Chapter 2
Hydrological Setting

James McPhee

Abstract From a hydrological perspective, Chile is a country of extremes. Its rivers and aquifers exist in a wide array of geographical settings, and are characterized by presenting regimes of extraordinary variability in space and time. From the driest desert on Earth to Patagonia, communities and ecosystems have adapted to endure periods of persisting drought, relentless precipitation, as well as favorable conditions for the emergence of a burgeoning agricultural sector. With mounting evidence of global change processes, it is still unclear how these regimes will evolve in the future, and what are the challenges that water managers will need to face in order to balance increasing water demand and the need for water security. This chapter describes the major hydrological regimes associated with water resource relevant regions in the country, highlighting the hydrological processes, variability and uncertainties pertaining to water resource management. A global assessment of the state of hydrologic knowledge, data availability and future directions for research and management are provided.

Keywords Chile · Chilean watersheds · Hydrology · Hydrometeorological regions · Water regimes

2.1 Chile and Its Climate

Chile's location and latitudinal span determine one of the most extremely variable climatic settings worldwide. From north-to-south precipitation increases and temperature decreases (Donoso 2017).

Well into the subtropical circle, Chile's Northern Macroregion holds the world's driest desert, the Atacama, where annual precipitation averages less than 25 mm/year. The hyper-aridity of this region is due to the "South Pacific High" anticyclone, which blocks moist air masses traveling from the west, preventing frontal precipitation from occurring between the latitudes of 15 and 25 °S. Despite this condition,

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the eastern border of the Atacama, neighboring with Southwestern Bolivia and Northwestern Argentina, is influenced by the climate of the South American High Plateau. There, convective precipitation systems significantly increase annual precipitation to 200 mm–800 mm, which can sustain aquatic ecosystems. These precipitation events occur during the austral summer, typically between the months of December and February (Minvielle and Garreaud 2011).

Further South, the Central Macroregion of Chile (25–40 °S) presents a classical Mediterranean climate, with an average annual precipitation of 940 mm, which is heavily concentrated during the winter months of June through September (Southern hemisphere). Semi-arid conditions prevail in what is known as Chile's *Norte Chico (25–33* °S). The high elevation of the Andes Cordillera [4000–6000 meters above sea level-(masl)] sustains a seasonal snowpack that accumulates during the winter and melts rapidly at the beginning of spring. A climatic threshold has been identified at 34 °S, whereby precipitation increases significantly and interannual variability shows different characteristics. An important terrain feature in Central Chile is the presence of two mountain chains, the Andes and the Coastal ranges, which run parallel to each other in a north-south direction. They are separated by a central depression that holds a rich agricultural region. These mountain ranges induce the orographic enhancement of frontal systems approaching from the west, also generating rain shadows in the areas immediately to their east. The southern edge of Central Chile is characterized by larger precipitation amounts, with a more extended rainy season.

The Southern Macroregion of Chile (40–45 °S) is characterized by large annual precipitation amounts over an extended rainy season, reaching on average 2963 mm/year. Here, a broken coastline coexists with relatively high mountains, which induce strong precipitation orographic gradients such that annual precipitation amounts can vary one order of magnitude along a distance of less than 200 km.

Finally, the Austral Macroregion, is characterized by slightly lower precipitation amounts without a clearly defined rainy season, as well as a highly eroded landscape and low temperatures throughout the year.

2.2 Hydrometeorological Regions

The climatic situation described above, combined with the severe topographical and geological changes, proper to the mountainous characteristics of the country, result in a wide range of hydrological regimes throughout the different river basins in Chile. In a very broad sense, it is possible to group these river basins into 4 Macroregions – North, Central, South, and Austral – listed below. By no means is this grouping intended to be the definite categorization, but it is provided here as a way of simplifying to some extent the understanding of the patterns of variability existing in the country. Figure 2.1 identifies sample watersheds, representative of Chile's Hydrometeorological Macroregions.

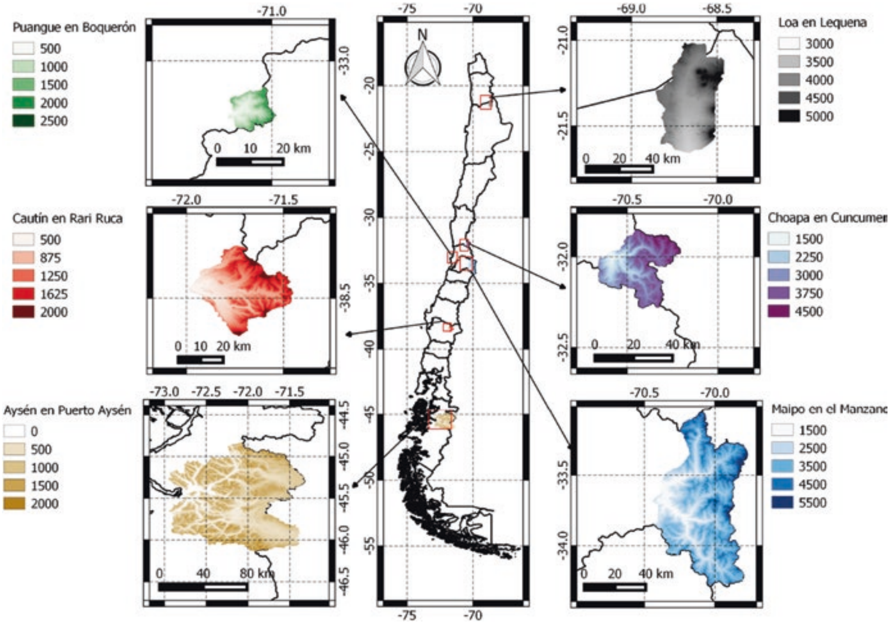

Fig. 2.1 Altitude (masl) of sample watersheds representative of Chile's Hydrometeorological Macroregions. (Elaborated based on public data)

2.2.1 North Macroregion: Edorheic and Exorheic Atacama Desert Waterseds

Non-negligible precipitation in the high elevations in the Andean High Plateau generates surface and subsurface water flows that feed endorheic and exorheic[1] basins in the hyper-arid North Macroregion. Endorheic basins typically present surface water bodies such as shallow lagoons, or salars, within them. Evaporation from these lagoons is usually the only water outlet in the basin, which yields highly saline surface waters. At some locations, groundwater flows west from the high-plateau and seeps to the surface in the steep hillslopes leading to the Atacama Desert. These flows constitute oasis where human populations have been established for centuries. These exorheic basins cut through the desert, and streams are fed from intense convective storms occurring during the southern summer or fall, and sometimes from snowmelt streaming from the upper reaches of the desert Andes, where a shallow snowpack can usually be found in the winter months. The average daily annual flow is very low in watersheds of this Macroregion. For example, as can be seen in Fig. 2.2 annual average daily water flow during summer months in the Loa Basin is

[1] Endorheic is a closed drainage basin that allows no flow to external water bodies; exorheic, is a basin that drains to other water bodies such as the ocean.

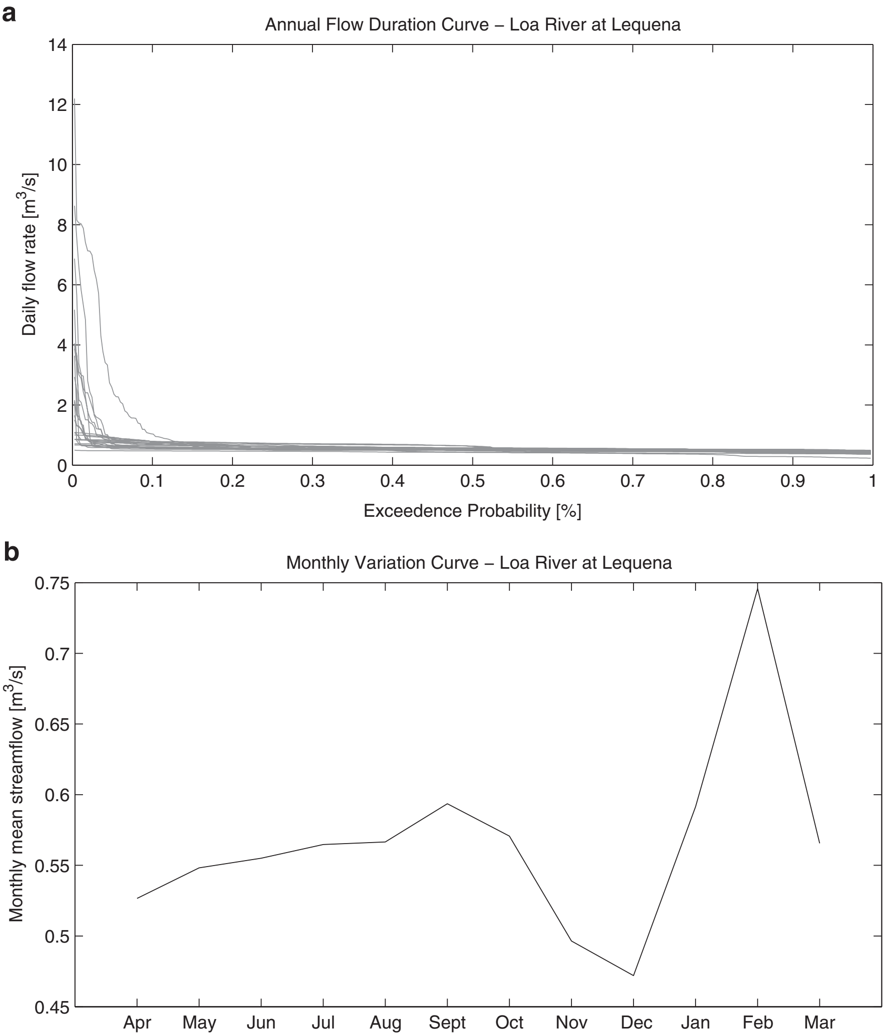

Fig. 2.2 (**a**) Ensemble of annual flow duration curves of mean daily flows, (**b**) Mean monthly flow climatology, Loa River at Lequena station. (Elaborated based on public data)

0.7 m³/s[2] during 20–80% of the time. In these northern basins, surface-subsurface water interaction is a significant component of the hydrological cycle, and this in turn signifies a heightened role of groundwater as a water source in many river basins where surface streams run dry for extended periods of time. Because precipitation in this zone occurs mainly in remote, unpopulated regions, predominantly in the form of convective storms, a great deal of uncertainty in water resource

[2] 1 $m^3/s = 259 \times 10^6$ m^3/month.

availability stems from the difficulty in estimating areal precipitation, as well as effective groundwater recharge.

In this Macroregion, aquifers have a significant role as a source of water resources, mainly for mining and agricultural activities. Annual estimated recharge is 10 m^3/s while average discharge ranges between 10 m^3/s and 20 m^3/s. Thus, sustainability of actual groundwater use is a major concern in these regions.

2.2.2 Central Macroregion

2.2.2.1 Snow-Dominated Central Chile Watersheds

Between latitudes 25 °S and 40 °S the most salient hydrological processes are the accumulation and melt cycles of snow and ice (cryosphere) in the Andes Cordillera, which result in the snow- and ice-dominated hydrological regimes of most of the watersheds that supply water to human and environmental systems. The Andes, whose peak elevation in this region is in the order of 4000–6000 masl, generates an orographic enhancement effect that favors snow accumulation on the western slope of the cordillera. Mean annual precipitation values here more than doubles what can be observed in the lower elevation central valley, and range between 500 and 2500 mm per year in the mountain reaches (Cornwell et al. 2016). With more than 1000 individual glaciers, and covering a surface area exceeding 900 km^2, glaciers are able to reduce the interannual variability observed in precipitation, sustaining base flows in mountain watersheds; thus, playing a relevant hydrological role. Their effect is most significant during the dry late-summer months of February and March, and under drought conditions their hydrological input may exceed 50% of dry-season flows in large mountain basins (Ohlanders et al. 2013; Rodriguez et al. 2016). Like other mountain regions of the world, the cryosphere of the Andes is rapidly disappearing due to recent trends in temperature, and less significantly, precipitation. The effect of global warming can be especially seen in the areal extent of glaciers in this region, which have been shrinking rapidly since records were first established (Masiokas et al. 2016). Annual average daily flow in these watersheds is 500 times that of the North Macroregion. Figure 2.3 presents the Maipo basin's annual average daily water flows. These range between 100 m^3/s and 300 m^3/s during 20–80% of the time, concentrated in spring and summer months.

Groundwater resources in this macroregion are replenished by a combination of precipitation and riverbed infiltration during the high-melt flow season (McPhee et al. 2012) and, thus, recharge is significantly greater reaching 50–100 m^3/s. There is limited information on average annual discharge, and thus there is uncertainty with respect to the sustainability of groundwater use in these regions.

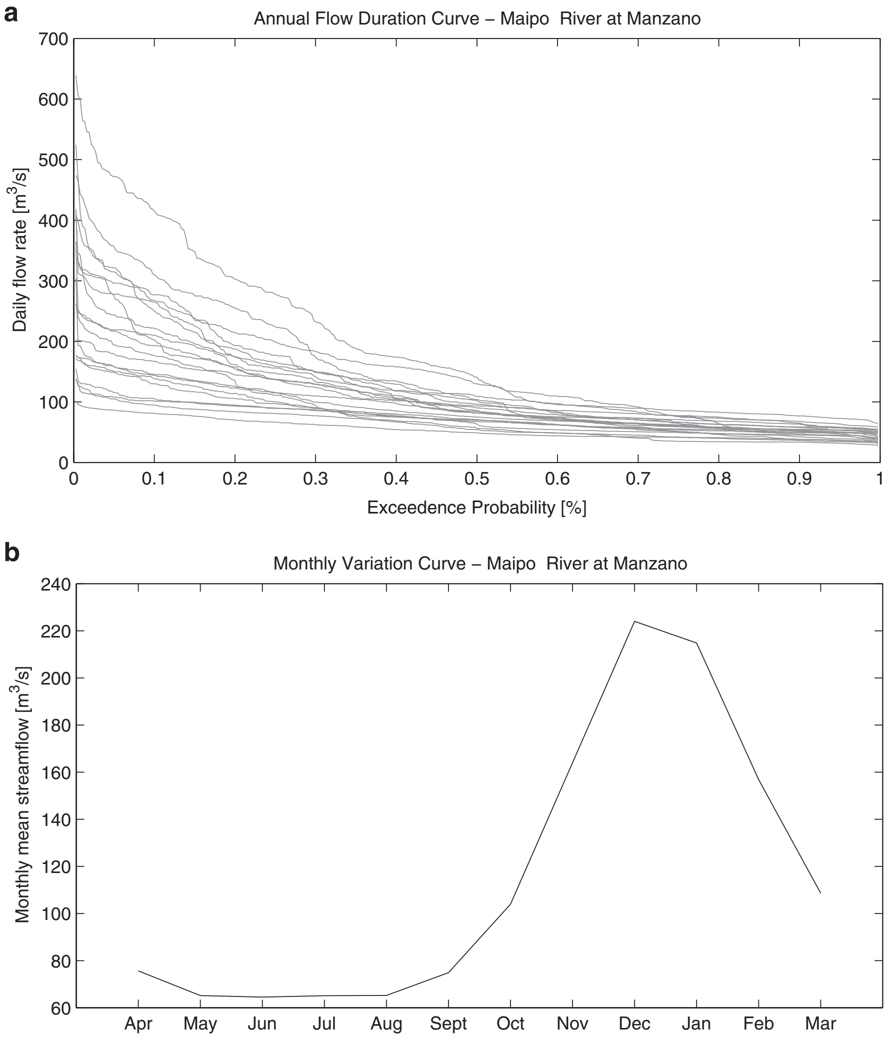

Fig. 2.3 (**a**) Ensemble of annual duration curves of mean daily flows, (**b**) mean monthly flow climatology, Maipo River at El Manzano station. (Elaborated based on public data)

2.2.2.2 Mediterranean Coastal Rivers

Along the Chilean coast, between latitudes 33 and 40 °S, the coastal range is of sufficient height to generate an orographic enhancement effect that sustains many small and medium size watersheds. Many of these coastal range watersheds lack stream gages, but are nevertheless relevant for sustaining small rural communities and ecologically relevant hydrological systems.

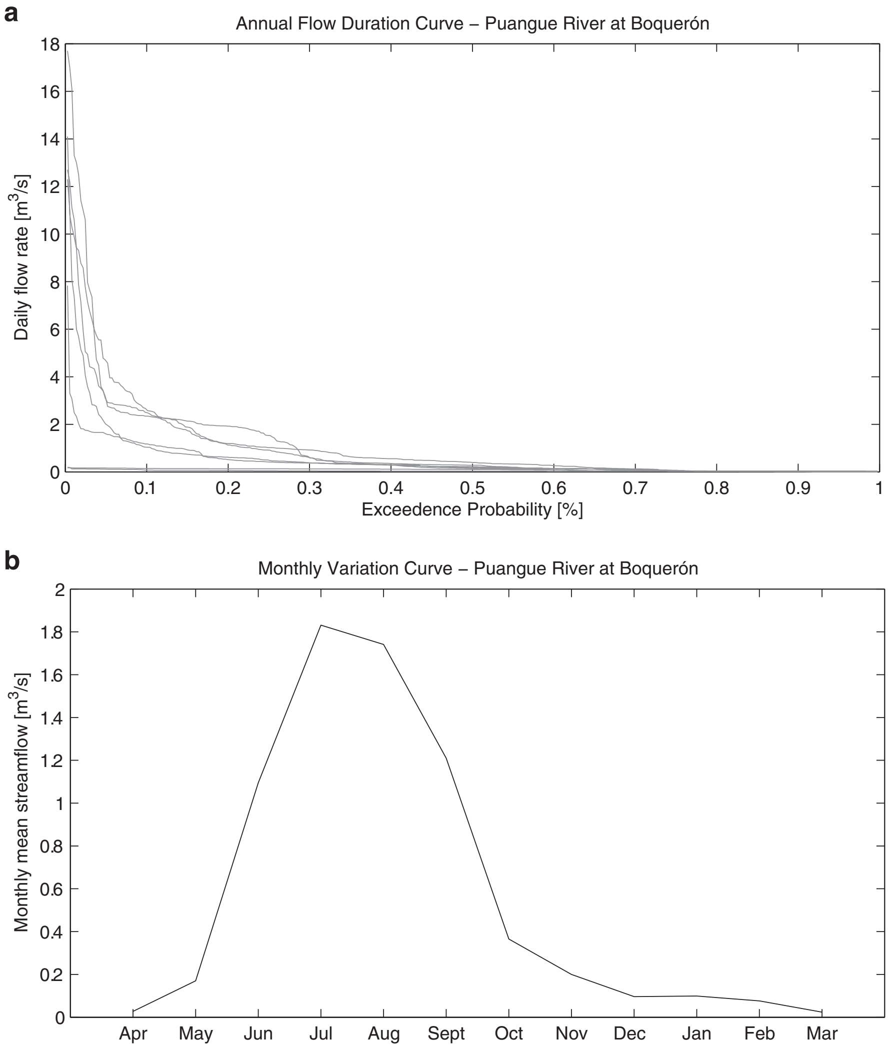

Fig. 2.4 (**a**) Ensemble of annual duration curves of mean daily flows, (**b**) mean monthly flow climatology, Puangue Creek at El Boquerón station. (Elaborated based on public data)

No significant snowpack can accumulate at the low elevation of the coastal range, so the hydrological regime here is exclusively rain-fed, with peak flows during storms in the winter months between June–August. Base flows are sustained mostly by subsurface flows, and depending on the amount of annual precipitation and catchment area, both intermittent and perennial streams can be found. Thus, annual average daily water flows in these rivers is significantly lower than in the Snow-dominated Central Chile watersheds. The Puanque river has an average daily water flow between 0.5 m^3/s and 1.6 m^3/s during 40% and 80% of the time (Fig. 2.4).

2.2.3 South Macroregion: Temperate Humid Watersheds

The northern edge of the Patagonia region is characterized by a marked increase in annual precipitation, which allows for the existence of dense deciduous and evergreen forests. The Andes Cordillera drops significantly in height in this region, reaching elevations in the order of 2000 MASL. Nevertheless, lower winter temperatures associated with the higher latitude here allow for the accumulation of a sizeable snowpack at the higher reaches of the Andes. This leads to the fact that the hydrological regime here is of a mixed nature, with rainfall-runoff processes dominating in winter months and snowmelt contributing to river flows in spring and early summer. Intense past volcanic activity originated a peculiar type of soils in this region, such that a low-permeability ash layer of volcanic nature can be found underneath medium to shallow organic soils. Therefore, groundwater storage is generally assumed to be of little importance in this area, as infiltration may not penetrate to the lower strata, limiting the available volume for groundwater storage. However, the influence of root systems and high organic content of the upper soil layer favors high porosity conditions, which are also supposed to allow for a significant shallow-subsurface flow component. Interannual variability in precipitation is lower here compared to what can be observed in the northern half of the country. Therefore, annual streamflow distribution tends to be quite consistent; the Cautin Basin has average daily water flows between 80 m^3/s and 120 m^3/s during 20% and 80% of the time (Fig. 2.5). Also, even though many of these rivers are rain-fed, the prevalence of spring and summer frontal systems sustains fairly significant base flows even during the driest season of the year (Fig. 2.5).

2.2.4 Austral Macroregion: Cold Humid Patagonia Watersheds

Patagonia's climate is characterized by precipitation that is fairly distributed throughout the year, with a somewhat rainier season during the austral winter but generally showing significant rainfall throughout the year. Low temperatures at these higher latitudes allows for snow peaks to exist longer in many river basins, even when the Andes Cordillera seldom exceeds 1000 masl in elevation here. These snowy peaks and glaciers that cap many volcanoes in the region contribute to sustain base flows at the end of the very short dry season, between January and March. During the rest of the year, consistent precipitation feeds streamflow in river networks that respond quickly to storms due to the generally high moisture content of soils. Many large rivers in the Patagonia region show a distinctly glacial hydrological regime, as they are fed by ice-melt from the Northern and Southern Patagonian Ice Fields, the largest ice masses in the southern hemisphere outside Antarctica. The eastern portion of this region is located in a rain shadow, because the Andes here is

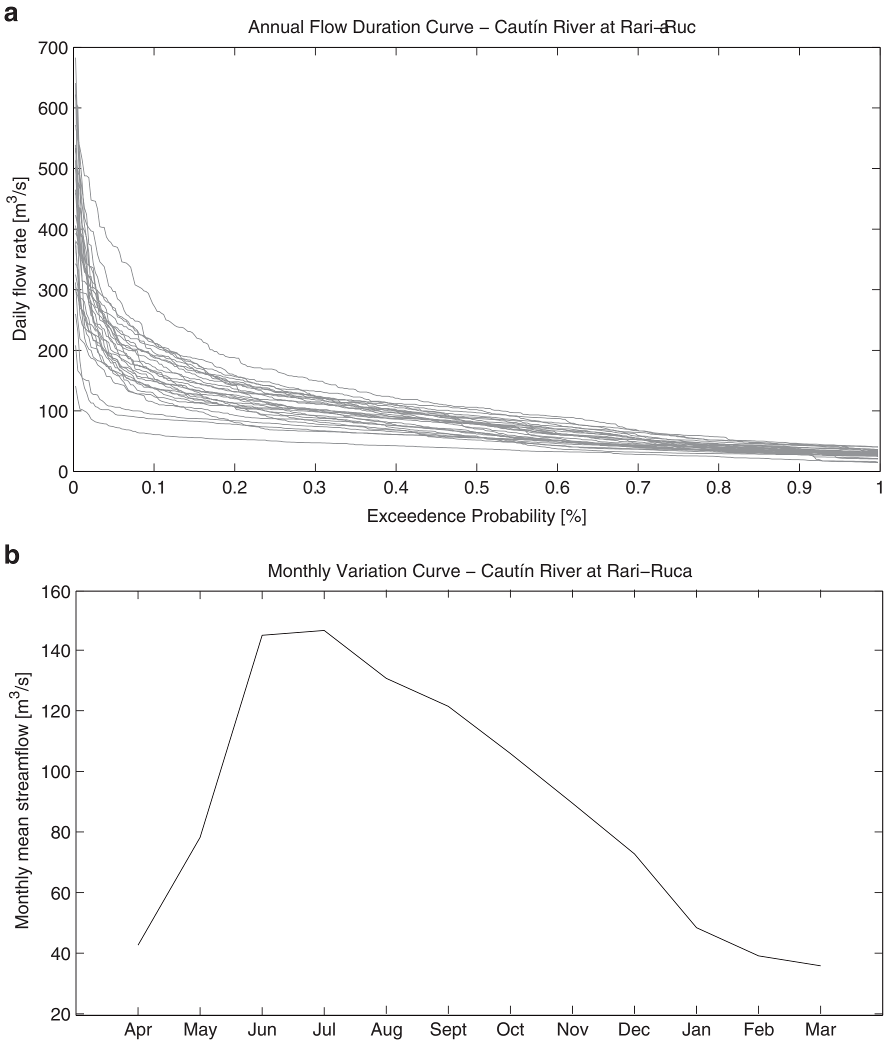

Fig. 2.5 (**a**) ensemble of annual duration curves of mean daily flows, (**b**) mean monthly flow climatology, Cautín River at Rari Ruca station. (Elaborated based on public data)

highest near the Pacific Ocean. Therefore, vegetation is usually scarcer there and significant erosion can be observed in some areas. Streamflow interannual variability is even smaller as we travel south, as the close disposition of daily flow duration curves can attest (Fig. 2.6). Given the increased surface water supply, groundwater is not an important water source.

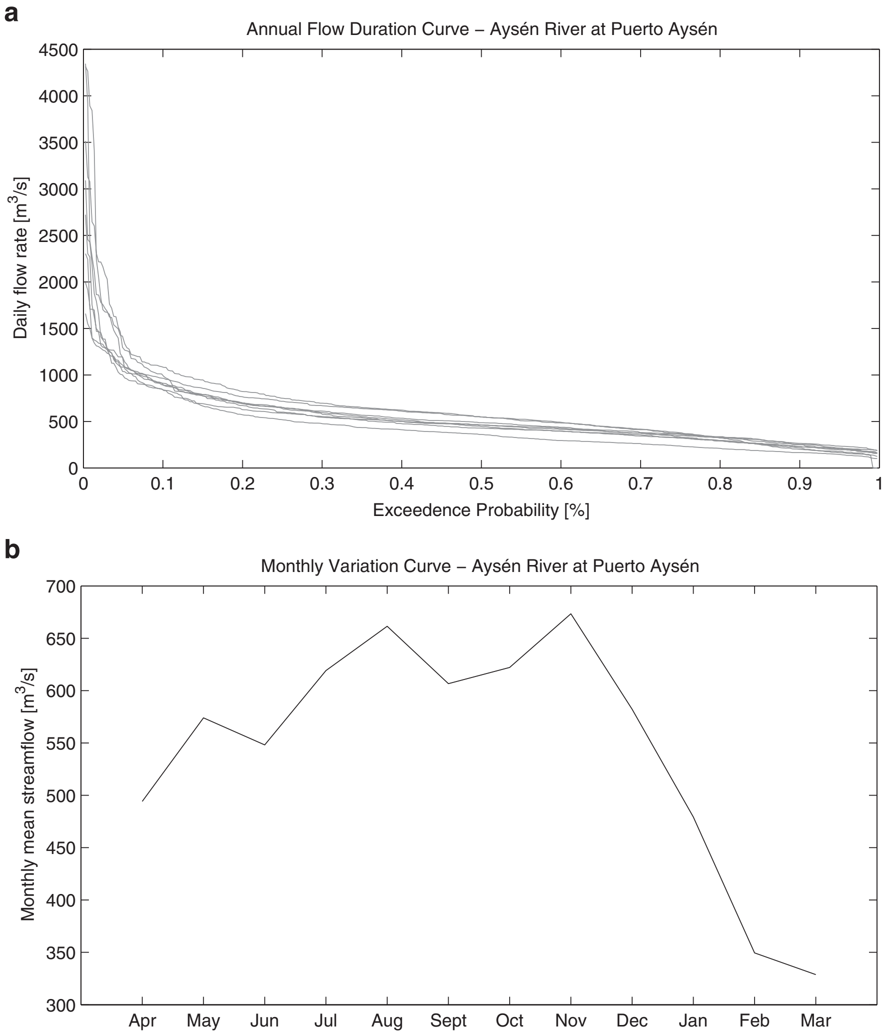

Fig. 2.6 (**a**) ensemble of annual duration curves of mean daily flows, (**b**) mean monthly flow climatology, Aysén River at Puerto Aysén station. (Elaborated based on public data)

2.3 Conclusions

The material presented in this chapter demonstrates the dramatic diversity of hydrological settings in Chilean watersheds. Drastically different runoff generation mechanisms, as well as distinct patterns of seasonal and interannual variability, emerge. Precipitation input is a major source of uncertainty when attempting to issue hydrological predictions, because the monitoring network is limited in high-elevation upstream areas, where usually runoff generation is more effective. A second source of uncertainty in the northern half of the country is the extent, capacity, and natural recharge rate of major aquifer systems. A limited observation well network, and a potentially large volume of un-gauged groundwater extractions hinder severely the ability of public and private actors to quantify the water balance of groundwater systems. In mountainous snow and glacier dominated watersheds, remote sensing technology has increased significantly the ability of monitoring valuable resources. Nevertheless, challenges still exist, since most satellite-based platforms can only quantify the areal extent of snow and ice, whereas actual water equivalent volumes are still only measurable at discrete, point locations. In temperate humid regions, land use change represents the largest source of uncertainty in predicting future hydrological behavior.

Throughout the country, extreme events have a high destructive potential. Short, intense storms in northern Chile are known to generate large flash floods and debris flows events that affect with some recurrence many populated areas in the arid north and central Chile. Warm storms and convective summer events may mobilize large volumes of soils from mountain watersheds, interfering with water supply and representing a danger to people and property. Large winter floods are common in low-laying areas in Southern Chile, often affecting both urban and rural populations.

The above phenomena may be exacerbated by climate change which is expected to affect Chile in a complex fashion, both through increased temperatures year-round and through decreased annual precipitation in the central region of the country, between latitudes 25 and 45 °S (Donoso 2017).

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