RESEARCH ARTICLE

# Anthropocene and streamflow: Long-term perspective of streamflow variability and water rights

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Since 1981, water allocation in Chile has been based on a water use rights (WURs) market, with limited regulatory and supervisory mechanisms. The volume to be granted as permanent and eventual WURs is calculated from streamflow records, if stream gauge data are available, or from hydrologic parameter transfer from gauged to ungauged catchments, usually with less than 50 years of record. To test the performance of this allocation system, while analyzing the long-term natural variability in water resources, we investigated a 400 year-long (1590–2015) tree-ring reconstruction of runoff and historical water rights for Perquilauquén at Quella catchment, a tributary to the Maule River in Central Chile (35°S–36°30S). Furthermore, we assess how the current legislation would perform under a projected climate scenario, based on historical climate simulations of runoff calibrated against observed data, and future projections. Our analyses indicate that the allocation methodology currently applied by the Water Authority in Chile is very sensitive to the time window of data used, which leads to an underestimation of variability and long-term trends. According to the WURs database provided by the Chilean Water Directorate, WURs at Perquilauquén at Quella are already over-allocated. Considering regional climate projections, this condition will be exacerbated in the future. Furthermore, serious problems regarding the access and quality of information on already-granted WURs and actual water usage have been diagnosed, which further encumber environmental strategies to deal with and adapt to climate change. We emphasize the urgent need for a review and revision of current water allocation methodologies and water law in Chile, which are not concordant with the dynamics and non-stationarity of hydrological processes. Water scarcity and water governance are two of the key issues to be faced by Chile in the Anthropocene.

## 1 Introduction

The Chilean water allocation system is based on a Water Use Rights (WURs) market, which was established by the 1981 Water Code (Congreso de la República de Chile, 1981). Under this system, based on water rights or entitlements, the allocation of available water resources in the most efficient manner is determined by the market, with limited regulatory and supervisory mechanisms (Hearne and Donoso, 2014; Ríos and Quiroz, 1995; Rivera

et al., 2016). Hence, little attention has been given to the impacts of the Water Code on important areas such as environmental protection, resolution of water conflicts and river basin management (Bauer, 2004).

Central Chile (CC, 33°–38°S) harbors more than 74% of the total Chilean population (INE, 2017), and accounts for 75% of the country's total irrigated agriculture (Demaria et al., 2013a). Furthermore, this region is responsible for 73% of national consumptive water diversions (MOP, 2012). The region has faced an extraordinary drought in the period 2010–2016 (Boisier et al., 2016; Garreaud et al., 2017; Boisier et al., 2018), the so-called Central Chilean Mega Drought (MD), characterized by a long and uninterrupted sequence of below-average rainfall years. The MD has resulted in major reductions of surface runoff and has important ecological and socioeconomic repercussions (Garreaud et al., 2017). In 2015, the Chilean Directorate of Water Resources (*Dirección General de Aguas,* or DGA) indicated that eleven CC rivers were depleted (DGA, 2016), and ten out of 56 provinces were declared as "zones of water shortages" during 2017. These provinces concentrate a 56% of the total Chilean population (INE, 2017),

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including the Valparaíso, Santiago Metropolitan, and Maule regions (DGA, 2018).

In this context, two important concepts regarding water deficit arise and should not be confused: water shortages and drought. Water shortage refers to water deficits caused by a larger demand than the physical availability of a resource. One of the causes of water shortages in CC catchments is speculative water hoarding, where a large number of WUR properties have been requested but are not actually used. In an attempt to regulate water hoarding and to reduce water shortages in CC, Law 20017 (Congreso de la República de Chile, 2005) was promulgated in 2005 to modify the Water Code by requiring fees for non-use of water rights, hereafter "patent", payments to properties with assigned WURs who have not made total or partial use of the resource. To date, the problem has not been resolved, mainly due to the fact that those areas with larger water demand are also the areas where WURs have a higher market price than the patents, thus encouraging water hoarding (Valenzuela et al., 2013). A new reform of the Water Code, the Law 21064, introduces modifications to the audit and patent payment to WURs properties mechanisms, with several approval steps still pending in the Chilean Congress (Biblioteca del Congreso Nacional de Chile, 2018).

On the other hand, drought-related water shortages are a consequence of the climatic variability of water catchments. This variability may be a combination of natural variability and anthropogenic climate change. According to observations in CC, sustained increases in temperature and reductions in precipitation (Boisier et al., 2018; Demaria et al., 2013a, Fuenzalida et al., 2007) have led to runoff reductions of up to 40% (Magrin et al., 2014), and are projected to continue reducing runoff into the future (Bozkurt et al., 2017; Demaria et al., 2013a; Prosser, 2011; Prudhomme et al., 2014; Samaniego et al., 2009).

Furthermore, Meza et al. (2012) indicate that climate change has the potential to affect water resources in CC catchments, in terms of both supply and demand, because of increasing occurrence of severe droughts. Indeed, Boisier et al. (2016, 2018) have already attributed a quarter of the CC MD to climate change. Moreover, in a recent analysis of multi-century tree ring runoff reconstructions for three Chilean rivers, Muñoz et al. (2016) found an increase in extreme low flows during the last 50 years in the context of 400 years of streamflow variability. These findings demonstrate that variability in river flows is featuring human-induced changes. However, the anthropogenic impacts on the hydrological cycle are not fully understood.

Human impacts on water resources and availability, as well as on the hydrological cycle, represent a clear manifestation of the Anthropocene (Crutzen, 2006; Steffen et al., 2007), a geological epoch in which humankind has greatly influenced the environment, outcompeting natural variability (Crutzen, 2006). Impacts on surface runoff, a key component of the hydrological cycle and considered an indicator of climate change, have already been detected for CC catchments and are of particular relevance to this study (Boisier et al., 2018). In particular, the diversion of surface water is a direct human disturbance on hydrological cycle. Moreover, as stated by other authors, the challenges derived from an intensified water cycle, particularly drought and its governance, are key to water management in the Anthropocene (Van Loon et al., 2016).

In Chile, available water volume granted as WURs is calculated using gauged runoff data. However, because existing data are usually not very extensive over time (~40–50 years at the most), they do not allow for an observation of long-term natural hydrological variability. Runoff variability works at time scales ranging from hours to centuries; a few decades of gauged data are not long enough to characterize the multi-decadal variability of runoff, which has been shown to be significant in this region (Quintana and Aceituno, 2012). This context raises the question of how well existing water allocation methodology in Chile works in the context of a changing climate.

Paleoclimatic methods can be incorporated as they provide a century-scale perspective on climate variability. In CC, tree rings are a good proxy for hydroclimatic variability, because tree growth depends on water availability and changes in temperature (Muñoz, 2015) – the same variables that determine runoff (Barria et al., 2017; Lara et al., 2015).

Streamflow reconstructions have been successfully conducted for several rivers in CC. From north to south, dendrochronology reconstructions for the Maule (Urrutia et al., 2011), Biobío (Muñoz et al., 2016; Barria et al., 2017), Imperial (Fernandez et al., 2017), Puelo (Lara et al., 2008) and Baker (Lara et al., 2015) rivers have been developed; all reconstructions explain around 50% of observed runoff variance. However, to our knowledge, these paleo-reconstruction data have not yet been applied for water resource management assessments in Chile, but have been successfully used in United States and Canada, by developing collaborations between paleoclimatologists and water managers to improve the way new reconstruction methodologies are understood and applied (Woodhouse and Lukas, 2006; Rice et al., 2009; Yang et al., 2012; Sauchyn et al., 2015).

Observed negative trends in precipitation and runoff in CC also raise the question of how water resources will evolve over future decades. In this context, runoff projections represent a fundamental input for water managers dealing with current water shortages and threatened water availability. For example, streamflow projections have been obtained for the Mataquito (Demaria et al., 2013a) and Limarí rivers (Vicuña et al., 2010), and projections indicate striking reductions in annual runoff for the second half of the 21st century. Recently, Bozkurt et al. (2018) applied a gridded daily precipitation and temperature dataset to drive and validate the Variable Infiltration Capacity (VIC) hydrological model and produce runoff projections for four Central Chilean catchments. The study demonstrated increases in the frequency and severity of extreme events such as floods and droughts. Meza et al. (2012) have analyzed the impacts of climate change on Maipo River water demand, the main tributary of the Chilean capital of Santiago. This study indicates that the agricultural sector is the most sensitive to climate change as water demand is projected to increase as a consequence of increases in temperature and reductions in precipitation and runoff.

To date, there has been no integrative analysis in Chile, using reconstructed, observed and projected runoff in order to provide insights on the potential shortcomings of the existing water allocation system. We address this gap by developing such analysis in a sub-catchment of Maule river (35°S–36°30S), located in the southern part of the Mediterranean climatic region of CC.

The Maule River is one of the largest rivers in the region, located in south-central Chile, and in the southern part of the Mediterranean climatic region. The river has a drainage area of 21,060 km², of which 26% is used for agriculture. One of the most important water-dependent activities within the catchment is hydropower generation. The Maule River has an installed power capacity of ~1500 MW (CADE-IDEPE, 2004). This represents approximately 10% of the installed power capacity of the Chilean Central Interconnected System (CIS), which supplies energy to about 90% of the national population. Given the importance of the water balance in this catchment for both agricultural activities and hydropower generation, there is a need to link water allocation, as an indicator of water demand, with water availability, considering the historical variability of water resources and projected hydrological changes within the catchment.

Within this context, this study aims to provide a novel methodology for integrating the results provided by hydrological research of multi-centennial runoff and future climate change projections with a compilation of existing consumptive surface water rights in a CC catchment. Specifically, four research questions are addressed:

- How (un)usual is the current scenario of water availability, considering long-term water variability in the catchment?
- How sensitive are calculations of water availability in a catchment of CC to the time window considered for analysis?
- How do existing consumptive surface water rights in a CC catchment compare to the available volume calculated using the Directorate of Water Resources (*Dirección General de Aguas*, or DGA) procedures?
- On a seasonal time scale, will future water availability in a CC catchment satisfy the consumptive surface water rights already granted?

Section 2 of this paper describes the study area, data, and methodology for updating the tree ring reconstruction (2.3.1), the water allocation calculation (2.3.2), and the collection of water rights (2.3.3). Section 3 presents and explains the results of the various aspects of this work. Finally, Section 4 provides discussion and conclusions.

## 2 Study area, data and methodology
### 2.1 Study area
This study focuses on the Perquilauquén at Quella river, a sub-catchment of the Maule River, which flows in a north-west direction, draining an area of 1825 km² (**Figure 1A**). Irrigation is primarily applied to agriculture and pasture-land, both water-intensive activities.

### 2.2 Data
This study incorporates four sources of data on the Perquilauquén at Quella catchment, described in the following sections: observed hydro-meteorological data, a multi-centennial runoff reconstruction time-series, an ensemble of monthly runoff projections, and information on granted WURs provided by the DGA.

#### 2.2.1 Observed hydro-meteorological data
Monthly runoff data were obtained from the Perquilauquén at Quella station for the observed period (1963–2015) and monthly precipitation data were extracted from the Digua en Embalse station located near the outlet of the catchment for the 1947–2015 period (**Figure 1** and **Table 1**). According to **Figure 1B**, the catchment has a Mediterranean-like climate characterized by a wet season (from April to November) during which most precipitation falls during austral winter months (June to August). **Figure 1B** also indicates that Perquilauquén at Quella has a pluvial runoff regime with a maximum flow of ~150 mm/month during the austral winter months (June to August), closely reflecting annual variations in precipitation.

#### 2.2.2 Reconstruction data
The long-term streamflow data used in this study were obtained from the Maule streamflow reconstruction developed by Urrutia et al. (2011). Urrutia et al. (2011) reconstructed ~400 years (1590–2000) of annual streamflow, using a hydrological year defined from April of the current year to March of the following year. The reconstruction was based on data from three streamflow gauges located on the tributaries of the Maule River, which represent 18% to 29% of annual flow (Urrutia et al., 2011). Four tree ring chronologies of *Austrocedrus chilensis* were used as predictors for a multiple regression model to reconstruct Maule River runoff. The reconstruction explained 42% of the observed runoff variance and demonstrated good calibration. More details about this reconstruction can be found in Urrutia et al. (2011). This reconstruction ends in 2000, prior to the CC Mega Drought, and a statistical method, described in Section 2.3.1, was used to extend the reconstruction up to 2015 and to downscale it to the Perquilauquen at Quella subcatchment scale.

**Table 1:** Catchment characteristics. DOI: https://doi.org/10.1525/elementa.340.t1

| Station | Area (km²) | Mean annual runoff (m³sec⁻¹) | Mean accumulated annual precipitation (mm) | Standard deviation (m³sec⁻¹) | CV |
|---|---|---|---|---|---|
| Perquilauquén at Quella | 1825.08 | 56.4 | | 23.61 | 0.42 |
| Digua at Embalse | – | – | 1490.97 | 426.58 | 0.29 |
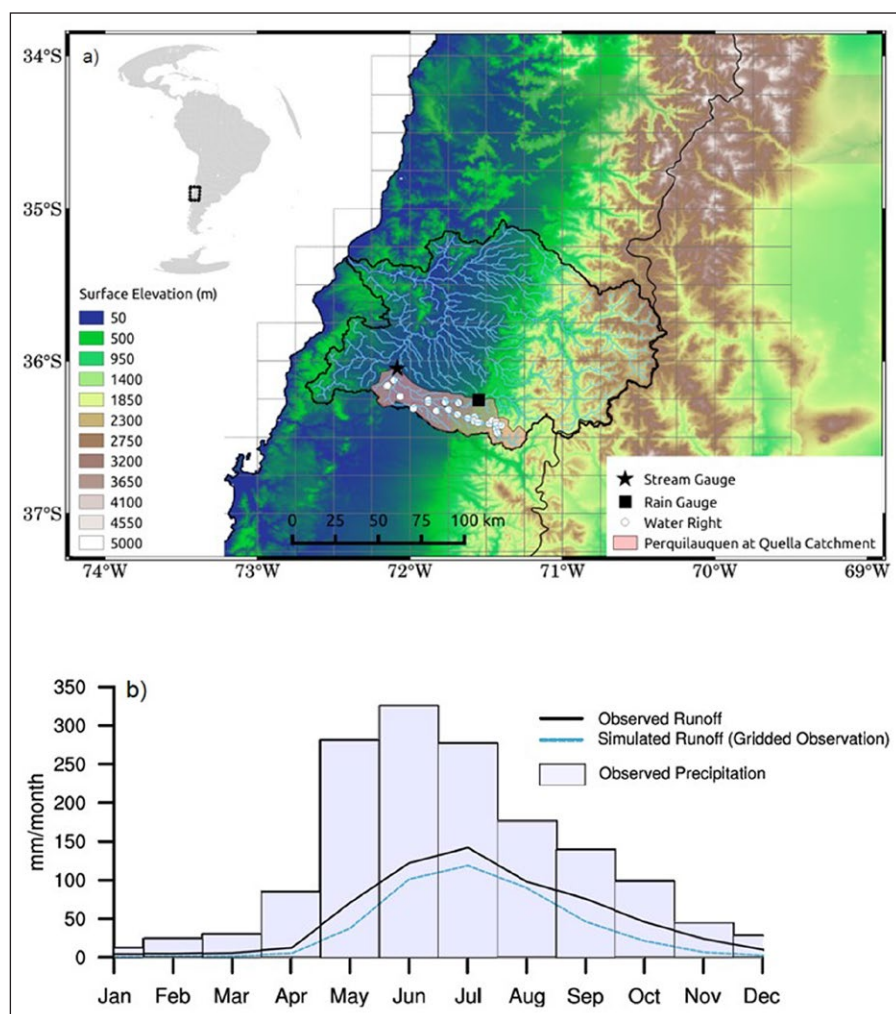
**Figure 1: a)** Location of Perquilauquén at Quella catchment. **b)** Annual cycle of observed precipitation (bars), observed runoff (black line), and simulated runoff using CMIP5 ensemble for the period 1970–2005 (light blue line). DOI: https://doi.org/10.1525/elementa.340.f1

### 2.2.3 Runoff projections

Bozkurt et al. (2018) obtained runoff projections under climate change scenarios for four basins in CC, using the Variable Infiltration Capacity (VIC) hydrological model (Liang et al., 1994). The VIC model is a spatially distributed and process-based hydrologic model (Liang et al., 1994). Model inputs include land-cover distribution, soil information and meteorological forcing data to reproduce a number of key hydrologic variables such as evapotranspiration, snow water equivalent, soil moisture, surface runoff and baseflow. Runoff projection data used in this study represent the sum of surface runoff and baseflow from each grid cell, without routing. Detailed descriptions of the VIC model, calibration and validation can be found in Demaria et al. (2013b) and Bozkurt et al. (2018).

To generate the forcing meteorological input data for VIC model, Bozkurt et al. (2018) used an observation-based gridded dataset of precipitation and temperature (1960–2005) at 0.25° × 0.25° spatial resolution produced for CC by Demaria et al. (2013b) to downscale 26 General Circulation Model (GCM) outputs from the Coupled Model Intercomparison Project phase 5 (CMIP5; Taylor et al. (2012)) through a bias correction technique, imposing observed statistical probability distribution function onto modeled climate variables (Piani et al., 2010).

Historical (1960–2005) and future projected daily precipitation and temperatures from the 26 CMIP5 models under the RCP8.5 scenario (2006–2099) were corrected for bias and were then used to drive the validated VIC model for four catchments in Central Chile, including the Maule river basin and its sub-catchments, such as Perquilauquen at Quella catchment (**Figure 1A**).

### 2.2.4 Collection of granted water rights

Water entitlements are classified according to their use as either permanent or eventual water rights. PEWRs (permanently exercisable water rights) correspond to runoff with probability of exceedance greater than 85%, which can be used uninterruptedly. EEWRs (eventually exercisable water rights) correspond to large streamflow volumes, calculated as runoff with 5% probability of exceedance (DGA, 2008), which can be used only after permanent water rights have been satisfied and while respecting stipulated ecological river runoff. Ecological runoff is defined as the minimum runoff required to satisfy the environmental needs of the river ecosystem.

The granted water rights database available at the Chilean catchment information collected by CAMELS-CL (Alvarez-Garreton et al., 2018) was used to collect information about monthly granted surface water rights in the

Perquilauquén in Quella River. Geographical information systems were used to:

- Plot all water rights in the VII and VIII Regions.
- Select the water rights located within the study basin.

Identify and classify permanent and eventual water rights within the group of water rights previously plotted.

### 2.3 Methodology

Runoff analysis for Perquilaquén at Quella and corresponding WURs followed four stages. First, a downscaling and extension of the tree ring reconstruction of runoff time series using the observed data was performed (section 2.3.1). Second, following DGA procedure, the available volume of runoff to be granted as permanently and eventually exercisable surface water rights on an annual basis was calculated considering 400 years of reconstructed runoff (1590–2000), observed gauged runoff (1963–2015) and projected runoff for 2006 to 2098 (section 2.3.2). Despite the availability of observed data for the catchment until 2015, the CMIP5 experimental setup ran the GCMs considering projected scenarios of future GHG emissions for the period 2006 to 2098. Third, a more extensive study of WURs was conducted looking at seasonal analysis of available water volume to be granted as water rights for observed and projected runoff. Finally, available granted consumptive surface water rights at Perquilauquén at Quella were retrieved from the DGA and analyzed for a multi-centennial context. This methodology was developed and applied by a multidisciplinary team, in the fields of dendro-chronology, climatology, hydrology and law.

#### 2.3.1 Perquilauquén at Quella runoff reconstruction extension

The Urrutia et al. (2011) tree ring runoff reconstruction downscaled at Perquilauquén at Quella sub-catchment scale covers the 1590–2000 period, given that tree ring chronologies are not available for the 2000–2015 period. In order to extend and downscale the reconstruction until 2015 (and to the sub-catchment scale) and cover the CC Mega Drought, a correction based on Juckes et al. (2007) was applied to the runoff reconstruction data to fit its variance (42% of the variance of gauged runoff) to that of the observed time series. First, a ratio between the standard deviation of observed and reconstructed annual runoff (April–March) for the 1963–2000 period was calculated. Second, runoff reconstruction data were corrected using the calculated ratio to obtain a reconstructed runoff time series for the complete period 1690–2015.

#### 2.3.2 Determination of permanently and eventually exercisable water availability

According to the DGA and as governed by the Water Code, the available water supply in a catchment is determined on a monthly basis as follows:

**Permanently exercisable water rights (PEWRs):**

$$Q_{PEWR\ i} = Q_{85\ i} - Q_{ecol\ i} \qquad \text{(Eq. 1)}$$

Where,
$Q_{85\ i}$ = 85% probability of exceedance runoff for month i

$Q_{ecol\ i}$ = Ecological runoff for month i

**Eventually exercisable water rights (EEWRs):**

$$Q_{EEWR\ i} = Q_{5\ i} - Q_{available\ permanently\ i} \qquad \text{(Eq. 2)}$$

Where,
$Q_5$ = 5% probability of exceedance runoff for month i

**Monthly ecological runoff** is calculated as follows:

i) If $0.5 \times Q_{95\ i}$ is less than $0.2 \times$ the mean annual runoff $Q_{annual}$, then,

$$Q_{ecol\ i} = 0.5 \times Q_{95\ i} \qquad \text{(Eq. 3)}$$

ii) If $0.2 \times Q_{annual}$ is less than $0.5 \times Q_{95\ i}$, then,

$$Q_{ecol\ i} = 0.2 \times Q_{annual} \qquad \text{(Eq. 4)}$$

The available volume to be granted as WURs for the Perquilauquén River was calculated considering:

1. Permanent and eventually available volume, calculated for each month using gauged runoff (OBS, 1963–2015).
2. Permanent and eventually available volume on an annual basis, calculated using OBS, reconstructed (REC, 1590–2015), and projected (PROJ, 2050–2098) runoff to allow for comparison.

Lognormal and empirical distribution functions were used to calculate different exceedance probabilities for runoff.

#### 2.3.3 Determination of water supply projections at a seasonal time scale

To analyze the evolution of water availability at different seasons through the end of the century, we conducted a complementary calculation. Permanent and eventually available water volume on a seasonal basis was calculated using both OBS and PROJ runoff to allow for comparison and to determine the seasons during which the river is more susceptible to water shortages. We applied Eq. 1, Eq. 2, Eq. 3 and Eq. 4 to autumn (March–May), winter (June–August), spring (September–November) and summer (December–February) time series during the OBS and the PROJ period to obtain and compare PEWR and EEWR.

## 3 Results

In this section, we assess the water supply and granted WURs of one CC catchment on a multicentennial time scale, using the methodology described in Section 2.3. It is worth noting that this methodology can be extended and applied to other Mediterranean-like climate catchments of the region, assuming data availability.

### 3.1 Reconstruction extension

We applied the variance correction methodology described in Section 2.3.1 to extend the tree ring runoff reconstruction developed by Urrutia et al. (2011) for the period 1590–2000 up to the year 2015. The comparison between original runoff reconstruction data and the variance- corrected reconstruction extended to the year 2015 is presented in Figure S1 (Supplementary Material). Although this meth-

odology presents the limitation of changing the variability of the original reconstruction (ratio between the standard deviation of the observed and the reconstructed runoff was of 1.5), it has the advantage of including the MD in a multi-century runoff reconstruction. As presented in Figure S1, once the original runoff reconstruction is corrected, both time series show the same multidecadal fluctuations.

We fitted a 20-year moving average to the data (indicated by a bold black line) along with the extended annual runoff time series and observed annual runoff (solid line with cross marks) in **Figure 2**. The 20-year moving average time series indicates important multidecadal variability, which may be related to the Pacific Decadal Oscillation (PDO) and the Southern Annular Mode (SAM) signal as already reported in previous studies developed in the region (Urrutia et al., 2011; Muñoz et al., 2016; Barria et al., 2017). We ranked the 20-year moving average time series and compared annual runoff during the MD period against the long dry spells observed in the reconstructed time series. The period of the MD in Perquilauquén at Quella is ranked among the fifth most severe dry spells during the last four centuries, indicating that although is not an unprecedented event in the catchment, it is extraordinary. This result also reinforces the importance of analyzing water availability for a long-term context rather than using only a few decades of station-based information. The five most severe dry spells found in the reconstruction for the Perquilauquén at Quella catchment are indicated with red lines in **Figure 2** and correspond to the periods 1612–1631, 1812–1831, 1908–1927, 1952–1971 and 2006–2015. Similarly, we analyzed the extreme dry spells in the original (not variance-corrected) reconstruction (see Fig S1 of the Supplementary Material), which indicated that periods of extreme dry spells (droughts) are coincident with the original and extended reconstruction, except for the most recent MD period, which is not covered by the original time series.

## 3.2 Annual available water supply in a multi-centennial context

In order to calculate the theoretical annual available water supply to be granted as WURs in the catchment, and to assess this volume in a multi-centennial context, we calculated annual runoff with 95%, 85%, 50% and 5% probability of exceedance at the catchment for the OBS period (1963–2015), the reconstructed time series (REC, 1590–2015) and the projections of runoff for the second half of the 21st century (PROJ, 2050–2098). Supported by the Lilliefors test (Lilliefors, 1969), we fitted a lognormal distribution to the OBS, REC and PROJ annual runoff time series to calculate the runoff for the different probabilities of exceedances. We then used the calculation procedures established by the DGA (Section 2.3.2) and obtained the theoretical PEWRs and EEWRs at Perquilauquén at Quella, which by definition are the available runoff to be granted as WUR (results summarized in **Table 2**). Important differences between PEWRs and EEWRs can be observed, depending on the period of calculation, indicating the sensitivity of DGA methodology to the time window. Theoretical PEWRs based over the REC period are 30% larger than theoretical PEWRs for the OBS period. If OBS WURs were calculated using information before the MD, considering the 1963–2000 or the 1963–2009 periods (not shown), PEWRs would have been $75.9 \times 10^7 m^3$ and $76.3 \times 10^7 m^3$, respectively, 19% and 15% higher than PEWRs calculated considering the entire OBS period and including the MD years (2010–2015). This is because the MD was an extraordinary event, even in the context of significant decadal variability in the region, as evidenced by the tree ring reconstruction. In contrast, theoretical PEWRs calculated based on the PROJ period are 41% lower than calculated PEWRs based on OBS data. Available EEWRs in the catchment, calculated based on REC and PROJ time periods, indicate that volumes are
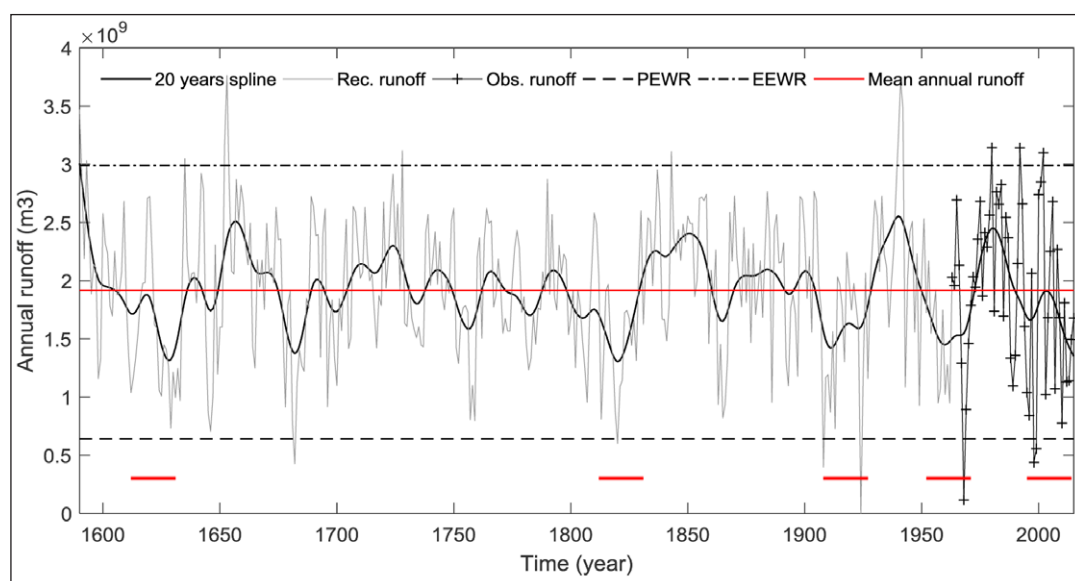


**Figure 2:** Extended and variance-corrected reconstructed annual runoff time series (black line) and observed annual time series (line with crosses). The dashed line represents theoretical OBS PEWR, calculated using annual runoff for the observed period (1963–2015); the dot-dash line represents OBS EEWR calculated using annual runoff during the observed period (1963–2015). DOI: https://doi.org/10.1525/elementa.340.f2

**Table 2:** Determination of annual PEWR and EEWR using observed, reconstructed and projected data. DOI: https://doi.org/10.1525/elementa.340.t2

| V annual ($10^7 m^3$) | Observed period (1963–2015) | Reconstruction (1590–2015) | Projection (2050–2098) |
|---|---|---|---|
| **Q95** | 74.90 | 96.30 | 37.50 |
| **Q85** | 99.80 | 122.00 | 49.00 |
| **Q50** | 162.00 | 181.00 | 99.10 |
| **Q5** | 363.00 | 340.00 | 230.00 |
| **Ecological flow** | 35.80 | 38.40 | 18.80 |
| **PEWR** | 63.90 | 83.10 | 30.30 |
| **EEWR** | 299.00 | 257.00 | 199.00 |
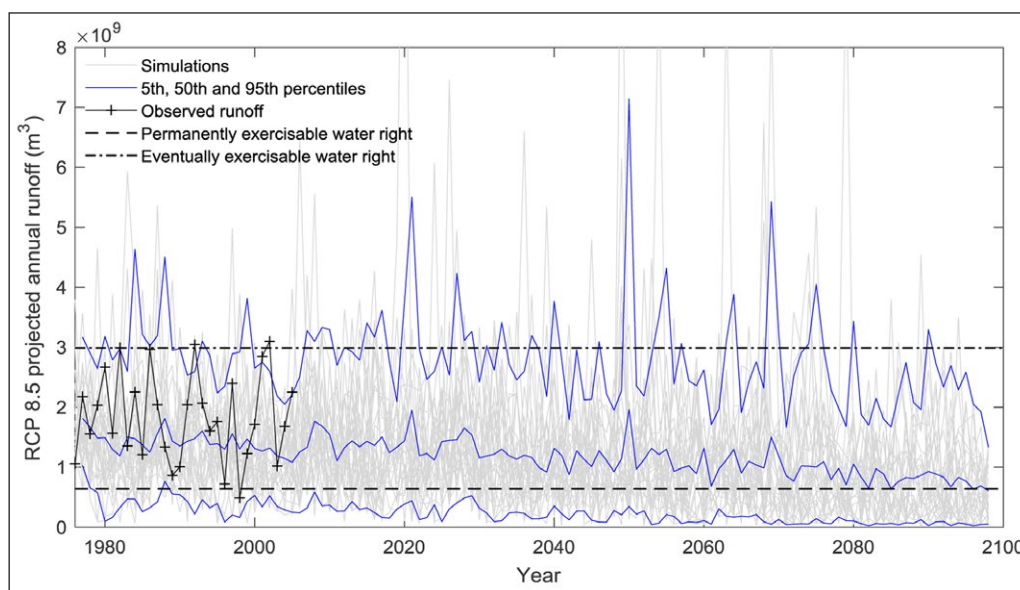


**Figure 3:** Annual runoff simulations using CMIP5 ensemble (grey lines) for the historical and projected period (2006–2080). Blue lines indicate the 5th, median and 95th percentiles of simulated data. Black lines with crosses indicate observed mean annual runoff for the catchment. The dashed line indicates the OBS PEWR calculated using annual runoff for the observed period (1963–2015) and the dot-dashed line indicates OBS EEWR calculated using annual runoff for the observed period (1963–2015). DOI: https://doi.org/10.1525/elementa.340.f3

14% and 39% lower than those obtained based on the OBS period, respectively.

**Figure 2** presents extended reconstructed time series along with calculated PEWR and EEWR based on OBS data. These results indicate that the REC annual runoff exceeds the OBS EEWR for ten different years, while OBS EEWR is exceeded three times during the observed period. On the other hand, REC annual runoff is below OBS PEWR in four different years, while OBS annual runoff is below OBS PEWR on three occasions. According to the results presented in **Table 2** and in **Figure 3**, the reconstructed time series indicate reductions in streamflow during past decades (OBS period) that explain why the theoretical OBS PEWR, and OBS EEWR are lower than theoretical REC PEWR and REC EEWR.

**Figure 3** presents simulations of annual runoff using the CMIP5 ensemble for the Perquilauquén at Quella catchment, along with calculated PEWR and EEWR based on the OBS period. According to these results, CMIP5 projections

indicate continuous reductions in annual runoff through to the end of the 21st century. Calculating PEWR and EEWR based on OBS data can overestimate the volume of water actually available as water supply during the second half of the century. Of particular concern, according to **Figure 3**, median annual runoff simulated using the CMIP5 ensemble gradually approaches calculated OBS PEWR (by around 2080), which corresponds to a volume with high probability of exceedance during the OBS period. That is one of the main conclusions of the study, which indicate that current calculations used to grant water rights overestimate water supply for coming decades.

In **Figure 4**, we present a comparison of the exceedance probability of annual OBS, REC and PROJ data. The 5% exceedance probability of REC runoff is 6% lower than OBS extremes, whereas the 95% exceedance probability of REC runoff is 29% higher than OBS extremes, indicating that REC runoff has greater variability than OBS runoff and that overall, annual runoff decreases for the OBS period as
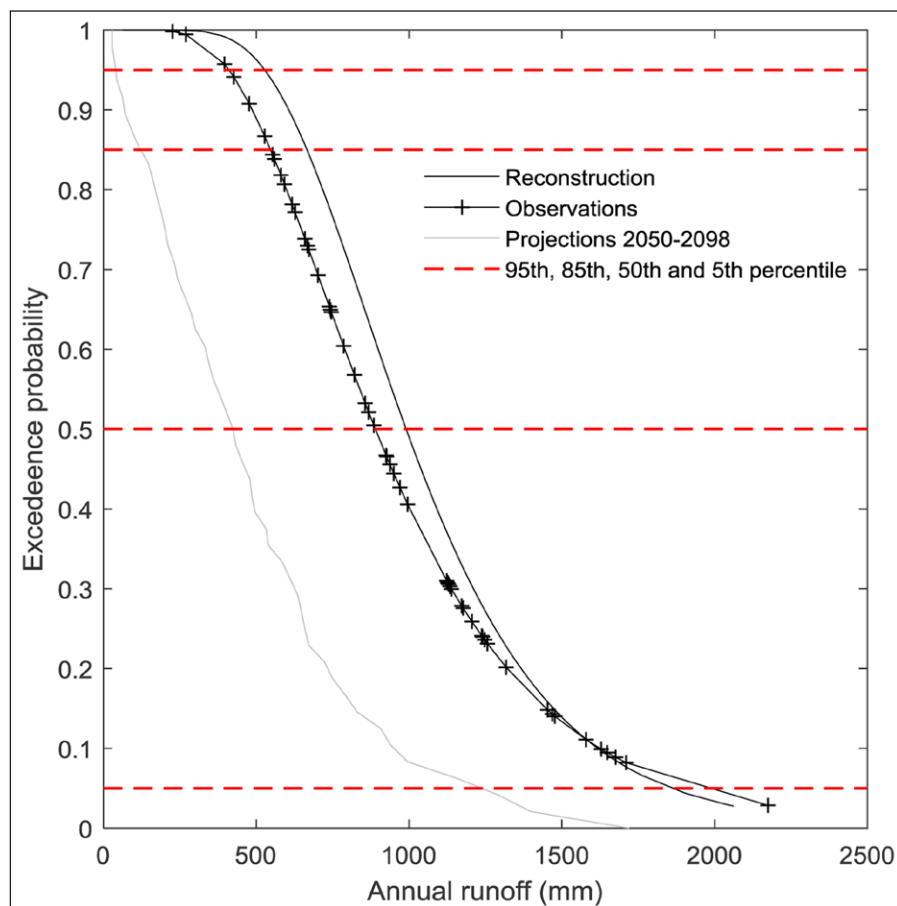
**Figure 4:** Exceedance probability of annual runoff considering observed (OBS), reconstructed (REC) and projected (PROJ) time series. Red lines correspond to 95th, 85th, 50th and 5th percentiles. DOI: https://doi.org/10.1525/elementa.340.f4

compared to the REC period. These values of exceedance probabilities would show an even greater departure from present day values if OBS were to be calculated for a period excluding the MD. This result indicates that WURs granted by the DGA before evaluating the MD are based on significant overestimation of current water availability in the catchment. Regarding projections, the results presented in **Table 2** and in **Figure 4** indicate that all calculated percentiles of annual runoff (5%, 50%, 85% and 95%) for the PROJ period are lower than those for the OBS period (1963–2015). On average, PROJ annual runoff is 39% lower than in the OBS period for all percentiles calculated.

### 3.3 Comparison of currently available water supply and runoff projections at a seasonal time scale
In order to analyze how current calculations of water availability change when considering projected runoff at annual and seasonal scales, we calculated the probability of exceedance of annual and seasonal runoff for the OBS and PROJ periods. These results are presented in **Figures 5** and **6**, respectively.

**Figures 5** and **6** indicate that there are large differences between the probability of exceedance of the PROJ and OBS runoff for all seasons, with PROJ runoff considerably lower than in OBS runoff for the second half of the century. According to **Figures 5, 6A** and **6D**, based on OBS data, annual, autumn and summer water supply is projected to

be lower than calculated EEWRs by the second half of the century (2050–2098).

Runoff is projected to decrease for all seasons during the second half of the century. For winter runoff, OBS PEWR correspond to runoff with 98% of exceedance probability, which shifts to an 80% exceedance probability during the PROJ period 2050–2098. For the summer season, PEWR shift from an exceedance probability of 82% during the OBS period to a 72% exceedance probability during the PROJ period. Annual PEWR vary from a probability of exceedance of 99% (OBS) to 84% (PROJ) exceedance probability. In autumn and spring, the PEWR probability of exceedance varies from 94% (OBS) to 82% (PROJ) and 96% (OBS) to 71% (PROJ), respectively. The largest difference between OBS and PROJ runoff for the Perquilauquén at Quella River occurs during the spring season.

### 3.4 Granted water rights and comparison with currently available water supply
To compare theoretical and currently allocated water rights (which contains monthly allocated volumes), we calculated monthly PEWRs and EEWRs from the OBS monthly data (**Table 3**).

Based on the analysis of the public DGA database, we found 1986 consumptive and surface granted PEWRs and 18 consumptive and surface granted EEWRs within the Perquilauquén at Quella catchment which, according to
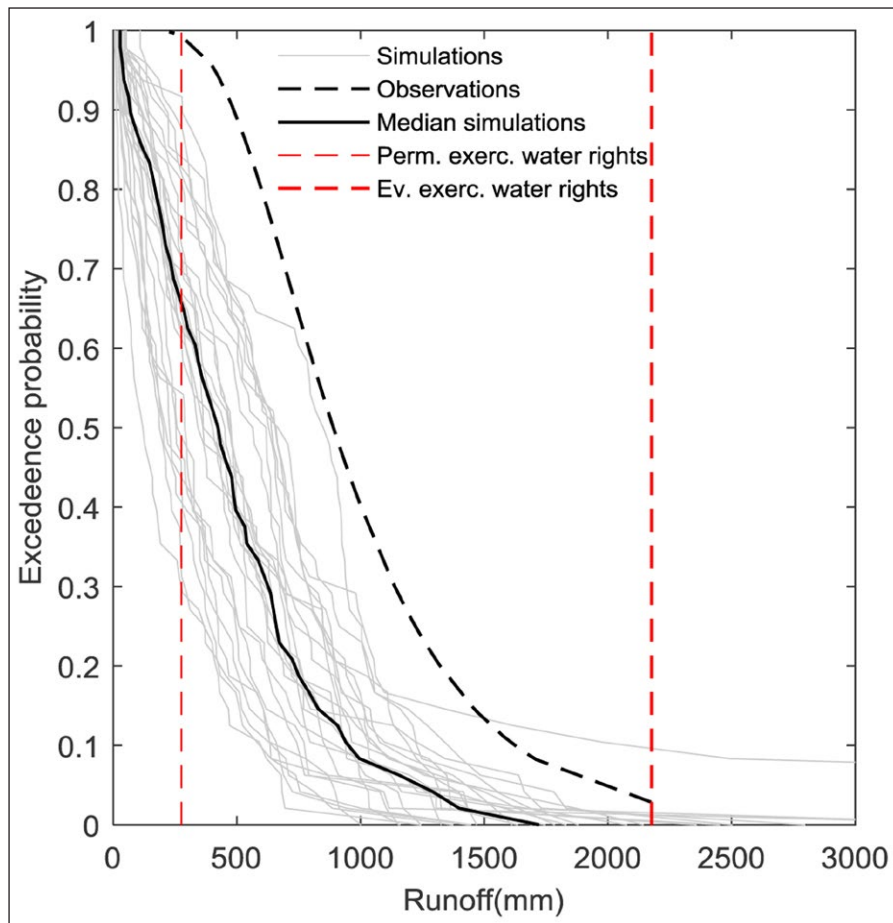
**Figure 5:** Exceedance probability of projected annual runoff. Dashed red line and bold dashed red line indicate theoretical OBS PEWR and theoretical OBS EEWE, respectively, calculated based on observed data (1963–2015). Dashed black line represents mean annual runoff during the observed period (1963–2015), and each grey line is one GCM in the ensemble. DOI: https://doi.org/10.1525/elementa.340.f5

their legal resolutions, were conferred between 1991 and 2014. Importantly, 97% of these rights were granted as "water shares"; the equivalent volume of these shares must be determined by local authorities and other relevant bodies regulating water use rights, hence can not be directly transformed into water volumes. Furthermore, these data correspond to surface and consumptive water rights, which means that all groundwater rights are not included in these analyses. Information regarding currently granted consumptive PEWRs and EEWRs collected from the DGA is presented in **Table 4**, and locations for these rights are plotted in **Figure 1A**. It is worth noting that the DGA provides information on granted WURs, but the Directorate does not perform monitoring of actual usage.

As explained in Section 2.3.2, we used the lognormal distribution for the OBS period (1963–2015) at the Perquilauquén at Quella station to obtain the 95%, 85%, 50% and 5% probabilities of exceedance to obtain theoretical monthly available PEWRs and EEWRs for the catchment (**Table 3**). A comparison between theoretical monthly PEWRs and EEWRs and currently granted PEWRs and EEWRs as obtained from the DGA public database are presented in **Figure 7A** and **7B**, respectively.

According to the results presented in **Tables 3** and **4** and in **Figure 7**, the greatest water availability to be

granted as permanent and eventual water rights (theoretical PEWRs and EEWRs) takes place during winter months (June–August). 61% of theoretical PEWRs occur during the winter season, and winter flow contributes 51% of the total annual volume for the theoretical EEWRs. On the other hand, considering currently granted PEWRs obtained from the DGA, the largest percentage of annual volume (35%) has been granted during winter months (June–August), with 22% granted in autumn and 19% during spring. According to our analyses, only 4% of total annual water supply is available to be granted as water rights during the summer months (December–February). Nevertheless, the public database of granted water rights provided by the DGA indicates that 21.5% and 21% of total annual volume has been granted as PEWRs and EEWRs during the summer season, respectively.

According to **Figure 7A**, the Perquilauquén at Quella catchment is therefore over-allocated, with granted PEWRs exceeding available monthly volume calculated according to DGA methodology in every month (in other words, theoretical OBS PEWR). This is very concerning, considering that PEWRs authorize the holder to use the water in the corresponding amount unless the catchment does not have a sufficient volume to satisfy this water right. Potentially, all of the theoretical volume available in the
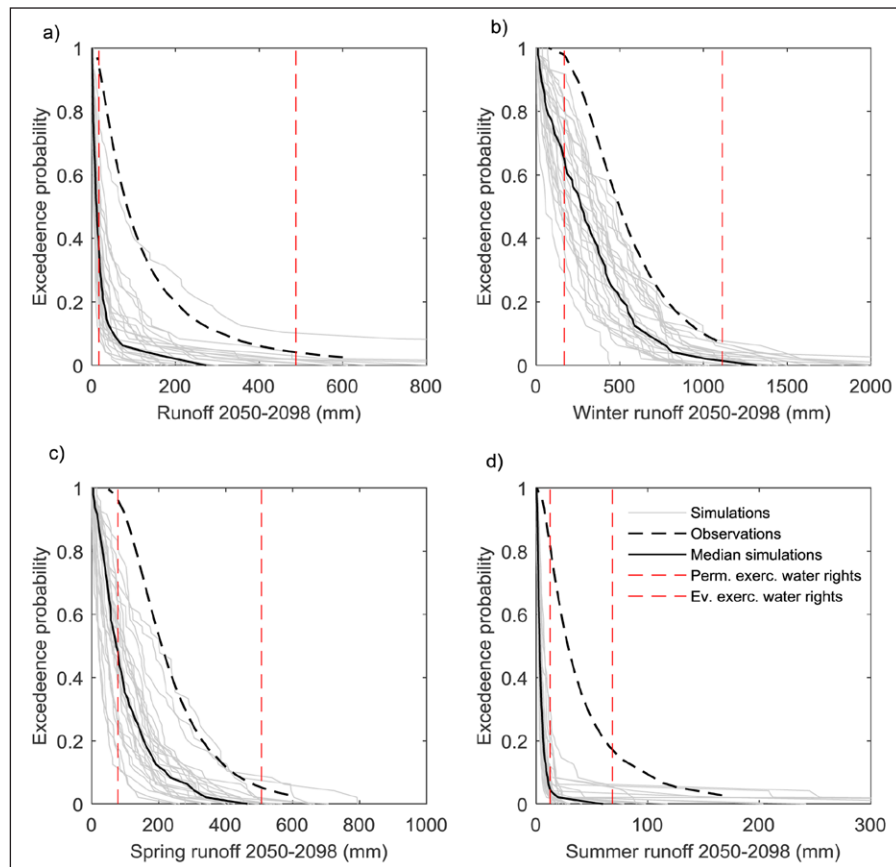
**Figure 6:** Exceedance probability of projected seasonal runoff for the period 2050–2098. Dashed red line and bold dashed red line indicate PEWR and EEWE, respectively. Dashed black line represents mean annual runoff during the observed period (1963–2005): **(a)** autumn, **(b)** winter, **(c)** spring and **(d)** summer. DOI: https://doi.org/10.1525/elementa.340.f6

**Table 3:** Determination of theoretical PEWR and EEWR according to observed data. DOI: https://doi.org/10.1525/elementa.340.t3

| Monthly runoff ($10^7 m^3$) | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Q95** | 0.07 | 0.18 | 0.15 | 0.23 | 1.55 | 4.74 | 9.76 | 9.81 | 7.10 | 2.91 | 1.16 | 0.42 |
| **Q85** | 0.80 | 0.60 | 0.49 | 0.72 | 2.94 | 12.30 | 16.40 | 14.10 | 11.80 | 5.47 | 2.51 | 1.20 |
| **Q50** | 1.57 | 1.13 | 1.20 | 1.78 | 9.06 | 25.80 | 33.40 | 25.80 | 18.50 | 10.80 | 5.17 | 3.17 |
| **Q5** | 3.27 | 2.76 | 5.00 | 10.20 | 77.10 | 81.60 | 85.30 | 66.80 | 51.00 | 35.70 | 20.10 | 8.70 |
| **Ecological flow** | 0.03 | 0.09 | 0.08 | 0.12 | 0.77 | 2.37 | 4.88 | 4.90 | 3.55 | 1.45 | 0.58 | 0.21 |
| **PEWR** | 0.76 | 0.51 | 0.42 | 0.60 | 2.17 | 9.89 | 11.50 | 9.21 | 8.26 | 4.02 | 1.93 | 1.00 |
| **EEWR** | 2.51 | 2.25 | 4.59 | 9.58 | 74.90 | 71.70 | 73.90 | 57.60 | 42.70 | 31.70 | 18.10 | 7.70 |

river could be consumed. **Figure 7B** indicates that EEWRs are also over-allocated in summer months (December to February) and March. However, because EEWRs authorize the use of water only when the catchment has a surplus and after supplying all previously-granted PEWRs and EEWRs, the PEWRs situation is much more concerning. It is worth noting that the influence of return flows is implicit in the calculation of water availability because the analyzes are based on fluviometric data measured in the outlet of the subcatchment analyzed. Then, when return flows occurred, that input is measured in the gauge and is part of the calculation of water availability.

Furthermore, and acknowledging the critical situation regarding granted PEWRs in the catchment, we explore and compare the evolution of annual granted and theoretical (station-based) PEWRs, as presented in **Figure 8**. According to these results, a substantial jump or increment in the volume of granted PEWRs (red line) occurred in 1996; after this date, annual granted WURs have exceeded available theoretical WURs in the catchment. The drastic increment of granted PEWRs in 1996 could be related to the severe drought that affected the central zone of Chile that year or may be related to an increase in the registration of granted WURs by their holders that year.

**Table 4:** Permanently and eventually exercisable granted water rights (DGA). DOI: https://doi.org/10.1525/elementa.340.t4

| Granted Water Rights ($10^7 m^3$) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Permanently Granted Rights** | 9,55 | 8,64 | 9,56 | 9,25 | 9,56 | 12,23 | 19,89 | 12,65 | 9,25 | 9,56 | 9,25 | 9,56 |
| **Eventually Granted Rights** | 8,56 | 7,74 | 8,59 | 8,34 | 8,61 | 13,51 | 13,95 | 13,95 | 13,5 | 8,6 | 8,33 | 8,58 |
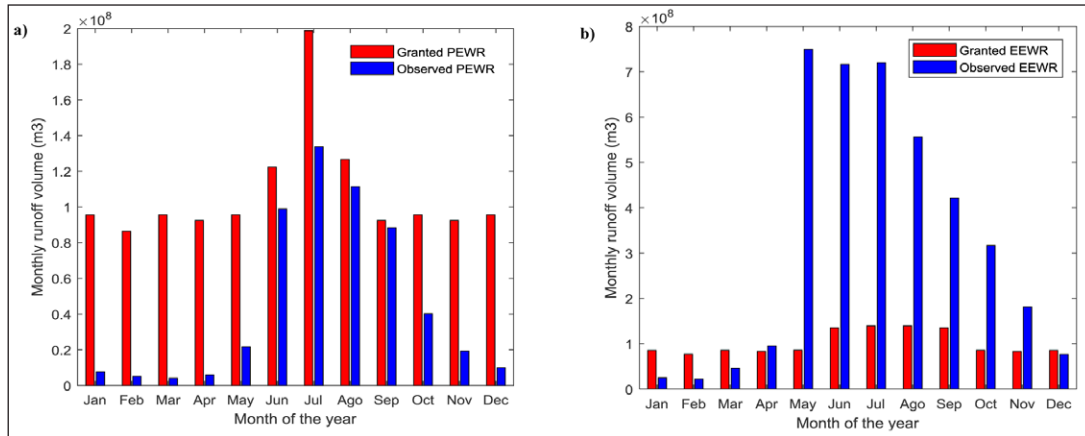


**Figure 7: a)** Comparison of theoretical OBS PEWR and granted PEWR at Perquilauquén at Quella catchment. **b)** Comparison of theoretical OBS EEWR and granted EEWR at Perquilauquén at Quella catchment. DOI: https://doi.org/10.1525/elementa.340.f7
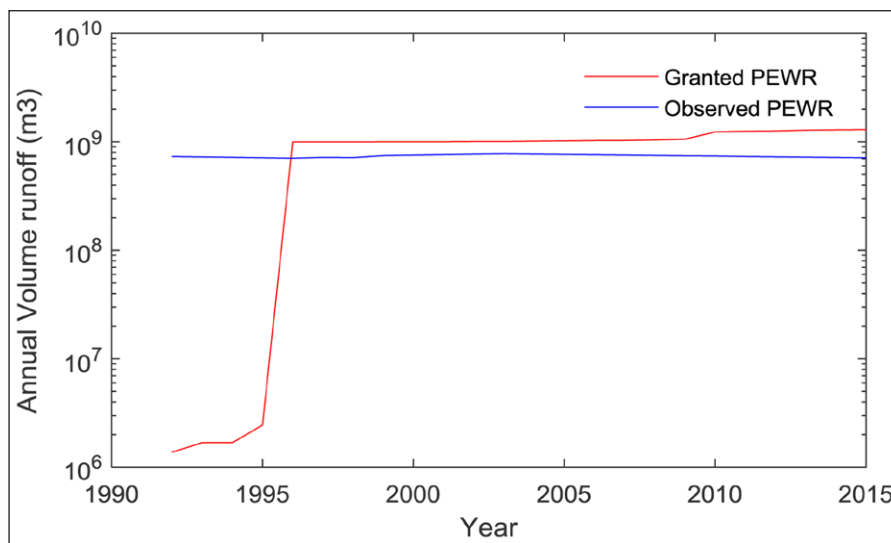


**Figure 8:** Comparison of change in theoretical OBS Annual PEWR and granted Annual PEWR at Perquilauquén at Quella catchment. DOI: https://doi.org/10.1525/elementa.340.f8

The information collected from the DGA has considerable limitations. Not all granted water rights and corresponding transactions have been recorded to the public database; therefore, we interpret the information presented in **Table 4** as an underestimation of the actual granted WURs in this catchment in particular, and for the country overall.

## 4 Discussion and Conclusions

A comprehensive and integrative methodology was applied to analyze water use rights (WURs) in a multi-centennial historical context and under a projected climate change scenario. The trans-disciplinary approach inte-

grated insight from water engineers, climatologists and lawyers to assess and draw conclusions about a key process in natural resources management in Chile: water allocation. The methodology was applied to one catchment in Central Chile but could be extended to other regions where runoff reconstructions exist or can be obtained.

This integrative methodology has faced some important difficulties, specifically related to data limitations of allocated water rights. First, an important lack of reliable water uses rights records. A World Bank report (World Bank, 2011) determined that a considerable number of WURs have not been registered in the DGA database.

This difficulty could be addressed by site visits to review WURs entitlements registered in local municipalities or other governing authorities within the catchment. However, this represents a very time-consuming task beyond the scope of this study and is proposed for future investigations. Recognizing these limitations, the study focuses on the methodological development to critically assess current water availability in a multi-centennial context. Second, the DGA public database does not contain any information about the effective use of WURs; together with the DGA's inability to audit water users, this implies that the database used in the present study may include water rights that have been granted but are not actually used. Finally, there is the difficulty of working with runoff data in a catchment that is no longer in natural state. Nevertheless, according to the visual inspection performed by the authors and the information published by Rubio and McPhee (2010), Perquilauquén at Quella is a suitable case study for calibrating and running hydrological models such as those used in this study.

The results presented in this study suggest that the available volume to be granted as WURs in a CC catchment, Perquilauquén at Quella, is highly sensitive to the period included in calculations. There are large differences between the calculated available annual volume to be granted as permanent and eventual water rights in the catchment when considering ~400 year reconstructed runoff (REC, 1590–2015), observed runoff (OBS, 1963–2015) and projected runoff for the second half of the century (PROJ, 2050–2098). Overall, the theoretical annual volume to be granted as permanently and eventually exercisable water rights (PEWRs and EEWRs, respectively)- in Perquilauquén at Quella is 30% larger than the observed period for the reconstructed runoff, whereas it is 41% lower than the observed period for the projected runoff. Additionally, calculations of water availability during the observed period considering the years before the Mega Drought (1963–2009) result in an overestimation of the OBS PEWRs by approximately 19%, indicating an important dependence of results on the time window considered for evaluation.

These results are especially concerning if we consider current drought conditions as well as the occurrence of extreme events such as the recent Mega Drought in the region. Furthermore, projections indicate drier climatic conditions for coming decades, with the greatest reductions projected for the summer season.

A seasonal analysis of water availability found that for all seasons, the available volume to be granted as permanent and eventual water rights is considerably lower when calculated using the PROJ (2050–2080) data than when using the OBS (1963–2015) data. Specifically, the available volume to be granted as PEWR for the spring season varies from a 96% to 71% probability of exceedance runoff between the OBS and PROJ periods, respectively. Similar reductions are observed for other seasons. Therefore, current assessments of runoff availability may overestimate available water volumes to be granted as WURs for the second half of the century.

On the other hand, according to an analysis of granted consumptive PEWRs collated by the DGA and presented in this study, the Perquilauquén at Quella River is over-allocated during every month of the year. Considering the incompleteness of the DGA database, the over-assignment of WURs may be even greater than indicated by these records. In terms of consumptive EEWRs, the Perquilauquén at Quella River is also over-allocated, but only during summer months. Establishing the necessary conditions to implement an Integrated Water Resource Management Plan represents a critical task; the structure for such a plan is currently under discussion and design by relevant authorities and water users in Chile (*Instituto de Ingenieros*, 2012).

From a legal perspective, the results presented in this study reveal serious shortcomings regarding the quality and availability of critical environmental data such as water entitlements. First of all, under existing water legislation, WURs holders are not required to inform the Directorate of Water of their existing entitlements, or of WURs transfers. Second, of the 2004 granted WURs on record for the catchment under study, 1947 (97%) of these are registered as "water shares", meaning their volume equivalents vary depending on the subcatchment and local organizations that own and use this water, a factor that further complicates the potential to quantify actual water allocations. Asymmetries and difficulties in access to this information are in conflict with the Principle 10 of the Rio Declaration (United Nations, 1992), which seeks to ensure public access to information concerning the environment.

Additionally, the comparison of theoretical calculations of runoff availability over varying periods of time reveals a significant gap between the rigid nature of legal processes and regulations (such as the Chilean Water Code) and the non-stationarity of hydrological and biological processes (such as the dynamic water cycle). The current legal rationale of WURs, which are defined as property rights that can be inherited in perpetuity, fails to recognize the dynamic nature of hydrology (water supply), which will only increase under a changing climate, and in this way also poses challenges to developing and implementing effective climate change adaptation in the country (MOP, 2012).

In conclusion, given the profound human influence on water resources and availability in the Anthropocene, it is important to evaluate water availability over longer time scales (i.e., multi-centennial) and to use integrative methodologies. The runoff reconstructions allow us to observe the recently experienced Mega Drought (2010–2015) within the context of century-long historical records, highlighting that this region is prone to multi-year droughts. Moreover, given that the runoff projections suggest important declines in the future, the set of this information should be considered a key input for water managers. Appropriate water management and water use strategies for the region need to be developed in order to ensure an appropriate water shortage and drought regulations in CC catchments.

Furthermore, water rights calculations need to be reviewed and revised in order to improve water use and distribution and ensure the conservation of ecological flows and ecosystem services in the region. Similarly, legal frameworks for water management in Chile require important reconsiderations in order to ensure their coherence with the biophysical framework (ecological

requirements) of the country, especially in the context of climate change, drawing special attention to the role of water governance to address water scarcity issues in Chile in the Anthropocene.

## Data Accessibility Statement

## Supplemental file

The supplemental file for this article can be found as follows:

· **Figure S1.** Comparison of original, extended and variance-corrected Perquilauquén at Quella runoff reconstruction. DOI: https://doi.org/10.1525/elementa.340.s1

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## Competing interests

The authors have no competing interests to declare.

## Author contribution

· Contributed to conception and design: PB, MR, PM, AM, DB and CA
· Contributed to acquisition of data: PB, AM, DB, CA
· Contributed to analysis and interpretation of data: PB, MR, PM, AM, DB and CA
· Drafted and/or revised the article: PB, MR, PM, AM, DB and CA
· Approved the submitted version for publication: PB, MR, PM, AM, DB and CA

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