing is favored early in the ablation season by the cooling effect of latent heat exchange at elevations between 3500 and 5000 masl. Refreezing of melting snow contributes to snowpack densification, which in turn can lead to firn formation and subsequent solid ice appearance at the accumulation zone of mountain glaciers.

6.3.2 Temperate

The central portion of the country presents a mountain climate such that regional annual precipitation increases steadily in the north-south direction, with a documented step increase around 34°S (González-Reyes et al. 2017). At the same time, the mountain range decreases in elevation, so that mean temperature in mountain watersheds tends to increase from north to south, although at a slower rate due to the increase in latitude. As a result, we observe a variety of snow distribution patterns and variability regimes. From north to south, annual precipitation goes from 500 to 2500 mm w.e. in mountain watersheds. Most of it occurs as snowfall in the northern part of the domain, while the southernmost watersheds do receive liquid precipitation, mostly in early spring but also sometimes during the winter season. The winter snowline fluctuates between 1400 and 2700 m asl (Saavedra et al. 2017, 2018) and snow duration typically lies in the 30 to 120 day range. Central Chile, on the other hand, is more closely associated with typically alpine conditions, with deeper snowpacks, snow duration in the order of three months, and with net solar radiation playing the most important part in determining snow ablation. Here, the elevation range between 3000–4000 m asl is the most prominent in terms of surface area and snow accumulation, thus comprising the majority of the snow water equivalent volume reserves in the region (Cornwell et al. 2016). The southern part of this subdomain presents snowpack at lower elevations, which in many areas interacts with forested ecosystems, which can intercept a large fraction (20%) of local precipitation (Huerta et al. 2019). Because it occurs in a more humid environment, sensible heat is the only form of turbulent exchange influencing the snow energy balance, and ablation is much more strongly determined by radiative exchange. Snowpacks in this region are deeper, warmer and with higher liquid content, possibly because of the occurrence (anecdotal evidence) of rain-on-snow events with some frequency.

Using meteorological data from three weather stations along this portion of the Andes domain (Tascadero, Valle Nevado and Nevados de Chillán), (McPhee et al. 2017) ran the Snowpack model, illustrating the differences described above in terms of snowpack approximately one meter, for a maximum snow water equivalent of 500 and 580 mm, respectively (Fig. 6.2). In the latter two cases, the time period between peak SWE and snow disappearance from the ground is 30 and 60 days, which yields melt rates of approximately 16,7 and 9,7 mm d^{-1}, respectively. At Tascadero, the time from peak SWE to snow disappearance is almost 3 months, but this is heavily influenced for the unusual timing of snow accumulation that year. Considering the last month of melt only, the resulting melt rate at Tascadero is 8.3 mm d^{-1}, which is lower than that of Valle Nevado. This non-intuitive result, in which the shallowest snowpack in Northern Chile takes as much time to melt as the deepest snowpack in the southern portion of the country, illustrates some of the complexity of predicting snow dynamics in mountainous environments.

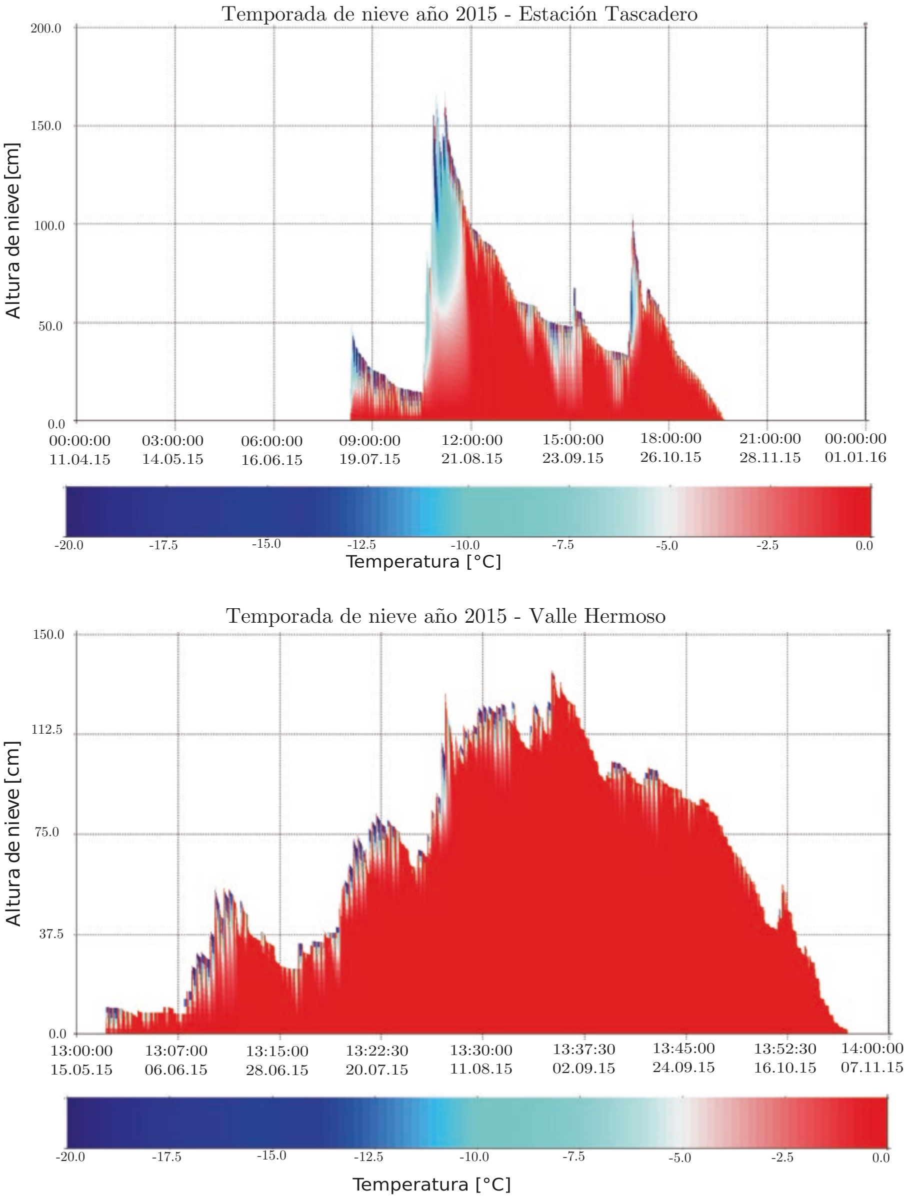

Fig. 6.2 Snowpack model simulations for three representative sites in the Andes Cordillera for the 2015 winter season. Left panels show snow depth and temperature (color scale); right panels show simulated snow water equivalent. (Adapted from McPhee et al. 2017)

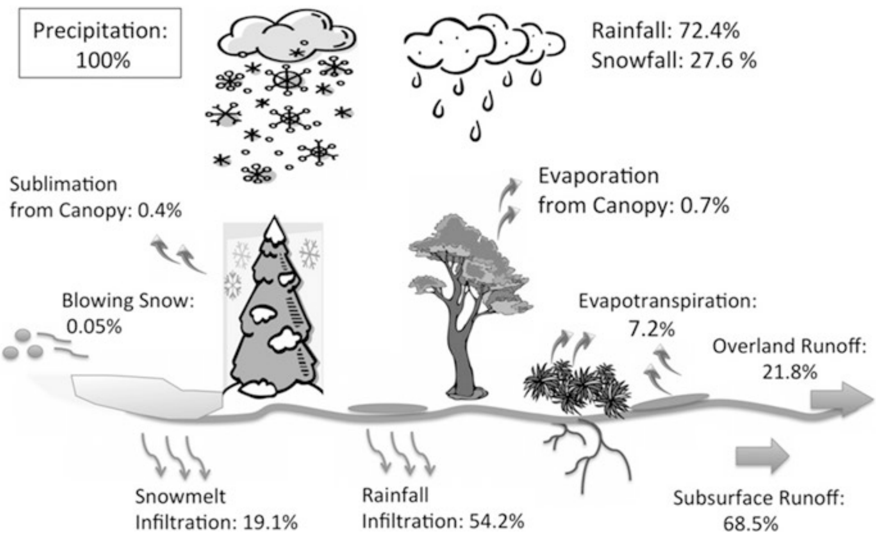

Fig. 6.3 Water budget for the Upper Baker River Basin. (Adapted from Krogh et al. 2015)

6.3.3 Wet (Patagonia)

South of 40°S, the Andes Cordillera is generally lower than 1500 m asl, but exists within a cold, rainy climate that enables the accumulation of a significant snowpack. In the Patagonian Andes, annual precipitation can exceed 5000 mm. Long-term, systematic measurements of snow accumulation and properties are not available in this region, so much of the knowledge available about its hydroclimate is derived from numerical models, and weather reanalyses (Krogh et al. 2015; Schaefer et al. 2015). However, precipitation is distributed year round and the fraction of snowfall to annual precipitation decreases to less than 50%. Krogh and others (2015) combined atmospheric reanalyses and a physically based hydrological model to study the processes that drive hydrological variability in the Baker River basin, in the Aysén Region of Chile's Patagonia (Fig. 6.3). Some key findings of this study include the demonstration that existing meteorological networks provide very little predictive ability in terms of winter (solid) precipitation, when compared with reanalysis data. Also, they show that solid precipitation accounts for about one third of total annual precipitation in this humid environment, and that turbulent fluxes play a very minor role in the snow energy balance. West-East climatological gradients are strong in this region, due to the rain-shadow effect imposed by the Andes Cordillera. Thus, peak SWE accumulation may decrease ten-fold, from 2000 mm in the western mountain subcatchment to 200 mm in the eastern plains near the border between Chile and Argentina. Mernild et al. (2017) estimated up to 5000 mm w.e. of snow accumulation in some areas at the Patagonia Ice Fields, also based in a combination of reanalysis data and hydrological modeling. Snow cover in this region is most significant at elevations above 500 m asl. Above 1000 m asl, estimates show snow on the ground for over 150 days per year (Mernild et al. 2017).

6.4 Glacier Types and Distribution

Glaciers extend along the length of Chile (17°40′–55°30’S) and are found in all climate extremes, from the arid summits of the Altiplano in the North to the wet southernmost islands south of Tierra del Fuego. The first detailed inventory that spans the length of Chile recorded a glacierized area of 23,641 ± 1185 km^2 with 24,114 identified glaciers, which account for nearly 80% of glacier area in South America (Segovia and Videla 2017; Barcaza et al. 2017). This corresponds to the official inventory completed in 2014 by Chile’s Water Directorate (Dirección General de Aguas of the Ministry of Public Works). The official glacier areas and numbers are those published by Segovia and Videla (2017), with a small discrepancy with Barcaza et al. (2017), who present 67 km^2 more and 105 less glaciers than the official inventory. Here we present the official data (Segovia and Videla 2017).

The inventory was separated into four main regions (“macrozones”), and found that of the inventoried glacier area, 0,8% occurred in the northern macrozone of the semi-arid and arid Andes (17°40′ – 32°15’S), 3,6% in the central Chilean Andes (32°15′– 36°12’S), 7,2% in the southern Chilean Andes (36°37′ – 46°03’S), and the remaining 88,4% could be found in Patagonia, Tierra del Fuego and the fjord archipelago (46°03′ – 55°30’S). Given the long geographic extent, glaciers display differing characteristics such that almost all glacier types can be found in the country. These include classifications based on thermal regimes (cold-based and polythermal glaciers in northern Chile, and mainly temperate glaciers in central and southern Chile), sediment cover (debris-covered and debris-free) and formation (glaciers and rock glaciers – both of glacigenic-ice cored and cryogenic-permafrost origin, Jones et al. 2019).

Debris-free and debris-covered glaciers are defined as containing principally snow and ice, whereas rock glaciers are a mixture of rock, sediment and ice (Cogley et al. 2011). Janke et al. (2015) differentiated between debris-covered and rock glaciers based on sediment cover and ice content. They defined debris-covered glaciers as having a sediment layer covering at least 25% of the glacier surface, compared with rock glaciers which have a thicker sediment cover (more than 3 m), and on average contain less than 45% ice. Rock glaciers in the arid and semiarid Andes are formed glacigenically (formed from debris-covered glaciers) or cryogenically (formed due to the geological processes associated with frozen ground), and polygenic-origin rock glaciers can also be identified (Schaffer et al. 2019).

6.4.1 Northern and Central Chile

This region, called by Lliboutry (1998) the “Dry Andes”, exhibits extremely dry conditions in the north, and semi-arid conditions towards the south. Whilst snow is the dominant water source during spring and early summer in northern and central Chile, during mid- summer and especially at the end of the melt season in low precipitation years, glaciers and in some basins rock glaciers as well, play an important role in maintaining baseflow of mountain streams and recharging local aquifers. In Northern Chile, glaciers, debris-covered glaciers and rock glaciers cover 180 km^2 (Segovia and Videla 2017). Glaciers are largely confined to elevations above 4500 m asl, whereas rock glaciers dominate between 4000 and 4400 m asl (Schaffer et al. 2019). Rock glaciers are more numerous than glaciers, representing 52% of the total glacier area (Segovia and Videla 2017), with several examples of glacier-rock glacier complexes (Fig. 6.4).

Glacier size in northern Chile is largely controlled by precipitation rates (F. Pellicciotti et al. 2014; Sagredo and Lowell 2012), as temperatures are on average too low to provoke large amounts of melting (Ayala et al. 2017). On debris-free surfaces, sublimation rates often dominate, and can be as high as 90% of all glacier ablation (MacDonell et al. 2013). High sublimation rates aid the development of penitentes on glacier surfaces, and these are a common sight on glaciers in northern Chile (Fig. 6.5) (Corripio and Purves 2005). Whilst penitentes can be thought of as an oddity of the area, they play an important role in controlling the energy balance of glacier surfaces (Corripio and Purves 2005; Lhermitte et al. 2014), and subsequent mass balance changes (L. I. Nicholson et al. 2016; Sinclair and MacDonell 2016). Penitentes on glaciers in northern Chile are perennial features that enhance sublimation in the early summer months, and increase melt rates later in the summer season (Sinclair and MacDonell 2016). Studies suggest that penitentes enhance shortwave radiation received at the surface by causing radiation trapping within the penitente feature (Lhermitte et al. 2014). Additionally, it is likely that penitentes act to increase humidity within the structure, therein decreasing sublimation potential on clean ice surfaces. Due to the high sublimation rates experienced on horizontal glacier surfaces (MacDonell et al. 2013), any modification to the energy balance

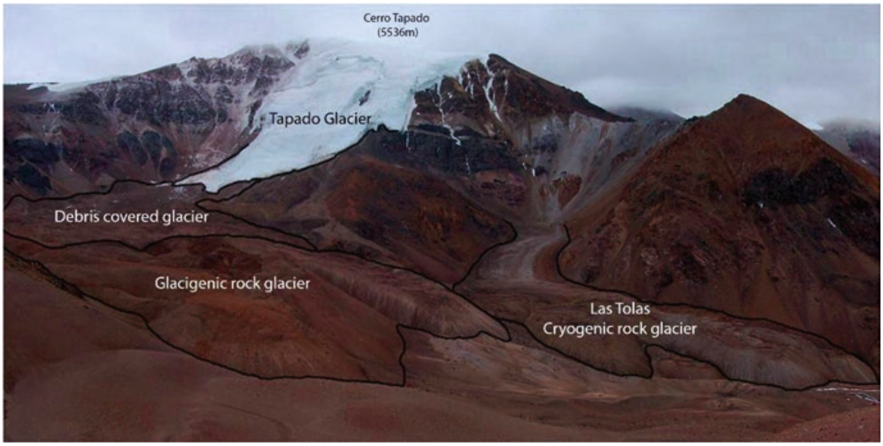

Fig. 6.4 An example of a glacier complex in Northern-Central Chile which contains glaciers and rock glaciers (Tapado Glacier, Elqui River Basin (30°S)) (Schaffer et al. 2019)

Fig. 6.5 2 m-high *penitentes* on the Esperanza Glacier, Huasco Valley (29°S)

will have a significant impact on meltwater generation and subsequent glacier contributions to streamflow.

Rock glaciers account for 64% of all glaciers (in number) found in northern Chile (Segovia and Videla 2017), and several authors have proposed that the abundance of rock glaciers makes them important water sources and stores in northern Chile (Brenning 2005; Azócar and Brenning 2010), although this view has been contested (e.g. Arenson and Jakob 2010). More direct studies are needed to evaluate their hydrological role (Jones et al. 2019). A recent review by Schaffer et al. (2019) integrated existing studies of rock glacier hydrology with previously unpublished streamflow measurements to estimate runoff from rock glaciers during the summer in the Elqui River Basin (30°S), and found that rock glaciers likely contributed between 9% and 20% of total streamflow, which was lower than that supplied by glaciers, but much more than some authors have suggested. As the study was limited in scope, there is an urgent need to better quantify rock glacier contribution, and also their wider role in the drainage system, given that rock glaciers likely impact the transit time of snowmelt in the upper catchment.

In addition, there are ongoing discussions regarding the internal structure of rock glaciers (Monnier and Kinnard 2013), formation processes and level of activity (Giardino et al. 2011). Whilst these studies are generally geomorphologically-focused, their results may have important consequences for how we conceptualize drainage system behavior. For example, as there is substantial evidence to suggest that debris-covered glaciers are actively changing into rock glaciers, the likely impacts on streamflow include their volumetric contribution to streamflow (ice in rock glaciers is theoretically more protected than ice in debris-covered glaciers), increased storage of snow melt in the basin, and changes to water quality (water originating from rock glaciers is thought to contain higher solute concentrations (Rodriguez et al. 2016).

The central region is characterised by a mediterranean climate, with relatively mild wet winters and dry summers (Bown et al. 2008; Pellicciotti et al. 2008). Incoming solar radiation is very high during summer, and relative humidity is low (Pellicciotti et al. 2008). The precipitation at high altitudes (above 2500 m a.s.l.) fluctuates between 500 mm a^{-1} in the northern semi-arid part, to up to 2500 mm a^{-1} at 36°S. The 0 °C isotherm altitude decreases in the same latitudinal range, from about 4000 m a.s.l. at 32°S to 3000 m a.s.l. at 36°S (Carrasco et al. 2005).

In the central region, debris-free glaciers are larger, with frequent debris-covered ablation areas, together with active rock glaciers (Nicholson et al. 2009; Bodin et al. 2010). Rock glaciers are widely distributed and well developed in the central Andes, representing 32% of the total glacier area, with a lower limit to their distribution at about 3000 m a.s.l. (Bodin et al. 2010). In the Aconcagua River basin, debris-free glacier area is 1/3 of the total (Bown et al. 2008), while rock glaciers represent 61% of the total glacier area (Segovia and Videla 2017).

The largest glacier in central Chile is Universidad, located in Tinguiririca basin (34°40'S) with an area of 27.6 km^2 (Wilson et al. 2016). Universidad possibly surged in 1943 (Lliboutry 1958), and since 1967 it has exhibited periods of increased and decreased flow velocity, in response to climatic trends (Wilson et al. 2016). Universidad has shown a total retreat of 465 m in the period 1967–2015, and is thinning at a rate of 2.4 m/y in the ablation area (Buglio, personal communication), based on airborne LiDAR data in the period 2011–2015.

There are a few other glaciers in the central region that have exhibited surging behavior, such as Juncal Sur (Fig. 6.6, with an area of 21.4 km^2, the largest glacier in the Maipo Valley east of Santiago (Lliboutry 1998). Juncal Sur is currently retreating at a rate of 62 m/a, losing an area of 0.11 km^2/a, with a total loss of 5.3 km^2, which results in an area loss of 20.5% in the period 1955–2013 (Malmros et al. 2016), with an associated thinning of 1.1 m/y in the ablation area (Buglio, personal communication 2019) in the period 2011–2015. Airborne LiDAR data of the ablation areas of 27 glaciers in Central Chile between Monos de Agua in Aconcagua basin (32°59'S) and Tinguiririca Volcano (34°49'S) shows a mean thinning of 1.2 m/a in 2011–2015 (Buglio, personal communication).

A couple of glaciers (Aparejo in the Maipo Valley and a glacier in the southern flank of Tinguiririca Volcano) in the central region have experienced a sudden slide and subsequent ice avalanche, having detached from the bed, (Iribarren et al. 2014, 2015; Ugalde et al. 2015). Under warming conditions, cryospheric hazards are predicted to increase (Irribarren et al. 2015), including mountain slope failure in the high Andes driven partially by snow and ice melt, such as the rockslide and debris flow at Estero Parraguirre in 1987 which produced about 40 casualties (Casassa and Marangunic 1993).

Fig. 6.6 Ablation area of Juncal Sur Glacier, March 2019, showing the three main tributaries, with a prominent subglacial channel draining from the medial moraine at the glacier front. North is upwards in the photograph

6.4.2 Southern Chile (G)

Glaciers in Southern Chile are located within the Wet Andes (Lliboutry 1998). They can be classified in two groups, one is the "Southern Macrozone" (36°37′–46°03'S), with a glacier area of 1701 km^2 which represents 7,2% of Chile's glaciers, including ice capped volcanoes in Chile's lake district and northernmost Patagonia. The "Austral Macrozone" (46°03′–55°30'S) corresponds to Patagonia, Tierra del Fuego and the fjord archipelago with a glacier area of 20,906 km^2, that is 88,4% of all glaciers in Chile, concentrated in the Northern and Southern Patagonia Icefields (NPI, SPI) and in Cordillera Darwin Icefield, which constitute the largest ice masses of the Southern Hemisphere outside of Antarctica. This region is strongly influenced by the westerly winds and associated precipitation, which exhibits a very strong west-east gradient (Weidemann et al. 2018a). North-south gradients, including temperature, are also pronounced, with an ELA dropping from 3200 m in the north (36°37′) (Carrasco et al. 2008) to about 500 m south of Tierra del Fuego (Izagirre, personal communication). Precipitation seasonality shows a latitudinal trend, with the northernmost region showing a concentrated precipitation regime over the winter months (JJA) and the southernmost area receiving precipitation year round.

The icefields in Patagonia and Tierra del Fuego are associated with large outlet glaciers which typically calve into lakes and the Pacific Ocean fjords, the largest of which is Pío XI Glacier in SPI with an area of 1241 km^2, the biggest in the Andes

(Segovia and Videla 2017). Shaeffer and others (2015) estimated a surface mass balance between −11 m w.e. in the frontal area of the glaciers of SPI and 15 m w.e. near the ice divide for the 1975–2011 period, with calving increasing in the 2000–2011 period compared with the previous years. The ablation estimates are reasonable since they agree with ground-based data (e.g. Weidemann et al. 2018b). However, the accumulation estimations are subject to relatively high uncertainty, deriving from the lack of reliable distributed precipitation input estimates and the unknown value of snow density in accumulation areas. The maximum measured accumulation rate is 17.8 m w.e. near the ice divide at Tyndall Glacier in SPI, based on analysis of a 46 m long firn core (Shiraiwa et al. 2002). Calving rates are also quite uncertain due to lack of ice thickness and velocity measurements in glacier outlets. Ice thicknesses in excess of 1400 m have been measured on the inland plateau of NPI and SPI (Millan et al. 2019; Casassa 1987). Velocity calculations have been made possible for vast areas of the Patagonian icefields based on satellite data, which allow to delineate basin limits and estimate calving fluxes (e.g. Sakakibara and Sugiyama 2014; Mouginot and Rignot 2015). Most outlet glaciers in the Patagonian Icefields are retreating and thinning at an accelerating rate with a record of 30 m/a at HPS 12 (Rignot et al. 2003). A recent assessment of geodetic mass balance of glaciers has been performed for the entire Andes, showing that the Patagonian icefields are responsible for 83% of all mass loss in the Andes, with a mass loss of 0.9 +/− 0.08 m/a w.e. (Braun et al. 2019). The ice loss in Patagonia (Fig. 6.7) has been attributed to atmospheric warming (Rasmussen et al. 2007) in combination with dynamic adjustments of glaciers (Braun et al. 2019).

6.5 Snow, Glaciers and Water Resources in North-Central Chile

In the region between the Copiapó and BíoBío river basins, the energy-driven hydrological regime of mountain rivers makes water available in spring and summer, when irrigation demands are higher, and thus has allowed for the development of a very active agricultural sector. The spring thaw begins to occur in September–October, and melt water streaming from snow peaks in spring and early summer (October–December), while and glacier ice melt contributes more during mid to end of the summer (January–February). The relative contribution of snow and glacier melt to river flow in the mediterranean Andes watersheds varies depending on many factors, but it is appropriate to say that snow melt accounts, on an annual average, for the majority of river flow. However, during dry years, glacier melt in partially glacierized basins can contribute a significant fraction of end of the summer flows, reaching up to 60–70% during dry years according to several sources (Peña and Nazarala 1987; Ayala et al. 2017; Rodriguez et al. 2016; Ohlanders et al. 2013; Casassa et al. 2015). Mean annual contribution from glaciers is between 3% and 44% of total streamflow (Gascoin et al. 2011; Ragettli and Pellicciotti 2012; Casassa

Fig. 6.7 San Rafael Glacier, the second largest outlet glacier in the Northern Patagonia Icefield, at 46°41′S is the lowest-latitude tidewater glacier in the world. The glacier is 2 km wide at the front, 49 km long and has an area of 724 km^2 (Segovia and Videla 2017). The front was thinning at a rate of 3.5 m/y in the period 1975–2000 (Rignot et al. 2003) and retreated at 25 m/y in 2011–2017

et al. 2015; Schaffer et al. 2019), depending on the basin and the location of the measured/modelled streamflow. Highest glacier contributions are observed in years with relatively low precipitation, and at high elevations. One recent example was outlined in Ayala et al. (2017) who estimated that glaciers in the Yeso River Basin (sub-catchment of the Maipo River) contributed approximately $\frac{2}{3}$ of streamflow during 2015, which was one of the driest years on record. Similar values were obtained by Casassa et al. (2015), who showed that 63% of the streamflow at Mapocho and Maipo rivers during a very dry year, at the end of the summer, originates from glacier melt as they drain into the central valley. However, the hydrological relevance of the glaciers strongly decreases downstream from the headwaters of the glacial valleys (Casassa et al. 2015), similar to what happens in other mountain areas (Kaser et al. 2010). In glacierized basins, therefore, streamflow variability is lower than that of annual precipitation, showing the relevant role of glaciers as natural water reservoirs, including the role of rock glaciers in basins with scarce debris-free and debris-covered glaciers such as Elqui (Shaffer et al. 2019).

Water resource availability is predicted seasonally in snow-driven rivers through forecasts, which are issued by the end of the winter season (September). Different agencies issue streamflow forecasts at diverse river reaches, but the official product in the country is issued by the Water Directorate at the Ministry of Public Works. These forecasts are prepared with statistical models that combine through multiple regression data on winter precipitation, historical streamflow data and end-of-winter SWE accumulation measured at a network of stations. This network, comprising approximately 20 locations out of which 10 include automatic SWE sensors (snow pillows or snow scales), spans a geographical range of about 1000 km in the Andes range, between the Copiapó and Ñuble rivers. In terms of seasonal (spring and summer) streamflow volume, these forecasts show a mean error of approximately 20% (Mendoza et al. 2014). The information provided by SWE data is therefore critical in producing forecasts with appropriate statistical properties, and that large scale climatic indices can provide useful data for forecasts to be issued with longer lead times, such as 2 or 3 months.

6.6 Climate Change and Chile's Disappearing Cryosphere

Glacier changes in the region have only been reconstructed from remote sensing, from comparison of an inventory based on ASTER images from 2004 with earlier inventories based on aerial photographs from 1955 and 1984. The results of this analysis of area changes indicate that glaciers have been retreating since the 1950s, and at a rate higher than those of the central region (in % of their initial surface) (Nicholson et al. 2009). Rabatel et al. (2011) suggested that this shrinkage results primarily from a decreasing trend in precipitation observed in the sub-tropical region, and that no link between glacier area changes and temperature evolution exists. Glacier changes have been documented by Rivera et al. (2002) for the entire region and by Bown et al. (2008) for the Aconcagua River basin using remote sensing images (Instituto Geografico Militar maps from 1955 and 1997, Landsat TM (year 1987), Landsat ETM+ (year 1999), the Shuttle Radar Topography Mission (SRTM) DEM for the year 2000 and two ASTER images (for 2003 and 2006)). Nicholson et al. (2009) extended previous records for three glaciers in the region (Juncal Sur, Juncal Norte, Olivares Gamma) and compared them to those for three glaciers in the Norte Chico (Tronquitos, Guanaco and Estrecho). Glaciers in the region are shrinking, with lost-area ratios of three of the major glaciers of −2.4%, for Juncal Norte Glacier, − 10.9%, for Juncal Sur, and − 8.2% for Olivares Gamma over 51 years from 1955 (Rivera et al. 2002). The Aconcagua River basin (between 32 and 33°S) is one of the four major basins of the Central Andes (together with the Maipo (33°S), Cachapoal (34°S) and Tinguiririca (35°S)), and its upper section is one of the best studied of the glacierised basins in Chile (Pellicciotti et al. 2008; Ragettli and Pellicciotti 2012; Ohlanders et al. 2013; Rodriguez et al. 2016; Ragettli et al. 2014). An update of older glacier inventories for the basin has been carried out by Bown et al. (2008). The basin is located at the boundary between semi-arid and temperate conditions, and it contains 14% of the total ice between 32 and 35°S (Bown et al. 2008). It has experienced an area loss of 20% between 1955 and 2006. However, glacier changes are not homogeneous, and local effects seem to play an important role in determining this distinct response. The Juncal Norte Glacier, in particular, seems to exhibit a distinct change. Bown et al. (2008) estimated that it lost 1.5 km^2 between 1955 and 2006. Variations of its front are smaller than those of other glaciers in the region, and of the neighbouring Juncal Sur glacier (Bown et al. 2008), pointing to the importance of local topographic effects on radiation receipts, spatial effects such as wind and gravitational snow redistribution, and the accurate description of the interplay between complex topography and energy fluxes reaching the glacier surface. Bown et al. (2008) suggested therefore that more accurate methods other than remote sensing should be used to detect and understand glacier variations. The temporal variability of glacier mass balance can also be large: mass balance observations from the small Echaurren Norte Glacier (0.226 km^2 in 2008, 33.5°S) indicate a positive net mass balance for the period between 1977 and 1991 (Escobar, Casassa and Pozo 1995), but an overall very negative net mass balance until 2008 (Masiokas et al. 2016). This is the only glacier in Chile for which such a long record is available, but the results cannot be extrapolated given the small size of the glacier, which makes it less representative of regional patterns.

In the Chilean Lake District, glaciers are mostly located over active volcanoes, and this peculiar feature has been investigated in terms of their surface energy balance (Brock et al. 2007) as well as studies of mass balance (Rivera et al. 2005) and ice volumetric changes (Rivera et al. 2006). Volume changes are due to both the climate drivers and the effusive and geothermal activity of the volcanoes (Rivera et al. 2006). Volcanic activity can affect the glaciers in two opposed ways: by insulating the ice with ash and debris, resulting in reduced surface ablation, and by enhancing subglacial melting due to geothermal activity, resulting in greater thinning than in non-active volcanic environments. Rivera et al. (2006) found that glaciers on volcanoes were mainly shrinking in response to climatic driving factors, and in particular a decreasing trend in precipitation between 1930 and 2000. However, they also found that glacier response is highly heterogeneous and due to the specific eruption and activity histories of the individual volcanoes.

The Patagonian Andes contain over 20,000 km^2 of glaciers, representing the largest glacierised area in South America. Glaciers are mostly concentrated south of 45°S, with the Northern and Southern Patagonian Icefields covering about 4200 and 13,000 km^2, respectively. Glaciers in Patagonia are strongly retreating and thinning (Rignot et al. 2003; Rivera et al. 2007; Masiokas et al. 2008; Willis et al. 2012), but very little is known about the reasons and how these changes are linked to changes in the climate (Masiokas et al. 2008; Schaefer et al. 2013). Masiokas et al. (2008) have attributed the recession to a trend towards drier and warmer conditions detected over the 1912–2002 period. They analysed a series of long, homogeneous annual, cold-season and warm-season regionalized temperature and precipitation records and showed that averaged warm season (October– March) temperatures have increased by 0.056 °C per decade, whereas cold season (April–September) precipitation (on average about 73.5% of annual totals) has declined at a rate of about 5% per decade. In one of the very few modelling studies, Schaefer et al. (2013) used a glacier mass balance model to evaluate the past and future surface mass balance of the Northern Patagonian Icefield, and found that accumulation increased from 1990 to 2011 as compared to 1975–1990, while calving losses doubled in 2000–2009 as compared to 1975–2000. They also used the model to predict future changes up to the end of the century, obtaining increasing rates of mass loss.

In terms of snow cover and snowmelt availability, climate change projections for most of the Chilean territory indicate warmer and drier conditions. Under such a climate, reductions in peak SWE accumulation (and associated snowmelt volume), increases in the mean wintertime snowline elevation and reductions in snowcover duration are to be expected. The exact magnitude of these changes is less understood and projections are hindered by the large uncertainties still affecting appropriate modeling of mass and energy balance in remote mountain regions. Nevertheless, some studies have pointed at the nonlinearity of the highest reaches of the Andes Cordillera in terms of its cryosphere climate change response. For example, (Cortés et al. 2011) demonstrated that the timing of river flows in north-central Chile experienced little change in the last half of the twentieth century, unlike other mountain chains in the world, which have experienced earlier melt and streamflow due to warming in the past decades (Stewart et al. 2004, 2005). This finding only applies to rivers in the high-elevation headwater basins north of 34°S, while the mountain region between 34° and 40°S did experience statistically significant trends, probably attributable to a decrease in spring (SON) and summer (DJF) precipitation over the last few decades. Lopez-Moreno et al. (2017), through a modeling study, found that the low-temperature conditions found in typical snowpacks in the Coquimbo region of Chile induce a lower sensitivity to warming, expressed in smaller changes in SWE accumulation and snow cover duration than that expected in other mountain regions of the world.

6.7 Conclusions

The cryosphere in the Andes of Chile is a key component of the hydrological cycle, allowing the existence of human settlements, agricultural and industrial activity, and rich ecosystems. Snow and glaciers contribute water resources at different spatial and temporal scales, in an interplay that until now is only partially understood due to the lack of long-term instrumental records, and the complexity of physical mechanisms linking the atmospheric-land surface and subsurface hydrological systems. Fortunately, in recent years the scientific community has expanded the available knowledge through a combination of observational and modeling studies that have shed light on many aspects of the cryosphere distribution, dynamics, and relation to the local climate and physiography. The widespread availability of remotely sensed data and advances in process understanding, derived from increasingly common field studies, have allowed these developments. Yet, knowledge gaps do persist, and include:

- Meteorological conditions in remote, high-elevation catchments, and feedbacks between atmospheric and land-surface conditions.
- The extent and hydrological role of rock and debris-covered glaciers.
- The extent and hydrological role of seasonally and permanently frozen ground (permafrost).
- The relative importance of precipitation and temperature anomalies in driving glacier mass balance dynamics at different climatic regions.
- The role of penitentes in snow and glacier energy balance.
- The relevance of calving rates in glacier mass balance in southern Chile.
- The prevalence of rain-on-snow events and their role in hydrological risk.
- Cryospheric hazards related to glacier stability, dry and wet calving, Glacial Lake Outburst Floods, and high mountain slope stability.
- Accurate projections of the impact of climate change on the above.

These knowledge gaps in turn pose important challenges for science and public policies, because reliable, long term observations of cryospheric processes are key inputs for obtaining better estimates of future impacts due to global warming. Automated, state-of-the art snow water equivalent measurements are paramount for evaluating simulated estimates of catchment or regional-scale water resource availability. Long-term glacier mass balance monitoring programs for representative glaciers in different hydroclimatic regions must be strengthened and sustained in order to better constrain future-climate simulations of glacier ice evolution, and research programs aimed at characterizing and understanding uncertain and non-linear processes should be carried out. Because of the complexity of field monitoring programs, the diversity of the cryospheric settings in the Andes and the relatively small scientific community currently working on these topics, research policies should favor the creation of public-private-academic consortiums, so that synergies in data collection and analysis could be maximized. The increase in scientific knowledge will also help to improve the protection status of the cryosphere within the environmental law regime in Chile, which needs to be strengthened in view of increasing water demand and having detached from the bed, industrial activities in the central Andes, particularly mining (Azócar and Brenning 2010). At present (2019) a glacier law proposal is under debate in Congress which can clearly benefit from science-based knowledge.

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Chapter 7
Floods

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Abstract Due to its particular geographic and climatic characteristics, Chile is periodically affected by floods that in many cases have produced significant socio-economic impacts. Furthermore, there is a national concern about whether or not the frequency and magnitude of these events will increase in the future due to climate change. This chapter presents different approaches for flood modeling and characterization used in Chile, as not only the most common fluvial and pluvial floods take place, but also events related to anthropic intervention, volcanic activity, landslides, snowmelt, and glacial activity. Then, some of the relevant historical flood events occurred in Chile are described. Finally, strategies to cope with floods are presented and discussed, with some of them having acquired increasing importance under the National Policy for Disasters Risk Management recently promulgated.

Keywords Extreme events · Floods · Risk management · Climate change

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7.1 Introduction

Flooding is a temporary overflow of water onto land that is normally dry. Three characteristics are common to most floods: (1) they have a relatively short duration with a quite abrupt rising limb in the hydrograph, (2) one or more physical variables describing the flood (e.g. flow depth, surface width, velocity, sediment transport rate) reach large values that are in the upper side of the probability distribution, and (3) several negative impacts can take place, such as infrastructure and environmental destruction and loss of human life. Floods and other hydrometeorological hazard events are the most frequent and damaging natural disasters in the world (Guha-Sapir et al. 2011). Global annual economic losses due to floods have increased from ~US$7,000 million in 1980 to ~US$24,000 million during the period 2001–2011 (Kundzewicz et al. 2014). Such rise is mostly due to the continuous population growth and migration to cities (Bouwer 2011), as well as the increase in the frequency of extreme hydrometeorological events in the midlatitudes, which are projected to continue during the twenty-first century (IPCC 2013).

Natural hazards and risk assessment are of extreme relevance for Chile, a country whose average annual economic losses between 1980 and 2011 due to multiple natural disasters has been estimated to represent 1.2% of the gross domestic product, more than for any other country of the G20 group (CNID-CREDEN 2016). Within this context, floods are one of the central hazards; in fact Chile is ranked among the 30 countries under highest water-related risk by 2025, including drought and flood risk (Luo et al. 2015).

In this chapter we review the issue of flood in Chile, the main characteristic of these events in Chile, the factors driving them, the local strategies and approaches to cope with them, as well as the future challenges this topic imposes to the country, especially under a context of global change.

7.2 Floods in Chile, Types and Processes Involved

In its long and narrow latitudinal extension, Chile comprises a wide range of climatic zones and presents a geography dominated by two important mountain ranges, the Andes and the Coastal range (Toledo and Zapater 1991). Precipitation, seismic and volcanic activity, and anthropic pressure over natural basins, alter the zonal climatic characteristics and make the territory prone to the occurrence of different types of floods, particularly, fluvial floods and pluvial floods (Di Castri and Hayek 1976; Peña and Klohn 1990). Other type of floods particularly triggered by the interaction with the sea (i.e. coastal flooding and storm surges), are not considered hereafter in this chapter.

7.2.1 Fluvial Floods

Fluvial floods or river floods are a natural process in which river discharge overtops the river bank and flows through areas where it normally does not (Tockner et al. 2010). These events become a hazard when human settlements are located in river floodplains. Several causes are known to generate the fluvial floods that occur in Chile (Rojas et al. 2014). The most frequent ones are related to intense or persistent precipitation events, particularly with concurrent high temperature conditions that raise the freezing level. Of less recurrence, but still relevant in the national context, floods may be generated by: volcanic activity, co-seismic landslides, nivo-glacial processes, and anthropogenic intervention.

7.2.1.1 Precipitation

Precipitation corresponds to the most common mechanism that triggers fluvial floods in Chile, being the detonating factor of 68% of the events that took place in the twentieth century (Rojas et al. 2014). Floods related to precipitation have been recorded all throughout Chile, and their magnitude is directly related to basin size and the amount of rainfall (Peña and Klohn 1990). Intense precipitation events may be produced by frontal systems usually intensified by El Niño Southern Oscillation (ENSO) in both warm and cold conditions, or by convective storms, depending on the climatic region and time of the year. A particular type of precipitation-related flood develops in mountainous basins in central Chile when warm temperatures and storm events happen together (Vicuña et al. 2013; Castro et al. 2019). In these cases, warm fronts raise the freezing level or 0 °C isotherm, which increases the pluvial contributing area of the basin, thus leading to violent and sudden floods (Carrasco et al. 2005; Garreaud 2013; Rojas et al. 2014). Garreaud (2013) classifies precipitation events as warm storms when average air temperature during the precipitation period is greater than 10.5 °C, at Quinta Normal raingauge (33.4°S, 70.7°W, 535 m.a.s.l.). A dramatic example of these events occurred in Santiago in May 3, 1993, where a moderate rainfall with extremely warm conditions triggered massive debris flows and landslides along the Andean foothills (further details are given in Sect. 7.4.). Other significant events originated by extreme precipitation are those reported in the semiarid regions of the country, as the ones identified by Soto et al. (2017).

7.2.1.2 Volcanic, Co-Seismic Activity and Nivo-Glacial Processes

The relationship between volcanic activity and fluvial floods lies mainly in two phenomena: the generation of lahar flows, and the discharge increase derived from snowmelt (Rojas et al. 2014). In both cases, rivers can experience major flooding that can produce extensive damage. Most of the volcanic related floods have been recorded in the Araucanía region, and are associated with the eruptions of the Villarrica and Llaima volcanoes. A well-documented flood of this type occurred in 1971 after the eruption of Villarrica volcano (Peña and Klohn 1990). A maximum discharge of 3,500 m^3/s was estimated for this flood, and according to lake water height records, 25 hm^3 of lahar flows entered the Villarrica and Calafquén Lakes in just 4 h. Similar situation occurred in the Blanco River after the eruption of Chaitén volcano in 2008 (Mandujano and Rodríguez 2016; Tonon et al. 2017). Floods and lahars triggered after the eruption inundated the town of Chaitén and its 4,600 residents had to be evacuated (Carn et al. 2009; Lara 2009).

Floods caused by landslides associated with seismic activity may be produced by the obstruction of a river reach followed by a sudden release of the dammed water, or by the generation of debris flows (Peña 1986). The flood event of Valdivia in 1960 is an emblematic case of this type (Mazzorana et al. 2019; Peña and Klohn 1990). After the earthquake of May 22nd in 1960, a landslide dammed the San Pedro River downstream of Riñihue Lake. With the obstruction, the lake gathered an additional water volume of 2,000 hm^3. Despite the dam break was performed in a controlled manner, approximately 40% or the urban areas of Valdivia were flooded (Mazzorana et al. 2019). Furthermore, a maximum discharge of 7,450 m^3/s was recorded, equivalent to approximately 4 times the 100 year meteorological flood (Canisius 1961; Peña and Klohn 1990).

The most relevant nivo-glacial related floods are generated by GLOF (Glacial Lake Outburst Flood)/IDLOF (Ice-Dammed Lake Outburst Flood) processes. These events correspond to a sudden and unexpected release of a water volume impounded by a glacier or an end-moraine (Iribarren Anacona et al. 2015; Peña and Klohn 1990; Wilson et al. 2018). Events of this type are concentrated in the surroundings of the Ice Fields in southern Chile, but are not exclusive to this region (Rojas et al. 2014). One of the most violent recorded GLOF/IDLOF events in Chile occurred in the Manflas River in 1985, in which a sub-glacial lake, formed under the Río Seco de los Tronquitos glacier, outburst through one of its walls (Iribarren Anacona et al. 2018; Peña and Escobar 1987). The flood was extremely violent, with an estimated peak flow of 11,000 m^3/s at the glacier's foot and a hydrograph base time of just 15 min (Peña and Escobar 1987). Another case of this type of flood occurred in the Colonia river valley in Patagonia. During 2008–2009, an unexpected sequence of 5 GLOF events drained the Cachet 2 Lake and flooded large parts of the Colonia and Baker river valleys (Dussaillant et al. 2010; Jacquet et al. 2017). These floods have a significant effect on the floodplain of rivers, particularly the vegetation cover (Bastianon et al. 2012), and might occur more frequently in the future due to the potential impacts of climate change on glacier dynamics (Dussaillant et al. 2010).

7.2.1.3 Anthropic Intervention

Floods related to anthropic intervention are produced by the break, mismanagement, or sudden breach of hydraulic and fluvial infrastructure (Rojas et al. 2014). These events have been experienced mainly in Chilean regions where most of the hydraulic infrastructure is concentrated (Maule and Biobío regions). The recurrent overflow of Tutuven dam in the Maule region is an example of these floods (Urrutia de Hazbún and Lanza 1993). Another example of this type of flood is that of the failure of mining tailing deposits. Several of these events after the La Ligua earthquake in March 28th, 1965 (Malgrange et al. 1981), affected the new and old El Cobre tailing dams where 200 people died (Harper et al. 1992). Finally, a more recent example of floods caused by anthropogenic intervention is that of the Mapocho River in April 16th, 2017 (Fig. 7.1), when a riverbed modification due to an urban highway construction produced a major flood that affected the business district of Santiago (Yáñez-Morroni et al. 2018). Nevertheless, fluvial floods took place in many other locations in central Chile during this event.

7.2.2 Pluvial Floods

In addition to fluvial flooding, several Chilean urban areas are prone to another type of situation known as pluvial floods or urban floods (sometimes also called inland flows). These events are not associated with rivers bursting over their banks, but rather to waterlogging occurring within the city, particularly in low lying and highly impervious areas with little or no coverage of urban drainage systems (CIGIDEN 2016; Falconer et al. 2009; Houston et al. 2011). Pluvial flooding causes relate to the lack of stormwater infrastructure, natural land use change for impervious areas

Fig. 7.1 The Mapocho river flood in 2016, an example of floods caused by anthropogenic intervention. (Source: www.24horas.cl)

characteristic of urban development, and improper urban planning and city management (Blanc et al. 2012; Butler and Davies 2004; MOP 2013). Such factors reported elsewhere are also observed in Chilean cities (Estellé et al. 2012). Urban floods are the most frequent type of flooding in Chilean cities, with several occurrences in the twenty and twentyfirst centuries. For example, 21 flood events were registered in the period (1943–2011) in the Great Concepcion Metropolitan Area. In coping with urban floods, since 2008 the Chilean government has been able to reduce small flooding events (i.e. return period less 10 years), but with negligible improvements for high return period risks, hence several authors (e.g. Rojas et al. 2017; Barria et al. 2019) recommend to rethink and improve urban planning in Chile.

7.3 Flood Characterization and Modeling

Flood modeling and characterization are of paramount importance for several human activities, as it allows objective and quantitative decision-making with respect to natural hazard assessment and land-use planning (Sivapalan et al. 2003), and has direct applications in the planning, design and operation of components of water systems and fluvial infrastructure (Akhtar et al. 2009). As in other places in the world, in Chile floods are characterized by means of several measurable magnitudes, which have their own way of affecting the population and their goods. Typically used magnitudes are the maximum discharge, maximum depth, flow speed, flood duration, sediment transport measurements, among others (MOP 1995). Nevertheless, the amount, quality and accuracy of the measurements differ among these variables and the sampling time. For example, daily measurements of flow discharge are much more common than hourly ones. On the other hand, flow discharge data are much more available and reliable than sediment concentrations, particularly during flash floods, although they are extremely important in flood modeling and the characterization of the destructive power (Contreras and Escauriaza 2020).

Different approaches for flood modeling have been developed and implemented throughout the years, with most of them oriented towards engineering design. Chilean governmental agencies have developed handbooks for infrastructure design in which flood modeling concepts are covered. Some of the most widely used ones are: *Manual de cálculo de crecidas y caudales mínimos en cuencas sin información fluviométrica* (MOP 1995); *Manual de Carreteras* (MOP 2010); *Manual de Drenaje Urbano* (MOP 2013). Moreover, the last two manuals specify return periods for the design of a variety of infrastructure. Although these manuals are widely used, they are not reviewed and updated with the desirable frequency. In particular the MOP (1995) handbook, which is used for the prediction of floods in ungauged basins, probably deserves an update after 25 years of use, particularly given the major advances in the topic during the Prediction in Ungauged Basins initiative of the International Association of Hydrological Sciences that took place between 2003 and 2013 (Hrachowitz et al. 2013).

The modeling methods currently used in Chile available in these manuals can be classified into three groups, depending on the availability of data: statistical direct approaches, statistical indirect approaches, and rainfall-runoff approaches (Fig. 7.2).

– Statistical direct approaches: these methods are based on frequency analysis of peak flow discharges or other design variables, and thus can be used when long streamflow records are available for the study site. Using a statistical direct approach leads to a relationship between the design variable and its probability of excess or return period, yet without a deep understanding of the physical processes that trigger the flood. One of the most commonly used probability density functions in Chile is the Type I extreme value or Gumbel distribution.
– Statistical indirect approaches: these methods are used when streamflow data are not available at the site of interest, but they are available nearby in locations with similar hydroclimatic conditions. In this case, statistical regionalization procedures or transpositions can be used to estimate the relationship between the design variable and its probability of excess at the site of interest. Nonetheless, there is no official regional flow frequency method nor a single widely used approach promoted by the state similar to, for instance, Bulletin 17C (England et al. 2019).
– Rainfall-runoff approaches: these methods relate precipitation and flow discharges in sites where statistical approaches cannot be used due to the lack of long streamflow records. Conceptual, empirical and physically-based computer models are used for this purpose. Although most of the models used in Chile were developed elsewhere -including the rational method, methods based on arrangements of linear reservoirs and synthetic unit hydrograph methods- there are certain approaches that consider either a further development or modifications, or others that were developed for the specific Chilean case. Some of these models are the DGA-AC method and the Verni-King Procedure (MOP 1995). For the use of these methods as well as a synthetic unit hydrograph approach, different homogeneous regions are defined, which in turn implies using parameter values that are specific to each region. Moreover, a modified rational method is proposed, in which the runoff coefficient varies with the return period and is defined after classifying the terrain in terms of 4 attributes (i.e. infiltration, vegetation, relief and surface retention). Finally, methodological differences in the

	1 Statistical Direct Approaches	2 Statistical Indirect Approaches	3 Rainfall-runoff approaches	
Methodology	Streamflow probabilities	Streamflow probabilities + Regionalization	For a precipitation event	Continuously in time
Input Variables	Streamflow time series in the study site	Streamflow time series in places with hydroclimatic similarities than the study site	Design rain (built from the historical records)	Continuous precipitation and other meteorological variables
Parameters	Statistical model parameters	Statistical model parameters and region parameters	Basin parameters and initial conditions	Basin parameters
Results	Streamflow (Q) v/s Return Period (T)	Q v/s T	Q v/s T, related to the precipitation T	Streamflow and other variables time series

Fig. 7.2 Methods used to estimate peak flows. (Adapted from CCG 2013)

estimation of peak flows during the rainy season (April–September) and the melting season (October–March) are sometimes considered, when data availability allows it.

Regardless of the methodology used, there are recommendations to compare and verify the results obtained with more than one methodology. Especially in cases where a rainfall-runoff approach is used, due to the lack of long term streamflow records, more than one method is recommended. There also are specifications that indicate which method has a better performance in each case (MOP 1995).

7.4 Relevant Flood Events in Chile

7.4.1 Atacama: March 2015 and May 2017

From March 24 to 26, 2015, the Atacama region in northern Chile experienced an unusual rainfall event accompanied by high positive surface temperature anomalies (Barrett et al. 2016). According to records of 13 rain gauges, an average rainfall of 45 mm fell over the Copiapó River Basin with maximum rainfall intensities of over 10 mm/h (Valdés-Pineda et al. 2017). These atmospheric conditions, over a region where hillslope vegetation is largely absent and stream channels are dry or ephemeral, lead to a catastrophic sediment-rich flooding (Wilcox et al. 2016) mainly in two river basins: the Copiapó River Basin and the Salado River Basin. A flood peak discharge of approximately 1,000 m^3/s was estimated at the basin outlet of the latter (Wilcox et al. 2016), a discharge larger than any other documented flood in the basin. The toll of the flooding included 31 deaths, 16 people disappeared, 30,000 people displaced, as well as widespread damages to homes, roads, bridges, and railroads (ONEMI 2015).

Another severe rainfall event occurred across the Atacama region in May, 2017. Once again, fluvial flooding caused loss of life, substantial damage to homes and roads, and community isolation (Moran et al. 2018). A total rainfall of 80.8 mm was recorded at the Copiapó en Pastillo rain gauge in a duration of 58 h. Despite being a much more extreme storm event than Atacama 2015, the maximum flows registered for the 2017 event are not considerably larger than the peaks registered in 2015 in the Copiapó River. An interesting analysis is presented in Fig. 7.3 with data recorded at Copiapó in Pastillo streamflow gauge. Panel (a) of this figure compares both rainfall events against the precipitation-duration-frequency (PDF) curves at the gauge, which show the theoretical cumulative precipitation for the most intense 1 h, 2 h, 3 h, and so on, for different return periods. For each event hourly precipitation was sorted in descending order and plotted in a cumulative manner against the cumulative time. The 2017 storm is overall a much less frequent event than that of 2015, with magnitudes for short durations (4–7 h) similar to those estimated for a 200-year storm, while for longer durations the magnitudes were comparable to the 50-year storm (24 h) and the 100-year storm (48 h). On the other hand, 2015 storm

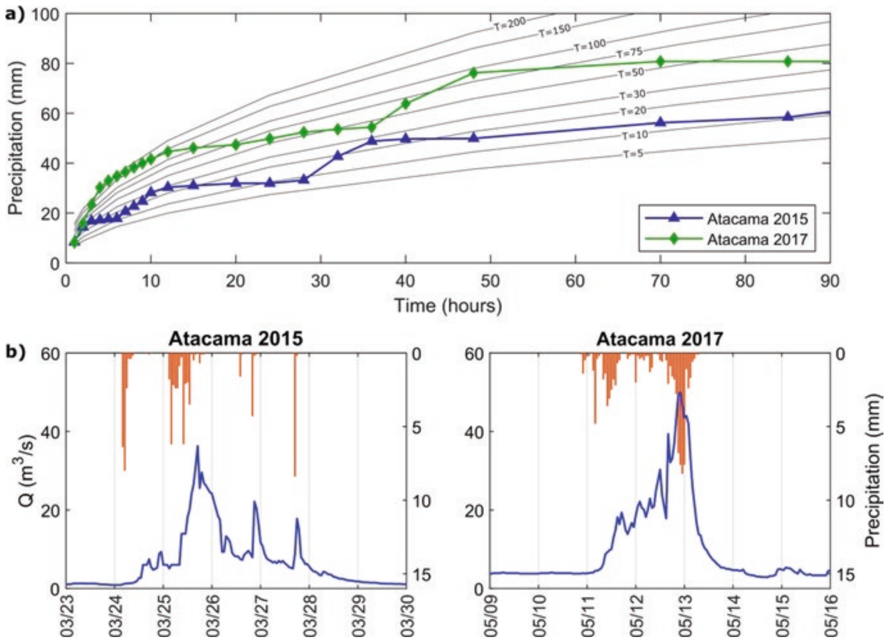

Fig. 7.3 Comparison between Precipitation-Duration-Frequency curves for Copiapó en Pastillo rain gauge and the evolution of storm events of Atacama 2015 and 2017 (**a**). Hydrographs and hyetographs recorded for both floods at the same location (**b**)

never exceeded the 30-year PDF curve. However, the large difference in the storm magnitude is translated in a much smaller difference in maximum flows in the Copiapó River. The peak discharge in 2017 and 2015 were 49.9 m^3/s (panel b) and 36.3 m^3/s (panel c) respectively. The explanation for this relatively minor difference underlies in the concurrent temperature. Precipitation in 2015 occurred under abnormally high temperatures in late March, while the 2017 event took place in May, in mid fall season, with lower temperatures. Thus, the pluvial contributing area was much smaller for the 2017 event compared to the event of March 2015. With less rainfall contributing area for Copiapó en Pastillo subbasin, the intense and extreme storm of 2017 produced a not so large maximum discharge in spite of being comparable to a 100-year storm.

7.4.2 *Santiago: May 1993*

Between the night of May 2nd, and the morning of May 3rd, 1993, a moderate rainfall accompanied by abnormally warm conditions fell over Santiago and the front range or *pre-cordillera* of the Andes mountains (Garreaud and Rutllant 1996; Garreaud 2013). Catastrophic floods were experienced in the eastern end of the city because of large flows at both Quebrada de Macul and Quebrada de Ramón (Fig. 7.4), two small subcatchments in the *pre-cordillera*. Maximum flows of 47.5 and 53.0 m^3/s were estimated for both subcatchments respectively, accompanied by important loads of sediment and mud (Vargas and Lara 1997). The event caused twenty-six deaths, 9 people missing, and 1,169 damaged homes (Garrido and Sepúlveda 2012).

In terms of precipitation, the event of May 3rd does not seem extraordinary. A return period close to 10 years has been associated with the storm in most regions of central Chile (Garreaud and Rutllant 1996). On the other hand, the estimated peak discharges at Quebrada de Macul and Quebrada de Ramón have an associated return period of 50 years (Vargas 1999). The abnormal temperature conditions of this event explain the production of a catastrophic inundation from a moderate rainfall. On average, the 0° isotherm at the Andean front range in Santiago is located at 2,000 m.a.s.l. (Garreaud 1992). Due to the warm condition of the May 3rd event, the freezing level rose up to 4,000 m.a.s.l. (Sepúlveda and Padilla 2008), way above the maximum elevations in both subcatchments, as illustrated by their hypsometric curves shown in Fig. 7.5. Thus, liquid precipitation over zones where it usually snows was the main factor that triggered the mudfloods and extreme maximum flows under a not extreme storm event.

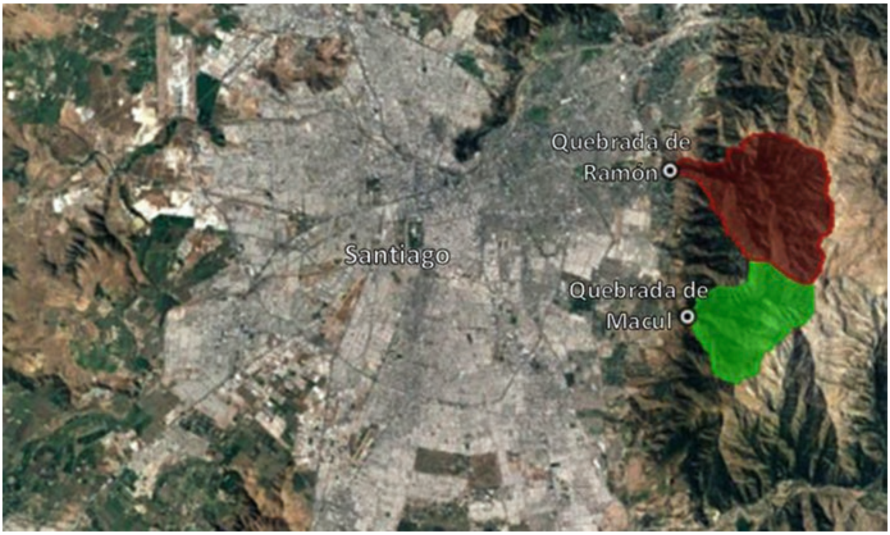

Fig. 7.4 Location of Quebrada de Ramón and Quebrada de Macul in the Andean front range, eastern Santiago

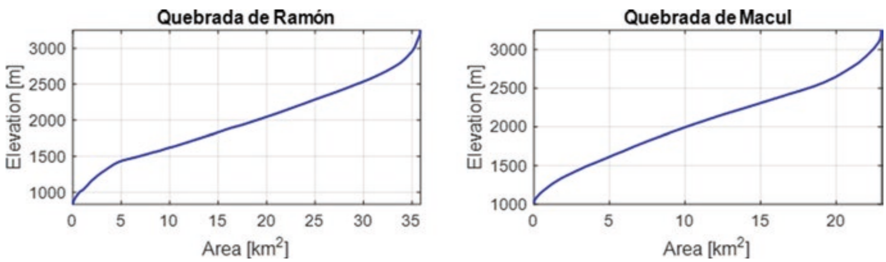

Fig. 7.5 Hypsometric curves for Quebrada de Ramón and Quebrada de Macul basins

7.4.3 Biobío 2006

A frontal precipitation system of great magnitude affected central Chile between July 10 and 13, 2006 (Vidal and Martel 2007). Indeed, this event literally split Chile in two for several days, as the main highway along the country was severely damaged in several points. The storm reached its maximum intensity in the Biobío Region, particularly in the uppermost locations of the Biobío River basin. A total rainfall of 400 mm was recorded during July 11 and 12, where the average winter rainfall for 48 hours is not greater than 100 mm (ONEMI 2006). The event triggered a 100-year flood in the lower Biobio River, which reached a maximum discharge of 15,700 m^3/s (van Heemst et al. 2018). Severe damages were caused by the flood, which left a toll of 22 deaths, 62,000 people affected, and destroyed houses, roads and bridges (ONEMI 2011).

Together with the extreme nature of the precipitation event, the anthropic intervention played an important role in aggravating the impacts of the flood (Vidal and Martel 2007). The Concepción Metropolitan Area, second largest urban settlement in Chile, is located along the lower reach of the Biobío River. The increasing growth of the urban area (Fig. 7.6) has modified large sections of the river channel and floodplains, resulting in an increase of impervious areas and reduction of vegetation cover (Rojas et al. 2013b, 2017; Vidal and Romero 2010). Furthermore, the presence of urban drainage and fluvial infrastructure have also altered the hydrologic regime of the river (Vidal and Martel 2007). All these interventions lead to an increase of surface runoff volumes, and a reduction of basins response time (Henríquez and Azócar 2006; Niehoff et al. 2002; Rojas et al. 2013a). With that, natural hazard risk levels also increase and the occurrence of disasters is enhanced, particularly floods and waterlogging (Bronstert et al. 2002; Wheater and Evans 2009; Pattison and Lane 2012). The Biobio 2006 event is an example of the influence of anthropic intervention over basins and their hydrologic regimes, which can lead to severe consequences.

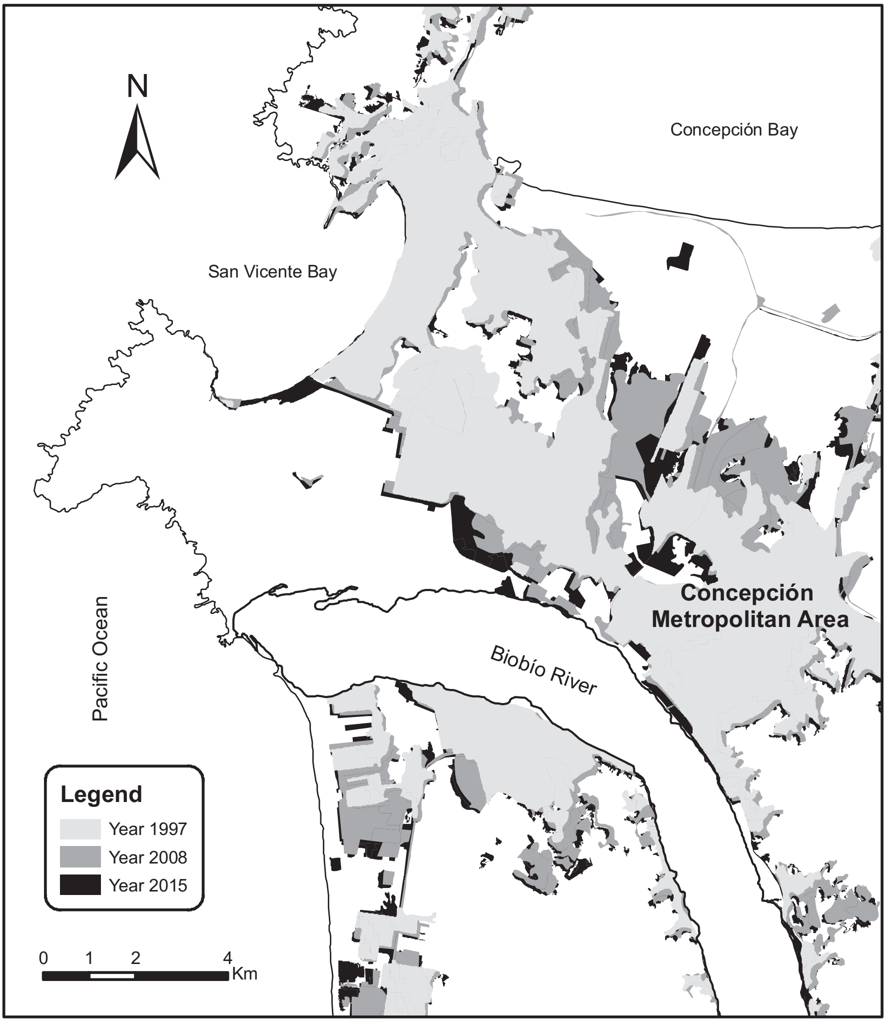

Fig. 7.6 Urban sprawl, Concepción Metropolitan Area

7.5 Coping with Floods in Chile: Current Status and Future Challenges

Climate change is expected to impact several hydroclimatic conditions in Chile. Climate projections indicate that there will be a reduction in precipitation, while temperatures will rise (e.g. Chadwick et al. 2018). These changes will severely impact water resources, causing a reduction and a shift in streamflows (e.g. Vicuña et al. 2011, 2012; Meza et al. 2012; Demaria et al. 2013). Unfortunately, the expected streamflow reductions are not related with a reduction in flooding probability.

Although annual precipitation and streamflows are presenting significant reductions in Chile as discussed elsewhere in this book, flooding and large peaks are becoming more frequent in some rivers. An example of this is shown in a study about the connection between hydrological extreme events and climate change in the Mataquito River basin in central south Chile (35°S), located in the Mediterranean region (Vicuña et al. 2013). The Mataquito basin shows a significant reduction both in precipitation and streamflows, but also temperature is consistently increasing. The rising temperatures have caused more frequent and greater peak flows, and a shift in them from the snowmelt season to the rainy season. Mataquito basin is experiencing greater peak flow discharges with smaller precipitation events, due to an elevation of the snow line caused by higher concurrent temperatures with precipitation events. Because of the general setting of Chile, with large relief changes in relatively short distances, the combined effect of precipitation with higher temperatures imposes a big challenge for the future, particularly in those cities that are not only exposed to floods, but also very dependent on mountain rivers for water supply. Large floods during warm events have consistently increased the turbidity, which in turns has led to water shutoffs (Vicuña et al. 2018).

Given the increasing importance of extreme events -as well as other natural non-hydrometeorological hazards- in Chile, the country has launched several initiatives to increase resilience through a more comprehensive/holistic approach, in which territorial and urban planning are considered as central elements to cope with natural hazards (Camus et al. 2016). For example, Chilean government through the Science and Technology National Research Commission (known today as the National Agency for Research and Development) built a research grant to fund the implementation of new research centers in priority areas, being natural disasters and climate change two of these areas. With this grant, the Research Center for integrated Disaster Risk Management (*Centro de Investigación para la Gestión Integrada del Riesgo de Desastres*, CIGIDEN) and the Center for Climate and Resilience Research (Centro de Ciencia del Clima y la Resiliencia, $(CR)^2$) were formed by the end of 2012. CIGIDEN objective is to develop interdisciplinary knowledge about natural disasters and transfer that knowledge to the public. CIGIDEN is also focused in giving solutions and improvements in the response of the population to disasters in each one of its phases: preparation, response, recovery and mitigation. On the other hand, $(CR)^2$ focuses on improving the understanding of the earth system and developing resilience in Chile. Furthermore, in 2011 the government released a guide for natural risk analysis in land planning (SUBDERE 2011), while in 2016 the government promulgated The National Policy for Disasters Risk Management to improve the response to natural disasters caused by geological, volcanic, seismic, tsunami, and hydrometeorological hazards (Ministerio del Interior y Seguridad Pública 2016). This policy states the central framework to reduce the adverse effects caused by natural and anthropogenic disasters in Chile. It has the objective of advancing in a sustainable and safer development, by promoting territorial planning that effectively incorporates flood zones and other areas exposed to hazards, reducing poverty, adaptation to climate change, etc. This National Policy formulates a new legal framework that strengthens government institutions for disasters risk management.

Challenges in the issue of floods in Chile are multiple, and to a large extent, quite related to the main concerns elsewhere. Some of these are the following:

– Floods within the context of climate change is a big issue given the large implications in infrastructure design and urban planning. Currently there is a big need for approaches and tools dealing with non-stationarity and uncertainty. Although the international research in this field is very active, and the scientific literature is currently covering this issue (see Salas et al. 2018 for a good review), there is still a gap to fill so that the state-of-art can be transformed into applications that can be used by practitioners. Moreover, the geophysical and climatic context of Chile has to be taken into consideration so that methodologies developed elsewhere can be correctly used in Chile.
– Early warning systems for floods are not officially implemented in Chile. Currently, the early warning is driven by meteorological forecasts produced by the National Weather Agency (DMC). These forecasts are for the entire country and provide estimates of precipitation and temperatures that are used by the state to declare a general early warning, which does not focus necessarily on floods. Interestingly, more advances have been undertaken towards a national early warning system for tsunamis (Catalán et al. 2020). Recent academic efforts in early warning systems of floods based on meteorological forecast and/or in-situ monitoring (De la Fuente et al. 2019; Ibañez et al. 2020; Contreras et al. 2020) may become the scientific basis for future development in this regard.
– Non-structural measures for flood control must be largely implemented. Traditionally, flood control has been mainly a matter of grey infrastructure, very invasive and poorly integrated to the urban/social context. Alternatives or complements to this approach are available and must be incorporated within the plethora of options to deal with floods. Some of these alternatives are the variety of non-structural measures for flood protection (Kundzewicz 2002), as well as green infrastructure that can bring multiple additional benefits for the communities (Alves et al. 2018). The recently developed Chilean urban drainage manual (MOP 2013) provides a variety of alternatives and design approaches in this regard.

7.6 Conclusions

Due to its particular geographic and climatic characteristics, Chile is periodically affected by floods that in many cases have produced significant socioeconomic impacts. This chapter discussed floods in Chile and their triggering factors, and provides some of the emblematic examples of floods. Overall, floods in Chile can occur because of a variety of factors and not only due to heavy precipitation. High temperatures that raise the freezing level, as well as other triggering factors related to the geological setting, are relevant as well. Some of the current challenges in coping with floods are the formal incorporation of non-stationarity in modeling and design, the implementation of early warning systems at a national level, and the use of non-structural measures and green infrastructure in flood protection.

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Chapter 8
Droughts

Bonifacio Fernández and Jorge Gironás

Abstract Droughts are extreme hydrological events that can be observed in the lower tail of the probability distribution describing water resources at a point. As a natural random phenomenon of an accidental nature, they are complex phenomena, and their properties cannot be totally anticipated. In this chapter we review the special characteristics of drought in Chile. First, some general aspects of droughts are discussed, including drought definition and modeling. The second part is devoted to the occurrence and identification of drought in Chile, including historical droughts since the sixteenth century, with special emphasis on those occurred in the twentieth and twentyfirst centuries. Finally, some topics in relation to coping with droughts in Chile are discussed.

Keywords Drought · Definition · Modeling · Identification · Historical droughts · Coping with droughts

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8.1 General Aspects of Droughts

Drought is part of normal climate, but as a natural random phenomenon of an accidental nature, its properties cannot be totally anticipated. It is one of the natural hazards that affect the greatest amount of people and generates the largest economic losses in the world, (FAO 2002; World Bank 2003). As point out (Mishra et al. 2009), it is a large regional phenomenon of slow development whose spatial limits as well as beginning and end are hard to identify. Additionally, its non-violent impacts are silent, and its negative effects accumulate over a lengthy period of time. Hence its impacts can manifest even years after the actual drought event has concluded. Finally a drought can have different meanings for different people or social groups, (Fernández and Gironás 2017).

8.1.1 Drought Definition and Types

There is a consensus among many institutions and organizations, that management of water resources in drought situations requires a precise definition of this phenomenon, especially if responsibilities, additional resources or socio-economic assistances are to be assigned (WMO 1986, UN Secretariat 1994). Summarizing several definition of droughts, Fernández and Gironás (2017), indicates that a random water shortage to be considered as a drought should be severe if compared to the normal values, extended over a significant period of time and also extended over a large region. Nevertheless, these properties are subjective as they depend on the existing demand and the perception of the negative impacts that these water deficits cause. Overall, droughts are random temporary events of a meteorological nature, which cause a significant reduction in the availability of water as compared to the normal conditions of the region, and produce negative environmental and social effects (Yevjevich et al. 1983).

Some definitions of drought are related to the components of the hydrological cycle and their interaction with human activity, and have proven to be useful to characterize specific situations, as well as to monitor the behavior of the water resources in a region. The following four types of drought definitions are commonly used in the literature (e.g. Wilhite and Glantz 1985; American Meteorological Society 2004; Mishra and Singh 2010; Fernández and Gironás 2017): meteorological drought, hydrological drought, agricultural drought and socioeconomic drought.

8.1.2 Drought Modeling and Characterization

Drought characteristics behave like random variables whose values cannot be predicted with accuracy until the event actually occurs. Hence, the statistical study of these characteristics is very important, mainly for the planning and management of water resources. Several probabilistic and stochastic analyses can be applied to characterize different drought aspects, such as the frequency analysis, the estimation of the return period, and other spatial and temporal multivariate analyses (Mishra and Singh 2010).

Yevjevich (1967) proposed the use of theory of runs to study droughts from a statistical perspective. In order to identify and to characterize droughts, two random variables are defined: water supply (or water availability) and water demand. Then one can construct a new stochastic time series given by the difference between these series. Thus, a drought is defined as a negative run or succession of negative values of this new time series, which implies that the supply is not able to satisfy the demand. A particular drought is characterized by the duration D, the severity or magnitude of the deficit S given by the sum of the deficits, the average drought intensity $I = S/D$, and the maximum intensity I_m. Due to the random character of the series of supply and demand, all the properties previously defined are also random variables.

Applying the basic concepts of the theory of runs to identify and characterize droughts Dracup et al. (1980) indicate that a quantitative study of droughts in a certain region implies the selection of: (1) the variable representing the water supply given the type of drought under study, (2) the variable representing the water demand or level of truncation of the water supply time series that reflects the needs properly, and (3) relevant time intervals to be used in the analysis (i.e. day, month, year). Lastly, Dracup et al. (1980) are in favor of selecting a regional approach in order to consider a large area with different statistical properties of the variables representing the supply and demand in each location. Spatial properties of droughts can be studied by considering the time series previously described simultaneously in different locations. This approach allows characterizing properties such as the extension or the surface area affected by drought and its magnitude, including the total volume of deficit in the entire area during the hole drought duration.

8.2 Droughts in Chile

8.2.1 Historical Droughts

Although it is recognized that droughts in Chile are a recurrent and natural phenomenon, (Vicuña-Mackenna 1970), only a few regular written records are available since 1540. In the colonial period, due to the low demand for water in the region, given the few inhabitants and few productive tasks, harmful effects of the water shortage were noted and documented in the years 1637 to 1640, (Piwonka 1999). Later Vicuña-Mackenna (1970), highlights the great droughts of the eighteenth century that would have lasted 20 and 30 years, between 1705 and 1723, with several years of intermittent droughts, and between 1770 and 1797, which was so severe that prompted the construction of works to bring water from Maipo River to Mapocho. In the nineteenth century this same author highlights as comparable the droughts of 1832 and 1863.

Until the mid-nineteenth century the characterization of dry years is rather subjective, according to the effects that the scarcity of water has on the population and agriculture, reflected in particular in the Session Acts of the Cabildo, references in the press, invocations, processions, and prayers. Aldunce and Gonzalez (2009), collect and systematize information on disasters caused by droughts and extreme rains, and their impact on agriculture. Based mainly on the work of Bonilla (1999), Urrutia and Lanza (1993), and Toro (1971) they listed the years classified as dry between 1540 and 2000, for the central zone, and for Santiago. They emphasize that the information of some years is not exactly co-existent between these sources of information. The amount of dry years detected in each of the centuries according to this compilation is indicated in Table 8.1. Despite the significant differences in the number of droughts of the nineteenth and twentieth centuries, the total is very similar, with an amount of 75 dry years, which represent 16% of the total. This figure differs from the one reported by Bonilla (1999), which indicates that between 1540 and 1986 there would have been 51 dry years and 52 very dry years, that is, 23% of the 450 years. In any case, this indicates that until the end of the century twenty would have been considered as dry years those with a precipitation between 75% and 85% of probability of exceedance, so that there was a condition of drought every 4 to 5 years on average. In addition it is appreciated that the longest drought would have been the one that occurred between 1770 and 1782, with a succession of 13 dry or very dry years.

The large number of dry years that would have been detected in Central Chile in the twentieth century is influenced by the significant increase in water demand, as well as the better conditions for the registration and evaluation of water resources throughout the territory.

Table 8.1 Number of years considered as "dry" between 1541 and 2003 in the central zone and in Santiago

Century	Number of dry years	
	Central zone	Santiago
XVI[a]	2	0
XVII	9	6
XVIII	14	15
XIX	5	34
XX	45	24
Total	75	79

Source: own elaboration according to the data from Aldunce and González (2009)

[a]Only since the foundation of Santiago in1541

8.2.2 *Droughts in the Twentieth Century*

At the end of the twentieth century numerous studies were carried out to identify and quantitatively characterize droughts in the central zone of Chile with statistical tools (Fernández 1991), applied to meteorological droughts, (Fernández and Velasquez 1987), hydrological droughts, (Fernández et al. 1990a, b; Fernández 1997), and agricultural droughts, Fernández et al. 1988a, b. Studies are also carried out to calculate the probabilities of occurrence of historical droughts, in order to estimate the return period of observed meteorological droughts, hydrological droughts, and periods of scarcity in arid regions, (Fernández and Vergara 1998; Fernández and Salas 1999a, b, 2001).

Using the basic concept of the run theory Fernández and Velasquez (1987) studied the behavior of meteorological droughts in the central zone of Chile, in a three-dimension system: time (t), space (x), and demand minus supply, or deficit (Z). It was applied to the so-called Central Zone of Chile, from the north of the IV Región of Coquimbo, up to the south of the X Región of Los Lagos, with 1290 km long. This zone was divided in 43 sectors, each considering the total widespread of Chile, and 30 km north to south. The annual precipitation on these areas was estimated based on available data of precipitation gauging stations. The demand was considered as the mean areal annual precipitation with different level of exceedance. Then droughts were detected as the zone and years were estimated precipitation is less than that with a known exceedance probability. 70 years were included, from 1915 up to 1984. The properties of the drought detected are in Table 8.2.

Hydrological droughts were detected and characterized using a similar procedure, applied to 26 basins from Elqui, north of the IV Región of Coquimbo, to Chapo, Souh of X Región of Los Lagos with an extension of 1330 km. All of them are controlled by stream flow gauging station and represent natural behavior, before the occurrence of regulation and important uses. The water supply was represented by observed monthly values of streamflow in each basin from 1940 to 1984. Water demands correspond to monthly streamflow values with a given exceedance probability. Note that water supply and demand in this case are periodic. Each drought was considered as a set of values of deficit affecting contiguous basins during an interrupted period of time. The number of hydrological droughts detected in these

Table 8.2 Properties of meteorological droughts detected in the central zone of Chile in the period 1915 to 1984 for different levels of demand. (Source: Fernández and Velasquez 1987)

	Mean values		Critical drought	
Demand level	Duration, years	Extension, km	Duration, years	Extension, km
0.95	1.17	160	2.0	1110
0.90	1.21	167	3.0	1110
0.85	1.38	195	3.5	1200
0.75	1.43	205	4.0	1290
0.65	1.89	321	4.0	1290
0.50	3.34	513	4.0	1290

Table 8.3 Number of hydrological droughts detected in the central zone of Chile in the period 1940–1984, and the duration and extension of the critical drought

Demand level	Mean values		Critical drought	
	Duration, months	Extension, km	Duration, months	Extension, km
0.95	1.6	82.6	22	957
0.90	1.9	99.4	24	1137
0.80	2.3	116.4	61	1330
0.70	2.8	143.2	62	1330
0.60	3.2	168.7	67	1330
0.50	3.7	179.3	71	1330

Source: Fernández et al. (1990a)

basins during the period 1940–1984, and the duration and extension of the critical drought are in Table 8.3. Critical drought is defined as the longest and larger drought in the period.

It is observed that the critical droughts for exceedance probability of 80% or less affect all the basins considered, reflecting the high spatial dependence of the water resources in the zone.

A comparison of the meteorological and hydrological drought was performed using the same basins, (Fernández 1991; Fernández et al. 1990b). In this case for meteorological droughts water supply was estimated as a monthly time series of mean areal precipitation on each basin, and for hydrological drought water supply was estimated as a monthly time series of streamflow expressed as effective monthly precipitation. Meteorological droughts on the area of a basin produce a consequent hydrological drought although of different properties. A comparison of the mean values of the properties of meteorological an hydrological droughts it is clear that for a similar level of demand the hydrological droughts are longer, but less intense and extend. That means the meteorological phenomena is of great spatial coverture, but concentrated in time, and intense. Conversely the hydrological phenomena is not such intense, but it influences during a longer time on the same basin.

A more general idea of the behavior of droughts in the central zone of Chile during the second half of the XXth century, 1950–1995, was developed to estimate the social and economic impact of droughts in this zone, (DGA 1997; Fernández 1997). The water supply was estimated as a time series of the total water resources available in each one of 48 basins and sub basins between the Copiapó river in the north, and the Biobio river in the south. A graphic representation of the drought conditions in the space (horizontal axes), and time (vertical axes) plane in the 48 areas during the years 1950 at 1994 like, is illustrated in the Fig. 8.1.

During this period the drought that started in 1968 in the hole central zone and continued up to the 1971 year was the most important one. During the last part of the twentieth century it was used as an extreme condition of water resources scarcity in the management of the water resources in the central zone of Chile. Note that this drought was most relevant in the central-north part of the zone. The second most important is that of 1988–1990, and this was more relevant in the southern part

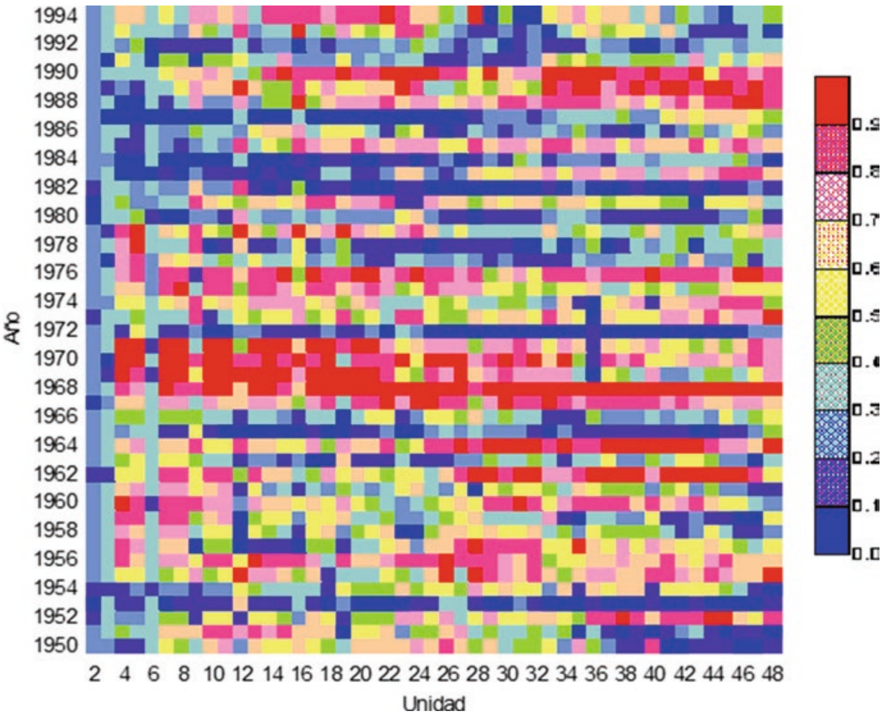

Fig. 8.1 Space time representation of water resources availability in 48 sub basins of the central zone, from Elqui to Biobio, in the period 1950–1994. The 1968–1971 drought and the 1988–1990 drought can be observed. (Source: Fernández 1997)

of the zone. Since in the northern part of this zone activities related to agriculture are more important, and in the southern to hydroelectricity, the impacts of each one of these droughts are very different. The economic impacts of droughts in this zone during this period were estimated using this information about the behavior of water resources. The mean annual losses due to water scarcity was estimated as USD$491 millions, principally in the agriculture sector with USD$435millions. The increasing cost for electricity production depends on the available water in the Laja lake. For an average level the increase in cost due to a severe drought was estimated as USD$1806. In this period the worst situation was that of the so called 68 drought, affecting the hole zone from 1967 to 1969. The drought impacts a total of 6 millions of hectares, affecting the job of almost 500.000 persons, and a total estimated cost of almost USD$1000 millions, (Nuñez Cobo et al. 2018; UNESCO 2012).

8.2.3 Droughts in the Beginning of the Twenty-first Century

In 2012 the DGA adopted the Standard Precipitation Index, SPI (McKee et al. 1993) and the Standard Runoff Index, SRI (Shukla and Wood 2008) as suitable indices for drought monitoring and identification of meteorological and hydrological drought, respectively. The SPI is calculated using monthly rainfall records for each administrative area of the country (regions, provinces and/or municipalities), with the objective of identifying the spatial coverage or extension of meteorological drought. On the other hand, the SRI is calculated using monthly streamflow records for the corresponding river basin, in order to identify water shortage in them. They were considered temporal scales of 1, 3, 6, and 12 months to build and analyze the time series for all the rain and streamflow gauges in the database, which allowed characterizing short- and long-term drought events (DGA 2009; Fernández and Gironás 2015).

In this case the information to calculate the SPI and the SRI corresponds to complete homogeneous series of monthly rainfall and streamflow data respectively, of at least 30 years long (Wu et al. 2001, 2007), which were then fitted to a two-parameter Gamma distribution as recommended by McKee et al. (1993). Finally, a classification of the severity of drought events based on relatively large ranges of value for the SPI or SRI for drought events in Chile, which allows their identification and tracking, as in Table 8.4.

Broadly speaking, under the classification proposed, 6 out of 10 years would be normal, 2 are dry and 2 are wet, whereas dry, very dry or extremely dry years would have a return period of 5 years.

The SPI for 6 months was used to identify meteorological droughts in every place of the country, independently of the climate classification. In Fig. 8.2 SPI 6 months time series is used to identify droughts in Copiapó, an arid region, and in Puerto Montt, a very humid zone.

In the arid zone, Copiapó, were the mean annual precipitation is about 30 mm, several droughts are detected, but all of them are classified as "dry". But in the very humid zone, with a mean annual precipitation of about 2000 mm, such as Puerto Montt, four droughts in the period 1979–2009 are considered "Extremely Dry", beside several "dry" and "very dry" events.

Table 8.4 Classification of drought events for values of SPI or ICE and its cumulative probability used by DGA in Chile since 2012

Ranges SPI or SRI	Probability of occurrence	Classification used by DGA (2009)
< −2.05	0.02	Extremely dry
−2.05 to −1.28	0.08	Very dry
−1.28 to −0.84	0.10	Dry
−0.84 to 0.84	0.60	Normal
0.84 to 1.28	0.10	Wet
1.28 to 2.05	0.08	Very wet
> 2.05	0.02	Extremely wet

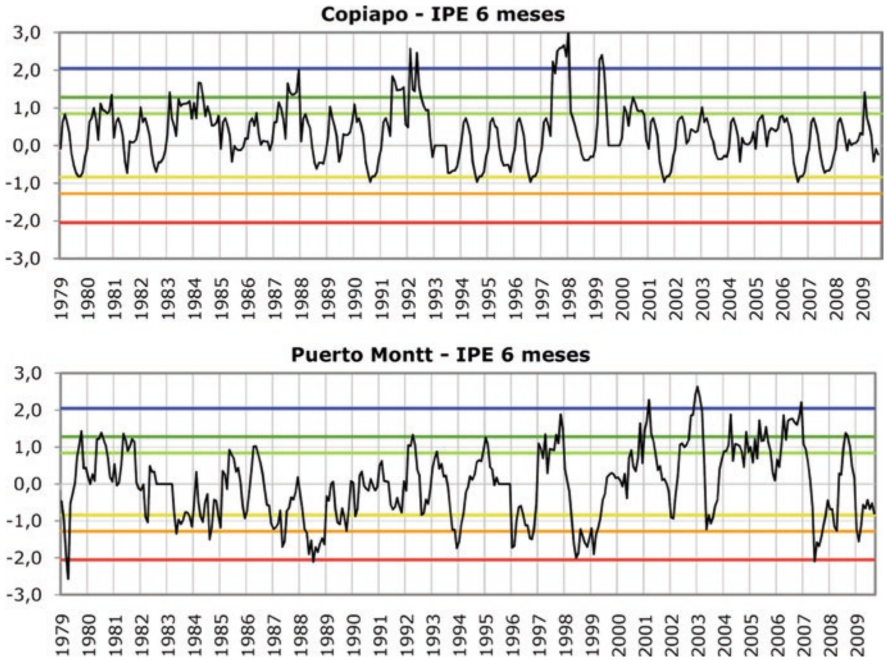

Fig. 8.2 SPI (IPE in Spanish) of 6 months accumulation values for the period 1979–2009 in Copiapó and Puerto Montt. (Source: DGA 2009)

Similarly, the SRI for 6 months was used to identify hydrological droughts in every basin of the country, independently of the climate classification. In Fig. 8.3 SRI 6 months is used to identify droughts in the Copiapó river at La Puerta, an arid region, and in the Bio Bio river at Rucalhue, a humid basin.

In the Copiapó river there are only three periods of hydrological droughts, all of them considered as "Very Dry". It can be observed that these droughts period arrive following several years of consecutive "dry" periods of meteorological droughts. In the Bio Bio river at Rucalhue, one of the larger rivers in the humid zone of the central south of Chile, it was detected three "extremely dry" droughts, and several "very dry" and "dry" droughts. The "extremely dry" droughts follow a similar "Extremely dry" meteorological droughts.

In order to have a general idea of the behavior of droughts in the central zone of Chile, from Copiapó to Puerto Montt, during the 1979 to 2009 period, a two-dimension graphs are presented (DGA 2009), with time, in months, in the horizontal axis, and space, or basins, in the vertical axis, form north in the upper side to south in the bottom. Each pixel has a color depending of the classification of the months in the place according to the value of the SPI for meteorological droughts, Fig. 8.4, and the SRI value for the hydrological droughts, Fig. 8.5. A clear pixel

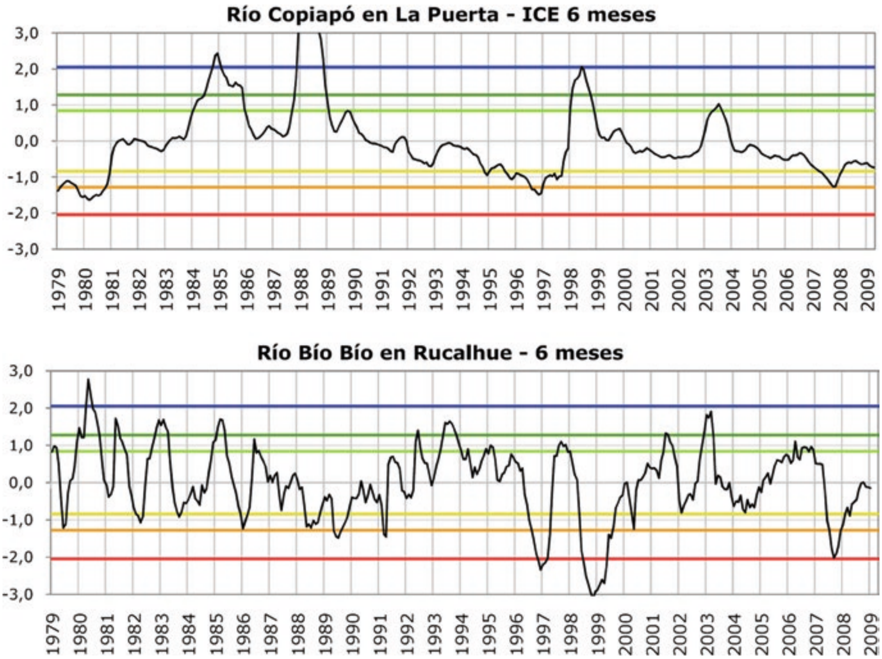

Fig. 8.3 SRI (ICE in Spanish) for 6 months accumulation values for the period 1979–2009 in Copiapó river at La Puerta and in Bio Bio river at Rucalhue. (Source: DGA 2009)

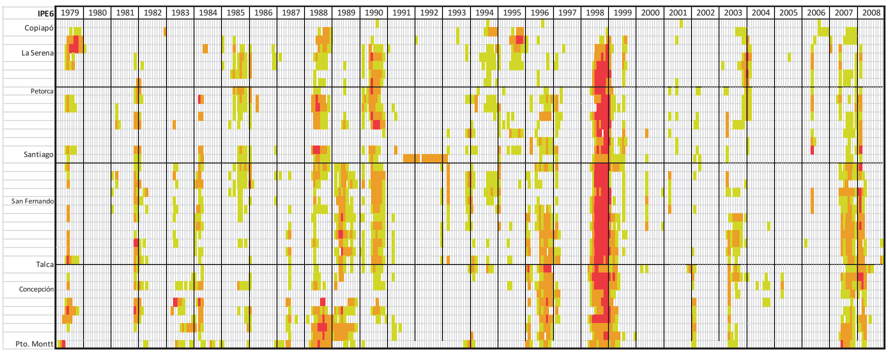

Fig. 8.4 Values of SPI of 6 months for meteorological droughts in the period 1979–2009 in the zone from Copiapó to Puerto Montt

indicates a normal or humid situation. Yellow corresponds to a “dry” drought, orange a “Very dry” and red to a “Extremely dry” situation.

It can be observed that the meteorological droughts are more numerous than the hydrological ones. Both, in general, cover the whole territory, but the meteorological ones are shorter, of lesser duration and usually more intense.

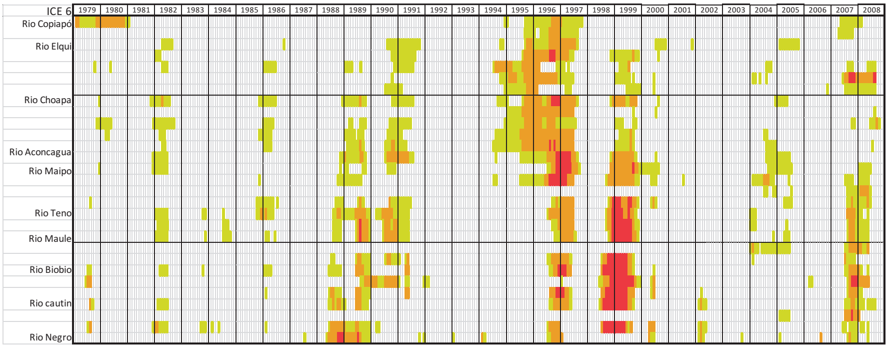

Fig. 8.5 Values of SRI of 6 months for hydrological droughts in the period 1979–2009 in the zone from the Copiapó river basin to Chapo Lake river basin, near to Puerto Montt

In this period, 1979–2009, the most important drought event, due to its intensity, severity and duration is the 1998'drought, which includes the years 1994, 1995, 1996 and 1998, with an interruption of a very wet year in 1997 (Nuñez Cobo et al. 2018). The 1998 year was classified as the third most dry of the twentieth century (Aldunce and González 2009). SNA, 1998, recognized that at least the production of 602,000 hectares were affected in 1998, and the losses of the agronomic sector was estimated in US $250 millions in the period between 1994 y 1997.

More recently the (2010–2015) multi-year, regional-scale dry event has been referred to as the Central Chile megadrought (Garreaud et al. 2015). A preliminary survey conducted by the CR2 group, Garreaud et al. (2017), found significant impacts of this long drought in surface hydrology, groundwater, sediment exportation into the ocean, vegetation and fire activity along Central Chile and they show also that such multi-year drought is already unprecedented in the historical record and quite unusual in the last millennium. In this context, it is the opinion of the CR2 group, (CR2 2015), that the long and spatially extensive meteorological drought occurring offers an analog of the region's future from which key lessons can be learned, since, this situation seems to differ from the intense but short-lived droughts that characterize Central Chile's climate and may lead to environmental effects that haven't been observed before. This drought has continued to affect practically the entire territory, as can be seen in the analysis carried out by DMC, 2019, whose climate report of the year 2018 shows the behavior of the SPI throughout Chile from 1961 to 2018, as illustrated in Fig. 8.6. It can be appreciate the mega drought (until now 2007–2018), which although it has not been as intense as those registered in the twentieth century, it does accumulate a significant number of years with below normal rainfall, and without wet years in between.

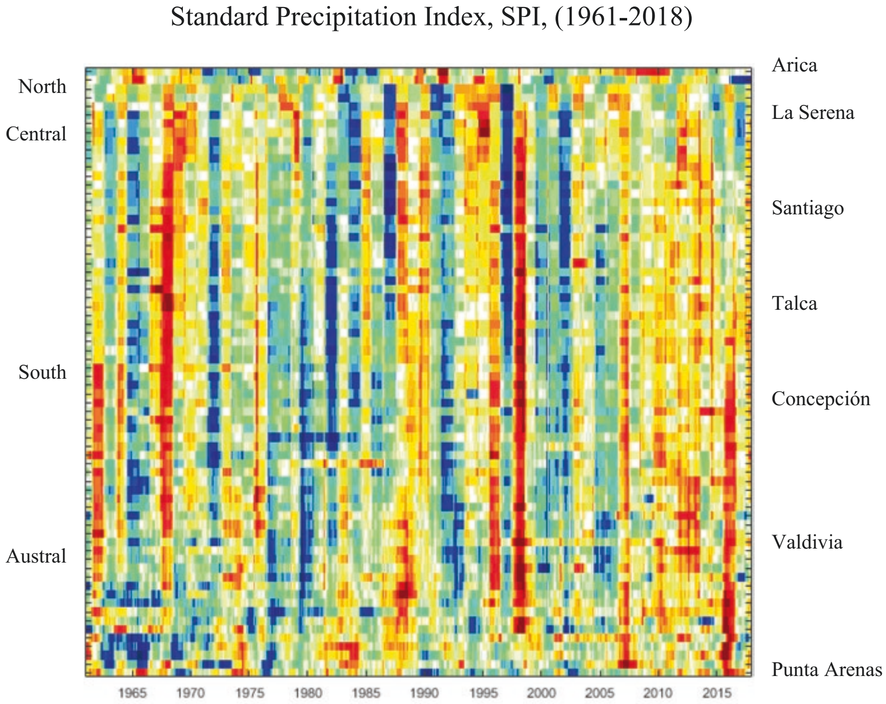

Fig. 8.6 Values of SPI for meteorological droughts in the period 1961–2018 in Chile from Arica, in the North, to Punta Arenas, in the South. (Source: Reproduced from DMC 2019)

8.3 Coping with Droughts in Chile

Drought must be integrally and actively considered in water planning and management (Wilhite and Buchanan-Smith 2005). Hence, drought characterization becomes fundamental in water management as it allows incorporating the temporal and spatial dynamics of water supply and water demand aspects of their shortage over the society, economics and environment.

Nuñez Cobo et al. (2018), note the fragmented and disjointed nature of the legal framework in Chile for the management of water resources in general and in particular in conditions of scarcity. This is due to the fact that the attributions, instruments and capacities are distributed among various public entities and institutions. In the case of drought risk management, the response capacities fall in four state departments. Interior and Public Safety in relation to disaster management through the ONEMI (National Office of Emergencies of the Department of the Interior); Public Works through the DGA (National Water Agency) attributes; Agriculture and its support services to agriculture; and Energy for the effects of electrical rationing. In addition to these there is a significant number of actors, programs and initiatives to respond to a scarcity condition, with different capacities and areas of institutional and regional action, which have been systematized by Aldunce et al. (2015, 2016).

Water resources management in Chile is regulated by the Water Code of 1981, which indicates the role of public institutions when coping with drought during periods of scarcity. A great challenge of this centralized management of water resources is to consider the variety of climates that occur in an area covering more than 4000 km from North to South. From east to west, due the altitude differences include coastal areas, valleys and Mediterranean mountain watersheds. Besides that, from the administrative point of view Chile is divided into 17 regions, 53 provinces and 346 municipalities of different sizes. The limits of these administrative units do not necessarily coincide with the watersheds' boundaries, though a basin is rarely located in more than one region.

The Water Code gives the National Water Agency (National Water Agency, DGA), the power to use technical criteria to identify and declare extraordinary drought conditions, prior to any other further management decision related to water resources management. In 2012 the DGA, through Resolution 1674 (DGA 2012), adopted the SPI (McKee et al. 1993) and the SRI (Shukla and Wood 2008) as suitable indices for drought monitoring and identification of meteorological and hydrological drought, respectively, using a value of these indices lower than −0,84 to declare extraordinary drought in a zone. For groundwater resources, used by Urban Sanitary Services and Rural Potable Water (APR), in general adopted the criteria to declare Extraordinary Drought condition when the capacity of extractions is below the 50% of the water rights assigned. Follow the Resolution all these criteria should be reviewed every ten years. At this time, 2020, DGA is working in the review of this Resolution and to improve an Drought Observatory, in order to include information to the stakeholders and users of water, following and anticipate drought conditions in real time in the whole national territory, including meteorological and hydrological forecasting.

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Chapter 9
Catchment-Scale Natural Water Balance in Chile

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Abstract Characterizing the temporal evolution of water storages and fluxes over large domains can not only help to improve understanding on the interplay between physical controls, climate and hydrological behavior, but also to inform water management decisions. In this chapter, a historical context, the methodology and catchment-scale results for ongoing efforts to characterize the natural water balance in Chile are provided. To this end, the Variable Infiltration Capacity (VIC) hydrological model is run using gridded meteorological forcings estimated from in-situ observations and reanalysis data. Details on the criteria for selecting near-natural catchments, the collection and generation of datasets, and hydrological model descriptions are provided. The main insights on the annual and seasonal water balances across the study domain and perspectives for future work are discussed.

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Keywords Water balance · Catchment · Infiltration · VIC · Gridded data · Meteorology · Runoff

9.1 Introduction

The natural availability of water resources at the catchment scale depends on complex interactions of water and energy fluxes and storages at a range of spatiotemporal scales. Given the growing water demands from different sectors – associated to increased global population – and changing climatic conditions due to natural variability and anthropogenic forcings (e.g., Milly et al. 2005, 2008; Huntington 2006; IPCC 2013), there is an imperative need for accurate water balance estimations to inform management decisions.

A key challenge for such estimates is the scarcity of ground measurements (including hydro-meteorological variables, physical properties and water-use) to represent natural systems. This is a critical issue in Chile, where topography is complex, and both economy and population are highly-centralized (40% of the latter is spanned over 2% of the country's area). Given the lack of an adequate observational network, modeling techniques are required to estimate water balance components across the complete domain (Müller Schmied et al. 2016), a task challenged by many sources of uncertainty.

9.1.1 Modeling the Water Balance at the Catchment Scale

The urgency to quantify natural water resources has motivated water balance studies worldwide, spanning from the regional to the global scale. While some efforts have focused on the partitioning of annual precipitation into runoff and evapotranspiration (e.g., Sankarasubramanian and Vogel 2002; Carmona et al. 2014; Mizukami et al. 2016), others have aimed to provide seasonal characterizations (e.g., Vandewiele and Elias 1995; Martinez and Gupta 2010; Berghuijs et al. 2014), or even daily (e.g., Parajka et al. 2007; Tian et al. 2017) water balance estimates. A common path forward is the use of large samples of catchments to learn from diversity (e.g., Sivapalan 2018), practice referred to as large-sample hydrology (Andréassian et al. 2006; Gupta et al. 2014). In particular, large-sample hydrology can help to understand the interplay between physical similarity (e.g., topographic descriptors, land cover characteristics), climatic similarity, and hydrologic similarity, with the aim to develop techniques to address the problem of prediction in ungagged basins (PUB; see review by Hrachowitz et al. 2013).

Although many authors have stressed the need to understand, quantify and reduce hydrologic uncertainty in a changing world (Addor et al. 2014; Mendoza et al. 2016; Clark et al. 2016), improving process understanding under current climatic conditions is a critical first step (e.g., Blöschl and Montanari 2010). Over the past decades, many water balance studies have benefited from advances in process-based hydrological models (e.g., Wigmosta et al. 1994; Chen et al. 1996; Liang et al. 1996; Pomeroy et al. 2007; Oleson et al. 2010; Niu et al. 2011; Clark et al. 2015). Likewise, the need for more realistic hydrological simulations has pushed towards more emphasis on process-based model evaluation (e.g., Gupta et al. 2008, 2009; Martinez and Gupta 2010; Tian et al. 2012; Coron et al. 2014), which is enriched as new observational technologies arise (e.g., Kinar and Pomeroy 2015; McCabe et al. 2017). Further, the community has seen major advances in parameter estimation methods through novel algorithms (e.g., Kavetski et al. 2006; Gharari et al. 2013) and improved objective criteria formulations (e.g., Shafii and Tolson 2015; Beck et al. 2016; Fowler et al. 2018).

9.1.2 Previous Water Balance Characterizations in Chile

The first attempt to estimate annual water balances in South America was led by UNESCO (1982), which proposed a general equation to relate changes in storage (ΔS), precipitation (P), incoming surface runoff (Q_{si}), incoming groundwater fluxes (Q_{gi}), evaporation from water bodies (E), actual evapotranspiration (ET), outgoing surface runoff (Q_{so}), and outgoing groundwater fluxes (Q_{go}) at annual time steps:

$$\Delta S = P + Q_{si} + Q_{gi} - E - ET - Q_{so} - Q_{go} + \eta \tag{9.1}$$

In Eq. (9.1), all terms are expressed in [$L^3\ T^{-1}$], and η represents the estimation error. UNESCO (1982) also recommended to simplify Eq. (9.1) for large areas and very long time periods:

$$\bar{P} - \bar{Q} = \overline{\langle ET \rangle} + \eta \tag{9.2}$$

where $\langle \cdot \rangle$ represents a spatial average, the horizontal bar represents average over time, Q represents the net runoff leaving the basin, and ET stands for all evapotranspiration losses. The proposed approach motivated subsequent applications of Eq. (9.1) over large basins in Central and Southern Chile, neglecting interannual variations in water storage and groundwater runoff (Chilean Water Directorate – DGA 1983a, b, 1984a, 1985). In these studies, unknown fluxes were computed by successive iterations to minimize the error term η, and the results were processed to provide various types of products (e.g., mean annual isohyet and isotherm maps, mean annual ET and annual runoff maps). DGA (1984b) incorporated – for the first time – endorheic basins in water balance estimations across Northern Chile.

These and other studies helped to set a general framework for the current official water balance database, valid for a 30-year period (1951–1980) in continental Chile (DGA 1987). The results presented therein were obtained through Eq. (9.2), setting Q = 0 for endorheic basins, estimating ET with Turc's formula, allowing interannual variations in storage ($\Delta S \neq 0$) for arid domains, and a maximum closure error $\eta_{max} = 0.1Q$. The official water balance database has been intensively used as a reference to assess water availability in a myriad of technical applications, including water allocations (See Chaps. 8 and 18).

9.1.3 Aims and Scope of this Chapter

In order to improve and update the official national water balance, DGA (2017) revisited the problem, proposing the use of new datasets and physically-motivated models to improve process understanding. This chapter summarizes the main results from the first three stages of this initiative, whose main goals are: (i) to propose a methodology for updating the national water balance (DGA 2017), (ii) to apply the proposed approach in catchments located in Northern and Central Chile (DGA 2018), and (iii) to apply the proposed approach in catchments located in southern and Austral regions (DGA 2019). The water balance results presented here build upon two key elements:

- A gridded meteorological dataset based on in-situ observations and reanalysis data.
- The calibration and validation of the Variable Infiltration Capacity (VIC) macro-scale hydrological model (Wood et al. 1992; Liang et al. 1994) in naturalized catchments across continental Chile.

The following sections describe the proposed modeling framework, the criteria for selecting near-natural catchments, the collection and generation of datasets, and hydrological model descriptions. Then, the results, discussion and perspectives for future work are presented.

9.2 Approach

9.2.1 Study Domain and Basin Selection

A set of near-natural catchments from the CAMELS-CL dataset (Alvarez-Garreton et al. 2018) was used. In CAMELS-CL, the location of DGA streamflow gauges is used to delineate catchment polygons, generate basin-scale time series of hydro-meteorological variables, and produce a suite of catchment attributes (topographic, geologic, land cover, climatic, hydrologic and human intervention indices). The main difference between the catchment polygons used here and the BNA catchment boundaries – described in Chap. 8 – (DGA-CIREN 2014) is that the latter do not necessarily match the location of streamflow gauges, and thus cannot be directly used for calibration and validation in hydrologic modelling.

The criterion for selecting near-natural catchments was based on the allocation of water rights. Hence, a maximum threshold value of 5% was adopted for the ratio of annual water volume allocated as permanent consumptive rights to mean annual streamflow (Table 3 in Alvarez-Garreton et al. 2018). In addition, catchments containing large dams were filtered out. From this process, 100 near-natural basins between 18 °S and 55 °S were selected, most of which are located in central and southern Chile. Notwithstanding this, the selected basins feature a wide range of attributes, including areas spanning 17–27,000 km^2, mean elevations ranging 120–4700 m a.m.s.l., mean slopes varying from 50 to 300 m km^{-1}, and markedly different land cover types (e.g., from completely covered by native forests to completely covered by impervious land). These basin characteristics contain valuable information that can be used for land surface characterization and process representations.

9.2.2 Forcing and Streamflow Data

Characterizing the hydroclimatology of continental Chile is difficult due to many factors, including the diversity and complexity of landscapes across the territory, the major influence of the Andes on spatial precipitation patterns, and the lack of high-altitude ground observations (e.g., Mendoza et al. 2012; Cornwell et al. 2016). Since coherent and homogeneous forcing variables are required for water balance estimates, DGA (2017) introduced the new meteorological dataset CR2MET as part of the national water balance updating project. CR2MET has a 0.05° × 0.05° horizontal resolution and a 3-hour temporal resolution over continental Chile, providing time series of precipitation and daily maximum, mean and minimum temperature for the period 1979–2016. The precipitation product builds upon a statistical downscaling technique that uses topographic descriptors and large-scale variables – such as water vapor fluxes and moisture fluxes – from ERA-Interim (Dee et al. 2011) and ERA5 (Copernicus Climate Change Service (C3S) 2017) as predictors, and daily precipitation records (from stations) as the predictand. A similar approach is used to generate daily maximum and minimum temperature time series, including additional predictors from MODIS land-surface products that provide a better characterization of spatial heterogeneities (e.g., different land cover types). Finally, 3-hourly precipitation and temperature datasets are post-processed from daily-products by adjusting the sub-daily distribution provided by ERA-Interim.

Additional meteorological variables, such as relative humidity and wind speed, were obtained at the CR2MET spatial resolution by interpolating a blend between the ERA-Interim (Dee et al. 2011) and ERA5 (C3S 2017) reanalysis datasets. It should be noted that such blend of products was created since ERA5 was not available for the entire study period (1985–2015) at the moment of data acquisition (early 2018, where only 2010–2016 data were available). However, the updated reanalysis information – despite the short temporal coverage – was included due to several improvements on its development.

Streamflow data were acquired from flow gauges maintained by the DGA – available from the CR2 Climate Explorer (http://explorador.cr2.cl/) – which span varying degrees of data quality and record length. A continuous 4-year record period within 1990–2010 was required from each station to be considered for hydrologic model calibration. If this condition was not met firsthand, we looked into the sub-periods 1985–1990 and 2010–2015. Once the minimum record length requirement was met, all the information available was used in the calibration process. Figure 9.1

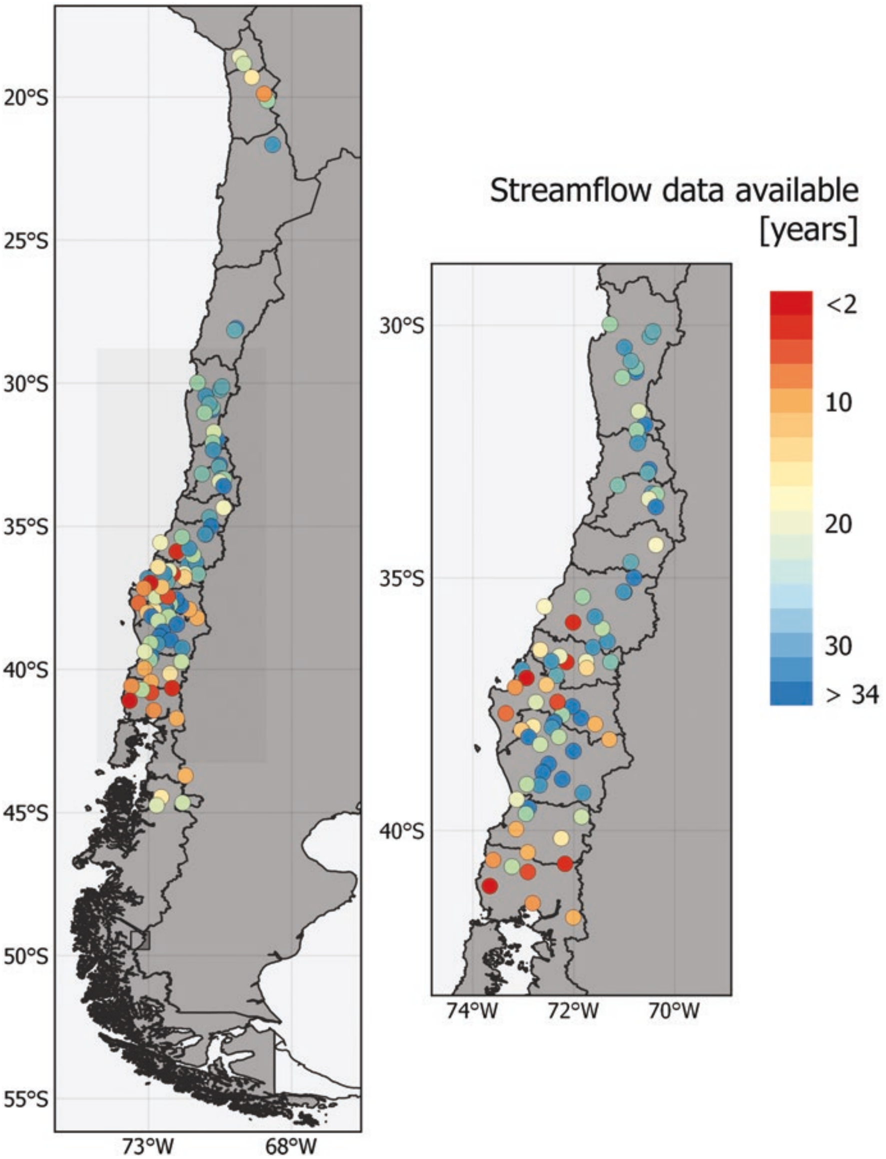

Fig. 9.1 Location of streamflow stations and data availability for selected 'near-natural' basins

shows the location of the stations that met such requirement and the number of water years with available data. It is noteworthy that most of the stations are located between 30°S and 45°S, where most of the population lives and economic activities take place. A few streamflow gauges are located northern than 30°S due to the small number of prevailing water courses in a domain with dry climatic conditions (as shown in Chap. 2).

Table 9.1 List of VIC parameters calibrated

N°	Parameter	Description
1	infilt	Variable infiltration curve parameter (binfilt)
2	D_s	Fraction of Ds_{max} where non-linear baseflow begins
3	Ds_{max}	Maximum velocity (mm day^{-1}) of baseflow
4	W_s	Fraction of maximum soil moisture where non-linear baseflow occurs
5	C	Exponent used in baseflow curve
6	$depth_1$	Thickness (m) of each soil moisture layer
7	$depth_2$	
8	$depth_3$	
9	K_{sat}	Saturated hydrologic conductivity (mm day^{-1})
10	New_{alb}	Fresh snow albedo
11	Alb_{acum_a}	Snow albedo curve parameter
12	Alb_{thaw_a}	Snow albedo curve parameter
13	T_{rain}	Minimum temperature (°C) for rainfall occurrence
14	r_{snow}	Snow surface roughness (m)

9.2.3 Hydrological Modeling

The Variable Infiltration Capacity model (VIC, Liang et al. 1994), a physically-motivated, distributed hydrological model that resolves mass and energy balances, was configured for this study. In VIC, each grid cell can have up to three soil layers and multiple land cover types. Two soil layers represent the interaction between moisture and vegetation, and the bottom soil layer is used to simulate baseflow processes. Snowpack dynamics are simulated by a two-layer mass and energy balance model (Cherkauer and Lettenmaier 2003; Andreadis et al. 2009), where the surface layer solves the energy balance between the snowpack and the atmosphere, and the lower layer stores the excess snow mass from the thin upper surface layer.

The updated water balance considers the standard three-layer soil implementation, with up to nine different land cover classes, a 0.05° × 0.05° horizontal resolution, and 3-hour simulation time steps. The calibration process involves 14 parameters (Table 9.1) using the Shuffled Complex Evolution (SCE-UA; Duan et al. 1993) algorithm, and a 3-year warm-up period before computing performance metrics. The Kling-Gupta efficiency (KGE) criterion (Gupta et al. 2009) evaluated over daily streamflow time series was used as objective function:

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \tag{9.3}$$

Where r is the linear correlation coefficient between simulated and observed flows, β is the ratio of the mean of simulated flows, μ_s, to the mean of observed flow, μ_o, and γ is the ratio of the standard deviation of simulated flows, σ_s, to the standard deviation of observed flows, σ_o. Streamflow simulations were also assessed through the Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe 1970). Finally, modeled fractional snow-covered area (fSCA) and snow water equivalent (SWE) were contrasted against MODIS fSCA and SWE from the Cortés and Margulis (2017) dataset to identify biases in mountainous precipitation, threshold snow and rain temperature, and snow surface roughness (T_{rain} and r_{snow} in Table 9.1, respectively).

9.3 Water Balance Results

9.3.1 Assessment of CR2MET Products

Figure 9.2 depicts observed and modeled (i.e., CR2MET) climatological mean annual values for precipitation and maximum temperature for the period 1979–2016. Both estimations and observations follow similar spatial distributions. The zoom-in panels for each variable illustrate the level of detail achieved in CR2MET products due to the use of 5-km topographic information. Further, the orographic effect of the Andes Cordillera plays a fundamental role in Northern and Central Chile (Fig. 9.3), with the smallest precipitation amounts near the coast. The opposite spatial pattern is observed in the Southern region (bottom panel in Fig. 9.3), where larger precipitation amounts are observed near the coastline due to prevailing westerly winds (Garreaud 2009).

A leave-one-out cross-validation procedure was conducted to assess the quality of CR2MET products. Figure 9.4 compares the seasonal behavior of observed and

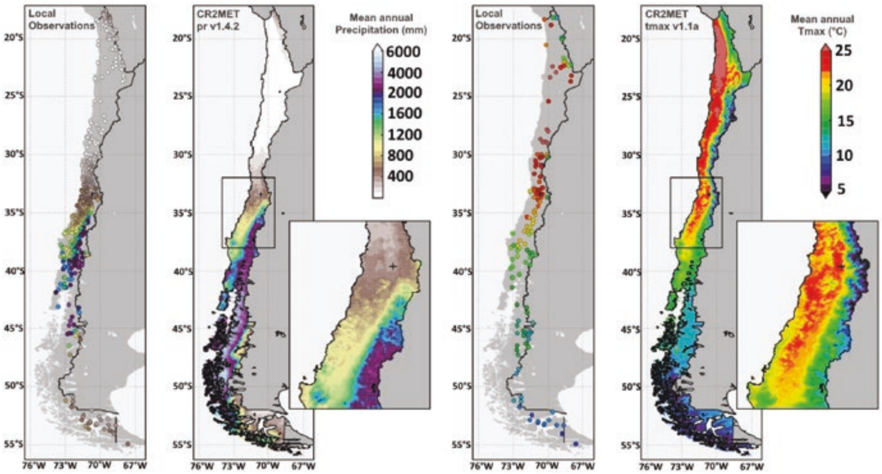

Fig. 9.2 Climatological mean values (1979–2016) for (left) annual precipitation and (right) annual maximum daily temperature. Maps with points show observed values in measuring stations, whereas maps with continuous coloring show the CR2MET estimated values for the same period

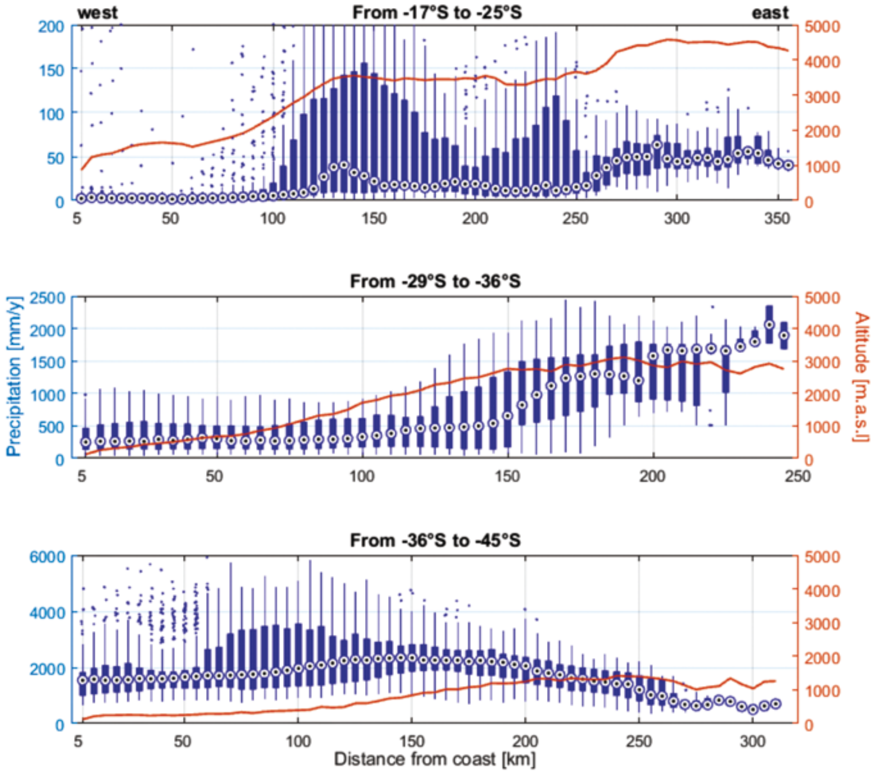

Fig. 9.3 Mean annual precipitation versus distance from the coastline for grid cells located at three different latitudinal regions (blue boxplots). Each boxplot shows the median as white circles inside the box, the interquartile range (difference between the 25th and 75th percentiles) as the length of the box, and outliers as blue dots. The red line represents terrain elevation (secondary axis)

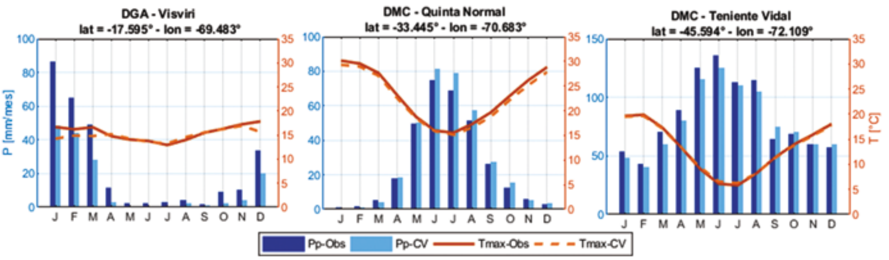

Fig. 9.4 Comparison between observations (Obs) and cross-validated estimations (CV) for mean monthly precipitation (P) and maximum temperature (Tmax) at three sites: (left) Visviri, (center) Quinta Normal, and (c) Teniente Vidal

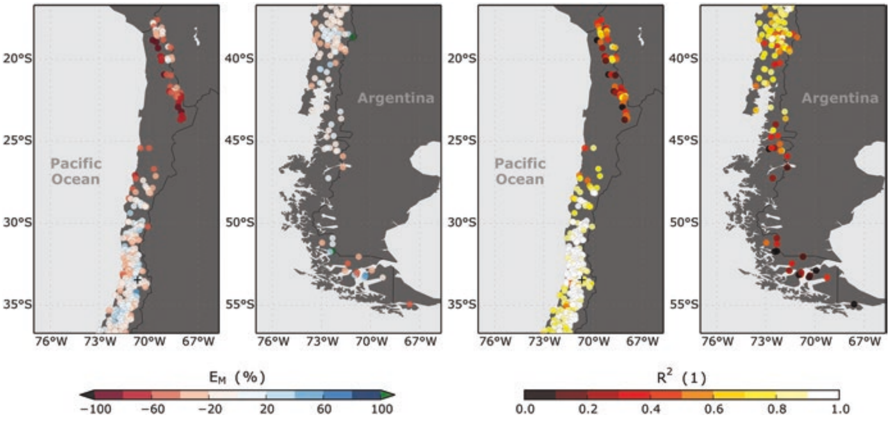

Fig. 9.5 Cross-validation performance metrics for daily precipitation estimates (1979–2015). (Left) Percent bias (E_M), and (right) coefficient of determination (R^2)

estimated monthly precipitation and maximum temperature at three stations located in the Altiplano (DGA-Visviri), Central Chile (DMC-Quinta Normal) and the Patagonian area (DMC-Teniente Vidal). These stations are good examples of the diverse climatic conditions within the study area, including summer Altiplano monsoons (Visviri), Mediterranean climate (Quinta Normal), and Oceanic climate (Teniente Vidal). Overall, seasonal cycles are well reproduced, although both climatic variables in Northern stations remain the hardest to accurately estimate.

Figure 9.5 shows the spatial distribution of two metrics – percent bias and coefficient of determination (R^2) – for cross-validated daily precipitation estimates (1979–2015). Overall, larger biases and lower R^2 values are estimated at the northernmost stations (Altiplanic region). Because of the low annual precipitations (Fig. 9.2), estimates of this variable across northern stations can yield relatively large biases. Similarly, low performance metrics are obtained for the far south region, where values of $R^2 < 0.2$ are observed. Inter-region differences in the accuracy of CR2MET estimates can be partly attributed to the heterogeneous distribution of meteorological stations across the country, i.e., the scant number of stations at the Altiplano and Patagonia regions impairs the development of robust regression equations. Conversely, higher R^2 values are obtained in Central Chile, since excluding one station barely affects the model training process.

9.3.2 Individual Basin Calibration

Figure 9.6 displays model calibration results across the study domain. Although a relatively homogeneous spatial distribution of daily KGE is achieved (upper left panel in Fig. 9.6), considerable differences in NSE are observed between Northern and Central-Southern catchments (upper right panel in Fig. 9.6). In the latter group, a better model performance is obtained because snow processes – a dominant control in

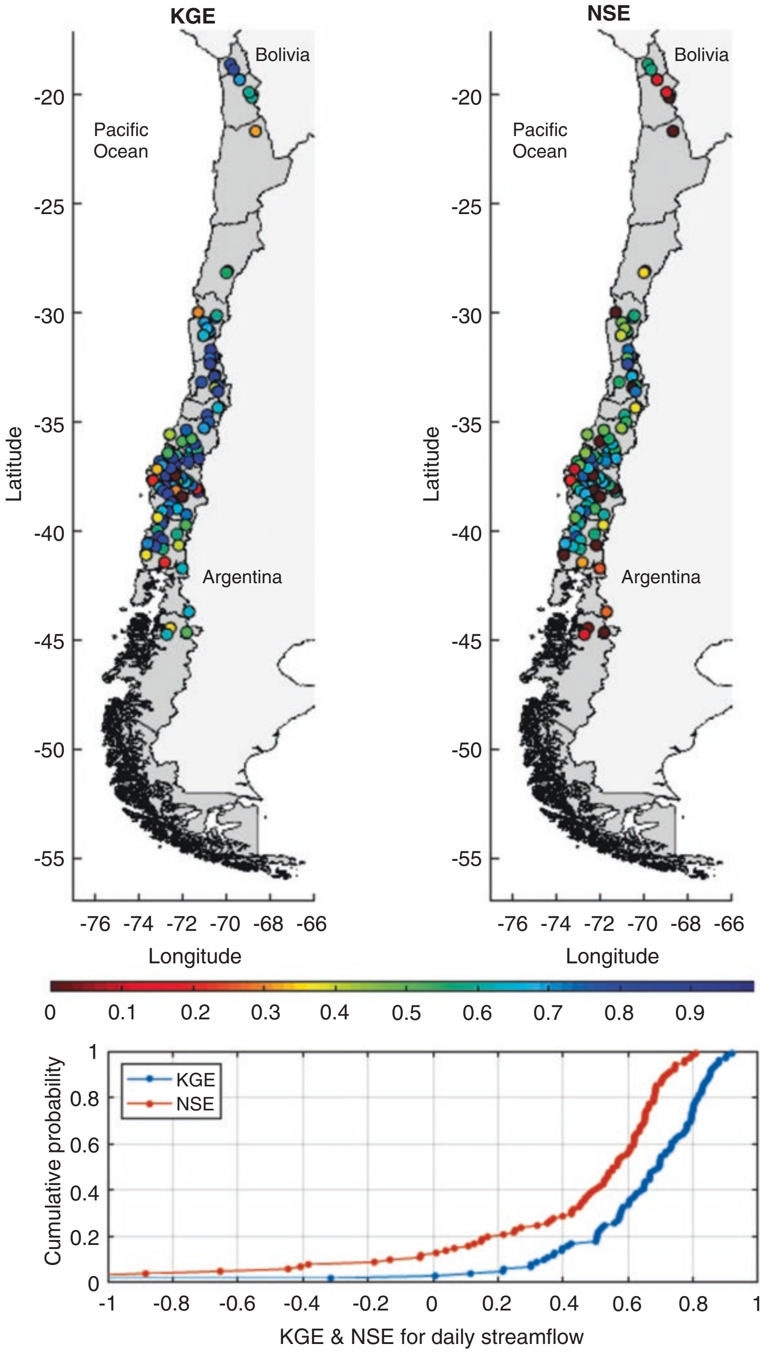

Fig. 9.6 Performance of daily streamflow simulations: (upper-left) KGE, (upper-right) NSE, and (bottom) cumulative probability distributions for calibrated basins in natural regime

the hydrology of this region – are well represented in VIC. On the other hand, northern basins are dominated by groundwater contributions throughout the year, with occasional flashfloods occurring between December and February due to Altiplano heavy rainfall events. Groundwater modeling remains a difficult task in this region because surface basin boundaries do not necessarily match groundwater drainage boundaries (Montgomery et al. 2003). Furthermore, VIC does not include aquifers nor horizontal connectivity between grid cells, missing relevant process representations in arid catchments. Such structural deficiency has already been noticed and demonstrated in other study domains (e.g., Demaria et al. 2007; Newman et al. 2017).

Despite the above issues, and according to the criteria proposed by Moriasi et al. (2007), model performance is "very good" in 40% of the catchments in terms of KGE (values above 0.75, Fig. 9.6), whereas in 60% of the basins the performance is "good" (values above 0.65), while 80% provide "satisfactory" scores (values above 0.5). NSE values are lower than KGE, which is expected as calibration focused on the latter score.

9.3.3 Annual Water Balance

During the analysis period (1985–2015), the partitioning of precipitation into evapotranspiration and runoff (Q) shows dependency with latitude (Fig. 9.7). Such relationship can be attributed to variations in available solar energy that modulates evapotranspiration processes, and the spatial variability of precipitation across continental Chile. In Northern catchments, the influence of convective storms is stronger than in Central Chile, where frontal systems explain most of annual precipitation (Garreaud 2009). In the Altiplano region, more than 90% of annual precipitation (P) becomes evapotranspiration (ET) (Fig. 9.7), while ET/P is less than 10% in some basins located in Southern Chile.

In terms of water budget, considerable spatial variations in climatological runoff ratios and evapotranspiration ratios (1985–2015 period) are observed (Fig. 9.7).

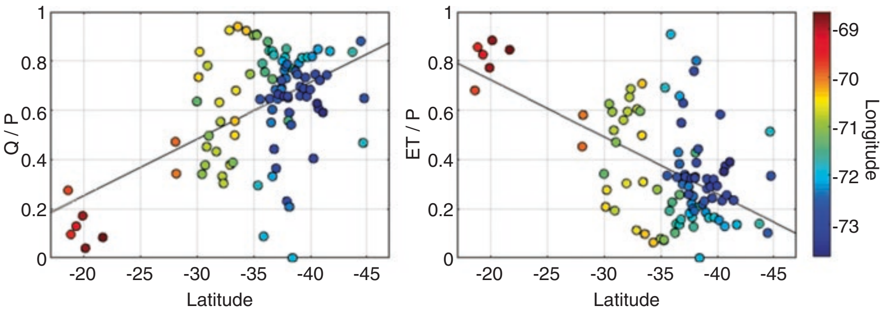

Fig. 9.7 Latitudinal and longitudinal variations at the catchment-scale (left) annual runoff ratio Q/P, and (right) evapotranspiration ratio ET/P across the study domain

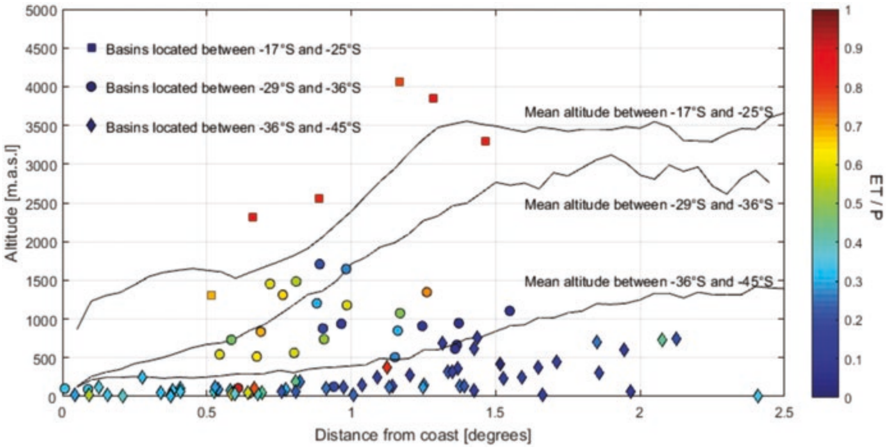

Fig. 9.8 Mean altitude and spatial variation of ET/P ratios at three different latitudinal domains: (i) northern region (17°–25° S); (ii) central region (29°–36° S; and southern region, between 36° and 45° S)

Northern and Andean catchments are very arid, and most precipitation (~70%) evapotranspirates to the atmosphere. Detailed analyses of longitudinal cross sections (northern, central and southern latitudes, Fig. 9.8) reveal that the largest evapotranspiration demands occur in Northern high-elevation catchments, with a decrease towards the coast due to lower atmospheric moisture in the Pacific Ocean (Fig. 9.8). Central and Southern regions show larger spatial heterogeneities, with no clear trend in water budget components, except in the southern region where the influence of the ocean results in decreased ET/P ratios towards the coast.

9.3.4 Seasonal Water Balance

To examine differences in seasonal hydrologic behavior among basins, the catchments were classified based on meteorological data using the Autoclass-C software (Cheeseman and Stutz 1996; Sawicz et al. 2011). Three climatic descriptors were included in the classification process: precipitation seasonality (p-seasonality, Woods 2009; Addor et al. 2017; Alvarez-Garreton et al. 2018), fraction of snow events (snow-frac) and aridity index. The above indices were computed for each 0.05° × 0.05° grid cell – as defined in the CR2MET dataset – and then spatially averaged within the catchments' boundaries. As a result, four clusters of catchments were identified (markers in Fig. 9.9, right panel), with differences in seasonal water balance, illustrated as mean monthly variations in precipitation, runoff, evapotranspiration and water storage – calculated as the sum of model states – following the Wundt's Diagram (Wundt 1953). The first group (star marker) belongs to the Altiplano region, where precipitation occurs between December to March due to the

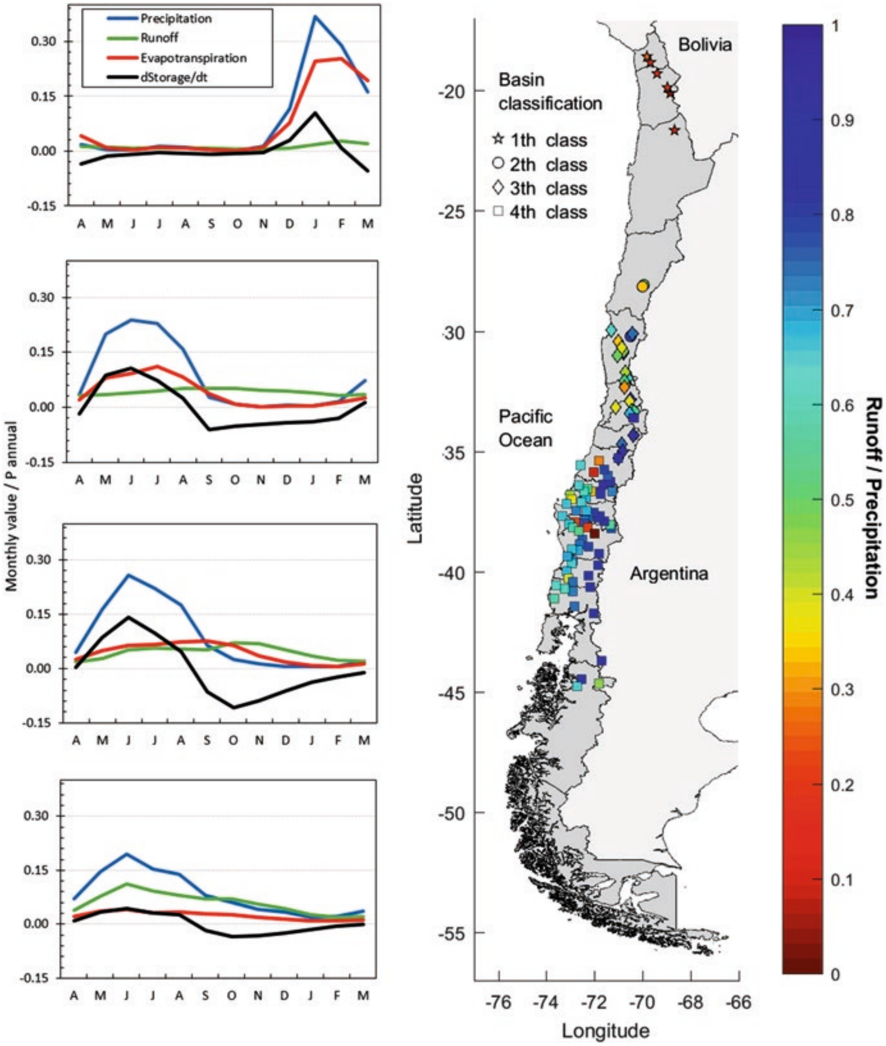

Fig. 9.9 (*Left*) Average monthly water balance components (normalized by annual precipitation) and (*right*) runoff coefficients during 1985–2015, for the basin types 1 to 4 (displayed from top to bottom along the left panels) obtained from the climate-based catchment classification. Different symbols in the right panel represent different catchment types

South American Monsoon (Garreaud 2009), activating evapotranspiration and runoff fluxes within the same season (left panel in Fig. 9.9). In these catchments, there is an important water storage component and the main flux is evapotranspiration, while runoff ratio is less than 10%. Most of northern-central basins (29°S–35°S) located in the Andes Cordillera have a strong dependency on snow accumulation and melting processes (circle and diamond markers in left panel of Fig. 9.9).

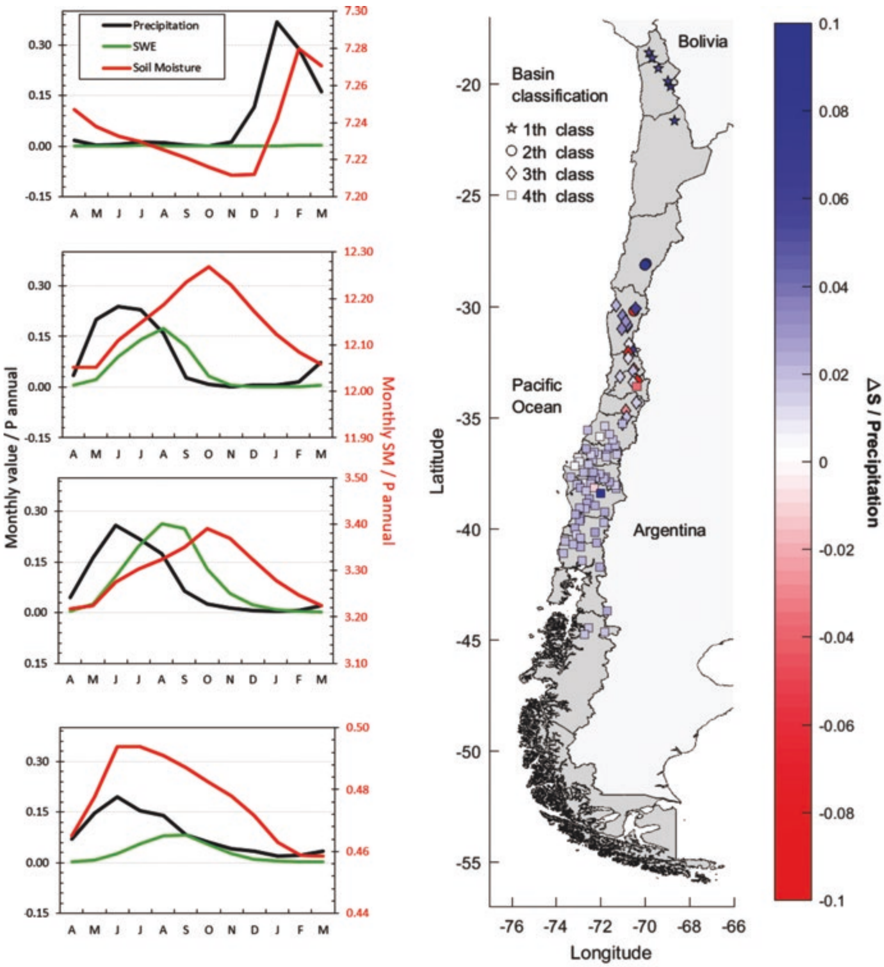

Fig. 9.10 (*Left*) Average mean monthly soil moisture (SM), SWE and (*right*) annual variations in total basin storage (normalized by mean annual precipitation) during 1985–2015, for the basin types 1 to 4 (displayed from top to bottom along the left panels) obtained from the climate-based catchment classification. Different symbols in the right panel represent different catchment types

Snowmelt typically begins in late September, at the beginning of the spring season, and the water stored as snow and soil moisture is released during spring and summer, respectively (Fig. 9.10). Evapotranspiration in northern basins (28°S–30°S, circle markers) depends on the water available from precipitation, while snow sublimation becomes a relevant water balance control in catchments located in Central Chile (diamond markers). Southern basins (square markers) are rainfall-dominated, with the largest amounts recorded in winter and a weaker influence of snow processes on the seasonal water balance. Therefore, the largest (smallest) runoff volumes are observed in winter (summer), as the water stored in the soil is released. Finally, variations in total storage during 1985–2015 are less than 5% of the mean annual precipitation in most catchments (Fig. 9.10).

9.4 Discussion

Quantifying natural water resources in continental Chile is a challenging task, given the large physiographic, climatic and hydrological heterogeneities across the territory. This chapter depicts the main results from an ongoing, interdisciplinary effort to update the national water balance database (DGA 2017). The results presented here build upon hydrological model simulations conducted with the Variable Infiltration Capacity (VIC) model, using datasets that characterize climate (CR2MET) and catchment attributes (CAMELS-CL) in continental Chile.

CR2MET represents a milestone in the development of meteorological information for scarce data regions, especially in the arid Northern regions, high Andean mountains and Patagonia. Overall, CR2MET provides reliable precipitation and temperature estimates at annual and seasonal time scales. Due to higher density of stations in Central Chile (−30 to −40°S), the accuracy of CR2MET products is larger (i.e., higher R^2 and lower biases) within this sub-domain. Similarly, the CAMELS-CL database is the first harmonized compilation of basin attributes and hydrometeorological time series at the catchment scale for continental Chile, with the novel contribution of human intervention descriptors. Therefore, 'near-natural' catchments can be identified and used for detailed process-based studies using hydrological models.

In general, good calibration results are obtained in terms of KGE and NSE scores, excepting arid catchments (Northern Chile) due to model structural deficiencies – specifically, the lack of aquifer representation and lateral connectivity between modeling units. The water balance analysis shows a large spatial heterogeneity in precipitation partitioning, with 90% becoming evapotranspiration in the Altiplano region whereas in Southern Chile the runoff ratio is greater than 80%. Although no clear dependencies with latitude are found, a strong relationship with longitude is obtained in central and southern Chile, with higher ET/P values near the coast and lower values as one approaches the Andes Cordillera.

The climate-based classification – conducted for 'near natural' basins – provides four groups of basins with different hydrological behavior:

- Basins in the Altiplano region, with precipitation and runoff peaks during summer (i.e., January–March) and high ET/P values.
- Northern-central basins with headwaters in the Andes Cordillera, where most ET occurs during winter (April–September).
- Mountain basins in Central Chile, where runoff peaks during spring and summer (i.e., October–March), and the largest ET values are observed during the spring season (i.e., October–December). In these basins, ET is decoupled with P due to

snowpack presence (which provides water availability) and increased incoming energy.

- Southern catchments, where precipitation and peak runoff occur during winter (i.e., April–September).

Despite outstanding advances in hydrological modeling tools and new climate and catchment datasets, developing robust methods for water balance estimates in ungauged basins remains a critical challenge. Indeed, the area covered by all the basins included in this study represents only 17% of continental Chile. Future work will expand water balance estimates to the rest of the territory through the implementation of parameter regionalization techniques, and will include projections of climate change impacts on relevant fluxes and storages.

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Chapter 10
Water Quality

Pablo Pastén, Alejandra Vega, Katherine Lizama, Paula Guerra, and Jaime Pizarro

Abstract Water quality in Chile is characterized by diverse hydrochemical environments and their interaction with human activities and natural factors. The main water monitoring network is operated by the DGA (Dirección General de Aguas) with 1013 water quality monitoring stations for surface water, groundwater, rural drinking water systems and lakes. Boron, electric conductivity (a proxy of dissolved salts) and low pH are critical parameters in the North Macrozone. High concentrations of arsenic and copper are found throughout the North and Central Macrozones, whereas nitrate is a concern throughout the Southern Macrozone. Lakes and reservoirs exhibit a wide span of chlorophyll "a" (from oligotrophic to hypertrophic), mainly attributed to diffuse pollution, while they rarely show high concentrations of metals and metalloids. Out of the 101 watersheds defined by the DGA, only five have ambient water quality standards in place, highlighting the urgency to expand this number to protect valuable and pristine freshwater ecosystems. Over the last few years, the Chilean water quality monitoring network has seen great improvements; however, there is an urgent need to develop quantitative and conceptual water quality models to purposefully convert data into information. The "black box" statistical description of hydrochemical parameters has limited use to inform science-based decision making. Water quality is a key determinant for human and ecosystem health in urban and rural settings in Chile; thus its knowledge and protection should promote local and global sustainable development goals.

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Keywords Water quality · Hydrochemical · Monitoring network · Arsenic · Copper · Nitrate · Chlorophyll · Diffuse pollution · Metals · Standards · Freshwater · Ecosystems

10.1 Introduction

A diverse range of hydrogeochemical environments characterizes water quality in Chile, posing challenges for water quality control and monitoring. Chilean hydrogeochemical environments are determined by a complex interaction between hydrological, hydrodynamic and biogeochemical processes, framed by the Andean geology and a range of socioeconomic activities like mining, industry, agriculture and urban use. The occurrence, mobilization and fate of pollutants are controlled by a combination of natural and anthropic factors implying that water quality -along with water availability- plays a fundamental role in determining the uses of water resources in Chile (Vega et al. 2018a; Pastén et al. 2019).

This chapter first describes the water quality monitoring and surveillance in Chile. While several water quality data sources are depicted, special focus is given on the countrywide government network. The onset of the secondary ambient water quality standards (NSCAs), that still considers less than 5% of watersheds in Chile, is described as a key regulatory and surveillance effort for protecting and improving water quality in priority watersheds. Next, the chapter discusses the key trends in water quality and underlying hydrochemical factors with focus on metals in streams and groundwater and nutrients in lakes. The dynamics of arsenic in surface waters is discussed as a notable parameter of interest that reflects the interaction between human and natural sources. Finally, the integrated use of conceptual and quantitative models coupled to monitoring and surveillance of water quality is highlighted as a fundamental tool to achieve a common understanding of water quality and to pursue shared local and global development agendas. This work builds on two other recent reviews of water quality in Chile by the authors of this chapter, where additional information is found (Vega et al. 2018a; Pastén et al. 2019).

10.2 Water Quality Monitoring and Surveillance in Chile

10.2.1 The DGA Water Quality Monitoring Network

The DGA (Dirección General de Aguas, the Chilean water agency) within the MOP (Ministerio de Obras Públicas, the Chilean Ministry of Public Works) is instructed by law to implement and operate a water quality-monitoring network. A different chapter in this book presents a detailed account of the DGA role in measuring water resources, including gauging of water levels and flows, and maintaining a public water database for water resources. Thus, this section will only highlight the issues related to water quality.

Figure 10.1 shows the distribution of water quality monitoring stations in Chile along with key indicators like population density, number of watersheds, and average rainfall for each Macrozone. In 2016, the network had 829 water quality monitoring stations (Dirección General de Aguas 2016), including surface streams, groundwater, and water bodies. A substantial increase to 1013 (Dirección General de Aguas 2019) stations as of March 2019 was possible since monitoring stations from the rural drinking water system (APR, Agua Potable Rural) and from the lake monitoring network were added (Dirección General de Aguas 2018).

The distribution of water quality stations initially followed the hydrological monitoring network (Dirección General de Aguas 2014); while later additions focused on assessing environmental pressures, and protecting critical water bodies. "Baseline" monitoring stations on the headwater watershed intend to assess water quality in the natural state and "impact" monitoring stations downstream of pressures on water quality intend to identify effects of pollutant sources. The Center Macrozone has the highest number of monitoring stations (517) -more than 50% of all water quality monitoring stations- and population density (142 inhabitants/km^2), yet it only comprises less than 16% of watersheds in Chile. Although the percentage of watersheds without water quality monitoring stations (39% in 2014 according to Dirección General de Aguas (2014), excluding the APR and lake monitoring

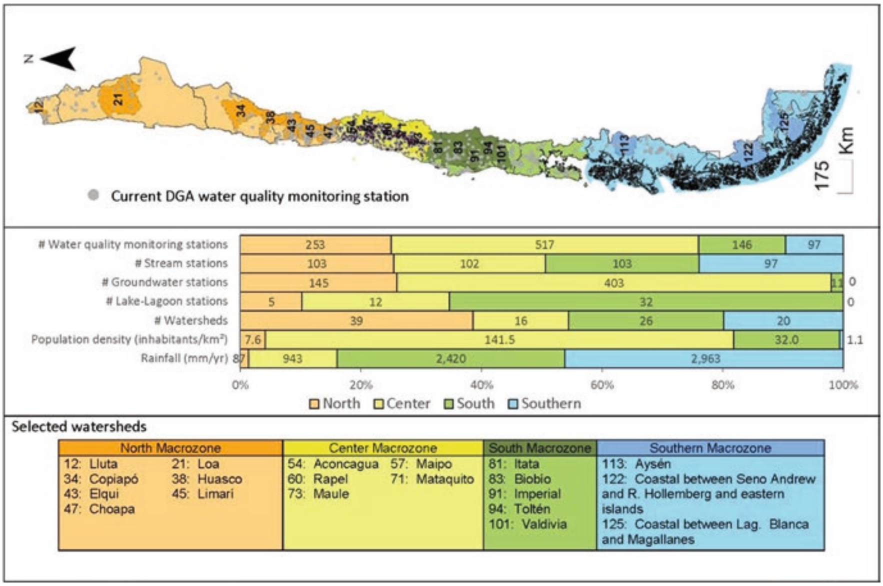

Fig. 10.1 DGA water quality monitoring network and selected watersheds for hydrochemistry overview. (Source: compiled by the authors considering information from Dirección General de Aguas (2016) and Dirección General de Aguas (2019))

networks) has decreased, there is a widely recognized need to increase the spatial coverage and monitoring frequency of the network (Dirección General de Aguas 2014; Dirección General de Aguas 2017).

Table 10.1 lists the parameters measured by the DGA monitoring network and others entities, which includes parameters measured *in-situ* and in the laboratory.

Table 10.1 Water quality parameters measured by the DGA, DIRECTEMAR[1] and MMA[2]

Category	Parameters	DGA	DIRECTEMAR	MMA Wetlands
In-situ	pH, electrical conductivity, temperature, dissolved oxygen	✓	✓	✓
	Salinity, transparency			✓
	ORP		✓	
Total metals	Arsenic	✓	✓	✓
	Aluminum	✓		✓
	Chromium	✓		
	Cadmium, copper, lead, mercury, zinc	✓	✓	
	Cobalt, iron, manganese, molybdenum, nickel, selenium, silver	✓		
Dissolved metals	Arsenic		✓	✓
	Aluminum			✓
	Cadmium, copper, lead, mercury, zinc		✓	
Nutrients	Nitrate, nitrite	✓	✓	✓
	Total nitrogen			✓
	Total phosphorus		(✓)[3]	✓
	Ammonium		(✓)[4]	✓
	Orthophosphate or phosphate	✓	✓	✓
	Boron	✓		
Organics (aggregated)	Chemical oxygen demand and/or biochemical oxygen demand (BOD)	✓	(✓)[3]	✓
	Total hydrocarbons or similar (e.g. PAHs)		(✓)[4]	✓
Biological parameters	Chlorophyll "a"		(✓)[3]	✓
	Fecal coliforms		✓	✓
	Fecal streptococci, phytoplankton, zooplankton			✓
Macroelements	Chloride, calcium, magnesium, sodium, potassium	✓		
	Sulfate	✓		✓
Other	Alkalinity			✓
	Suspended solids		✓	✓

Source: information obtained from DGA (2014; 2017), DIRECTEMAR (2017, 2019) and Ministerio del Medio Ambiente (2016)

Notes: (1) DIRECTEMAR, the maritime water agency within the Chilean Navy and Ministry of Defense; (2) MMA, Ministerio de Medio Ambiente, Ministry of the Environment; (3) Total phosphorus, chlorophyll "a", and COD are measured in freshwaters; (4) Ammonium and PAHs (polycyclic aromatic hydrocarbons) are measured in marine waters

Since 2017, in most monitoring stations sampling is performed by DGA staff, 4 times per year (summer, fall, winter, and spring) in surface waters and 2 times per year (Fall and Spring) for groundwater (Gobierno de Chile 2017). The frequency and parameters vary when the monitoring station is part of the monitoring program of NSCAs; however, NSCAs are available for less than 5% of the watersheds in Chile (more information about NSCAs and their monitoring plans is provided below in Sect. 10.2.2). In selected stations, the DGA measures occasionally other parameters like chlorophyll “a”, turbidity, pesticides, phosphate, dissolved oxygen, and bicarbonate. Only a few monitoring stations in the network have functioning multi-parameter water quality sensors that feed real-time measurements to the online public information system. The DGA later processes, reviews and validates raw information from multi-parameter probes. Once reviewed, water quality monitoring data are uploaded to the Banco Nacional de Aguas (BNA), the national water resources data bank.

The basic parameters suggested by UN Water (2017) are part of the parameters measured by the DGA, whereas progressive monitoring parameters suggested by UN Water (2017) are still missing. Budget, infrastructure, and logistics seriously limit the number and frequency of measured parameters. This implies a lack of systematic measurements of critical parameters like BOD, alkalinity, turbidity, suspended solids, and dissolved metals across the network. For example, samples cannot be delivered from remote locations to the laboratory within the 24 h required by common protocols for BOD measurement. Similarly, measurement of dissolved metals after on-site filtration and preservation would require substantial resources -including DGA personnel training- if they were systematically measured across the network. The ISO 17025[1] accredited DGA central laboratory performs the chemical analyses of samples from their regular monitoring network. Currently, the DGA central laboratory also performs ~60% of the analyses defined by the NSCAs, while they plan to analyze ~80% of the parameters by 2022.

Finally, the DGA monitoring network should aim to systematically include two other sets of parameters: contaminants in sediments and emerging contaminants. Sediments are a repository of metals that may be formed or mobilized by hydrological (e.g., hydraulic and energy infrastructure and operations) and hydrochemical controls (e.g., pollutant discharge), a relevant condition in metal-rich watersheds in Northern and Central Chile (Pizarro et al. 2003, 2009; Contreras et al. 2015). Emerging contaminants should be screened for systematic measurement in specific watersheds (Petrie et al. 2015; Tang et al. 2017). They include toxic species unique to Chilean waters, like perchlorate and other pollutants related to human activities (Vega et al. 2018b). For example, there are very few studies in Chile of fluxes and dynamics of contaminants from urban and industrial wastewaters, including pharmaceuticals, personal care products, pesticides, disinfection byproducts, and industry-specific pollutants (e.g., those from pulp mills, mining, and aquaculture).

[1] ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories. International Organization for Standardization.

Some data about these pollutants may exist for specific monitoring stations, as part of the surveillance programs for ambient water quality standards (Programa de Medición y Control de la Calidad del Agua, PMCCAs) or from sampling campaigns of other agencies (see Sect. 10.2.3), but their spatial and temporal coverage are limited at best.

10.2.2 Surveillance Programs for Ambient Water Quality Standards (PMCCAs for NSCAs)

The first ambient water quality standard (NSCA) for a watershed was established in 2010 (Serrano River watershed, Southern Chile). Currently, five of the 101 watersheds cataloged by the DGA have a NSCA (3 rivers and 2 lakes); while 4 watersheds have PMCCAs in place. Table 10.2 lists the watersheds currently with NSCA and PMMA and the years they were established.

Figure 10.2 shows a diagram with the process for establishing NSCAs and PMMCAs. The national priority list for environmental regulations set by the Government triggers the process for establishing a NSCA for a specific watershed. It starts with a project draft that includes a thorough revision of information (e.g., DGA monitoring network, scientific studies, reports), and a proposal of surveillance areas and recommended range for specific water quality parameters. The draft becomes available for public consultation and comments, which are considered in a Final Draft later submitted for official promulgation. Appeals may be submitted within 90-days of promulgation; thereafter the NSCA becomes official and are due for review after 5 years. Although the NSCA creation process may take less than 2 years, NSCAs have taken considerably longer; for example, the process for the Maipo watershed's NSCA started in 2004 and became an official regulation in 2014.

Surveillance programs (PMCCAs) of NSCAs are a multi-agency endeavor. The MMA (Ministerio de Medio Ambiente, Ministry of the Environment) proposes surveillance areas, monitoring stations, parameters, frequency of monitoring, agencies that should carry out measurements and sampling, among other information. The

Table 10.2 Watersheds currently with NSCAs

Watershed	Official	PMCCA	Comments
Serrano River	2010	2012	
Llanquihue lake	2010	2012	
Villarrica lake	2013	2016	Declared saturated zone for chlorophyll "a", dissolved phosphorus, and transparency, 2018. Decontamination plan in preparation.
Maipo River	2014	2018	
Biobío River	2015	In prep.	

Source: Own elaboration; data obtained from www.leychile.cl, revised April 2019

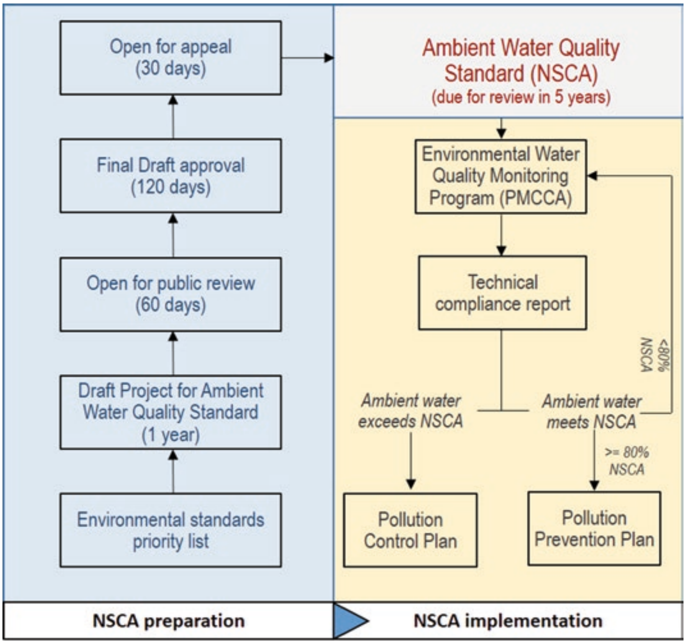

Fig. 10.2 NSCA preparation and surveillance processes. (Source: based on Ministerio del Medio Ambiente (2017))

SMA (Superintendencia de Medio Ambiente, Superintendence of the Environment) promulgates the PMCCA in consultation with the MMA, which prepares a technical memorandum that describes the commitments of the agencies involved in the surveillance. The surveillance network comprises a "control network" and an "observation network". The first one provides the primary parameters for checking compliance and is under responsibility of the DGA. The second is under responsibility of the MMA and provides complementary information (e.g., bioindicators, ecotoxicology), and may include new monitoring stations used for reviewing NSCAs every 5 years.

The SMA generates a technical compliance report that compiles and assesses the information fed by all reporting agencies to the PMCCA. It determines whether a parameter is lower than 80% of the established value in the NSCA, falls within 80–100% of the NSCA (it prompts a pollution prevention plan; the affected area is declared latent), or exceeds the NSCA (it prompts a decontamination plan; the affected area is declared saturated). To date, only the Villarrica Lake watershed has been declared saturated by nutrient pollution parameters (chlorophyll "a", transparency, and dissolved phosphorus) and a decontamination plan is being prepared.

The international experience shows that NSCAs play a key role in water quality monitoring, surveillance and control. It is urgent that Chile expands the number of watersheds with NSCAs, extension, parameters, frequency, and data platforms of its water quality monitoring networks.

10.2.3 Other Water Quality Monitoring and Surveillance Programs

Other sources of water quality information are available with a range of thematic foci, specific objectives, spatial coverage, parameters list, frequency, data availability, and methodological approaches. They include networks and platforms operated and/or coordinated by:

- Dirección de Territorio Marítimo y Marina Mercante (DIRECTEMAR, the maritime water agency within the Chilean Navy and Ministry of Defense): it operates ~150 monitoring stations associated to the POAL (Programa de Observación del Ambiente Litoral, the program for coastline surveillance) (DIRECTEMAR 2016). This program monitors physicochemical and biological parameters in waters, sediments, and biota in 47 water bodies (40 maritime, 1 insular maritime, 3 lacustrine, 2 riverine, and 1 antartic) once or twice a year. Monitoring sites are selected considering anthropogenic pressures such as industrial and municipal wastewater discharges, fish farming, fishing, recreational, and navigation hotspots (DIRECTEMAR 2017). Although DIRECTEMAR results are publicly available as spreadsheets through the institutional website, a critical analysis of such data is needed. While DIRECTEMAR measures parameters and matrices not measured by the DGA (e.g., hydrocarbons, metals in sediments, metal bioaccumulation in mollusks), adequate selection of parameters and methodologies should be assured for improved interface with other networks.
- Ministerio de Medio Ambiente: the MMA assessed the trophic state of 33 freshwater and coastal wetland ecosystems in 2011. Since then, monitoring has continued once or twice a year in 21 sites shown in Table 10.3, as part of the national wetlands action plan (Plan Nacional de Acción de Humedales) (Ministerio del Medio Ambiente 2016). Although water quality data generated by this program is available on a case-by-case basis, the MMA is currently developing a national wetland platform (Plataforma Nacional de Humedales) where such data will be easily available. This monitoring program focuses on the protection of biological diversity and ecosystem services in sensitive and unique wetland ecosystems.

Table 10.3 Aquatic ecosystems monitored by the MMA (from north to south)

Elqui 1 y 2 River	Maipo River	Mataquito River
Tongoy Creek	El Yali lagoon	Maule River
Limarí River	El Yali Creek	Lanalhue Lake
Choapa River	Rapel River	Lleulleu Lake
Petorca River	Nilahue Creek	Imperial River
La Ligua River	Torca lagoon	Budi Lake
Aconcagua River	Vichuquén Lake	Toltén River

Source: information obtained from Ministerio del Medio Ambiente (2016)

- Superintendencia de Servicios Sanitarios (SISS: Superintendence of Sanitary Services). It oversees companies that provide sanitary services through surveillance plans and self-control testing performed by water companies. The main purpose of these measurements is to check whether drinking water and treated wastewater discharge standards are met. SISS provides aggregated compliance reports that are publicly available online, although specific data may be available upon request. Table 10.4 shows that sulfate, total dissolved solids, fluoride, and chloride are the main parameters with non-compliance in urban drinking water systems during 2018. While the frequency is low, the drinking water systems of Tierra Amarilla, Chañaral, and Copiapó in Northern Chile show chronic cases of

Table 10.4 Drinking water systems showing non-compliance with one or more drinking water parameters in 2018[1]

Parameter	Non-compliance events and associated %	Drinking water supply system showing non-compliance[2]
Sulfate	41 (0.88%)	Copiapó, Tierra Amarilla, Chañaral, caldera, Pichidangui.
Total dissolved solids	38 (0.82%)	Copiapó, Tierra Amarilla, Chañaral, caldera, La Tirana.
Turbidity	29 (0.61%)	Lota, Punta Arenas, El Colorado, Florida, Matilla, Barrancas, Cabrero, Cauquenes, Concepción, Machalí, Monte Águila, Nancagua, Penco-Lirquén, Pichilemu, Quillón, Quintero, Rafael, Rengo, Santa Juana, Tomé.
Fluoride	13 (0.28%)	Buin-Paine-Linderos, Chicureo, Rancagua, Chamisero, Chépica, Copiapó, Maipo Laguna Negra, Nancagua, San Gabriel, Tiltil.
Chloride	10 (0.22%)	Copiapó, Arapiki, Chañaral, Tierra Amarilla, los Molles.
pH	8 (0.17%)	Aguas La Serena, Collipulli, El Colorado, Lastarria, San Antonio, Servicios Sanitarios de la Estación, Talca, Villa Alemana.
Total iron	8 (0.17%)	Cauquenes, Penco-Lirquén, Coelemu, Guanaqueros, Osorno 5000, Santa Rosa del Peral.
True color	7 (0.15%)	Quillón, Cauquenes, Hualqui, Los Ángeles, Rancagua, Tierra Amarilla.
Odour	6 (0.13%)	Barrancas, Copiapó, Florida, Machalí, Rancagua, Temuco-Centro.
Taste	4 (0.09%)	Barrancas, Florida, Machalí, Rancagua.
Free residual chlorine	4 (0.08%)	El Abrazo, Maipo Laguna Negra, Quillón, Rancagua.
Nitrate	2 (0.04%)	Izarra, Tierra Amarilla.
Total manganese	2 (0.04%)	Santa Rosa del Peral, Tierra Amarilla.
Arsenic	1 (0.02%)	Servicios Sanitarios de la Estación.
Total coliforms	1 (0.02%)	Quepe.

Source: SISS (2018a). Notes: [1] This table does not include rural drinking water systems (APR). [2] Listed from highest to lowest frequency of non-compliance non-compliance. During 2017, the SISS applied 80 penalties, of which 76 were to SSCs (Sanitary Services Companies) and 4 to industrial discharges of wastewater (SISS 2018b). SISS oversees the tariffs and the compliance of SSCs with standards.

- Sanitary Services Companies (SSCs): mostly of private ownership, they provide services including drinking water, sewerage, and water treatment within concession areas. SSCs perform routine measurements of drinking water sources, finished drinking water at the point of use, influent municipal wastewater, treated wastewater discharge, and industrial wastewater entering their sewage network. Part of that information is used for compliance self-reporting and is publicly available through the SISS information outlet.
- Servicio de Evaluación Ambiental (SEA, service for environmental impact assessment): it maintains a database that records the environmental impact assessment process for projects that meet the criteria established by the Chilean environmental framework law (Ley 19.300 sobre Bases Generales del Medio Ambiente). Environmental impact assessments contain water quality baselines for projects that may release or mobilize pollutants into water. Since other water quality data may not be available in the project area, monitoring campaigns are performed and reported to provide a baseline before the project starts. Although this information is publicly available via the www.e-seia.cl site, the location of monitoring sites, definition of water quality parameters, sampling frequency, and measurement methodologies are tailored to each project. Thus, water quality data from environmental impact assessments are scattered; and no systematic data outlet for water quality data is available yet.
- Superintendencia de Medio Ambiente (SMA, Superintendence of the Environment): while the SMA plays its role in NSCA's surveillance, it also assesses compliance of projects with the conditions sanctioned during the environmental impact assessment process. When project noncompliance occurs, the SMA initiates administrative procedures and fines to enforce the conditions set by the environmental permits or standards. Compliance audits and reports are publicly available via the SNIFA system (Sistema Nacional de Fiscalización Ambiental, national system for environmental inspection). Similarly to the SEA case, water quality data from surveillance and compliance assessment are scattered and no systematic data outlet is available yet.

10.3 Key Trends and Underlying Hydrochemical Factors

10.3.1 Hydrochemical Trends in Streams and Groundwaters at a Glance

Boxplot diagrams (Fig.10.3) in Figs. 10.4 and 10.5 show at a glance the hydrochemical variability of Chilean waters in selected watersheds shown in Fig. 10.1, for streams and groundwaters, respectively. The historical series for 2000–2016 at the corresponding DGA monitoring stations were used to calculate average, median, maximum, minimum, quartiles, and atypical values within each watershed.

The values of pH in surface waters fall in the range 6.5–8.5, with the exception of streams affected by acid drainage, notably in the Lluta and Elqui watersheds, and to a lower extent in the Aconcagua, Maipo and Rapel watersheds. Such lower pH values are not observed in groundwater.

The ranges for electric conductivity (EC) in surface waters are well below 1 mS/cm throughout the country, except for streams in Northern Chile, notably in the Lluta, Loa, and Elqui, where some streams may have conductivity values well above 5 mS/cm. Most high values are associated to streams that receive acid drainage (e.g., Azufre River in the Lluta watershed and Malo River in the Elqui watershed), saline hotsprings and salt flat effluents (e.g., El Tatio Geyser field in the Loa watershed, Colpitas River in the Lluta watershed), and mining-related waters (e.g., Estero Carén in the Rapel watershed). Following surface water trends, the groundwater electric conductivity decreases from North to South, with highest values in the North Macrozone. This variation in electrical conductivities may be attributed to higher evaporation rates and lower dilution rates as suggested by the average rainfall shown in Fig. 10.1.

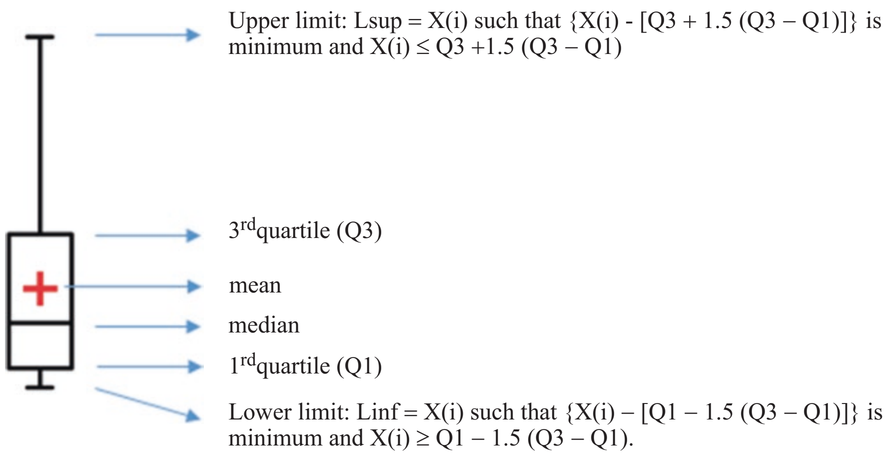

Fig. 10.3 Boxplot representation showing key statistical descriptors

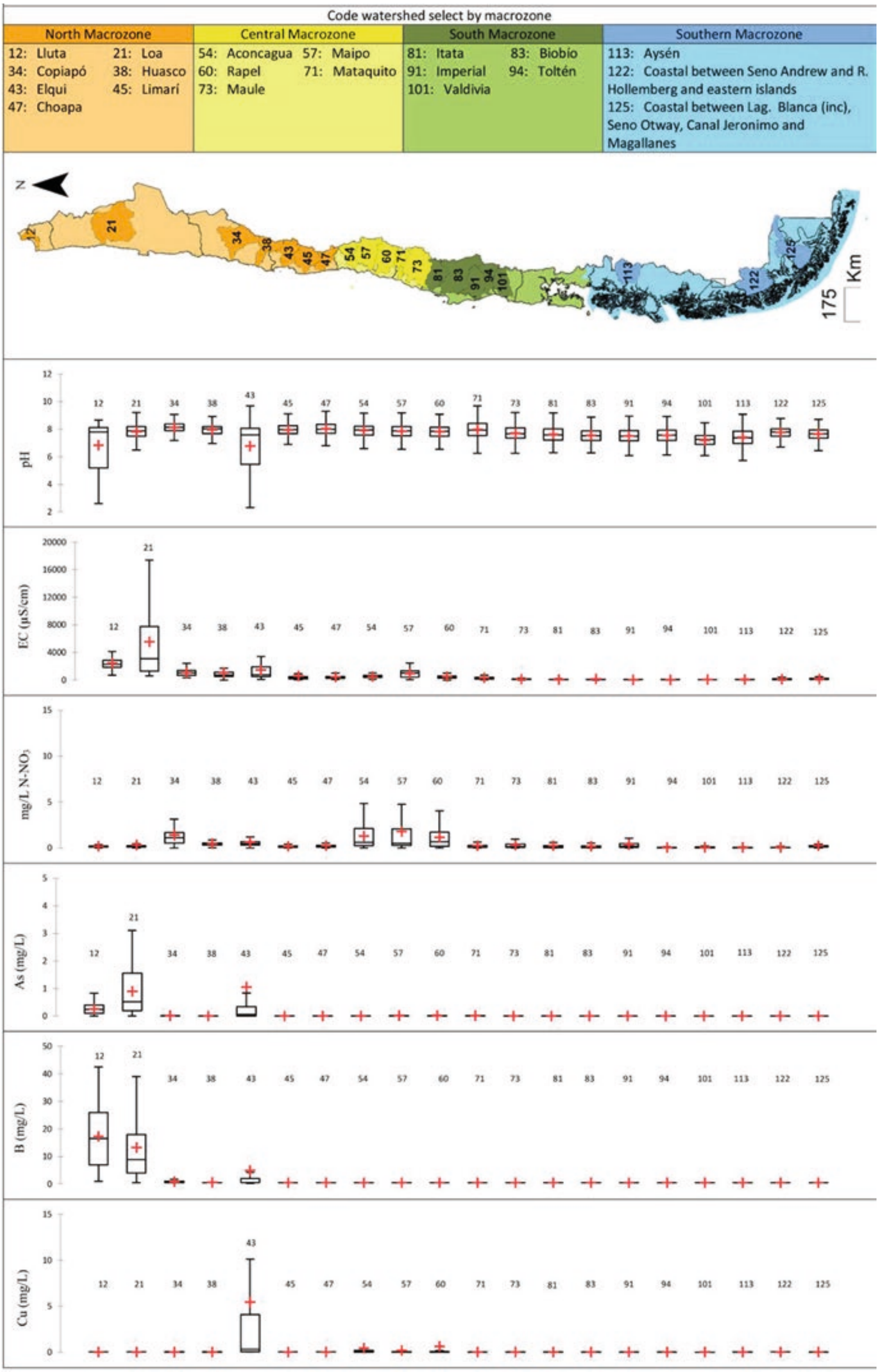

Fig. 10.4 Water quality in streams. (Source: information obtained from BNA (2000–2016))

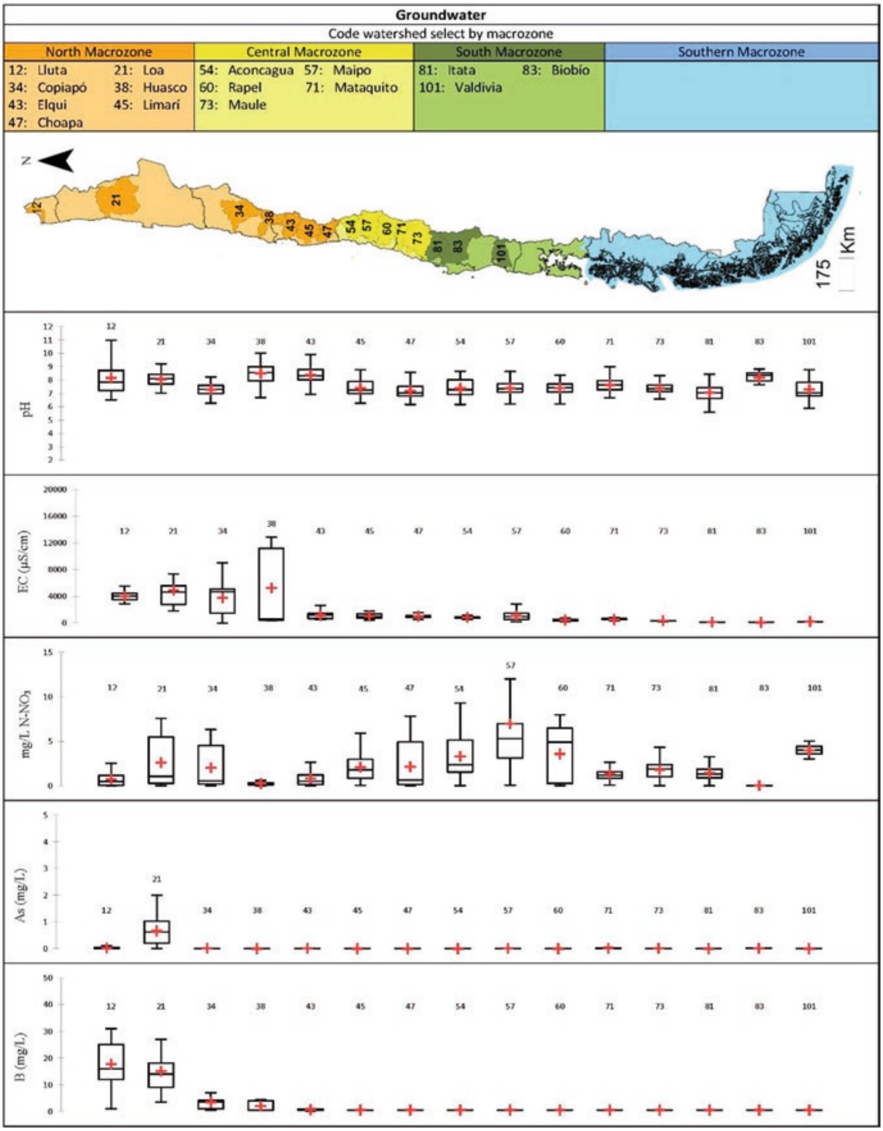

Fig. 10.5 Water quality in groundwaters. (Source: information obtained from BNA (2000–2016))

Nitrates in surface streams show higher concentrations in Central Chile (e.g., Aconcagua, Maipo, and Rapel watersheds), and in Northern Chile (e.g., Loa, Copiapó, Elqui watersheds), however some excursions to high values are found in the South (e.g., Itata, Biobío, Imperial watersheds). In groundwater, the highest nitrate concentrations are found in Central Chile (notably, the Maipo watershed), with high values also in the North (e.g., Loa, Copiapó watersheds). Enrichment for nitrates may be attributed to a combination of geological deposits, mainly in Northern Chile, and pollution from agriculture and urban metabolism (i.e., treated wastewater without nutrient control, urban runoff), from Elqui watershed, to the South (Arumi et al. 2005; Pizarro et al. 2010).

Arsenic in surface streams is enriched notably in the Lluta, Loa, and Elqui watersheds. While in groundwater it is usually found in lower concentrations, in many places it is above the drinking water standards (e.g., aquifer in the northern area of the Santiago metropolitan area, Maipo watershed). Due to its importance and complex dynamics, the case of arsenic is presented with more detail below in Sect. 10.3.2.

The highest concentrations of boron are found in Northern Chile (e.g., Lluta, Loa, and Elqui watersheds) and are linked to geological sources, high evaporation, and limited dilution. Boron is a well-known toxic that limits agriculture (phytotoxic) and impairs drinking water sources (the WHO guideline is 2.4 mg/L) (World Health Organization 2017).

Copper enrichment in surface waters may be observed in several watersheds in Northern and Central Chile (e.g., Elqui, Aconcagua, Maipo and Rapel), especially in streams affected by acid drainage. Copper mobilization from copper-rich geologic repositories in the Andes may be enhanced by historic and active mining, characteristic of Northern and Central Chile. This is relevant considering that the largest copper reserves in the world are upstream from Santiago, a metropolitan area with ~seven million inhabitants.

10.3.2 The Case of Arsenic in Streams and Groundwater

Arsenic is a toxic pollutant for humans and ecosystems at very low concentrations (Smedley and Kinniburgh 2002). Natural processes and human activities mobilize arsenic from geological deposits in several watersheds in Chile, impairing their use as source for drinking water, irrigation, and aquatic habitats (Oyarzun et al. 2012, 2013; Bugueño et al. 2014; Guerra et al. 2016b). Arsenic sources include hydrothermal waters (e.g., El Tatio geothermal field in the Loa watershed, and the Aguas Calientes waters in the Lluta watershed) and acid drainage (e.g., Malo River in the Elqui watershed, Estero Yerba Loca in the Maipo watershed). In acid drainage, arsenic-rich minerals (e.g., arsenopyrite) are dissolved or oxidized, for example by exposing them to water and oxygen due to open pit or underground mining. Arsenic may also come from arsenic-rich waste that has been inadequately disposed by legacy or current mining activities.

The mobility of arsenic strongly depends on its chemical speciation: the distribution of chemical forms in an environmental matrix. While dissolved arsenic is more mobile than arsenic bound to particles, the latter may form arsenic repositories in sediments (e.g., reservoirs and river sections with low velocity that allow particle settling and gravel and sand beds that capture fine particles). Arsenic may be mobilized in acute episodes triggered by human intervention (e.g., sediment purge from dams), hydrology (e.g., high flow season) and other sources of pollution (e.g., input of nutrients or organics that may render anoxic conditions) (Guerra et al. 2016a).

The chemical speciation of arsenic in Andean watersheds is controlled by the interaction of biogeochemical, hydrological, and hydrochemical processes. The concentrations and chemical speciation of iron, manganese, and aluminum phases are likely to control the speciation of arsenic, dynamics that strongly depends on pH and redox conditions. If organic-rich reducing environments are found (e.g., sediment columns well below the oxic-anoxic interface), sulfides may capture arsenic if iron is present and pH is circumneutral (Vega et al. 2017). In oxidizing environments (e.g., shallow streams with good aeration), iron, manganese, and aluminum oxides and oxyhydroxides are likely to bind dissolved arsenic, a process that depends highly on the mineralogy of the solid and pH (in general $5 < pH < 9$, waters not too acidic nor too alkaline) (Lee et al. 2002). The occurrence of microbial communities and riverine plants, the effect of daily freeze-thaw cycles, the interactions with natural organic matter, and the effect of incomplete mixing in confluences have been observed to impact the fate of arsenic in Andean watersheds (Bugueño et al. 2014; Guerra et al. 2016a, b; Arce et al. 2017).

Finally, Fig. 10.6 shows a map of arsenic in surface and groundwater considering the DGA database for 1967–2018 from BNA. Not only high concentrations of arsenic are observed in Northern Chile, but also in Central and Southern Chile, when the 10 ppb reference value is considered. From a sustainability point of view, this is important since arsenic removal from groundwater sources down to the 10 ppb WHO drinking water guideline is challenging.

10.3.3 Lakes and Reservoirs

The monitoring network for lakes and reservoirs is very limited compared to the monitoring network for streams and groundwaters (Fig. 10.1). Nevertheless, an analysis of chlorophyll "a" to assess the trophic state of 9 water bodies in the DGA network for 2000–2014 (Table 10.5) indicates conditions that span from hypertrophy to oligotrophy. For the Aculeo Lagoon, 48% of the chlorophyll "a" measurements show hypertrophic conditions (>25 μg/L) while 32% indicate eutrophy (9–25 μg/L). In the case of the San Pedro Lagoon, 11% of measurements show eutrophy, and 55% indicate mesotrophy (3.5–9 μg/L). The remaining water bodies show conditions that are predominantly oligotrophic (<3.5 μg/L) to mesotrophic. Other studies have reported eutrophic conditions for the Peñuelas and Rapel reservoirs. The Llanquihue and Villarrica lakes are the only ones that have NSCAs and PMMCAs in place. The Villarrica Lake was declared a saturated zone for chlorophyll "a", dissolved phosphorus, and transparency in 2018. Although Southern Chile is characterized for lakes with pristine waters with monomictic lakes and oligotrophic conditions, there is increasing concern about the effect of diffuse pollution from agriculture, forestry and insufficiently treated wastewater effluents. Pizarro et al. (2016) found that lakes in watersheds with limited change in soil use

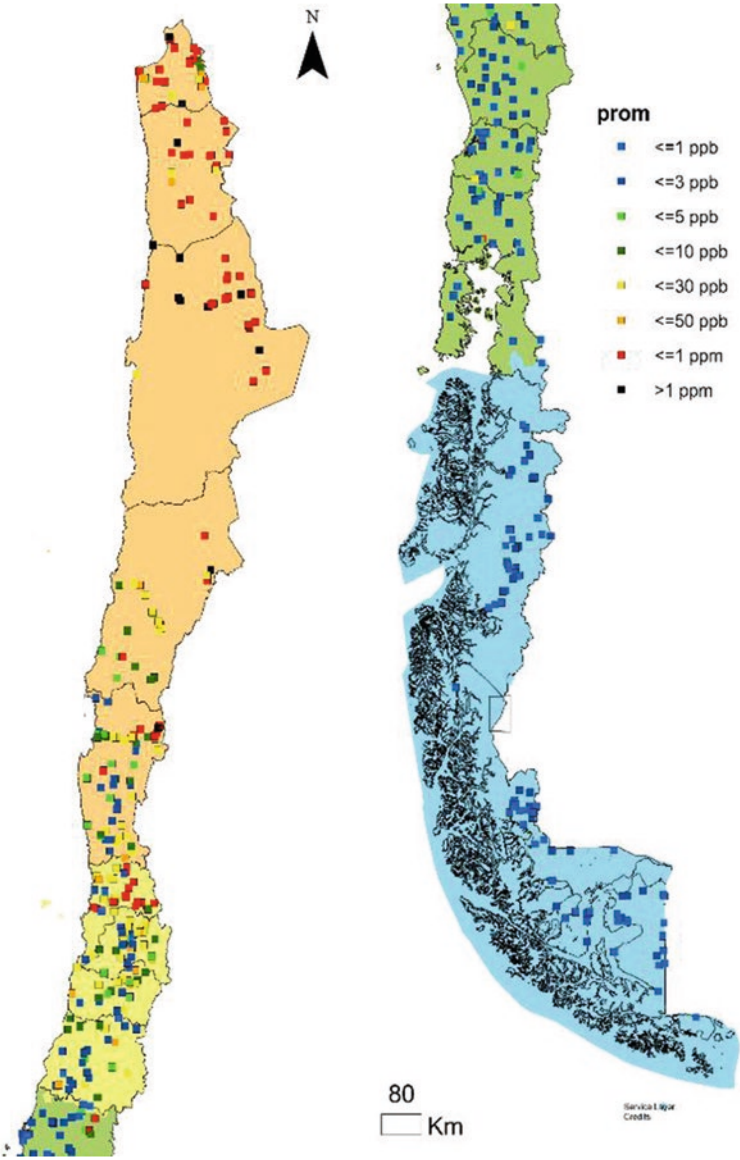

Fig. 10.6 Average arsenic concentrations in surface and groundwater. Source: raw data processed from BNA (1967–2018)

and native forest coverage have shown limited change in nitrogen and phosphorus, while those nutrients have increased in watersheds with increasing forestry, agriculture, and tourism development.

Table 10.5 Trophic state of water bodies in the DGA lake monitoring network

Lake	% samples within each trophic state according to chlorophile “a” measurements			
	Hypertrophic (>25 μg/L)	Eutrophic (25–9 μg/L)	Mesotrophic (9–3.5 μg/L)	Oligotrophic (< 3.5 μg/L)
Aculeo	48	32	12	8
Caburgua	–	–	4	96
Calafquén	–	–	–	100
Colico	–	–	–	100
Neltume	–	–	–	100
Panguipulli	–	–	8	92
Riñihue	–	–	8	92
San Pedro	–	11	55	34
Villarrica	–	–	13	87

Source: based on data from BNA (2000–2014)

Finally, metals and metalloids in sediments are scarcely monitored (see Sect. 10.2), but there is strong evidence of enrichment in sediments in existing reservoirs (e.g., Puclaro in the Elqui watershed, and Rapel reservoir in the Rapel watershed). This is a relevant issue for irrigation and/or energy infrastructure under construction or planned downstream rivers with metal enrichment (e.g., Chironta dam in the Lluta watershed) (Contreras et al. 2015).

10.4 Models and Monitoring for Development Agendas

Water quality plays a fundamental role in shared local and global agendas for sustainability, climate change, and risk and disaster management. For example, water quality is deeply entrenched in SDG 6 (Sustainable Development Goals 6: Clean water and sanitation) of the 2030 UN Agenda for Sustainable Development (UN 2015), where it is central to safe drinking water and sanitation, as well as for assessing the state of ambient waters. The proportion of water bodies with good ambient water quality defines Indicator 6.3.2, and the change in water quality over time for water-related ecosystems defines Indicator 6.6.1c of SDG 6.

Achieving local and global agendas requires a shared understanding of water quality, as proposed by Fig. 10.7. Ever-increasing water quality conflicts show that a shared understanding of water quality is often elusive. A statistical description of water quality is not sufficient to capture complex, interdependent physical, chemical and biological phenomena that control water quality. Furthermore, a statistical description of water quality does not reveal the connections between water quality and human pressures (e.g., industrial and mining effluents, water extractions, energy infrastructure, agriculture, and urbanization). This is a critical aspect when development agendas seek to balance socioeconomic development with the protection of human and ecosystem health. Therefore, the “black-box statistical understanding”

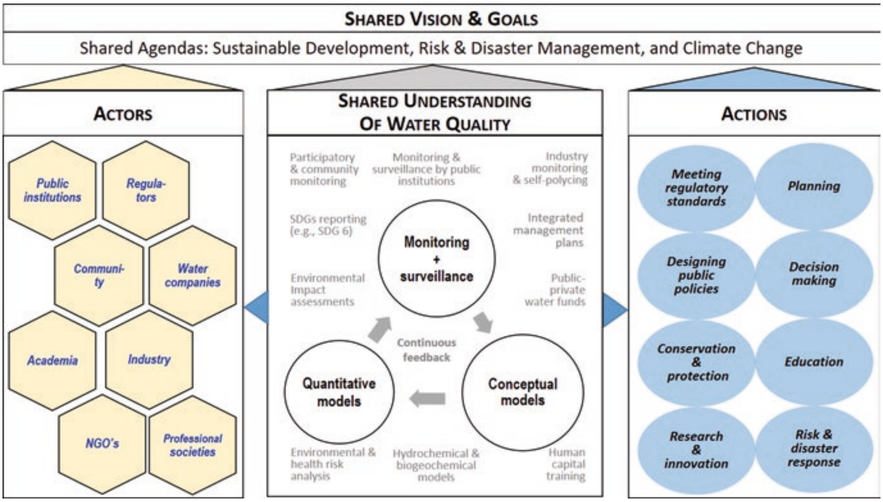

Fig. 10.7 Integrating water quality conceptual and quantitative models with monitoring & surveillance towards a shared understanding of water quality and goals in local and global agendas

of water quality in aquatic systems should transform into a "process-based" understanding that allows setting purposeful standards, surveillance, and control plans.

Figure 10.7 proposes integrating water quality conceptual and quantitative models with monitoring and surveillance towards a shared understanding of water quality. Public and private actors of the water cycle should use models as a science-based shared platform for discussion, decision-making, regulatory action, public policy design, and enforcement, among other actions towards pursuing shared local and global agendas. Monitoring and surveillance should continuously feed data to improve conceptual and quantitative models, while models should provide feedback for improved monitoring and surveillance. This continuous learning cycle should deliver a compelling tool for water quality control and protection in the context of complex socio-environmental systems. An active research agenda on water resources and the involvement of regulators, community, professional societies, NGO's, and industry are needed for a multi-scale, multi-actor shared understanding of water quality.

10.5 Conclusions

The complex interaction between hydrological, hydrodynamic and biogeochemical processes, determine diverse hydrochemical conditions in Chile, which impact -and are impacted by- a range of socioeconomic activities like mining, industry, agriculture and urban water use. The DGA network primarily monitors water quality and quantity, although several other institutions are involved in water quality monitoring and surveillance. The main water quality issues are related to high salinity in Northern Chile, the presence of high concentrations of toxic metals and metalloids in Northern and Central Chile, and the increasing presence of nutrients in Central and Southern Chile. While safe drinking water and sanitation indicators are very good, less than 5% of the 101 watersheds in Chile have ambient water quality standards. Monitoring and surveillance efforts should feed conceptual and quantitative models towards a shared understanding of water quality in Chile and pursuing shared development agendas.

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Chapter 11
River Basin Policy and Management

Humberto Peña

Abstract This chapter presents a brief overview on how Chile uses and manages water resources, responding to challenges that arise from the objectives of social and economic development, as well as environmental sustainability. Considering that the current system of water resources management is the result of a process that started in the nineteenth century, an analysis of the origins of these early uses and regulations is presented. Subsequently, the legal and institutional framework that shapes the current water management system is described, and the hydraulic infrastructure and the administrative organizations that perform such management in practice is discussed. Furthermore, the answers provided by the current system to the new requirements derived from economic dynamics are analyzed, in the context of growing problems of water shortages and of social concern for the environment. Finally, the chapter presents the main conclusions and pending issues that must be addressed to devise an adequate management system that attends to the complex demands of society.

Keywords River basin · Policy · Management · Economic development · Environmental sustainability · Legal · Institutional · Administrative · Infrastructure · Organizations

11.1 Introduction

This chapter presents a brief overview on how Chile uses and manages water resources, responding to challenges that arise from the objectives of social and economic development and of environmental sustainability. Considering that the current system of management of water resources is the result of a process that started in the nineteenth century, an analysis of the origins of these early uses and

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regulations is presented (Sect. 11.2). Subsequently, the legal and institutional framework that shapes the current water management system is described (Sect. 11.3), and the hydraulic infrastructure and the administrative organizations that perform such management in practice is discussed (Sect. 11.4). Furthermore, the answers provided by the current system to the new requirements derived from economic dynamics are analyzed, in the context of growing problems of water shortages and of social concern for the environment (Sect. 11.5). Finally, the chapter presents conclusions and pending issues that must be addressed to devise an adequate management system that attends to the complex demands of society (Sect. 11.6).

11.2 Historical Background of Water Resource Management in Chile

11.2.1 Irrigation Development and Other Uses

The current system of water management in Chile results from a process of expansion of the water uses and organization of users initiated in the nineteenth century. Indeed, since the 1830s, with the transformation of Santiago's neighboring countryside (which was of low agricultural value until that time) into a green and productive territory thanks to the building of the San Carlos Canal, initiatives for the building of irrigation canals and small earth dams proliferated in the small northern and central zones of the country. These initiatives were led by mining entrepreneurs, merchants, and landowners. As a result of such efforts, in 1875 the extent of irrigated land reached 465,000 ha, i.e. 63% of the total product of cultivated land in the country. However, changes in economic conditions, higher complexity and cost of new hydraulic developments, and the decrease of unused water resources caused a decline in private interest in irrigation initiatives. Therefore, in the following decades, it would be the State that, having greater capacity than the private sector, would approach complex projects of high cost and long term profitability developing the extensive hydraulic works in response of the insistent demand of agriculturalists (Correa 1938; Villalobos et al. 1987; Ortega 2005).

This unplanned expansion process, essentially generated by the technical and economic opportunities presented in the central and northern zones to incorporate irrigation, had by 1940 allowed the building of a network of 455 main canals between the Aconcagua and the Maule river basins. Further, hundreds of minor canals in the north of the country, and 17 major dams with a total storage capacity of 433 million cubic meters at a national level were also built. The permanently irrigated surface (with a hydrological exceedance probability of 85%) had already reached 850 thousand hectares (Correa 1938; IING 1970; Figueroa et al. 1987), equivalent to 80% of the current irrigated surface with the same security of supply. On the other hand, hydroelectricity, developed from the late nineteenth century to supply the rising energy demands of the most important urban centers and mining, represented in the same year between 40% and 50% of electrical energy production in the country (Braun et al. 2000).

After 1940, political changes in the country led to a new role for the State with regard to water use, which had two main consequences: the initiation of an industrialization policy, at whose center were the policies of electrification and hydroelectricity; and the strengthening of irrigation plans driven by the State. The plans were no longer seen as conjunctural initiatives in the framework of a public works plan to control unemployment, but as a base for national productive expansion and food security. With regard to irrigation, this strategic vision would remain until late 1970, and until 2000 in the case of hydroelectricity. Thus, existing canal systems were expanded (for example, the Maule system) and a strong impetus was given to the construction of large dams to mitigate the effects of hydrological variability both in agriculture and in hydroelectricity, increasing the total irrigated surface and power generation (Peña 2018a). With the combined public works and incorporated areas during this period, the irrigated surface attained a high hydrological security of approximately one million hectares, and a total dam storage capacity of 3600 million cubic meters.

11.2.2 Building a Regulatory Framework and the Beginnings of Collective Management

For the orderly handling of this hydraulic infrastructure, it became essential to devise a legal framework for water management. With this objective, the first step was the Civil Code text, introduced in 1855, which bestowed upon rivers and waters running by natural basins the status of public ownership resources, and that of private upon some minor sources. Moreover, it established the power to confer the status of "water rights conceded by the competent authority" upon public waters.

Similarly, to determine whether water resources were sufficient to supply the total extraction capacity of the canals during drought periods in different rivers, the "Ordinance concerning the distribution of water in rivers that divide provinces and departments" was introduced in 1872, in which general rules were established for the distribution of water during shortage periods. Starting from this there were ordinances promulgated to regulate the use of water in the main rivers (Aconcagua (1872), Tinguiririca (1872), Teno (1872), Copiapó (1875), and Huasco (1875)). This reflected the virtual exhaust of those rivers for the concession of new grants, and consequently, the end of a period with intensive canal building.

The provisions of the Civil Code and the ordinances were complemented by the promulgation of the Civil Procedure Code in 1902 (which introduced the figure of the Surveillance Board as the representative of the users), the municipal laws of 1887 and 1891, and finally with Law N° 2139 concerning Canal Associations (1908). This last law was a set of rules that regulated the administration of the extensive hydraulic infrastructure developed to that date. This framework incorporated various elements, which constitute the basis of national water management to date, meaning that water use in main rivers would be managed by irrigators with great autonomy. This framework contains many specific features, including the following: the distinction between water rights for permanent use and those for eventual use, which occur when there is an abundance of water; the water distribution between users in periods of shortage, proportionally or by turns; the water users participation in functions related to the resource's distribution and organizing surveillance boards constituted by representatives of the canals that draw water from particular natural sources; and the designation of a Judge of Water for each river, in charge of distributing flow rates.

Finally, in 1951 the first Water Code was introduced. This legal body collected, perfected, and complemented different regulations and practices developed over the course of almost a hundred years. It defined the procedures of access, advertising and opposition to new water rights requests; furthermore, it regulated the functioning of users' organizations, which had to autonomously distribute water in the canals, and the possibility of establishing diverse easements.

The Water Code of 1951 was applicable until 1967, when a new text in the framework of the Agrarian Reform process was approved. The new code had poor implementation (it was implemented only in the first section of the Mapocho river), however, the agrarian reform process meant the expropriation of almost 700,000 ha of irrigated land (Avendaño 2017) and a reassignment of water inside the expropriated zones according to the size of the irrigation surfaces. In 1981 the currently valid code was decreed, which has undergone its corresponding modifications.

11.3 Legal and Institutional Framework for Water Management

11.3.1 Water Legislation: General Considerations

Water resource management in Chile is determined by an extensive set of legal and regulatory texts, the Water Code (W.C.) being the principal, which have been in force since 1981 and were modified in 2005. Other legal bodies have specific rules referring to environmental concerns or to services related to water use.

The Water Code establishes that even when water is legally a public ownership resource (one whose domain belongs to the nation and whose use corresponds to all the inhabitants of the nation), the rights-of-use can be granted to individuals and to Chilean Treasury. They can use, enyoy and dispose of them, as any other good susceptible to private appropriation, and have a similar legal protection.

In addition, the water right is given in perpetuity and is defined as a main good, rather than as the land or industrial purpose for which it would have been destined, so it can be freely transferred, giving rise to a water rights market. Thus, once granted, this right of use can be dedicated to any use for which the holder can contribute the necessary works, with the restrictions that may arise from eventual environmental impacts associated with the uses, or with third party rights.

Requests for these water rights are directed to the competent authority (Dirección General de Aguas) through a regulated procedure that considers the request, allows for opposition to be presented, and directs the allocation of administrative and legal resources for appeals. The applicant must justify that the requested flow rates are necessary for the purposes intended (W.C art. 147 bis), and the authority must grant the right if there is availability and third-party rights are not affected. The above is without prejudice to the State capacity to reserve flow rates for domestic, public interest (C.A. art.147 bis) and environmental (C.A. art. 129 bis 1) purposes. Moreover, with the aim of discouraging the accumulation of rights for speculative purposes, the payment of a patent of temporally increasing value was established, applicable to unused water rights (W.C. Book I. Title XI).

Water rights can be constituted over surface waters and groundwaters, have consumptive or non-consumptive character (when there is an obligation to return the flow to the channel), and have a continuous (distributed on a pro rata basis during shortages) or eventual (withheld during shortage periods) basis. In the title for the water right, the water intake point is defined (and the restitution point in the case of non-consumptive rights), in addition to whether it is continuous or eventual, the authorized maximum flow rates expressed in units of volume per time, and the specific conditions that must be complied with during its use (for example, the obligation to maintain environmental flows).

In general, projects which involve water resource usage are regulated by Law N° 19,300 of 1994, or the Law of General Bases of the Environment (LBMA), with its modification by Law 20,173 of 2007. These regulations allowed the development of the System of Environmental Impact Assessment (SEIA). This is the most important tool that has been derived in the new environmental institutions in Chile, and it allows the revision of principal investment projects, both of public and private character. The system assesses the impact of such projects on the environment, according to criteria established by law, and from this assessment an environmental authorization is issued, containing measures of mitigation, compensation, restoration, and/or prevention of the possible impacts. In addition, LBMA creates a set of tools articulated for protection, prevention, and control of environmental pollution, highlighting rules related to discharge of liquid wastes into the sewer system, the courses of superficial water and lakes (and the groundwater), and the enactment of environmental quality standards in water bodies, constituting the objective to regulate the set of activities related to such bodies.

11.3.2 Public and Private Functions in Water Management, and Institutionality

Considering the strategic value of water for national economic and social development, and for environmental conservation, the current legal framework delivers to the State, among others, the following main functions: the investigation and measurement of water resources (DGA); the regulation of water usage (DGA); the regulation of services associated with water resources, drinking water and sanitation particularly, and the promotion of conditions for its efficient economic development; the conservation and protection of water resources in a framework of sustainable environmental development; the provision of basic water requirements to the poorest sectors of the population; the protection of the population and goods from flood impacts and other extreme phenomena associated with water; the development of irrigation works which, because of their complexity and magnitude, are unable to be developed directly by the private sector; and, in general, the promotion and support of the development of domestic irrigation activities.

In Chile, the institutional structure is characterized by having a governing entity for water resources that is independent of the user sectors and the project development sectors. Water related services (drinking water, sanitation, and energy) have a distinct and specialized institution for their regulation. The measurement, investigation, and cadaster functions are integrated into the responsibilities of the governing institution. Environmental institutionality integrates transversely into the public bodies that have environmental competences. Sectoral promotion and the construction of hydraulic works (particularly irrigation) are managed by bodies that are independent of the governing institution.

Within the 42 bodies related in some way to water resource management and development (World Bank 2013), the following should be noted. The General Water Directorate (DGA) is a state body in charge of applying the regulations established in the W.C. The Ministry for the Environment (MMA), has two specialized entities: the Environmental Evaluation Service (SEA), which is responsible for managing the System of Environmental Impact Assessment (SEIA); and the Superintendency for the Environment (SMA). The regulatory body for the sanitation sector is the Superintendency of Sanitary Services (SISS). The energy sector is managed by the National Commission of Energy (CNE). The National Commission of Irrigation (CNR) is responsible for national irrigation policy, and the Directorate for Hydraulic Works (DOH) of the Ministry of Public Works, a technical body of the State, is in charge of the realization of hydraulic infrastructure projects, including the building of a rain water primary drainage network in urban zones, and rural potable water systems (APR). Indirectly, the Budget Office (DIPRES) of the Ministry of Finance and the Ministry of Social Development are implicated in the sector, controlling the quality of State investment (Fig. 11.1).

In addition to public bodies, there are user organizations (OUAs) with relevant functions in water management. They are autonomous entities, of private character, supervised by the State. Its objectives are distributing water resources according to

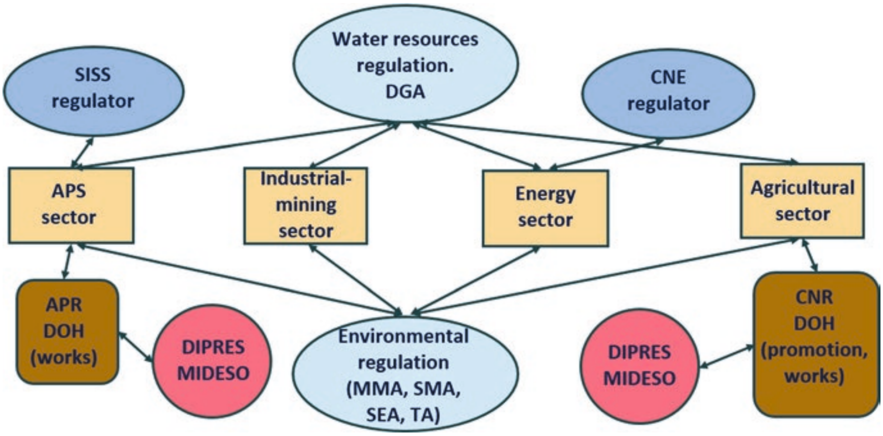

Fig. 11.1 Main institutions in the public sector for water resource management

the water usage rights of its users, building, maintaining, improving, and managing the distribution systems, and resolving any conflicts that may arise. Among them are the Surveillance Boards (JdV), which have jurisdiction over a particular basin or section of a river, and the Canal Associations and Water Communities that operate at the level of artificial works, whether they be canals, aqueducts, wells, or other constructed water systems.

11.4 Water Resource Management in Basins

11.4.1 The Physical Geographical Framework and Basin Sectioning

In Chile, the presence of the Andes Mountains and the short river length from source to mouth give rise to basins of modest size. The geomorphological and geological conformation of the valleys, with steep slopes, localized rocky narrowing, and aquifers of small dimensions produce an extremely active interaction of surface waters with groundwater along the channels. In this context, irrigation water usage, historically with a low level of efficiency, favored the return to the system of the fraction of extracted flow not effectively consumed, through the so-called “return flows”, or through percolation to aquifers. In this way, water resources generated in the mountainous zone of the upper basins, with a snow or pluvio-snow regime, are reused successively several times along the channels. Thus, in the north and center of the country, the answer found over a century ago was to use the flow recovery of the rivers downstream to manage water resources through the use of localized systems built at the level of stretches of river (“Sections”), instead of at the level of the entire river or basin. This accepted that the available water in the stretch or section can be distributed in its entirety, according to water rights belonging to that section, without the obligation of delivering water to constituted rights in other sections downstream. Thus, for example, the main basins located between the Elqui and Maule rivers contain between 5 and 15 sections managed independently (DGA/REG 1991).

11.4.2 The Water Management Infrastructure

Since the nineteenth century, a significant hydraulic infrastructure has been developed throughout the country, consisting of approximately 6400 canals with intakes from natural rivers. If canals forming the primary and secondary network are included, a total in the order of 12,000 irrigation canals is reached, with an estimated length of 40,000 km. This network is complemented by 1180 minor or medium dams, and 38 major regulation works built by the State for irrigation purposes. The national storage capacity (without considering dams built exclusively for electricity generation) represents a total of 4460 million m^3. These dams include Maule Lake and Laja Lake, natural systems augmented by man-made structures. The construction of dams in the north has been a priority due to greater shortages and higher flow variability in that zone. Thus, the storage capacity equals 82% of the mean runoff from the Coquimbo region to the north, while such capacity equals 6% in Metropolitan and Valparaíso regions, and just 5% in the zone between the O'Higgins and Araucanía regions. These values can be compared to the situation in the USA and EU, where the equivalent parameter reaches 33% and 16% respectively. The above shows that, with a few exceptions, flows in the first zone are almost completely regulated (Peña 2016).

The canal network consists predominantly of ground canals, with distribution systems whose structures distribute flow based on fixed proportions, according to the rights of different users; there is no delivery on demand, with a few exceptions. There is some limited use of telemetry systems, remotely operating gates, and pressurized conducting systems.

11.4.3 Water Distribution by Users

Water distribution is the responsibility of the Surveillance Boards, canal associations, and water communities, formed by water rights owners (see 3.2). These organizations are carefully regulated with reference to the Water Code; the internal organization, attributions, forms of users' participation, and the DGA's supervisory faculties are indicated, among others. There are 3489 organizations officially registered, including 46 surveillance boards (DGA 2016).

The user organizations self-finance their operations and the maintenance and improvement of the water infrastructure, and have policing and conflict resolution functions. Surveillance boards must take extraordinary distribution measures during shortage periods. For that purpose, they normally use flow forecasts to define the water release plan during the irrigation period. The President of the Republic, with the DGA report, can declare a zone to be in “extraordinary drought”. In those cases, the DGA can authorize emergency measures regarding water usage, and, eventually, intervene in distribution, replacing the role of the surveillance board.

In central Chile, while the irrigation water supply remains critical during the final months of summer, energy demands are higher during winter periods. Consequently, competition for the opportunity to discharge stored resources is generated between the irrigation and electricity sectors. This situation, exacerbated by the fact that user organizations are entities fundamentally constituted by irrigators, has been the cause of judicial proceedings and, in recent years, has given rise to negotiations to attempt to obtain mutual benefits, including economic compensations (Peña 2018a).

National development of surface water management over the past century contrasts with the scant progress made in groundwater management. Although different aquifers present overexploitation problems, there is just one groundwater community with an effective strategy in groundwater management, and 10 other recently constituted communities remain in a period of consolidation. In practice, there is neither control over extraction, nor plans for groundwater management. Thus, it is a considerably delayed matter that requires urgent progress (Peña 2018b).

11.5 New Requirements for Water Resource Management

11.5.1 General Considerations

Since the 1980s, water resource systems, with their rules, institutions, and incentive systems, have had to answer challenges different from those of food and energy security from previous periods. Economic policies of international trade based on export products associated with water management (copper, fruticulture, wines, salmon farming, cellulose, etc.) have generated a strong economic dynamic associated with the supply of new demands. In addition, water management has incorporated an important concern for environmental conservation and protection.

These challenges have been presented in a context of great natural runoff usage in most of the country. Regarding existing water scarcity levels and the natural limitation that water resource management introduces to development, there are three markedly differentiated zones. The first is the region from Metropolitan Region of Santiago, MR, to the north: in this zone almost all of the resources naturally generated in basins are used and water availability constitutes the main limitation for its economic growth. Water demands represent on average 88% of the natural flow of the basins, and flow discharges to the sea in extreme drought years are null or insignificant, and have shown significant abundances in only a few wet years. On the other hand, the high economic productivity associated with irrigation causes irrigated areas to proliferate, increasing coverage by 50% in some basins. In this context, there are important sustainability problems in the current usage, which has become clear with the droughts of recent years (Peña 2016). The second region is from the Rapel basin to the Araucanía region: a zone that occasionally presents local water availability problems to meet current demands. However, with proper management and infrastructure, water resources would allow unrestricted development of current demands, even with a significant increase in irrigated surfaces. The third is the Los Ríos region to the south: this zone, in general, is characterized by abundant water resources and a low demand of consumptive character. In this context, water resource management must respond to the supply of new demands and to the incorporation of environmental conservation objectives.

11.5.2 Supplying of New Demands

According to the current management system's regulations and incentives, to meet new demands the following strategies have been adopted:

(a) Water usage not yet assigned by the State: new consumptive rights-of-use on surface waters were constituted in some historically marginal sectors. These include lower courses from some main rivers and secondary tributaries located from MR to the south and in the Bío-Bío basin southern rivers, where irrigation had been little used (DGA 2001–2005). On the other hand, interest in hydroelectric generation caused an explosive increase in non-consumptive water rights requests. Such rights could be constituted as long as they do not interfere with consumptive rights granted previously and, since 2005, as long as they do not affect national interests. Number of rights granted reach 9600 with a permanent flow discharge of approximately 22,000 m^3/s, corresponding mainly to the south and austral zone rivers (DGA 2016).

Since the 1980s, groundwater has played a central role in supplying new demands, because it was previously an underused resource. Thus, annual requests to the DGA concerning new rights exceeded 100 in 1980 and some 800 in the year 2000; furthermore, the number of irrigation wells increased sevenfold in 10 years (Peña 2018a, b). Currently, the number of rights over groundwater reaches 47,000, with a maximum authorized extraction flow of 450 m^3/s. This process has caused limited access for new users in 157 aquifer sectors through declarations of restriction and prohibition areas covering almost all aquifers from the Rapel river basin to the north (DGA 2016).

(b) Improvements in efficiency: economic dynamics and shortages have caused significant improvements in water resource usage efficiency. In the irrigation sector, incorporation of new methods of technical irrigation (dripping, micro-aspersion, aspersion) has had a positive impact, in particular in agricultural zones associated with export products. At present, it is estimated that nearly 40% of agricultural surface uses these techniques. In the industrial and mining sectors, an equivalent change has been produced. For example, copper mining went from an average consumption of approximately 2 m^3 per ton of treated mineral in the 80s to 0.75 m^3/ton in 2000; the current standard consumption is in the order of 0.5 m^3/ton (Peña et al. 2004) (Peña 2016).

(c) Market and reassignment of water rights: according to the current legal framework, reassignment of water rights is effected through market mechanisms. It is a highly segregated market that depends on local supply and demand peculiarities, where two kinds of goods can be traded: water rights, on which users take long-term decisions; and the water resource itself, obeying short term considerations, meaning, in practice, the leasing of rights-of-use. According to studies carried out, the national rights-of-use market presents a high price variability and a relatively low depth, with annual transactions from 2% to 6% of existing rights in basins with greater shortages (EMG 2011). Without limiting the aforementioned rights, the number of annual water rights transfers in the country, independent of other goods transfers, such as land, exceed 1000 (EMG 2011), and play an important role in supplying new demand. Transfers are usually made from agriculture to sanitation companies, or to other agricultural users. In recent years, the mining industry has chosen seawater desalination, given uncertainty associated with social opposition to such transfers, and the regulatory framework (Cristi et al. 2014). The background of transaction prices shows values generally decreasing from north to south: US$ 15,000/l/s to US$ 60,000/l/s in Coquimbo to the north; US$ 4000 to 6000/l/s in the Aconcagua and Metropolitan regions; and US$500 to US$3000 to the south of the Metropolitan region (Peña 2016).

The temporary transfers market has little activity and there is limited information about it, with the exception of the Paloma system, where the existence of large interannual regulation dams and a network of canals lends a certainty to the transactions, and generates low transaction costs. In this case, in periods of drought in some sectors up to 16% of the rights have been reallocated in one year, while prices increased by 10 times in comparison with normal values (Peña 1997).

11.5.3 Water Quality Management and Environment Protection

In practice, the pollution control of bodies of water started in the late 1990s with the introduction of emission standards controlling the quality of discharges into the sewage system (DS609/98), the surface water (DS 90/2000), and the groundwater (DS 46/2002). This allows the control of approximately 3800 industrial establishments, of which 600 emit discharges into surface water or groundwater, and the rest to the sewage system. Likewise, urban wastewater treatment increased from a coverage of 17% in 1998 to 100% since 2012 (SISS 2012). However, this progress in emissions control and advances in the establishment of secondary quality standards has been marginal: just six secondary quality standards have been introduced, while most rivers, lakes, and aquifers remain without such regulation. Thus, there are no bodies of water declared as latent or saturated zones in the whole country, and, consequently, there have been no implemented prevention or decontamination plans. In addition, despite the widespread and excessive use of fertilizers and pesticides (OECD/CEPAL 2016), no rule has been established for diffuse pollution control.

According to the historical use of national water resources, considering resource extraction for productive purposes without environmental limitations, most of the central and northern zone canals have no obligation to maintain environmental flows. An exception is in projects approved since the implementation of the system of environmental impact assessment and in hydraulic developments with rights of water usage approved under the reform of the Water Code from 2005. In addition, there are zones with special environmental protection, conditioning water resource management to those objectives. Thus, 216 aquifer systems supplying *vegas* and *bofedales* in Arica and the Parinacota, Tarapacá, and Antofagasta regions are protected; the National System of State Protected Areas (SNASPE) includes 101 zones in different protection categories, and there are 13 Ramsar sites (DGA 2016).

11.6 Conclusions

The background presented shows that, fundamentally, the legal framework, infrastructure, and practices related to water management in Chile were established over a century ago, in the basis of a system of water rights granted by the State and managed by users. In this system, the State has active participation in developing irrigation through the construction and financing of great regulation works and the associated canal systems.

In recent decades, in a scenario characterized by the assignment of main water resources to former users, resource management had to answer economic dynamics generated by a development strategy based on export products that are directly associated to water usage, and by the need to address environmental concerns.

In the current system, based on the reassignment of water between users, the incentives provided by the legal framework and the existing programs for efficient use of water resources, and development of unused water resources, have supplied new demands; however, this also presents increasing problems in specific basins.

On the other hand, regulations established since the 1990s tarjeting localized water pollution have successfully begun to solve the main problems, in particular those arising from urban wastewater. Likewise, the environmental regulations applicable to new projects and developments, and the introduction of a special protection regime for certain zones with vulnerable ecosystems, have incorporated environmental conservation criteria in water resource management. However, the century-old practices consisting of depleting water extraction from the rivers, the existence of environmental liabilities with highly polluting deposits, and topics associated to diffuse pollution of agricultural character, have not yet been the subject of improvement programs or normative changes, and present a significant delay.

The main weakness shown by the water resource management system in Chile is the absence of tools that allow for strategic planning and an integrated water resources management program oriented to guarantee sustainability in the long term (Peña et al. 2012). It is an urgent need considering the multiple and complex processes presented in the framework of basins related to the development of new demands, climate change, market based water rights reassignment, development of new sources, changes of usage and efficiency, increasing demands for environmental protection and conservation, changes in the vegetation coverage of the watersheds and numerous further considerations. All of the above is characterized by the abundant interactions between the decisions of multiple actors and the externalities generated throughout the hydrological system.

The limitations of the current system do not allow proper handling of externalities associated with successive water usage caused by basin sectioning. Nor does it allow the optimization of the joint use of surface water and groundwater; adaption to reduced water availability due to climate change; integration of environmental and water quality aspects to water resource management; development of multisectorial water usage; nor the coordination of territorial ordering with water management.

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Chapter 12
Agricultural Uses

Francisco Meza, Pilar Gil, and Oscar Melo

Abstract The agricultural sector is the primary water user in the country, with withdrawals of around 82%, while mining, industrial and urban sanitary uses share 18%. Given its relevance, we discuss the aspects that determine the present and future water demands by this sector. We also identify significant knowledge gaps that need to be addressed to ensure the sustainable use of water resources in the country. General characteristics of irrigation in the main macro-zones of Chile are presented, followed by an assessment of the current situation of surface and underground water use, as well as of rainfed agriculture. The significant impact of recent trends in water use in agriculture, including the evolution of irrigation systems, water quality demands, and the impact of the ongoing drought are discussed. Finally, future projections and challenges for water use in agriculture, including climate change impacts, and future trends are analyzed.

Keywords Agriculture · Water demands · Irrigation · Groundwater · Rainfed agriculture

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12.1 Introduction

Chilean agriculture, livestock and forestry holdings have been always one of the most important economic sectors. Over decades, these activities have developed and flourished almost along the entire territory, generating a sectorial GDP of USD 7.3 billion and being one of the most labor intensive sectors of the country, demanding more than 700,000 jobs annually (ODEPA 2017a). The vast majority of the holdings correspond to units of less than 5 hectares, representing 41.6% of the surface for agriculture, forestry and livestock use. According to the latest National Agricultural Census (INE 2007), total cultivated area reaches 2,123,942 hectares, with 1,303,210 hectares dedicated to annual and permanent crops. Based on the same source, irrigated agriculture represents 1,200,000 hectares, which corresponds approximately to 50% of the cultivated area. However, over the last years there has been a rapid transformation of the agriculture with a notorious decrease of the surface allocated to annual crops, being rapidly replaced by perennial horticultural crops and vineyards that can be grown only if water is secured via irrigation, so it is very likely that the share of irrigated agriculture, would be, at present times, substantially higher.

The agricultural sector is the main water user in the country, with withdrawals of around 82%, while mining 3%, industrial 8%, and urban sanitary system 7%, (DGA 2016). Hydropower generation is the most important non-consumptive sector (i.e. water is used to generate electricity and then returned to the river basin with minimum evaporative loses). There is a significantly high level of competition among sectors, especially in northern and central part of the territory where water is relatively scarce and most of the water rights have been already allocated.

The basic structure of water governance in Chile is centered on transferable water use rights, and based upon water user associations at different levels of organizations, and the water authority (Dirección General de Agua, DGA). Farmers own surface and underground consumptive water use rights, though not all of them have regularized their rights according to the 1981 Water Code. This code leaves the allocation of new water rights to the water authority, but recognizes customary users. The management of river or aquifer waters is left to the private water users associations, which may include water user from different economic activities besides farming. Also, there are water user associations that manage major canals and water communities in addition to smaller sections of a canal. These associations are mostly composed by farmers, and tend to be better organized where water is scarcer.

Given the relevance of agriculture as consumer of water resources in Chile, our aim is to discuss the most important aspects that determine the present and future magnitude and seasonality of water demands by this sector, and to identify major gaps in knowledge that need to be addressed to ensure a sustainable use of water resources in the country.

12.2 General Characteristics of Irrigation in the Main Macrozones of Chile

From the total arable land in Chile (5.1 million hectares), it is estimated that 3.3 million do not have surface water distribution or irrigation infrastructure and therefore correspond to rainfed agriculture, while 1.8 million hectares would be under the influence of surface water that is conducted via channels. It should be noted that only 1.2 million hectares of irrigated land have a high reliability of water supply, being regarded as having permanent water rights associated to that surface (i.e. water rights defined based on the flow with 85% of exceedance probability). The remaining 0.6 million hectares would correspond to contingent water rights (INE 2007). As it was mentioned before, these figures are obtained based on information from the latest agricultural census, which was carried out more than 11 years ago (INE 2007). Thus it is to be expected that, due to changes in the planted area during the last years, and the influence of climate change on the location of production areas, the current scenario would be different from what the official numbers say.

From the point of view of water resources, Chile has 101 hydrographic basins whose surface and underground water resources are distributed within the 756,102 km^2 of its continental territory (DGA 2016). Hydrological sources are composed mainly by 1251 rivers and 12,784 bodies of water (lakes and lagoons), in addition to 24,114 glaciers that also contribute to the runoff in the dry season. The average precipitation at the country level is 1525 mm/year; part of this precipitation becomes superficial runoff, which flows through the different basins, with a total average at the country level of 29,245 m^3/s (DGA 2016).

On average, Chile is considered as a privileged country in terms of water resources. Total runoff is equivalent to of 51,218 m^3/ person/year, which is considerably higher than the world average (6600 m^3/person/year) and much higher than the international threshold for sustainable development (2000 m^3/person/year) (World Bank 2010). However, Chile has a highly heterogeneous spatial distribution of water resources. From the Metropolitan Region (Central zone of Chile) to the north, water shortage conditions prevail. Average per capita runoff is below 500 m^3/person/year. Drought cycles are recurrent, aggravating water scarcity; the last event of drought has lasted for more than ten years, and because of its great impact and extension has been called “the Mega-drought” (Garreaud et al. 2017).

Administratively, Chile is divided into 15 regions or districts (I to XV) which coincide in part with the divisions of the main hydrographic basins of the country. However, according to Dirección General de Aguas (DGA 2016), four zones can be identified in terms of water resources, which are described below.

12.2.1 Northern Macrozone

This area has 39 hydrographic basins according to the “Hydrographic Basin Inventory” (DGA 2013). It covers a total area of 300,904 km^2, and is formed by the administrative regions of Arica and Parinacota (XV Region), Tarapacá (I Region), Antofagasta (II Region), Atacama (III Region) and Coquimbo (IV region). This area harbors 2,282,106 inhabitants, which corresponds to 12.67% of the total national population. This area is characterized by an arid to semi-arid climate, with scarce rainfall reaching 87 mm/year. Regarding surface water resources, this area has a very low runoff of 36.9 m^3/s, equivalent to 0.13% of the national total and being the lowest runoff per capita with a total of 510 m^3/person/year. One of the main economic activities that takes place in the Northern Macrozone is Mining, concentrating 78% of the companies. This activity requires water for its processes, with an estimated demand of 10.41 m^3/s. (DGA 2016).

Agriculture in this region is dominated by smallholder familiar farming, concentrated in horticultural crops, sweet corn, lettuce, tomato, bell pepper. Fruit trees are mostly citrus, mangoes, and olives. There is a large fraction of the territory dedicated to pastures that support a small size livestock productive systems mostly goats and sheep shepherd’s (INE 2007). As we move southward in this macrozone, in the Coquimbo region, agriculture becomes more intensified with relative large exploitations dedicated to table grapes, wine grapes, mandarines, avocados and blueberries (INE 2007). Due to the relatively low and highly concentrated precipitation, dams are of utmost importance to maintain agricultural activities. Among the most important we can find the Lautaro and Santa Juana reservoirs in the Atacama region, and Puclaro and the Paloma System (Paloma, Recoleta and Cogotí interconnected reservoirs) in the Coquimbo region (DGA 2016).

12.2.2 Central Macrozone

This zone concentrates the largest number of inhabitants of the country, with a total of 11,101,673 people, approximately 61.65% of the Chilean population. This zone has an area of 78,482 km^2, and have 16 hydrographic basins (Dirección General de Agua 2013). It includes the administrative districts of Valparaíso (V Region), Metropolitan Region of Santiago (RM), Libertador General Bernardo O’Higgins (VI Region) and Maule (VII Region). This area presents a Mediterranean climate with moderate rainfall, with an annual average of 943 mm/year that is concentrated in winter and with a prolonged dry season of 7–8 months. The sum of the surface runoff of this macrozone corresponds to 1116 m^3/s, which is equivalent to 3.8% of the total national runoff, with an average per capita of 3169 m^3/person/year. This area concentrates the largest surface of arable soils for cultivation, which, together with its favorable climatic characteristics (i.e. strong seasonality with occasional extreme events that affect crop yields) and relatively large water availability, allows for the development of a diversified and rather productive agricultural, forestry and livestock systems, mainly focused on exported fruits and vegetables for domestic market (INE 2007). In this area, the agricultural activity uses an estimated total of 389.25 m^3/s of water for irrigation, while 38.17 m^3/s is demanded for domestic use. As a comparison, the industrial sector has an estimated demand of 20.23 m^3/s and mining demands reach estimated value of 4.04 m^3/s for production processes (DGA 2016). Several reservoirs of medium to large storing capacity have been built in the region. The most important ones are the Peñuelas and Yeso reservoir (domestic water consumption); Convento Viejo (Irrigation) and the Rapel lake, Colbún and Laguna Maule (Hydropower and Irrigation) (DGA 2016).

12.2.3 Southern Macrozone

This macrozone covers a total area of 135,925 Km^2, with 4,349,639 inhabitants, which corresponds to 24.16% of the national total. This area includes the districts of Biobío (VIII Region), La Araucanía (IX Region), Los Ríos (XIV Region) and Los Lagos (X Region). This area hold 26 basins according to Dirección General de Agua (2013), were total runoff reaches 7834 m^3/s (representing a 26.8% of the total national runoff), reaching 56,799 m^3/person/year. This zone is characterized by a temperate to maritime Mediterranean climate with abundant rainfall (2420 mm/year in average). In this area, forestry and farming activity are based on the production of annual crops, cattle and forests (INE 2007) In recent years, fruit industry has moved to this area due to favorable climatic conditions associated with ongoing climate change and because fruit production has become comparatively more profitable than extensive agriculture. It is estimated that forestry and agricultural activity consume a total of 84.26 m^3/s for irrigation in this area, while 13.89 m^3/s is the estimated demand for the industry sector, and 9.91 m^3/s is destined to domestic use (DGA 2016).

This zone has undergone one of the most accelerated transformations in its agriculture. Pasture and livestock systems as well as annual crops such as wheat and barley have been replaced by an export oriented agriculture based on fruit trees such as walnuts, blueberries, European hazelnut, and cherries (ODEPA and CIREN 2016). These systems coexist with traditional annual crops such as potatoes and, towards the south, with a fairly sophisticated dairy industry.

Almost all of these productive systems rely on irrigation. Even though the climate of the region shows relatively abundant rainfall with low interannual variability, the nature of the invested capital and the high value product have made farmers to invest in irrigation systems such as drip irrigation and center pivot types.

12.2.4 Austral Macrozone

This has the highest runoff of the entire national territory, with 20,258 m^3/s, which is equivalent to 69.3% of the total country. This implies that per capita runoff is 2,340,227 m^3/person/year. The area encompasses the administrative districts of

Aysén (XI Region), Magallanes (XII Region) and the Chilean Antarctic territory. It totals an area of 240,791 km^2, with a total of 272,989 inhabitants, which corresponds to only the 1.52% of the total country. This zone has 20 basins according to the "Inventory of Hydrographic Basins" (Dirección General de Agua 2013). The austral zone is characterized by a high annual precipitation amounts, that reach on average 2963 mm/year. Regarding the economic activities carried out in the area, livestock, forestry and mining stand out. Of them, the demand for water is focused on the industrial sector with an estimated consumption of 5.99 m^3/s, followed by the mining with an estimated value of 2.83 m^3/s, followed by the agricultural sector that has a demand estimated of 1.76 m^3/s of water and 0.67 m^3/s for potable water use.

12.2.5 Status of Water Resources and Groundwater Use

In the last decade, due to the reduction in rainfall, a sustained decrease in the available surface water has been observed. The scarcity of fresh water supply in some areas, has resulted in conflict between consumptive water users (water used for agricultural, industrial, mining and domestic use, excludes water used in hydroelectric plants). Chilean legislation allows that, when depletion of a water source is confirmed, the State can issue a decree of surface water source exhaustion; this legal instrument, serves to restrict the constitution of new rights for using surface water of consumptive type and permanent exercise in the natural source of the respective surface water (river, lake, lagoon or other) where the availability of the water resource has been exhausted. Between the years 1952–2015 a total of 11 declarations of exhaustion have been dictated, whose area reaches 76,131 km^2; 82% of this area corresponds to the Northern Macrozone.

It is estimated that Chile has an important volume of underground water resources. The estimated average recharge reaches 55 m3/s from the RM to the north, while to the south of VI Region, the estimated recharge would be around 160 m^3/s between regions VII and X (Southern zone) (DGA 2016). Regarding the Austral zone, there is no consolidated information on it potential of recharge (Word Bank, 2011). The effective use of groundwater was estimated of 88 m^3/s in 2003, of which 49% is used for agriculture, 35% for population supply and 16% for industries (Salazar 2003).

Groundwater is particularly important for the mining and domestic use. Groundwater for agriculture is also important in regions XV, I, II, III, and IV (Northern Macrozone) (World Bank 2011). Due to the shortage of rainfall that has occurred in the last decade, and that has mainly affected the Northern and Central Macrozones of Chile, coupled with the displacement of intensive production areas to the Southern Macrozone, the demand for underground water has increased, which has caused the depletion of some aquifers, mainly concentrated in the northern and central areas.

As explained for the case of surface water, in the case of groundwater there are also legal instruments to declare restriction and even prohibition of exploitation of groundwater. Between 1997 and 2015, 144 areas of Restriction of exploitation of

Table 12.1 Agricultural uses of water in the between Atacama and Biobio regions

Region	Tributary flow (m^3/s)	Surplus flow (m^3/s)	Extracted Water Km^3	Irrigation Demand Km^3	Available for Irrigat. Km^3	Deficit or Surplus Km^3
Atacama	0.19	0.05	0.13	0.12	0.05	−0.06
Coquimbo	1.15	0.57	0.48	0.53	0.43	−0.10
Valparaíso	1.20	0.60	0.57	0.65	0.45	−0.19
Metropolitana	3.66	2.14	1.14	1.03	0.91	−0.12
O′ Higgins	4.10	4.66	2.05	1.58	1.84	0.26
Maule	8.10	15.25	4.05	2.24	3.65	1.40
Biobío	20.15	26.81	8.06	1.25	4.84	3.59
Total			16.47	7.39	12.17	

groundwater have been decreed by DGA, which corresponds to a total of 87,541 km^2 of the surface, with respect to the zones of prohibition, the DGA has only declared 6 zones between the years 1983 to 1999 with a total of 11,052 km^2 of committed surface, being the Northern Macrozone the one that concentrates the greater number of sectors with this mandate (World Bank 2011).

A summary of water demands for agriculture is presented in the study of ODEPA (2017a) and synthesized in the table below (Table 12.1).

12.2.6 Rainfed Agriculture

Rainfed areas in Chile normally have favorable climate conditions for the development of a productive agriculture, particularly in specific areas such as coastal zones, where diurnal temperature range is moderate and only few frost events can be observed. As we move south, rainfall increases and interannual variability decreases, generating adequate conditions for crop growth and development. Soil health turns out to be the most limiting condition for the development of profitable agriculture; soil degradation via erosion, high loss of soil carbon and soil organic matter, and relatively low soil nutrient availability, which results into low natural fertility, limit agricultural productivity. Groundwater resources are presented as an alternative only in certain areas, but wells traditionally have low yields. Many of these areas have been reforested with pine and eucalyptus, which, although have stopped erosion, have negatively affected water availability (Gligo 2015).

In Chile, different rainfed areas can be identified. Coastal dryland corresponds to the area between the western slope of the Cordillera de la Costa, the coastal terraces and the districts with coastal climatic influence between the Atacama and the Los Lagos Region. The inner dryland area is the one that extends between Regions of Valparaíso and Araucanía, basically covering the eastern slope of the Cordillera de la Costa (ODEPA 2000). A clear latitudinal gradient of rainfall can be observed. Its origin is the location and strength of the Pacific Subtropical High (Pacific Anticyclone) that moves to lower latitudes in winter and allows the entry of polar fronts that generate rainfall conditions in winter. In addition, the topography and latitude of the area facilitate the rise and cooling of air masses resulting in increased condensation. Another representative dry area corresponds to the foothills of the Andes, which extends between the central valley and the Andes mountain range. This area is mainly used for annual crops. It has a much smaller dry season than the inner dryland area (2–3 months), and presents an excess of rains in autumn-winter (Canto 1989).

Rainfall in the dry land is very poorly distributed, with a dry period between one and eight months (shortened as it goes further to the south) (World Bank 1995). The average of annual rainfall is between 500 and 1000 mm (Selker 2000), which occur abundantly during some months (autumn-winter), leaving the soil with high moisture availability (Subiabre 2000). There is great variation in rainfall between year to year, with three consecutive years of drought, which causes large losses in agricultural production. The proximity to the Pacific Ocean moderates temperature regimes in coastal areas, extending 15 Km inland, generating humidity and frost control conditions that are favorable for agricultural development (World Bank 1995).

The Chilean rainfed areas can also be divided according to its latitude. The semiarid Mediterranean zone, for example, is between parallels 30 and 32, and is dominated by extensive livestock systems (goats and sheep) based on natural pastures with occasional crops of winter cereals (wheat and oats). The Mediterranean marine zone extends between parallel 32 to 38, where greater rainfall is observed which allows the establishment of mixed systems of winter crops (wheat, oats, lentils, chickpeas, raps), livestock (sheep, beef cattle) and prairies (natural and artificial). The southern rainfed area extends from 38th parallel to the south, and is characterized by the existence of cattle and dairy systems, based on natural meadows alternated with winter crops.

Among the most important crops produced in the Chilean rainfed zone, the more relevant are vineyards (24,734.81 hectares), olives (unknown exact surface), potato (22,000 ha), wheat (139,000 ha), oats (65,000 ha), sugar beet, raps and lupine (29,500 hectares in total). The quinoa crop (1000 ha) also stands out in the north. Regarding forest plantations, in the Chilean dry land they reach over 100,000 hectares planted from the Valparaiso to the Los Ríos region, concentrating the production in the Maule region with 1,165,000 hectares (INE 2007).

12.3 Recent Trends in Water Use in Agriculture

12.3.1 Evolution of Irrigation Systems

Chile has had an important evolution in terms of new techniques of irrigation systems, which is partly explained by the Law of Promotion for Private Investment in Irrigation and Drainage (Law No. 18,450, of 1985), which subsidizes minor and medium irrigation infrastructure. This law is administered by the National Irrigation Commission, under the Ministry of Agriculture of Chile. According to the last Agricultural Census (INE 2007), the irrigation surface with traditional or gravitational systems decreased from 91% to 72% of the irrigated area in 10 years, while the area irrigated under pressurized systems such as sprinkler increased from 3% to 5%, and the area irrigated under pressurized micro irrigation (drip, micro-sprinkler and others) grew from 6% to 23%. As already mentioned, the official data of the last census (2007) are quite old, and it is estimated that currently, the surface irrigated with pressurized systems (considering sprinkler and micro-irrigation systems) is currently reaching 40% of the irrigated area (Martin 2018, personal communication). A large part of the irrigation projects co-financed by the Law 18,450 have been developed considering the availability of water resources for an irrigation security of 85%. However, climate change, competition for the resource and over-exploitation have resulted in that a fraction of the surface that is supposed to have high irrigation reliability, today does not have access to water, and therefore several irrigation projects have been abandoned. In a long-term projection, rainfed sectors will enter to what we consider irrigated agriculture, and for this groundwater will be consumed, or new irrigation investments and infrastructure will have to be constructed in order to transfer water from one area to another.

12.3.2 Water Quality Demands

Water quality has been identified as a limiting factor and a source of risk in agricultural production. Because a large share of production is exported as fresh produce, quality controls, good agricultural practices and certifications require a minimum water quality. Local vegetable production, on the other hand, does not have explicit water quality requirements except through minimum health standards. This has been one of the critical points for agriculture, especially small farms that usually do not have the means to treat water.

Agriculture is also a source of water pollution, and environmental regulation in Chile is starting to require the adoption of conservation measures (Melo and Perez 2018). Although high levels of nitrogen and phosphorus have been detected in several water bodies, its link to agricultural activities has been harder to prove. Nevertheless, it is certain that this issue is becoming a relevant constraint for agriculture that calls for a rational use of fertilizers and pesticides.

The natural chemical characteristics of water presents a great variability throughout the national territory, with a high concentration of salts in the arid zones (Northern Macrozone), that decrease towards the more humid regions. The quality of surface water is conditioned in Chile by some characteristics of the hydrographic systems: (a) the conditions of aridity or semi-aridity of an important part of the territory, raising the salinity levels of natural waters; (b) the short route of the rivers, product of the short transversal extension of the country; (c) the heterogeneous spatial distribution of the population and industrial activity, concentrated mainly in the Regions Metropolitana, Valparaíso and Bío Bío; (d) the effect of activities that use fresh water: mining, agricultural and forestry, which are of great importance for national development (World Bank 2011).

Regarding water quality characteristics that restrict agricultural productivity, these vary depending on the area. In the Northern Macrozone for example, there are surface and underground waters with high salt contents, with values of electrical conductivity (EC) between 500 and 2000 μmhos/cm and more (World Bank 2011). This condition decreases significantly towards the Central Macrozone, where only some areas have restricted waters, especially those whose water source crosses areas of high demographic concentration (eg: Maipo and Mapocho River in the Metropolitan Region of Santiago). Towards the Southern Macrozone, the quality of the water improves remarkably, finding waters with EC lower than 200 μmhos/cm. Regarding the content of chemical elements in water, the microelements of greatest attention are arsenic, boron and some heavy metals such as copper, molybdenum, manganese and iron, which are often found in the northern most area of the Northern Macrozone, which is associated with the volcanism of the Altiplanic zone. The boron content also constitutes an important restriction for many of the waters of Atacama and Coquimbo regions, where fruit and vegetable production is important. Regarding the quality of groundwater, because of its interaction with surface waters, it is observed that its chemical quality is not very different from that of the surface waters that recharge it, although it is observed that groundwater presents a better physical and microbiological quality (World Bank 2011).

It should be noted that, during periods of drought, a greater water quality deterioration effect due to pollution processes can be expected, due to lower dilution capacity in reduced surface water flows. According to current regulations (Norma Chilena n° 1333, NCH1333), contaminated water cannot be used for irrigation, increasing pressure for water resources with adequate quality levels. An increase in the availability of water for irrigation can occur as pollution treatment plants or the use of technologies for desalination, increases. Chilean standard for drinking water is rather high, since it is designed to protect human health (Norma Chilena n° 409, NCH409). Water regulations for irrigation (NCH 1333) consider physical, chemical and food safety parameters that have lower standards than those associated to drinking water. It should be noted that NCH 1333 establishes a maximum limit of total coliforms of 1000 NMP/100 ml (most probable number in 100 ml), which is a much higher tolerance range than what is required other countries. In Chile, large part of its holdings regulated by the Global gap regulations, which required that irrigation water comply with NCH 1333 for products oriented to external markets.

Today there are several challenges involving the issue of water quality for agricultural production in Chile. Access to high quality water to achieve high yields is of the utmost importance for economic profitability, and thus, under current climate and environmental conditions, this resource is becoming scarce. Environmental regulations are increasing, and thus, producers have to be concern about water treatment operations. Among the major challenges, food safety is one of the main concern. As an export oriented economy, internal production processes are subjected to external laws and regulations. For instance, the new American law called "Food Safety Modernization Act" (FSMA), requires that all fresh products consumed in the USA, independently of its origin, must be free of *Escherichia coli* bacteria. Thus, water used for harvest and post-harvest processes, have to be free of E. coli (0 colonies per

100 ml of water). Also, water used in pre harvest operations (irrigation, foliar applications, etc.) cannot have more than 410 colonies of E. coli per 100 ml of water. On the other hand, the European market has other requirements, such as, for example, the restriction on the tolerable limit to chlorides and perchlorates in fresh products, which is a problem as the use of sodium hypochlorite as a disinfecting agent is restricted. Europe also increased requirements related to environmental issues; this is how the requirement of the Rainforest Alliance standard has been established in many markets, which requires, for example, maintaining a certain animal biodiversity in the properties, a subject that contradicts the requirement of water safety.

12.3.3 Impacts of the Recent Mega Drought

Irrigated areas of central and southern Chile are subjected of a strong interannual variability in their precipitation and, most recently, temperature regime. In the last years we have identified and significantly long period of precipitation below average precipitation over a large part of the territory (30°–38°S). This phenomenon has been denominated as the Mega-Drought (Garreaud et al. 2017). Boisier et al. (2016) estimate that a quarter of this rainfall deficit is of anthropogenic origin. The impacts of this drought would be more difficult to overcome in agricultural systems with high degrees of vulnerability.

Drought impacts can be detected not only via traditional drought indices (Oertel et al. 2018; Meza 2013) but also can be traced back to the behavior of vegetation. A study of Zambrano et al. (2016) using vegetation condition index (VCI) allowed the identification of temporal and spatial variations of vegetation conditions associated with stress because of rainfall deficit. These results show a very short-term vegetation response to rainfall deficit in September, which is reflected in the vegetation in November, and also explains to a large degree the variation in vegetation stress.

Under such conditions there are some adaptation responses that have been already implemented by farmers that claim that have experienced drought such as investments for water accumulation, modernization of irrigation systems, rationalization of water use (including strategic water allocation for high value crops at the expense of annual crops of low economic value), and partnership activities (Roco et al. 2016).

12.4 Future Projections and Challenges for Water Use in Agriculture

12.4.1 Climate Change Impacts

Agricultural water use in Chile strongly depend on climate fluctuations. There have been studies that link water demands to large scale climatic phenomenon such as the El Niño Southern Oscillation (Meza 2005). Even though these type of interannual

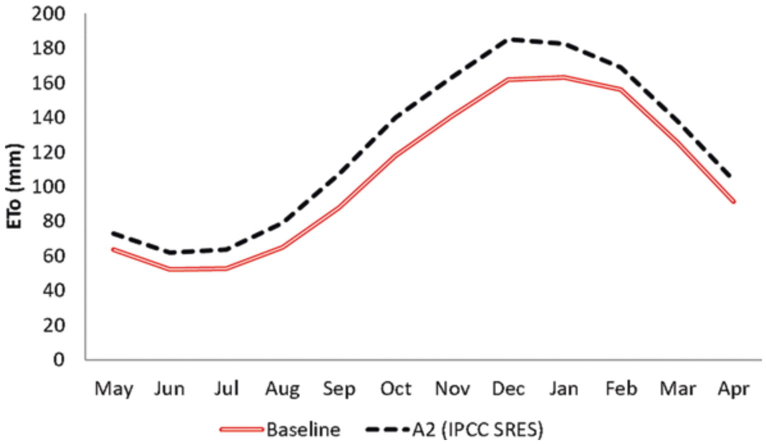

Fig. 12.1 Sensitivity of evapotranspiration to climate change scenarios. (Adapted from Meza et al. 2012)

fluctuations have evolved over time, they can still be regarded as part of the stationary climate. However, new insights about the responses of our planet to increases in greenhouse gases indicate that future climate conditions will be different and are likely to affect agricultural systems. Climate change is one of the most challenging socio-environmental problems that our modern society has to face in order to ensure a sustainable and fair development. Water demands in agriculture are also sensible to such phenomenon. Water withdrawals are a consequence of surface exposed (irrigated land), atmospheric demands (reference evapotranspiration) and irrigation efficiency. It is expected that water demands increase by 5–8% for each degree of increase in temperature. This impacts could represent a net increase of water demands of up to 800 m^3/ha (ODEPA 2017b).

The net effects on water demands and reliability of water use rights have been studied in central Chile. Figure 12.1 shows the expected changes in reference evapotranspiration (ETo) as a consequence of a severe climate change scenario (i.e scenario known as A2 in the special report of emission scenarios of the Imtergubernmantal Pannel on Climate Change). The combination of increasing demands and variable and reduced supply of water compromise the ability of water systems to satisfy crop water requirements with potential impacts on productivity and demand coverage (Meza et al. 2014).

12.5 Future Trends

In recent years Chile, as well as other countries, has seen a big push in the development of renewable sources of electricity. It saw a rapid increase in run of river operations, but also some water users' associations developed hydro power projects using waters of irrigation channels. The former requires obtaining non-consumptive water use rights and the latter is usually implemented using the same consumptive rights owned by farmers. This has brought conflict not only between traditional hydro power producer but also within water user associations.

A rapidly increasing demand for water, a trend of diminishing water availability and more frequent droughts has brought new conflict to water users' communities. In some cases, existent infrastructure, like large reservoirs, has not been able to cope with requirements. The limited prevalence of temporal transfers among farmer has not been able to help alleviate the effects of scarcity bringing a more efficient allocation. In some cases, as dictated by the Water Code, the water authority has had to intervene and reallocate water between user to allow a fairer distribution of the remaining water. This scenario, together with weak water user's association in many areas of the country, represents one of the most pressing challenges faced by farmers in the country.

An alternative strategy to face this situation is with "new" sources of water and additional infrastructure to replace the storage function of snow or carry water between basins. Water reuse and desalination are being considered by different policies and a plan to increase storage capacity as well as to evaluate infiltration technologies to recharge aquifers is already underway. Although, most of the municipal wastewater is treated and already being used there is still no legal clarity about who is the owner. Also, all coastal cities are not treating the used water, it is just being diluted a few miles into the ocean. This represents a potential new source of water that can at the same time bring environmental benefits. Desalination is already a reality in the northern part of Chile and is expected to continue growing. But for the time being cost is too high for agriculture although not for other user, thus could relieve pressure on the resource. There have been several proposals to connect different basins of the country and currently there is a group of farmers pushing for the development, that is the public funding, of an aqueduct system that could connect several of the large reservoirs in the country. How timely will these solutions come is an open question, given the significant investment required, limited technological experience in the country and slow policy making process.

12.6 Conclusions and Future Research Needs

Water demands from agriculture represents, by far, the largest fraction of water withdrawals from surface and groundwater resources. A rapid transformation of the agricultural landscape in Chile, with a decrease in cereals and annual crops and an expansion of perennial fruit trees and vineyards, especially in areas that traditionally have fostered extensive rainfed production systems has created a new scenario of increasing water demands. Climate variability and climate change directly affect agricultural water demands by modifying the evapotranspiration rates. Increasing demands due to surface expansion and new climate conditions, and competition for water resources with other socio-economic sectors stress existing water provision systems.

Considering the current situation of water resources in Chile, agricultural activity needs prompt solutions, and one of them involves improving the management of water available for irrigation. The medium and short-term actions involve the participation of irrigation communities (water communities, monitoring boards), in order to improve the efficiency of catchment, conduction and distribution of water. This is how the installation of ponds or micro-ponds by irrigation communities, the improvement of water intake structures and actions aimed of improving channels coating, are very important steps to increase the available volume of water for growers.

Actions at the level of water communities can be much more viable and take shorter term than those involving large-scale public policies. However, the most important role in the context of making efforts to deal with water scarcity for irrigation is still at the level of the farmer or irrigator. The farm management of irrigation water is a concept that involves maximizing the water resource, incorporating management actions that go from the source to the emitter. It includes infrastructure for collecting and accumulating water, operation and control of the irrigation system, so that the system used operates at its potential, that is, as close as possible to its theoretical efficiency. Another important point in farm water management is to know the available flow in periods of limited availability, since with this data in hand, when comparing the real with the historical data (flow with 85% probability of exceedance if the source were superficial) plus the knowledge of the water demand of the crop, it is possible to estimate the feasible surface for irrigation, what we will call maximum irrigation surface.

Logically, dealing with a water scarcity scenario requires to make use of increasingly efficient systems. Nowadays, the most common practice in irrigation systems is the incorporation of new technologies that aim at an efficiency closer to 100%. Among them we can highlight irrigation systems with special technologies to be buried (systems with antisiphon integrated drippers, copper nanoparticle technologies, etc.), or high efficiency emitters such as anti-draining and "nano-irrigation" appealing are today part of the fine-tuning in the irrigation management. Other technologies have been incorporated to develop better filtering systems, self-cleaning valves, etc. Even though new irrigation technologies exist in the market, there is still a large gap between the potential use of irrigation technologies and the knowledge and expereince required by professionals and farmers to operate them at highest efficiency levels. Although today, in addition to high efficiency irrigation systems, there are several monitoring systems for soil and plant water status (e.g., capacitance probes, digital dendrometry, etc.), many times the estimation of water consumption by the crop is inaccurate or the information is not properly used. There is also great ignorance or lack of use of irrigation budgets that have to consider the soil water holding capacity. It is very probable that more than the introduction of new irrigation technologies in our reality, we should return to the basics and strengthen the preparation in irrigation management by professionals and farmers, together with learning how to use satellite and remote sensing technologies.

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Chapter 13
Domestic Uses of Water

María Molinos-Senante and Guillermo Donoso

Abstract Since many years ago, Chile has made several efforts and reforms to provide drinking water for domestic uses, and has become a success story and example for urban settings in Latin America. Although the coverage of drinking water supply is almost universal (99.9%) in Chilean cities, in rural areas however the coverage is only 52.3%, and drinking water supply services are managed by local communities through a national program implemented since 1964 by the Ministerio de Obras Públicas, MOP. The legal and institutional framework of the water and sanitation sector in Chile is described for urban and rural areas. Then, the evolution of urban water supply, including coverage, consumption, and its main sources is presented, followed by the evolution of rural water supply. Water supply continuity and the vulnerability to drought are also analysed, as well as the informal rural water supply. Finally, some conclusions about the current situation of the sanitary sector are provided.

Keywords Domestic · Uses · Drinking water supply · Urban uses · Rural drinking water · Legal framework · Sanitation sector · Coverage · Consumption

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13.1 Introduction

Access to drinking water is a human right that was formally recognized by the United Nations Economic and Social Council in 2002 which established "the human right to water entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses". Moreover, the Sustainable Development Goals adopted by United Nations in 2015 included achieve universal and equitable access to safe water for all by 2030 as Goal 6. All these international agreements have been supported and signed by Chile. Nevertheless, it should be noted that the efforts and reforms made by Chile to provide drinking water for domestic uses started many years ago becoming a success story and example thorough Latin America (Marques 2010).

In urban settings, currently, the coverage of drinking water supply is almost universal (99.9%) and water services are mostly provided by private and concessionary water companies. On the other hand, in rural areas, coverage is 52.3% and drinking water supply services are managed by local communities thorough a national program namely "Rural Potable Water Program" implemented since 1964 by the Ministry of Public Works.

13.2 Institutional Framework

Currently, the legal and institutional framework of the water and sanitation sector in Chile is different for urban and rural settings as the result of several reforms carried out across time. In 1977, SENDOS (National Service of Sanitary Works) was created which was responsible for the administration and operation of water and sanitation services in both urban and rural settings through eleven regional directorates from 1977 to 1989. A second major reform of the Chilean water and sanitation sector was implemented between 1988 and 1990. It involved the legal and institutional separation of rural and urban water and sanitation services (WSS). During this period, three main water and sanitation laws were adopted whose focus was on urban settings while rural settings were excluded. First, in 1988 the "General Law of Sanitation Services" was adopted which continues in force today. It defines the operation rules of the urban water companies and the conditions in which WSS should be provided (Calvo and Celedón 2006). Second, also in 1988 the "General Law of Tariffs" was passed which determines the procedures to set water and sanitation tariffs in urban settings. Finally, in 1990 the Law 18902 was issued which creates the national urban water regulator namely "Superintendencia de Servicios Sanitarios (SISS)" which is a technical, regulatory and supervisory agency of the water companies providing water and sanitation services in urban settings (Molinos-Senante and Sala-Garrido 2015).

13.2.1 Urban areas

In the framework of urban settings and after the creation of the national urban water regulator (SISS), a remarkable reform was started in 1998 with the adoption of the Law 19,549 which established the current legal framework for urban WSS. It was the main transformative driver of the privatization of the water and sanitation sector in Chile which was conducted between 1998 and 2004 following two approaches. On the one hand, from 1998 to 2000 the five main Chilean water companies sold strategic participations to private consortia with experience in the water industry, stock exchanges were opened and shares were offered to the employees of the water companies (SISS 2016). On the other hand, between 2001 and 2004, most of the public water companies were privatized via concession. Thus, the water companies acquired the exclusive right to provide WSS in a given urban area for a period of 30 years. As a result of this privatization process, currently 95.8% of the urban customers are supplied by private water companies and only 0.1% by public companies.

Currently and according to the "General Law of Tariffs", the process to set water tariffs is based on the definition of a hypothetical efficient firm, i.e., an "ideal firm" (Marques 2010). Under this approach the performance of the "real" water company is compared with a virtual, efficient company known as the "model" company, which is considered to be the benchmark. It is a theoretical water company created by the regulator which satisfies water demand in an optimal manner considering prevailing norms and the geographical, demographic and technological restrictions that characterize the operation of the service (Gobierno de Chile 1988). This model corresponds to a water company without assets, which must make the investment to provide WSS and establish a development investment plan (Donoso 2017). Water and sanitation tariffs are updated each 5 years, or if and when any unexpected changes in the contract conditions occur (Molinos-Senante 2018).

13.2.2 Rural areas

The Rural Potable Water Program of the Waterworks Directorate (DOH) of the Public Works Ministry (MOP) was created in 1964, in response to the fact that at that time, 94% of the rural population did not have access to drinking water. The purpose of the program was to contribute to improve health conditions and well-being of the rural population. To this end, the objective of the program was to provide rural population residing in concentrated[1] and semi-concentrated[2] locations potable water in quantity, quality and continuity in accordance with current regulations (Fuster and Donoso 2018; Fuster et al. 2016).

[1] A concentrated rural locality has a minimum population of 100/150–3000 inhabitants and a density of at least 15 homes per kilometer in the drinking water network.

[2] A semi-concentrated rural locality has at least 80 inhabitants and at least 8 homes per kilometer in the future network.

To achieve its objectives, the Program delivers the following goods and services. In first place, the Program provides a rural potable water infrastructure system (APR) that complies with the technical standards of the Ministry of Public Works and socio-economic evaluation standards of the Ministry of Social Development (MDS). The infrastructure's administration, operation, and maintenance are licensed to APR committees and cooperatives for an indefinite time period. Secondly, the program also invests in the improvement, expansion and conservation of the APR infrastructure. The expansion of the system consists of increasing the maximum number of households that are supplied by the APR. On the other hand, improvement and conservation are investments to increase the quality of the service (pressure, water quality and quantity) and/or to reduce water losses. In third place, consulting, training, and supervision in technical, administrative, financial and organizational aspects is provided to the committees and cooperatives.

The legal and institutional framework of the rural water and sanitation sector in Chile was just recently established in 2017 with the adoption of the Law 20,998 (Ley Servicios Sanitarios Rurales). This regulatory body defines the operation rules of the rural water committees and cooperatives, the conditions in which WSS should be provided, and the procedures to set water and sanitation tariffs in rural settings. It also creates the Subdirección de Servicios Sanitarios Rurales (SSR) which assumes the functions and responsibilities of the Rural Potable Water Program of the Ministry of Public Works. More specifically, the SSR will be responsible for licensing rural water and sanitation operators, investments in drinking water and sanitation in rural settings, socioeconomic evaluation of projects in sanitation and drinking water, and developing a registry of operators (Fuster and Donoso 2018). The SISS extends its regulatory mandate of tariff setting and monitoring of operators to include rural water committees and cooperatives.

13.3 Evolution of Urban Water Supply

13.3.1 Coverage

Over the last 20 years, the Chilean urban water industry has achieved significant improvement in water supply coverage. As it is shown in Fig. 13.1, since 2000 almost all the urban population has access to drinking water though private or concessionary water companies. Currently (December 2017), 14,029,059 people which represent the 99.97% of the Chilean urban population have access to drinking water complying with the quality standards established by the Chilean regulations (NCh409) (SISS 2017).

While the number of people living in the different regions of Chile is very heterogeneous, the percentage of drinking water supply coverage is homogeneous through the national territory (see Table 13.1).

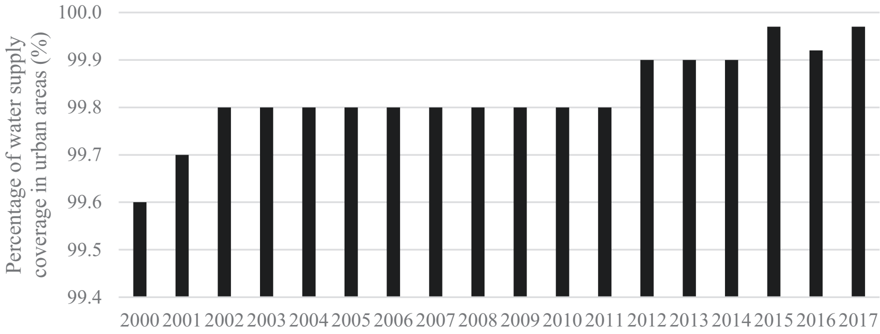

Fig. 13.1 Evolution of the coverage of drinking water supply coverage in Chilean urban areas. (Source: Own elaboration from SISS water and sewerage management reports)

Table 13.1 Urban population and coverage of drinking water services in Chilean urban areas

Region	Population with drinking water service	Coverage of drinking water service (%)
Tarapacá	294,535	99.9
Arica y Parinacota	195,506	100.0
Antofagasta	531,884	100.0
Atacama	229,148	99.8
Coquimbo	548,543	100.0
Valparaiso	1,459,562	99.9
Metropolitana	6,641,509	100.0
O'Higgins	552,425	100.0
Maule	575,733	100.0
Biobío	1,522,638	100.0
Araucanía	528,437	99.8
De los Ríos	225,223	100.0
Los Lagos	509,635	100.0
Aysén	74,873	100.0
Magallanes	139,408	100.0
Total Chile	14,029,059	99.97

Source: adapted from SISS (2017)

13.3.2 Consumption

As in other countries, water consumption per capita shows a downward trend (see Fig. 13.2) and between 2000 and 2017, it has been reduced from 22.7 to 18.2 m^3 per customer per month. It involves an average water consumption of 170.7 liters per capita per day. However, water consumption is not uniform across the country since water demand of companies ranges between 127.2 (Aguas Patagonia) to 611.5 (Aguas Manquehue) liters per capita per day. This finding means that there is a non-negligible room to reduce water use in some urban areas which requires awareness building about the need for more sustainable use of water resources.

Despite the reduction in water consumption per capita, the total volume of water consumed in Chile has increased over time (see Fig. 13.3) due to the increase in the urban population and the non-reduction of water losses.

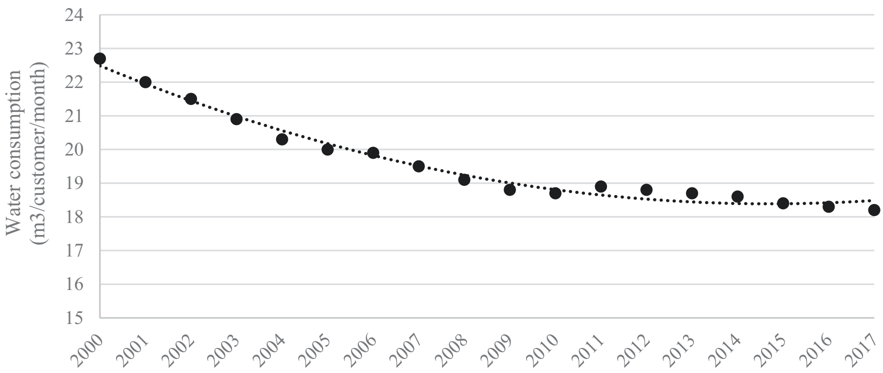

Fig. 13.2 Evolution of the average water consumption per capita in Chile. (Source: Own elaboration from SISS water and sewerage management reports)

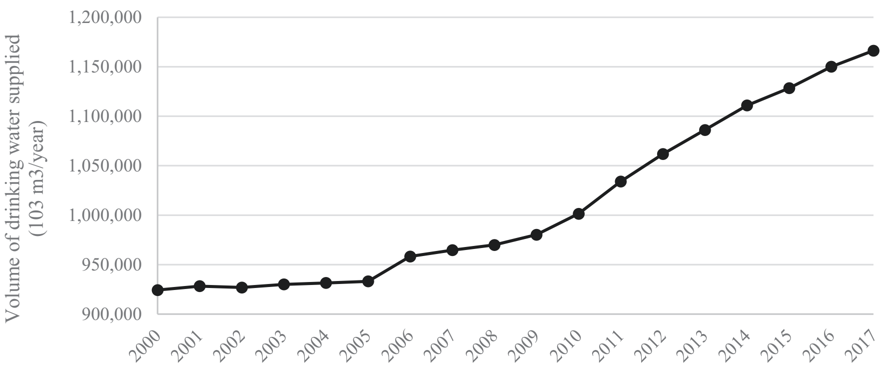

Fig. 13.3 Evolution of the total water consumption in Chile. (Source: Own elaboration from SISS water and sewerage management reports)

13.3.3 Main Sources of Water

The source of raw water to produce drinking water depends on its availability, quality and technical and economic feasibility for their exploitation. In the North of the country (from Arica to Coquimbo regions), most of raw water is groundwater due to the scarcity of surface water. The Antofagasta region is an exception to this trend since a large percentage of the region is supplied by desalinated sea water. By contrast, in the South of Chile, surface water is abundant and has good quality. Hence, it is the main source of raw water. In the Centre of the country, both groundwater and surface water are used. In 2017, the total capacity of drinking water production was 95,559 l/s of which 50,933 l/s (53.3%) are from groundwater, 43,670 l/s (45.7%) are from surface water and 956 l/s (1%) are from desalted sea water (Fig. 13.4). To extract this volume of raw water, at national level there are 1627 water catchments.

In response to the increase in total demand for drinking water (Fig. 13.3), the production capacity, i.e., the volume of raw water to be treated, has also risen over time from 84,311 l/s in 2010 to 95,559 l/s in 2017. It involves an increase of 13% in 7 years.

Before the distribution of water to people, the raw water must be treated in order to meet the quality standards established by law. For this, throughout the country, there are 242 drinking water treatment plants using different technologies depending on the quality of the raw water. Figure 13.5

shows that most of the facilities use only pressure filters (149 out of 242). It should be noted that 17 drinking water treatment plants apply reverse osmosis processes for producing drinking water. All these facilities are located in Antofagasta region and are used for sea water desalination.

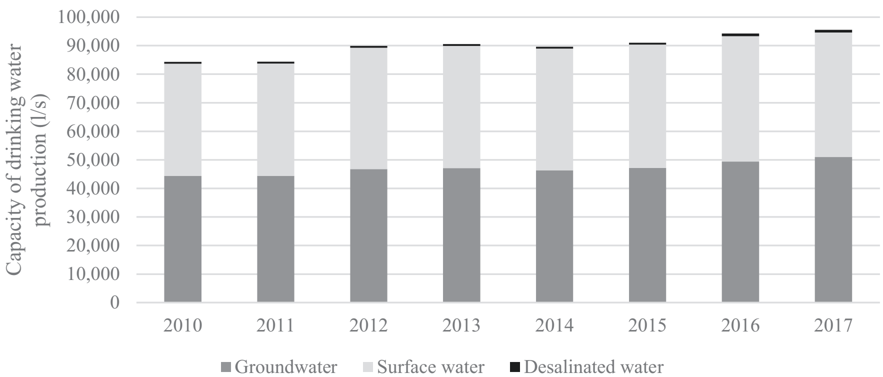

Fig. 13.4 Evolution of the capacity of drinking water production and their sources in Chile. (Source: Own elaboration from SISS water and sewerage management reports)

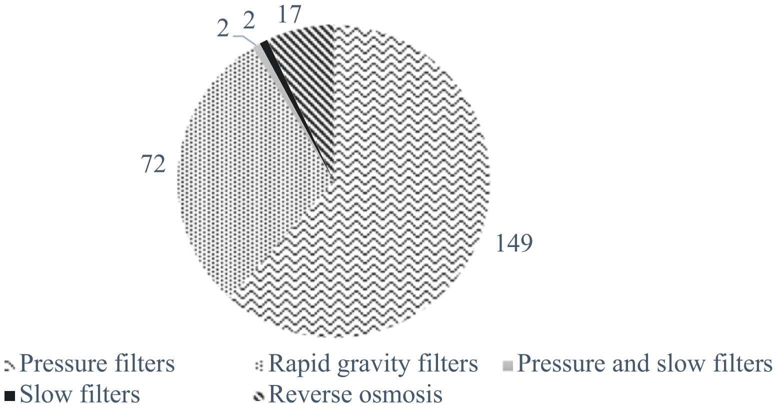

Fig. 13.5 Technologies used for treating raw water in Chile. (Source: adapted from SISS 2017)

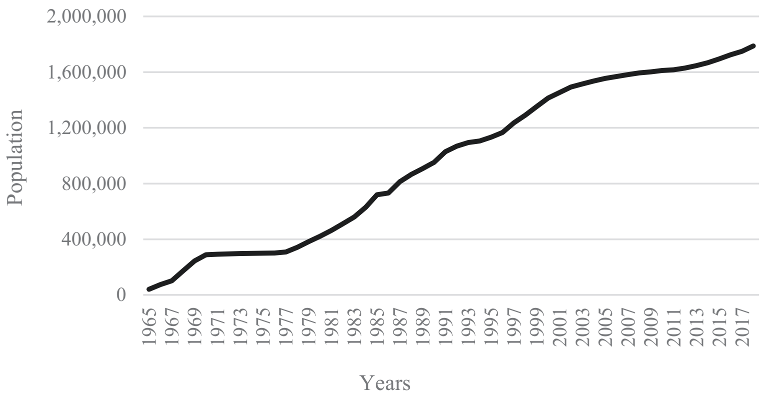

Fig. 13.6 Total rural population with formal drinking water supply. (Source: APR Program-MOP)

13.4 Evolution of Rural Water Supply

13.4.1 Coverage

Since its founding until 2018, the Rural Potable Water Program has provided APR infrastructure to 1903 concentrated and semi-concentrated towns, serving 1,787,916 beneficiaries and increasing the rural water coverage from 6% in 1960 to 52.3% by the year 2018 (Fig. 13.6 and Table 13.2).

The percentage of rural drinking water supply coverage is heterogeneous throughout the national territory (see Table 13.2) ranging from 19.7% in Magallanes Region to 82.2% in Aysén. The central regions[3] present the highest average

[3] Valparaíso, Metropolitana, O'Higgins and Maule.

Table 13.2 Rural population and coverage of drinking water services in Chilean rural areas

Region	Number of APR	Average Age (years up to 2018)	Rural population with drinking water service (Number)	Coverage of drinking water service of rural population (%)
Arica-Parinacota	27	18.1	16,348	73.0
Tarapacá	22	15.2	15,176	68.1
Antofagasta	15	16.3	12,592	58.6
Atacama	39	20.7	17,140	51.3
Coquimbo	192	26.0	158,192	74.7
Valparaíso	161	27.0	212,984	77.9
Metropolitana	109	26.5	185,904	58.7
O'Higgins	219	28.2	277,156	77.3
Maule	295	25.1	280,192	57.9
Bio-Bio	227	22.2	211,120	39.3
Araucanía	235	19.0	161,616	29.1
Los Ríos	126	13.8	84,252	41.7
Los Lagos	181	13.8	127,812	35.3
Aysen	44	20.7	24,140	82.2
Magallanes	11	16.4	3292	19.7
Total	1903	20.6	1,787,916	52.3

Source: APR Program-MOP

coverage with 68%, followed by the northern[4] regions with 65.2%, while the southern[5] and extreme southern[6] regions present the lowest average coverages of 36,4% and 36%, respectively.

13.4.2 *Water Supply Continuity*

The Program established technical standards that all new systems must meet so that, at least in its beginning, it provides drinking water in quantity, quality and continuity in accordance with current regulations. However, over time several APRs have presented water supply interruptions. Table 13.3 shows that the percentage of rural population that faced water cuts between 2014 and 2017 ranged from 8.7% to 22.5%.

There are significant regional differences in the population that is affected by water supply cuts (Fig. 13.7) ranging between 2% to over 90%. The most affected region has been Valparaíso where 92% of the serviced rural population suffered water supply interruptions in 2017. Arica-Parinacota and Atacama regions also have faced important water supply cuts, increasing from approximately 30% in 2014 to

[4] Arica Parinacota, Tarapacá, Antofagasta, Atacama and Coquimbo.

[5] Biobío, Araucanía, De los Rios and Los Lagos.

[6] Aysén and Magallanes.

Table 13.3 Covered Rural Population that presented water supply interruptions

Year	Affected Population	%
2014	323,197	18.1
2015	390,842	21.9
2016	155,961	8.7
2017	402,117	22.5

Source: APR Program-MOP

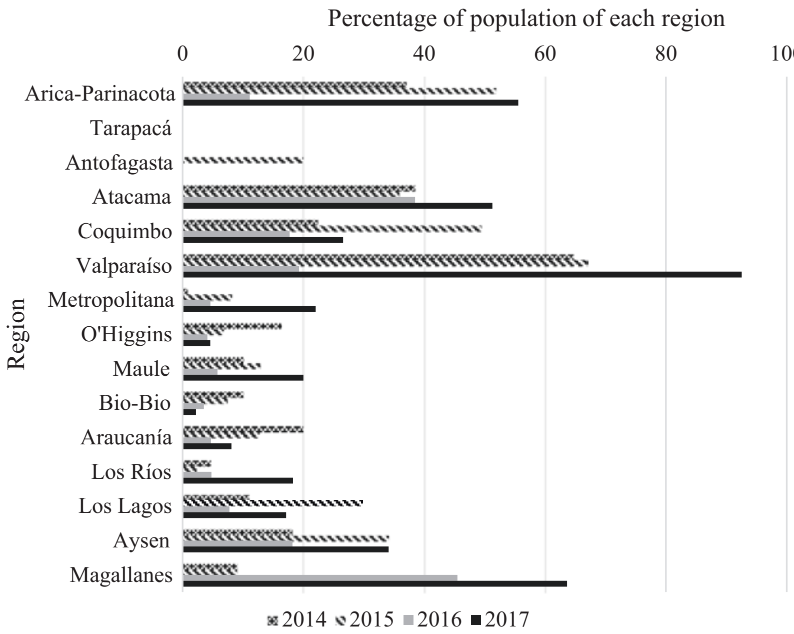

Fig. 13.7 Percentage of Covered Rural Population that presented water supply interruptions. (Source: APR Program-MOP)

over 50% in 2017. This increase is driven by the drought that affected the APR's water sources. Magallanes, in the extreme south, also presents an important increase in the affected population reaching over 60% in 2017.

13.4.3 Vulnerability to Droughts

The capacity to respond to droughts has become relevant, since 5% of the serviced rural population suffered water cuts due to lack of water in their catchment sources is product of the prolonged drought. The response to this problem has been to supply water with tank trucks, purchase of water storage tanks and finance emergency initiatives aimed at providing drinking water supply to the affected APRs. According to figures provided by the Secretariat of the Interior, of the Ministry of the Interior and Public Security, the emergency expenses have increased by 3000% between 2010 and 2017, going from US$1.2 million in 2010, to more than US$40 million in 2015, year when the historical maximum water deficit occurred.

This practice of supplying water with tank trucks during water shortage periods has been extended and generalized to an important number of the regions of Chile (Fig. 13.8). It is quite indicative that the southern regions, characterized by greater water availability, present the highest expenditures, particularly BioBio and Araucanía.

13.4.4 Informal Rural Water Supply

In Chile there are approximately 1.5 MM people without formal drinking water supply systems. The informal water supply source for the rural population not covered by APRs are mainly tank trucks, individual or community wells, and rivers or water springs. As can be seen in Fig. 13.9 the main water supply source for households in the northern regions are tank trucks (59%), while in the central and southern regions they are wells and river or springs, respectively.

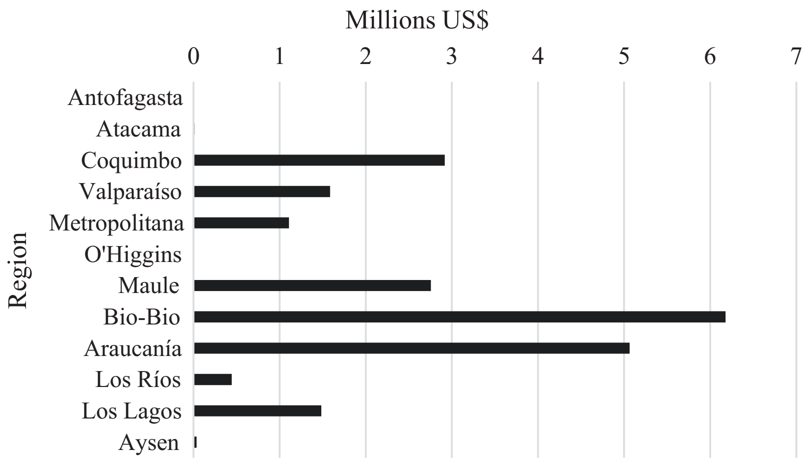

Fig. 13.8 Emergency expenses to supply water during droughts (Million US$). (Source: Undersecretariat of the Interior)

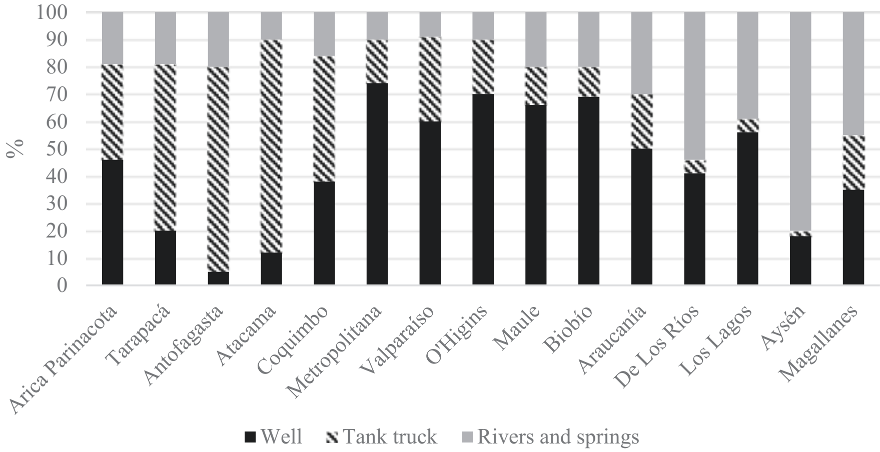

Fig. 13.9 Informal Water Source per Region. (Source: Census 2017 and Casen 2017)

13.5 Conclusions

Over the last 30 years, the urban water and sanitation system underwent major changes as a result of decentralization and market reforms. Private participation was successfully incorporated and a regulatory framework that has contributed to cost recovery and affordability of the reform was implemented. Virtually universal levels of coverage have been achieved in both urban drinking water supply and wastewater collection and treatment.

However, the system faces important challenges. Increasing water demand will become difficult to satisfy due to greater water scarcity and increasing extreme climatic events. Water companies and the regulator should develop and implement plans for climate change adaptation given that its impacts are already a reality in Chile. Associated with the above, an important challenge relates to reducing water losses which is related to low reposition rates of water distribution networks. Additionally, the tariff setting procedure assumes that the regulator has sufficiently precise information to estimate the efficient company's costs without using the real company's information; however, this has not, in general, been the case.

The APR program has been effective in installing water-supply infrastructure in concentrated and semi-concentrated rural towns, increasing water coverage to 52.3%. However, unlike urban service providers, the rural water-supply and sanitation sector has not been subject to regulation like urban services. This has led to tariffs have not allowed for full cost recovery and, thus, adequate funding and maintenance to satisfy growing demand. Maintenance plans with timelines over a year are necessary to ensure system continuity and prevent system failures that have caused water outages.

Also the APR program has been effective in increasing rural water supply coverage, however, access to improved drinking water sources in the rural sector must be further improved. Although the APR committees and cooperatives have shown good performance indicators in the various aspects of providing drinking water to rural populations, management capacities could be improved in order to deliver a more sustainable and quality service. Increasing management skills would allow leadership to improve their own ability to manage their systems so that they can be self-sufficient and cost effective.

The Law 20998 (Ley Servicios Sanitarios Rurales) partially responds to these challenges by defining operational rules, conditions in which WSS must be provided, and the procedures to set water and sanitation tariffs in rural settings. One area, which still needs defining, is the content of regulations stipulating the procedures outlined in the new law. The regulations should define and explain the procedures required in order to apply for a new license and the conditions which would cause expiration of said license. These procedures, which remain undetermined, will be key for an effective implementation of the new law and to reduce the precariousness and vulnerability of rural water supply installations.

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Chapter 14
Mining and Industrial Uses

Denisse Duhalde, Daniela Castillo, Ricardo Oyarzún, Jorge Oyarzún, and José Luis Arumí

Abstract This chapter addresses the relationship between water resources and important economic activities in Chile, particularly mining and the manufacturing industry. This assessment involves aspects related to the importance of these industries in the Chilean economy, their water demand throughout the country, associated environmental impacts and, finally, the challenges faced by these sectors in terms of the sustainable use of water resources. To understand the interactions between the aforementioned economic activities and water, one must first consider the climate heterogeneity of Chile. The north of the country has a desert climate while the south is becoming increasingly rainy. On the other hand, mining activity takes place mainly in the area of the country with the greatest water scarcity, while the manufacturing industry is highly diversified throughout Chile. The direct options available to these sectors for achieving sustainable water management are centered on the use of more and better technologies related to recirculation of process water and the use of seawater.

Keywords Mining · Industry · Water scarcity · Uses · Recirculation · Seawater

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14.1 Introduction

As in the rest of the world, in Chile water is among the natural resources that are fundamental for various economic activities, a reality that determines its importance as one of the linchpins of the national development strategy. Against this backdrop, this chapter discusses the primary uses of water in manufacturing industry and mining activities, with particular focus on the latter, given the role that these economic sectors have historically played in the development of the country.

It should be noted that the Chilean classification of economic activities (CIIU4.CL), based on the International Standard Industrial Classification (INE 2012; SII 2018), describes mining as "working of mines and quarries," which includes extraction of minerals (metallic and non-metallic minerals, rocks, coal, crude oil and natural gas) and support or complementary activities necessary for preparing and processing the raw material for sale. In addition, the CIIU4.CL classification for "manufacturing industries" involves the physical transformation of raw material, whether substances or components, into new products from agriculture, forestry, fishing, livestock and working of quarries and mines, as well as products from other manufacturing activities. They can be grouped into foods; drinks and tobacco products; textiles, articles of clothing, leather and footwear; wood and furniture; cellulose, paper and printed materials; petroleum products; chemicals, rubber and plastic; non-metallic minerals and base metal; and metal products, machinery and equipment.

With respect to the national economy, in 2017 the GDP reached a total of approximately US$277 billion (World Bank 2018), with the manufacturing and mining industries each contributing around 10% (Central Bank of Chile 2017) (Fig. 14.1).

Regarding the international market, copper mining is among the country's flagship economic activities, accounting for almost one third of worldwide production, with an annual output of approximately 5.6 million tons (COCHILCO 2017; SERNAGEOMIN 2017). As with copper, the country's iodine production of 17,976 tons in 2017 makes it the world's leading producer. The country is also second in the production of molybdenum and lithium compounds (SERNAGEOMIN 2017).

With regard to the distribution of the manufacturing industry and mining throughout the country, it is necessary to note that the heterogeneity of the climate and

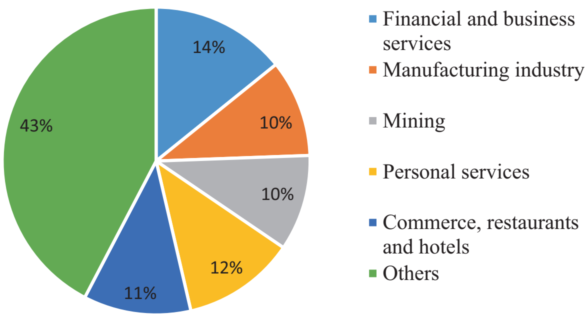

Fig. 14.1 Shares of the GDP (2017) of the main economic activities. (Modified from Central Bank of Chile 2017)

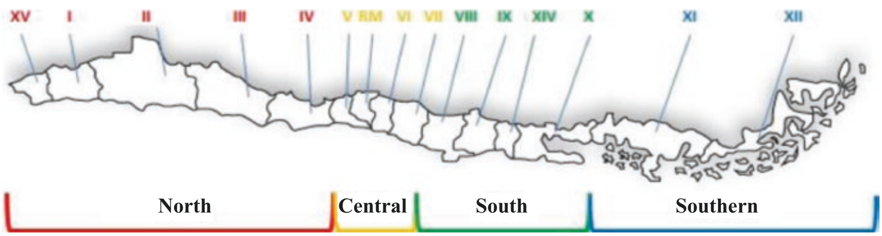

Fig. 14.2 Macro-regions of Chile

availability of natural resources, including water, determine the country's production scenario. Thus, mining is the leading activity in the north, while agroindustry predominates in the central zone and cellulose and fishing industry installations do so in the south (World Bank 2011, 2015). To best address the aforementioned differences, the analysis in this chapter will break the country into four macro-regions, which are indicated in Fig. 14.2.

Against the backdrop of high variability in water availability along the length of the country it proves important to analyze the different needs of each economic sector, with an emphasis in this chapter on mining and industry, as well as the eventual environmental impacts that these activities could have on water bodies.

14.2 Current Water Consumption

14.2.1 Mining Sector

Uses (Quantity) by Macro-Region

Although the consumptive use of water in mining is estimated at only 3% of the national total, most mining operations are located in the north and central macro-regions of the country, which present recurring water scarcity problems (DGA 2016), putting mining operations in a critical state. In fact, the nationwide water demand for mining is estimated at approximately 20 m^3s^{-1} – accounting for around 50% of the water required in the north macro-region – which is mainly for major copper mining operations (DGA 2016; SONAMI 2016). A breakdown of mining water demand by macro-region is presented in Table 14.1.

Water in mining is used in a series of activities and processes, from the test boring stage to closure plans (for example, reforestation programs). Among the various uses of water in the operation stage, the most important are its applications in dust suppression at mining sites and on roads, in crushing, grinding, concentration (flotation, classification and thickening) and mineral leaching processes, in the transport of minerals and tailings and, finally, in camps and service areas (Fig. 14.3).

Table 14.1 Water demand for mining in m^3s^{-1}

Macro-region	North					Central				South				Far South	
Region	XV	I	II	III	IV	V	RM	VI	VII	VIII	IX	XIV	X	XI	XII
Regional demand	0.0	1.5	6.3	1.9	0.7	1.3	0.9	1.9	0.0	1.2	0.0	0.0	1.5	2.6	0.2
Macro-regional demand	**10.4**						4.0				1.5			2.8	

Modified from DGA (2016)

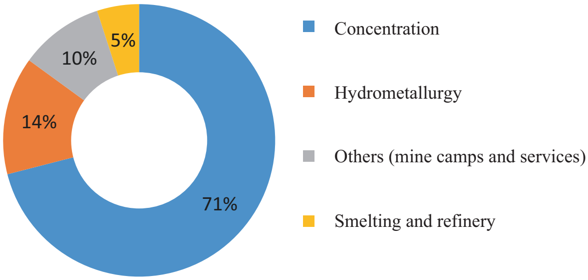

Fig. 14.3 Main uses of water in mining operations in Chile. (Modified from COCHILCO 2017)

Water Sources

The water used in different economic activities can be classified according to its origin: surface (continental water bodies located on the Earth's surface such as rivers and lakes) underground (aquifers formed by fractured rocks or alluvial fill) and sea water (water extracted from the coast, which can be used directly in processes or previously desalinated). However, in addition to these sources, in mining there are two others: mine (commonly called "mine water"), generally underground (defined in art. 56 of the Water Code and art. 110 of the Mining Code as water found in a mining operation), and third party water (which refers to water purchased from third parties, which can come from various sources). Figure 14.4 illustrates the changes over the last 5 years, between 2012 and 2017, in the main sources of water of major Chilean mining operations, which account for approximately 75.0% of the demand of the national mining sector.

Although groundwater and surface water are still the main sources of freshwater for mining processes, the use of seawater (which is currently used at certain mining sites in Chile in proportions of 45.0% desalinated and 55.0% non-desalinated) and recirculated process water has recently increased. The latter accounts for around 74.0% of all water used in copper mining (COCHILCO 2015), a percentage that proves significant given that copper mining is the most important extractive industry in the country. Both the use of seawater and the management and use of process water allow a considerable reduction in the need to extract freshwater from natural continental sources, which is important amid the marked water scarcity conditions in the area known as the country's mining zone (central and north macro-regions).

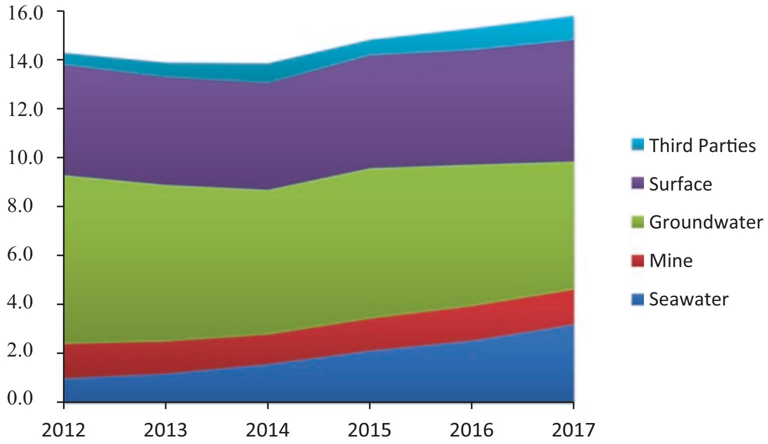

Fig. 14.4 Annual water consumption in major mining operations by source. (Modified from Mining Council 2018)

Mining Sector Impacts on Water Quality and Quantity

Effects on water bodies in terms of water quality and quantity are determined by the type of mineral processed, the process itself and the mineral ore.

The recirculation of process water and use of seawater have resulted in a systematic decrease in extractions from bodies of freshwater along with decreases in liquid mining waste discharges. In any case, normal operating conditions always present potential problems in the form of environmental effects and/or pollution. In fact, acid rock drainage is a relatively common and difficult-to-manage problem originating in the oxidation of sulfide minerals (particularly pyrite) and translates into the generation of acidic solutions that favor solubility and thus environmental transport of heavy metals. The occurrence of this process is magnified by mining activities involving the removal and accumulation of sulfur-containing materials (for example, tailings and dumps). However, the alkalinity associated with the arid climate of north-central Chile is a natural factor that to a certain degree mitigates the effect of acid drainage there.

Another situation at mining sites that can result in the alteration of groundwater quality is infiltration of water from tailings dams, since, despite being processed, tailings usually contain concentrated pyrite and other compounds resulting from the metallurgical beneficiation process, the oxidation of which can cause acidic conditions.

A past practice consisted of transporting and disposing of mining effluents (generated mainly in the copper sulfide concentration process) in surface watercourses. An emblematic case is the dumping of tailing material from the Potrerillos and El Salvador mines into the Salado River between 1938 and 1989. This activity had various environmental impacts such as an increase in the heavy metal concentration (Mo, Cu, among others) and sediment in the river and Chañaral Bay.

In the case of non-metallic mining, lithium extraction from the high-Andes salt flats of the north of Chile begins with the pumping of brine from wells near the salt flats for subsequent evaporation and processing. Brine extraction decreases the quantity of groundwater along with its quality. This activity has taken on importance in recent years due to the need for lithium for battery manufacturing.

Pollutant loads are declared by the different economic activities that qualify as discharge sources (D.S. 90 N° 90/2001) on the Ministry of the Environment portal, the PRTR (Pollutant Release and Transfer Register) (MMA 2018b). Pollutant loads consist of liquid waste discharges into surface water, groundwater and seawater (D.S. 90 N° 90/2001), groundwater (D.S. N° 46/2003) and sewage networks (D.S. N° 609/1998). With respect to mining, in 2016 the pollutant load increased to a total of approximately 94,000 t/year. In Fig. 14.5 the breakdown by pollutant on a national level is shown. Due to the various mining activities throughout the country, there are variations in the relative importance of the main pollutants, which are identified by macro-region below.

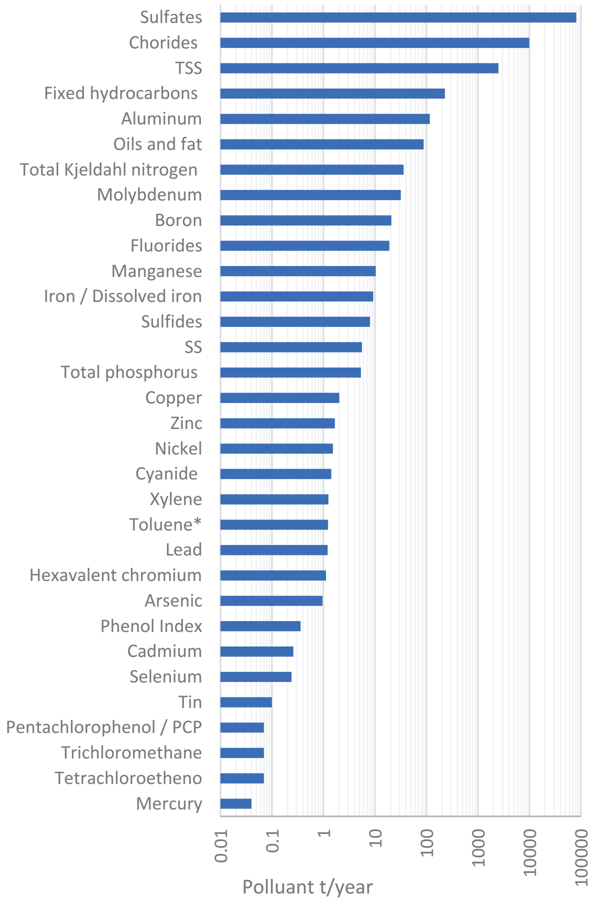

Fig. 14.5 Pollutant load released by mining in Chile (Modified from MMA 2016). Toluene*: includes methyl benzene/toluol/phenylmethanol; *TSS* total suspended solids, *SS* settleable solids

- North macro-region: the total pollutant load reaches a value of approximately 6000 t/year. Of this total, the greatest contributor is "working of other mines and quarries" (84.0%), a category that refers to the extraction of various minerals such as feldspars, asphalt, quartz, mica, lapis lazuli, etc. In second place, copper extraction accounts for 15.9%, while iron extraction less than 1.0%. The main contaminant, consisting of chlorides, accounts for approximately 96.4%, followed by sulfates, at 3.1%.
- Central macro-region: the total here is around 85,000 t/year, with 99.7% related to copper extraction operations. The primary pollutant consists of sulfates, at 94.3%, followed by chlorides, at 4.8%.
- South macro-region: the total is approximately 2200 t/year, related to the extraction of rock, sand and clay in Los Lagos Region. Total suspended solids are the main pollutant recorded, at 94.8%, followed by aluminum, at 4.9%.
- Far-south macro-region: this area accounts for approximately 346 tons/year, associated mainly with "working of other mines and quarries." The primary pollutant consists of sulfates, at 96.2%, followed by settleable solids and total suspended solids, at 1.6% and 1.3%, respectively.

14.2.2 Other Industrial Activities

Uses (Quantity) by Macro-region

Like mining, the manufacturing industry requires water for various processes and operations such as cooling and washing and as a production input, among other uses. In this context, the General Water Directorate recently estimated the water consumption of the industry to be 43.9 m^3s^{-1} (DGA 2016). The central macro-region leads the national industrial sector in water consumption, with 20.2 m^3s^{-1}, followed by the south macro-region, with 13.9 m^3s^{-1}. Nonetheless, it is necessary to stress that in these macro-regions there are regions – the Metropolitan Region in the central and the VIII region in the south – that are important industrial centers, which would explain why each of these regions accounts for approximately 25.0% of national water demand (Table 14.2).

Table 14.2 Water demand in the manufacturing industry in m^3s^{-1}

Macro-region	North					Central				South				Far South	
Region	XV	I	II	III	IV	V	RM	VI	VII	VIII	IX	XIV	X	XI	XII
Regional demand	0.3	1.4	1.3	0.5	0.3	4.8	10.4	1.2	3.8	9.5	0.3	1.6	2.5	0.1	5.9
Macro-regional demand	3.7					20.2				13.9				6.0	

14.2.3 Water Sources

An estimate of the water sources used by the manufacturing industry can be carried out based on the water rights granted by economic activity (Table 14.3). From the data presented it can be concluded that around 66.0% of the water rights granted for industry are for surface water and 33.0% for groundwater.

14.2.4 Water Quality and Quantity Impact of Other Industrial Activities

The information declared in 2016 by the industrial sector indicated a total pollutant load on the order 34 million tons per year, a liquid waste discharge value obtained from the declarations on the PRTR portal. Figure 14.6 shows a national breakdown by pollutant, with the main pollutant being settleable solids. The breakdown by macro-region is presented below:

- North macro-region: a total of approximately two million tons per year is generated. Of this amount the vast majority consists of settleable solids (99.4%) from production, processing and preservation of meat and meat products and production of non-alcoholic drinks and animal feed.
- Central macro-region: a total declared value of around 19 million tons per year is presented. As in the north macro-region, the most common pollutant consists of settleable solids (99.8%) given the production, processing and preservation of meat and meat products, among other food products.
- South macro-region: a total of about 13 million tons of year can be identified, with the processing of fish and fish products, dairy products and meat being the main generators of discharged pollutants. Settleable solids again account for almost the entire contaminant load (99.5%).
- Far-south macro-region: a value of approximately 90,000 tons per year is generated here, with the same trend regarding settleable solids (97.1%), which originate mainly in the fish processing industry.

Table 14.3 Industrial water rights by source type

	Surface			Groundwater		
	WUR	Flow granted[a]	Total flow granted	WUR	Flow granted[a]	Total flow granted
Classification	N°	L/s	L/s	N°	L/s	L/s
Consumptive	332	69	22,908	201	10	2010
Non-consumptive	504	3845	1,937,880	78	10	780

Modified from MMA (2018a)
[a]Value estimated based on data from the data from the DGA (2016)
WUR Water use right

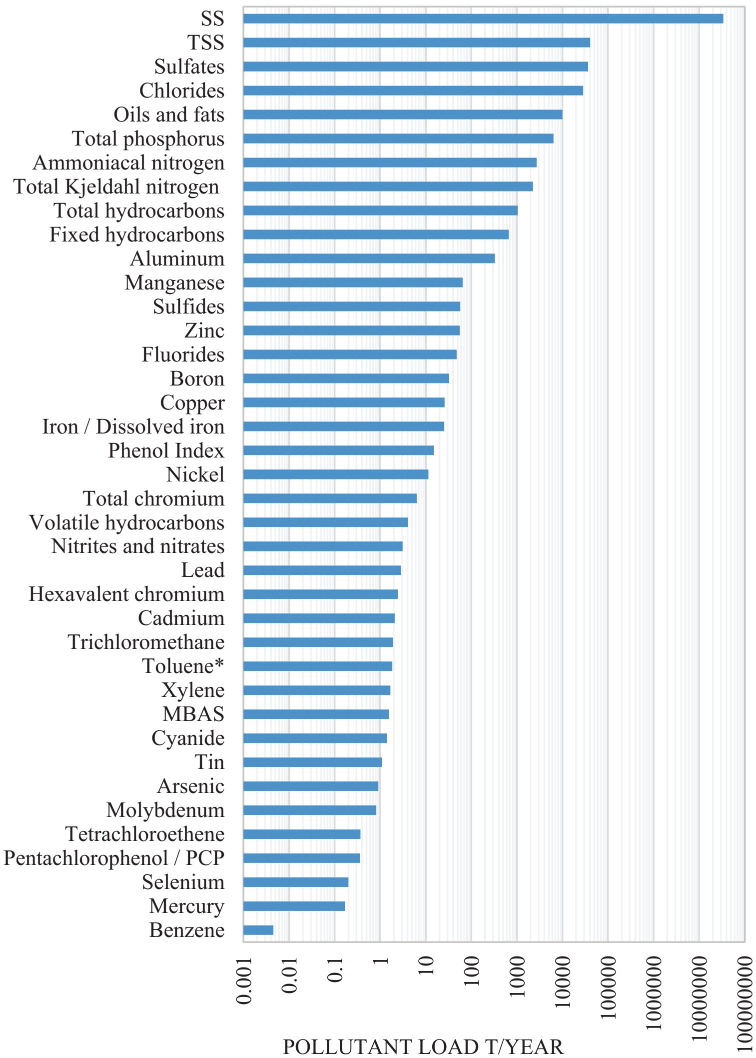

Fig. 14.6 Pollutant load released by different industrial (non-mining) activities in Chile. (Modified from MMA 2018b). Toluene*: includes methyl benzene/toluol/phenylmethanol; *TSS* total suspended solids, *SS* settleable solids, *MBAS* Methylene blue active substances

14.3 Improvements in Water Management and Water Requirement Projections

As has been made apparent, Chile presents wide variability in water availability and demand along the length of the country. In addition, the occurrence of extreme natural events, whether geological or meteorological, such as earthquakes, volcanic eruptions, prolonged droughts, fires, floods and mudslides bring about drinking water supply problems, disturbances in production development and consequences for environmental conservation and protection. Thus, amid this scenario, it is necessary to ensure the availability of water resources such that the ability to meet the various requirements of the country is not affected.

Independent of the eventual modifications that could be incorporated into water resources legislation in Chile, both mining and the manufacturing industry must continue efforts in water use optimization in processes, use of seawater and the search for other "non-conventional" sources.

In mining an increase in the water recirculation rate has been achieved, especially in major mining operations, thanks to their economies of scale and greater implementation of new technologies. For copper mining in particular, these measures must be replicated and strengthened in order to achieve an expected water consumption no greater than 10.7 m^3s^{-1} by 2026, associated with an estimated production of 6.16 Mt/year (COCHILCO 2016). The reduction in and optimization of water consumption is focused mainly on mineral concentration and hydrometallurgical processes, as well as the implementation of tailings thickening and filtration technologies, which have been crucial in mid-sized mining operations. With respect to mine tailings, Fundación Chile, within the framework of the Tranque program, recently (2018) proposed strengthening the management of tailings deposits in Chile, prioritizing the monitoring of the physical and chemical stability of dams, parameters that directly influence the effects that these wastes can have on water bodies (Fundación Chile 2018).

In the search for new sources of water, desalinated seawater is not the only complement to traditional sources; instead, the reuse of duly treated domestic waste water is envisioned for various production activities. In fact, in countries such as the United States, Saudi Arabia, Israel, Singapore Spain and Australia major advances in water reuse have been made, mostly for agricultural irrigation and green areas and use in industrial cooling systems and boilers, as well as aquifer recharge (Fundación Chile 2017; MOP 2012). Nonetheless, these options require high investment and operating costs associated with treatment and the redistribution of waste water plants. However, it has been seen that in comparison to a desalination plant (for the same capacity) the investment and operating costs are lower by 72.0% and 90.0%, respectively (Fundación Chile 2016), making it a very attractive option with high potential.

14.4 Final Remarks

Although mining and the manufacturing industry do not account for most water consumption in the country, water scarcity in the north has complicated the sustainable development of these activities, particularly mining, which is Chile's flagship activity internationally.

With respect to the manufacturing industry, nationwide, the main parameter present in discharges into various water bodies is settleable solids. However, the great variety of production areas in the manufacturing industry makes the collection of data on the use of water resources more difficult than in the mining industry.

Meanwhile, in the mining industry, despite advances in optimizing the use of water, an unfavorable situation is the result of both the scale of the environmental interventions (pits) and the magnitude of the waste (dumps, tailings and spoil tips) of major mining operations, which hinder measures to control and mitigate the environmental impacts associated with water resources.

Finally, to sustain production processes in both mining and the manufacturing industry, both sectors have kept a focus on the efficient management of water resources based on recirculation and the search for water from other sources such as seawater. Thus, an approach that combines or integrates these elements, considering not only quantity aspects but also elements of quantity and water pollution risks, is necessary.

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Chapter 15
Hydroelectric Uses

Sebastián Vicuña, Marcelo Olivares, Chris Hermansen, Mark Falvey, and Fernando Purcell

Abstract The historic development of hydroelectricity in Chile, and its special relationship with the geographic and climatological characteristics of the country are presented. The current operating hydroelectric plants, and the role of hydroelectricity in the electric power system are explained. Following, the future hydroelectric potential is discussed, based on the hydrological conditions and the environmental, social and economic restrictions. The effect of climate change impacts on the hydroelectric potential is provided. Finally, future directions of hydroelectricity development in Chile are discussed.

Keywords Hydroelectricity · Operating plants · Electric power system · Potential · Environmental restrictions · Climate change

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15.1 Introduction: Historic Development of Hydroelectricity in Chile

Chile is a country of abundant rivers that descend rapidly from the Andes mountain range to the sea, making it an ideal setting for hydroelectric development. These conditions are especially auspicious in the central southern part of the country, where runoff is significant and the Andes mountain range remains high (see Chap. 4). For this reason, hydroelectricity has occupied a prominent place, in the energy development of Chile as can be seen in Fig. 15.1. Since the end of the nineteenth century - when the first hydroelectric plant was built - Chileans have felt that the country has advanced hand in hand with hydroelectric power. Hydroelectric power plants meant progress in the early stages of Chile's economic development (Ministerio de Energía 2017a, b). The National Electrification Plan of 1938 conceived the construction of hydroelectric power stations to bring to the rural world the advances that energy was already yielding in urban areas: a new impetus was given to the irrigation of agricultural land by means of electric pumps and cooperatives were organized that distributed electricity to small rural communities without electricity. Thus, the National Electricity Company (1943) built power plants and transmission systems from Arica to Magallanes, considerably increasing the production and consumption of electricity, especially in rural areas (Purcell 2018).

By the end of the 1960s, large-reservoir plants began to be built. In the mid-1980s, a process of privatization of state electricity companies began. Generation (as well

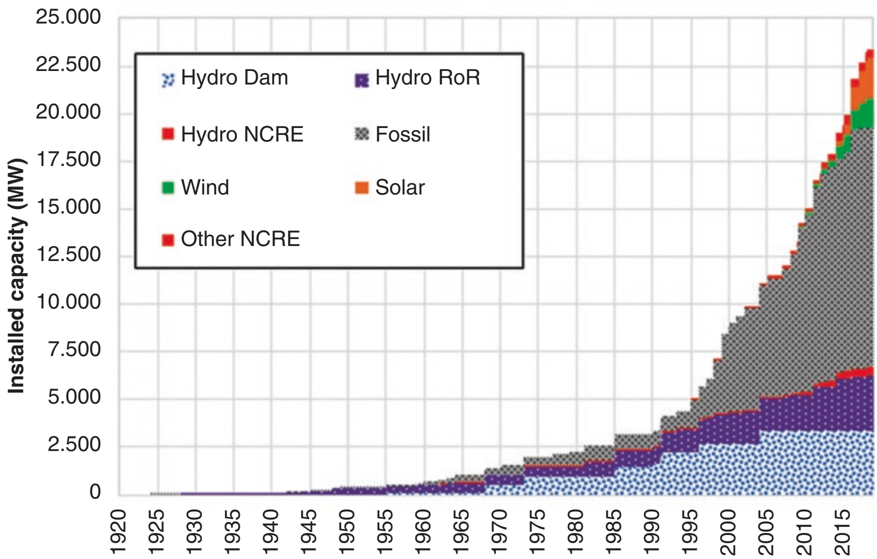


Fig. 15.1 Historic development of electric generation facilities in Chile. Hydroelectric plants are separated into dam, run of river projects, and hydro NCRE. Fossil includes coal, oil and natural gas. (Source: Own elaboration with data from http://energiaabierta.cl/)

as electricity distribution), in the hands of private companies, faced a growth in electricity demand. The country embarked on a historical process of economic development and elimination of social gaps, which required more and more energy. Thus, during the 1990s and early twenty-first century, several large power stations were built. However, at the same time, society was changing and some were beginning to question the net gain arising from accelerated growth.

During the last decade, Chileans' disenchantment with hydroelectric development has increased. The abundant social capital accumulated by hydroelectricity for more than a century seems to have almost run out in 10 years. The society has been expressing its apprehensions about hydroelectric generation with growing vehemence. The result has been a stagnation in the development of hydroelectric resources since the beginning of the twenty-first century, with fossil fuel generation (mostly coal) and recently non-conventional renewables (mostly solar and wind) fulfilling the growing demand for electricity.

In the region, Chile is not the exception in the development of hydroelectric plants as a source of electricity. In other Latin American and Caribbean countries hydroelectric generation has followed a similar trajectory, currently accounting for nearly 50% of the region's power generation. In comparison, the world average electricity production from hydroelectricity is 16.5% (see Table 15.1). The importance of the role of hydroelectricity in the electricity system in Chile and the related hydrologic conditions are explained in the next chapter.

15.2 Hydroelectricity and Water Resources in Chile

15.2.1 Currently Operating Hydroelectric Plants

Today there are 6666 MW of hydroelectric installed capacity in Chile (Energia Abierta website http://energiaabierta.cl/). As can be seen in Table 15.3 and Fig. 15.2 currently installed projects are distributed throughout the country, with a concentration in two basins (Biobio and Maule). which together provide 4497 MW of installed capacity (67% of total). Although most of the projects (105 out of 148) have an installed capacity below 20 MW (which is the legal upper limit to be considered a non-conventional renewable energy, NCRE, of generation according to Chilean

Table 15.1 Comparison of sources of electricity generation in Latin America and Caribbean countries and worldwide (% of total generation)

Region	Coal	Natural gas	Oil	Hydroelectric	Renewable (not Hydro)	Nuclear
World	41.2	22.0	3.6	16.5	6.1	10.8
Latin America and the Caribbean	6.7	26.6	10.4	47.9	6.6	1.9
Chile	36.4	14.4	6.6	32.4	10.1	–

Source: https://databank.worldbank.org

Table 15.2 Hydro projects (distribution by size)

Size class (MW)	Number of projects	Installed capacity
<1	24	12
1–10	66	235
10–20	15	221
20–40	11	325
40–100	16	1000
100–250	8	1201
>250	8	3673

Source: http://energiaabierta.cl/

Table 15.3 Hydro projects (distribution by basin)

Basin	Installed capacity	Number of projects
Maipo	367	17
Rapel	1010	9
Mataquito	5	2
Maule	1601	21
Itata	20	1
Bio-Bio	2896	30
Imperial	6	1
Tolten	47	10
Bueno	186	24
Valdivia	54	4
Yelcho	1	1
Others	473	28

Source: http://energiaabierta.cl/

regulations), most (73%) of the total installed capacity is actually provided by just 16 large scale projects with installed capacities greater than 100 MW (see Table 15.2).

15.2.2 Role of Hydroelectricity in Electric Power System

Despite the growing contribution of small renewables (equivalent to NCRE as presented in Fig. 15.1), Chile's power system can still be considered hydrothermal i.e. a power system dominated by thermal and hydroelectric plants. Hydroelectricity plays a crucial role in hydrothermal power systems. Besides its contribution in terms of energy production and firm power, hydroelectricity provides regulation capacity, which can be expressed in terms of several ancillary services. Notably, the peaking capability of hydroelectricity is likely its most distinguishable feature and its most valuable contribution to a power system. The ability to rapidly change their

Fig. 15.2 Location of operating hydroelectric plants in Chile. (Source: Own elaboration with data from http://energiaabierta.cl/)

power output allows hydroelectric plants to contribute to balancing demand and generation on short time scales. Therefore, the role of hydroelectricity in power systems is determined by its operational scheme, which can vary from one plant to another. Figure 15.3 shows the daily operational pattern for major hydroelectric plants in the Chilean system for a typical day in summer, the dry season in Chile. There is significant sub-daily variation for many of the powerplants, which is clear evidence of the use of hydropower to match changing energy demands over the course of the day. Note that that these large power variations are achievable because most of the plants shown in Fig. 15.1 are linked to reservoirs. In the case of run-of-river plants, power generation is much more dependent on the hydrologic variability of the river, and given their nominal lack of storage capacity, at least at seasonal time scales cannot cope with system's variability. However, some run-of-river hydroelectric plants operate on a short-time peaking scheme based on the limited storage capacity provided by the head pond, tunnels, surge tank, and penstock. In Chile, this peaking scheme in run-of-river plants is common (Haas et al. 2013).

Although net water consumption for hydroelectric production is limited to the evaporation of water from reservoirs, the operation of hydroelectric facilities can still have far reaching hydrological and ecological impacts. In the case of run-of-river hydroelectricity, the river reach between the diversion and restitution point is subject to reduced flow, which can affect in-stream water uses, such as recreation. This effect is typically mitigated by imposing minimum environmental flows established in the context of environmental impact assessment. Beyond minimum

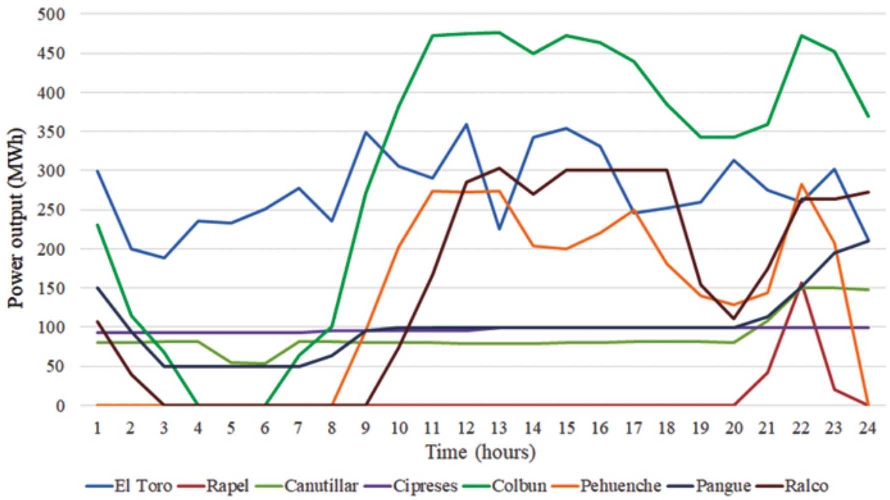


Fig. 15.3 Hourly power production (MWh) for a typical day in summer 2012. (Source: Own elaboration with data from CDEC-SIC)

in-stream flows requirements, the tradeoffs between in-stream recreation and water use to feed a large run-of-river power plant were studied by Génova et al. (2019). A more complex impact is associated with hydropeaking, the fluctuating operating pattern observed in many hydroelectric plants, especially those involving significant storage capacity. Note that operational decisions are not made by each power plant, but by an Independent System Operator (ISO), based on the result of an optimization model that aims at meeting load at minimum cost. The Chilean regulatory framework stipulates that the ISO's orders are compulsory and independent of each companies' supply contracts (Olivares et al. 2015).

The case of the Ralco-Pangue cascade reservoir system illustrates the effects of hydropeaking. Ralco, located upstream, exhibits a more fluctuating pattern, whereas the downstream plant Pangue shows a much more stable power output (Fig. 15.3). This can be observed in more detail in Fig. 15.4 for 16 consecutive days in May 2011.

Multiple indicators have been proposed to assess sub-daily hydrologic alteration (Zimmerman et al. 2010). The Richard-Bakers index (Baker et al. 2004) measures the cumulative flow differences between consecutive hours within a day. The smaller the index, the more stable are river flows. Multiple days can then be analyzed in terms of duration curves, which represent the cumulative frequency of the indicator's value. For example, Fig. 15.5 shows the duration curves for the Richard-Baker index downstream of Ralco and Pangue power plants in the Biobío river, as well as the reconstructed natural flow regime. Natural river flows are quite stable at the sub-daily level, with R-B values very close to zero except for very few events of slightly higher values. Downstream of both plants, sub-daily hydrologic alteration is substantially higher as compared to the natural regime. However, Ralco's duration curve lies to the right of Pangue's, which means the latter (downstream) plant,

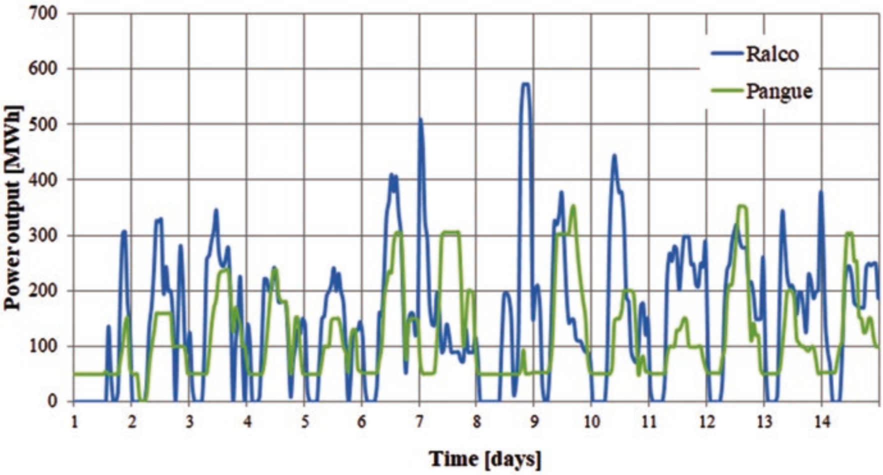


Fig. 15.4 Power output in the Ralco-Pangue system in May, 2011. (Source: Modified from Fernández 2012)

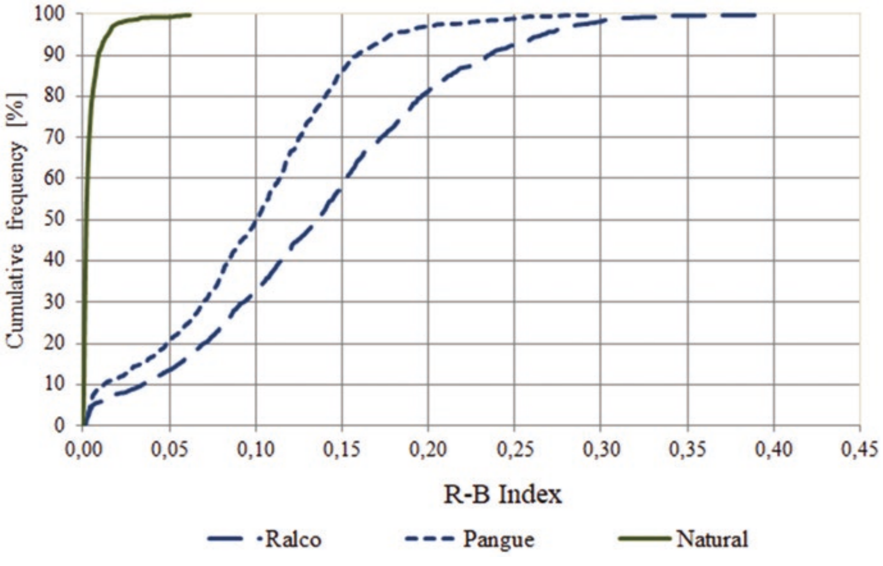


Fig. 15.5 Duration curve of R-B index Oct. 2008–Sep. 2011. (Source: Modified from Fernández 2012)

mitigates to a certain extent the hydropeaking produced upstream. A systematic study of the effect of operational constraints on Chilean hydroelectric reservoirs to mitigate hydropeaking was developed by Olivares et al. (2015).

Hydropeaking can affect water quality both in the reservoir and downstream. The effect of hydropeaking of water quality in the Rapel reservoir was studied by Carpentier et al. (2017). Hydropeaking effects can be exacerbated by massive introduction of renewable energy based on inherently variable sources, such as wind and solar. In the case of massive wind power development, Haas et al. (2015) found an increase in hydropeaking on most reservoir hydroelectric plants.

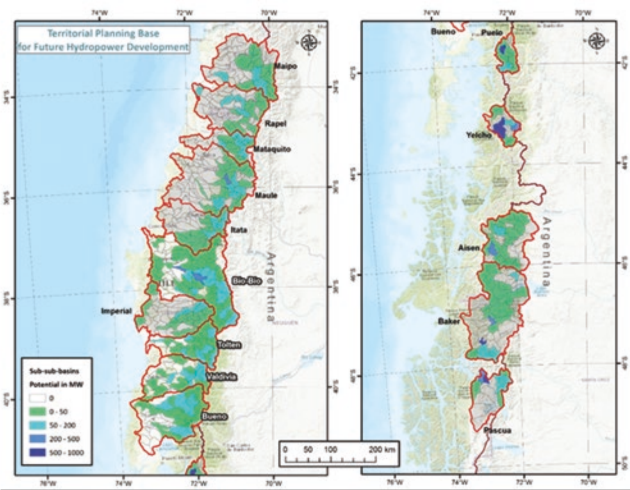
15.2.3 Future Hydroelectric Potential

Despite it's current hydropower capacity, many of Chile's mountain river basins remain largely unexploited. In order to quantify the future growth potential of hydroelectricity the Ministry of Energy has published a detailed estimation of the countries hydropower potential (Ministry of Energy 2017a, b). The method considers allocated, but unused, non-consumptive water use rights to locate potential hydropower projects, combined with a hydrological model to simulate river flow and power generation on the river reach where each project is located. A detailed description of the hydroelectric potential scheme may be found in Santana et al. (2014). What follows is a very brief description of its key characteristics.

Sustaining the methodology is a physically-based numerical simulation of river flow with high spatial detail over the domain of interest. The simulation employs the VIC (Variable Infiltration Capacity) hydrological model (Liang et al. 1994) to represent the land surface and soil processes (infiltration, snow accumulation) that lead to runoff generation. Atmospheric variables at the land-surface interface, including precipitation, temperature and solar radiation, were simulated using the WRF (Weather Research and Forecasting Model). The numerical simulation was carried out at 5 km spatial resolution (both WRF and VIC), over a computational domain that extends from central Chile (30°S) to southern Patagonia (44°S), and over a simulation period from 1990 until 2009. Total runoff was saved at daily intervals, and subsequently routed (Lohmann et al. 1998) through a detailed stream network model generated from a high resolution digital elevation model using the TauDEM software package (Tarboton 1997). As a result of these procedures, the model provides a 19 years of daily discharge data at any river reach in the study domain.

The location of future projects is associated with the location of existing unused water rights. Considering the extensive allocation and later trading of water rights, this is a reasonable guess. The method considers all non-consumptive water rights in the area of interest, excluding only those for which the water use has been explicitly declared as other than hydroelectricity or those that are associated with existing projects. The water rights are grouped by their restitution point, as rights with shared restitution points are assumed to potentially belong to the same project. Grouped water rights are subsequently used to define a single potential power station characterized by a set of one or more intake points and a single outlet point. The maximum flow used by the hydroelectric plant (its *design flow*) is determined from an empirical relationship between design flow of 19 existing hydroelectric plants in Chile and the stream flow allocated in their associated water rights (Santana et al. 2014). With the design flow (Q_d, m^3/s) specified, the power plant capacity (P_{in}, MW) is readily determined from the drop (∂z, meters) between the lowest intake point and the restitution point, i.e., $P_{in} = (8/1000)\ \partial z\ Q_d$, where the factor of 8/1000 takes into account gravitational acceleration and an assumed efficiency of 81.6%.

As a final step, the physical runoff model provides daily river flow at each intake point, allowing the day-to-day variability of power generation to be estimated over the entire simulation period. The results of this analysis are presented in Figs. 15.6 and 15.7. The results show that the future potential is more than double of current



Basin name	Future Potential (MW)
Río Bio-Bio	2.453
Río Yelcho	1.376
Río Maule	990
Río Tolten	900
Río Puelo	883
Río Valdivia	805
Río Bueno	802
Río Mataquito	721
Río Itata	519
Río Maipo	498
Río Imperial	441
Río Rapel	438
Aysen Region	3.940
Others (RM-X Región)	510
TOTAL	15.275

Fig. 15.6 Future potential hydroelectricity development distributed for different subbasins in Chile. (Source: Ministry of Energy 2017a, b)

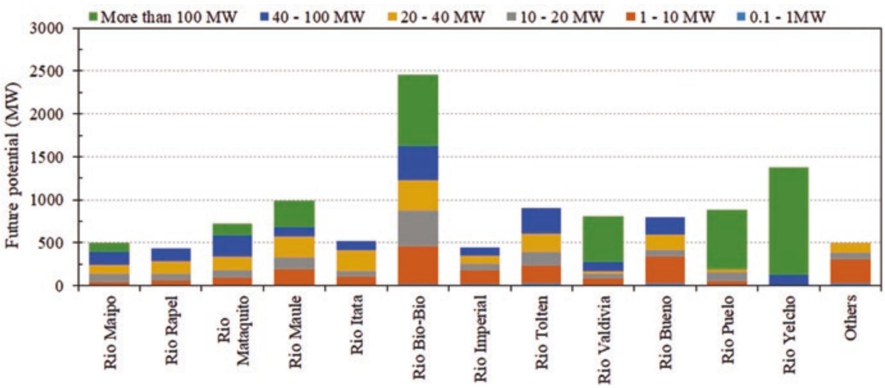


Fig. 15.7 Future potential hydroelectricity development classified by basin and size of potential project. (Source: Ministry of Energy 2017a, b)

hydroelectric power developed. This potential is concentrated in some basins (Biobio and some of the Patagonia basins) and, as expected, in the upper zones of the basins. In terms of size of projects, although the distribution in numbers is heterogeneous the different classes contribute comparable amounts of energy.

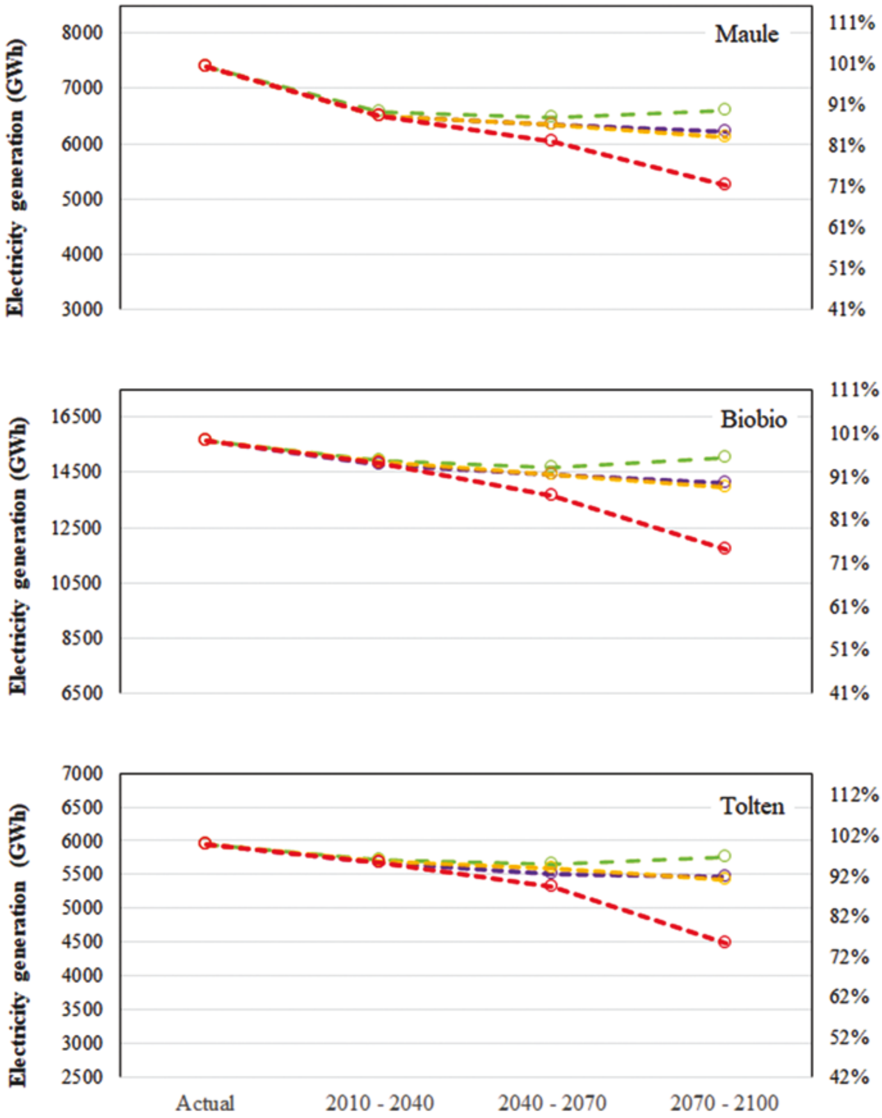


Fig. 15.8 Potential for future hydroelectric generation in the Maule, Biobio and Toltén basins. (Source: Ministry of Energy 2016a)

15.2.4 Climate Change Impacts on Hydroelectric Potential

The links between climate change and hydroelectricity are many and reflect the many and complex mechanisms that affect this problem. On one hand, hydroelectricity can reduce or increase greenhouse gas emissions (GHG), reducing or increasing the causes of climate change (depending on the type and location of project), and on the other hand, hydroelectricity is a source of generation is sensitive to climate change impacts on the water cycle. The information related to the second issue is described here.

Recently there has been a series of studies that analyzed the potential impacts of climate change on hydroelectric generation in Chile. The first of these works was developed for the study Economics of Climate Change (CEPAL 2009, 2012a, b). In this work, the impacts associated with two GHG emission scenarios in the electric generation of the Maule Alto, Laja and Biobío systems was analyzed. Based on the analysis of these basins, possible impacts on the rest of the country's hydroelectric systems were inferred, finding that the product of the expected climate change reduction in average rainfall and increase in temperature (see Chap. 19) implies a reduction in the hydroelectric generation capacity of the central area of the country. These inferences were later confirmed through hydrological modeling for the main hydroelectric basins of the country, in a study developed by the University of Chile for the Ministry of Energy (Ministry of Energy 2011). Subsequently, within the framework of the "Cuencas Project" (Ministry of Energy 2016a), another analysis of the possible impacts of climate change was carried out, considering the new climate change scenarios used in the Fifth IPCC Report, with special focus on four major river basins. Figure 15.8 shows the expected impacts in terms of future hydroelectric development potential for a series of GHG emission scenarios (RCP scenarios). The Fig. 15.8 shows that a 30% reduction in future generation potential, could occur in a scenario with a high level of GHG emissions (RCP 8.5) towards the end of the century. To understand the impacts of these scenarios with a greater level of detail, the Ministry of Energy contracted a technical study to determine the impact of climate change on the expected potential of hydroelectric generation in the Maule river basin. Using a hydrological modeling of the upper part of the Maule basin (including the sub-basins of Melado, Invernada, Maule Alto, Claro and Garzas), the study showed that climate change leads to significant changes in the hydrological conditions of the contributing sub-basins systems, including a reduction in the entrance flows on the one hand and on the other an advancement of the spring and summer flows towards the winter months (Fig. 15.9).

It can be concluded that, according to the scenarios expected for the central zone of Chile, the projected climate change can alter average hydrological conditions, reducing the potential for future generation, and altering the hydrograph and the operation of reservoirs. However, further studies are required to account for the expected impacts in the extreme operating conditions of hydroelectric plants. It is important to highlight that, to date, all efforts to relate the impacts of climate change to hydroelectric generation have been associated with possible changes in

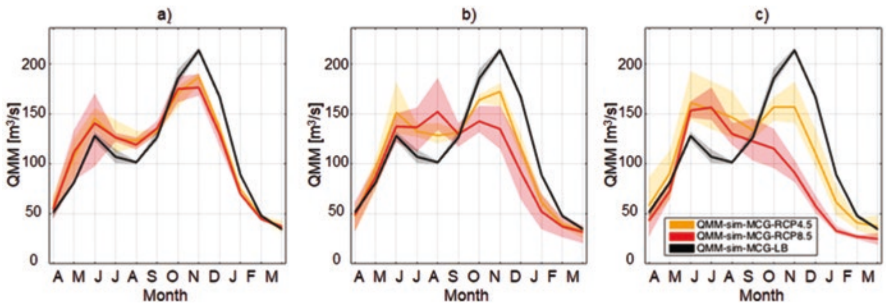


Fig. 15.9 Monthly average flows in the Melado River sub-basin for historical scenarios and different GHG emission scenarios for periods (**a**) 2009–2039; (**b**) 2039–2069 and (**c**) 2069–2099. (Source: Ministry of Energy 2016b)

generation potential. The risks and ecosystem opportunities that could result from the combined effect of climate change and hydromorphological alterations associated with hydroelectric projects have not yet been studied in Chile although progress has been made in other parts of the world, such as California (Viers 2011; Null et al. 2013).

15.3 Future Directions of Hydroelectricity Development in Chile

The future development of hydroelectricity in Chile is unclear. The fast-growing implementation of non-hydro non-conventional renewable electricity, which has lowered bidding prices for new development, plus the increasing restrictions associated with environmental concerns and competition with other uses of water seems to have slowed current development.

On the other hand, there seems to be a non-traditional hydroelectric development associated with projects located in the north of Chile such as Valhalla (http://valhalla.cl/es/) or ENACAP (https://www.iagua.es/enapac). These projects combine in innovative ways inexpensive electricity generated via solar or wind sources together with desalination plants and hydroelectric capacity to create a virtuous water-energy nexus using the energy storage capacity of hydroelectricity. Pump storage facilities that could optimize daily differences between electricity demand and supply are also part of future potential development of this type of electricity.

In any case, operating and new developments must take into account concerns related to environmental and other uses of water flow. Given the current trend toward more environmentally sound siting, design and operation of hydropower projects, the introduction of more sophisticated tools of analysis is required. In particular, the environmental impact assessment (EIA) process should start considering more realistic operating patterns, especially at the sub-daily scale, by adopting a power system modeling approach. Not only would this allow assessing the impact of new projects in the context of the entire power system, but also evaluate the effectiveness of mitigation measures, including both operational constraints and structural measures such as re-regulation reservoirs. Moreover, given the single-project focus of the EIA, a more systemic approach could be introduced within the framework of Strategic Environmental Assessment, at least regarding the siting of new hydropower developments. These concerns, among others, were taken into consideration as part of the agreements of a stakeholder process led by the Ministry of Energy (Ministry of Energy 2017a, b).

On the other hand, a challenge facing Chile is the potential conflict between hydropower production and irrigation on major reservoirs, such as in the Maule and Laja basins. These multi-purpose systems operate under the jurisdiction of the ISO, but must comply with irrigation agreements established back in the mid twentieth century. These irrigation agreements have been recently represented explicitly within the hydrothermal optimization model, which represents an improvement over the offline verification approach used before. Beyond irrigation agreements, recent attempts have been made to explicitly represent the tradeoffs between hydropower and irrigation, under a power grid perspective (González et al. 2016).

15.4 Conclusions

Hydroelectricity has been a key source of electricity generation in Chile and many other countries in Latin America. Up until the late 1990s, hydroelectricity accounted for more than 80% of Chile's total installed generation capacity. Today, with slightly over 6500 MW, hydroelectricity represents less than a third of installed capacity, the rest of which is dominated by fossil fuel-based thermoelectric plants and a rapidly growing non-conventional renewable (mostly wind and solar) generation capacity. Current hydroelectric capacity is concentrated in the central-south part of the country, particularly in the Maule and Biobio basins, which together hold almost 70% of total capacity. Although most projects are small in size (less than 20 MW), most of the capacity is provided by just a few large scale projects.

Hydroelectricity plays a crucial role in the operation of the Chilean electricity system, especially through the regulating role of large reservoirs, which allow an optimal use of fossil resources, taking into consideration variation of climate at shorter and longer time scales. This situation also transforms into an environmental concern when hydroelectric projects are operated to maximize revenues through hydropeaking.

According to studies developed by the Energy Ministry, there is an unused hydroelectric capacity that more than doubles Chile's currently installed hydroelectric capacity. However, such future development must take into consideration the potential impacts of climate change, which projects diminishing precipitation and rising temperatures, leading to lower river flows and reduced energy generation. In addition, future development must take into consideration growing environmental concerns and conflicts with other water users such as the agricultural sector.

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Chapter 16
The Chilean Forest Sector and its Relationship with Water Resources

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Abstract A general description of the Chilean forest sector and its relationship with water resources are presented, including the precipitation-runoff-vegetation relationships. Then, the effect of afforestation over the water balance is analyzed and the relationship between water production and forest masses in the central south zone of Chile, based on a research in a representative basin are presented. Finally, some conclusions are discussed.

Keywords Forest · Precipitation · Runoff · Vegetation · Afforestation · Water balance

16.1 Introduction

Forest ecosystems represent a crucial role in the hydrological cycle because of these influences in the quantity and quality of available water, in addition to regulating surface and underground water flows. Woodlands provide environmental services

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such as internal nutrient cycle, soil protection, biodiversity conservation, climate regulation, and what is most important in Mediterranean climates, control of surface and underground waters. Under a scenario of global climate change, water supply in quantity and quality turns into one of the main ecosystem functions of forests, particularly and of the soil vegetation complex in general, complex that helps decisively in water flow regulation (Oyarzún et al. 2005). This occurs even more in the Chilean case by being an eminently mountainous country and where this complex is the major factor destined to promote water infiltration into the ground and the further aquifer recharge, in high zones outside to riverbeds.

On the other hand, Chile has developed a strong afforestation process in Andes and Coastal Mountain Range zones for more than 80 years, covering more than 2.5 million has. Despite the efforts of researching the impact of these processes, these have remained in a micro river basins level, lower to 100 ha. The above does not allow us to evaluate the impact of the soil vegetation complex in water balance, mainly because the impact of the hydrogeological variable fails to be warned and quantified. The exception is represented by a study carried out by Pizarro et al. (2005) in the Purapel river basin, where they observed the hydrological behavior of exotic and native vegetations in a coastal basin, finding no significant hydrological differences between both coverages. Nevertheless, Little et al. (2009) concluded different aspects to the ones addressed by Pizarro et al. (2005) over the same basin.

From the above, there is the scientific doubt about the minimum threshold of needed vegetation cover to make a significant vegetation damping effect. Moreover, this minimum threshold will depend on the precipitation's intensity, being defined as an inversely proportional relationship between interception and precipitations intensity. In this framework should be noted that a high rainfall intensity could determine a water runoff coefficient reaching a value close to 1 in a short time, so practically all the water falling is draining. This happens because rainfall's kinetic energy exceeds the interception capacity of the forested area quickly and saturates in the same way the water infiltration capacity in the ground. It is this runoff coefficient that high, the possibility of sediment transport to lower zones increases exponentially, as well as the possibility of damaging the ground structure and incorporating particles to the current flow, increasing the erosive phenomenon. Conversely, in case of low rainfall intensity, the aerial interception of water and ground infiltration capacities can have the time needed to recover or keep under certain thresholds, resulting in low expression of water runoff. That follows the need to study the rainfall intensity and its effect on the interception because it determines higher or lower possibilities for sediment emissions towards low zones.

From those mentioned above, it is expected that global pressure about water resources increases significantly in the future. Many agree that by the year 2025, 1,8 billion people will live in regions with absolute water scarcity, and two thirds of the global population could experience water stress conditions (FAO 2007). In this way, humanity is witnessing increasing problems related to extreme events, such as droughts and floods. The water availability and quality in many regions of the world are becoming more threatened because of excessive use of the resource, the pollution of water bodies, and the negative impacts of climate change projected in different parts of the globe. In this way, Chile is not an exception. During the last decades, it has been verified the presence of climate change and variability phenomena, which has affected water supply along a significant part of the country. Similarly, demands for the resource have increased in the different productive sectors. This alarming situation has given rise to a tension between the diverse water users, such as mining and agricultural companies and communities, as well as tensions between different productive sectors.

In the context of tensions with the forest sector, it should be noted previously that forest ecosystems play a crucial role in the hydrological cycle. A key challenge faced by the ones involved in managing land, natural forests and forest plantations, and in general the soil vegetation complex, and the water resources, is to maximize a wide range of benefits of the forest ecosystems, without undermining water resources and their ecosystemic functions. This challenge is particularly relevant in the context of adaptation to climate change, which strengthens the importance of sustainable management in the forest sector increasingly.

16.2 The Chilean Forest Sector

The natural isolation of Chile has resulted in high endemism of the country's flora (Armesto et al. 1998). In the same way, its geographical condition, which extends from the parallel 17 ° 30′S to 56 ° 00′S (more than 4000 km) determines the existence of a high climatic diversity, which can be summarized in 3 macrozones: arid in the northern zone (to the parallel of Santiago), semi-arid – subhumid (from Santiago to Ñuble) and humid (from Ñuble to the south).

Likewise, the vegetation of Chile presents variations according to climatic and geographical conditions, and in this context, the forest masses are concentrated from the Valparaíso Region to that of Magallanes (Conaf 2017).

The evolution of Chilean forests has been marked by the transformation of forest land to agricultural land during the nineteenth century until the mid-twentieth century, due to the need to produce food and livestock, building construction and the mining industry. This transformation was generally carried out without major conservation measures and resulted in extensive and profound desertification processes in the arid and semi-arid territory, as well as processes of soil and vegetation degradation in humid and sub-humid areas. For example, in the Coquimbo Region, located 500 km north of Santiago, there was a desertification that has been maintained in many parts of the Region until today, mainly due to the lack of rainfall that defines a fragile ecosystem condition that is very Hard to be restored. In this context, enormous efforts have been made of massive afforestation with shrub species (Atriplex nummularia), small trees (Acacia sp), and smaller trees (Eucaliptus sp), among others. These efforts, despite being relevant (more than 60,000 hectares planted in this region) do not respond to all the potential demand of a massive forest hydrological restoration process, especially in climate change scenarios and where the soil-vegetation complex plays a decisive role in the precipitation-runoff process.

In the case of the northern zone of Chile, between 17 ° 30′ at 28° south latitude, there is a situation that corresponds to a hyper-arid zone with rainfall ranging from 40 mm per year (Atacama Region) to 1 mm per year (Arica and Parinacota Region). This has influenced the almost zero expression of vegetation and a very small role of the soil-vegetation complex in the precipitation-surface runoff and underground runoff process. However, in the highland area located in the Andean buttresses and over 4000 meters above sea level, it is possible to find Vegas and bofedales (Ciren 2013), characterized by maintaining a soil saturated with water. In these areas, there is vegetation of the scrub type and cacti. The presence of a saturated soil defines the extent and size of the vegetation. Thus, for example, the Pampa del Tamarugal, unlike wetlands, presents vegetation of the tree type, including inside it contains a national reserve (of the same name) with an area of 1340 km^2 (Conaf s/f). This difference in the habits and extension of the vegetation is explained by the hydrogeology of the Pampa del Tamarugal, because it has an aquifer, fed by the mountain and altiplano precipitation reaching recharge rates of up to 1000 l/s (CIDERH 2012).

Another exceptional case linked to the country's forest hydrology is presented in the Fray Jorge National Park, located in the Coquimbo Region, 400 kilometers north of Santiago.

In this area of the arid type are trees from the central-southern zone of Chile, such as olivillo (Aextoxicon punctcatum) and cinnamon (Drimys winteri), and the reason is that the area corresponds to an ancient relict, where the trees have maintained as a product of the horizontal rainfall determined by the coastal fogs that are trapped by the vegetation present in the place.

In the sub-humid and humid zone located between 33 ° 54′ and 43° 42′ south latitude, a high process of environmental degradation was manifested as a product of indiscriminate exploitation and burning of the native forest for the purpose of enabling agricultural land, which began in the second half of the nineteenth century (Camus and Solari 2008). Importantly, this process of land use change responded to the government policies of the time, which sought to colonize southern Chile, thus reducing the forest area of the territory. This decrease resulted in an increase in erosion and sedimentation on hillsides and natural channels. The magnitude of this deforestation reached approximately 19 million hectares by the end of the twentieth century (Unesco 2017). This defined a catastrophic result in environmental terms, reaching situations that manifested total devastation of the territory. In this context, both in the coastal zone and in the Andean pre-mountain range, a massive process of afforestation of these territories was developed based on the Pinus radiata species, a process that began strongly from the year 1931 with the enactment of the law of Forests and later took greater force from 1974 with Decree Law 701 on forest development. This afforestation impulse set the tone for the creation of a forestry industry that currently generates a high diversification of products based on the exploitation of these territories and that offers cellulose, paper, and sawn timber to international markets, among other products. This process defined a change in the landscape like the one that is noticed when contrasting the vision that the Malleco viaduct delivered in the nineteenth century with the one that is seen today (Fig. 16.1).

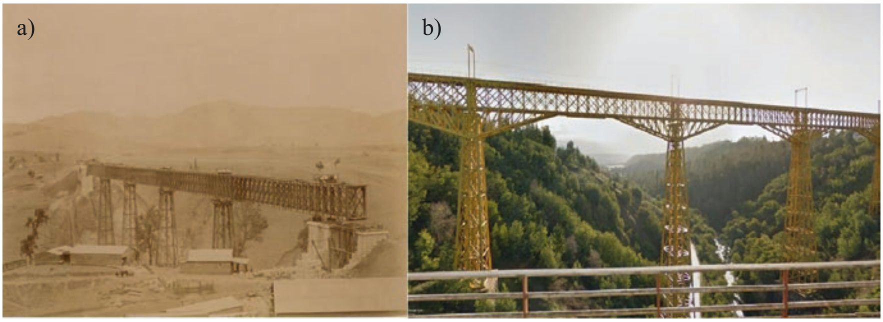


Fig. 16.1 (**a**) Construction of the viaduct in 1888, source: Memoriachilena.cl. (**b**) Malleco Viaduct in 2013, source: Google Streetview

At present, most wood products and wood products come from forest crops. This defines a forest model that reduces the productive pressure on the native forest and moves it to managed plantations. This, coupled with the recovery of the native forest in various areas of the country (MMA 2015), has determined a critical role that the soil-vegetation complex is playing in the rainfall-runoff process in the last 30 years.

There is a southern cold semi-arid zone, located between 43 ° 42′S and 56 ° 00′S, which is characterized by its ecosystem fragility, with tree vegetation defined by native forests represented by species such as lenga (Nothofagus pumilio) and ñirre (Nothofagus antarctica). This area is characterized by the presence of shallow temperatures and strong winds. In the nineteenth and mid-twentieth century, its forests were intensively exploited for productive purposes (Peri et al. 2013) and land authorization for agriculture. In the last 50 years, this area has had a tourist boom that has generated greater care for the environment, which has defined the recovery of native forests (GORE 2012), although in a still low proportion, compared to the devastation suffered by these territories. In hydrological terms, its main contributions come from the rainfall of 400 mm per year, with a significant presence of snow. This makes the role it plays from a hydrological point of view, the soil-vegetation complex, highly relevant.

16.3 The Precipitation-Runoff-Vegetation Relationships

The relationship between precipitations, runoff, and vegetation is an essential element for the sustainable management of river basins. In order to properly analyze the effects of vegetation over water production (Fig. 16.2) and sediments transport, it must be considered that the air coverage and vegetation cause rainfall's kinetic energy to decrease, a situation that decreases the erosion by splattering and disaggregation of soil particles (Santos et al. 2011).

On the other hand, leaf litter and undergrowth, help to decrease surface runoff, retaining water for more time in the ground and increasing infiltration and aquifer

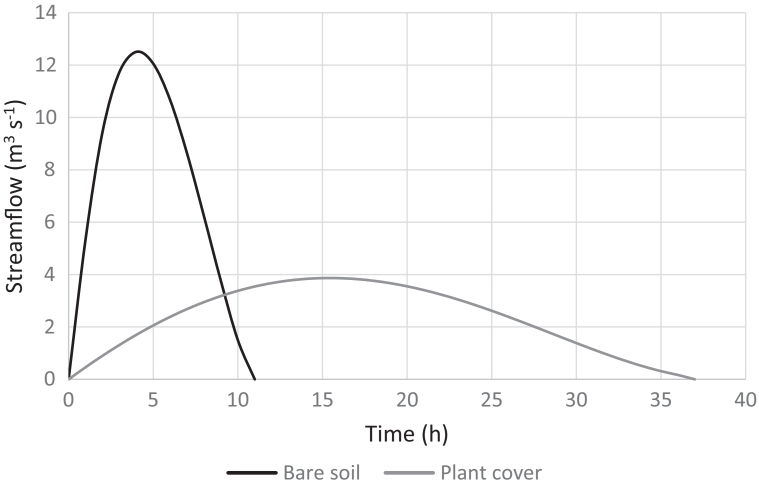


Fig. 16.2 Graphical representation of the influence of vegetation on hydrographs

recharge rates, which also contributes to the soil protection. In this way, when the water volume that comes to the ground decreases, the circulant flow decreases as well, which causes the capacity of sediment transport downstream to decrease. As a result of this situation, the forest mass generates more excellent protection of the ground (López 1994), keeping its productivity.

16.3.1 Effect of Afforestation over the Water Balance

The relationships between vegetation and runoff have been addressed for more than 100 years, but deeply studied during much less time (Cheng et al. 2002). Marsh (1874) cited by Black (1991), was for example, who did extensive observations around the world, related to vegetation removal and its corresponding increase in runoff, erosion, and sedimentation. Likewise, during the last 50 years, numerous observations related to vegetation removal and afforestation were carried out, allowing the existence of relevant background about the effects of afforestation on the water resource. Thus, the impact of forest plantations in the erosion decrease of the soil and the consolidation of river basins has been evaluated positively (Guiller and Malmqvist 1998; Ellies 2000; Cheng et al. 2002).

Many authors agree that the main effect of forest plantations over the water balance is the amount of precipitation retained by the canopy (water losses by interception) and that, therefore, its participation decreases in the water balance of these ecosystems (Feller 1981; Calder 1998; Huber and Trecaman 2000; Putuhena and Cordery 2000). In this framework, Huber and Iroumé (2001) studied the processes of precipitations interception in 29 tests with different kinds of arboreal covering (native forest and forest plantations) established between the VIII and the X regions of Chile. This research found that plantations present precipitation retentions between 18% and 35%, while the native forest presents interception between 14% and 40%, being the losses by interception higher in the forest plantations on average, compared to native forests.

From the total rainfall coming to the forest ground (net precipitation), a fraction comes by crossing the canopy or by dripping from leaves (direct rainfall). The remaining part comes from trees shaft, to reach the ground surface (shaft runoff). Its relative value, with respect to the total amount of precipitations is not relevant but can be important from a forest point of view, because it reaches the base of the trunks, where the greater amount of tree roots is concentrated (Huber and Trecaman 2000). However, it is important to point out that the effect of vegetation cover can be negligible, when precipitations are very intense (Cheng et al. 2002) or when floods correspond to high return periods (Sikka et al. 2003).

Liu et al. (2018) studied the relationships between precipitation, vegetation cover, and runoff, finding that a higher density of trees implies greater interception. Regarding the relationship between interception and precipitation, it was found that this relationship is negative logarithmic. Likewise, Zhang et al. (2017) reviewed scientific studies of 312 basins, finding that changes in vegetation cover modify the hydrological cycle, but the magnitude of this change will depend on the size of the basin and its water availability.

As a result, forest masses tend to decrease the surface water flows, increase infiltration, flatten flood waves and therefore there is less sediments production, while deforestation produces opposite effects, making vegetation cover to decrease and enabling the expression of a greater volume of surface runoff.

In this context, with Chile having a Mediterranean climate, meaning that rainfalls occur during winter when vegetation is mostly in latency, there is an urgent need of having a better understanding about interactions between such ecosystems and water resources, with the purpose of incorporating the results of investigations in public policy.

The amount of water used by trees has been a focus of countless studies around the world, a process that begun more than a century ago (Bosch and Hewlett 1982; McCulloch and Robinson 1993). Trees consume water through two different processes. Transpiration and interception taken together, these two processes are called evapotranspiration. Both processes are strongly affected by the amount of sunlight, temperature, and atmospheric humidity, as well as wind velocity. In this way, trees can use more water than most of the other types of vegetation, although the matter of doing it or not, and to what extent, depends on many factors (Jofré et al. 2014).

On the other hand, it is also necessary to consider the existing interactions between the soil vegetation complex and hydrology. Thus, and according to the effectiveness of the kind of vegetative cover, Iroumé and Huber (2000), analyzed two parcels under different kinds of forest canopy (Oregon pine and native forest) and their effect in the water flow rates in La Araucanía Region, concluding that direct precipitation and shaft runoff were of 66 mm and 8% for the native forest parcel and of 60 mm and 6% for Oregon pine, respectively. These values reflect less interception capacity that the native forest canopy has, compared to the Oregon pine. However, when comparing this kind of cover with a meadow or low vegetation type cover, potential reductions in the flood flows over the experimental basin have been detected (where both parcels are located), because of the rainfall interception by the forests cover. These results show the importance of forest cover in interception processes, rainfall redistribution, and runoff generation.

In addition, there is the effect of live or dead cover over the ground, which decreases the kinetic energy of the rainfall, increasing the surface flow circulation resistance and decreasing the line of maximum circulation slope; this implies an increase of water retention originated by precipitations, favoring infiltration and subsurface runoff. Ward and Trimble (2004) point out that the infiltration rate in forests with the unaltered ground typically exceeds the rainfall intensity. According to thus, subsurface flows prevail.

Finally, there are root systems, which promote water infiltration towards underground layers, also improving its quality. Germer et al. (2010), state that in a deep root system and well-developed of arboreal vegetation, the organic material, the biological activity of the soil, the high porosity, and low apparent density, especially of the horizon A, favor subsurface flows.

16.3.2 Relationship Between Water Production and Forest Masses in the Central South Zone of Chile

The Purapel river basin in Nirivilo has an area of 265 km^2, and its regime is rainy. In 1950 approximately 63.2% of the Purapel basin corresponded to native forests, and by 1997 it had been reduced to 19.7%. In parallel, forest plantation coverage increased from 0.0% in the mid-50s to 51.7% in 1997 (Pizarro et al. 2005). That is, the tree cover of the basin was maintained, but replacing the native forest with plantations. In this context, Pizarro et al. (2005) investigated the effects of the change in land use on water production in the basin. For this, the precipitation data, flows, runoff coefficients, and basin reserves between 1969–2000, stratified in two periods 1969–1978 and 1979–2000, were analyzed. This to visualize the influence of vegetation on runoff, finding that there are no significant statistical differences between both plant coverings and attributing the differences found to the increase in rainfall in the 1980s. In other words, rainfall is the most relevant factor in the production of water inside a basin and especially in the case of Mediterranean climates, with rains in winter. Likewise, Pizarro et al. (2006) increased the scope of the study carried out in 2005, evaluating the temporal evolution of the maximum flows in the Purapel river basin and its relationship with the forest masses. The results of this research are following the statement by Pizarro et al. (2005)

On the other hand, Iroumé et al. (2006) identified the effects of vegetation on water production. For this, they selected four experimental basins in southern Chile (humid climate), recording the hydrological behavior of rainfall, runoff, and tree cover. In the period between 1997 and 1999, approximately 70% of the land in the basins had forest plantations (Pino radiata). Likewise, information on flows and rainfall was collected after the forestry exploitation of the basins (1999–2002), finding that the average surface flows increased by up to 110% post-exploitation and maximum flows by 32%.

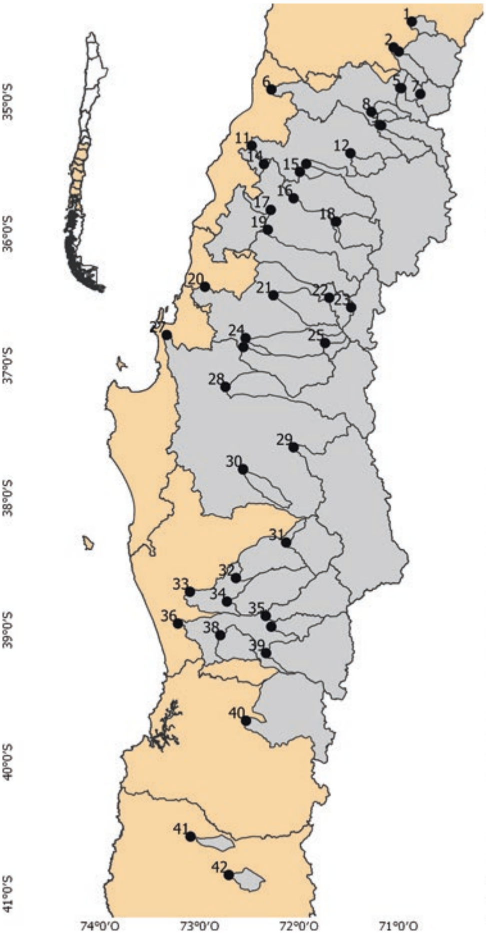
A similar research carried out by Little et al. (2009), studied the production of water in two coastal basins: Cauquenes in the Arrayán and Purapel in Nirivilo. Both basins underwent a process of land use change in the early 1970s, being mostly covered by exotic plantations. Within this framework, they verified the influence of vegetation cover on surface runoff based on the 1975 coverage; 1990 and 2000. Also, rainfall was segregated in two periods 1981–1990 and 1991–2000. The above in order to calibrate a multiple regression model that explained the runoff according to the coverage and rainfall. The model found that forest plantations decrease summer flows from 13.1 to 7.5 mm and 7.3 to 5 mm in the Purapel basins in Nirivilo and Cauquenes in the Arrayán, respectively. However, there is a questioning of this study because they used linear regressions based on data that do not behave normally and suffer from not being parametric.

In the framework described above, CTHA (2014) carried out a study requested by the Forest National Corporation in the year 2013, which had as objective to determine if the forest and agricultural activities have affected the surface runoff in the basins of the central zone (O'Higgins, Maule, Biobío, Araucanía, and Los Lagos regions). Working together with the Directorate General for Water (DGA) and the Unit of Hydrology and Forest Certification of CONAF, 42 river basins were selected with fluviometric control of at least 20 years of record and with a minimum of human intervention (Fig. 16.3).

Subsequently, the current land use was determined for every basin, using the CONAF's Native Forest Cadaster (CBN) of 2013. For this, it was necessary to group the almost 60 categories considered in the cadaster in 7 macro categories. These are Native Forest, Mixed Forest, Plantation, Bushed, Meadow, Agricultural, and No Use. This classification was carried out with the Unit of Hydrology and Forest Certification of CONAF.

To characterize the runoff behavior, there was a recompilation of fluviometric data available for mean flow rate and maximum instantaneous flow rate (peak) in monthly and annual level for the 42 selected stations, information provided by the Direccion General de Aguas (DGA). On a monthly scale, there were chosen the months with summer influence (October, November, December, January, February, March, and April). A non-parametric Mann-Kendall trend analysis was applied to the mean and maximum flow rates series at monthly and annual levels of every basin. There was also a non-parametric Sen test to obtain the trend magnitude.

A graphic analysis of the relationship between the flow rate trend behavior and the surface of every kind of soil, considering three types of cover (Native forest, Plantations, and Agricultural) were performed through the Mann-Kendall Trend test. It was observed that in months from October to April, most of the stations present a negative trend for mean flow rates, and this magnitude does not vary with any one of the vegetative covers. In the rest of the months, there are stations with a



ID	Fluviometric Stations	Native forest cover (%)	Plantation forest cover (%)	Area (km²)
1	Claro en Hacienda Las Nieves	6.7	0	245
2	Claro en El Valle	23.6	6.4	364
3	Tinguiririca bajo Los Briones	1.7	1.7	1,439
4	Teno después de junta con Claro	8.2	0.2	1,206
5	Claro en Los Queñes	11.2	0.4	353
6	Mataquito en Licantén	14.9	5.9	5,721
7	Teno bajo Quebrada Infernillo	0.1	0	596
8	Upeo en Upeo	34.4	3.4	215
9	Palos en junta con Colorado	17.7	0.2	496
10	Colorado en junta con Palos	12.5	0	877
11	Maule en Forel	13.4	15.5	20,840
12	Lircay en Las Rastras	53.8	17.1	380
13	Maule en Longitudinal	8.3	0.6	5,931
14	Purapel en Nirivilo	4.3	67.1	263
15	Loncomilla en Las Brisas	16.2	21.9	10,276
16	Loncomilla en Bodega	12.2	26.9	7,449
17	Cauquenes en Desembocadura	3.7	44.6	1,596
18	Achibueno en La Recova	43.6	8.1	892
19	Perquilauquén en Quella	18.6	21.5	2,078
20	Itata en Coelemu	20.5	21.1	9,950
21	Cato en puente Cato	25.9	32.9	944
22	Ñuble en San Fabián	42.9	0.2	1,650
23	Ñuble en La Punilla	34.5	0	1,255
24	Diguillín en Longitudinal	29.2	39.2	1,412
25	Diguillín en San Lorenzo	48.5	0.1	203
26	Itata en General Cruz	23.5	30.4	1,691
27	Biobío en Desembocadura	29.1	25.6	24,251
28	Laja en puente Perales	25.9	15.6	3,592
29	Biobío en Rucalhue	52	1	6,903
30	Mininco en Longitudinal	11.2	61.3	444
31	Cautín en Rari-Ruca	53.4	2.6	1,297
32	Cautín en Cajón	35.9	7.5	2,726
33	Cautín en Almagro	27.8	8.1	5,597
34	Quepe en Quepe	29.1	8.6	1,699
35	Allipén en Los Laureles	45.4	6.6	1,649
36	Toltén en Teodoro Schmidt	43.2	7.5	7,841
37	Curaco en Colico	60.2	6.7	539
38	Donguil en Gorbea	13.1	12.2	735
39	Toltén en Villarica	62.1	1.1	2,866
40	San Pedro en Lago Riñihue	64.9	1	3,304
41	Damas en Tacamo	19.6	0.6	252
42	Coihueco antes junta Pichicope	74.5	4.7	324

Fig. 16.3 Area (km^2) and current land use of every basin

positive and negative trend, but in the same way, the trend magnitude does not vary with vegetative covers percentage.

Similarly, the Fig. 16.4 shows that the correlation coefficient between mean flow rates trend magnitude and the percentage of used surface in the basin by the different analyzed uses has low values, under 0,4; this means that the relationship between both variables is low.

At the annual level, surface with plantation shows a positive correlation with mean flow rates, while with native forest and agricultural use, the coefficient is negative, but with values near 0.

Similar results were obtained for peak flow trend, even considering that over 20% of the surface with these uses has impact over the basin, there is no evident relationship between these covers and the trends. April presents more considerable significance in trends, but it is not related to land use.

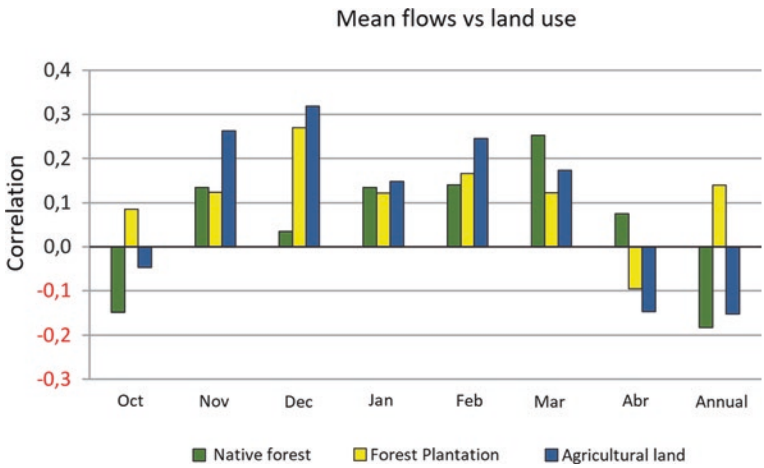


Fig. 16.4 Correlation coefficient between mean flow rates (Mann- Kendall test) and current land uses: native forest, plantation and agricultural use

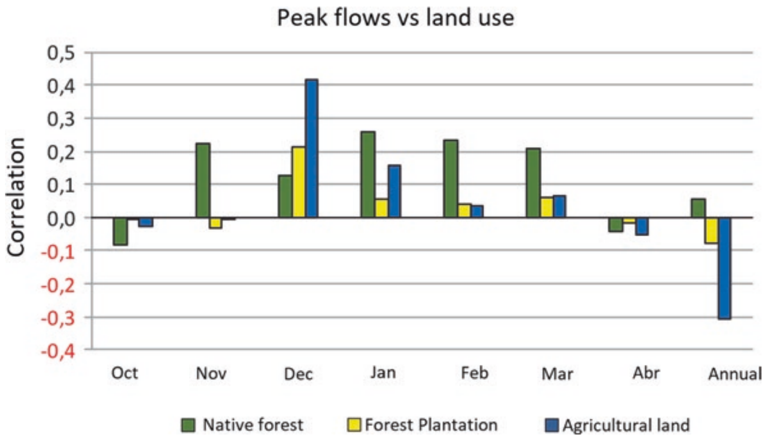


Fig. 16.5 Correlation coefficient between surface by kind of land use and Mann Kendall trend for every peak flow rate

The Fig. 16.5 shows that the correlation coefficient between peak flow rates trend magnitude, and the percentage of used surface in the basin by the different analyzed uses has low values. Agricultural use is the one with the most significant correlation coefficient reaching 0.42 in December, meaning that for greater agricultural use, the greater the peak flow rate trend it gets. In this sense, on a monthly level, the native forest behaves like agricultural use, while plantations would have a more positive effect when peak flow rates trends decrease. However, these values are low and do not allow them to obtain conclusions. In the annual level, the surfaces with plantation and agricultural use would show a negative correlation with the peak flow rates, meaning that they have a positive effect. However, the values are shallow.

In this context, 42 basins of center south zone of Chile, would demonstrate that it is not possible to state that the kind of land use is the cause or a significant factor of water production trends (mean or maximum flow rates) of every basin and with that it is also valid for artificial plantations to use. This implies that there are other variables that could explain in a better way the water availability variations at the outlet of a basin, such as precipitations, the water demands change by users that are endogenous or exogenous to the basin, the hydrogeological behavior of the basins and the water extractions from the flow rates, among others.

However, relations between the Chilean forestry sector and water resources are more complex if arid and semi-arid areas are incorporated, where there were abundant forest resources, but today there are important desertification processes in these territories (Huaico 2018). Therefore, it is important to visualize in general the behavior of the soil-vegetation complex and its relation to the precipitation-runoff process. In the case of desertified lands in arid and semi-arid areas, there is a situation that rainfall, which is low in amount, although with non-negligible intensities, (Unesco 2007) is quickly transformed into surface runoff rather than underground runoff, since that aquifer recharge in these territories tends to occur primarily in riverbeds. This is because from Santiago to the north there is an elevation of the Cordillera de los Andes and the presence of strong transverse mountain ranges is verified, which makes the landscape an area with high slopes and low capacity to retain surface flows on hillsides. This situation can be reversed through engineering techniques that define the construction of works that retain surface runoff flows, to favor the percolation of water (infiltration dikes and ditches among others, Fig. 16.6) on the one hand, but also through of reforestation processes of these desertified spaces, given the water retention capacity of the vegetation in contact with the soil. This retention in high areas, can not only restore hydrological balances in desertified scenarios and under high climatic uncertainty but also promote greater and better care of biodiversity. To this is added a reduction in the emission of sediments as a result of the decrease in erosion processes in high areas (Valentin et al. 2005), which tend to mitigate the harmful effects of excessive sediment transport to low

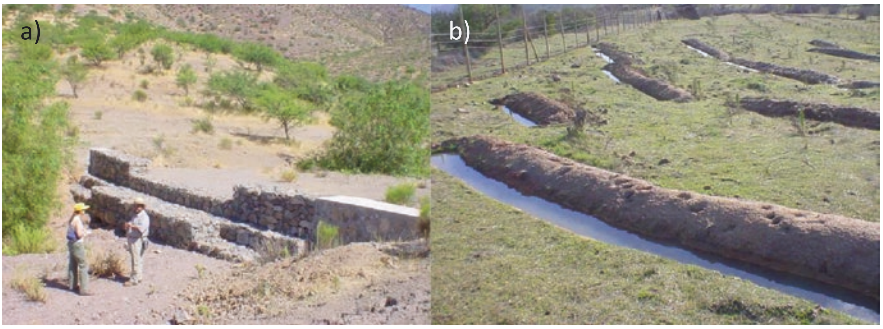


Fig. 16.6 (**a**) Masonry dike. (**b**) Infiltration Trench

areas, that impacts civil works, the hydraulic configuration of the beds and human lives, among other aspects.

Therefore, when referring to the relations between the Chilean forestry sector and water resources, mention should be made of a very large group that covers the entire national territory and where there may or may not be forest, forest, or bush formations or herbaceous vegetation, but where this vegetation interacts with the soil, defining a special behavior of the complex soil vegetation. This behavior, added to the existing hydrogeological framework, governs the relationships between surface and underground runoff and hence the importance of knowing the variables that affect this process and being able to evaluate them in their various forms. This is even more important in a territory such as the Chilean, dominated mostly by the Mediterranean climate, which defines the fall in winter rainfall, at which time the vegetation is in total or partial latency, which determines a low water consumption and ends up promoting the existence of obstacles to the passage of water, favoring the deep infiltration of water in the soil and increasing the chances of reaching the aquifers. That is the significant role of the complex soil vegetation in Mediterranean climates and an important way to understand the rainfall runoff process in these territories.

16.4 Conclusions

Based on what has been raised about the relationship between the Chilean forestry sector and water resources, the following conclusions can be reached:

(a) Several studies account for the relationships between the forest masses and the rainfall-runoff process. These do not always coincide and give an account of the need to increase research efforts to save the questions that exist regarding the subject, particularly those related to the level of water consumption by the forest masses.
(b) The forest masses are an instrument of fundamental water regulation in a country like Chile, which has a Mediterranean climate with rains in winter, where the vegetation is in total or partial latency and decreases its consumption. On the contrary, this vegetation is an obstacle to the passage of water in the maximum energy line and is, therefore, a determining factor to promote the recharges of aquifers.
(c) The most relevant factor to be studied in the situation in Chile is the role of the soil-vegetation complex, which has a determining role not only in rainy areas but also in arid and semi-arid areas. This is more relevant when considering the relationship of this complex with the hydrogeological characteristics of the territories.
(d) It is also necessary to expand studies to large watersheds, in order to allow the expression of all hydrological variables, especially the hydrogeological variables that regulate water reserves, which is especially important in climate change scenarios.

This should enable a greater understanding of the precipitation-runoff process in a mountainous country and with high altitude differences over short distances, in addition to the role of the complex soil vegetation, which gives it a special condition that must be considered for the proper understanding of the phenomena.

(e) Forestry legislation must implement incentives for the stabilization of degraded basins, through vegetation. To protect natural water sources and decrease soil erosion in bare basins.

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Chapter 17
Environmental and Recreational Uses

Francisco Riestra, Agustín Silva, and Christian Valenzuela

Abstract Ecological valuation, nature conservation and environmental protection have acquired significant importance in Chile, as knowledge and awareness of environmental sustainability increase, and the need to maintain ecosystem services provided by river basins becomes more evident. In this chapter we review the legal and institutional framework related with environmental and recreational uses of water, including the Water Code and other regulatory legal bodies, such as the SEA (Service of Environmental Evaluation), the Environmental law, the general law for fishing an aquaculture, as well as regulations about recreational fishing, and the maritime, fluvial and lacustrine policy. We also describe the available legal measures to promote a more sustainable use of water, including shortage decrees, non-consumptive water rights, temporary reductions of uses, fees for non-use of water rights and other penalties. The chapter also discusses the concepts of ecological, environmental and reserve flows, and aspects related to the protection of aquifers and wetlands. Finally, conflicts between water rights and environmental and recreational uses are commented, with a focus on fishing, tourism, ancestral uses, and conservation and water use exploitation in national parks.

Keywords Ecology · Environment · Recreation · Sustainability · Ecosystem · Reserve flow · Ecological flows · Environmental flows · Wetlands · Water rights · SEA · Fishing · Aquaculture · Tourism · Ancestral uses · National parks · Water Code

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17.1 Introduction

Human activities affecting rivers and aquatic life are varied: irrigation, hydroelectricity, drinking water, fish farms, industrial use, food extraction, aggregate or sand extraction, navigation, the sink of point or diffuse pollutants, *inter alia*.

The uses of water can be conflicting and even opposed, affecting larger areas, at greater distances and with greater intensity depending on the growing technological power and development of the countries.

In Chile there are special features related to the water use rights (DAA) related to its granting and nature, such as lack of priorities of use, granted in perpetuity, existence of over-granting, hoarding, payment for non-use of water, between others. Notwithstanding the importance of the 2005 amendments to the 1981 Water Code (CdA), it becomes necessary to make progress on pending issues such as environmental flows and other urgent issues, such as the effective conservation of aquatic ecosystems (Fundación Chile et al. 2019).

Ecological valuation, nature conservation and environmental protection have acquired significant importance, there is greater knowledge and awareness of environmental sustainability and, today in particular, of the need to maintain the ecosystem services of our basins.

Although water quality is not addressed in this document, it is important to note that the CdA practically does not touch the subject, and although emission standards have been important in Chile, those of secondary quality of waters for the preservation of aquatic ecosystems, or the very protection of species or ecosystems in our country is scarce and incipient, which is reflected in the complex ecological status of inland aquatic species (Peredo-Parada et al. 2009), on a path that seems to have no return unless more significant and definitive measures are taken. This chapter presents brief descriptions and critical analysis of some instruments related to the environmental and recreational uses of water currently in force in Chile.

17.2 Legal and Institutional Framework

17.2.1 Water Code (CdA)

17.2.1.1 Ecological Flows

The CdA has included environmental or perhaps recreational uses under the formula of minimum ecological flow, whose legal enshrinement is a fairly recent development. In fact, the original version of the 1981 CdA made no reference to this concept, which was also not included in the 1969 and 1951 applicable codes.[1]

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[1] Far from environmental considerations, the previous Water Codes rather expressly allowed the total depletion of surface courses for the granting of DAA. In this regard, Article 53 of the 1969

Law 20.017 of 2005 incorporated Article 129 bis 1 into the CdA, which for the first time legally established the power of the General Water Directorate (DGA 2016) to develop minimum ecological flows.

Subsequently, Law 20.417 of 2010, amended Article 42 of the General Environmental Bases Law of 1994, and Article 129 bis 1 of the CdA, stating the participation of the Ministry of Environment (MMA) in the preparation of the regulation for establishing the minimum ecological flows in the new DAA. For its part, the regulation to determine the criteria and procedures for this purpose were promulgated in 2012 by MMA Decree No. 14 of 2012, modified by MMA Decree No. 71 of 2015.

More recently, with Law 21.064 of 2018, new references to ecological flow were included in the CdA, mainly due to: (i) Failure to comply with the restriction of ecological flow constitutes a cause for increased fines[2]; and (ii) It is established that for zones declared as scarce, the DGA can authorize extractions without the need to constitute DAA and without respecting ecological flows.[3]

However, it should be recalled that even before the incorporation of Article 129 bis 1, the DGA had already established in its founding resolutions the restriction of extractions for environmental or ecological flow (Riestra 2007, 2018 *fide* Boettiger 2012), practice which was questioned by sectors of the doctrine (Vergara 1999 *fide* Boettiger 2012). To this effect, an ecological flow regulation was even incorporated in the Manual of Norms and Procedures for the administration of water resources of the year 1999,[4] making its application more systematic.

Notwithstanding the foregoing, the implementation of the ecological flow in Chile, in a timely, sporadic and discretionary way, goes back to the years 1982–1983[5] in the DAA, on the basis of the Political Constitution and the protection of third party rights mentioned in the CdA, effectively understanding the environment as a third party, which needs water and whose rights must be respected (committed flow).

The above has been applied for more than 22 years in the DAA without being expressly included in the CdA, which shows that, although legal changes are essential, technicians concerned with the issue can be advanced, backed by the authority and political will. The current regulations set the power to establish minimum ecological flows but limits its application "*to the new rights that are constituted, (…) not being able to affect existing exploitation rights*". This has generated several discussions, among which the following can be highlighted:

There has been no consensus as to whether to apply ecological flows to DAA whose exercise is transferred from one point to another. On the one hand, the Comptroller General of the Republic has indicated that a transfer does not imply the

Code expressly stated that "While there is available flow, the grant must be granted", a rule that reiterated the provisions of Article 43 of the 1951 Water Code.

[2] Article 173 bis N° 3 del CdA.

[3] Article 314 del CdA.

[4] Approved by Resolution DGA N° 1700 (Exenta) of 1999.

[5] DGA Decisions No. 22 of 1982 and No. 442 of 1983.

granting of a new DAA.[6] On the other hand, the Supreme Court has indicated that it applies to the ecological flow to the DAA that is transferred.[7]

The 2014 CdA reform project sought to resolve this controversy, extending the legal power to establish ecological flows also to transfers, which could even generate disincentives for individuals to complete the procedure (replacing it with other permits, such as the "channel concession" of Article 39 of the CdA or the installation of conduit pipes), an aspect that was eliminated through the replacement indication of 2019 to the aforementioned draft amendment to the CdA.

In practice, although the DGA does not establish a minimum ecological flow in the Resolution approving a transfer of DAA, on many occasions, but again at its discretion, it deducts the calculated minimum ecological flow from the availability. Thus, in the DGA's balances, there is a "committed" flow that is discounted without charge from a previously constituted DAA.

It is controversial that the notion of ecological flow is related to the limitation to a specific DAA and not to a general restriction on the source, extended to all users therein. It is not entirely appropriate to increase the flow available in rivers -for environmental - restricting purposes under certain specific DAA, rather, corresponds to all holders of a DAA source to bear such a burden, so at some point ecological flows by sub-basins, sub-basins or river sections should be set (Muñoz 2015; Vergara 1999), which is similar to what the Surveillance Boards do by temporarily reducing, in periods of shortage, the equivalence in liters per second associated with each action within the channel (Article 274 of the CdA).

In fact, a general restriction measure, and not a particular one, is more in line with criteria contained in our water legislation, where the decrease in the availability of the resource is usually assumed proportionally by all the holders of the source in question.[8] On the other hand, the general and egalitarian restriction of extractions is in line with a modern conception of ecological flow, where the limitation is associated with the source sector (Embid 1994) and not unequally with respect to the individually granted DAA, which is what has been done to date in Chile.

This reasoning of mere logic is constitutionally recognized under the so-called "Principle of the Equal Distribution of Public Charges", enshrined in Article 19, paragraphs 2 and 20, of the Political Constitution of Chile.

In 2016, the DGA developed the study "Impact of the application of minimum retroactive ecological flow in basins of the IV, V and VI Regions", evidencing that most of the DAA in the central area of the country do not have a minimum ecological flow of the total analyzed in the study (only 8% does), therefore, the minimum retroactive ecological flow directly impacts productive activities currently under development, reducing the number of hectares for agricultural production,

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[6] Opinion No. 25027 of 4 July 2002.

[7] Judgment in Case No. 9.654-2009, of 24 May 2012, entitled "Menichetti con Dirección General de Aguas", recital No. 11.

[8] For example, see Articles 17, 62, 211, 314 y 274 No. 2 and 3, CdA and Article 39 from MOP Supreme Decree No. 203, of 2013, regarding norms exploration and exploitation groundwater resources.

generating a loss of production from industries such as mining, and reduction in the supply of drinking water to sanitation companies, all on the understanding that this minimum retroactive ecological flow would be respected. In channels really needing it, it would be expected that at least the Surveillance Boards could consider and control it, to avoid the current ecological state of some ecosystems; in the central - northern part of the country we have become accustomed to seeing our dry rivers, and although there is talk of a mega drought or at least a general decrease in rainfall since 2008, what produces this situation is the extraction of water for productive uses without considering a minimum ecological flow.

17.2.1.2 Environmental Flow

The environmental flow, in the case of Chile, is something rather recent in terms of its denomination and determination. In summary, the difference between the minimum ecological flow of the CdA for the DAA and the ecological flow established in the Environmental Impact Assessment System (SEIA) is made for the projects that enter this evaluation from 1994 onwards, and that from 2016 onwards are called environmental flows with the definition of the Brisbane Declaration (2007): “Environmental flows describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems”, a definition that is incorporated into the Methodological Guide to determine the environmental flow for hydroelectric plants in the SEIA [Environmental Assessment Service (SEA) 2016].

For other projects, the DGA today applies Minute 267/2011 that establishes Criteria and methodology for the determination of Ecological Flow within the Framework of the SEIA.

The environmental flow in the SEIA implies a restriction to the exercise of the DAA for the specific project being evaluated.

In Chile, the minimum ecological flows (DAA) and the environmental flows (SEIA) are fixed and very difficult to modify, which contrasts with the basic methodological concept of these environmental management instruments, which must be evaluated in subsequent monitoring to allow adjustments according to the results obtained (adaptive), and as the objective for which they were established (tourism, landscape, protection of a species or community, an ecosystem, etc.) is fulfilled, it also becomes an aspect to improve in the future.

17.2.1.3 Reserve Flows

In those sources where there is still availability to establish new DAA, the State can make use of the reserve of flows, a mechanism enshrined in Article 147 bis, third paragraph of the CdA in its 2005 amendment (Law 20.017).

This mechanism has been used in recent years in numerous surface and underground sources quite successfully, mainly in the southern area.[9] On the basis of technical reports and subsequent decrees by the Ministry of Public Works (MOP) that have declared flow reserves due to exceptional circumstances of national interest (tourism or conservation), multiple applications for new DAA from different sources have been rejected, allowing a subsequent responsible and strategic allocation of the resource.

Unfortunately, this mechanism has operated in few sources in the country (approximately 20, which we hope to maintain this condition), not operating in most of them that have their waters compromised in DAA or have been declared zones of restriction, prohibition or exhaustion.

17.2.1.4 Protection of Aquifers that Feed Plains (*vegas*) and Wetlands (*bofedales*) in the Regions of Arica and Parinacota, Tarapacá and Antofagasta

In 1992, the DGA promoted the modification of Articles 58 and 63 of the CdA to prohibit the exploration and exploitation of groundwater in the aquifers feeding plains and wetlands in the regions of Arica and Parinacota, Tarapacá and Antofagasta. This is due to the fact that the aquifers are the sustenance of the agro-livestock and survival activities of the Andean communities. These changes in legislation allowed the establishment of measures to protect these unique ecosystems and the ancestral use that the communities had made of them.

In 1993, the DGA began carrying out studies to identify and locate areas of *vegas* and *bofedales* to identify their feeder aquifers, which in 1996 led to the DGA Resolution No. 909, which defined the boundaries of said aquifers. The foregoing implies that in these areas it is not possible to authorize groundwater exploration or constitute groundwater DAA without a prior favorable environmental assessment. In the regions of Arica and Parinacota and Tarapacá, 139 wetlands were protected, with an area of approximately 335 km^2, equivalent to 0.5% of the total regional area. In the Antofagasta Region, 167 wetlands were protected with an associated area of 2798 km^2, equal to 2.22% of the total area of the region.

In 2003, DGA Resolution No. 529 modified the delimitation of these aquifers for the Antofagasta Region, leaving 228 wetlands protected and an area of 5149 km^2 equivalent to 4.07% of the total regional area.

It is important to highlight that the protected *vegas* and *bofedales* in the north of the country are also very important in the migration of birds of international importance that in this area do not have coastal lagoons for their feeding and resting, so they use the lagoons associated with these altiplano systems, which is why many of these lagoons, in addition to the protection given by the CdA, are within the National System of State Protected Areas under the responsibility of the National Forestry Corporation.

[9] Notwithstanding that, for example, flow reserves have also been decreed in the North of the country. Supreme Decree MOP No. 2114 of 2014, which rejected applications for DAA and reserved flows for human consumption in the Huasco Valley, can be revised for this purpose.

17.2.1.5 Shortage Decrees

Shortages decrees are regulated in Article 314 of the CdA and are a mechanism that allows: to extract water without DAA to deal with emergencies; and to reduce or modify withdrawals by water users in sectors affected by extraordinary droughts, forcing them to reorganize and/or reduce their withdrawals. These decrees have been issued in numerous occasions[10] and have the particularity of being essentially temporary, since they can last a maximum of 6 months, which cannot be extended.

On the other hand, decrees of scarcity entail the obligation for the Treasury to compensate the damages that are generated to individuals. Unlike compensation for expropriation, this compensation refers to a time limitation of the property and is not regulated. It is not known to what extent these declarations have actually affected private interests, or whether compensation lawsuits have been filed against the MOP because of the shortages decrees.

According to the wording of the rule that enshrines this figure, it is aimed at authorizing extractions without having DAA and without respecting ecological flows, so it focuses on water withdrawals for human and productive consumption rather than the protection environmental or recreational uses.

17.2.1.6 Non Consumptive Water Rights

Non-consumptive DAA, which have the obligation to return the water extracted, often operate as true defenders of flows in various basins in the south of the country, preventing the granting of new consumptive DAA (which do not have an obligation to return) upstream that could reduce their backup flow.

In fact, the granting of a non-consumptive DAA by the DGA may prevent the constitution of new upstream DAA, when the reduction in the existing flow in the river implied by the new DAA entails the assignment of previously constituted DAA located downstream.

This situation constitutes a positive externality of the system from an environmental point of view or from the recreational use of the water resource, guaranteeing the availability of water in non-consumptive DAA sources, insofar as they are not used in any project that actually carries out water extraction in the river. In some cases, non-consumptive DAA have been applied for in order to conserve water in said river section and with no real intention of effective or productive use of the water.

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[10] I.e.: In 2008, the DGA issued six such decrees; one in 2009, four in 2010, 15 in 2011, 10 in 2012, seven in 2013, 13 in 2014, 12 in 2015, eight in 2016, 10 in 2017, 11 in 2018 and 24 more decrees in 2019.

17.2.1.7 Temporary Exercise Reduction

The temporary exercise reduction is a tool that already existed in the 1981 CdA,[11] and was strengthened and extended by Law No. 21,064, published in the Official Gazette dated January 27, 2018. Following the referred modification, the mechanism today confers the DGA extraordinary powers to temporarily reduce the exercise that some users of groundwater can extract groundwater.

These new powers for the authority were harmonized with the amendment of Article 299 of the CdA, which empowers the DGA to prevent certain extractions, even if they are within the jurisdiction of a Supervisory Board (prior to the modification, the DGA could only intervene if such a Board did not exist) (Muñoz 2018).

It should be noted that, in its wording, the rule is certainly confusing: it does not specify whether the temporary reduction would affect and apportion certain DAA ("some users") or all users of a given source. This distinction is fundamental, since an arbitrary and partial affectation would undoubtedly violate basic rights that even have constitutional protection, such as equality before the law and - particularly - the principle of "equal distribution of public charges".

If the reduction affects only certain specific users, the rule fails to specify whether they are entitled to compensation or not. The application of this measure may undoubtedly give rise to legal challenges or defenses by those affected, as the same rule warns. It is not yet possible to make a practical analysis in this regard, since, according to the authority, this measure has never been applied.[12]

17.2.1.8 Fee for Non-Use of Water Rights

The patents for non-use (PNU) of DAA were created in 2005, preceded by a debate of almost 13 years, mainly to discourage hoarding and speculation (Valenzuela 2009). However, its unrestricted application may lead to negative impacts from the point of view of environmental preservation or recreational uses, since, DAA intended for such purposes are currently taxed with PNU, since such uses are carried out by allowing water to pass without extraction works.

The PNU does not substantially affect recreational or environmental objectives when it refers to DAA located in areas of relative abundance of the resource (such as the south of the country), where the problem is not so much their physical shortage, but rather the lack of titles and infrastructure to exploit the resource.

Regarding the possible improvements of the PNU, it has been part of the debate to incorporate exceptions so as not to discriminate against some purposes without works, such as environmental, tourist, landscape or recreational purposes, complementing them with mechanisms so that these ends are not used as alibis for hoarding and speculation. In the last substitute indication for the project of reform to the

[11] Art. 62, CdA.

[12] Response to information request via Transparency Law to DGA No. 116714 of 2018.

CdA, presented by the executive in January 2019, a subparagraph is incorporated in this regard.

It is important to highlight that the PNU is unique in the world, only in Chile it there a charge for nonuse (criterion of abundance of the resource) instead of charging for the use or simple tenure (scarcity criterion), a criterion that is applied in other countries and states when there is some charge associated with water tenure. In that sense, different experts have argued that the PNU instrument is inadequate (Gómez-Lobo and Paredes 2000; Domper 2003; Jara and Melo 2003; Valenzuela 2009; Cristi and Poblete 2011; Valenzuela et al. 2013; Libertad y Desarrollo 2019).

17.2.1.9 Uses and Modifications of Channels

Article 41 of the CdA establishes that the DGA must previously approve any modification or alteration of any kind in natural or artificial channels.

This rule obeys the preventive and precautionary environmental principles - it is "*easy, economical, effective and efficient to protect the environment through instruments that anticipate, prevent, avoid or minimize environmental damage, which through ex post formulas* (...)" (Bermúdez 2014) -, but its wording is so absolute and categorical that it can lead to unwanted results: Legally, without prior permission from the DGA, it is not even possible to install a bicycle path in a natural riverbed, or improve its riversides with an ecohydrological criterion, or of putting in value of these systems with a temporary walk on the riverbed. Activities such as those mentioned could have established pre-defined requirements, instead of bureaucratic reviews on a case by case basis. On the other hand, there are no environmental considerations in these permits, except those granted through the SEIA.

It is common for cities to settle on rivers, there are several urban rivers that cover large areas of highly demanded sectors, so in several of the large cities the natural channels are spaces that have increasingly served recreational uses.

Today, rivers like the Mapocho do not have the health problems they represented a couple of decades ago, so it is perfectly feasible to develop temporary uses of the riverbed for recreational purposes.

17.2.1.10 Penalties

Penalties for violations of provisions of the CdA were substantially increased with the entry into force of Law No. 21,064, dated January 27, 2018. In particular, unauthorized extraction was previously sanctioned with a fine of up to 20 "UTM" (Chilean indexation unit), while today said fine starts at 501 UTM (currently equivalent to more than CLP$ 25,000,000.– or USD$ 31.250.-), without prejudice to the criminal penalties corresponding to the offence of encroachment of water.[13] This modification is in line with the proposals developed by the World Bank (2013).

[13] Under article 459 of the Penal Code, illegal extraction and other offences are punishable by minimum to medium-term imprisonment (61 days to 3 years) and a fine of 20 to 5000 UTM.

The increase in fines undoubtedly discourages illegal extractions, facilitating the existence of remaining flows at the sources, which favors environmental and recreational uses. However, for the sanctions to have the deterrent effect that motivated their establishment, it is indispensable that the legal change be accompanied by a strengthening of the control of illegal extractions.

In terms of compliance with minimum ecological flows, the DGA (2017) inspected 103 DAA in the southern central regions of the country (O'Higgins, Maule and Biobío), of which 74% are greater than 50 l/s, 63% is about 100 l/s and 35% are greater than 1000 l/s; only 50 collected water at the time of inspection, 40% did not meet the minimum established ecological flow (20 of 50), especially in the Biobío region where 13 of 28 were in breach.

Of the 103 DAA audited, only 17 were associated with a project submitted to the SEIA, in six cases the DAA was not exercised, seven complied with the requirement of the Resolution of Environmental Qualification and five were not in breach.

The study is worrying, because, although there are few ecological flows established in the DAA, there is no control of compliance, with a high percentage of non-compliance (46% of the DAA audited in the Biobío region). Unfortunately, the breaches detected in the study did not result in effective sanctions from the DGA, or the Superintendence of the Environment in the case of environmental qualification resolutions.

The positive news of the study from the environmental point of view, is that a large part of the DAA and/or projects approved by the SEIA are not being carried out or executed and, therefore, the water follows its course in the river. However, if these DAA do not respect established ecological flows at their start, it is not a sustainable situation over time.

17.2.2 Other Regulatory Bodies

17.2.2.1 Methodological Guide to Determine Environmental Flow for Hydroelectric Power Plants (SEA)

Despite the absence of explicit legal instruction, the SEA (2016) issued a guide to standardize criteria in the determination of environmental flows, which may be required as a voluntary environmental commitment, condition or requirement to verify that a given project does not generate significant impacts.

As explained in a previous section, unlike the minimum ecological flows, the environmental flows involve the use of more complex estimation methodologies, the review by other Public Services in addition to the DGA, and consequently a more complete analysis and according to the existing ecosystems and the uses of the channel, and therefore, the maintenance of larger volumes at the source, so this figure contributes directly to environmental uses, even without having a normative hierarchy.

17.2.2.2 Urgent and Transitory Measures

These measures are established in Articles 3, letters g) and h), and 48 of the Organic Law of the Superintendence of the Environment, and allow said body to adopt a series of actions to avoid imminent damage to the environment or to people's health, such as the temporary suspension of the resolution of environmental qualification or ordering specific monitoring and analysis programs that will be the responsibility of the offender.

17.2.2.3 General Law of Bases of the Environment Law on the General Basis of the Environment

Article 42 of Law 19,300 empowers the MMA, in conjunction with the competent body, to order the presentation of and compliance with a management plan, in order to maintain water flows and soil conservation or landscape values. Although it served in the 90s to justify the ecological flow in SEIA, it has not had an express application in terms of flows given to the particularity in the DAA of the country, which prevents taking measures such as a flow management plan affecting DAA holders.

The Environmental Legislation refers directly and indirectly to Environmental and Recreational uses in other normative bodies. For example, in January 2020, the Law on Urban Wetlands was enacted, giving the Ministry of the Environment the power to declare the protection of the area, either officially or at the request of a Municipality. In turn, it modifies the General Law on Urban Planning and Construction and the Law on the General Basis of the Environment, to incorporate urban wetlands as protected areas under these regulations.

17.2.2.4 General Law of Fishing and Aquaculture

The general law on fisheries and aquaculture regulates the preservation of hydrobiological resources, and all extractive, aquaculture and research fishing activities are carried out in terrestrial waters. One of the main contributions is Article 136, related to penalties (imprisonment) and sanctions (fines and measures) to which without authorization or contravening its conditions or violating the applicable regulations introduced or mandated to enter the sea, rivers, lakes or any another body of water, chemical, biological or physical pollutants that cause damage to hydrobiological resources (usable by man Art. 2, No. 36).

17.2.2.5 Regulations About Recreational Fishing

The regulations are not responsible for the effects of introduced and feral species, considered hydrobiological resources (mainly Salmonids), and have caused obvious and irreversible damage to the native species of fish in the rivers and lakes of Chile.

Law 20,256, which establishes the rules of recreational fishing, in its Article 3, letter d), establishes a definition of minimum flow as “amount of water that ensures adequate habitat availability for the different vital stages of the hydrobiological species present in a preferential area and the adequate exercise of recreational fishing activities”.

This law regulates recreational activities available in natural streams and pools of water in the country, providing some tools to keep the species that inhabit these waters. However, these flows would only be indicative since when being awarded the DAA said minimum flow is not required.

17.2.2.6 General Regulation of Maritime, Fluvial and Lacustrine Police

In accordance with the provisions of this regulation, approved by DS No. 1340 bis of 1941, the Maritime, River and Lake Police, includes everything related to order, discipline and security in maritime, river and lake ports, both in ships and vessels at anchor or underway, as well as in the port enclosures and other places within the jurisdiction of the maritime authority (territorial sea, ports, bays, canals, lakes, navigable rivers and islands).

17.3 Controversies Between Water Rights and Environmental and Recreational Uses

17.3.1 Fee to Water Use Rights Applied for Purposes of Non-use

Some of the main non-consumptive uses of water are: hydroelectric power generation, aquaculture, fishing, transportation, wildlife, recreation and waste acceptance (Gayoso et al. 2000). Of all of these, the only uses that require works are the first two. The remainder are *in situ* uses, some of which have been the subject of debate regarding the collection of the UNP, specifically those DAA associated with fishing, wildlife (environmental), ancestral use by native peoples and recreation. Additionally, a normally non-consumptive use without works in Chile that has been guaranteed through the DAA, and which has provoked numerous claims against the collection of PNU, is the ancestral use, specifically that made by people belonging to the Mapuche ethnic group in the south of Chile.

17.3.1.1 Fishing

This section deals with fishing in superficial natural sources understood as an economic activity that provides fish as a product, not including sport fishing, which is included in a subsequent discussion (see point 3.1.2. Tourism and conservation).

Fishing is an economic-productive activity just like aquaculture, both need a certain amount of water that they do not consume and that they can guarantee through non-consumptive DAA. The difference is that aquaculture constructs works that capture the water, then lead them to their fish breeding plants, and finally return it to a riverbed, or else maintain works within the same riverbed - the latter being less and less accepted; while fishing is only interested in flow of water through natural surface sources to provide fish, i.e., unlike aquaculture, fishing does not require river works, and therefore its non-consumptive DAA are affected to the PNU, notwithstanding that the DGA itself recommended this modality to protect some river sections from growing productive activities that effectively extract the waters before the PNU. Similarly, some DAA associated with aquaculture are partially affected by the PNU because they have large flows, in circumstances that their collection and restitution works do not have the capacity to conduct all the water constituted in DAA. Aquaculture companies opt for this path in order to ensure water in quality and quantity, both upstream, to prevent other users from contaminating them, and downstream, to have greater dilution flow of their own waste.

17.3.1.2 Tourism and Conservation

In 1998, the Municipality of the district of Pucón (Araucanía region) approached the DGA concerned about the increasing occupation of rivers by hydroelectricity and aquaculture in southern Chile. This concern had its origin in that these activities were incompatible and exclusive with the primary economic vocation of the district of Pucón: tourism associated with nature. At that time, the PNU was not part of the CdA, therefore, the DGA had no problem recommending the obvious: protect the sections of rivers of interest through non-consumptive DAA ownership, a recommendation that the Municipality of Pucón took up.

The DGA considers recreational and environmental uses of water to be non-consumptive and non-productive, the former being understood as an activity that generates social, sociological and aesthetic well-being through a direct or indirect relationship with water; while the latter is related to the sustainability of a given ecosystem, taking into account the need to preserve, in sufficient quality and quantity, water as an indispensable resource for life (Gayoso, Iroumé & Rojas, 2000). These definitions fit exactly with what the Municipality of Pucón sought to protect through DAA ownership, with the additional fact that the combination of tourism and conservation - or recreational and environmental use - in this case leads to direct economic benefits, supporting service activities. The paradox, then, is that this type of use has the disadvantage in that it does not require works: the burden of the PNU.

The Municipality of Pucón, the most emblematic DAA owner identified with this situation, filed an appeal for reconsideration in 2009 with the arguments that in its opinion should be applied to exempt their DAA from the payment of PNU, which was rejected by the DGA, since the law is clear in not distinguishing these environmental uses or exempting them from paying PNU. This situation led the Municipality of Pucón, in 2015, to an accumulation of seven years of unpaid PNU, for 10 non-consumptive DAA in nine rivers, totaling just over 36,000 UTM in debts (approximately 2.6 million dollars), presenting a new appeal for reconsideration that was also rejected by the DGA. The normal procedure is that these DAA would have been auctioned for non-payment of the PNU, however, the issue became increasingly politicized and sensitive, to the point that the auctions ordered by the CdA for the case of non-payment were never carried out for the DAA in question. Already in the list of PNU of the year 2016, the 10 DAA of the Municipality of Pucón did not appear, because the Court of Appeals of Temuco accepted a claim of the Municipality invalidating the last decision of rejection. The DGA could have complied with the order of the Court of Appeals of Temuco, which was basically to decree an evidentiary stage so that the Municipality could provide evidence in defense of its claims, or it could have filed an appeal in Supreme Court with very strong arguments against the outcome of the claim, however, it did not do so and removed the DAA of the Municipality from the PNU list from 2016 onwards, without an administrative or judicial act ordering it, probably because it was politically advisable.

17.3.1.3 Ancestral Use

The ancestral use of water shall be understood as that made by particular indigenous and indigenous communities. While irrigation is one of the uses in which indigenous people occupy their DAA (Díaz and Elgueta 2001; Palacios 2003; Gentes 2004), there are other reasons why the waters are important for the original peoples: religious significance- Spiritual (Grebe 1986), of contemplation or only existence, recreational, use through pitchers and jars, and even to preserve the scenic beauty and to initiate ventures related to ethnic tourism, all aspects where the works of capture are not necessary.

The collection of PNU to indigenous DAA has affected only the Mapuche ethnic group, between the regions of Biobío and Los Lagos, because other ethnic groups in northern Chile, such as Aymará and Atacameña, normally have DAA constituted under the PNU exemption limit. However, the amount of reconsideration resources has been so high - 27.5% of total resources in 2011 - that it has become a critical issue, both within and outside the DGA.

In their appeals for reconsideration, the Mapuche initially claimed that their DAA had been acquired through the Land and Water Fund of the National Corporation for Indigenous Development (CONADI), which used them for the community's way of life, and even for drinking water solutions. However, the DGA rejected these resources based on the provisions of the CdA (non-existence of works), without considering the provisions of Article 22 of Law 19,253 (Ministry of

Planning and Cooperation) of 1993, which provides that the DAA for the benefit of indigenous lands acquired with resources from the above-mentioned Land and Water Fund may not be disposed of for 25 years, counted from the day of their registration in the corresponding Real Estate Registrar. This last point is fundamental, since it realizes that, although the Mapuche do not pay the PNU, it is not legally appropriate to auction off their DAA acquired through the aforementioned fund.

The issue began to receive such a stir, and the pressure was so great, that initially the DGA made its own interpretation to remove some of these DAA from the PNU listings, but only those belonging to indigenous communities and not to natural persons of those ethnicities, because the latter could have the same incentives as any other DAA owner to hoard and speculate. In summary, the DGA demanded three requirements from indigenous communities to receive their resources and be released from the UNP payment:

(a) CONADI certificate that accredits the legal personality of the community that owns the DAA;
(b) That the DAA have been acquired with money from the Land and Water Fund of CONADI; and.
(c) Certificate that accredits at least the submission of an application to a tender of the National Institute of Agricultural Development (INDAP) to acquire bonds for irrigation, that is, the DGA does not require the indigenous community to have won an INDAP tender, pretending with this third requirement only to know the intention of future use of the water through collection works.

The aforementioned formula avoided charging a smaller portion of the universe of indigenous DAA included in the PNU listings, so the controversy continued.

Within the framework of this work, a simple filter was carried out regarding the DAA belonging to indigenous communities originally included in the latest PNU listings,[14] and was found that that, while in the 2013, 2014 and 2015 processes there were 56, 55 and 46 community DAA respectively, in the 2016–2019 processes the number of DAA belonging to these type of holders fell to three.[15] This is because, in 2015, the DGA already had the legal arguments, mainly based on Supreme Court rulings, to exempt the DAA acquired by the Land and Water Fund of CONADI from PNU, removing them from all PNU listings, both at the request of a party and ex officio.

All of the above is within a legislative framework where, since May 2012, a bill that reforms the CdA rests in the National Congress, exempting individual indigenous and indigenous communities DAA from the PNU - the bill also seeks to exempt small farmers, an exemption that has cross-sectional support from the

[14] No individual indigenous people were included in this filter, because it is not a simple universe to determine with the data present in the PNU lists: there are owners without indigenous surnames who obtained their DAA through CONADI's Land and Water Fund, while there are also owners with indigenous surnames who acquired their DAA on their own.

[15] These DAA were kept on the PNU lists since they were not acquired by CONADI's Land and Water Fund and therefore are not prohibited from disposal.

Chilean political forces but was included in major reform projects (with more Articles) to the CdA, which have not achieved consensus on other issues.

17.3.2 Water Use Rights Within National Parks

The legal concepts of DAA and national parks have in common the regulation of public domain assets and the inclusion of natural and environmental resources, such as water (as a specific natural resource) and ecosystems (composed of several natural components). In terms of their differences, their orientations and administration models stand out: the economic and private legal regime in the case of DAA, environmental protection, and public legal regime in the case of national parks (Tallar 2019).

The controversy has settled over whether or not the Chilean legal system allows the existence of DAA within national parks. In this regard, Tallar (2019) reviews the contradictions within national legislation, doctrine, and jurisprudence. As an example of the latter, it shows cases where judicial rulings have ratified DAA within national parks, while others have rejected the possibility of constituting them within these areas.

17.4 Conclusions and Recommendations

Our aquatic ecosystems are highly degraded due to lack of water, pollution, the introduction of exotic species, and intervention of the channels without environmental considerations.

- The instruments available are insufficient, others uprightly unnecessary.
- Conservation measures or protection of freshwater aquatic species and aquatic ecosystems are inadequate.
- There are several institutions related to the problem in several Ministries; however, they are rather dispersed powers without coordination or leadership.
- In normative matters (Laws, Norms, Regulations, and Guides), methodologies and practical application of minimum ecological and environmental flows, significant progress has been made in the DAA and the SEIA in Chile since the mid-1990s.
- It is not equitable among the different owners of DAA or suitable for ecosystems that the minimum ecological flows are related to DAA in particular and not to each water source or basin in general.
- The minimum ecological flows are insufficient and of little application in the north central area of the country, it is necessary to move forward in retroactive measures (mandatory, indicative or voluntary) in order to allow progress in the effective protection of aquatic ecosystems.

- It is necessary to make progress in the monitoring and actual control of the minimum ecological flows in the DAA and of the ecological and/or environmental flows of the Environmental Qualification Resolutions of the SEIA.
- Even if there is no availability to establish new DAA, the State could make use of the tool for reserving flows through purchases and expropriations of DAA (Valenzuela and Silva 2019), or, with respect to those DAA waived by their owners or by the Ministry of National Assets by virtue of the non-allocation of the same after the second auction for non-payment of the PNU.
- The CdA practically does not grant any recognition to the aquatic ecosystems or *in situ* uses of our rivers, leaving these activities defenseless (sport fishing, navigation, tourism, landscape, etc.), which finally translates into conflicts that are resolved in some cases in the SEIA or among private parties, where the DAA are at the expense of such activities.

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Chapter 18
Economics of Water Resources

Guillermo Donoso

Abstract Economic and social changes that have occurred in Chile in recent decades have affected water management in multiple ways. In particular, its adoption of an export-oriented growth strategy since the 1980s, based on developing natural-resource intensive activities in the primary sector has led to significant increases in water demand. Decoupling of economic growth from water demands is, thus, a priority so as to not limit future economic growth and social development. In this chapter an overview of the water sector in the national economy and growth is presented. Then the economic value of water resources is covered, analyzing its apparent productivity, as well as the water-energy-food nexus. Finally, some conclusions are presented.

Keywords Economy · Social · Water management · Export · Natural resources · Economic growth · Social development

18.1 Introduction

Economic and social changes that have occurred in Chile in recent decades have affected water management in multiple ways. In particular, its adoption of an export-oriented growth strategy since the 1980s, based on developing natural-resource intensive activities in the primary sector has led to significant increases in water demand. Decoupling of economic growth from water demands is, thus, a priority so as to not limit future economic growth and social development.

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The chapter is structured as follows. The next section presents an overview of the water sector in the national economy and growth as well as. Section 18.3 covers the economic value of water resources, analyzing its apparent productivity. The water-energy-food nexus is discussed in sect. 18.4. Finally, Section 18.5 concludes the chapter.

18.2 Overview of Water Management in Chile

18.2.1 Participation of the Water Sector in the National Economy and Development

Chile's economy has grown continuously over the past 30 years at a significantly higher rate than average world growth during the same period. GDP more than doubled in real terms in less than 30 years (Fig. 18.1).

Structural policies and policy reforms played a central role in Chile's growth. Chile implemented important structural reforms in many areas since the mid-1980s. The most important reforms included, liberalization of the capital accounts, reduction and harmonization of import tariffs, liberalization of foreign exchange markets, public sector restructuring and state-owned enterprise privatization, sector deregulation and adoption of social policies aimed at reducing poverty and improving equity (Schmidt-Hebbel 2006; Anríquez and Melo 2018).

Primary, secondary, and tertiary sector's growth has been relatively balanced. Between 1990 and 2015, the relative share of the primary sector (agriculture and livestock, fishing, and mining) slightly decreased from 12% to 11%, the secondary sector (manufacturing) decreased from 20% to 17%, while the tertiary sector

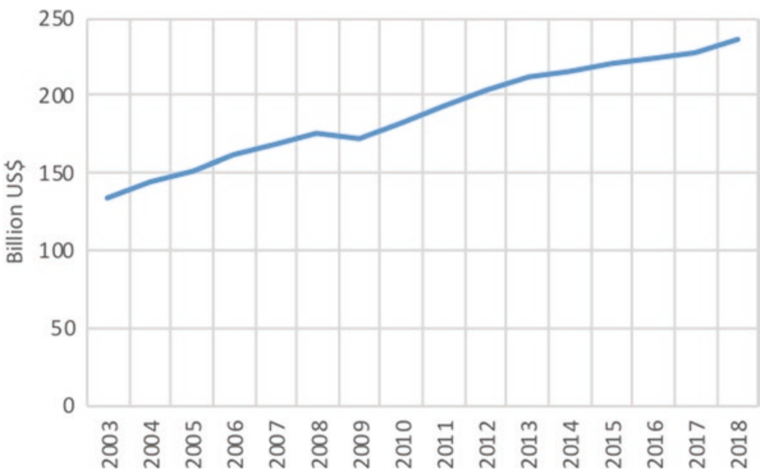

Fig. 18.1 GDP (Banco Central de Chile 2019)

(services and others) remained stable at a 68% of GDP (Schmidt-Hebbel 2006; Banco Central de Chile 2019).

The explanation for Chile's different sectoral growth is mainly its adoption of an export-oriented growth strategy since the 1980s, based on developing natural-resource intensive activities in the primary sector and in resource-processing manufacturing subsectors.

Due to this strategy, the share of mining (largely copper) in GDP declined from 7.3% in 1988 to 5.4% in 2018, the share of fisheries remained stable, at approximately 1.2% of GDP, while agriculture and livestock has declined between 1988 and 2018, from 4.6% to 3.0% (Banco Central de Chile 2019; ODEPA 2019a).

Associated to Chile's economic growth, total consumptive water use has increased. Sectoral water consumption trends are diverse responding to sectoral economic growth. The agricultural sector in Chile, the largest water user, increased its water consumption 31% between 1997 and 2007. This trend is expected to continue in the future since the declaration of the goal for Chile to become a world agricultural and food production power in the twenty-first century, requires at least a 36% increase in the total area under irrigation. Even though per capita water consumption of potable water in the urban sector decreased 20% between 2003 and 2017 (SISS 2017), its total volume increased 25% during the same period, due to significant increase in urban population. During the same period, total water consumption in the mining sector has nearly doubled. Raw and desalinated sea water use in copper mining doubled during the period spanning 2010–2015, representing in 2015 14% of all water consumed by this sector (Acosta 2018).

Decoupling of economic growth from water demands in Chile has not been an automatic by-product of growth in national incomes and requires dedicated policies to improve water allocation between competing uses so as to not limit future economic growth (Fig. 18.2).

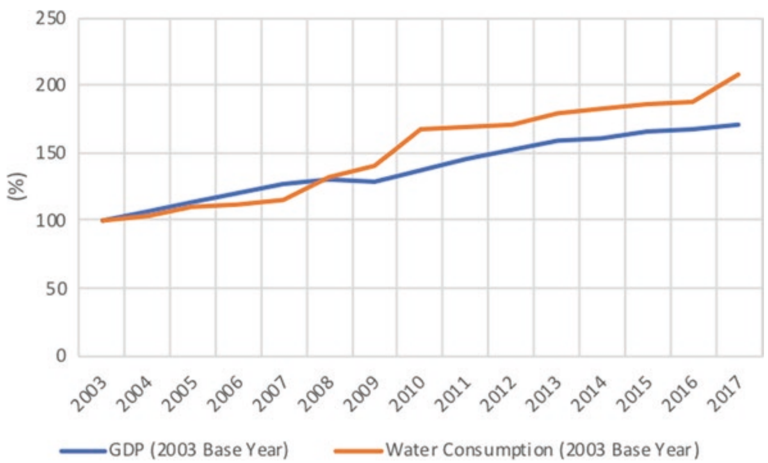

Fig. 18.2 Economic and consumptive water growth (Banco Central de Chile 2019; DGA 2016)

In recent times, groundwater has increasingly become a significant water supply source. Granted groundwater rights flow increased 224.4% between 2001 and 2017, while surface water rights flows grew 160%. The importance of groundwater as a water source is particularly evident in the north. In the future this trend is expected to grow as a consequence of the increased water use due to increased economic growth, together with population growth, urbanization, water quality deterioration, as well as projected climate change impacts on the availability of surface water.

The rapid development of groundwater use has generated a number of problems threatening the sustainability of water resources. Groundwater levels have been declining in a number of regions, revealing that aquifers have been exploited beyond sustainable limits (World Bank 2011). Groundwater over-allocation has increased water conflicts. At first, conflicts concerning groundwater were typically in the North and Center Macroregions of the country. However, the intensification of its use has expanded the territorial extent of such conflicts (Rivera et al. 2016; Herrera et al. 2019). For the period 1981–2000, problems related to property protection and the environment were the major drivers of conflicts; in the period 2001–2008, regularization of water rights stands out as an important cause of disputes; and during the period 2009–2014, overexploitation of groundwater due to surface water scarcity and poor DGA control on groundwater wells were the most frequent causes of conflicts (Herrera et al. 2019). Everything presumes that the number and complexity of water related conflicts will continue to expand.

Water rights markets in Chile have also enabled Chile's economic growth by facilitating the reallocation of water use from lower to higher value users and providing access to water resources at a lower cost than alternative sources such as investment in water infrastructure and desalination (Hearne 2018). Water rights markets are mainly driven by relative water scarcity due to economic growth, especially of water intensive sectors.

The volume of water reallocated by water markets has grown overtime throughout the nation and, thus, water markets have matured (Hearne and Donoso 2014; Hearne 2018). Coquimbo and Araucanía regions present the highest number of water rights transactions, followed by the Maule and Metropolitan regions (Cristi et al. 2014). Some of these market transactions may be for all of a seller's total water rights (WR), and thus not marginal. However, there are many transactions for relatively small quantities of water. The large percentage of small value transactions challenges the argument that high transactions costs limit market trading (Hearne 2018).

The majority of transactions have been between agricultural users, with resulting efficiency gains. Intersectoral transfers of water have been relatively infrequent. The O'Higgins and Metropolitan regions present the highest valuation of flow rates with an average of US$23,600/l/s and US$16,400/l/s, respectively (Cristi et al. 2014). However, water rights transaction prices are highly variable. This wide range of prices reveals that markets are imperfect and subject to individual bargaining power of buyers and sellers (Donoso et al. 2014).

18.2.2 Water Use and Efficiency per Sector Over Time

Consumptive water use in Chile is dominated by irrigation, representing 82%, followed by industrial, mining and potable water supply, which account for 8%, 3% and 7% of total water consumptive water use, respectively (Fig. 18.3).

Irrigation surface has increased in response to public policies launched in the mid-1980s (Martin and Saavedra 2018), reaching approximately, 1,100,000 ha (ODEPA 2019b). The introduction of efficient irrigation systems in Chile during the past 15 years has led to a significant increase in the proportion of irrigated land with efficient irrigation technology. Average irrigation efficiency increased by 17% between 1997 and 2007, rising from 48.6% to 56.9% (Martin and Saavedra 2018; Donoso 2017). At present, 30% of Chile's total irrigated surface is equipped with efficient irrigation technologies such as drip and sprinkler systems.

Thus, agricultural growth has been achieved, in part, by intensification of production, constant land use transition from agricultural use in import competing crops into higher value export crops (fruits and nuts), accompanied by a marginal expansion of agricultural land, and increases in water use efficiency (Donoso 2018).

Nevertheless, water use efficiency (WUE), defined from an economic perspective as the economic return per unit of water used for crop production, is on average low. Molinos-Senante et al. (2016) finds that average WUE score is 0.450 for farmers in the Limary basin, even when irrigation efficiency is 69% in that basin. Thus, as de Oliveira et al. (2009) points out, there is a considerable possibility of reducing water consumption in the Limary basin, without affecting production levels.

However, inadequate agricultural water use is salinizing, waterlogging, and eroding agricultural lands and polluting water. Chile has about 35% of their irrigated lands affected by salinity (Ringler et al. 2010), most of which are concentrated in the northern macroregion.

Although mining is the productive sector that consumes the least amount of water, in some arid areas of Northern Chile it is a relevant user ranking first or second followed by the agricultural sector. In arid northern regions, water withdrawal

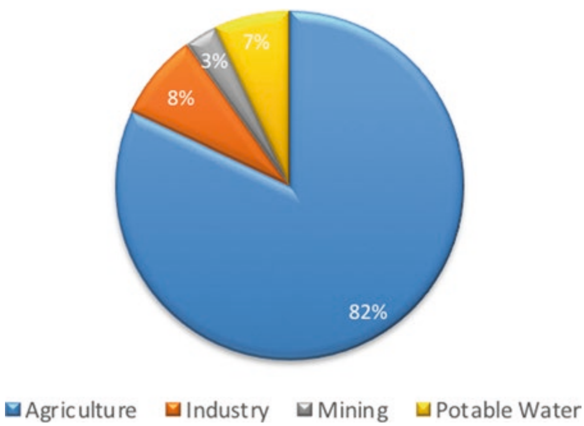

Fig. 18.3 Consumptive water use by economic sector (DGA 2016)

from mining is mainly from aquifers (Acosta 2018). Mining has significantly increased their water use efficiency from 2m^3/ton of treated ore in the 80s to 0.532m^3/ton of treated ore in 2015 (Peña et al. 2011; Acosta 2018). The main driver has been the increased value of water due to increasing copper production and the absence of alternative low-cost water supplies. New water demands owing to new mining developments that have not been able to be met by efficiency improvements, have been mainly supplied with desalinated water. The increase in raw and desalinated seawater use between 2010 and 2015 has doubled, reaching in 2015 approximately 14% of the total water used (Acosta 2018). It is estimated that this tendency will continue in the near future (Cochilco 2016).

The industrial sector has also increased water use efficiency. For example, the pulp industry reduced its water consumption from 130m^3/ton in the 80s to 40m^3/ton in 2012 (Peña et al. 2011).

On the other hand, domestic water use efficiency has not improved in the past years. Technical water use efficiency in urban water supply is rather low, due to high levels of non-revenue water, of which 74% corresponded to water losses (Molinos-Senante et al. 2018). In spite that the Chilean water regulator establishes that the maximum percentage of non-revenue water should be 20%, most water companies in Chile exhibit larger percentages. The majority of Chilean water supply companies (61%) present a percentage of non-revenue water above 30%, while only 26% present a percentage below the regulator's target of 20% (SISS 2017).

18.3 Economic Value of Water Resources: National and Sectoral Water Productivity

Water productivity is defined as the ratio between an output linked to a water use and its water consumption. It provides a description of how well water resources are made productive (i.e. generating value) in their different uses. Economic water productivity, measured in monetary units per unit volume (\$/m^3), provides a tool to attribute value and productivity to all water uses and users within a hydrological domain. An indicator of economic water productivity is the apparent water productivity, estimated by the ratio of GDP to water consumption. Table 18.1 presents the estimates of Chile's apparent water productivity.

Table 18.1 Apparent water productivity (Banco Central de Chile 2019; DGA 2016)

Economic sector	Water consumption (MM m^3/year)	GDP (MM \$/year)	Water productivity (\$/m^3)
Agricultural and forestry	16,611	8720	0.52
Industry	1383	39,487	28.55
Mining	630	27,666	43.89
Country	20,353	281,249	13.82

Chile's economic water productivity is $13.82/m^3/year, significantly higher than Latinamerica and the Carribean's (LAC) average of $6.6/m^3/year (World Bank 2019; Mekonnen and Hoekstra 2011). The industrial sector's apparent water productivity is $28.55/m^3, about half of the economic value of water in the mining sector, whose apparent water productivity is $43.89/m^3.

Agriculture represents the lowest economic water productivity of Chile, which is lower than the sector's average economic water productivity in LAC of $1.01/m^3 (World Bank 2019; Mekonnen and Hoekstra 2011). Economic water productivity within the sector varies between $0.2/m^3 for cereal and $0.85/m^3 for fruit production (Banco Central de Chile 2019; DGA 2016; Donoso et al. 2016). These results explain, in part, the significant reduction in the land devoted to cereals and increases in land devoted to fruits, which led to a reduction of agriculture's water footprint (Donoso et al. 2016).

18.4 Food-Water-Energy Nexus (FWE) in Chile

18.4.1 Current Situation of the FEW Nexus in Chile

Food-Water-Energy are critical resources that are to a great extent linked to one another, meaning that changes in any one in particular can affect one or both of the other areas. As the case with water demand, energy consumption is also coupled to economic growth in Chile (Fig. 18.4); thus, water and energy demands for urban water supply, mining, and export-oriented agriculture will continue to grow as the economy grows, unless dedicated policies are implemented to decouple this relationship.

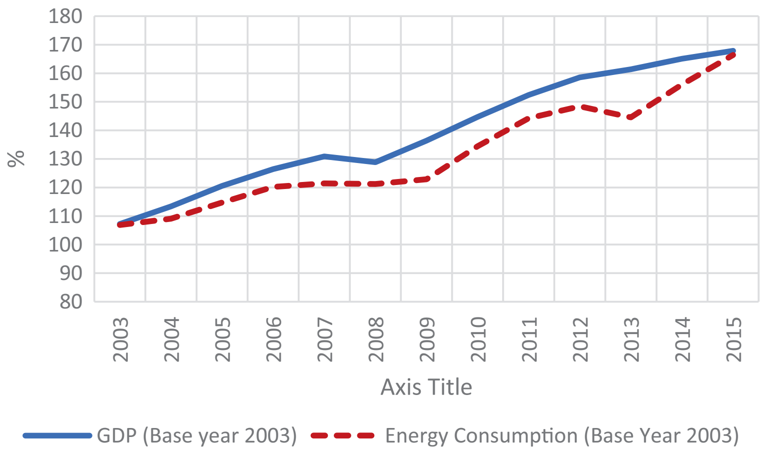

Fig. 18.4 Economic and energy consumption growth (Banco Central de Chile 2019; CNE 2017)

18.4.2 Drivers and Challenges of the FEW Nexus

Vicuña et al. (2011) estimates that mining will generate additional demands for fresh water to satisfy production expansion projects and future investments. This generates higher energy demands not only for desalinization but also for pumping water from the coastal zone towards the projects that are located at high altitudes above sea level. Cochilco (2017a) estimates a 2.7% yearly average growth in energy consumption between 2017 and 2018 for the mining sector. Non-conventional renewable energies can be coupled to seawater desalination plants, so as to produce a more sustainable water supply.

Urban water consumption has also increased due to the increase in the urban population and the non-reduction of water losses. This trend is expected to continue where water and energy consumption is projected to increase 10% and 15%, respectively (Vicuña 2011).

The total area under irrigation is projected to increase by at least 36% by 2020 (Martin and Saavedra 2018). Additionally, Chile has achieved an average irrigation efficiency of 57% (Donoso 2017). This is due to an 85.1% increase in higher efficiency technological irrigation methods and a 298.2% increase in the area in which micro-irrigation was used (Martin and Saavedra 2018). However, modernization of irrigation has increased energy consumption. Recognizing this, the Ministry of Agriculture promotes the use of non-conventional renewable energies in the agricultural sector (Ministerio de Energía 2016).

The FEW nexus is getting more entwined product of global climate change. Climate change projections show that temperatures will increase, and rainfall will decline in most of Chile (MMA 2016), causing changes in streamflow patterns. Snow driven basins in the north and center of the country will tend to be driven by a mix of rainfall and snow (Vicuña et al. 2011). This will further increase competition for water resources and increase groundwater pumping to meet demands. Thus, increased water scarcity due to projected climate change impacts for Chile will be a significant driver for FEW nexus.

Therefore, Chile faces increasing pressure on water resources and energy, incentivizing the need to look for alternative water and energy sources, particularly in water-scarce areas with large inter-sectoral competition for water. The national energy strategy for Chile (Ministerio de Energía 2012) for 2012–30 recognizes this and places special emphasis on increasing energy efficiency and the participation of non-conventional renewable energy sources. Since 2014, more than 40% of the generation projects that have been built each year correspond to non-conventional renewable energy sources.

Historically, Chile has opted for a policy of water resources supply management to cope with the growing scarcity. The State's policy on water management has focused on alternatives and new technologies aimed at improving the availability of the resource. To this end, three pillars have been proposed: (i) regulate the flows through investment in major reservoirs, (ii) implement artificial recharge projects for aquifers, and (iii) invest in desalination.

18.4.2.1 Projection of Large Hydraulic Infrastructure

The Direction of Public Works (Dirección de Obras Hidaúlicas – DOH) has developed an investment plan to increase the storage capacity in reservoirs (DOH 2016). The plan considers an investment of MM$5700 for the construction of 25 reservoirs between 2015 and 2025. This would increase actual storage by 70%, passing from 4200 MM m^3 to 7200 MM m^3 (DOH 2016).

Four of these are projected for the north, three for the center-north, fifteen for the central zone and three for the center-south. As for capacities, eight of them will exceed 100 Hm^3 and only one 500 Hm^3.

Additionally, together with the National Irrigation Commission (Comisión Nacional de Riego – CNR) the DOH projects the construction of 20 small reservoirs, with a storage capacity of less than 50 thousand m^3, so as to mitigate the drought situation in rural areas of the country, focused mainly towards vulnerable agricultural sectors. This plan considers an investment of MM$450 (Delegado Presidencial para los recursos hídricos 2014).

18.4.2.2 Projection of Non-conventional Water Supplies

(a) **Desalinization**

In the northern regions, the option to satisfy increased water demand from the mining sector, is through desalination plants. It is estimated that consumption of desalinated water for mining operations will increase from 2.9 m^3/s in 2016 to 11.2 m^3/s in 2028 (Cochilco 2017b). Thus, more than 150 MM m^3/year are being considered in desalination plants. An example of this is the launch of the EWS (Escondida Water Supply) project, BHP Billiton's second desalination plant in Puerto Coloso, with a capacity of processing 80,000 m^3/year, which once completed, will be the largest plant of its kind in Latin America and Europe.

Chile's National Drought Strategy also considers investing MM$265 in desalinization plants to supply human consumption in areas with structural water shortages such as Copiapó and La Ligua-Petorca (Delegado Presidencial para los recursos hídricos 2014).

(b) **Water Reuse**

Currently, Chile is the most advanced country in wastewater treatment in Latin America, treating 99.93% of its urban sewer water. This translates into a total annual discharge of 1200 MM m^3/year of treated wastewater of which 240 MM m^3/year are discharged into the sea through emissaries. The DGA has estimated that reusing the water discharged through emissaries would cover 10% of Chile's water deficit (DGA 2016). Hence, reuse of treated wastewaters is a promising water source for Chile. However, conflicts over use rights and the lack of a regulatory framework are hindering its potential.

The reuse of treated water has been developed up to now in an informal way and without the support of a regulatory, institutional and financial framework that orders, promotes and controls this complementary water source. Although it is possible to detect certain informal or indirect cases of treated wastewater reuse in Chile, they are isolated practices. Actual reuse is very low, approximately 1% of its potential, focused only on irrigation (SISS 2017). In order to advance in the use of this valuable resource, Chile must adapt its regulatory-institutional-financial framework.

However, as in other countries, increasing its use also requires considering an array of factors such as social attitudes toward treated wastewater, quality of agricultural produce, chemical quality of the water, and health, among others.

18.5 Conclusions

As a result of its structural economic and policy reforms, since Chile's return to democracy in 1990, real per capita GDP per capita increased in real terms over 100%. In response to this accelerated growth, given that water consumption is coupled to economic growth, water demands during the same period grew significantly. Due to the growth in water consumption, several basins in the north and central regions are overexploited presenting important water stress situations leading to economic vulnerability. Thus, water and energy will become critical limiting factors for future growth.

Chile has opted for a policy of water resources supply management to cope with the growing scarcity. However, this policy on its own is unsustainable, given that as water availability increases so does water consumption, leading once again to water scarcity.

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Chapter 19
Impacts of Climate Change on Water Resources in Chile

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Abstract To analyze the effects of climate change on water resources in Chile, historical climate trends and future projections are examined first. To understand the potential impacts of climate change on water resources in Chile, the main hydrological regimes and their sensitivity to changes in precipitation and temperature are then analyzed. Subsequently, the proposed adaptation strategies to climate change impacts on hydrology and water management are presented. Finally, the chapter provides some final perspectives to implement adaptation strategies, understanding linkages between ecosystem services, infrastructure and water security, but also considering the particular characteristics of water governance in Chile.

Keywords Climate change · Climate trends · Impacts · Precipitation · Temperature · Adaptation strategies · Water governance

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19.1 Introduction: Global Changes in Climate and the Water Cycle

The water vapor holding capacity of the air depends directly on temperature. Therefore, the water vapor content increases as the atmosphere warms in response to the increasing concentration of greenhouse gases (GHGs). Since water vapor is an effective GHG, the rising amount of this gas results in the amplification of the greenhouse effect triggered by anthropogenic emissions of carbon dioxide (CO_2) and other GHGs. I.e., the so-called water vapor feedback nearly doubles the climate impacts of rising CO_2 (Held and Soden 2000). Aside from these effects on the holding capacity of water vapor in the atmosphere, the GHGs-induced changes in the planetary energy balance also alter the patterns of large-scale atmospheric circulation and precipitation. Hence, although there is an acceleration in the global hydrological cycle (Huntington 2006), the precipitation response to GHGs forcing is not spatially uniform across the planet and several regions are affected by a drying pathway, notably across the subtropics (Collins et al. 2013). Both thermodynamic and dynamic changes in the atmosphere contribute to modify the intensity and frequency of precipitation.

Alterations in regional climate patterns lead to changes in water resources (Milly et al. 2005). Figure 19.1 – taken from the Water Resources Chapter of the last IPCC

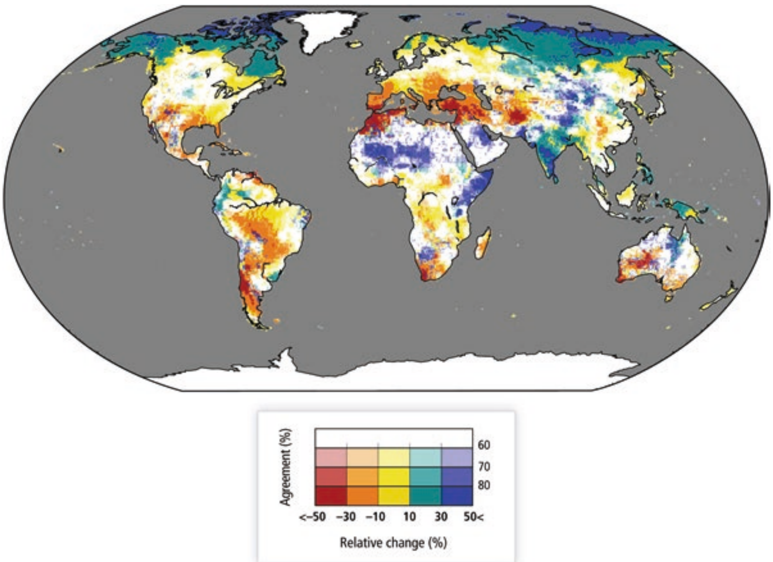

Fig. 19.1 Changes in average annual flow for a temperature rise scenario of 2 °C compared to the 1980–2010 period. The colors show the average change considering 5 GCMs and 11 Global Hydrological Models (GHMs), and the intensity in the color shows the level of agreement in the sign of the projected change considering the combinations of 55 GHM-GCM (percentage of runs according to the sign of change) (Jiménez Cisneros et al. 2014)

report (Jiménez Cisneros et al. 2014) – illustrates areas of the planet where runoff is expected to increase (e.g., high latitudes and humid areas in latitudes around the equator) and others where runoff could decrease (e.g., mid-latitudes and subtropical arid zones). It should be noted that runoff does not necessarily respond proportionally to changes in precipitation (e.g., Addor et al. 2017). Additionally, temperature variations alter evapotranspiration (ET), the partitioning of solid and liquid precipitation, and the rate of accumulation and melt of snow and ice in cold areas. For example, an increase in temperature reduces the overall snow accumulation, and therefore snowmelt runoff volumes during the warm seasons. According to Barnett et al. (2005), more than one sixth of the world's population lives in regions where these processes are relevant. The rising temperature and the atmospheric water demand increase plants' evapotranspiration rates, affecting the structure and functioning of natural ecosystems and agroecosystems (see Chap. 12 for details of climate change impacts on agriculture). This effect is particularly relevant in semi-arid areas, where evapotranspiration is a dominant component of the water balance. Potential increases in evapotranspiration rates and possible changes in surface runoff may result in a reduction of water that eventually percolates into aquifers. Under such conditions, sustaining water extracting activities would likely require increasing groundwater pumping rates, diminishing long-term aquifer storage.

In addition to climate-driven hydrologic changes, potential shifts in the intensity and frequency of extreme precipitation events and environmental conditions (e.g., changes in land use) may enhance the occurrence of floods (see Chap. 20). In general, changes in this kind of events are more difficult to detect, attribute, and project into the future, because of their phenomenologically more complex nature and the existence of multiple non-climatic forcing factors that tend to distort the climate attribution signal (e.g., the change of land use and its effects on floods). However, it is already possible to identify regions of the planet where the effects begin to be noticeable as a result of changes in the intensity of rainfall or the complementary effect of increased temperatures (e.g., Yin et al. 2018).

19.2 Regional Climate Variability and Change

To analyze the effects of climate change on water resources in Chile, historical climate trends and future projections are examined first. Figure 19.2 displays projected changes based on the Representative Concentration Pathway 8.5 (RCP8.5), a socioeconomic scenario with almost no mitigation measures for carbon emissions, increasing CO_2 concentration to ~1350 ppm in 2100 (Moss et al. 2010). The results show a large heterogeneity in the response of the various precipitation regimes to anthropogenic forcing in South America. Further, there are areas where an increase in mean annual precipitation is expected (e.g., the La Plata Basin or the Pacific coast around the Equator), and others where a precipitation decrease is projected (e.g., Northeast Brazil or central Chile and southern Argentina). In continental Chile, models project a precipitation decline under a carbon-intensive scenario, affecting

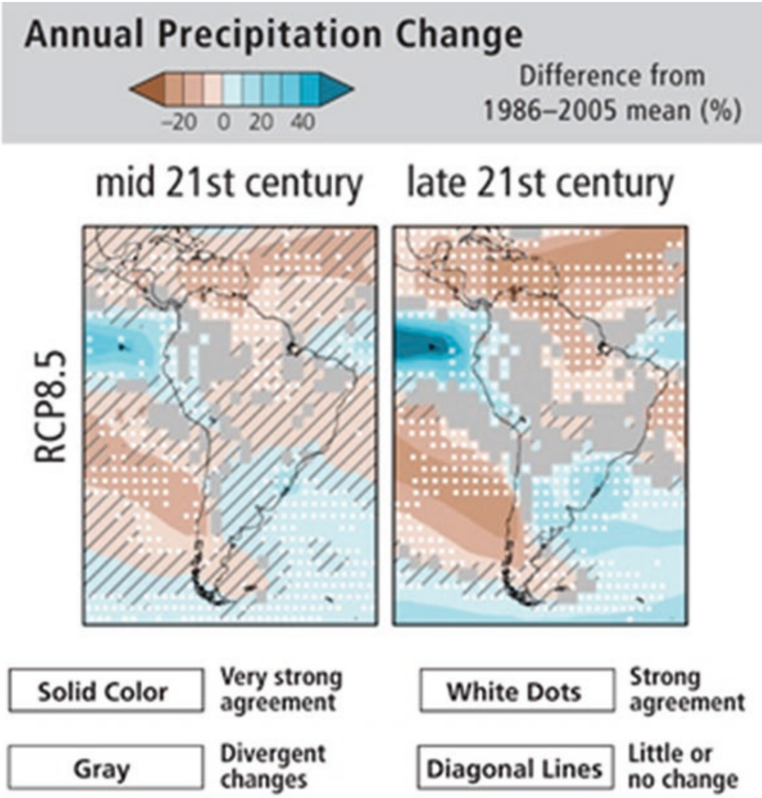

Fig. 19.2 Projections of average change in annual average temperature and annual precipitation for the RCP 8.5 in South America mid twenty-first century. (Adapted from Magrin et al. 2014)

the central and southern areas of the country. In contrast to most regions in the world, the precipitation decline in the southeast Pacific is systematically simulated by GCMs. As described in Chap. 2, this robust regional climate change signature is related to the well-known hemispheric-scale circulation anomalies driven by the GHG forcing. In line with the global pattern, temperature projections in South America show a consistent increase across the continent, with larger warming in areas located far from the modulating effects of oceans (see Fig. 19.2).

Do historical temperature and precipitation records in Chile echo the expected (i.e., modeled) patterns of climate change in response to anthropogenic forcing? In contrast to global averages, the answer is not as straightforward at the regional scale given the major role that natural (internal) climate variability plays within the observational period, leading to long-term changes with similar or larger amplitude than the trends induced by external climate drivers (e.g., rising GHG). The climate of Chile is modulated at different time scales by well-known natural mechanisms, such as El Niño-Southern Oscillation (ENSO, inter-annual) and the Pacific Decadal Oscillation (PDO, decadal; see Chap. 2). The PDO is the leading mode of sea-surface temperature variability in the Pacific Ocean, and affects the climate of many regions in a similar way than ENSO, but over longer time scales (e.g., Dong and Dai 2015). For instance, a negative to positive shift in the PDO phase around the 1970s led to consistent (El Niño-like) effects in South America and Chile (Boisier and Aceituno 2006; Schulz et al. 2011; Quintana and Aceituno 2012; Jacques-Coper and Garreaud 2014). Moreover, a transition from a positive to a negative PDO phase (la Niña-like) drives –at least partially– a negative temperature trend on coastal regions in Chile since the late 1970s to the 2000s, contrasting the anthropogenic warming observed in most regions worldwide (Falvey and Garreaud 2009). Nonetheless, the observed cooling was circumscribed to coastal areas and the boundary layer of the atmosphere, while a marked warming prevailed in upper levels and across the Andes, in line with global temperature trends (Boisier and Aceituno 2006; Falvey and Garreaud 2009; Vuille et al. 2015).

Such as for the recent coastal temperature trends, natural low-frequency climate variability associated with the PDO have likely modulated the precipitation regime in Chile (Quintana and Aceituno 2012). Indeed, precipitation records indicate a significant trend in central Chile since late 1970s, which is coherent in sign (drying) with the PDO drift toward a "La Niña" phase. However, further analyses of these records and the contrast with several climate simulations revealed that the PDO, although being a key driving factor, cannot fully explain the strong precipitation decline (about 7% per decade) observed between 1979 and 2014 (Boisier et al. 2016). The same study showed that anthropogenic climate forcings very likely contributed to the amplitude (about a third) of the trend observed in this period. Further research has shown that the drying trend in central-southern Chile dominates in longer time periods (1960-present), and exhibits a pattern of seasonal change largely consistent with that expected from the combination of historical anthropogenic drivers, including the GHG increase and the stratospheric O_3 depletion (Boisier et al. 2018). It is noteworthy that O_3 depletion explains a particularly large drying trend observed in southern Chile during the summer.

19.3 Projected Hydrologic and Water Availability Changes in Continental Chile

To understand the potential impacts of climate change on water resources in Chile, it is important to consider the main hydrological regimes and their sensitivity to changes in precipitation and temperature. Based on the large-sample hydrological assessment of Alvarez-Garreton et al. (2018) for 516 basins across continental Chile and the land use characterization described by Zhao et al. (2016), it is possible to identify the following potential impacts on the hydrology of the country:

- The arid and semi-arid basins of the country (20°–30° S) show strong seasonality in runoff, with floods triggered by heavy rainfall events, long lasting baseflow conditions and large evapotranspiration rates. Annual precipitation changes in this region are highly uncertain, so it is also unclear whether total runoff volume will increase or reduce. However, expected increases in potential evapotranspiration (PET) could end up satisfying an already negative PET-ET balance (this is similar to Category 1 and partly Category 2 basins as presented in Chap. 9).

- In Central Chile (30°–45° S), snow accumulation and melting processes have a primary role in runoff production of Andean catchments. Hence, temperature shifts will affect hydrologic regime by modifying the snowline elevation, reducing snow accumulation and anticipating the snowmelt onset, resulting in decreased runoff volumes during spring and summer (Vicuña et al. 2013). This impact in seasonality superimposes to the robust drying signal towards the southern regions (this is similar to some basins in Category 2 and Category 3 as presented in Chap. 9).
- Finally, increases in runoff volumes throughout the year are projected for the southern most regions (45°–55° S), which are associated with precipitation and temperature increases, accelerating the melt of ice bodies. It should be noted, however, that a weaker temperature increase is projected for this area (this is similar to basins in Category 4 as presented in Chap. 9).

Climate change impacts on hydrologic and water use conditions haven been examined in detail in a number of basins in Chile using different downscaling techniques, hydrologic models, and considerations regarding the various sources of uncertainty. A spatial illustration of such studies and the type of climate change scenario considered is shown in Fig. 19.3. Covering all basins in the country, global

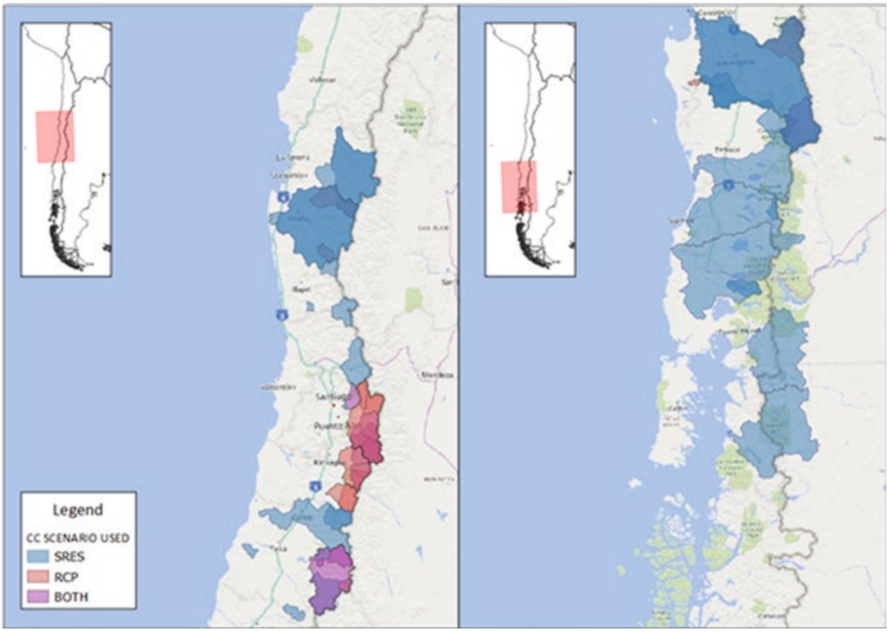

Fig. 19.3 Basins in Chile with detailed basin scale climate change assessments. Colors present different climate change scenarios used in these assessments

and regional-scale hydroclimate projections indicate that annual runoff may reduce up to 40% in central-southern Chile, the region holding most of the country's agricultural activities (Jiménez Cisneros et al. 2014; DGA 2018). Moreover, the combined temperature and precipitation projections in Andean watersheds may produce a change in snow accumulation and, therefore, in streamflow seasonality. A shift towards earlier dates in the occurrence of maximum flow may have consequences on spring and summer runoff (Vicuña et al. 2011; Demaria et al. 2013; Meza et al. 2014; Bozkurt et al. 2018).

In the context of a new national water balance characterization (DGA 2017), GCM output downscaling and hydrological modeling initiatives have been conducted to provide a diagnosis of possible future conditions in Chile at a 5-km horizontal resolution. Figure 19.4 illustrates the present-day and projected changes in mean annual precipitation and in near-surface maximum daily temperature under the RCP8.5 scenario. The climatological precipitation and temperature maps result from a statistical model that combines large-scale reanalysis outputs and local observations (CR2MET; see http://www.cr2.cl/datos-productos-grillados/). This product is used as a reference to downscale data from four GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012). These models (CCSM4, MIROC-ESM, CSIRO-MK-3-6-0, IPSL-CM5A-LR) were selected based on their ability to reproduce the large-scale conditions that govern the mean climate and variability in Chile (DGA 2017). As in almost all GCM projections under a carbon-intensive scenario, the downscaled precipitation from the selected models indicate a pronounced drying pattern in central-southern Chile towards the mid twenty-first century, albeit the change magnitude varies significantly from model to model. By contrast, in the extreme north and southern regions there is a weaker trend towards increasing precipitation (Fig. 19.4). Daily maximum temperature is projected to increase throughout continental Chile, but the warming is substantiality greater in the northern regions of the country, leading to differences with respect to current conditions above +2.5 °C near the Andean Plateau (Fig. 19.4). A similar pattern of change is obtained for daily minimum temperature (not shown).

The downscaled precipitation and temperature time series, along with other key meteorological variables, were used to force the Variable Infiltration Capacity macro-scale hydrological model (VIC; Liang et al. 1994, 1996). The resulting basin-averaged ensemble mean changes in precipitation, ET and runoff for the period 2030–2060 are shown in Fig. 19.5. for a domain that spans northern and central southern (up to 45° S) Chile. These results show the distinctive drying pattern in this part of the country, in addition to changes in hydrological fluxes. In terms of ET, it is possible to appreciate three different regional patterns:

- The extreme arid north does not show a clear pattern, partly due to extremely low water fluxes in this region.
- The impact on ET in water-limited regions is more clearly seen across Mediterranean areas (30–37°S) in Chile, where a reduction in ET is projected most likely due to decreased precipitation and soil moisture.

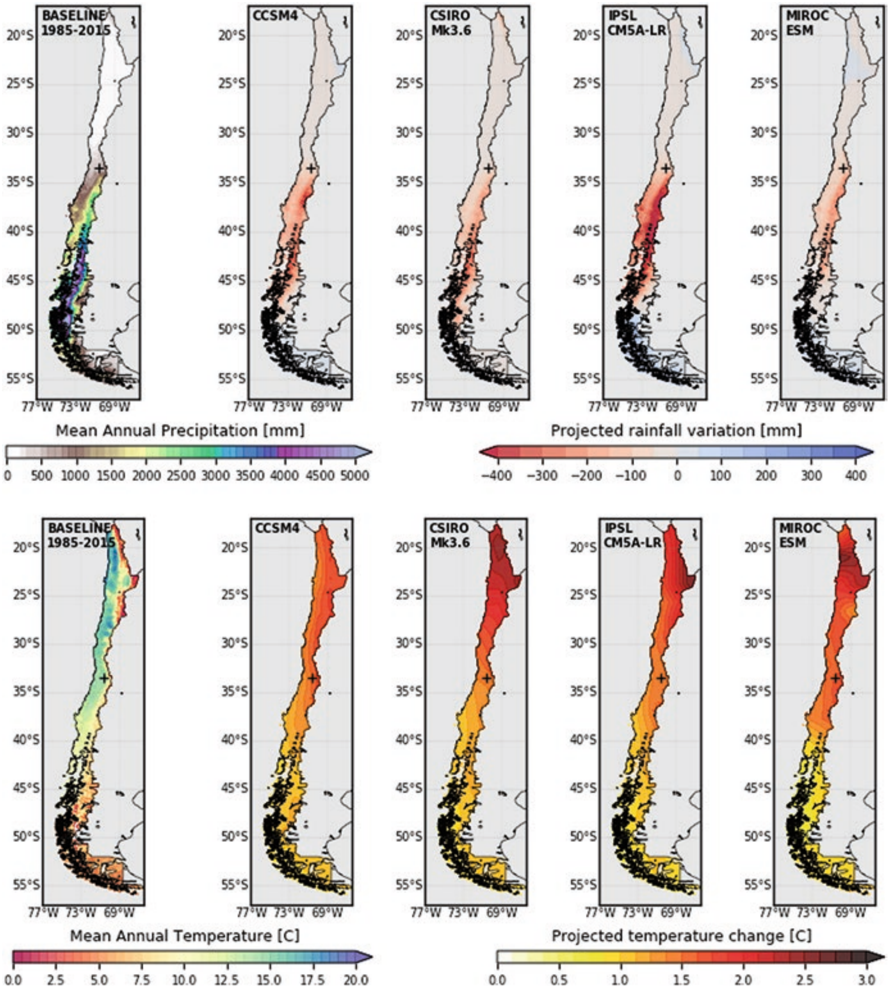

Fig. 19.4 Projection of average change in annual precipitation (figure above) and maximum daily temperature during summer (figure below) associated to percentile 90% for the RCP 8.5. Left panel: climatology period 1985–2015. Other panels: different GCMs. Period 2030–2060. (DGA 2018)

- The central and southern regions show an increase in ET that overcomes the reduction in precipitation. Hence, increase in PET with temperature (for both natural and irrigated land) leads to more ET because of the enhanced soil moisture storage.

Overall, the modeled changes in ET and concomitant effects on surface hydrology are significantly weaker than those driven by precipitation. Hence, regardless of whether ET increases or reduces, there is a clear runoff reduction across all domain,

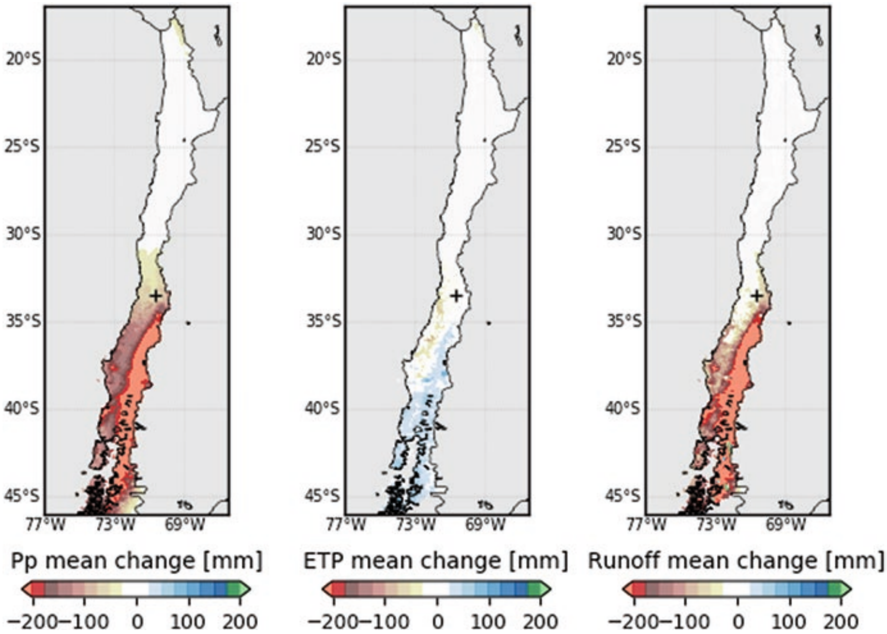

Fig. 19.5 Multimodel mean change in precipitation, evapotranspiration and runoff (corrected by irrigation demand) between the periods 1985–2015 and 2030–2060 projected by VIC model. (Data taken from DGA 2018)

with similar spatial pattern and amplitude of change to those projected for precipitation (Fig. 19.5).

We also examine climate change impacts on the timing of relevant hydrological variables. Figure 19.6 displays projected changes in precipitation, ET and runoff, averaged for different climate scenarios and basins in four distinct Chilean climatic regions (introduced earlier in the text; see Chap. 9 for a complete description of these regions). Figure 19.7 presents the change in snow water equivalent (SWE), averaged over all basin categories. It is noteworthy that the timing of change is not comparable across variables and regions. With the exception of the southernmost basins (Category 4), reductions in precipitation are more relevant during winter. Changes in ET are weak in most basins, excepting an increase in this variable during winter in Category 3 basins. On the other hand, runoff reductions are more relevant, notably during spring. This change in runoff timing corresponds well with the effects of precipitation and temperature changes on snow-dominated basins, with less water being accumulated in snowpack, and hence reducing runoff in months and basins where snowmelt contribution is relevant.

Agricultural activities could also lead to an increase in ET demands and irrigation, which depend on water availability during spring and summer. The mismatch between demand and supply affects the ability to sustain different water uses, and their assessment requires tools that relate water availability with consumption. In

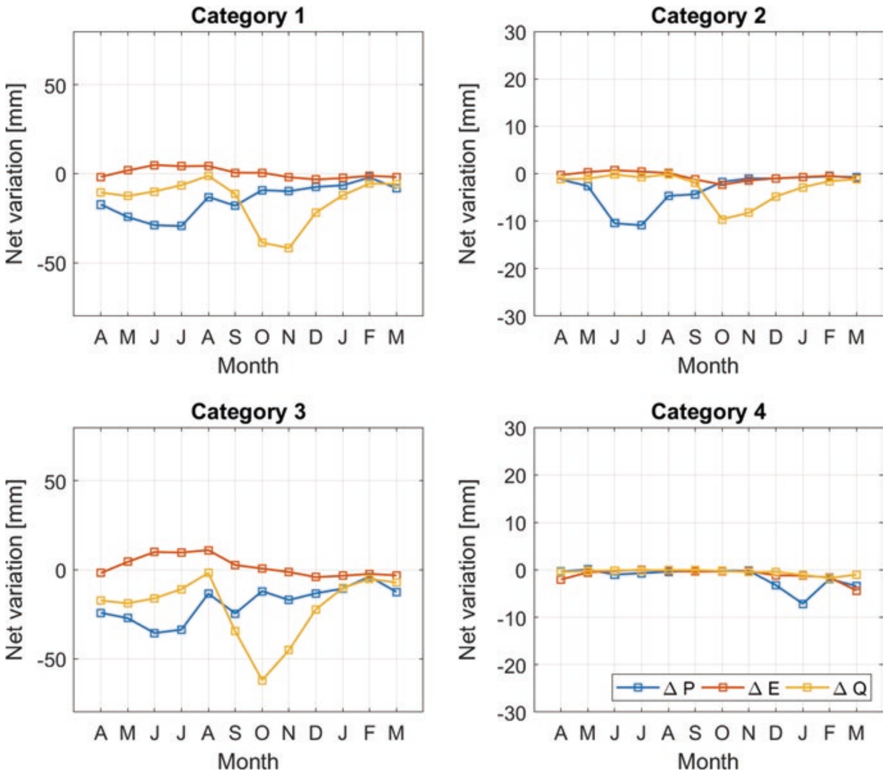

Fig. 19.6 Monthly average absolute changes in P, ET and Q. Averaged across scenarios and spatially according to four regions described in Chap. 9

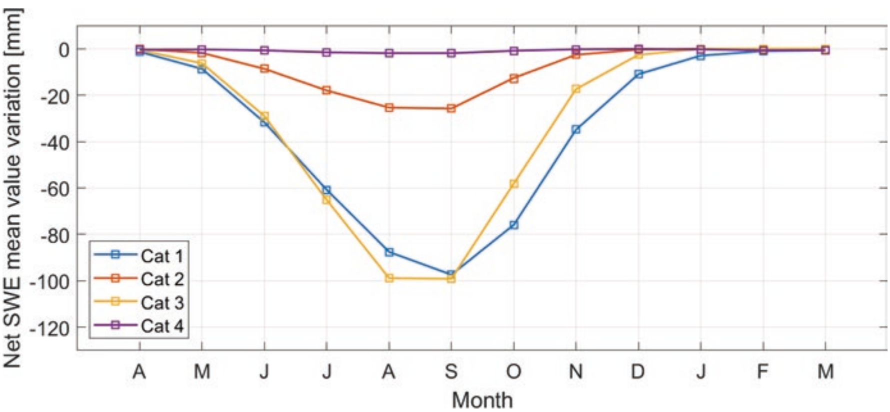

Fig. 19.7 Monthly average SWE changes. Averaged across scenarios and basins for different categories

this regard, the most intensive water use extractions are located in Central Chile. The Maipo River basin, located in the semi-arid central Chile (33°S) and holding the large metropolitan area of Santiago, provides an example of hydrological impacts on water usage. This watershed has been subject of several studies that illustrate the expected impacts of hydrologic change on water consumption (e.g., Meza et al. 2012, 2014). Using different hydrological and water resources models, the MAPA project (www.maipoadaptacion.cl) included a vulnerability analysis in different sectors of the Maipo River basin affected by climate change. Figure 19.8 illustrates projected climate change impacts on glacier melt and hydrological conditions affecting hydropower generation and environmental flows in the mountain range. According to different scenarios, these effects could propagate towards reduced volumes of water stored in El Yeso Reservoir, the main supply of drinking water for the city of Santiago. Worsened water supply conditions for irrigation are also expected as a result of a projected increased water demand.

19.4 Adaptation to Climate Change Impacts on Hydrology and Water Management

The adaptation process requires (i) the assessment of climate change impacts, and (ii) to design different strategies to address these impacts, their subsequent implementation and evaluation of achievements or failures in terms of reducing vulnerability. To design adaptation measures, the MAPA project proposed the conceptual framework presented in Fig. 19.9 (from Ocampo-Melgar et al. 2016), which is based on the existing relationship between water security and human well-being that this water security partly contributes.

As shown in Fig. 19.9a, the concept of water security allows to recognize the dual nature of water as a resource (for the support of livelihood, productive activities and ecosystems) and as a threat (pollution and hydrometeorological disasters). The framework also recognizes the role of terrestrial ecosystems in providing different services that will contribute to this human well-being (MEA 2005), including the provision and regulation of water flows. This physical context (water flow with certain conditions of quantity and quality) can be subsequently modified (controlled or regulated) using infrastructure and rules that allow water allocation for different uses (including on-site uses) when the supply is deficient or reducing disastrous effects when the flow is excessive. Finally, the framework allows generating a last modulation of this physical context through different efficiency or productivity measures (including land use), before generating positive or negative impacts that ultimately translate into human well-being. All these connections can suffer alterations due to climate change or other changes in demands, capacity to regulate and distribute water flows, productivity levels and efficiency that could end up affecting human welfare.

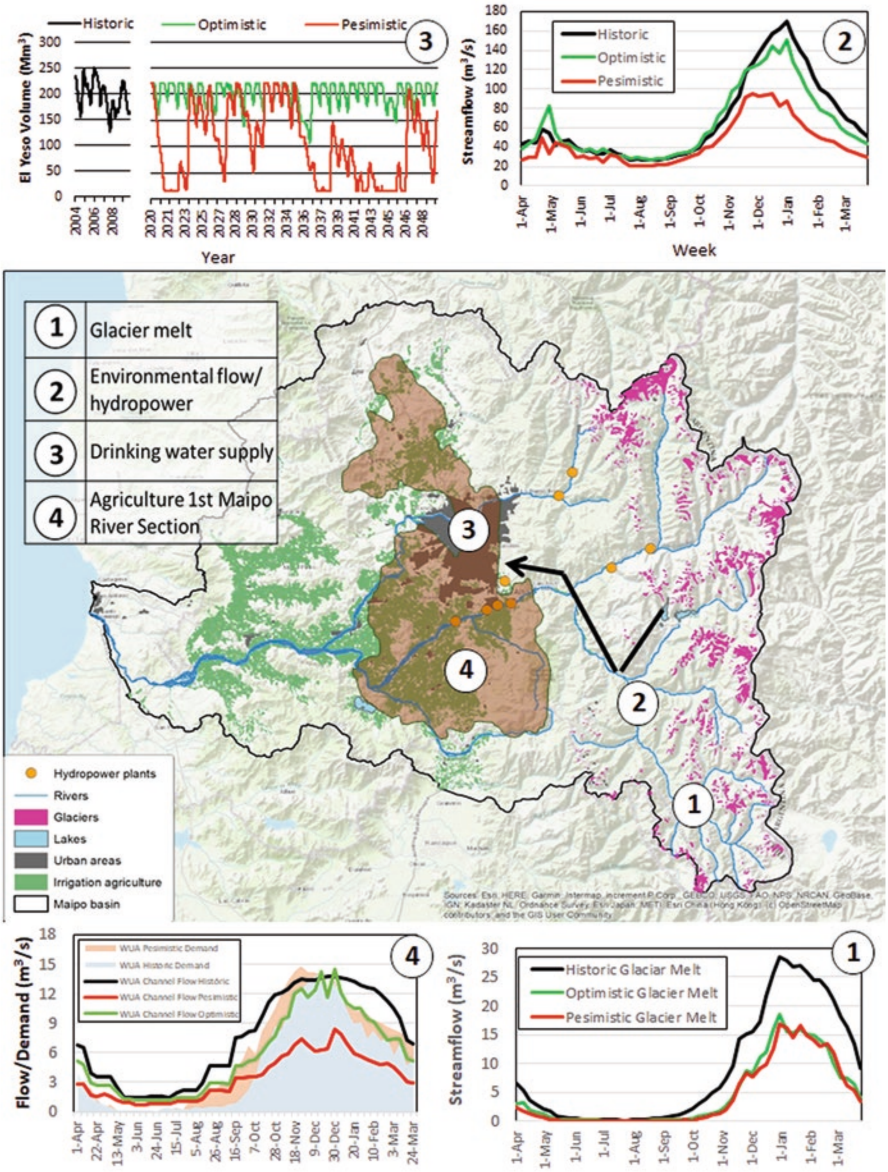

Fig. 19.8 Summary of vulnerability analysis associated with the MAPA project. Climate change impacts are highlighted in (1) melting of glaciers, (2) hydrological conditions in the mountain range; (3) level of water accumulation in El Yeso Reservoir (supply of potable water in Santiago) and (4) demand and supply of water for irrigation in one of the irrigation associations in the first Section of the Maipo River. Source: MMA 2016

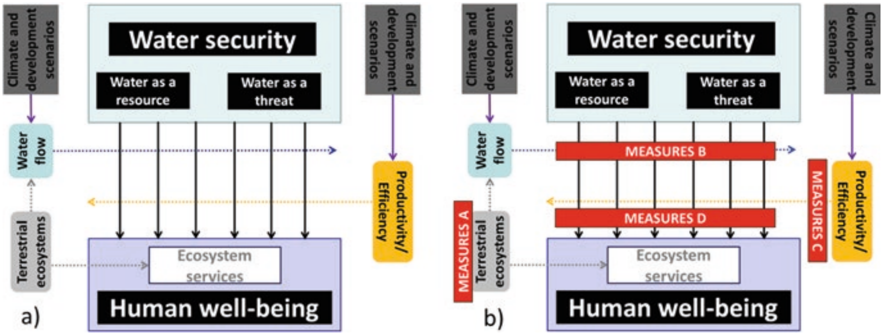

Fig. 19.9 (**a**) Role of ecosystem services, water security and levels of productivity and efficiency in achieving human well-being. (**b**) Inclusion of four types of adaptation measures to address the threats that future scenarios could have on human well-being and water security

Based on this conceptual framework, which also serves to design adjustment strategies to other types of changes, the identification of possible adaptation measures to climate change impacts is relatively clear (Fig. 19.9b). First, measures related to the protection and restoration of terrestrial ecosystems can be considered and, therefore, services that provide adequate water flows – i.e., provision and regulation services (Type A Measures). Then, measures that tend to change river flows (including aquifers) can be considered through infrastructure or modifications in the distribution rules (spatial and temporal) of available water (Type B Measures). A third group of measures is related to improvements in productivity and efficiency to maintain certain human welfare objectives, given the physical context provided by water quantity and quality (Type C Measures). Finally, a fourth group of measures considers that the threatened human welfare component is directly preserved or improved (Type D Measures), without improving the physical context or the products. Figure 19.10 shows some concrete examples of measures classified in these categories, whose effectiveness was evaluated in the context of the MAPA project.

Aside from the selection and design of adaptation measures, there are opportunities and limitations at the organizational and institutional levels (laws, capacities, and public and private organizations) that will define the capacity to implement them. In the case of Chile, the different institutional arrangements associated to the water allocation and distribution system become relevant in this context. One can recognize, for example, the Water Code and other components of the legal water governance, the General Directorate of Water and many other public services such as the National Irrigation Commission. The latter supports planning and implementation of different public objectives and user organizations – among other private actors – that finally execute water distribution and consumption actions. In the study conducted by the World Bank (2011), it is possible to find a description of the Chilean water governance, whose relation to global change was analyzed in detail by Vicuña and Meza (2012). They concluded that “global change introduces a paradigmatic change in the vision we have of the availability of water resources”, posing important challenges in water resources management, either by decreasing and

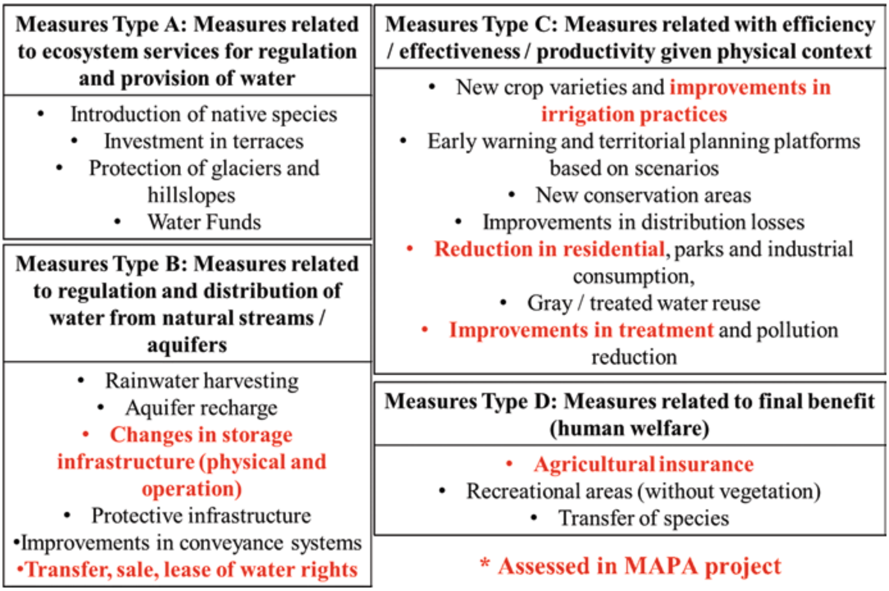

Fig. 19.10 Examples of measures to adapt to the impacts of climate change on water resources based on the conceptual framework defined in Fig. 19.9b

changing the water supply timing. According to the institutional framework and the hydrological diversity of Chilean catchments, it is expected that this type of impacts will generate a response (autonomous adaptation) tending to:

- Restrictions on the use of water at a productive level.
- Increased groundwater consumption.
- Increased efficiency in the use of water in the agricultural sector (main water consumer).
- Transfer via water market from agricultural sector to urban (higher economic value of water)

Given the non-integrated management system that operates in some Chilean basins (Borgias and Bauer 2018), it is expected that these changes will lead to decreased return flows (spills) or water not consumed by evaporation towards the lower parts of the basins, affecting consumptive or non-consumptive, productive or ecosystem users located downstream. In terms of investment and use of infrastructure, climate change implies a revision of protocols that will affect all the life stages of this type of projects, being unclear whether this will result in a greater need for infrastructure, or complementary strategies to improve flexibility or efficiency in the use of water.

19.5 Final Perspectives

Recent climatic trends are consistent with future projections in Chile in terms of precipitation reduction in the Central area, and increase in temperature across the country. These climatic changes affect hydrologic conditions, decreasing runoff during spring and summer, as a result of an accelerated seasonal cycle associated with the increase in temperature. Such impact is highly relevant since most of the population and productive activities (e.g., industry, agriculture) are located in Central Chile, as presented throughout this book (see Chaps. 10, 11, 12, 13,14, 15 and 16). Therefore, it is critical to implement adaptation strategies, understanding linkages between ecosystem services, infrastructure and water security, but also considering the particular characteristics of water governance in Chile.

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Chapter 20
Impacts of Urbanization and Land Use Change over Water Resources

Tomás Bunster, Jorge Gironás, Carolina Rojas, and Carlos Bonilla

Abstract Anthropogenic land use changes have taken place through time, and will continue in the future as the country develops. Such changes have affected the occurrence of hydrological processes, and impacted water resources. This chapter describes these changes and their evolution through time. Urban and population growth, expansion and intensification of agriculture and productive forestry, and the occurrence of wildfires in Chile are characterized. Furthermore, the main impacts over water resources and current practices to cope with these changes are presented. Finally, future challenges are described, together with the concluding remarks.

Keywords Land use · Urbanization · Wildfire · Population growth

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20.1 Introduction

Over the past centuries, one of the primary modes of human intervention over the global environment has been the conversion of land. This land conversion can range from the modification of a landscape character without affecting its classification, to a complete replacement of one land cover with another (Mölders 2011). Around the world, these changes have been driven mainly by the need to feed and shelter the growing human enterprise. The expansion and intensification of agriculture, establishment and/or growth of urban settlements, and extraction of natural resources are some examples of anthropic activities that alter the land use of a certain location. The demands of increasing numbers of people at higher standards of living will most likely accelerate these land use changes around the world (DeFries and Eshleman 2004), together with an overall global environment modification.

Land use changes over the Earth's surface have multiple consequences for biophysical systems at different spatial and temporal scales, ranging from urban heat islands (Ward et al. 2016) and alterations in streamflow patterns (Andréassian 2004; Rogger et al. 2017; Wheater and Evans 2009), to modified patterns of global atmospheric circulation (Werth and Avissar 2002) and the loss of biodiversity (Newbold et al. 2015; Pauchard et al. 2006). Of especial interest are the consequences land use change has over hydrological processes and water resources, as they directly affect human development. Impacts over water resources include modifications in water demands from changing land use practices (e.g., irrigation and urbanization), changes in water supply from altered hydrological processes (e.g., runoff generation and groundwater recharge), and alterations in water quality (e.g., nonpoint source pollution and combined sewer overflow in cities). Understanding these impacts requires a multidisciplinary approach gathering hydrology, ecology, and geography, among others.

Chile is not oblivious to the worldwide reality of land use change and its impacts on water resources. Between the years 1992 and 2017 the population of Chile increased from 13.3 to 17.5 million (INE 2018), together with a widespread urban development observed in several locations (e.g., Azócar et al. 2003; De Mattos et al. 2014; Vidal and Romero 2010). Both agricultural and productive forest land uses have increased significantly in the past decades (ODEPA 2017), with agriculture consuming approximately 73% of the total water withdrawals in the country, as discussed in other chapters in this book. Furthermore, severe wildfires have affected the Chilean territory over the past decades, which also have significant impact over land use change and water resources (Úbeda and Sarricolea 2016). These processes are expected to be intensified by the development of the Chilean society thrusting towards higher standards of living. Thus, it becomes of paramount importance to understand and characterize the land use changes currently experienced in the country.

This chapter presents the main anthropogenic land use changes affecting water resources in Chile and their impacts over hydrological processes. Urban and population growth, expansion and intensification of agriculture and productive forestry, and the wildfire phenomenon in Chile are characterized first. Impacts over water resources, current practices to cope with these impacts, and future challenges are then described for each land use change. Finally, concluding remarks and an overall synthesis are given.

20.2 Main Anthropogenic Changes

As the country evolves and the population grows, significant land uses changes have taken place. Chile, and in particular the central and south portion, has gone through substantial land uses changes due to human activities (Echeverría et al. 2006; Echeverría et al. 2007). Unfortunately, many of these changes are related to various unsustainable practices, such as logging to supply the growing wood and paper products demands, as well as the conversion of native forest and natural lands to grasslands, crops and urban areas as a result of man-made fires (Armesto et al. 2010). A major change is the rapid forests disappearance, with deforestation rates as high as 5.4% per year in certain landscapes of the country. Such rate is one the highest in Latin America in recent decades (Echeverría et al. 2006). Indeed, the replacement of native forests for plantations of exotic species represents between 52% and 80% of forest area losses between 1994 and 1998, in regions X and VIII, respectively (Lara et al. 2002). The destructive use of native forests is a problem, and annual forest loss rates between 1.1% and 2.7% are estimated in large areas of the Cordillera de la Costa in the X and VII Regions, respectively (Echeverría 2003).

On the other hand, urban development has also changed several landscapes in the country, and thus it has become a subject of great geographical interest (Castro and Brignardello 1998), due to its vertiginous characteristics and its almost irreversible consequences (Romero et al. 2003). The increasing urbanization process has led to an urban population rate of 87.8% (INE 2018), which will exceed 90% by 2025 (Cepal 2016). Currently, there are ~34 cities with population over 50,000 inhabitants, while ~45% of the population lives in the 4 largest urban centers. Table 20.1 shows the list of Chilean cities with more than 150,000 people according to INE (2019). Nevertheless, this urbanization process is not only reflected in the increase in urban population, but also in the constant and accelerated process of expansion affecting cities (Romero et al. 2007). This phenomenon occurs throughout the territory, both in the largest cities like Santiago (Puertas et al. 2014), Valparaíso (Sandoval 2009) or Concepción-Talcahuano (Rojas et al. 2013; Almendras-Varela 2009), as well as intermediate and small cities (Azócar et al. 2003). This physical expansion has caused land uses and land cover changes, which transformed natural and semi-natural spaces, as well as areas occupied by vegetation and crops (Romero et al. 2007; Figueroa and Fuentes 2009). Some of the factors driving urban expansion in Chile include (Henríquez 2009) government policies, the influence of the landscape, population's mobility, the socioeconomic system and the market economy, which has motivated explosive growth, fragmentation and social segmentation of urban spaces (Romero and Toledo 1998). Furthermore, guided by a Scenario

Table 20.1 Population of Chilean cities with more than 150,000 inhabitants

City	Inhabitants
Gran Santiago	6,139,087
Gran Valparaíso	935,602
Gran Concepción	719,944
Gran La Serena	448,784
Antofagasta	348,517
Gran Temuco	312,503
Gran Iquique	293,068
Gran Rancagua	290,029
Gran Puerto Montt	238,175
Talca	206,069
Arica	202,131
Gran Chillán	191,629
Calama	157,575
Coronel y Lota	155,329
Copiapó	150,804
Valdivia	150,048

Building Team (i.e. a participatory instance with a group of public, private, and civil stakeholders) Henríquez-Dole et al. (2018) recently used a land change model to integrate strategic land use planning in the construction of future land use for the Maipo River Basin where Santiago is located. For more details about land-uses changes across the country, the reader is referred to a variety of studies available elsewhere (e.g. Aguayo et al. 2009; Almendras-Varela 2009; Nahuelhual et al. 2012; Rojas et al. 2013; De Mattos et al. 2014; Heilmayr et al. 2016; Rosero 2015: Pizarro 2018; Vergara Díaz et al. 2018; Sepúlveda-Varas et al. 2019).

20.3 Hydrologic Impacts of Urbanization

20.3.1 Surface Water Impacts

From a hydrological perspective, urban settlements translate into a massive land use change that severely impacts hydrologic processes, water balance, and water quality. On one hand, population growth and concentration leads to an increase in water demands due to domestic and industrial consumption, which alters the natural hydrologic regimes of rivers from where the water is extracted. In Chile, 15% of the total water demand is related to both these uses (MOP 2016). On the other hand, land imperviousness associated with urban development reduces soil infiltration capacity, depression storage, and evapotranspiration (MOP 2013), thus increasing surface runoff generation. In addition, the conveyance of runoff to the streams is modified by the existence of piped storm water drainage systems (Butler and Davies 2004; Wheater and Evans 2009). The result is a greater runoff volume discharging in a shorter time, reaching larger peak flows.

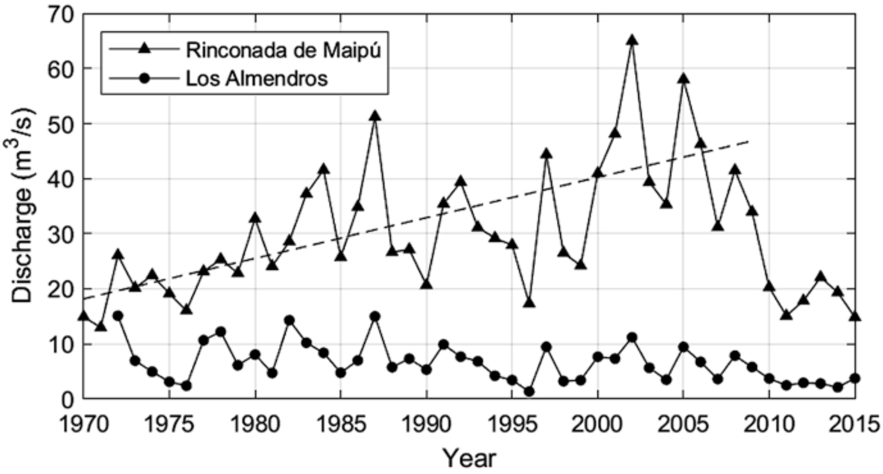

Fig. 20.1 Mean annual discharge recorded upstream (Los Almendros) and downstream (Rinconada de Maipú) of Santiago urban area in the Mapocho River during 1970–2015

Impacts of urbanization over surface water resources have been studied in the Chilean context, with a primary focus in Santiago and Concepción, the two largest urban settlements (e.g., Rivera et al. 2005; Romero and Vásquez 2005; Ebert et al. 2009; Zegpi and Fernández 2010; Vidal and Romero 2010; Rojas et al. 2017). One example of these impacts is the Mapocho River regime alteration due to Santiago's growth. Figure 20.1 shows the evolution of mean annual discharge for Mapocho in Los Almendros and Mapocho in Rinconada de Maipú flow gauges, located upstream and downstream of Santiago urban area, respectively. The contributing area of Los Almendros gauge has not been urbanized and is mostly natural land, whereas Rinconada de Maipú gauge captures most of Santiago's urban area, which has expanded at a rate of 8 km^2 per year for the past decades (Fuentes and Sierralta 2004). The greater runoff volumes produced by Santiago's urban growth are clearly noticeable through the positive trend observed in Rinconada de Maipú gauge. No such trend is observed in Los Almendros flow record, as the land use in its contributing area has not changed in recent years. Camaño and Arumí (2018) reported the same trend for peak discharges at the study site. Note also that annual discharges have reduced significantly after 2010, most likely due to the Megadrought affecting Central Chile since then (Boisier et al. 2016).

Besides impacts on hydrological processes, water quality issues also arise due to urban land use change. In Chilean urban areas, surface water pollution is produced mainly by combined sewer overflows (CSO) and nonpoint source (NPS) pollution. Combined sewer systems are sewerage networks that also work as stormwater drainage systems for precipitation events. On rainfall events, the discharge flowing through the system is greater than its capacity, thus leading to a wastewater effluent over watercourses with little or no treatment. Cities like Arica or downtown Santiago have combined sewers and are prone to CSO events. Furthermore, the issue has become more relevant in a variety of lakes in the south of the country, such as Lakes Villarrica, Panguipulli and Llanquihue (e.g., Diario UChile 2018; Diario La Izquierda 2019; Zerán Ruiz-Clavijo 2019). Currently CSO events are regulated by SISS (Ordenanza 3104), which can fine water companies in case rainfall intensities are considered not to be high enough to produce the CSO. On the other hand NPS pollution occurs throughout all urban areas in Chile. Pollutants present in streets and other urban surfaces, such as heavy metals, organic matter, and oils, are washed by precipitation and flow to watercourses with no treatment, generating severe consequences for water quality and biotic integrity on streams. Unfortunately very few studies have characterized this issue. Montt (2000) characterized the build-up and wash-off processes and measured runoff and pollutants concentrations in the city of Valdivia. Montt et al. (2003) monitored runoff quality for 7 storms in several locations in Santiago during 2001. They reported mean and instantaneous concentrations for 37 pollutants and compared them against local point-source pollution regulations. Some of the pollutants exceeding these regulations include aluminum, manganese, total kjeldah nitrogen, BOD, suspended solids, aluminum, iron and lead. Toro (2005) studied hydrodynamic properties of sediments in urban runoff in order to provide the basis for the design of settling tanks for stormwater control, whereas Gironás et al. (2008) proposed and modeled a perlite filter for this purpose. Nonetheless, no official regulation for stormwater pollution control exist in the country, although the National Drainage Manual (MOP 2013) defines the concept of Water Quality Control Volume (WQCV) and proposes values across the country, so that stormwater facilities can control the most polluted portion of the runoff. In this regard, Vargas et al. (2015) studied and proposed the WQCV to be used in bioretention systems in the city of Concepción.

20.3.2 Groundwater Impacts

Urbanization also has consequences for groundwater recharge and stream base flow. These effects are variable among physiographic and climatic regions and types of urban development (Bhaskar et al. 2016; Hopkins et al. 2015). Many studies suggest that the reduced infiltration due to larger impervious surface cover of urban areas decreases groundwater recharge and base flow (e.g., Hardison et al. 2009; Mejía et al. 2015; Price 2011). However, other authors have reported rising water tables and stream base flow (e.g., Rosburg et al. 2017; Sharp 2010; Townsend-Small et al. 2013) due to pipe leaking and urban irrigation.

In the Chilean context, Sanzana et al. (2019) assessed the impact of urban growth on groundwater levels in a peri-urban catchment in Santiago. They identified that drinking water pipe leaks and urban irrigation indeed contribute significantly to the groundwater recharge (i.e. it corresponds to ~10% of the total recharge to the aquifer, which is also recharged from lateral natural subcatchments). This contribution has been increasing through time with urban area (Fig. 20.2), which in turn has risen low flows and the water table. Muñoz et al. (2003) had also identified these sources

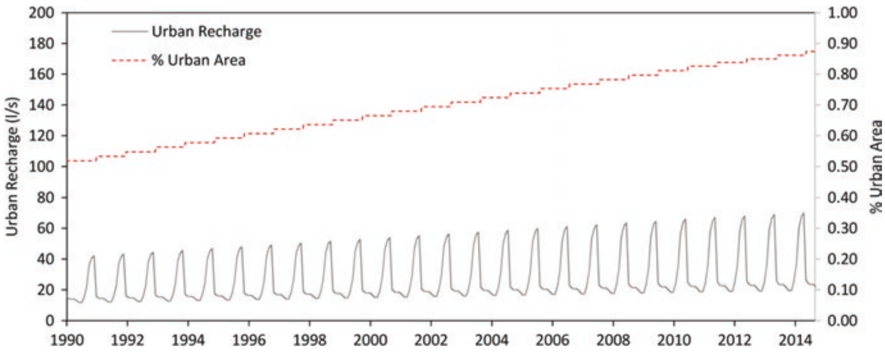

Fig. 20.2 The dynamics of urban recharge due to irrigation and pipe leaks in a peri-urban catchment under continuous urban development in Santiago. (From Sanzana et al. 2019)

of groundwater recharge in the site, with a significant contribution from urban consolidated areas. Sanzana et al. (2019) state that a future scenario with efficient irrigation practices and a reduced seepage from the potable water network would lead to a reduction of base flows and a decrease of up to 1.5 m the water table level.

Just like surface waters, water quality issues on groundwater resources also arise with urban development. Wastewater infiltration and leaking from sewer systems represents a potential health hazard, as it can pollute aquifers used for potable water supply (Foster and Chilton 2004). With the steadily increasing urban population and urban settlements, wastewater pollution becomes relevant for the rapidly developing urban centers of Chile. This issue was studied by Montt et al. (2003) when the Ministry of Public Works evaluated the possibility of massive stormwater infiltration devices, an idea that did not prosper.

20.3.3 Impacts over Wetlands and Ecosystems

Wetlands are disappearing by global pressure including land-use changes and urbanization. Unfortunately, fast rates of inland wetlands reductions are seen in the world, particularly in Latin American, where wetland losses correspond to 59% of global losses (Darrah et al. 2019). Urban wetlands have been identified by Ramsar (2018) as vital spaces for livable cities, as they enable a healthy living while providing several ecosystem services such as recreation and flood control. Chile is a territory with a high presence of wetlands, with many of them either limiting with or being surrounded by cities (i.e. urban wetlands). Nevertheless, none of these urban wetlands are identified as Ramsar sites, which has led to ignoring their protection and the appreciation of their natural benefits and the ecosystemic services they provide (Villagra et al. 2014). However, the local evidence has shown that urban wetlands provide flooding mitigation (Rojas et al. 2019), an essential benefit in places such as the metropolitan area of Concepción, where 21 flood events have occurred the last 50 years (Rojas et al. 2017). This issue is even more relevant as higher flood recurrence are expected in the area due to climate change.

Instead of favoring their protection, urban wetlands have normally been filled so that the land can be used to build social and private housings. Indeed, for a long time urban planning allowed systematically and deliberately the development of wetlands without any institutional questioning. Interestingly, local population of *Mapuche-Huilliche* in prehispanic times respected wetlands as fluvial and maritimes systems, and did not compromised them with their settlements; this practice started changing with the Spanish occupation (Alfaro et al. 2017). A few years ago this situation generated a political questioning and a socio-ecological conflict, not only because urban wetlands are part of the identity of local communities, but also because their loss was an externality of processes oriented towards providing new housing, and aesthetic appealing in some residential areas. This socio-ecological conflict became more notorious through time, especially in coastal cities. Some mediatic examples were those that took place in Algarrobo, Coquimbo, Concepción, Valdivia and Puerto Montt (Rojas et al. 2014). In fact, conservation of urban wetlands has awaken self–organized citizen movements in which local actors are essential. Examples of these movements are those around the *Los Batros* wetland in San Pedro de la Paz (Rojas 2018) and The *Angachilla* wetland in Valdivia (Correa et al. 2018). In this last case, the collaborative effort between urban planners, local communities and the government allowed the creation of a tool for management and protection of wetlands (Lara 2017), a small but significant step towards a more livable city (McDonnell and MacGregor-Fors 2016).

Most of the academic research has focused on Southern Chile. Pauchard et al. (2006) and Rojas et al. (2013) studied the negative effects of the continuous development of the city of Concepción over the biodiversity in wetlands, and shown the correlation between variables describing urbanization (i.e. urban density and distance to roads) and the type and richness of plants, as in Rojas et al. (2015). Furthermore, Silva et al. (2015) demonstrated the relevance of the wetland status over bird richness in the city of Valdivia, while Rojas et al. (2016) show how urban wetlands provide accessibility to open green spaces at a walking distance. Finally, Novoa et al. (2020) studied water quality issues in coastal wetlands

20.3.4 Current Practices to Control Impacts of Urbanization

From the point of view of the current practice, stormwater control in Chilean urban areas is regulated by the Law 19,525 from 1997, which makes the state responsible for drainage systems and stormwater control in populated centers. Each system is typically separated into a primary and secondary network, managed respectively by the Ministry of Public Works and the Ministry of Housing and Urban Development. The Law also created the Directorate of Hydraulic Works (DHW), which is in charge of elaborating Master Plans (MPs). More than 33 MPs have been prepared, covering more than 85% of the urban population (McPhee et al. 2015). These MPs have been guiding the implementation of stormwater infrastructures belonging mainly to the primary network. In addition to MPs, the state elaborated the National Urban Drainage Manual (MOP 2013) that summarizes the local development in the matter, and provides policies, methods and tools for the definition, design, construction and operation of drainage facilities. This manual integrates 4 spatial scales (i.e. residential, secondary system, primary system, and natural systems), for which objectives, responsibles and discharge conditions are provided. Moreover, stormwater practices are recommended for each scale based on 3 types of processes to be considered (i.e. infiltration, detention/retention and flow conveyance). Design procedures and examples are provided for all these practices. As the manual is still very recent, the impact it has had on the actual practice is not very clear yet.

From the scientific point of view, some studies are being developed to provide more basis for the implementation of sustainable urban drainage systems. For example Herrera et al. (2017) developed the model IHMORS for the simulation of hydrological processes at residential scales in Mediterranean environments where irrigation of green infrastructure is a must. This model was used by Reyes-Paecke et al. (2019) to evaluate the over-irrigation in public and private green areas in Santiago. Furthermore, Herrera et al. (2017) used IHMORS to evaluate and predict the ability of green roofs in Santiago to reduce runoff. These green roofs were implemented in a research facility dedicated to the study of thermal and hydrologic properties of green roofs and walls, which are described and characterized elsewhere (Reyes et al. 2016; Sandoval et al. 2017). In addition, Olate et al. (2011) assessed under different conditions the suitability of 16 native species to be used in green roofs, and concluded that Mediterranean species could be used for this purpose. Finally, the viability of green roofs as flood mitigation elements in Curicó (another city in central Chile) was studied by Mora-Melia et al. (2018), who developed a computer model and concluded that a massive implementation of green roofs is expected to control at least 50% of runoff volumes for minor to average storms, whereas only some semi-extensive and extensive green roofs are suitable to prevent flooding when strong rainfall events take place.

Other low impact development practices that have been studied are pervious pavements and rain gardens. De Solminihac et al. (2007) and Castro et al. (2009) studied porous concrete mixtures for concrete pervious pavements, and developed some prototypes that were installed in some parking lots and a large open patio to reduce runoff. On the other hand, Aravena and Dussaillant (2009) installed an experimental rain garden in Santiago and proposed a model implementing a finite-volume solution to the two-dimensional Richards equation to simulate stormwater infiltration and recharge to the garden.

20.4 Hydrologic Impacts of Agriculture and Productive Forestry

20.4.1 Surface Water Impacts

While urbanization has dramatic impacts on hydrologic processes, the effects of agriculture and forestry land use changes are more subtle although not less relevant. Agriculture has its larger impacts on water balance due to irrigation practices, being the main water user of the country, but also impacts hydrologic processes through the modification of soil properties. Degradation of soil structure (including compaction and shearing) induced by agricultural practices can lead to reduction in soil infiltration and storage capacity, increasing rapid runoff as overland flow (Alaoui et al. 2018; Germer et al. 2010; Rogger et al. 2017; Wheater and Evans 2009). Productive forest plantations, on the other hand, have their larger impacts on water yield from basins through alterations in transpiration, interception, and evaporation (Farley et al. 2005; Little et al. 2009; Zhang et al. 2017). The denser canopy and deeper roots of forest plantations compared to other forms of vegetation, such as crops, grasslands or shrublands, increases both evaporation and transpiration rates in plantation catchments. In turns, the higher evapotranspiration can lead to a reduction in both mean and low streamflows (Farley et al. 2005; Huber et al. 2008; Little et al. 2009; van Dijk and Keenan 2007). However, this impacts may depend on the scale of the catchment, the land use before afforestation, and climatic region (van Dijk and Keenan 2007; Zhang et al. 2017).

Studies in Chile regarding these impacts have been centered mainly on plantation forests, and little on agriculture land use. Several studies about interception losses from coniferous and broadleaved forests, and the influence of forestry on runoff and peak flows, are available (e.g., Huber and Iroumé 2001; Huber and Trecaman 2000; Huber et al. 2008, 2010; Iroumé and Huber 2000; Iroumé and Palacios 2013; Iroumé et al. 2006; Lara et al. 2009; Little et al. 2009; Nahuelhual et al. 2012; Soto-Schönherr and Iroumé 2016). General trends in Chile show that increased evapotranspiration caused by higher interception rates leads to a reduction in water yield of forested catchments. These results support the knowledge of hydrological effects associated with productive forest land use elsewhere. Finally, in a comprehensive study, Alvarez-Garreton et al. (2019) show that annual runoff consistently decreases in 25 large basins (i.e. with areas larger than 200 km^2) located in south-central Chile, as the native forest has been replaced with *Pinus radiata* D.Don and *Eucalyptus* spp. exotic forest plantations (FP). The magnitude of this change ranges from 2.2% to 7.2% and depends on factors such as the initial land cover partition within the basin, the replaced land cover class, and the basin area and climate. All these results have been recently confirmed by Fierro et al. (2019), who demonstrated that land-use changes is the main driver affecting Chilean Mediterranean ecosystems.

Agricultural land use and productive forestry also have impacts on surface water quality. Significant loads of nutrients, particularly nitrates and phosphates, and pesticides originate from agriculture. This pollutants are transported by runoff to water courses generating negative impacts over aquatic ecosystems and producing eutrophication (Conley et al. 2009; Wheater and Evans 2009). Little has been studied in Chile on this matter, nevertheless, water quality policies have been developed in which water quality standards are set (Melo and Perez 2018). Regarding productive forestry, negative impacts over water quality have arisen in Chile due to increased sediment loads associated with clearcuts in plantations managed under 12-year rotations for Eucalyptus and 20 years for Pinus Radiata (Oyarzun and Peña 1995; Lara et al. 2009).

20.4.2 Impacts over Wetlands and Ecosystems

Besides water resources, wetlands and ecosystems also suffer negative consequences due to agricultural lands and productive forests. On one hand, drainage of wetlands driven by the need to obtain suitable lands for agriculture and forestry plantations degrades these areas and reduces their ecosystemic services. This type of anthropic pressure has been reported in several locations in Chile, mainly due to firewood extraction and land clearance for agricultural use (e.g., Hauenstein et al. 2002; Peña-Cortés et al. 2006, 2009, 2011). On the other hand, wetlands also suffer from surrounding agricultural and productive forest land use changes. Replacement of natural land for agricultural fields has strong influence on nutrient load discharge to downstream water bodies (Oyarzun et al. 1997; Oyarzún and Huber 2003). Increased loads of nutrients, particularly nitrogen and phosphorous, have negative impacts over wetlands as they may produce eutrophication. Furthermore, increased sediment accumulation in wetlands is also known to damage the biological production of wetlands (White et al. 2002). Thus, agricultural activities with inadequate management and forest cutting influence the normal functioning of wetlands (Peña-Cortés et al. 2006).

One of the geographic zones in Chile with the greatest diversity of wetlands is the coast of the Araucanía Región. In this territory, anthropogenic impacts associated to land use changes over wetlands have been studied recently due to the cultural and environmental importance of these areas. Studies over swamp forests, a particular type of wetland characterized by the dominance of tree species, show that they are subject to a high pressure by the farming matrix that surrounds them and the artificial drainage of wetlands (Peña-Cortés et al. 2011). Another example is presented by Peña-Cortés et al. (2006), who show that 61% of the wetlands located around Lake Budi have a high degree of alteration in their functions produced by the impact of agricultural patterns. The challenge is to maintain and conserve wetlands in the national territory, minimizing the pressure on these ecosystems, restoring degraded areas, broadening studies on their ecosystem services, and determining conservation priorities.

20.5 Hydrologic Impacts of Wildfires

Wildfires have several impacts on soil hydrology, watershed management, ecosystem services, and sustainability (Bento-Gonçalves et al. 2012). Most common adverse effects on soils include the removal of soil organic matter, deterioration of their structure and porosity, loss of nutrients, and increased surface runoff and water erosion (Wittenberg 2012). Among the hydrologic impacts, wildfires can produce substantial effects on the streamflow regime, affecting annual and seasonal water yield, peak flows and floods, baseflows, and timing of flows (Neary et al. 2011). Also, wildfires substantially increase erosion potential and sediment yield, with resulting impacts on life and safety, transportation and water supply infrastructure, property, and ecosystems (Yochum and Norman 2015). Wildfires burn extensive forest areas around the world each year, and many fire-prone forest catchments are used for the supply of potable water to small communities up to large cities (Smith et al. 2011). Following wildfire, increased erosion rates and changes to runoff generation and pollutant sources may greatly increase fluxes of sediment, nutrients, and other water quality constituents, potentially contaminating water supplies.

Wildfires have been an issue of significance in Chile, a country where more than 8000 fires burnt around 130,000 ha in 2014 (Úbeda and Sarricolea 2016). Furthermore, during the summer of 2017, the central-southern region of Chile suffered the biggest wildfire in the country's history. A total of 518,000 ha of land were burned, and forest plantations were the most affected ecosystem. It cost more than US$370 million to combat the fire, 11 people were deceased, and 3000 houses were lost (De la Barrera et al. 2018). Two of the main reasons for the increase in wildfires occurrence are the increment in the area planted with flammable species, and the adoption of intensive forest management practices resulting in the accumulation of a high fuel load (Úbeda and Sarricolea 2016). Fires are an additional problem at the rural-urban interface, a condition that affects people living in Chile's most populated cities. Thus, the need for fire prevention systems and territorial plans that include fire risk assessments are some of the key aspects to prevent human and material damage (Úbeda and Sarricolea 2016).

20.5.1 Surface Water Impacts

Wildfires can change hydrological processes, increasing the risk of extreme flooding and erosion events. As a result of the rapid drying of topsoil after rain, wildfires increase the response of topsoil moisture to rainfall (Stoof et al. 2012). In regions with Mediterranean climates like central-southern Chile, changes resulting from vegetation removal after the fire have a significant role in increasing streamflow. Most of the time, increased effective rainfall and decreased transpiration are expected, increasing the amount of water available for surface and subsurface runoff. Also, the more rapid development of soil water repellency and decreased surface water storage increases the overland flow risk. Finally, a more rapid breakdown of post-fire soil water repellency occurred, increasing infiltration during extended rain events (Stoof et al. 2012). As a result of these processes, a large territory of populated areas is now more exposed to landslides and flooding hazards after the wildfires occurred in 2014 and 2017. The level of risk in these areas will depend on the vegetation that survived, the forest regeneration practices that are implemented, and also the storm intensity in the next rainy seasons and the main topographic characteristics of the area (De la Barrera et al. 2018). Indeed, it is demonstrated that floods and landslides are between 3.3 and 5.6 times more likely to happen in wildfire-affected areas (Diakakis et al. 2017).

20.5.2 Wildfires and Hydrologic Impacts in the Serrano River Basin

In addition to the mega-events occurred in 2014 and 2017, wildfires have also become a major threat to some soils and ecosystems in the Chilean Patagonia, where the Serrano River basin is located. Most of the fires in the Serrano River basin occur in the Torres del Paine National Park, a sensitive ecosystem and world biosphere reserve encompassing lakes, rivers, waterfalls, glaciers, forests, and wildlife. The number of visitors in the park increases the risk of ignition sources, with more than 60 fires recorded in the park since 1980, which have disturbed around 48,000 ha, nearly 20% of the park's area (Carkovic et al. 2015). The three largest wildfires in the park in recent years occurred in 1985, 2005, and 2011, affecting 6000 ha, 13,000 ha, and 17,000 ha, respectively (Bonilla et al. 2014; Carkovic et al. 2015). Figures 20.3 and 20.4 show the spatial distribution of these fires in the study area.

A comprehensive study conducted by Bonilla et al. (2014) evaluated the effects of the last three wildfires that occurred in the Serrano River basin. Actual field data were collected after sampling burned and unburned sites. Soil hydrology, water erosion, sediment yields, and water quality were predicted using the Water Erosion Prediction Project (WEPP) model with actual soil, vegetation, and weather data (Table 20.2). Two typical vegetation types found in the watershed were evaluated: forest and shrubs. The results showed that burned and unburned sites were not found to be significantly different in soil organic carbon (SOC) contents. However, because of the soil bareness, water erosion increased after the fire, mainly due to the effect of vegetation removal, but also due to changes in soil properties and soil erodibility. The sediment yield in the forest sites increased from 0.02 t ha^{-1} $year^{-1}$ to 9.25 t ha^{-1} $year^{-1}$, and the SOC losses increased from 0 to 0.54 t ha^{-1} $year^{-1}$. The same condition was found in the shrub sites. After the fire, the sediment yield increased from 0.00 t ha^{-1} $year^{-1}$ to 0.39 t ha^{-1} $year^{-1}$, and the SOC losses increased from 0 to 0.02 t ha^{-1} $year^{-1}$. Most sediment and nutrients ended in rivers and lakes affecting the water quality at the watershed scale.

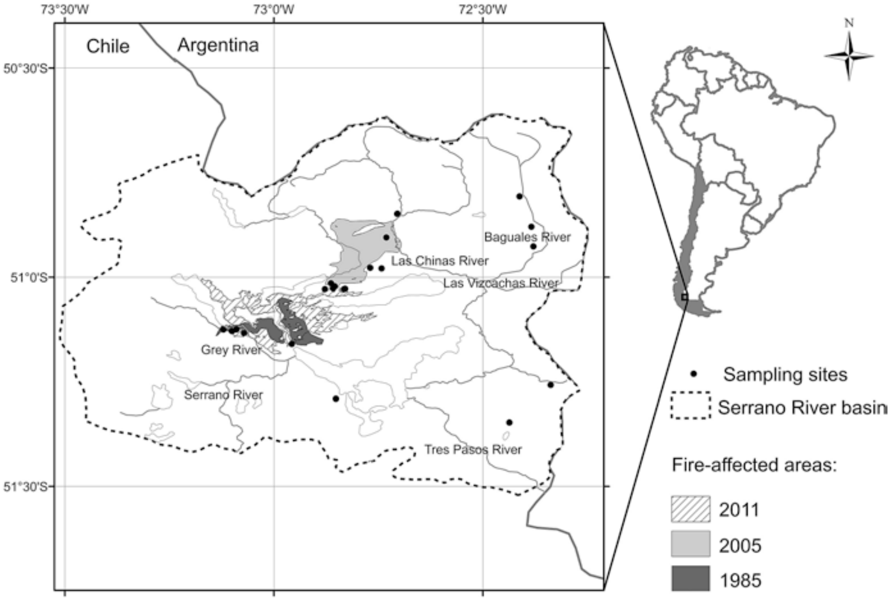

Fig. 20.3 Location of the Serrano River basin in the Chilean Patagonia and main wildfires occurred in recent years. (After Carkovic et al. 2015)

Fig. 20.4 Wildfire effects in the Serrano River basin. The photograph shows trees killed and foliage and forest floor consumed by fire and subject to water erosion. (After Bonilla et al. 2014)

Table 20.2 Summary results for simulated soil hydrology and water erosion scenarios at sites burned and unburned in the Serrano River basin. (Adapted from Bonilla et al. 2014)

	Sites			
	Unburned		Burned	
Vegetation type	Forest	Shrubs	Forest	Shrubs
Slope (%)	22	9	22	9
Interrill erodibility (millions kg s m^{-4})	0.131	0.125	0.288	0.192
Rill erodibility (x1000 s m^{-1})	0.215	0.138	0.234	0.229
Sediment yield (t ha^{-1} $year^{-1}$)	0.02	0.00	9.25	0.39
Organic carbon loss (t ha^{-1} $year^{-1}$)	0.001	0.000	0.537	0.017

20.6 Future Challenges

In terms of controlling the hydrologic impacts of urbanization, McPhee et al. (2015) provide a series of challenges that should be addressed in Chile: (1) improvement of hydro-meteorological information (both in time and space), and its use in design and analysis applications; (2) definition of floodplains across the entire country following a formal and consistent methodology; (3) use of distributed modeling and continuous simulation tools, so that the hydrological and environmental functioning of the entire urban systems are better understood and incorporated in the design of sustainable stormwater control; (4) implementation and monitoring of pilot programs to validate and improve the design of stormwater facilities and understand their interaction with the community; (5) formal incorporation of water quality aspects so that urban runoff events are regarded as pollution events to be controlled; (5) better consideration of local issues when defining stormwater master plans so that the most suitable stormwater facilities are implemented given the local context; and (6) education of the community about urban drainage problems so that people understand the operation, goals and benefits of stormwater facilities. The community is the user, beneficiary and, to a certain extent, responsible for the proper functioning of these facilities.

On the other hand, future challenges arise regarding urban wetlands. The evidence as well as recent conflicts should motivate the preservation, rehabilitation and wise use of urban wetlands towards the achievement of more resilient and sustainable cities and communities. An example of possible actions in this regard is the preservation of wetlands in coastal cities, as they could mitigate the effects of tsunamis in population density and vulnerable areas (Martínez and Aránguiz 2016). Moreover, the country has just passed a new law (*"Ley de Protección de Humedales Urbanos"*) to protect urban wetlands in Chilean cities. This law implies the official recognition of urban wetlands by the Chilean state and allows the regulation and planning of these natural spaces in cities. Thus, key regulations driving urban development including the law of urbanism and construction, and the law of environment, will have to consider this new law of urbans wetlands, and local governments will have to work with local communities to ensure their rational and sustainable use. The regulations to implement the law, which will define the procedures and criteria to declare wetlands as protected locations, were recently approved and will soon become official.

Regarding wildfires, there is a big need for a better understanding of the socio-cultural consequences of post-fire flooding and sedimentation. On the other hand, the last mega-fires that occurred in Chile demonstrated the need for prevention systems and territorial plans that include a fire risk assessment. Revisiting the planning and management in the aftermath of these wildfires would help the authorities to reduce the impacts on human lives, infrastructure, and the size of the affected areas.

20.7 Conclusions

This chapter discussed the hydrologic impacts of anthropogenic land uses changes in Chile. Such impacts have been very noticeable particularly due to urban development, agriculture and productive forestry. Several components of the hydrological cycle are deeply affected by these land-use changes, which in turn affects the hydrologic regimes of the corresponding basins. Moreover, water quality is also being affected, although the country has paid less attention to this issue. Overall, it is clear that land-use changes impact freshwater ecosystems and flow regimes in Mediterranean Chile, and thus these changes must be taken into account as much as climate change in the development of policies and strategies towards more livable cities and more sustainable agriculture and forestry activities.

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Chapter 21
Water Resources Research in Chile

José Vargas and Jorge Soto

Abstract Given the water resources characteristics in Chile and the new challenges in these matters, the importance of a constant development of research is recognized. In this chapter we review the investment in Research and Development in water resources in Chile and its incidence on the economic growth of the country during the last decades, following with the evolution of research challenges. Also, the research's public policy for the investment in water resources research is outlined, including public funds, funded investigation, the contribution of every research fund, and the comparison between the annual contribution of the State to funding research and its relationship with the GDP. Finally, some of the research areas and topics handled are exposed.

Keywords Research · Research topics · Research areas · Investment · Public policy · Funds · GDP

21.1 Introduction

Chile is a country located in South America, on the west side of the Andes Mountain Range, which has a length of 4.270 km and a surface of 756.096 km^2 in the continent, (IGM 2010). Chile's Length and geography influence the country's climates sequence, defining precipitation levels for each region, such as annual precipitations under 1 mm in Arica city in the extreme north of Chile; 360 mm in Santiago city in the central zone, 2.500 mm in Valdivia city in the south zone, or 4.866 mm in Tamar island to the southwest of Magallanes region in the austral zone (INE 2010). The

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annual mean precipitation in the country is around 1.522 mm, conditioning water availability, which on average at country level is around 5.475 m^3/year per capita with important territorial variations (Matus et al. 2004).

Water is essential for ecosystems, reason why variations in the resource's availability, could generate diverse effects over productive systems, economy and society (FAO 2010). Nowadays most of the water scarcity is produced by bad practices, inappropriate management and climate change (UNESCO 2003).

Challenges presented by global change processes, produce different scenarios of natural availability, in addition to demand projections given the economic growth. Thus, the "Estrategia Nacional de Recursos Hídricos 2012–2025" establishes that by 2010 the demand will widely exceed availability in the big north and the small north, and if changes do not occur then by 2025 this situation will become worse (DGA 2012).

Given the water resources characteristics in Chile and the new challenges in these matters, it is required a constant development of research. However, there is uncertainty about the number of researches per year, area, and amounts granted by different sources of public financing (CONAPHI-Chile 2016). As a result, this study is seeking to give an approximation to these questions, through an appropriate method for such objectives.

21.2 R + D in Water Resources

The importance of Research and Development (R + D) and their incidence in the economies' growth is recognized in the productivity of the countries. The international experience demonstrates that companies can enhance competitiveness by using R + D as focus of innovation and business strategies.

In the last years the statistics point out that Chile's investment in R + D has been kept in a range between 0,30 and 0,40% of its PIB, which represents a disadvantage with respect to other countries, even Latin-American ones, reaching investments of about 1% as average. If comparison is made with developed countries, the gap is even greater given that countries from the OCDE invest 2,4% on average while cases like South Korea is investing up to 4,36% in 2013. (Un Sueño Compartido para el Futuro de Chile).

Another important difference with more developed countries, is that in them the private sector contributes, on average, about half of the resources destined to science-technological research, while in Chile the private contribution does not overcome 20% of the total resources destined to such purposes. The latter implies that there are meditations like: "It is not correct to say that rich countries invest more in R & D because they are rich… they are rich because they invest more in R & D".

However, if the amount of persons availability dedicated to R + D is taken into account then differences are also very important. In Chile, by 2013 there were just 0,9 researchers for every 1.000 workers, in contrast to OCDE countries that on average had 7,6 and cases like Finland that had 15,9.

Deepen about R+ D reality of the countries is a central topic of public policy. In the case of Chile in the last years there has been a raising of awareness about its importance for our development, and that is how initiatives like creation of Innovation National Council for Competitiveness have surged; from programs such as Excellence Centers Attraction; or dictation of laws like Tax Incentive to R + D, creating a real incentive for companies that invest in these areas, and thus, promote a more innovative culture in Chilean companies and their consequent educational and social effects.

However, the diagnosis in R+ D matter is not auspicious. Not just the inversion is low, but the few public resources are dispersed over different institutions that do not dialogue between them and where it is required a greater association between basic and applied research.

Chile has proposed an important goal as it is to aspire to be the first developed country of Latin America. Without a doubt a great challenge. Achieving it will require a greater effort implementing actions based on education, science and technology, and there the role R + D plays can be very relevant. However, it will not be enough with just increasing the number of professionals linked to the area, neither increasing investment just because it presents better indicators; but making of it a real contribution with research focused on defined challenges through a country strategy.

It is not an objective in the present work to analyze which could be the priority areas where R+ D should be mostly channeled, but it has been motivated by a concern about having a perception of what is being made in water resources matter.

Why water resources? The answer could be of interest of the authors developing in that field, but today's reality is showing us that the topic goes further and has acquired relevance by itself. In fact, water is an irreplaceable element for the support of human life and relevant for the economic development of the countries. It is an essential supply for most of productive processes and despite of being a renewable resource, as countries grow economically, water shortage is shown gradually when increasing demands and arising conflicts by its use. Its vulnerability, displayed in the increasing degradation of its quality, can put in risk not just the countries development but also the very existence of life.

Since mid-80s, Chile though a stable macroeconomic policy and efficient fiscal policy, has been able to achieve a constant growth allowing to, according to the International Monetary Fund estimates, increase the annual income per inhabitant from approximately 3.950 to near 23.000 dollars and decrease poverty from 15% to less than 7% (International Monetary Fund, World Economic Outlook Database, April 2015).

The adopted strategy to achieve such growth has consisted basically of guiding productive capacity through the exports, opening internal and external economic borders, promoting competition and making an efficient resources assignment through market mechanisms and the creation of fair and clear economic rules.

The importance of the water resource in the development of that production and export capacity is evident in products like copper, fresh fruit, cellulose, agroindustry products and salmon, products where water use is a fundamental part of their productive process, representing more than 50% of national exportations (www.aduana.cl).

In a growing country like Chile, it is possible to appreciate a clear correlation between this growth and its water demands, as well as the emergence of environmental topics related to natural resources. Additionally, the expected impacts of climate change over water resources are relevant factors at the time of planning and managing their use implying new tools for evaluation and planning of adaptation measures.

Thus, being water resource a fundamental pillar for the country's development, its preservation and interrelation with environmental management, its linkage with territorial management, the actions to take against its pollution, the impacts by excess or shortage; are topics that necessarily must be in the national schedule of the next years and in them the research, having as central focus the water, seems like a priority task.

21.3 Research

21.3.1 Challenges

An analysis of the main challenges about water resources in Chile, has been made based on the documents: "Política Nacional de Recursos Hídricos" (DGA 1999 and Delegación Presidencial para los Recursos Hídricos 2015) and "Hacia un Plan Nacional de Gestión Integrada de Recursos Hídricos" (CEPAL 2003). These were later compared to the studies of CONAPHI-Chile 2005, and CONAPHI-Chile 2016.

It was observed an evolution of the challenges through time, as these were achieved, being it by research advance and/or national policy. It is noteworthy, for example, that the "drinking water and waste water treatment" challenge was declared as most urgent for Chile in 1999. The relevance was given by the sanitation costs of wastewater, the need of water quality regulations, the pertinence of the State participation in the sanitation, and the execution of these processes in rural zones. However, in the consultation made to the *stakeholders* both in 2005 and 2016, such challenge was no longer considered essential, because of the national advances in the matter (CONAPHI-Chile 2005, 2016).

Another case to highlight corresponds to the challenge: "development of the ground water in Chile", established as second priority in research matter during 1999 and 2003. However, by 2005 the specialists considerate that it was no longer a priority, dropping to the seventh place; while in 2016 it was not even considered as a challenge (CONAPHI-Chile 2005, 2016). Even so, the null consideration in 2016 could be due to the fact that the considered sample of *stakeholders* in the studio focused mostly in research centers, universities and state agencies in center-south of Chile, omitting the experience of key actors in complex zones, where the priority could have been high, like regions of the north macrozone.

On the contrary, there are some challenges that have remained through time. In the first case, it was highlighted the “efficient use of water” case, that in 2005 was considered as third priority, situation that remained until 2016 (CONAPHI-Chile 2005, 2016). While, the “environment and contamination” challenge outstood in the 1999 and 2003 documents in fifth place of priority; but in 2005 improved reaching the first place; and in 2016 came back to the fifth place (CONAPHI-Chile 2005, 2016). This situation could be due to the fact that research funds focused since 2000 to topics oriented to solve these problems and develop techniques to decontamination of water, implying a low priority in 2016.

On the other hand, new challenges with a high priority degree appear, such as “physical shortage of water” and “water management”, corresponding to the main challenges for Chile by 2016 (CONAPHI-Chile 2016). In Table 21.1 it is presented in decreasing order, the main water challenges for Chile by the year 2016 (CONAPHI-Chile 2016), grouped in *clusters* determined according to a Tukey test, to estimate the distance between options.

At the present and in function of the collected information, the authors consider that the challenges: “Physical water shortage”, “Efficient water use”, “Water management” and “groundwater development”, correspond to the main challenges, present and future for the country. This because of the greater demand of water resources for the different purposes to which the different basins along the country are exposed to; as well as the challenges that the climate change impose to Chile and the heterogeneous water supply. Thus, the four challenges listed are considered in the *cluster* a, in other words, classified in the first priority order.

In the same way, because of the actual and projected conditions of water resources’ supply and demand, the authors consider that there are new challenges for the medium and long term in Chile, which are related to: “desalinization” and “Transport and storage”. These new identified challenges require an important effort of research and development, to generate the basal knowledge that allows the execution of new solutions; leaving to the authors judgement, in an intermediate order of priority (*cluster* ab).

While, the economic growth and the population increment generate greater pressure over the resource, that will require the development of studies to take charge of

Table 21.1 Detection and grouping of water challenges in Chile by 2016 (CONAPHI-Chile 2016), according to the priority order

Challenges sorted by priority	Classification of priority orders (*clusters*)
Physical water shortage	a
Water management	a
Efficient water use	ab
Legal water shortage	ab
Water pollution	ab
Access to water	ab
Water supply	b

the "environment and contamination" challenge, as well as "drinking water and waste water treatment". The authors consider that these challenges are in second order of priority, in the cluster b. This does not detract the importance of these areas, but recognizes that, being considered priorities with high advance degrees in the periods 1999–2005 and 2006–2016, there is an important development of the area that allows to address challenges in a different way. However, it is recognized that these challenges, given the global context, will be more complex to address, reason why they stayed in second order of priority.

21.3.1.1 Causes of Challenges

In 2016 a survey was applied to 59 professionals from different areas linked to water resources in Chile. 76,27% of the sample was constituted by men, and 23,73% by women, with an average age of 47 years. In professional terms, 74,74% was constituted by professionals with master degree. People answering are working in different positions (professional, research, managerial); whether in state bodies, universities, public companies, independent research centers or nongovernmental organizations (CONAPHI-Chile 2016). CONAPHI-Chile (2016), through an interview to the *stakeholders* identified that the main challenges in water matter for Chile consisted mainly in problems of legal regulation and their inefficient management. In a second classification, climatic causes and lack of research and studies were also identified as problems (Table 21.2).

Additionally, the consulted *stakeholders* indicated other causes of the water challenges, such as the increasing economic interests and the lack of common sustainable use criteria by productive agents in the basins; the lack of instances of discussions and bonding, be it between users and decision makers; the lack of resources priority and the absence of coordinating organisms in basin level; functioning problems and the need to implement and/or strengthen users organizations; problems associated with current legislation, specially the consideration of water rights as a private good; the existence of opposite regulations and incentives generating adverse effects over the water resources management (CONAPHI-Chile 2016).

The latter, implied a complexity that must be addressed. This, because detailed information is required, that allows to make studies to be the base, both to establish improvements in the regulation that rules water resources in Chile, and to develop

Table 21.2 Causes of the challenges identified by 2016 (CONAPHI-Chile 2016), according to the order of priority

Challenges causes sorted by priority	Classification of priority orders
Problems associated to current regulation ruling water and other associated resources	a
Inefficient water management	a
Climatological causes	b
Lack of information and/or studies	b

plans or strategies that allow to improve their management. It also highlighted that three out of the four main identified causes, were due to human factors, specifically associated with management (be it legal, administrative or scientifically); and just one cause is out of human control (climate). All of the above, raised a challenge, for both national science and decision makers, in advancing in water challenges of the country.

Additionally, it stands out that the effect of climate change was not evaluated in the causes of the challenges identified by 2016 (CONAPHI-Chile 2016). The background and the additional challenges that today address the climate change, lead to these authors to consider that such factor, along with the climatological causes, could today be part of the first priority order (*cluster* a).

21.3.1.2 Foremost Affected

In the survey made in 2005, the *stakeholders* considered that the main challenges in water resources in Chile affected mostly to the people that is closer to these problems, but also to the country as a whole. To a lesser extent, the consulted identified that private sector, environment, common people and the whole planet was affected (CONAPHI-Chile 2005).

Given that identified challenges changed by 2016, perception of the main affected ones changed as well. These were, in priority order: environment, users and companies (CONAPHI-Chile 2016). It stands out that by 2005, it was observed a clear anthropocentric and productivity vision; which contrasted with the broader vision, both in environmental and social terms, for which the consulted *stakeholders* inclined in 2016 (Table 21.3).

21.3.1.3 Efforts Facing the Challenges

There was a variation of the perception of effort to face the water challenges of Chile. In 2005 a 40,00% of the consulted indicated that "yes", it is effective the way that addresses the correction of water problems/challenges of Chile, especially if it is about topics related to water shortage and pollution (CONAPHI-Chile 2005), which have been addressed with higher intensity regarding research and regulation generation, what would have allowed to solve the problems by 2016.

Table 21.3 Detection of foremost affected by 2016 (CONAPHI-Chile 2016), according to the priority order

Challenges causes sorted by priority	Priority order group
Ecosystems	a
Farmers	b
Urban users	c
Industries	d
Mining	d

However, consulted *stakeholders* in 2016 had a less optimistic perception, who indicated that "no", the way of work is not active to solve the water challenges (83,05%); attributing it to the lack of interest by the authorities (67,35%) and to a lesser extent the lack of interest of the researchers (2,04%). Additionally, the *stakeholders* highlighted the atomization of water management in state level; the low capacity of the user's organizations to manage the efficiently of the water resources; and the existence of conflicts of interest in the current water management system, redounding in the low interest in making modifications, beyond the aesthetic (CONAPHI-Chile 2016).

Then, it was consulted about who work to solve the main water challenges of Chile. The consulted in 2005, indicated that those are the universities who work actively searching answers and solutions to these challenges, and in second place the state institutions, followed in third place by private companies (CONAPHI-Chile 2005). By 2016, the universities are keeping the first place; followed in second place by the investigation centers and the state institutions, the nongovernmental organizations; the international institutions and state companies in third place; and finally, in fourth place the private companies (CONAPHI-Chile 2016).

The described situation, was possible to ratify when analyzing the efforts of research developed by universities, research centers and other institutions in diverse topics of water resources. These efforts gave as result a series of studies allowing to generate answers and improvement in the area, which depend mainly on tax contributions from different financing mechanisms, such as competitive funds in national or regional level, as well as studies resulting from bidding processes by different agencies.

21.3.2 Investment in Research Associated to Water Resource

21.3.2.1 Research's Public Policy

One of the first approaches to public policy, in the area of water resources research, was observed in the National Water Resources Strategy 2012–2025 (MOP 2013). This proposes five strategic axes for waters of Chile: (i) efficient and sustainable management, (ii) better institutionalism, (iii) face shortages, (iv) social equity: rural drinking water coverage, and (v) An informed citizenship. However, water resources research was not considered among its strategic axes, but a brief mention was made of the need for studies aimed at updating water balances, basin plans and methods of artificial infiltration of aquifers (MOP 2013).

Subsequently, he highlighted the National Policy for Water Resources, issued in January 2015, based on the collection of information generated by the Presidential Delegation for Water Resources (Ministry of Interior and Public Security 2015). In this case, and unlike the previous one, mention was made of the need for Research and Development (R&D) in water matters within its proposals, however, it was tackled tangentially.

Among the main references to the area of water resources research, he highlighted the need to develop a national agreement on research between the public and private sector, which was reflected in: "research between the public and private sector, including universities, technology centers, organizations of water, among others, to support and collaborate in the development of new information and technologies associated with water matters" (Ministry of Interior and Public Security 2015).

On the other hand, emphasis was placed on the creation of a permanent national fund, which allows financing competitive research projects: "aimed at combating water imbalance, promoting new technological initiatives to combat desertification, drought, the generation of new alternatives of water supply sources, as well as for obtaining relevant information on the topics of hydrological processes in the mountain range, accumulation and melting of snow and glaciers, fractured underground water systems, aquifer recharge and their characteristics, among others" (Ministry of Interior and Public Security 2015).

Finally, the promotion of special resources that allow the development of R + D + I, at the regional level, was proposed: "the permanent implementation of special resources focused on applied research, development and innovation (R + D + I) of resources will be promoted water, associated with transfer programs" (Ministry of Interior and Public Security 2015).

In spite of the foregoing, these public policy instruments have not necessarily translated into a clear focus on the priorities of the State of Chile, regarding research on water resources.

Despite this, and as noted in the research challenges section, there has historically been an underlying effort of publicly funded research funds to address the main research gaps, detected and declared by researchers and stakeholders. This was evidenced, by observing periodic changes in water challenges, and also in the considerable number of researches focused on these challenges per year, to fill the gaps identified.

In spite of this achievement, a general and clear guideline, emanating from the State of Chile, that allows to direct with greater force, the focus of the investigations that are developed through the fiscal contributions is required.

We believe that, eventually, the new Ministry of Science and Technology, could be a fundamental pillar that will guide the country's research efforts, and among them, the water resources that are strategic for the country.

21.3.2.2 Public Funds

A deep review of data obtained from regional governments, ministries, directions, services, state agencies and others, about the contribution in research and development (R + D) in water resources in Chile, for the 2000–2018 period, was performed. For that, the Transparence Law (20.285) and the annual memories of the organisms managing the diverse funds were used (CONAPHI-Chile 2016).

The work focused in the funds financing scientific research, such as the available in the Technological and Scientific Investigation National Commission (CONICYT) and the Agricultural Innovation Foundation (FIA); as well as the regional and national competitive funds like: the Innovation Fund for Competitiveness (FIC) and the National Fund of Regional Development (FNDR); and other sources of financing and/or guided studies, emanated from diverse public organisms (ministries, services, directions or agencies) with competence in water topics (CONAPHI-Chile 2016).

With the obtained information, it was generated a matrix that classified the data in function of the financing fund; the amounts involved in the studies and initiatives (expressed in Chilean pesos of 2018 value, Azqueta 2002); the execution time; and the research area in which the study is categorized, such as: hydraulics, hydrogeology, efficient water uses and water treatment (CONAPHI-Chile 2016). Then, there was a differentiation between researches, in function of the type of financing fund, as well as the objectives addressed by every study. Then, the ones generating direct R + D were identified (studies financed by different instruments, whose primary objective is research and development generation), as well as the studies emanating from institutions funds like CONICYT, FIA and funds like regional FIC; and those that generated indirect R + D (studies financed by different instruments, whose objective is giving solution to a specific problem, from which is derived in research and development generation.), that were related to general and periodic consultancies of the different state organisms, as well as local funds like FNDR (CONAPHI-Chile 2016).

Finally, once data is systemized, a general analysis of the funds was made, including: (i) number of investigations per year by fund; (ii) annual contribution of every fund in research about water resources, mean contributions and duration; and (iii) the comparison between annual contribution for research about water resources in Chile with National PIB of every year in the 2000–2018 period (CONAPHI-Chile 2016) (Table 21.4).

Table 21.4 Breakdown of funds that finance scientific research and considered periods for the study

Fund type	Agencies	Considered period
Funds financing scientific research	CONICYT	2000–2018
	FIA	2000–2018
Competitive funds of regional governments	FIC	2009–2018[a]
	FNDR	2000–2018
Other financing and/or consulting sources of organisms with competence in water resources	Ministries	2000–2018
	Services	2000–2018
	Directorates	2000–2018
	Agencies	2000–2018
	Superintendencies	2000–2018

[a]Innovation Funds for Competitiveness started since 2009

21.3.2.3 Number of Investigations Contributed by Fund for the 2000–2018 Period

Overall an analysis of 635 data samples was made, corresponding to research about water resources in Chile, financed by state funds coming from different financial funds. These, related mostly (64,17%) to research and development (R + D), while the remaining (35,83%) where consultancies that gave R + D contributions as a result (indirect R + D; Table 21.5).

The highest frequency of contributing founds in research were made through CONICYT that represented a 42,83% of the total of analyzed data, and to a lesser extent FIA with a 5,04% of the total (Table 21.5).

Regarding the number of investigations per year, it can be appreciated that 2011 presented the greatest number of investigations (79), mainly by effect of the consultancies and public organisms' investigations and the contributions of EIC. On the other hand, the year with the least research development in water matter was 2003 with only 8 studies (Table 21.5).

Table 21.5 Number of investigations per year by fund

Year	Considered fund or financing source					Researches per year
	CONICYT[a]	FIA	FIC	FNDR	Consultancies and research of public agencies	
2000	6	1	0	2	3	12
2001	13	0	0	8	4	25
2002	7	2	0	1	3	13
2003	3	0	0	3	2	8
2004	18	0	0	4	3	25
2005	10	2	0	5	3	20
2006	16	0	0	6	5	27
2007	28	1	0	9	10	48
2008	31	1	0	12	8	52
2009	24	2	2	9	3	40
2010	20	3	2	6	19	50
2011	16	5	20	10	28	79
2012	5	6	12	3	29	55
2013	8	4	11	1	2	26
2014	1	1	6	0	2	10
2015	12	2	28	0	4	46
2016	21	1	4	0	3	29
2017	20	1	19	0	9	49
2018	13	0	1	0	7	21
Total	272	32	105	79	147	635
%	42,83	5,04	16,54	12,44	23,15	100,00
Type	Direct R + D (64,17%)			Indirect R + D (35,83%)		100,00

[a]Some data for CONICYT has been obtained from: CONICYT 2004, 2005, 2007a, 2007b, 2008, 2009, 2010, 2011. Remaining data was obtained through Transparency Law 20.285

Finally, if trend in time is analyzed of the total annual number of studies, or the number of studies by financing fund, a trend to increase is observed, with a high degree of interannual variability (Table 21.5; Fig. 21.1).

21.3.2.4 Annual Contribution of Every Research Fund, Mean Contribution and Duration

In the 2000–2018 period, the State of Chile contributed $74.452.133.225 for the development of research in water resources. The contribution varied through time, presenting years with less financing like 2003, and other with high level of contribution like 2011. CONICYT was the organism with the highest contribution with $27.378.272.264, representing 36,77% of the total. The smaller contributed amount was given by FIA with $5.438.157.752 in the same period, representing the 7,30% (Table 21.6; Fig. 21.2). When decomposing the amount, it was obtained that a 67,29% equivalent to $50.106.295.047 was used to finance research and development (I + D); while the remaining 37,58% equivalent to $27.976.504.260, were consultancies giving indirect I + D contributions as a result (Table 21.6).

In the 2000–2018 time series, CONICYT was who with the highest frequency granted the maximum annual funds (7), followed by FIC (5), FNDR (4), and finally consultancies and public agencies research (2). It is noted that the FIA fund did not contributed with the annual maximum in any of the 18 years, which is explained by the orientation of such fund (Table 21.6; Fig. 21.2).

The historical analysis indicated that CONICYT financed 272 investigations in total, with an average amount of $66.563.180 (± 66.447.211), a minimum of

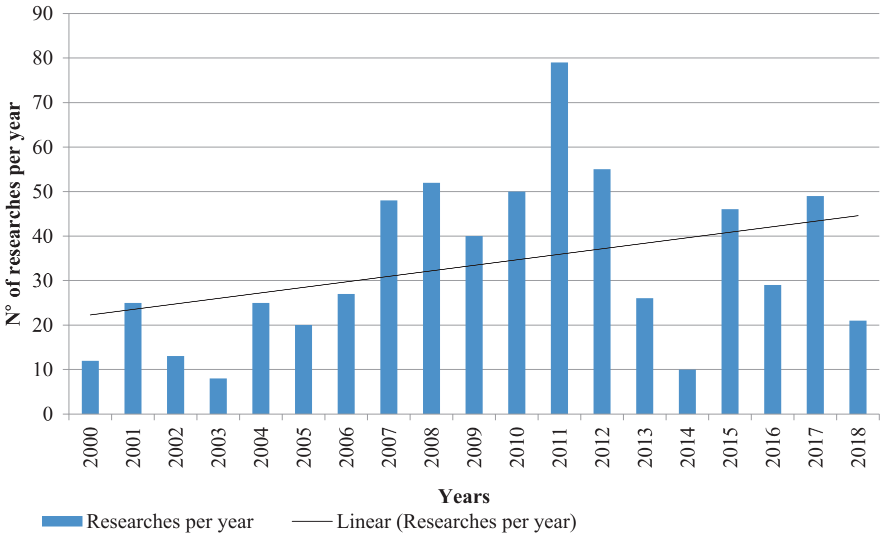

Fig. 21.1 Trend in time of the number of investigations in water resources

Table 21.6 Amounts contributed by every fond for research in water resources in CLP$ of 2018

	Fund					
Year	CONICYT	FIA	FIC	FNDR	Consultancies and research of public agencies	Dedicated funds per year
2000	1.917.002.718	271.884.205	0	74.180.530	666.369.440	2.929.436.893
2001	2.708.482.422	0	0	817.069.021	880.940.617	4.406.492.060
2002	1.802.140.727	313.140.932	0	294.053.329	259.115.872	2.668.450.859
2003	163.955.736	0	0	489.813.357	222.879.912	876.649.004
2004	1.460.123.427	0	0	518.461.452	870.842.777	2.849.427.656
2005	309.816.361	287.749.591	0	814.575.967	123.614.659	1.535.756.579
2006	755.526.862	0	0	782.847.050	625.547.675	2.163.921.587
2007	3.394.128.621	94.914.928	0	677.212.158	1.106.707.602	5.272.963.309
2008	1.554.015.252	250.718.678	0	1.576.480.183	2.230.803.459	5.612.017.572
2009	1.905.857.287	137.016.744	69.238.227	1.981.044.038	693.909.934	4.787.066.229
2010	1.126.105.753	699.565.421	350.536.601	297.747.125	1.129.269.833	3.603.224.734
2011	928.014.031	1.303.567.906	4.361.585.830	2.553.540.143	1.596.570.950	10.743.278.861
2012	815.814.456	1.015.367.217	2.401.425.192	2.523.545.501	3.410.052.517	10.166.204.882
2013	1.464.944.121	634.843.712	2.380.628.122	191.761.387	219.633.595	4.891.810.937
2014	53.110.335	189.319.482	1.517.031.452	0	0	1.759.461.269
2015	1.221.668.392	103.562.414	5.408.978.203	0	117.816.538	6.852.025.547
2016	2.166.899.679	136.506.524	800.441.404	0	230.097.639	3.333.945.246
2017	2.104.043.082	95.400.000	3.546.033.341	0	158.362.092	5.903.838.516
2018	1.526.623.000	0	192.480.000	0	264.603.076	1.983.706.076
Total	27.378.272.264	5.438.157.752	17.289.865.031	13.592.331.239	14.384.173.021	74.452.133.225
%	36,77	7,30	23,22	18,26	19,32	100,00
Tipo	Direct R + D (67,29%)			Indirect R + D (37,58%)		100,00

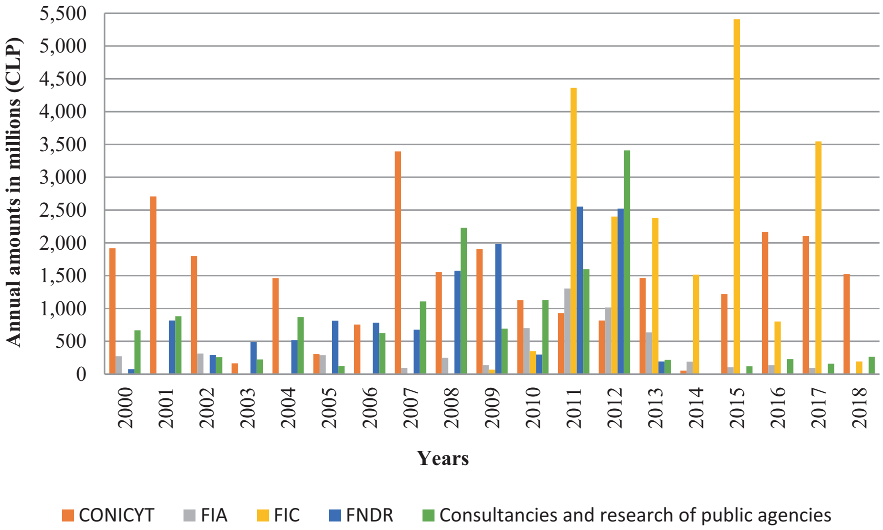

Fig. 21.2 Evolution of annual amounts contributed by every fund

$1.350.000 and a maximum of $551.100.000. The investigations of this organisms were characterized by an average duration of 3,00 years (±0,97), a minimum of 1,00 years and a maximum of 6,00 years.

On the other hand, the FIA financed 32 investigations, with an average contribution of $111.530.597 (±74.026.669). It is noted in contrast to CONICYT, that the minimum is $11.100.000 and the maximum is just $383.870.000. The average duration was 3,00 years (±1,02), with a minimum of 1,00 years and a maximum of 6,00 years.

For their part, investigations produced from the FIC were in total 105 with an average contribution of $158.350.175 (±116.009.678); being $18.982.000 the minimum and $768.000.000 the maximum. The average time of these investigations is 2,00 years (±1,14), while like in previous cases, the minimum was 1,00 years and the maximum 5,00 years.

In the case of FNDR some particularities were observed. It is noted, that this fund financed a total of 79 investigations, with an average amount of $99.579.794 (±202.623.480). Regarding the minimum, this was $176.000, while the maximum was $1.500.000.000, constituting both as extreme values of all funds. The investigations of this fund were characterized by an average duration of 2,00 years (±1,03), a minimum of 1,00 years and a maximum of 5,00 years.

Finally, consultancies and public agencies research, financed 147 investigations with an average amount of $72.819.896 (±90.911.284), with a minimum of $185.000 and a maximum of $550.000.000. Regarding time characteristics, the investigations of these financing funds were 2,00 years (±1,31) in average, a minimum of 1,00 years and a maximum of 6,00 years.

21.3.2.5 Comparison Between Annual Contributions and National PIB for the 2000–2018 Period

The data analysis indicated that the trend of contributions made by the State to finance research in water resources matter in the last 18 years represented a 0,0030% of PIB. When disaggregating the amount, the direct research, the investigations of direct R + D, represented 0,0022% on average; while investigations of indirect R + D, was 0,0010% of PIB on average (Table 21.7; Fig. 21.3).

However, the contribution varied through time. In the 2000–2003 period, State contribution for investigations in water resources, had a trend to decrease, which coincided with the smallest number and assigned amounts in research during such year. However, such decrease does not align with the PIB behavior, which was observed in a discrete increase. On the contrary, in the 2004–2009 period it was observed an increase trend of funds destined to research in water resources, just as the PIB. Finally, in the 2010–2018 period, it was observed an stable trend of research funds of direct R + D, while indirect R + D funds and PIB presented a decrease trend (Table 21.7; Fig. 21.3).

The latter implied a non-symmetrical relationship between PIB growth and funds variations destined to water research per year. Thus, a positive but weak correlation between annual PIB and total funds destined to research per year existed, reaching 0,4512. While, when disaggregating data, a correlation between PIB, and direct R + D funds and indirect R + D funds was observed, which was 0,1821and 0,5439, respectively.

Then, the granted PIB percentage was analyzed (Total PIB %) for research in water resources and the total number of investigations per year (Tables 21.5 and 21.7). This relationship obtains a determination coefficient of 0,6660, based on a linear adjustment of data (Fig. 21.4).

In other words, the relationship indicated that, if 0,0010% of annual PIB is granted in research funds, it would be expected to obtain at lease 15,28 ≈ 15 investigations associated to water resources, per year. Of the latter, 10 would be direct R + D (64,17%) following the observed trend in the last 18 years (Table 21.6; Fig. 21.4).

21.3.2.6 Topics and Research Areas

The data collected from different funds that finance water resources research in Chile, was classified in different work areas. The defined areas follow the example made by CONAPHI-Chile (2016): Awareness/Diffusion, Hydraulics, Hydrogeology, Hydrology, Water use optimization/Efficient use, Water treatment/Pollution and Socioeconomic assessment. In the 2000–2018 period, the research mainly focused on water treatment/pollution with a 32,91%, followed by water use optimization/efficient use with 24,57%, hydrology with 20,16%, hydrogeology 14,33%, hydraulics with just 3,78%, followed by awareness/diffusion with 2,20%, and finally, socioeconomic assessment with 2,05%. Particularly, CONICYT stood out by an

Table 21.7 Dispersed contribution in research over water resources compared with annual PIB

		Direct R + D		Indirect R + D		Total	
Year	PIB[a]	Amount	% PIB	Amount	% PIB	Amount	% PIB
2000	115.815.721.663.628	2.188.886.923	0,0022	740.549.970	0,0006	2.929.436.893	0,0025
2001	117.234.580.966.279	2.708.482.422	0,0022	1.698.009.638	0,0014	4.406.492.060	0,0038
2002	117.724.538.290.862	2.115.281.659	0,0022	553.169.200	0,0005	2.668.450.859	0,0023
2003	122.599.325.497.858	163.955.736	0,0022	712.693.269	0,0006	876.649.004	0,0007
2004	131.817.960.383.085	1.460.123.427	0,0022	1.389.304.228	0,0011	2.849.427.656	0,0022
2005	141.184.058.620.806	597.565.953	0,0022	938.190.626	0,0007	1.535.756.579	0,0011
2006	156.610.412.440.325	755.526.862	0,0022	1.408.394.725	0,0009	2.163.921.587	0,0014
2007	162.968.502.217.622	3.489.043.549	0,0022	1.783.919.760	0,0011	5.272.963.309	0,0032
2008	168.067.352.847.510	1.804.733.930	0,0022	3.807.283.642	0,0023	5.612.017.572	0,0033
2009	156.910.800.960.862	2.112.112.257	0,0022	2.674.953.972	0,0017	4.787.066.229	0,0031
2010	157.051.732.641.586	2.176.207.776	0,0022	1.427.016.959	0,0009	3.603.224.734	0,0023
2011	157.034.289.026.951	6.593.167.767	0,0022	4.150.111.093	0,0026	10.743.278.861	0,0068
2012	155.683.603.129.829	4.232.606.865	0,0022	5.933.598.017	0,0038	10.166.204.882	0,0065
2013	152.587.567.644.360	4.480.415.955	0,0022	411.394.983	0,0003	4.891.810.937	0,0032
2014	146.983.679.334.163	1.759.461.269	0,0022	0	0,0000	1.759.461.269	0,0012
2015	141.165.451.288.760	6.734.209.009	0,0022	117.816.538	0,0001	6.852.025.547	0,0049
2016	134.906.228.448.598	3.103.847.606	0,0022	230.097.639	0,0002	3.333.945.246	0,0025
2017	129.179.077.240.874	5.745.476.424	0,0022	158.362.092	0,0001	5.903.838.516	0,0046
2018	122.232.655.162.827	1.719.103.000	0,0022	264.603.076	0,0002	1.983.706.076	0,0016
Total	2.687.757.537.806.790	53.940.208.389	0,0426	28.399.469.428	0,0190	82.339.677.817	0,0571
Mean	141.460.923.042.462	2.838.958.336	0,0022	1.494.708.917	0,0010	4.333.667.254	0,0030

[a]Data obtained between 2000 and 2015 from: Central Bank 2006, 2007, 2008, 2011, 2012, 2013, 2014, 2015. Values between 2016 and 2017 were estimated according to PIB growth with respect to the last reported year (2015)

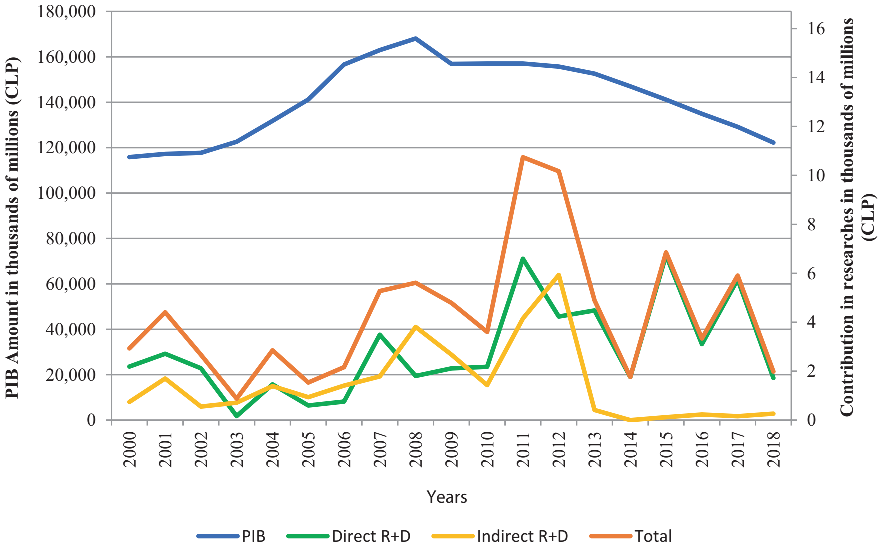

Fig. 21.3 Trend to disperse contribution in research about water resources compared to annual PIB

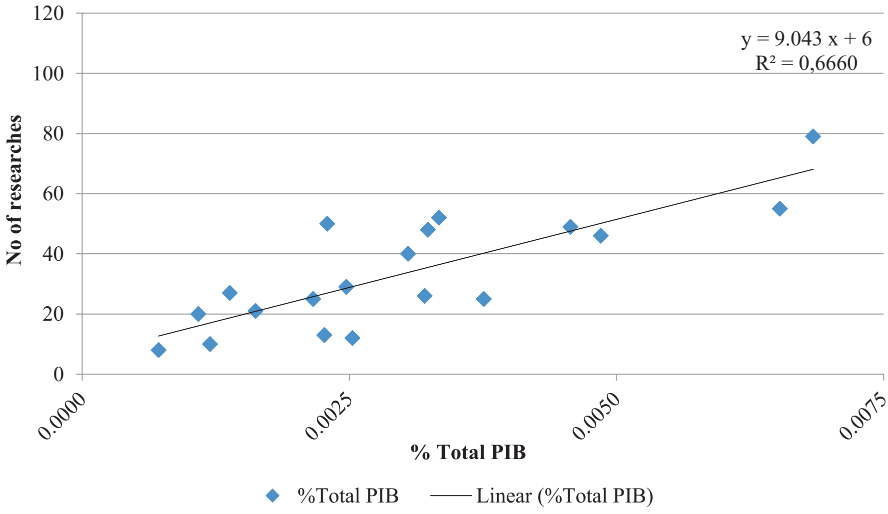

Fig. 21.4 PIB percentage (Total PIB%) and number of investigations in water topics per year

orientation to the studies financing associated to the water treatment and their decontamination, representing 143 investigations (48,15%); while socioeconomic assessment to a lesser extent, with only 2 investigations in 18 years, representing 0,67%. While, the FIA focused its contributions just in water use optimization/efficient use and water treatment/pollution, with 21 (65,63%) and 11 (34,38%) investigations, respectively (Fig. 21.5).While, the FIC focused its financing in the

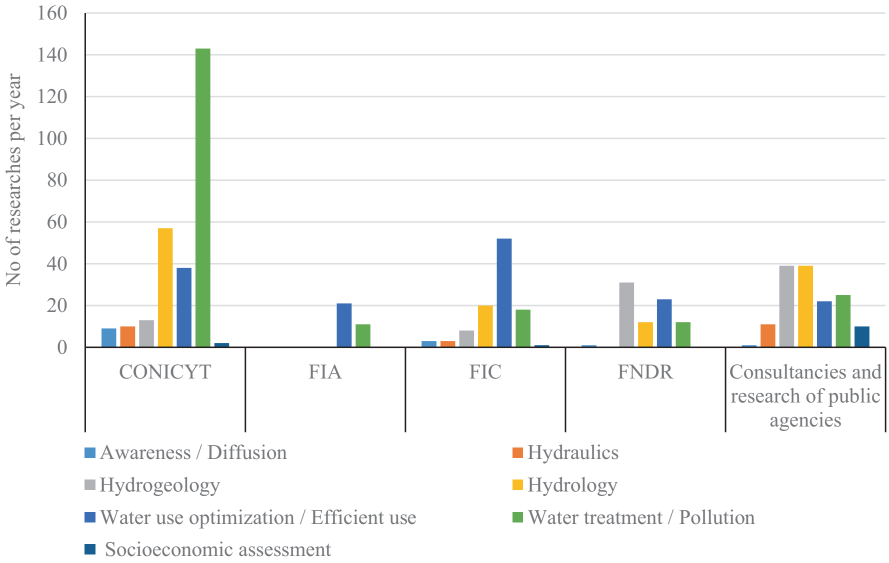

Fig. 21.5 Distribution of investigations in water resources according to the studio area, differentiated according to the fund

optimization of water use/efficient use with 49,52%, followed by hydrogeology with 19,05%. On the contrary the FNDR stood out by not presenting research in hydraulics, nor in socioeconomic assessment (Fig. 21.5). Finally, research emanated from consultancies and public agencies investigations, focused their financing in hydrogeology and hydrology, with 39 investigations each one (23,64%), followed by water treatment/decontamination with 25 investigations (15,15%; Fig. 21.5).

21.4 Conclusions

When comparing three moments in time, 1999, 2005 and 2016, it is evidenced a change in the detection of the main water challenges for Chile. When analyzing the change between 2005 and 2016, an evolution was observed from a clear anthropocentric and productivity vision from 2005, to a broader vision of 2016, both in environmental and social terms. However, the change in priorities, answered to the overcoming of old challenges because of the significant contribution of water resources research, as well as the regulations development.

Nowadays, and because of the water resources supply and demand scenarios of water resources, the economic, population and climate change effects growths; the challenges have evolved to “physical water shortage”, the “efficient water use”, the “water management” and the “underground waters development”, like the first priority ones (*cluster* a) for the future of Chile. In a condition of intermediate priority (*cluster* ab), there are recognized new challenges such as "desalination" and "conducting and storage". While, "environment and pollution" challenges, as well as "water supply and sanitation", are in second order of priority (*cluster* b), because of the advance and development of these matters in the previous period, allowing to address such challenges in a better way.

While, the specialist's perception about the efforts to solve the challenges/water problems turned negative between 2005 and 2016. However, Universities are still recognized as the best perceived organisms in terms of efforts in the search of answers and solutions to the water challenges of the country. The above because of the research generation and the development of diverse topics, water resources included.

The water resources research in Chile, mostly depends on the state contribution. This is obtained from different sources, such as national competitive funds, regionals ones, or through bidding from different agencies of the state. In the 2000–2018 period, the State of Chile through different institutional funds, has contributed for research in water matter in a total of $74.452.133.225. The contribution varies annually and by fund, being CONICYT the organism with the greatest contribution with 36,77% of the total. When decomposing the amount, it is obtained that $50.106.295.047 (67,29%) were used to finance research and direct development; while the remaining 37,58% consisted of studies that gave as a result indirect R + D contributions.

Definitely, it follows that the annual contribution of the State of Chile for research in water resources is $4.136.229.624 (±$2.636.432.330). Regarding the PIB, the trend of the contributions made by the State to finance research in water resources matter in the last 18 years represented a 0,0030% of the PIB on average. When disaggregating the amount, the direct R + D research, accounted for a 0,0022% on average; while the indirect R + D research, was 0,0010% of the PIB on average.

The $74.452.133.225 granted by the State of Chile, must be considered as a minimum value, given that the public agencies also make a series of non-tendered research, then, that does not record contributions or transfer of funds, and that also are not made by plant personnel. In the same way, the Universities also generate research in the area, through autonomous resources or through international funds, which neither have achieved to be considered by not counting with a system of contributions recording or accessible transfers of public funds.

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Chapter 22
Challenges for the Future

Bonifacio Fernández, Magdalena Barros, and Jorge Gironás

Abstract Water-related challenges involve aspects of scientific hydrology and water resources management. We studied research projects funded by the State of Chile through different institutional funds in the last 20 years to identify scientific challenges for hydrology in Chile, which are mainly related to the understanding of the water cycle and infrastructure design. Then, the recent evolution of the challenges in hydrology and water resources are analyzed, as they have been faced by several research, innovation, and development centers recently created. We also present the challenges in water resources management identified by many of these research centers and institutions, which deal mainly with eco- and socio-hydrological issues and integrated water resources management. Finally, some challenges related with water resources policy in Chile are commented as well.

Keywords Challenges · Future · Scientific hydrology · Water cycle · Infrastructure · Research · Ecohydrology · Integrated water resources management · Social hydrology

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22.1 Introduction

Today, the great challenge for hydrology worldwide is to provide the necessary information so that in the future water resource systems will be able to supply the growing demands of humanity for water in a sustainable manner, conserving the value of natural environments (James et al. 2017). Chile is not unaware of this situation, considering its very particular geographical and climatic situation, and the development conditions necessary to improve the quality of life of the population. This challenge involves aspects of scientific hydrology and water resources management. The effects of population increase and growth, of climate change, and of new technologies must be anticipated. All this requires better knowledge of hydrological systems, extreme events, current and emerging pollutants, and the interaction between human activity and the natural environment.

In the second edition of the Handbook of Applied Hydrology (Singh 2017), several authors present different challenges that hydrology will face in the future. Among them, O'Donnell and O'Connell (2017) mention the need to incorporate in the modeling of hydrological systems the impacts of human activity, not only as externalities or needs, but also including interactions, to understand how human activity interacts with aquatic environments and model this mutual dynamic feedback. He et al. (2017) address the variability of hydrological processes and systems in a changing environment. The sustainability of hydrological systems requires consideration of its important relationship with climate change, population growth, socioeconomic development, and the environment. This includes, in addition to quantitative aspects to support human, industrial and environmental needs, institutional recommendations for planning, management and conflict resolution. Mohtar et al. (2017) indicate that water security as an integral element of economic and social security requires new thinking to address a changing and increasingly demanding environment. They suggest a revision of the concept of "water security" to include not only aspects of current and projected availability of surface and groundwater resources, but also how lack of access to water threatens human, economic and social development and well-being. Rahman (2017) presents the idea of social hydrology as the evolution of water resources management. He raises the question of whether hydraulic engineers, scientists, hydrologists, and planners are making sufficient efforts to make water a sustainable resource for current and future generations. In addition to the mathematical capabilities available to solve water-related problems, there are lessons to be learned in the context of social impacts and how to play a relevant role in connecting people to water in order to achieve sustainable uses at all levels of society. At the global level, James et al. (2017) point out that to address future needs and reduce losses, in view of increasing uncertainties, knowledge needs to be built at least on the following aspects: (a) changes in the hydrological cycle, (b) related meteorological, geochemical, ecological and hydraulic processes, and (c) interaction between natural and built systems. They propose, as a strategy to face scarcity, to reduce fresh water withdrawals, to leave more water in channels and aquifers and to reduce treatment costs. Most of these challenges are also those of hydrology in Chile at the beginning of the twenty-first century.

22.2 Scientific Challenges for Hydrology in Chile

A review of the research projects funded by FONDECYT (https://www.conicyt.cl/documentos-y-estadisticas/estadisticas/estadisticas-por-programas/) in recent years shows how several of these challenges are being addressed, and where further efforts are needed. The scientific challenges of hydrology in Chile and their relation to recent research projects are analyzed below.

22.2.1 The Challenges of the Water Cycle

Hydrology faces significant challenges in understanding the changes taking place in the hydrological cycle and its components, so as to have accurate information on future behavior. James et al. (2017) make a review of the main components of the hydrological cycle and the aspects on which scientific attention should be focused. In Chile many of these challenges are evident if we analyze each of the main components of the hydrological cycle. To this end, Table 22.1 presents the research projects financed by Fondecyt between 2000 and 2014, classified according to the components of the hydrological cycle that they address.

Atmosphere Knowledge of the transport, mixing and deposition of water vapor in the atmosphere must be increased to move from simple correlations between global phenomena, greenhouse gas emissions and global temperature, in order to explain and predict the impact of climate change on hydrology. In Chile this is fundamental to advance in the explanation and prediction of the effect of the Amazonian climate on the resources of the Altiplano zone, (Segura et al. 2019), the behavior of the fronts in the central and southern zone and its effect on droughts and floods, (Garreaud et al. 2013, 2019, 2020), and storm phenomena in the north, (Bozkurt et al. 2015, 2016; Wilcox et al. 2016) and the rest of the country, (Vicuña et al. 2013).

Precipitation In spite of having a lot of information on precipitation, both in volume and intensity, there is a clear deficit in mountain areas, (Barrios et al. 2018). In Chile, there are practically no records for 2000 m above sea level, except for what occurs in the altiplano. In addition, there is a lack of information to model liquid and snow precipitation in areas of complex relief and on glaciers, (Vásquez et al. 2013; Stehr et al. 2009; Vásquez et al. 2015; Yáñez-Morroni et al. 2018; Pereira-Claren et al. 2019). Only a few experiments have been carried out to estimate precipitation by radar (Massmann et al. 2017) or remote sensing (Castro et al. 2014), as well as in the occurrence of floods and alluviums (Sarricolea et al. 2013).

Runoff The usual practice of estimating the frequency of extreme events, floods or droughts, based on the statistical distribution of observed events is giving poor results in the face of new conditions of climate change (Munoz et al. 2013, 2014; Castro et al. 2019). Another problem occurs with the estimation of flood zones in

Table 22.1 FONDECYT projects between 2000 and 2014 in topics related to the challenges of the hydrological cycle. Numbers assigned to the projects are given to facilitate revisions

Atmosphere
Forced downslope flow over the Andes in central Chile, 2000. 1000913.
Characteristics of the sporadic layers of the ionosphere on the Antarctic peninsula, 2001. 1010218.
The stratocumulus cloud deck off the subtropical west coast of south America: high frequency variability. 2002. 1020833.
Cut-off lows in western subtropical south America: climatology, associated mechanisms and their impacts on rainfall, 2003. 1030757.
Theoretical study of the atmospheric dust devil, 2006. 1061002.
The southern westerly winds in NW and SW Patagonia during and since the last glacial maximum: regional and global implications, 2007. 1070991.
Field study of atmospheric dust devils in the northern Chile, 2008. 1085095.
Dynamics of the atmospheric marine boundary layer off subtropical Chile, 2009. 1090412.
Tropical and mid-latitude climate changes over the last 17,000 years: paleoclimate modelling from the central and southern Andes, 2009. 1090588.
High resolution hydroclimate variability in the central Andes of Chile and Argentina during the last millennium: a tree-ring and modelling perspective, 2012. 1121106.
Dynamics of cloud transitions of an arid coastal atmospheric boundary layer, 2013. 1130111.
Extreme droughts in central of Chile. 2014, 1140637.
Mechanisms of orographic modification of precipitation during wintertime rainfall episodes in central Chile, 2004. 3040070.
Climatic regionalization and physical modeling of the cryosphere over Chile's Norte Chico region, 2007. 3070056.
Synoptic influence on the subtropical marine boundary layer in the southeast pacific: the symbol experiment, 2011. 3110100.
Rainfall response to climate change in Chile: a statistical downscaling approach, 2011. 3110120.
The role of the North Atlantic subtropical high on the recent variability of the American monsoon systems and its projections, 2014. 3140570.
The southern westerly winds in NW and SW Patagonia during and since the last glacial maximum: regional and global implications, 2010. 7100006.
A similarity coefficient for spatial and temporal processes, 2007. 11075095.
Long-term aridity changes in the south American altiplano reconstructed by the world's highest-elevation tree-rings, 2008. 11080169.
Thermodynamic characterization of the seasonal cycle of the south eastern pacific stratocumulus layer from multisatellite data and coupled models, 2010. 11100393.
Precipitation
On the interannual and interdecadal rainfall variability in south-central Chile (38o s-42.o s), 2001. 1010570.
The importance of fog and rain in ecosystems of fog oasis in the coastal desert of Tarapacá with special emphasis on vegetation and entomofauna, 2001. 1010801.
Extratropical source of interannual rainfall variability in Chile, 2008. 1080058.
Frontal modification by complex topography in south-central Chile, 2011. 1110169.
Influence of the precipitation interpolation method on predictive uncertainty of conceptual models of snowmelt runoff, 2011. 1110279.

(continued)

Table 22.1 (continued)

Combination of weather information and remotely sensed data to analyze the variability of water footprint indicators at a basin scale, 2012. 1120713.
Assessing the influence of precipitation on surface air temperature variability in South America and implications for climate change projections, 2014. 3140497.
Spatial configuration of rainfall irregularity in south-central Chile (29°s-44°s) and its relationship with synoptic types and low frequency variability patterns, 2013. 11130629.
Runoff
Influence of the pinus radiata forest on the production of water and the regime of the Purapel River VII region, 2001. 1010590.
Flow rate variability from instrumental records and growth rings in the eco-region of the Valdivian forests (35°–48° s) over the past 500–1000 years and its relation to climate change, 2005. 1050298.
Modeled and empirical regional paleoclimate variability in western Patagonia: glacial versus interglacial conditions, 2005. 1050416.
Glacial lake outburst floods in the Chilean Andes: measurements and modelling approach for early prediction, 2009. 1090752.
Operational framework for data sufficiency evaluation in distributed hydrologic modeling, 2006. 11060444.
Surface-hyporheic water interactions and riparian tree establishment in the Paloma river floodplain, Chilean Patagonia, 2008. 11080163.
Parameters determination of a Chilean native vegetation to implement the model soil-vegetation-atmosphere horas, 2011. 11110229.
Hydrological process dynamics in Andean basins. Identifying the driving forces, and implications in model predictability and climate change impact studies, 2012. 11121287.
Infiltration
Groundwater
Impact of salinity and groundwater fluctuations on moisture distribution and non-isothermal water fluxes in soils of arid zones, 2013. 1130522.
Mathematical modeling of solute transport in highly heterogeneous aquifers, 2011. 11110228.
Circulation in the ocean, lakes and water bodies
Turbulence and transport in the benthic boundary layer of lakes and estuaries experimentation, field study and modeling, 2004. 1040494.
Field, experimental and numerical study on mixing processes and internal waves in Coriolis affected lakes, 2008. 1080617.
The 2004 ecosystem regime shift of the Río Cruces wetland: testing the water depth hypothesis through numerical modeling and remote sensing analyses, 2011. 1110077.
Design, evaluation and application of spectral indices obtained from merged satellite images. An application to monitoring lentic ecosystems, 2006. 11060056
Legacy of a major volcanic events on river biogeochemistry and lake & coastal productivity: landscape limnology of the 1991 volcano Hudson eruption, 2011. 11110293.
Evapotranspiration
Determinación de evapotranspiración potencial (ETP) mediante información satelital a escala regional, 2004. 1040357.
Integrated model for estimating real evapotranspiration based on satellite images, atmospheric numerical models and surface observations, 2006. 1060544.

(continued)

Table 22.1 (continued)

Water yield, seasonal growth vegetation and transpiration rate of small headwater catchments in southern Chile, 2009. 1090345.
Transpiration, efficiency in water transport and tolerance to water stress in trees of the Chilean temperate forest: eco-physiological basis for efficient forest management and water production as an eco-systemic service, 2006. 11060404.
Development of a surface energy balance for modeling evapotranspiration of partially vegetated surfaces, 2010. 11100083.
Other processes related (erosion/sedimentation, hidrogeochemistry, hydrological an ecological processes)
Interaction of biotic and abiotic factors associated with the design and operation of wastewater treatment using activated sludge, 2004. 1040949.
Large woody debris in mountain basins: volume and effect on riverbed morphology, 2008. 1080249.
Use of environmental radionuclides to identify and quantify fine sediment sources in forested catchments, 2009. 1090574.
Channel dynamics of gravel bed river in Chile for a sustainable river management, 2009. 1090774.
Evaluation of the native Chilean riparian vegetation as a filter for agricultural diffuse pollution: nutrient uptake, sediment removal, and denitrification, 2011. 1110156.
Ecohydrological controls on nutrient export from forested headwater catchments in southern Chile, 2012. 1120188.
Sediment dynamics and management in small Andean catchments, 2013. 1130378.
Precipitation-runoff relations, soil loss, and sediment characteristics at field boundaries in central Chile: an integrated model for conservation planning, 2013. 1130928.
Chemical-hydrodynamic control of the partition of metals at river confluences: the case of cu, zn and as in Andean rivers, 2013. 1130936.
Multiscale physical processes in river restoration: hydrodynamic interactions with sediment transport and water quality, 2013. 1130940.
The sulfide diffusive exchange technology applied to wetlands for treatment of toxic acid mine drainage, 2014. 1140451.
Influence of anthropic, natural and biological spatial factors on the population structure of the gastropod c. Dombeyana in the Biobío river basin: an analysis from landscape genetics, 2014. 3140561.
Use of indicators of erosivity and erodibility to determine vulnerability to water erosion in the south-central zone of Chile, 2007. 11075057.
Advanced numerical modeling of sediment transport and scour around bridge foundations, 2008. 11080032.
Development of a model for forecast the soil depth movement and leaching of pesticides under agricultural conditions, 2008. 11085003.
Narrow buffer strips as mitigation measure to reduce nitrogen losses from corn fields: nitrogen budget and modelling nitrogen dynamics, 2011. 11110464.

Source: https://www.conicyt.cl/documentos-y-estadisticas/estadisticas/estadisticas-por-programas/

alluvial cones, urban settlements in riverbeds at the exit of mountains (Sanzana et al. 2017), and the hydraulic behavior of large amounts of debris and sediments that carry sudden floods or alluviums (Contreras Vargas and Escauriaza 2020; Mao et al. 2008; Meier et al. 2013).

Infiltration This is the main source of aquifer recharge. It depends on the characteristics of the soil and the properties of the precipitation. In this sense, large impermeable urban areas are affected by both infiltration and the characteristics of the floods that are generated in them, which requires a major change in the design of urban drainage (DOH MOP 2012). In agricultural areas, the most efficient irrigation systems, with low infiltration and controlled surpluses, are reducing aquifer recharge and recoveries, thereby reducing the resources available downstream. Despite the importance of the phenomenon, there is no research on it in recent FONDECYT projects.

Groundwater Groundwater constitutes a large part of the available resources, especially in northern and central Chile. However, a relevant consensus has not been reached on an integrated management of surface and groundwater resources and their protection, for which information is required on flows, quantities and qualities, in order to better understand recharge, movement of pollutants and better and more detailed control over extractions and discharges (Suárez et al. 2014). There has been a notorious advance in the hydrological modeling of the main aquifers by DGA, and partially in its relationship with the surface system, (DGA MOP et al. 2005; DGA MOP 2013, 2019), however, it has been complex to involve these models with an Integrated Water Resources Management System (Génova et al. 2019).

Circulation in the Ocean, Lakes and Water Bodies Hydrology must work together with scientists in oceanography, limnology and meteorology, to improve the knowledge and modeling of water quality and quantity and its chemical, biological properties in lakes, estuaries, coastlines, and water bodies in general (Niño and Miranda 2003; Niño et al. 2015).

Evapotranspiration Evapotranspiration from surfaces reduces runoff and decreases aquifer recharge. Natural vegetation cover is governed by sequences of precipitation and evapotranspiration (Sepúlveda et al. 2018a, b). In the large northern endorheic basins, evaporation from the salt flats accounts for most of the water demand (Hernández-López et al. 2016; Johnson et al. 2010; Kampf et al. 2005). Evaluation of evapotranspiration and its relationship with agricultural and environmental demands and its effect on the water balance of the basins is needed (DGA MOP 2017).

Other processes related to water flow that also deserve an updated analysis are sedimentation and erosion processes (Mao et al. 2013), geochemistry in natural basins (Leiva et al. 2014) and the cycling of numerous substances at different scales, biological and ecological processes, waste accumulation (Iroume-Arrau et al. 2017), and socio-economic phenomena.

22.2.2 *Scientific Challenges for Design*

James et al. (2017), further indicate that for the future use of water, and to resolve conflicts over the interaction between natural and built systems, there are significant challenges in infrastructure design. These include measures to match supply with demand, protection of fresh water sources, management of water rights and waste disposal.

The following, adapted to the Chilean situation and incorporating others specific to the country, are additional scientific challenges for hydrology, fundamentally oriented to the design of infrastructure: (a) The non-stationarity of hydrological processes requires careful use of statistics of past events to forecast future behavior, with more decisive support in physical hydrology to address statistical behavior. This is of special interest for extreme situations such as floods and droughts. (b) Explain the effect of climate change and its impacts on a small, downscaled scale, in order to be applied in the infrastructure design (Meza et al. 2015; Arumi-Ribera et al. 2011). (c) Evaluate the effects of abrupt changes caused by phenomena such as fires or large constructions (Bonilla et al. 2014; Carkovic et al. 2015). (d) Evaluation of environmental demands and ecological protection, for different realities. (e) Information on the occurrence and properties of rare storms and floods, (Gironás 2017; Contreras Vargas et al. 2018a, b). (f) Salinization of fresh water resources, whether by use in agricultural, municipal or industrial systems. (g) The hydrological cycle in urban areas, (Herrera et al. 2015; Gironás 2017). (h) The hydrological cycle in glaciers and snow (Vicuña et al. 2011; Gascoin et al. 2011; Jacquin-Sotomayor 2017; Gascoin et al. 2017). (k) Disposal of urban, agricultural and mining waste (tailings) (Bonilla Meléndez 1998, 1999; Kogan-Alterman and Herdener 2017). Table 22.2 shows the research projects developed through Fondecyt since 2000–2014 in relation to these topics.

22.3 Evolution of the Challenges of Hydrology and Water Resources

Rahman (2017), argues that in addition to the mathematical capabilities available to solve water-related problems, there are lessons to be learned in the context of the social impacts of water and how a greater role can be played in society by connecting people to water to achieve sustainable water use for their multiple needs.

The challenges of hydrology have evolved according to the needs of society and its vision of water as a fundamental element for human existence and for the natural systems of the planet. Chile has followed these trends, although some of them with a certain delay. Table 22.3 presents a summary of the hydrological challenges in the different stages according to Rahman (2017). The dates correspond rather to those indicated by this author, whose limits between stages are not necessarily applicable in Chile and may be temporarily diffuse.

Table 22.2 FONDECYT projects between 2000 and 2014 in topics related to scientific challenges for design. Numbers assigned to the projects are given to facilitate revisions

Experimental study of hydrological processes in Chilean urban areas at a residential/lot scale. 2013. 1131131.
A continuous urban stormwater model for quantifying the hydrologic response based on the morphologic characterization of the drainage system. 2009. 11090136.
Characterizing storage and its impact on hydrologic modeling in high elevation basins on the Andes cordillera between 30°s and 36°s. 2012. 1121184.
Modelling glacier meltwater production in the dry Andes. 2011. 3110053.
Possibilistic analysis of predictive uncertainty of watershed models with a snowmelt runoff component. 2007. 11070130.
From snowfall to streamflow: a modeling approach to assess the water budget of Norte Chico upper catchments. 2009. 11090445.
Snowmelt contribution to surface runoff and groundwater in Andean watersheds: monitoring and modelling. 2010. 11100119.
Understanding glacier response to climate change in Chile. 2013. 11130484.
Development of a technology for the removal of sulfate and organic matter from wastewater using anaerobic digestion. 2002. 1020201.
Dynamics and environmental fate of herbicides used in rice cultivation in Chile. 2007. 1070069.
Analysis and conceptual modeling of persistent organic compounds (pops) in rivers and groundwater in the province of Ñuble: an approach to risk assessment of intake in times of global water crisis.2012. 11121588.
Vulnerability of Mediterranean basins to global change: an assessment of the relevance of climate change, land use change and their synergies as driving forces acting in the Maipo basin. 2009. 1090393.
Water availability in a stressed Andean watershed in central Chile: vulnerability under climate variability. 2011. 1110298.

Source https://www.conicyt.cl/documentos-y-estadisticas/estadisticas/estadisticas-por-programas/

Table 22.3 Evolution of the challenges of hydrology and human resources management

Period (aprox.)	Challenges
1940 to 1970	Water Resources Development. Focused on large engineering projects, such as dams, irrigation, hydroelectricity, urban and industrial supply, flood control.
1970 to 1990	Water Resources Management. Oriented to the management of projects considering alternative options to avoid negative impacts on the environment.
1990 to 2000	Integrated Water Resources Management and Ecohydrology. Considering interrelated surface and groundwater, allocating costs and benefits. Environmental flows and the dynamics of aquatic systems are considered.
2000 to 2015	Social Hydrology. Man, as a dynamic agent in the hydrological cycle, learning from past mistakes and considering social aspects in water management.

Adapted from Rahman (2017)

Thus, initially, since 1940, the development of water resources is considered of as a way of responding to the need to supply large irrigation, hydroelectric, or urban development and industrial projects. At this time in Chile, the Ministry of Public

Works has played a fundamental role through the Directorate of Irrigation for agricultural development, and SENDOS for the supply of drinking water to large urban centers. In addition, together with CORFO, especially with ENDESA, they promote the construction of large reservoirs for irrigation and hydroelectricity. CORFO also encouraged the development of hydrogeology and the creation of companies to drill wells in the late 1960s, as a response to the great drought of that time that affected the central valley. Although ENDESA originally developed a comprehensive assessment of hydroelectric resources throughout Chile and the National Irrigation Commission did something similar with basins of agricultural potential, even today resources in extreme areas, small basins and aquifers, must be assessed for mining, agricultural, hydroelectric and rural water supply development.

From about 1970 onwards, new challenges appeared that focused on Water Resources Management by considering alternative options to reduce the negative impact of projects on the environment. In Chile this translates into a more active participation of the General Water Directorate (DGA) in the management of water resources, of the National Energy Commission (now the Ministry of Energy) in the management of the central interconnected system (SIC) for the operation of hydroelectric plants, with the formation of the CDEC (Centro de Despacho Económico de Carga, now the Coordinador Eléctrico Nacional, CEN), and a renewed concern for the characterization and management of droughts (Fernández 1997; Fernández and Vergara 1998; Fernández and Montt 2001). In 1981 the Water Code was modified to promote the productive use of the resource, irrigation efficiency was improved, and mining began intensive water reuse plans. In this aspect there are still pending challenges for the management of resources in the basins including the participation of users as well as planning of the territory in urban areas (Peña 2016; Donoso 2016).

According to Rahman (2017), since 1990 the challenge is to consider the relationships between surface and groundwater resources and their interrelationships in the basin, as well as to incorporate the costs and benefits of intervention, and consider the dynamics of aquatic systems, which translates into what is known as Ecohydrology and Integrated Water Resources Management. In these years it is agreed that water resource systems are part of an ecosystem and must be managed with greater intervention among those who have use rights, the state, civil society, farmers and other stakeholders. Progress is being made in modeling underground resources, mainly in the aquifers of the north and center of the country (Muñoz-Pardo et al. 2015; Muñoz et al. 2003; Vásquez et al. 2013), and efforts are being made for integrated resource management in several basins (DGA MOP et al. 2005; DGA MOP 2013, 2019), and the first advances in ecohydrology to establish the ecological flow in several basins in the allocation of surface resources, (DGA MOP 2009; énova and Olivares 2016), diffuse pollution in aquifers, (Bonilla Meléndez 1998, 1999) and in urban centers. Sanitary companies address the treatment of wastewater in cities and urban centers, so that the percentage of urban water treated goes from 20% in 1997 to 99.9% in 2016, considering the population connected to a sanitary service (SISS 2017).

Finally, following Rahman (2017), in the twenty-first century we face the challenges of the so-called Social Hydrology, considering human as a dynamic agent in the hydrological cycle, learning from the mistakes of the past and including the social aspects in water management. Sivapalan et al. (2012), indicate that the term "ecohydrology" was introduced to describe the relationship between water resource systems, landscape, hydrology and ecology. Later this concept evolved into social hydrology. In Chile, the General Law on the Basis of the Environment was enacted in 1994 and in 2010 the Ministry of the Environment was created. Environmental impact studies are required to have citizen participation in major water-related projects. As a point of inflection, in 2017, the companies Colbún and ENEL renounced definitively to carry out the hydroelectric development of hydroAysén, mainly due to the social pressure against the intervention in the basins of the Baker and Pascua rivers (Romero Toledo 2014).

22.3.1 Research, Innovation and Development Centers

In order to advance in research, innovation and development of water resources with a multidisciplinary perspective, and favoring collaboration, many specialized centers have been created that seek to respond to the challenges facing water resources in Chile. Many of them with the support of CONICYT through the Fund for Financing Research Centers in Priority Areas, FONDAP, (a program that aims to promote multidisciplinary work in groups of researchers in science, technology and social sciences in those thematic areas, where national science has reached a high level of development, has a significant number of researchers with proven productivity, and can make a significant contribution to problems relevant to the country), through the creation and consolidation of Centers of Excellence in Research. These centers aim to carry out research of excellence, promote associative research, train advanced human capital, establish national and international collaborative networks and disseminate the results to the scientific community and society. Recently 28 of these water-related centers and institutions have formed a collaboration network at national level.

Following are several of the active centers related to water resources. The objectives or stated mission reflecting the challenges that each has set for itself are shown.

- CAA. Water Center for Agriculture. University of Concepción. To gather the requirements of the different users of the O'Higgins region in terms of water resources, as well as to design, execute, and coordinate different initiatives to meet these requirements.
- CAZALAC. Regional Water Center for Arid and Semi-Arid Zones in Latin America and the Caribbean. UNESCO, Government of Belgium and University of La Serena. To strengthen the technical, social and educational development of the Latin American and Caribbean region based on improved water resources development and management in arid and semi-arid zones.
- BLIND. Center for Law and Water Management. Pontificia Universidad Católica de Chile. To develop research, continuing education and extension activities

related to the major principles and instruments constituting water regulatory frameworks.

- CEAZA. Center for Advanced Studies in Arid Zones of Coquimbo. To promote the scientific and technological development, through the accomplishment of advanced science at interdisciplinary level in arid zones, biological sciences and earth sciences, from the region of Coquimbo with a high impact in the territory and oriented to improve the quality of life of the people, promoting the citizen participation in science through activities of generation and transference of the knowledge.
- CEDEUS. Center for Sustainable Urban Development, Pontificia Universidad Católica de Chile and Universidad de Concepción. To understand urban dynamics, instruments and decision-making processes to develop sustained and equitable improvements in people's quality of life, through the recognition of biophysical limits and social demands in Chilean cities.
- CEITSAZA. Water Technology Research Center in the Desert. Northern Catholic University. Research and technological development for the sustainable and efficient management of water resources, mainly in arid zones, in an environmentally friendly way.
- CEQUA. Center for Quaternary Studies. Fire, Patagonia and Antarctica. Regional Government, CONICYT. To contribute to the generation of knowledge relevant to the ecosystems and natural resources of the southernmost region of Chile, which motivates the community to belong to its territory.
- CICITEM. Scientific and Technological Research Center for Mining. Catholic University of the North (UCN), University of Antofagasta (UA), Regional Government of Antofagasta and CONICYT. To support the innovation, development and sustainability of the mining industry and associated productive sectors, nationally and regionally, through high level scientific and technological research.
- CIDERH. Water Resources Research and Development Center. Arturo Prat University. To be a reference research center at regional, national and international level in sustainable and efficient management of water resources in arid zones
- CIGIDEN. Research Center for Integrated Management of Natural Disasters. A consortium of universities led by Pontificia Universidad Católica de Chile. To generate knowledge of excellence to prevent extreme events in nature from becoming disasters.
- GCC-PUC. Center for Global Change. Pontificia Universidad Católica de Chile. To be an interdisciplinary research center that promotes and gets involved in the necessary transformations in Chile and Latin America to respond to the challenges of global changes.
- ICHR. Water Resources Information Center. Directorate General for Water, MOP. Collects and makes available to users the water resources documentation available at the General Water Directorate.
- CR2. Climate and Resilience Science Center. University of Chile. It brings together researchers from different disciplines of natural and social sciences who study how climate change impacts on Chilean ecosystems and society and,

together with key actors, support the definition of adaptation and mitigation measures to build a society more resilient to climate change, and the country's transition to low-carbon development.
- CRHIAM. Water Resources Center for Agriculture and Mining. Universidad de Concepción. A multidisciplinary center of excellence in water resources to promote the sustainable use of water in two of the most important economic sectors for Chile: agriculture and mining.
- CTHA. Environmental Hydrology Technology Center. University of Talca. To generate strategic technical guidelines of an environmental and economic nature that allow for the sustainability of natural resource management, especially water and soil resources, providing engineering answers that allow for their concrete use in broad productive and social spectra, based on the application of known scientific methods and the generation of new methodological schemes.
- EULA. Environmental Science Center EULA. University of Concepción. Multi and interdisciplinary University Center of Environmental Sciences, oriented to the investigation, diffusion, permanent education and integral environmental advising for the public and private sector contributing with it, to the sustainable development of the region and the country.

22.3.2 Challenges for Water Resources Management

During the last few years, several institutions and interest groups have elaborated analyses of the water resources situation in Chile and indicated challenges that should be faced in order to advance in water management. Table 22.4 summarizes the challenges that are explicitly posed in several of these studies, classified according to what is indicated in Table 22.3. Many of the proposals made are similar and most of them are oriented towards Integrated Water Resources Management, or fall into what has been called Social Hydrology. There is an important consensus on several of the proposed initiatives, which are summarized below.

Water Resources Development
- Improve and expand the coverage of hydro-meteorological measurement and information systems, including water quality and hydro-biological indicators, involving other public institutions and users. In particular, measure water consumption and withdrawals by Water Rights owners, especially wells and withdrawals. Develop indicators for water risk management, regulate the demarcation of natural watercourses and the use of flood plains. Consider the spatial and temporal heterogeneity of water resources.
- Improve water management information systems with timely information. Online monitoring of flood and drought risks.
- To organize the water rights files with a complete and consistent record in the DGA and in the CBR (Conservador de Bienes Raíces), avoiding partial, double or absent registrations in order to regularize all the rights in each basin.

Table 22.4 Recommendations for the management of water resources from various documents

Document	Development of WRR	Management of WRR	Integrated Management and Ecohydrology	Social hydrology
	WRR estimation for the development of large engineering projects (irrigation, hydroelectricity, sanitation, mining, flood protection, hydraulic structures…)	Management and mitigation of impacts (management of reservoirs, droughts, floods,…)	Consider surface and ground water and dynamics of aquatic systems (biology, quality,…)	Social aspects. Human as a dynamic agent
GWP.2004. Hacia un plan Nacional de Gestión de Recursos Hídricos	Improve the transparency and the access to relevant information regarding hydrogeology, exploitation and vulnerability of aquifers.		Promote the efficient use of water, through a policy implemented with incentives, fines and fees.	Strengthening of user organizations, both of surface water and groundwater, to act in the distribution of water and in the conservation of water resources.
	Develop an instrument to be used in proposing natural channel boundaries, and incorporate it into land use planning.		Regularize wells without exploitation rights.	Strengthening of the water rights market.
			More active role of user organizations in aquifer management, quality monitoring and extraction control.	Development of an institutional framework for the integrated management of water resources.
			Promote integrated communities of surface and groundwater users.	Institutional reorganization of the Public Sector.
				Regulate the development of human settlements with a preventive approach to their impacts on natural channels.
				Creation of massive programs, increase the active role of the DGA in Public Education and strengthen strategic alliances with the Ministry of Education and Universities.

División de Recursos Hídricos, FCFM, U. De Chile. 2009. Auditoría Estratégica Nacional de Gestión Integrada de Cuencas Hidrográficas.			Determine the ecological flow and monitoring	Environmental, economic and social baseline.
			Hydrobiological indicators	Creation of the Basin Management Agency and design and implementation of the basin management plan.
			Design, development and monitoring of basins management plans.	Strengthening of public capacities, conflict resolution mechanisms, and the adoption of agreements.
			Optimize the process of issuing quality and emission standards.	
Banco Mundial. 2011. CHILE. Diagnóstico de la gestión de los recursos hídricos.			Strengthen the DGA.	Protect the water rights of vulnerable groups.
			Strengthen user organizations. (JdV)	Improve the protection of water requirements for ecosystems and associated services.
			Improve information and communication systems.	Improve water markets.
			Coordinate intra and inter sectoral	Integrate basins management and encourage the participation of the interested groups.
				Improve conflict resolution (between individuals, water users and the DGA).

(continued)

Table 22.4 (continued)

Document	Development of WRR	Management of WRR	Integrated Management and Ecohydrology	Social hydrology
MOP, 2011. Estrategia Nacional de Recursos Hídricos. Chile cuida su agua 2012-2025.	Improve available information	Protection of the quality and quantity of water resources.	Establish a policy that encourages the integrated management of water resources.	Rural drinking water coverage.
		Facing drought: reservoirs, artificial infiltration of aquifers, desalination, other unconventional water sources.		Informed citizenship
Instituto de Ingenieros de Chile. Comité de Expertos. 2012. Política Nacional de Recursos Hídricos. Hacia una gestión integrada de recursos hídricos, una propuesta.			Promote an Integrated Management of Water Resources with the coordinated action of the agents, in a medium and long-term systemic perspective.	Strengthen the water rights market.
				Registration of water rights in the CBR.
				Creation of a Water Resources Council for the basin or group of basins (CRH).
				Facilitate conflict resolution.
Valdés-Pineda et al. 2014. Water governance in Chile: Availability, management and climate change.	Improve the quantity and quality of instrumentation throughout the country.	Improve the efficiency of water use through private investment incentives towards irrigation technologies and infrastructure.	Decontamination plans.	Create an undersecretary of Water Resources.
			Increase funding sources for water-related research, infrastructure and management projects.	Create policies to encourage Integrated Water Resources Management (IWRM), emphasizing Water Use Organizations (WUO).
				Promote a culture oriented to water conservation.

DGA 2016. Atlas del Agua	Improve knowledge of the country's water systems (improve and expand measurement networks).	Create adequate tools for Chile's water heterogeneity.	Have a legal and institutional framework that considers both water diversity and scarcity as real phenomena.	Saving water and efficiently addressing situations of scarcity.
		Deal with the impacts of climate change.	A new institutional framework for water that allows establishing inter-institutional coordination to advance towards an integrated management of water resources.	Establish a culture of water in the population from an ethical approach (know, value and protect the water resource).
Peña 2016. Integrated Water Resources Management in Chile: Advances and Challenges. Ch 13 in Water policy in Chile, G. Donoso Editor. Springer.		Ensure adequate water availability and quality.	Conserve and protect water resources and ecosystems of the basin.	Integrated water resources management, propose a Master Basin Water Management Plan.
			More financial resources.	Promote the effective participation of civil society in the planning, conservation and sustainable development of water and environmental resources of the basin.

(continued)

Table 22.4 (continued)

Document	Development of WRR	Management of WRR	Integrated Management and Ecohydrology	Social hydrology
CNID, Comisión de I+D+/ para la sostenibilidad de los recursos hídricos. 2016. Ciencia e Innovación para los Desafíos del Agua en Chile.	Increase quality of information and increase coverage of the National Hydrometric Network in alliance with other public institutions.	Surface and groundwater management considering the country's territorial singularities.	Biological indicators for evaluating water quality and identifying polluting sources.	Improvements in water governance.
	Interoperability of public information platforms.	Platform for the control of extractions.	Ecological flows and characterization of environmental uses.	Development of local coordination platforms.
		Remote technology for crop water requirements.	Hydrobiological processes of aquatic systems.	Strengthening of capacities in the OUAs.
			Ecological state of fragile and vulnerable continental aquatic ecosystems.	Formation of macro regional tables STI (Science, Technology and Innovation) for IWRM.
			Dynamic restoration of channels and ecosystem services.	Development of a water culture in the school world through the STI.
				Rainwater management and green infrastructure in cities.
Escenarios Hídricos 2030. 2018. Radiografía del agua, brecha y risegos hídricos en Chile.	Survey of indicators in the territory, to know the Water Gap and Water Risk.			Alert the productive sectors of critical factors that may put their sustainability at risk.
				Promote a water culture.

Escenarios Hídricos 2030, 2019. Transición Hídrica. El futuro del Agua en Chile			Modify the way of managing and making information available.	Have governance at the basin level, represented by different water users to lead IWRM.
			Conservation, restoration and repair of ecosystems.	Efficiency in water consumption by all users, using the resource in a strategic and sustainable way in the basins.
			Define adequate institutions and regulations, along with functional coordination between institutions.	More public-private collaboration and multipurpose vision for the implementation of long-term water solutions.
				Optimal access to quality drinking water for all.
Escenarios hídricos 2030 Chile. 2019. MAS. Medidas, Acciones Soluciones. Seguridad Hídrica. ISBN: 978-956-8200-51-0	Monitoring and water research.	Migration and incorporation of new water sources.	Conservation and protection of our water ecosystems.	Efficiency and strategic use of water resources.
				Water Management and Institutionally: IWRM, basin organizations, Education, culture and information about water.
DGA, Comité de Expertos. 2012. Elaboración de una Política Nacional de Recursos hídricos en Chile	Have information about the quantity and quality of the waters, in a truthful and complete manner.	Promote mechanisms that ensure the use of water in accordance with the permitted uses.	Generate water management strategies consistent with available financial resources and promoting their economic sustainability.	IWRM, dynamic institutionally, strengthening the capacities of user associations.
				Enrich citizenship education in water issues, at basin and country level.

Water Resources Management

- Confront the impacts of climate change and scarcity with new non-conventional water sources (reservoirs, aquifer recharge, desalination, interbasins conexions, non-conventional sources).
- Ensure and protect the availability and quality of water for all uses.
- Improve efficiency of use with incentives for new technologies.
- Promote a platform for the control of extractions with timely information and registration.

Ecohydrology and Integrated Water Resources Management

- To generate a new institutional framework and coordination for Integrated Water Resources Management at the level of basins, considering surface and ground water users.
- To optimize the process for setting quality and emission standards.
- Strengthen the DGA and user organizations, intersectoral coordination, and provide them with reasonable financial resources.
- Design, preparation and monitoring of basin management plans and decontamination plans.
- Conserve, restore and repair water systems. Monitor the ecological status of fragile and vulnerable inland aquatic ecosystems, ecological flow, hydrobiological indices and indicators, and decontamination plans

Social Hydrology

- To promote a water culture and an informed citizenry (to know, value and protect the water resource), oriented to the conservation, saving, efficiency and sustainability of the resource.
- New institutional framework that includes governance at basin level with the participation of users, civil society and the state for integrated water resources management at basin level. Evaluate the creation of a Water Resources Council for the basin or group of basins, or the creation of an Sub-secretariat for water resources.
- Promote water saving, improve efficiency in consumption and strategic use of water resources. Improve conflict resolution systems.
- Strengthening the market for use rights. Improve the protection of the rights of vulnerable groups, rural drinking water coverage and ecosystem requirements.
- Promote and encourage rainwater management and green infrastructure in cities. Access to drinking water for all.

In these proposals there is a high degree of coincidence among the multiple participants and in all of them hydrology has a high degree of participation, from the generation of knowledge about the availability of the resources, their behavior, modeling and management of the aquatic systems. In addition, to achieve a comprehensive and long-term vision in water resources policies, it is necessary and urgent to consider the effects of climate change. Vicuña and Meza (2012), propose that it is necessary to include elements of adaptive rigidity in the operation of existing systems, such as the allocation of water rights and agreements on the operation of shared reservoirs between the agricultural and hydropower sectors, in order to take into account the most recent hydrological conditions and environmental needs. The challenge for hydrology and water resources management is therefore to achieve a flexible and dynamic water resources management system that includes long-term perspectives and integrity at the basin level (Vicuña and Meza 2012).

22.3.3 Challenges for a Water Resources Policy

All these challenges imply a legal framework given by the current constitutional provisions and the Water Code of 1981, according to which, although water is a national good of public use, the Water Rights of Use are negotiable goods of private appropriation, which are given in perpetuity and are not linked to the land or to a specific use, so that they can be freely transferred, generating a market of these rights. In 2005, the code was modified by generating a patent for non-use, in order to avoid speculation and hoarding of rights (Peña 2020). A relevant challenge for the management of water resources in Chile is currently to advance in the analysis of these matters and to agree on a political solution in several of the issues of the Water Code, such as the perpetuity of the rights, the need to protect the resources for small communities, the environmental uses and the uses in the riverbed, among others. The current code strongly favors the productive use of water resources, going from a situation of 40 years ago with little private investment for water use, to a current one in which most of rights are assigned to private uses, with many basins being overexploited. This problem happens mainly because the rights of use have been given away in fixed units but the water resources are essentially variable, which is evident in times of scarcity. These are major and urgent challenges for hydrology and water resources management in Chile.

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