APPENDIX 1 - Case study Chile

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Central-south Chile (30°–37°S) is a narrow strip of land (<200 km wide) between the Pacific Ocean and the Andes cordillera, home to more than 9 Mill inhabitants and many economical activities. It features an archetypical Mediterranean climate, with semi-arid conditions (annual precipitation of 100 to 1000 mm/year), strong seasonality (>70% of the precipitation in austral winter: JJA) and large interannual variability. The Andes cordillera is more than 4 km high here and enhances precipitation, most of which is retained as seasonal snowpack.

The megadrought afflicting this region started in 2010 and continues up to date, featuring mean precipitation deficits of 30% with some extreme dry years reaching up to 80% (2019 and 2021, as observed in Figure A.1.b). Such a long dry spell, partly attributed to anthropogenic climate change (Boisier et al., 2016, 2018), has been the driest decade in local history since the 14th century (Garreaud et al., 2017), and its impacts reveal key memory effects within different subsystems.

Hydrological system

Before the megadrought, precipitation variability in central Chile featured mostly dry years (below average) interrupted with a few very wet years that permitted the recovery of the hydrological system and natural vegetation. Such recovery capacity has been absent in the last 12 years (Figure A.1.b). During the megadrought, snow-dominated headwater basins with large memory have accumulated the effects of precipitation deficits and generated on average 30% less streamflow than previous single year droughts (Alvarez-Garreton et al., 2021). In some cases, this effect has overlapped with water extractions for human activities in downstream sections, leading to an amplification of drought signal over lowlands and the drying out of water bodies (Barría et al., 2021b; Muñoz et al., 2020).

It remains unclear how long it will take for these new hydrological states to recover after the megadrought finishes. These recovery times depend on the subsystems memory, as illustrated in Figure A.1. For example, a small reservoir (La Paloma, with 0.75 km3 capacity) had a 80% volume recovery after the year 2016, where precipitation had a slight increase compared to the rest of the decade. On the other hand, the large Laja lake (5.6 km3 capacity) recovered less than 20% in volume during that time.

A similar effect happens at the basin scale. In short memory pluvial basins water supply is more strongly dependent on the meteorological conditions of the current year, and thus a wet year would lead to a faster recovery than in long-memory snow-dominated or groundwater-dominated basins, or where groundwater has been disconnected from shallower water during the megadrought. The challenge is that most of these long-memory catchments correspond to semi-arid basins in central Chile where irrigated agriculture is concentrated. In those cases, water needs are usually met by exploiting groundwater reservoirs in unsustainable ways, leading to sustained water level depletions as those observed in Maipo, Aconcagua and Rapel (Figure A.1.e). The unsustainable use of groundwater in central Chile is already impacting society and ecosystems, and posing an intergenerational dilemma due to the depletion of reserves that will not be recovered within generational time frames (Alvarez-Garreton et al., 2023a; Duran-Llacer et al., 2020; Jódar et al., 2024; Taucare et al., 2024).

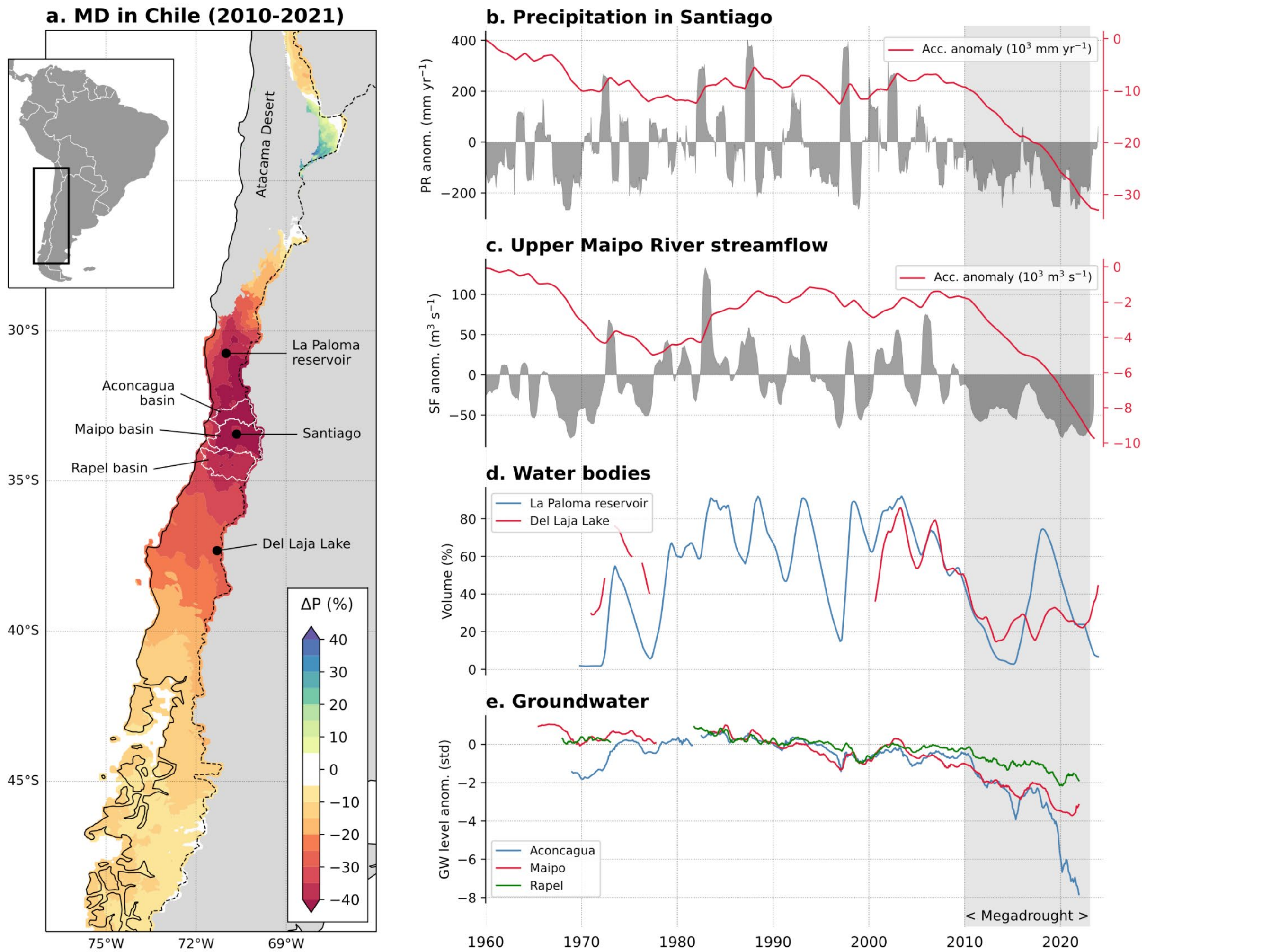

Figure A1: Megadrought in Chile: a) 2010-2021 mean annual precipitation anomaly in Chile, with respect to the 1980-2010 period (data source: CR2MET, (Boisier, 2023)). b) Monthly precipitation anomaly (12-month running sum) and accumulated precipitation anomaly in Santiago (Quinta Normal station, DMC). c) Monthly streamflow anomaly (12-month running mean) and accumulated streamflow anomaly in the Upper Maipo River (El Manzano station, DGA). d) Monthly water volume level (12-month running mean) in La Paloma Reservoir and Del Laja Lake (DGA). e) Groundwater level anomalies in the Aconcagua, Maipo, and Rapel watersheds (indices based on averaged standardized anomalies from 54, 70, and 49 observation wells, respectively).

Ecosystem

According to satellite observations, natural ecosystems have experienced significant vegetation browning following the extreme hyper-dry year of 2019 (Miranda et al., 2023). In the field, there has been mortality of less drought-tolerant tree species, the complete drying out of several branches and even the trunk of more resilient species. The more resilient species have resprouted in the year following the hyper-drought following a vegetative regeneration strategy. These drought effects have led to the lack of seedlings that depicts a risk of altering the composition and structure of these plant communities over time.

The dry conditions during the megadrought have been related to a higher occurrence of wildfires, as well as a larger burned area. Before the megadrought, wildfires were concentrated between the months of November and April, but now they extend from October to May, increasing the occurrence period from 6 to 8 months. Over 70% of the megafires reported in Chile have occurred between 2010 and 2018, where 50% of the burned area corresponds to industrial tree plantations. Notwithstanding this, it is worth noting that 99% of wildfires in Chile are initiated by human actions, whether they are accidental or intentional. Therefore, the behavior of the population is crucial in preventing and mitigating wildfires (González et al., 2018).

Social system

Some parts of the country have precarious water infrastructure, particularly in rural areas, where there are problems of water access even during wet periods. In this context, the megadrought has impacted a system that was already vulnerable before 2010, and these impacts have not diminished over time. This has led to an environment of increasing discomfort in rural communities. Several assessments of water management in Chile have concluded that the strategies to face drought impacts are reactive and tackle water scarcity in the short term, without an adequate plan for persistent drought conditions (Alvarez-Garreton et al., 2023c).

The vulnerability of social systems varies across sectors. In rural areas, people rely on self-organized communities with inadequate infrastructure and technical capacities for providing subsistence drinking water, leading to water cuts that have been remedied by cistern trucks, which is a non-structural reactive measure to address permanent water access requirements in rural communities (Nicolas-Chloé et al., 2022).

On the other hand, people in urban areas rely on water sanitation companies and have not been affected by water shortages, even when surface reservoirs have been significantly depleted since these companies have adequate groundwater infrastructure. An important adaptive measure taken by governmental agencies to face water scarcity in Santiago has been to build deep pumping wells for supplying drinking water for human consumption. This measure reveals that groundwater is seen as an additional water source, overlooking the fact that these reserves are limited by recharge rates, and that current withdrawals are already exceeding those rates (Alvarez-Garreton et al., 2023a; Duran-Llacer et al., 2020; Jódar et al., 2024;

Taucare et al., 2024). In this context, some sectors are not experiencing the consequences of a decade-long megadrought, causing overreliance on a system that has critical vulnerabilities.

From a broader perspective, the slow adaptation of policies to non-stationarity climatic and hydrological processes makes the water management system inadequate to face the drying trends projected for Chile. For example, most of the current water use rights were allocated as absolute flows based on the water availability from decades ago and, in seeking to provide legal certainty, the law does not permit to modify these allocated flows considering the current and projected climatic conditions (Barria et al., 2019; Barria et al., 2021a). This prohibition has led to overallocation of water use rights, as well as impeding the protection of environmental flows, and thus threatening the opportunity to reach water security (Alvarez-Garreton et al., 2023b).

Management

Climate projections for this region show a consistent decrease in precipitation, which may exacerbate current drought impacts in the following decades. Water management measures should prepare for these projections, advancing from the reactive approach currently adopted. Recent studies have provided specific recommendations to achieve this, including the following:

1) Adapting the water management system to account for a changing climate (Barría et al., 2019, 2021a).
2) To recognize that groundwater savings are not an independent source of additional water availability (Alvarez-Garreton et al., 2023a).
3) Strengthening the protection of environmental flows to avoid over allocation of water use rights and advance towards water security (Alvarez-Garreton et al., 2023b).

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