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ANÁLISIS DEL POTENCIAL DE LA INFORMACIÓN DE DERECHOS DE APROVECHAMIENTO DE AGUA PARA APLICACIONES HIDROLÓGICAS EN CHILE CONTINENTAL.

TESIS PARA OPTAR AL GRADO DE MAGÍSTER EN CIENCIAS DE LA INGENIERÍA, MENCIÓN RECURSOS Y MEDIO AMBIENTE HÍDRICO

NERY ANGELINA BUDDE GARCÍA

PROFESOR GUÍA:

PABLO MENDOZA ZÚÑIGA

MIEMBROS DE LA COMISIÓN:

CAMILA ÁLVAREZ GARRETÓN

NICOLÁS VÁSQUEZ PLACENCIA

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RESUMEN DE LA TESIS PARA OPTAR AL GRADO DE: Magíster en Ciencias de la Ingeniería, mención Recursos y Medio Ambiente Hídrico
POR: Nery Angelina Budde García
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PROFESOR GUIA: Pablo Mendoza Zúñiga

ANÁLISIS DEL POTENCIAL DE LA INFORMACIÓN DE DERECHOS DE APROVECHAMIENTO DE AGUA PARA APLICACIONES HIDROLÓGICAS EN CHILE CONTINENTAL.

La base de datos de Derechos de Aprovechamiento de Agua (DAA) de Chile contiene información relevante para estimar las demandas de agua, así como su disponibilidad para el otorgamiento de nuevos DAAs en el país. Si bien esta base de datos está disponible públicamente en el sitio web de la Dirección General de Aguas (DGA), contiene deficiencias que dificultan una correcta estimación de los caudales asignados como DAAs. En este trabajo, dicha información es revisada y corregida con el propósito de (i) realizar un análisis de los DAAs otorgados en Chile, y (ii) utilizarla en dos aplicaciones con énfasis en la variabilidad espacial y temporal de los caudales en cuencas intervenidas. Los resultados del análisis nacional muestran que el 79% del caudal asignado como DAAs a nivel nacional corresponde a la Región Metropolitana, lo cual solamente representa el ~8% del total de DAAs otorgados en Chile, evidenciando la desigualdad en la distribución del agua. El análisis propuesto también considera cuatro índices de intervención humana, que se basan en la relación entre los DAAs provenientes de fuentes superficiales y subterráneas, respecto a la precipitación y el caudal en régimen natural de las cuencas. El primer ejemplo de aplicación consiste en el desarrollo de un modelo estadístico para predecir la escorrentía en cuencas sin información fluviométrica, independientemente de su grado de intervención humana; no obstante, los resultados muestran que los índices de intervención humana propuestos en esta sección no se logran correlacionar con las extracciones de agua estimadas, e impiden explicar la variabilidad espacial del caudal. La segunda aplicación consiste en una caracterización espacio-temporal de los DAAs otorgados, así como el análisis de la oferta natural de agua frente a la demanda en las cuencas de los ríos Petorca (Región de Valparaíso) y Cachapoal (Región del Libertador General Bernardo O'Higgins), obteniendo como resultado que los índices de intervención humana propuestos sí logran explicar la variabilidad temporal del caudal en ambas cuencas. En general, este trabajo demuestra el potencial de la información contenida en la base de datos de DAA para aplicaciones hidrológicas, especialmente para estimaciones de disponibilidad hídrica, lo cual es de suma importancia en un contexto de cambio climático.

A Dios, por permitirme vivir esta gran experiencia en su debido momento

A mis padres, Carlos y Elba, por su apoyo incondicional; todo lo que soy es gracias a ellos

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I. INTRODUCCIÓN

La disponibilidad hídrica natural está determinada, en gran medida, por características climáticas (e.g., precipitación, temperatura, flujos radiativos) y físicas (e.g., topografía, uso y tipos de suelo), que se combinan a través de varias escalas espacio-temporales para definir la respuesta hidrológica a la escala de cuenca (e.g., Wagener et al., 2007; Berghuijs et al., 2014; Addor et al., 2018). Durante las últimas décadas se han reportado avances notables en la predicción de caudales en cuencas sin información fluviométrica (PUB, por sus siglas en inglés; ver Hrachowitz et al., 2013), facilitados en gran parte por el surgimiento de estudios de *large sample hydrology* (Andréassian et al., 2006; Gupta et al., 2014), rama de la hidrología que busca mejorar la comprensión de la respuesta hidrológica de una cuenca mediante el uso de criterios de similitud (i.e., física, climática e hidrológica) y su interrelación a partir de grandes muestras de cuencas. Sin embargo, los atributos que describen características climáticas y fisiográficas en las cuencas son insuficientes para cuantificar las respuestas hidrológicas.

Estudios previos han documentado los efectos de obras civiles, cambios en la cobertura del suelo y usos del agua en la producción de escorrentía, demostrando así la relación entre la actividad antropogénica y la hidrología (e.g., Vertessy, 2000; Brown et al., 2005; Ochoa-Tocachi et al., 2016; Alvarez-Garreton et al., 2019). Sin embargo, la inclusión de la intervención humana en estudios hidrológicos sigue siendo un reto, principalmente por la dificultad de sintetizar el comportamiento humano a través de índices.

Todo análisis que busque explorar la relación entre la intervención humana y la respuesta hidrológica requiere de, al menos, información sobre el uso del agua dentro de la(s) cuenca(s) de interés. En el caso de Chile, dicha información se determina a través de datos de derechos de aprovechamiento de agua (DAA) los cuales, desde 1981, son la base del sistema de asignación de agua en todo el país (Estado de Chile, 1981). El trabajo de Alvarez-Garreton et al. (2018) constituye un avance importante en esta línea, al ser la primera base integrada de datos a escala de cuenca que, además de proveer descriptores físicos e información hidrometeorológica, proporciona un índice de intervención humana basado en derechos de agua superficiales (consuntivos permanentes y continuos). Alvarez-Garreton et al. (2018) también expusieron el potencial de los índices de intervención humana para predecir firmas hidrológicas (i.e., índices que cuantifican el comportamiento de los caudales; McMillan, 2021) en cuencas sin información fluviométrica, lo que podría explorarse más a fondo incorporando la predictibilidad a partir de descriptores climáticos y fisiográficos (e.g., Addor et al., 2018).

Adicionalmente, existe un creciente interés por caracterizar la hidrología en zonas donde se proyecta que el cambio climático intensifique los problemas asociados a la escasez de agua, o incluso aumente la frecuencia y magnitud de los eventos de sequía, especialmente durante la segunda mitad del siglo XXI (Cepal, 2009; Bozkurt et al., 2019). Desde el año 2010, una mega sequía ha estado afectando a Chile Central (32-37° S; Garreaud et al., 2017, 2019), condición que se ha atribuido parcialmente (~ 25%) al cambio climático de origen antrópico (Boisier et al., 2016). La mayor parte de la población chilena vive en este dominio (INE, 2017a), donde se desarrollan intensivamente actividades agrícolas (INE, 2017b). Las condiciones sin precedentes de la mega sequía, combinadas con la agricultura de riego intensiva y el actual sistema de gestión del agua, han provocado e intensificado los problemas de escasez de agua en diferentes localidades de Chile Central (Muñoz et al., 2020).

Recientemente, Barría et al. (2019) evaluaron la vulnerabilidad del actual sistema de otorgamiento de derechos de agua en la cuenca del rio Perquilauquén en Quella, concluyendo que existe una sobre-asignación de recursos hídricos, condición que podría agravarse al considerar escenarios de menor disponibilidad hídrica futura (DGA, 2017, 2018b). Una situación similar se observa en otras cuencas de Chile Central. Por ejemplo, la cuenca del río Petorca (32,38° S, 71,37° W) ha sido gravemente afectada por la escasez hídrica, y el curso principal de agua ha sufrido una reducción generalizada durante las últimas décadas, llegando a un caudal nulo en algunos tramos, exponiendo el lecho del río (INDH, 2014; Nieto et al., 2018). El creciente número de plantaciones permanentes ha llevado a una creciente demanda de agua, particularmente subterránea, ya que las aguas superficiales han sido asignadas en su totalidad. Por otro lado, las aguas subterráneas contienen menos sedimentos y han mostrado una menor variabilidad durante los periodos secos, siendo así consideradas como la principal fuente de agua, aumentando considerablemente la perforación de pozos dentro de la cuenca (Budds, 2012). En abril de 1997, tras ser declarada agotada, la Dirección General de Aguas (DGA) declaró la cuenca del río Petorca como Área de Restricción; en julio del 2008, fue declarada como Área Prohibida, debido a que los niveles de extracción superaron la oferta de agua sostenible a largo plazo (DGA, 2018a).

De igual modo, el uso de derechos de agua no consuntivos también puede afectar la disponibilidad hídrica. Un ejemplo es la cuenca del río Cachapoal (34,27° S, 71,37° W) – subcuenca del río Rapel –, donde el caudal del río principal estuvo por debajo del mínimo histórico registrado durante enero del 2020 (DGA, 2020). Como consecuencia, los usuarios de agua en la tercera sección del río (i.e., cerca del punto de salida de la cuenca) han estado enfrentando escasez de agua. Aunque sus aguas superficiales no han sido declaradas agotadas por la DGA (ODEPA, 2015), la cuenca del río Rapel no cuenta con recursos hídricos superficiales para el otorgamiento de nuevos DAAs (DGA, 2016).

En resumen, la información sobre la distribución espacio-temporal de los DAAs es crucial para la planificación y gestión de los recursos hídricos. El objetivo de este trabajo es evaluar el potencial de la base de datos de DAA de la DGA para aplicaciones hidrológicas en Chile, formulando índices de intervención humana para ser utilizados en aplicaciones con muestras grandes de cuencas, o en estudios de cuencas individuales. Específicamente, se prueba la aplicabilidad de dichos índices para: (1) utilizarlos como variables explicativas en modelos estadísticos para predecir escorrentía en cuencas sin información fluviométrica, y (2) diagnosticar las compensaciones entre la disponibilidad natural de agua y las demandas históricas durante las últimas décadas, en dos cuencas de estudio ubicadas en Chile Central. Específicamente, se abordan las siguientes preguntas de investigación:

- ¿Cómo representar correctamente el grado de intervención humana en una cuenca, mediante los diferentes tipos de DAAs definidos en Chile?
- ¿Cómo combinar información de atributos fisiográficos, descriptores climáticos e intervención humana para predecir escorrentía en cuencas sin información fluviométrica?
- ¿Existirá una relación directa entre la intervención humana y la disponibilidad de agua en una cuenca, basada en los registros de caudales?

1.1. Objetivos

Los objetivos del presente trabajo de tesis son los siguientes:

1.1.1. Objetivo General

Evaluar el potencial de la base de datos de Derechos de Aprovechamiento de Agua de la DGA para su uso en aplicaciones hidrológicas en Chile continental.

1.1.2. Objetivos Específicos

- Revisar y corregir la información existente de DAAs, y caracterizar su distribución por tipo a lo largo del territorio nacional.
- Generar índices de intervención humana a partir de la caracterización de los DAAs.
- Desarrollar modelos estadísticos para predicción del caudal medio anual en cuencas de Chile continental, independientemente de su grado de intervención humana.
- Realizar un análisis espacio-temporal de la intervención humana en cuencas piloto, caracterizando su efecto en la disponibilidad de agua actual.

II. ARTÍCULO PARA PUBLICACIÓN

The potential of a Water Use Rights database for hydrological applications in continental Chile

Nery Budde[1], **Pablo A. Mendoza**[1,2], **Camila Alvarez-Garreton**[3,4], **and Nicolás Vásquez**[1]

[1]Department of Civil Engineering, Faculty of Physical and Mathematical Sciences, Universidad de Chile, Chile.
[2]Advanced Mining Technology Center (AMTC), Faculty of Physical and Mathematical Sciences, Universidad de Chile, Chile.
[3]Center for Climate and Resilience Research (CR2), Santiago, Chile.
[4]Department of Civil Engineering, Universidad de La Frontera, Temuco, Chile.

Abstract

The national Water Use Rights (WURs) database in Chile contains crucial information to estimate water available for granting new WURs. Although this database is available at the Chilean Water Directory (DGA) public website, it has many shortcomings that constrain an accurate estimation of allocated flow as WURs. In this study, we revise and correct this information in order to conduct a national-scale analysis of granted WURs and use it for two hydrological applications that involve the analysis of spatio-temporal runoff variability in catchments with high human intervention. Results from national-scale analysis show that 79% of flows allocated as WURs in the country are in the Metropolitan Region, which is equivalent to only ~8% of total number of granted WURs in Chile. We also propose four human intervention indices based on the relation between WURs (from surface water and groundwater), catchment-scale precipitation and naturalized runoff. The first example application involves the development of a statistical model to predict runoff in ungauged catchments, regardless of their human intervention degree. Neverless, the results show that human intervention indices proposed fail to correlate with estimated water extractions and cannot explain the spatial variability of mean annual runoff. The second application consists on a spatio-temporal characterization of granted WURs, and a temporal comparison between natural water supply and water demands in the Petorca and Cachapoal River basins, obtaining as a result that human intervention indices proposed in this application do explain the temporal variability of mean annual runoff in both catchments. Overall, this work demonstrates the potential of the information contained in the WUR database for hydrological applications, especially for water availability estimates.

Keywords: *Human intervention, Water use rights, Water availability, Water stress, Water management.*

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1. INTRODUCTION

During the last decades, several advances have been reported to predict runoff in ungauged basins (PUB; Hrachowitz et al., 2013) by using different types of similarity (i.e., physical, climatic and hydrological), catchment attributes and their relationship with hydrological signatures (i.e., indices that quantify streamflow behavior; McMillan, 2021). However, catchment attributes describing climatic and physiographic characteristics cannot fully explain hydrological responses in systems with human intervention. Previous studies have shown the effects of civil works, land cover change and water uses on runoff production, demonstrating the relationship between anthropogenic activity and hydrology (e.g., Vertessy, 2000; Brown et al., 2005; Ochoa-Tocachi et al., 2016; Alvarez-Garreton et al., 2019). Including human interventions in hydrological studies remains a challenge, mainly because of the difficulty of synthesizing human behavior through indices.

Exploring the relationship between human intervention and hydrological responses requires, at least, information about water use within the basin(s) of interest. In the case of Chilean water management system, such information is determined through water use rights (WUR) which, since 1981, have been the basis of the water allocation system across the country (Estado de Chile, 1981). Alvarez-Garreton et al. (2018) synthetized WURs for 516 Chilean basins, presenting the first integrated catchment database that, in addition to providing physical descriptors and hydrometeorological information, provides a human intervention degree based on surface water use rights (consumptive, permanent and continuous). Furthermore, Alvarez-Garreton et al. (2018) illustrated the potential of human intervention indices to predict hydrological signatures (specifically, mean annual runoff and mean annual runoff ratio) in ungauged basins.

Quantifying water use and its impacts on water availability is crucial for water management in regions where climate change could exacerbate water scarcity problems, by increasing the frequency and magnitude of drought events (Cepal, 2009; Bozkurt et al., 2019). Since 2010, a mega-drought has been affecting Central Chile (32-37° S; Garreaud et al., 2017, 2019), a condition that has been partially attributed to anthropogenic climate change (~ 25%; Boisier et al., 2016). Most of the Chilean population lives in this domain (INE, 2017a), where agriculture activities are intensively developed (INE, 2017b). The unprecedented mega-drought conditions, combined with intensive irrigated agriculture and the current water management system, have led to water scarcity problems in different locations of Central Chile (Muñoz et al., 2020).

Recently, Barría et al. (2019) evaluated the vulnerability of the current water allocation system in the Perquilauquén at Quella basin, concluding that there is an over-allocation of water resources, a condition that could be exacerbated considering future scenarios of lower water availability (DGA, 2017, 2018b). A similar situation can be observed in other catchments across Central Chile. For example, the Petorca River basin (32.38° S, 71.37° W) has been severely affected by water supply shortages, and the main water course has undergone a general reduction in streamflow during the last decades, exposing large portions of the riverbed (INDH, 2014; Nieto et al., 2018). The increasing number of permanent plantations has led to a growing water demand, especially groundwater resources, due to surface water overallocation. Conversely, groundwater contains less sediment and has shown less variability during dry periods, being considered as the main source for technified irrigation, increasing the drilling of wells within the basin (Budds, 2012). In April 1997, the Chilean Water Directorate (DGA, by its acronym in spanish) declared the Petorca River basin a Restriction Area and, in July 2008, it was declared a Prohibited Area, because extraction levels exceeded the long-term sustainable water supply (DGA, 2018a).

Further, non-consumptive WURs (i.e., water is allocated and then returned to the river downstream) may impact water availability in rivers. An interesting example is the Cachapoal River basin (34.27° S, 71.37° W) – a sub-catchment of the Rapel River basin –, whose main river streamflow went below the historical minimum recorded during January 2020 (DGA, 2020).

Therefore, water users along the third section of the river (i.e., close to the catchment outlet) have been facing water supply shortages. Although its surface water has not been declared exhausted by the DGA (ODEPA, 2015), the Rapel River basin does not have enough surface water resources for granting new WURs (DGA, 2016).

Information on the spatio-temporal distribution of WURs is crucial for water resources planning and management. This paper aims to assess the potential of the DGA's WUR database for hydrological applications in Chile, by formulating human intervention indices to be used in either large-sample applications, or individual basin studies. Specifically, we test the applicability of human intervention indices for: (1) use as explanatory variables for statistical models to predict runoff in ungauged basins, and (2) diagnosing trade-offs between natural water availability and historical demands over the last decades in two case study basins in Central Chile. Specifically, we address the following research questions:

- How can we represent human intervention degree, using the different types of WURs defined in Chile?
- How can we combine information from physiographic attributes, climate descriptors and human intervention degree to predict runoff in ungauged basins?
- Is there a direct relationship between human intervention and basin water availability based on streamflow records?

2. STUDY DOMAIN

In this study, we use catchment-scale data from the CAMELS-CL database (Alvarez-Garreton et al., 2018) to test the potential of WURs to predict streamflow in ungauged basins, regardless of their level of human intervention (see details in Section 4.2). The catchments included in CAMELS-CL span a wide range of hydroclimatic and physiographic conditions, and are located along six macro-zones (Figure 1): (i) the Far North, dominated by a cold desert climate and tundra along the Andes range; (ii) the Near North, characterized by a cold desert climate in the Atacama Region and a cold semi-arid climate in the Coquimbo Region; (iii) the Central Zone, dominated by a sub-humid Mediterranean climate; (iv) the Southern Zone, which includes a humid Mediterranean climate in the Bio-Bio and Araucanía Regions, and a temperate rain–oceanic climate in the Los Ríos and Los Lagos Regions; and finally, (v) the Austral and (vi) Southern Patagonia zones, dominated by rain-cool oceanic and cold steppe climates.

Further, we select two case study watersheds – the Petorca and the Cachapoal River basins (Figure 2 and Table 1) – to examine the temporal interplay between natural water availability and demands. A brief description of these basins is included below:

- The Petorca River basin (1970 km^2) is located in the Valparaíso Region, in a transition area between the semi-arid and Mediterranean climates (Muñoz et al., 2020). The river headwaters are in the Andes Cordillera (3900 m a.s.l.), with two main tributaries, the Sobrante and Pedernal rivers, that merge to create the Petorca River. Water use in the basin is dominated by agriculture (Budds, 2012), which coexists with other economic activities such as small mining, goat farming, subsistence agriculture, recreation areas and human consumption (DGA, 2014). Over the past decades, fruit plantations have increased (Panez-Pinto et al., 2018), with avocados and citrus fruits as the main products (INDH, 2014). According to Muñoz et al. (2020), the Petorca River basin does not have glaciers in its Andean subdomain, unlike most headwater basins with intensive agriculture in Central Chile. Therefore, water availability within the basin depends exclusively on precipitation and snow accumulation in the winter season.

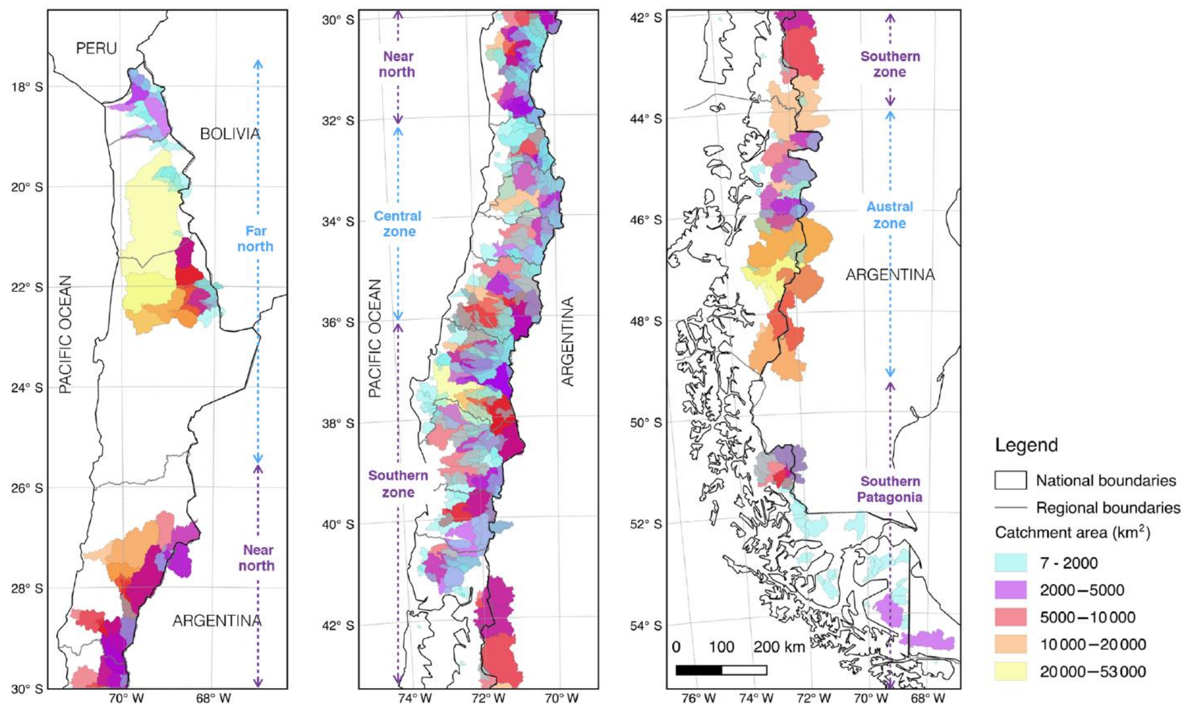

Figure 1 Catchment boundaries and contributing areas in km^2 (Alvarez-Garreton et al., 2018).

- The Cachapoal River basin (6265 km^2) spans 38% of the total area of the Libertador General Bernardo O'Higgins Region (CNR, 2005). The basin headwaters are in the Andes Cordillera, and the outlet is located at the junction with the Tinguiririca River, where the Rapel River begins. The basin has a temperate climate with spatial variations due to orographic effects. Above 3500 m a.s.l. the climatic severity is pronounced until reaching glacial conditions (Novoa, 2016). The basin is divided into three sections for water administration purposes, which are regulated by monitoring committees (Figueroa, 2008). The Cachapoal River basin is also one of the most productive agricultural areas in central-southern Chile: has 78% of the agricultural land in the O'Higgins Region and 12% of the country's arable land (INE, 2007; Antúnez & Felmer, 2009; Novoa, 2016), with plantation of cereals, legumes and fruits (peaches, apples, pears and grapes) (DGA, 2004). Mining activity is also present, as well as hydroelectric generation and uses for human consumption (Figueroa, 2008).

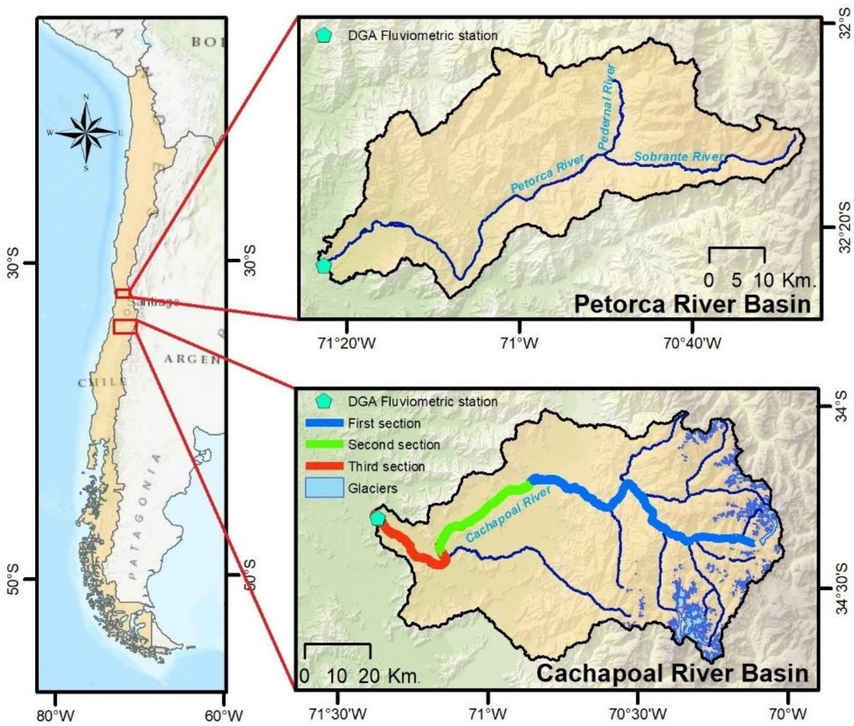

Figure 2 Location of the study basins.

Table 1 Main geomorphological and hydroclimatic descriptors for the case study basins.

Basin	Elevation outlet [m a.s.l.]	Mean elevation [m a.s.l.]	Maximum elevation [m a.s.l.]	Mean slope [m km^{-1}]	Annual precipitation [mm]*	Aridity index [-]	Human intervention [-]**
Petorca River	9	1296	3721	206.3	285	4.5	0.19
Cachapoal River	112	1508	5150	198.9	1007	1.2	0.33

* From the CAMELS-CL dataset, based on the CR2MET product.

**From the CAMELS-CL dataset; based on consumptive permanent continuous WURs, from surface water.

3. DATA

3.1. Hydrometeorological information

Daily time series of precipitation and streamflow records are obtained from the CAMELS-CL dataset for the 1979-2020 period. Catchment-scale precipitation time series are derived from the CR2MET dataset (DGA, 2017; Boisier et al., 2018), which contains meteorological information for continental Chile at a 0.05° x 0.05° horizontal resolution (~ 5 km). Streamflow time series are obtained from in situ measurements recorded by the DGA fluviometric stations Rio Petorca in Longotoma and Cachapoal en Puente Arqueado (both located at catchments outlet), which reflect the temporal evolution of human intervention in these basins.

To estimate water availability (in near-natural regime) for each study catchment case, we obtained streamflow time series from a national scale dataset that contains simulated states and fluxes (DGA, 2018b) for the historical period 1985-2015 at a daily time step. Such dataset was developed by running the Variable Infiltration Capacity (VIC; Liang et al., 1994) macroscale hydrological model at the 0.05°x0.05° horizontal resolution, using a combination of CR2MET, ERA-Interim and ERA5 output as meteorological forcings. The spatially distributed parameter fields used to simulate near-natural runoff were developed via parameter regionalization, based on the similarity between possible donor catchments – whose parameters were calibrated individually (Vásquez et al., 2021) – and each grid cell across the domain. The reader is referred to Vásquez et al. (2021) and DGA (2017, 2018b, 2019) for more details on individual model calibration and parameter regionalization procedures.

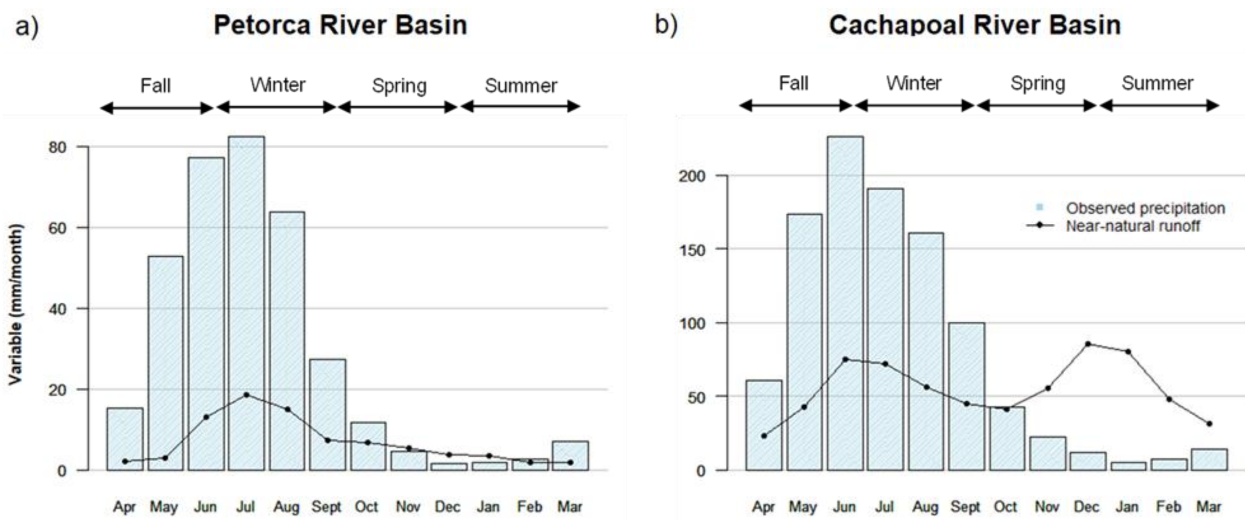

Figure 3 Average monthly cycles of precipitation and total runoff for the case study basins (period 1979-2015).

Figure 3 displays seasonal cycles of precipitation and near-natural runoff in the case study basins. The Petorca River basin has a rainfall-dominated regime, with a maximum runoff of ~19 mm/month in July. The Cachapoal River basin has a mixed hydrological regime, with the main contributions to runoff coming from snowmelt (November - February) – with a maximum monthly runoff of ~85 mm – and secondary contributions from rainfall events during fall and winter (May - September).

3.2. Granted water use rights

The DGA has a public database with information on WURs, including transfers of temporary assignment, changes in water supply points, and transfers reported by users. Specific information for water allocation points include source of exploitation (surface water or groundwater), the type of right (i.e., consumptive or non-consumptive), use (i.e., industrial, irrigation, domestic and drinking water, hydropower, fish farming, mining and classified as "other uses"), annual allocated flow (expressed in volume unit per time or as "shares") and temporary allocation (i.e., permanent and continuous, permanent and discontinuous, permanent and alternated, eventual and continuous, eventual and discontinuous, or eventual and alternated) (Alvarez-Garreton et al., 2018).

In this study, we use information from this database (128,015 registered WURs, updated to December 18, 2019) to conduct a national scale characterization of WURs, with emphasis on their spatial distribution across administrative regions in Chile. Further, we process relevant WURs to compute annual time series with allocated flows, as WURs, in the Petorca and Cachapoal River basins.

4. METHODS

4.1. Diagnostics of WUR information

First, we identify non-georeferenced WURs and those with incorrect location information. Subsequently, we estimate the spatial location using information on the watershed for which each WUR was assigned to. It should be noted that a fraction of these WURs had already been located by Munita (2018) for Northern and Central Chile, who used a rigorous location procedure by considering location references of water rights. The WURs that could not be georeferenced by this procedure were removed from the database. Once all WURs are georeferenced, flow units are standardized by conducting the conversions to lt/s. An equivalent of 1 "water shared" = 1 lt/s is used, since a "shared" water volume depends on a given course's flow (Correa-Parra et al., 2020), and this factor further complicates the task of quantifying actual water allocations (Barría et al. 2019).

Correa-Parra et al. (2020) reported various consistency problems in the original database. In light of this and additional issues detected during the quality control (QC) process, we decided to remove WURs with inconsistent or missing information – e.g., flow units that cannot be converted into water volumes, and no data for some water allocations –, and also remove "old" WURs that had a transfer in the temporal allocation of an existing WUR (and stayed in the database with file codes containing the initials "VT"). The final revised product is included in supplementary material.

4.2. Runoff prediction in ungauged basins

4.2.1. The potential of human intervention degree to predict mean annual runoff in ungauged basins

To predict mean annual streamflow in ungauged basins, regardless of their level of human intervention, we propose a simple model that can be adjusted in gauged basins:

$$Q_{obs} = Q_{nat} - \Delta Q_{HI} + \varepsilon \quad (1)$$

where Q_{obs} is the observed annual streamflow (measured by a DGA's station), Q_{nat} is the near-natural streamflow and ΔQ_{HI} represents actual water extractions, that we hypothesize can be estimated as a function of allocated WURs. To estimate near-natural Q_{nat}, a statistical model is adjusted for near-natural catchments using physiographic and climatic descriptors as predictors.

$$Q_{nat} = f(physical, clim) + \varepsilon \quad (2)$$

Then, ΔQ_{HI} can be computed as follows:

$$\Delta Q_{HI} = Q_{nat} - Q_{obs} \quad (3)$$

Finally, we test the potential of the following human intervention indices to explain the spatial variability in ΔQ_{HI}:

$$\text{Surface water intervention degree}_{(1)}\text{: (S.W. H.I.D.}_{(1)}\text{) [-]} \quad \frac{Annual\ flow\ of\ surface\ WUR\ (consumptive)}{Catchment - averaged\ annual\ precipitation} \qquad (4)$$

$$\text{Groundwater intervention degree}_{(1)}\text{: (GW H.I.D.}_{(1)}\text{) [-]} \quad \frac{Annual\ flow\ of\ groundwater\ WUR\ (consumptive)}{Catchment - averaged\ annual\ precipitation} \qquad (5)$$

In equations (4) and (5), catchment-averaged annual precipitation is assumed to be the main recharge of surface and groundwater sources, and H.I.D. values > 1 indicate water stress condition. It should be noted that non-consumptive WURs are not considered in the proposed human intervention indices, because we assume that their restitution point is located inside the basin and thus should not affect streamflow records at its outlet.

Further, S.W. H.I.D.$_{(1)}$ and GW H.I.D.$_{(1)}$ differ from the indices proposed by Alvarez-Garreton et al. (2018), since we consider groundwater extractions and temporal assignment types of WURs (i.e. permanent or eventual) as the WUR flow represents an annual average of the real assignment.

If strong correlations between ΔQ_{HI} and human intervention indices are obtained, a second statistical model can be adjusted using these indices as predictors, and streamflow in any ungauged basin could be estimated using physiographic attributes, climatic descriptors and human intervention degrees of that basin.

4.2.2. Predictor selection and model implementation

We examine topographic and geological attributes, land cover characteristics and climatic indices from the CAMELS-CL database (see Appendix A) to identify potential predictor variables for Q_{nat}. To this end, we compute the Pearson and Spearman rank correlation coefficients between these attributes and the mean annual runoff in 88 near-natural catchments, selecting the four predictors that provide the largest absolute values. The final suite of predictors and the type of statistical model is selected depending on the type (i.e., linear or non-linear) and strength of correlations.

Non-parametric models can alleviate the drawbacks of non-linear correlations between dependent and predictor variables and other traditional linear regression assumptions (i.e., dependent variable and/or model errors do not follow a normal distribution, non-independent model errors and/or observations and non-constant model error variances). Towler et al. (2009) made a brief overview of nonparametric methods, in which estimates at any point x* are influenced by neighboring data points. Thus, no single equation is fit to the entire data, since local fitting provides the capability to capture any nonlinear features in the data. Hence, we fit a local polynomial regression model using the LOCFIT library (Loader, 2020), implemented in the statistical software R. For more details on the implementation steps of local polynomials, the reader is referred to Towler et al. (2009) and Loader (1999).

Model results are evaluated using R-squared (R^2), root mean squared error (RMSE) and the generalized cross validation score (GCV):

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{y}_i - y_{avg})^2}{\sum_{i=1}^{n}(y_i - y_{avg})^2} \tag{6}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{7}$$

$$GCV = \frac{\sum_{i=1}^{n}\frac{(y_i - \hat{y}_i)^2}{n}}{(1 - \frac{m}{n})^2} \tag{8}$$

where $\hat{y}_i$ is the predicted value, y_i is the observed value, y_{avg} is the average of observed values, n is the number of data points, and m represents the degrees of freedom of the fitted polynomial. The model's predictive ability is assessed through leave-one-out cross validation (LOOCV).

4.3. Catchment-scale characterization of WURs and temporal analysis of human interventions

We characterize WURs in each catchment based on the number and flow volume, through classification according to their source (i.e., surface water or groundwater), type (i.e., consumptive or non-consumptive), and temporary assignment (i.e., eventual or permanent). We also propose two additional human intervention indices that consider the basin's near-natural mean annual flow as the available water:

Surface water intervention degree$_{(2)}$: (S.W. H.I.D.$_{(2)}$) [-]

$$\frac{Annual\ flow\ of\ surface\ WUR\ (consumptive)}{Basin's\ annual\ (near-natural\ regime)\ flow} \tag{9}$$

Groundwater intervention degree$_{(2)}$: (GW H.I.D.$_{(2)}$) [-]

$$\frac{Annual\ flow\ of\ groundwater\ WUR\ (consumptive)}{Basin's\ annual\ (near-natural\ regime)\ flow} \tag{10}$$

Hence, the inter-annual evolution of the previously defined indices is examined to detect imbalances between natural water supply and demands.

To what extent does the official information on WURs reflect the actual evolution of water extractions? To look for answers, we compare historical time series of near-natural (modeled) streamflow, streamflow measured at each station and allocated flow as WURs in the two case study basins: Petorca and Cachapoal River basins (see Figure 2). Specifically, we compare annual streamflow records with the difference (Q_{est}) between near-natural streamflow (Q_{nat}) and allocated flow as WURs (Q_{WUR}):

$$Q_{est} = Q_{nat} - Q_{WUR} \tag{11}$$

The analysis period for each basin depends on available streamflow records.

Finally, given the good performance of parameter regionalization in terms of mean annual streamflow (DGA, 2018b), we assume that any mismatch between annual streamflow records and Q_{est} to discrepancies between real water extractions – i.e., underestimation of allocated flow, under/over use of granted allocated flow and unauthorized extractions of surface and groundwater (Alvarez-Garreton et al., 2018) – and the reliability of station records.

5. RESULTS AND DISCUSSION

5.1. National scale WUR analysis

As a result of the QC process, 3.5% of total number of registered WURs were removed from the original database due to inconsistent attributes (i.e., WURs with "VT" file code, non-georeferenced WURs, WURs with Q=0 lt/s or without conversion to lt/s; see Figure 4a). Figure 4a also shows that nearly 78% of WURs in the original database have geographic coordinates properly assigned, while ~19% of WURs required georeferentiation (i.e., WURs with missing coordinates, that had to be determined following the steps described in Section 4.1). The distribution (number and allocated flow) of the latter group by region is presented in Figure 4b. The Coquimbo Region has the largest percentage of georeferenced WURs in quantity, although its average annual flow represents only 1% of all national georeferenced WURs. Conversely, the Aysén Region has the highest granted mean annual flow, distributed across a relatively low number of WURs.

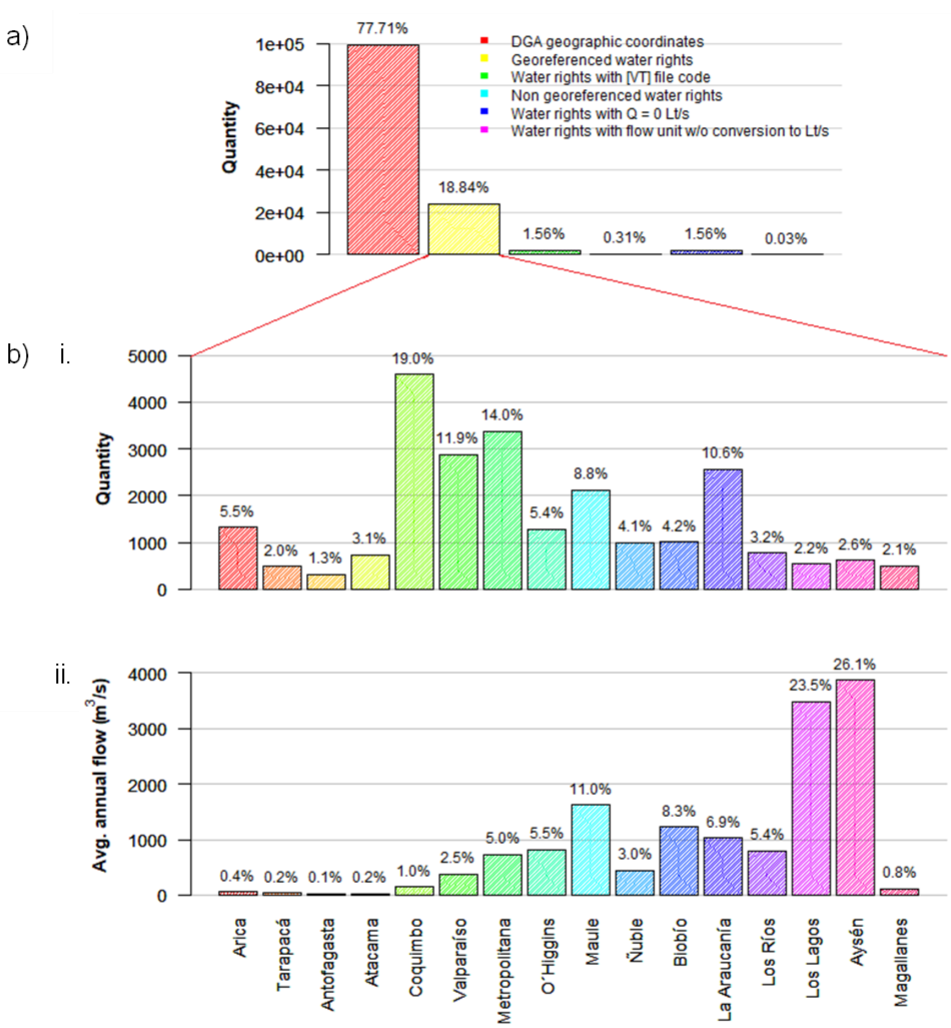

Figure 4 (a) Decomposition of WURs (from original database, without QC), and (b) georeferenced WURs by region in terms of (b.i) number and (b.ii) allocated water volume.

Figure 5 shows the location of granted WURs (after QC process) across continental Chile, as well as their distribution by region (number and allocated flow). The highest mean annual flows are allocated in the Andes range, along central-southern Chile (32-44° S) and, according to Correa-Parra et al. (2020), WURs in these areas are mainly associated to hydropower companies that supply electricity for urban areas, and to economic activities nearby. The distribution of WURs agrees with the inequality and very high concentration of allocated flow at Metropolitan Region also reported by Correa-Parra et al. (2020), which is equivalent to only 7.6% of the number of WURs granted for the entire country. In summary, water consumption primarily occurs in central Chile (where most of the population lives and most agriculture activities are developed), but also concentrate only ~8% of the existing water rights.

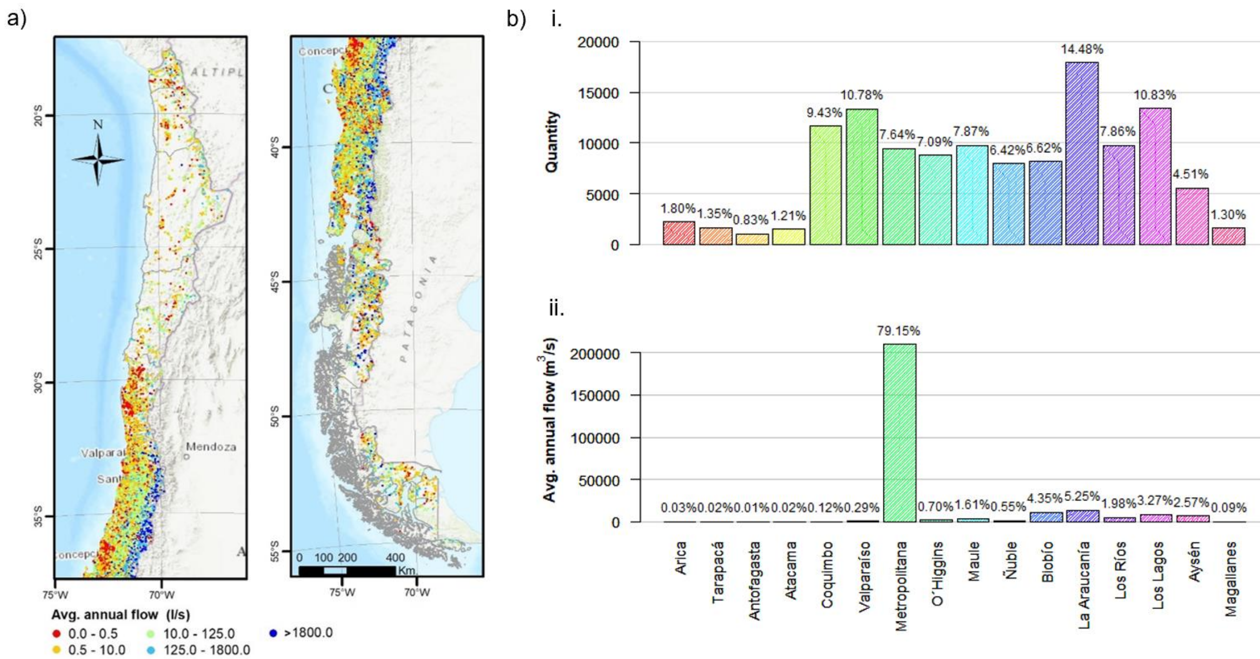

Figure 5 (a) Location of granted WURs across continental Chile after QC, and (b) distribution of WURs by region in terms of (b.i) number and (b.ii) allocated water volume.

The spatial distributions of WURs according to water source and type are shown in Figure 6 and 7, respectively. In agreement with Alvarez-Garreton et al. (2018) most consumptive groundwater rights are located in central Chile (especially in low elevation areas), with increasing spatial density towards the west, while most non-consumptive surface water rights (associated with hydropower production) are granted along mountainous Andean domains in central-southern Chile.

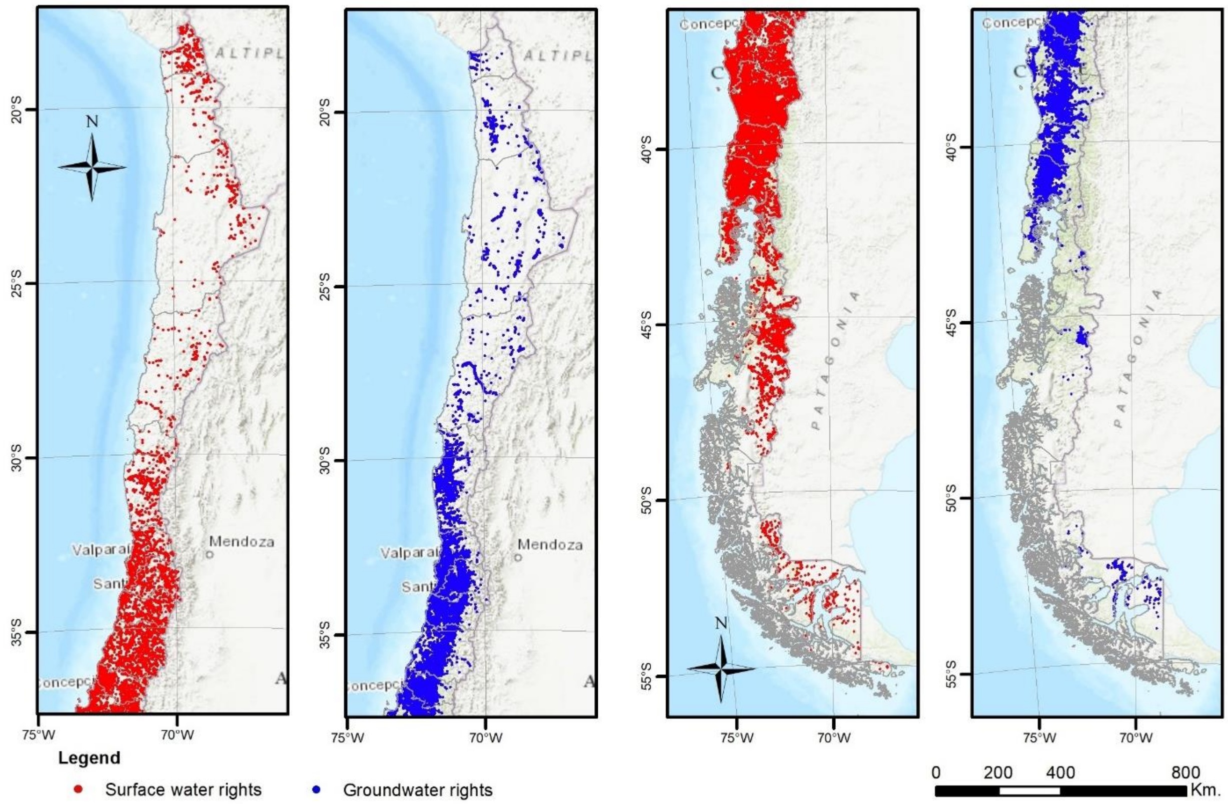

Figure 6 Spatial distribution of granted WURs in continental Chile, according to water source.

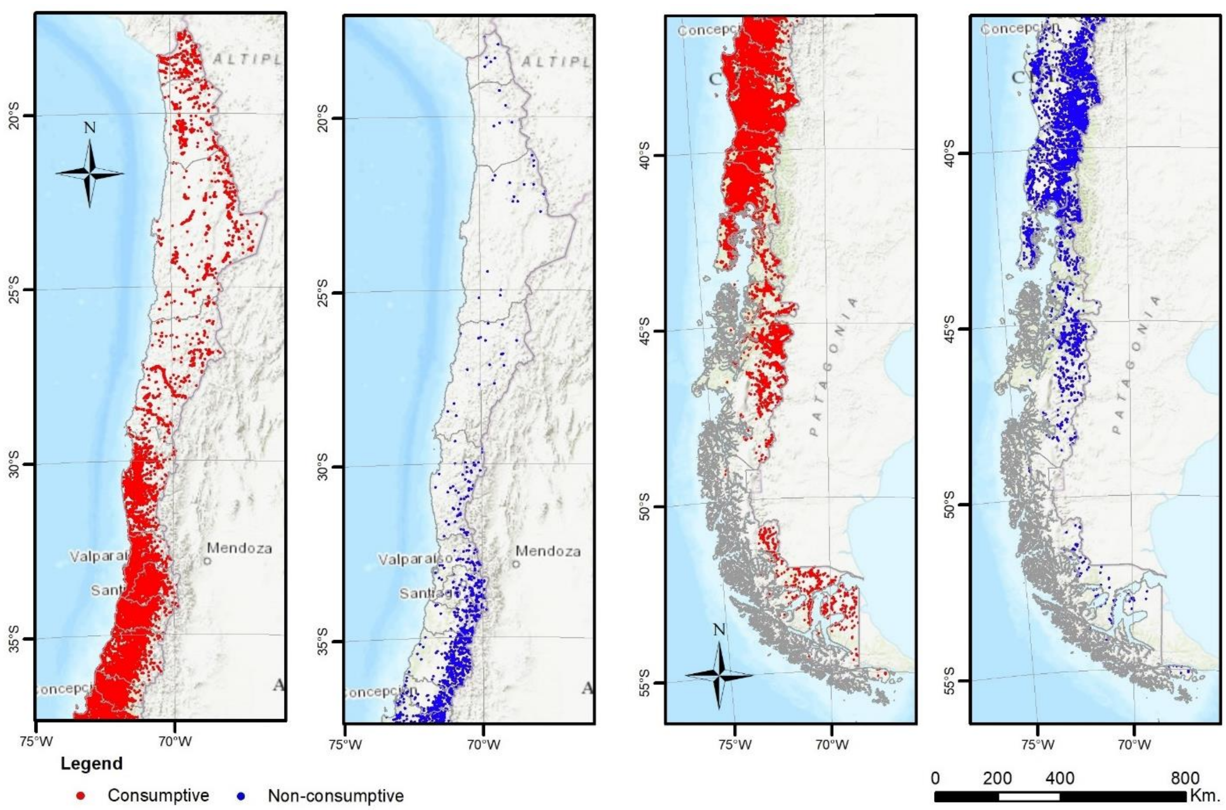

Figure 7 Spatial distribution of granted WURs in continental Chile, according to WUR type.

5.2. Example 1: Runoff prediction in ungauged basins

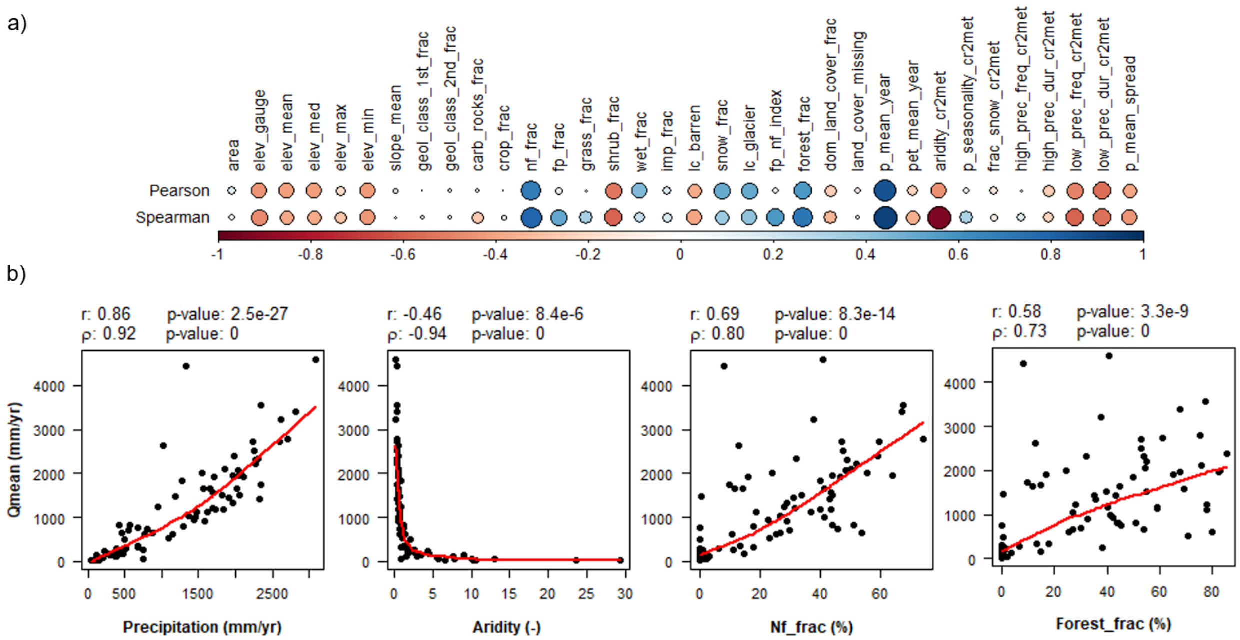

Figure 8 (a) Topographical and geological attributes, land cover characteristics and climatic indices analyzed from the CAMELS-CL database*, and (b) potential predictor variables for the statistical model.

* Attributes description can be found in Appendix A.

Figure 8a displays Pearson and Spearman's rank correlation coefficients between near-natural mean annual runoff and 34 catchment attributes, and Figure 8b shows scatter plots between mean annual runoff and the best four candidate predictors (i.e., those with the largest correlation values in Figure 8a), obtained with data from 88 near-natural catchments. The results indicate that precipitation and native forest fraction yield the highest predictive power, and therefore we select these as predictor variables for the local polynomial model, obtaining a good performance in both training (R^2 = 0.94) and LOOCV (R^2 = 0.74) modes (Figure 9).

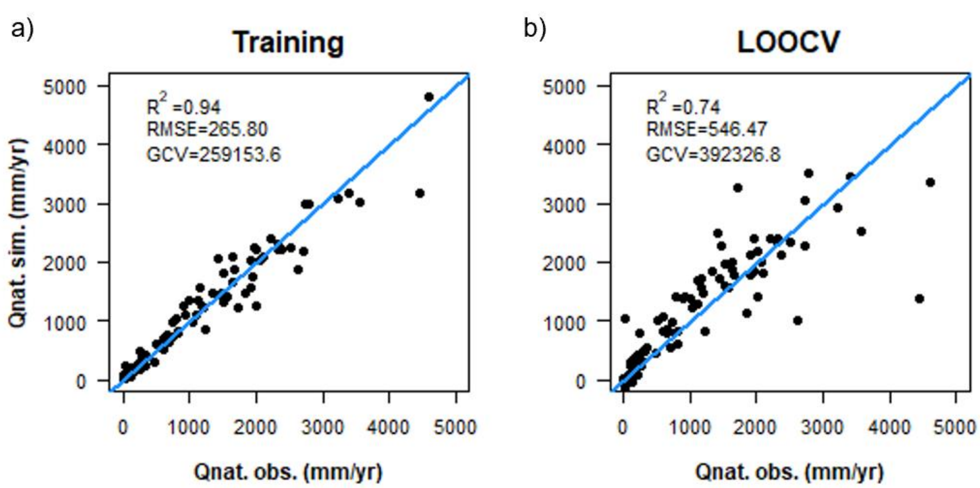

Figure 9 Simulated vs observed near-natural runoff in (a) training and (b) validation mode. Blue line corresponds to 1:1 line.

Figure 10 displays scatterplots and correlation coefficients between ΔQ_{HI} (computed with equation (3)) and the proposed human intervention indices defined in equations (4) and (5), for 126 catchments. It can be noted that there are negative ΔQ_{HI} values – i.e., catchments where Q_{obs} (measured runoff that include human alterations) is higher than Q_{nat} (modeled near-natural runoff) –, and that no clear relationships exist between ΔQ_{HI} and human intervention indices.

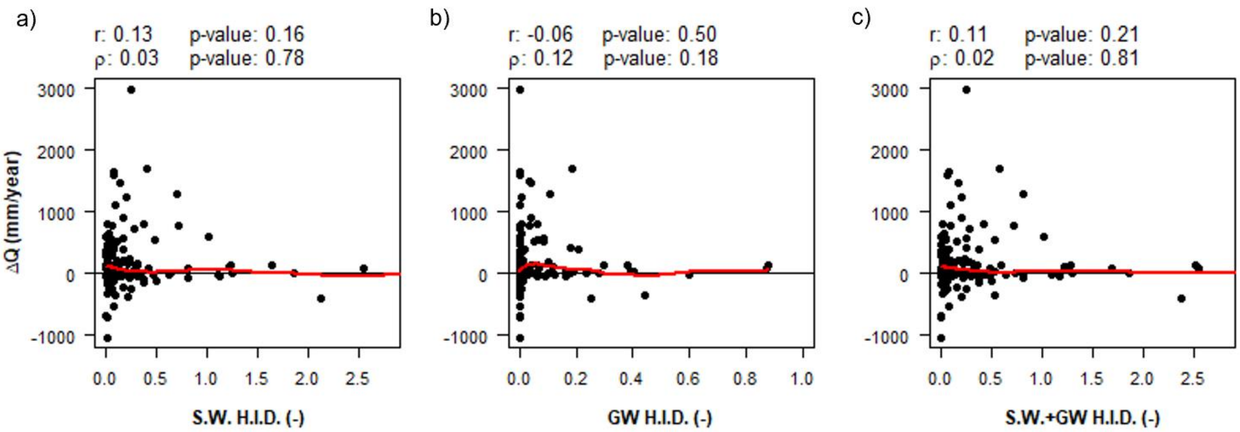

Figure 10 Correlations between ΔQ_{HI} and the proposed human intervention indices: (a) surface water H.I.D., (b) groundwater H.I.D., and (c) total (surface + groundwater) H.I.D.

The obtention of less natural water supply (Q_{nat}) than measured runoff at the catchment outlet (Q_{obs}) may be explained by differences (either hydroclimatic or physiographic) between the basins used to train the statistical model (i.e., near natural catchments), and also by differences between this sample of catchments and the sample used to make predictions (i.e., basins with altered runoff regimes). It should also be noted that model performance decreased considerably when applied in LOOCV mode (a 0.2 decrease in R^2, Figure 9). Additional reasons that could explain negative ΔQ_{HI} values (i.e., $Q_{nat} < Q_{obs}$) are: (i) groundwater contributions to river flow that cannot be represented by a statistical model, and (ii) measurement errors at the stream gages.

An alternative to alleviate the effects of the catchments sample used in the model may be implementing a clustering method to group catchments based on similarity criteria, and then fit a statistical model for each resulting cluster.

Finally, the lack of relationships between ΔQ_{HI} and human intervention indices may be explained by the underestimation of actual allocated flows due to: (i) non-consumptive water rights with their restitution point outside the catchment boundaries, (ii) wrong conversion of "shared" water volumes to lt/s, and (iii) ignored WURs due to missing information (see Figure 4a). Further, allocation estimates may differ considerably from the actual extractions within a catchment due to (under)overuse of a granted allocated flows and illegal diversions of surface and groundwater (Alvarez-Garreton et al., 2018).

5.3. Example 2: Temporal dynamics of water extractions

5.3.1. Spatio-temporal characterization of granted WURs in study basins

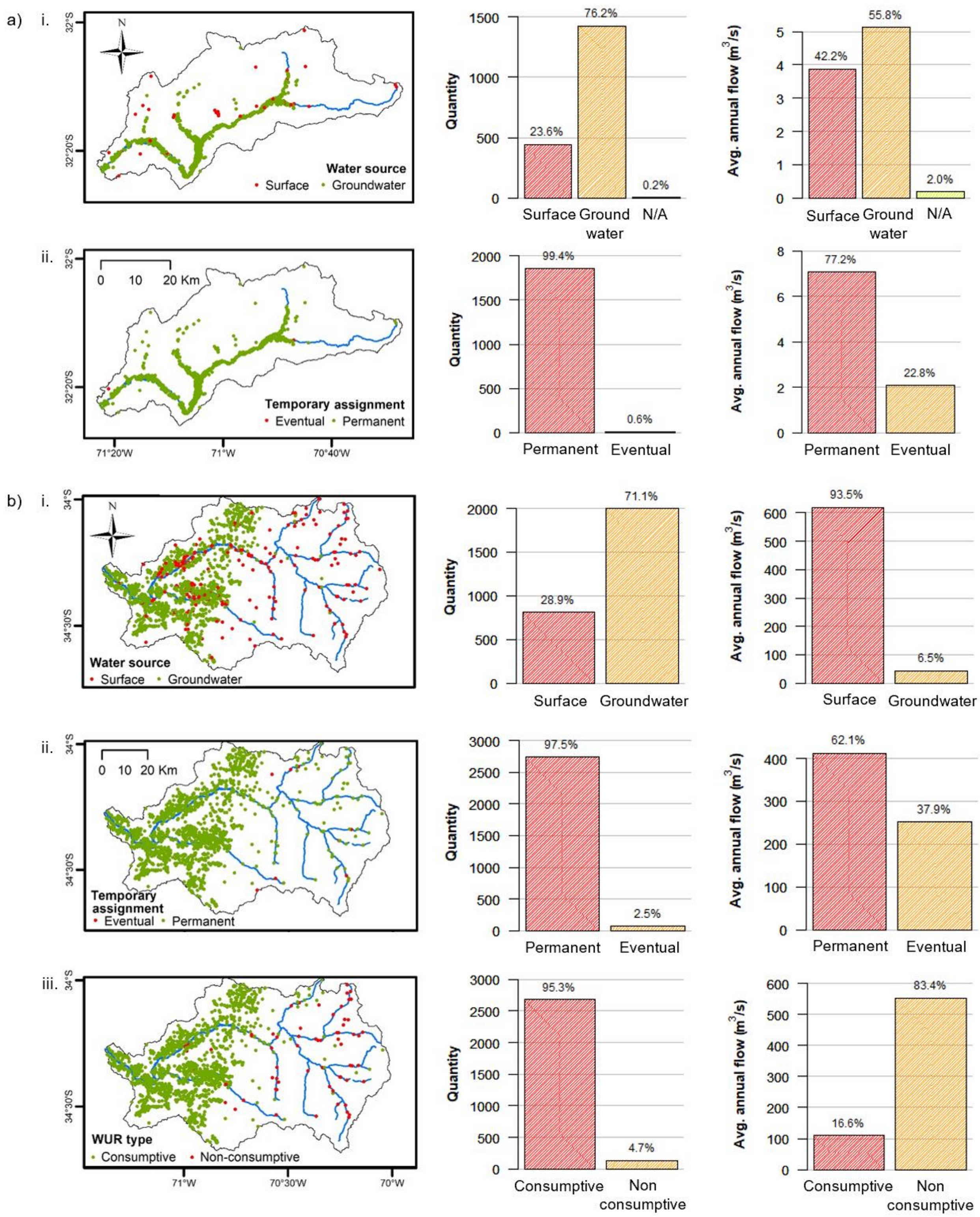

Figure 11 WURs characterization in the (a) Petorca, and (b) Cachapoal River basins, according to: (i) water source, (ii) temporary assignment, and (iii) WUR type.

From 1954 to 2019, 1873 WURs (all consumptive) have been granted in the Petorca River basin, which is equivalent to a mean annual flow of 9.2 m^3/s. The largest fraction of WURs comes from groundwater (76%), although the inter-source differences in volume are smaller than the differences in quantity (Figure 11a). Further, nearly all WURs are permanent (99%); however, 1% of WURs with eventual temporary assignment (11 WURs) are equivalent to 23% of the mean annual flow extracted in the basin.

Regarding the Cachapoal River basin, 2809 WURs have been granted from 1909 to 2019, which is equivalent to a mean annual flow of 663 m^3/s. As in the Petorca River basin, most WURs come from groundwater (71%), which are equivalent to 7% of the mean annual granted flow for the basin (Figure 11b). Also, most WURs are consumptive (95%), although non-consumptive WURs represent 83% of the mean annual granted flow. Finally, WURs are mostly permanent (98%), but the remaining 2% (eventual WURs) represents a significant fraction of the mean annual flow extracted in the basin (38%).

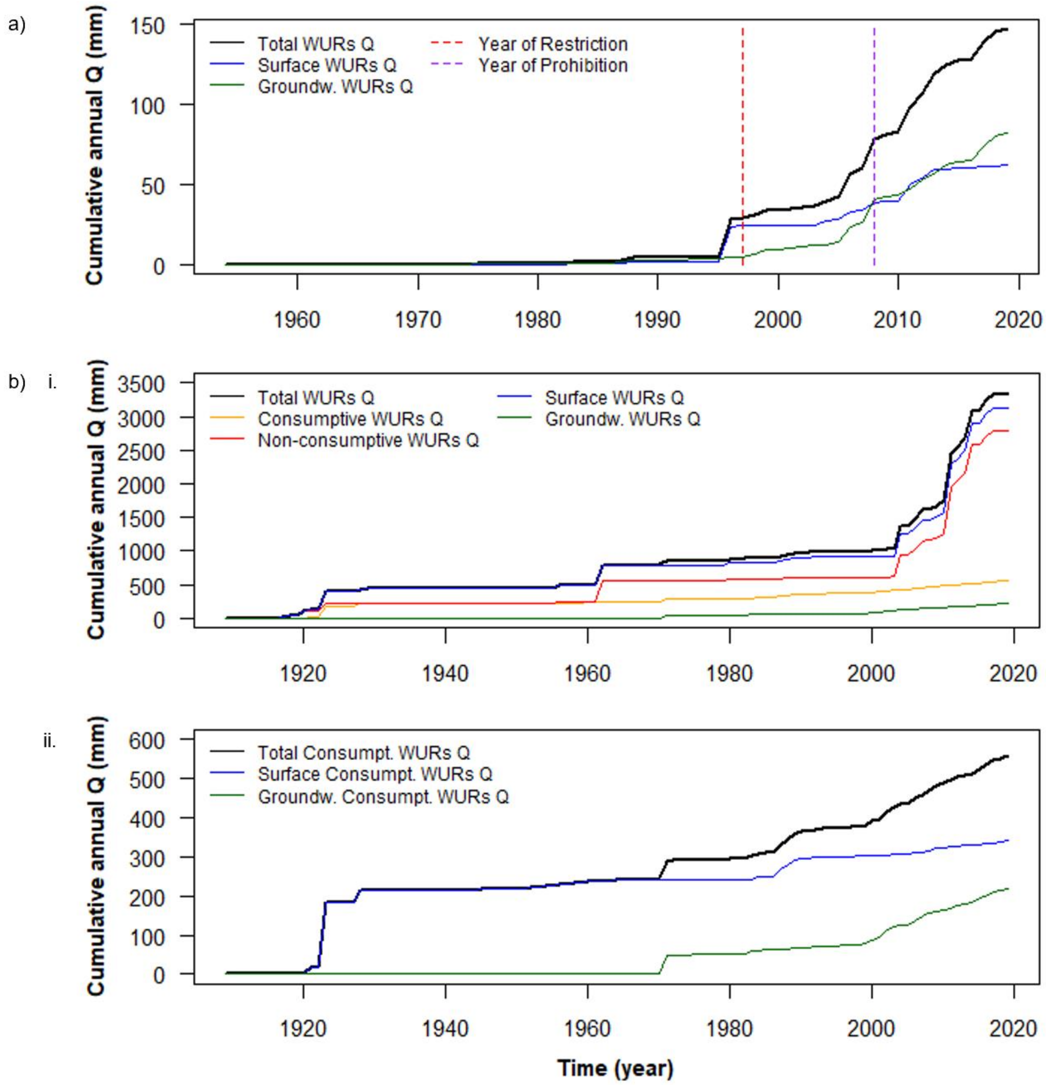

Figure 12 Temporal evolution of cumulative annual flows as WURs in the (a) Petorca (1954-2019), and (b) Cachapoal (1909-2019) River basins for (b.i) all granted WURs, and (b.ii) only consumptive WURs.

Figure 12a shows the evolution of allocated WURs in the Petorca River basin. It can be noted that surface WURs dominated over groundwater WURs until 1997, when the basin was declared a restricted area and the aquifers began to be exploited. The amount of groundwater flow assigned until 2005 was nearly duplicated in 2006. Declaring the basin as a prohibited area (in year 2008) did not reduce the amount of allocated WURs, and groundwater extractions increased considerably in subsequent years. On the other hand, surface water allocations have dominated in the Cachapoal River basin (Figure 12b.i), with a temporal evolution similar to that of non-consumptive WURs, suggesting that these come from surface water. Similarly, the results displayed in Figure 12b.i suggest that groundwater WURs are consumptive.

The evolution of allocated consumptive WURs in the Cachapoal River basin is presented in Figure 12b.ii, showing that the amount of assigned flow has been increasing considerably since 1970. The amount of allocated surface water has been increasing slightly since 2000, although the Rapel River basin does not have surface water availability for the granting of new WURs.

5.3.2. Natural water supply versus water demands

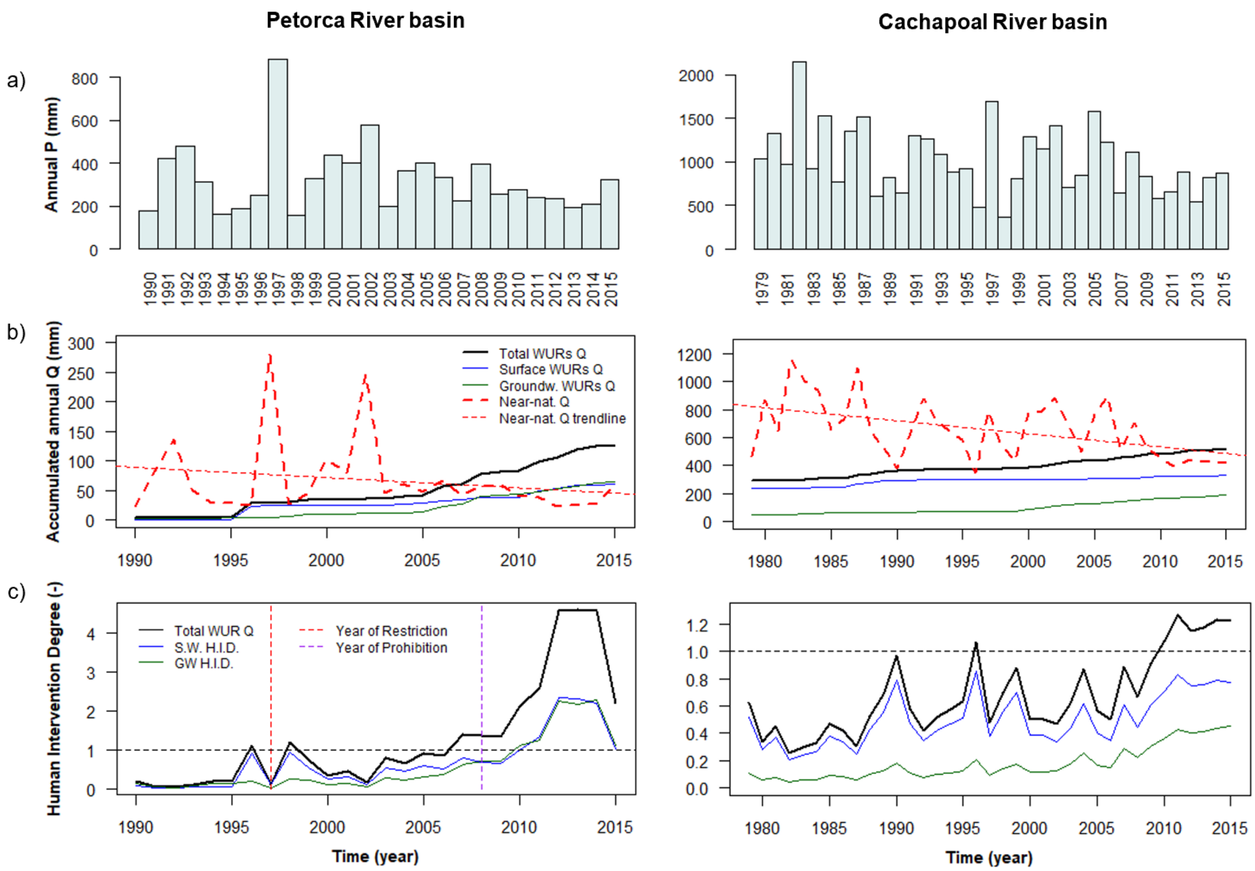

Figure 13 (a) Catchment-scale annual precipitation, (b) cumulative annual flows as WURs versus near-natural flow, and (c) evolution of human intervention degree indices in the Petorca (1990-2015), and the Cachapoal (1979-2015) River basins. In panel (b) near-natural flow trends are statistically significant (z_{MK} from Mann-Kendall test are -0.14 and -0.34 for the Petorca and Cachapoal River basins, respectively), considering a significance level of z_a=0.05. The analysis period for the Petorca River basin starts in 1990 due to a clearly increase of allocated water as WURs since that year (see Figure 12a). The horizontal dashed line in panel (c) shows the human intervention degree threshold of 1.

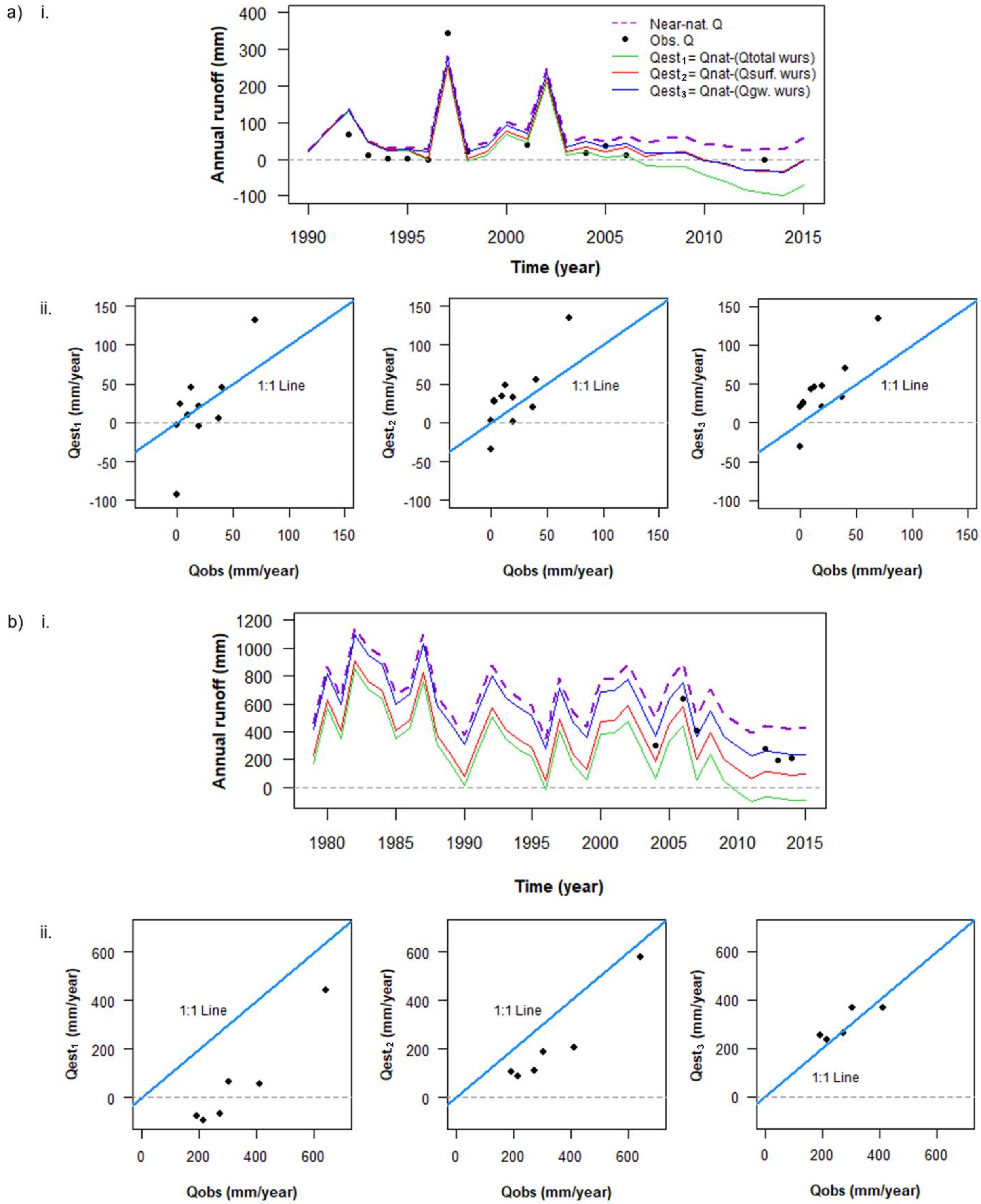

Figure 14 Mass balance results (i.e., available water, Qest) according to water source nature* in (a) the Petorca River basin (1990-2015), and (b) the Cachapoal River basin (1979-2015). Results are displayed in the form of (i) time series, and (ii) scatterplots of estimated flow (Qest) vs. station records. Observed flow is only shown for some years since both fluviometric stations have months (and years) without records.

* $Qest_1$, $Qest_2$, and $Qest_3$ are estimated considering allocated flow from total (surface water + groundwater), surface and groundwater WURs, respectively.

Figure 13 shows annual time series of precipitation, near-natural runoff, total flow from WURs and human intervention degree indices. Considering the total allocated flow as WURs, the Petorca River and the Cachapoal River basins have been under stress since 2007 and 2009, respectively (Figure 13b).

In the Petorca River basin, surface and groundwater extractions started exceeding natural supply in 2010 and, although the near-natural regime flow increases in 2015 due to larger precipitation amounts (Figure 13a), the stress in the basin is maintained because such increase is not enough to compensate surface or groundwater extractions, and due to continuous allocation of groundwater WURs. In the Cachapoal River basin, near-natural flow has a decreasing trend (m= -9.27 mm/year) with values slightly higher than surface WURs flow in 2015. Further, natural water supply is larger than both surface or groundwater diversions. Even more, climate change is expected to impact natural flows in Northern and Central Chile negatively in the near future (2030-2060) and, if the granting of surface WURs increases, water stress is going to reach the Cachapoal River basin in one or two decades (DGA, 2018b).

Figure 13c displays the temporal evolution of human intervention degree indices from surface (S.W. $H.I.D_{(2)}$) and groundwater (GW $H.I.D._{(2)}$) sources (equations 9 and 10, respectively). A "total intervention degree" index is added for comparison purposes, considering all allocated WURs (i.e., S.W. $H.I.D_{(2)}$ + GW $H.I.D_{(2)}$). The results are consistent with Figure 13b for both catchments. Surface diversions dominated in the Petorca River basin until 2008, when groundwater extractions reached similar levels. On the other hand, surface water extractions have always dominated in the Cachapoal River basin, and the associated human intervention degree showed little fluctuations since 2011 due to small variations in near-natural annual flow during the 2011-2015 period.

Figure 14 shows that mean annual streamflow measured at the outlet of the two case study basins cannot be fully explained by differences between natural water supply and the flow allocated as WURs (equation 11) – either surface, groundwater or their sum. In the Petorca River basin, available water estimates Q_{est} were similar to near-natural flows until 2003, indicating that extractions were very low and did not yield water stress in the basin. During the same period, measured flows are below available water estimates for most water years, suggesting an underestimation of real allocated flows (Section 5.2), overuse of a granted allocated flow and/or unauthorized extractions. Since 2004, measured flows are similar to available water flows; however, a negative balance ($Q_{est} < 0$) is observed since 2007 (2010) if the total flow (surface water or groundwater) allocated as WURs is considered in Q_{est} estimates.

In the Cachapoal River basin, a negative mass balance is obtained since 2010 when considering the total flow allocated as WURs. Also, observed annual flows are more similar to the available water flow estimated from groundwater (rather than surface) WURs. In this case, a granted allocated flow could be underutilized (or not used at all) yielding an overestimation of extracted flows.

Although observed annual runoff shows a better agreement with available water estimated from groundwater WURs (Q_{est3}) in both case study basins, we cannot confirm that surface and groundwater hydrology are actually connected (i.e., that groundwater extractions affect the streamflow). To test such hypothesis, detailed characterizations of aquifer type (if existing), granted WURs (type, quantity, allocated flow and spatial distribution), and a groundwater model would be required. In the Petorca River basin, we infer that groundwater extractions affect the streamflow due to: (i) actual water stress conditions (reported in previous studies; INDH, 2014; Nieto et al., 2018; DGA, 2018a), (ii) the quantity, allocated flows and spatial distribution of groundwater WURs, and (iii) measured streamflow is lower than available water estimate from surface and groundwater WURs. In the Cachapoal River basin we cannot make this assumption, since observed annual flows are higher than available water estimated from surface WURs, indicating that actual extracted flows are smaller than the total surface allocated flow.

However, the main assumptions of these analyses are the reliability of VIC estimates, and that the quality of station records is good in both catchments. In particular, the Petorca River basin shows a peak flow in 1997 when, although large precipitation amounts were recorded that year (see Figure 13a), its value exceeds the modeled natural flow. Further, both fluviometric stations have months (and years) with missing records in their respective analysis period.

6. CONCLUSIONS

The information contained in the WUR national database is critical for the quantification and management of Chilean water resources. In this work, we reviewed and corrected this information in order to create a high-quality publicly available dataset and demonstrate its potential for two types of hydrological applications: (1) runoff prediction in ungauged basins, via statistical modeling, and (2) temporal analysis of granted WURs in two case study basins. For the first example application, a suite of 214 gauged basins (88 with near-natural regimes, and 126 with considerable human intervention levels) from the CAMELS-CL dataset were used, while the second application is conducted in the Petorca and Cachapoal River basins. The main conclusions obtained from the analysis are:

- The national analysis of granted WURs in Chile shows that mean annual granted flow in the Metropolitan Region (~79%, equivalent to only ~8% of total granted WURs in Chile) is much higher than the flow volumes allocated in the rest of continental Chile, which is concerning given the increasing demand for water and climate changes projections for that area. This result illustrates the high inequality in the distribution of WURs flows across the country.
- Quantifying real allocated flow as WURs within a basin is challenging because (i) it requires assumptions (e.g., restitution point of non-consumptive rights, and equivalent for "shared" water volume in lt/s), and (ii) missing information. The georeferencing approach proposed here (i.e., for non-georeferenced WURs and those with incorrect location information) provides uncertain results when information associated to headwater subbasins with WURs assigned is omitted, and only analysis at the catchment scale is plausible. Likewise, actual streamflow diversions may differ considerably from allocation estimates due to poor regulation mechanisms, generating a non/sub/over use of a granted allocated flow and unauthorized extractions.
- The results obtained in both example applications suggest that the human intervention indices proposed here cannot explain the spatial variability of mean annual runoff in catchments with high intervention levels, but they do explain its temporal variability. Neverless, human intervention indices allows the estimate of water stress level within a basin and could help as a complement of the actual water allocation system.

Future work should focus on improving the formulation of human intervention indices, for which more detailed studies would be required to determine if surface and groundwater hydrology are connected and, if so, to what extent groundwater extractions may affect catchment-scale streamflow production.

Finally, Barría et al., (2021) pointed another problems (gathered from several studies: Mundial, 2011; Donoso, 2018; Fundación Chile, 2018; Barría et al., 2019) with the DGA WURs database, which prevents a realistic quantification of the water balance within a basin and thus reliable water availability calculations: (i) the aim of the public granted WURs database is to provide traceability of all the administrative processes that have affected WURs historically (purchases, sells etc.), generating several duplicates WURs which are not identified in the database, (ii) existence of pre Water Code 1981 WURs granted during the agrarian reform (1970) that have not been systematized in the DGA databases, and (iii) existence of WURs that do not require to be registered in the databases, such as mining water use and the subsistence water uses (DS56). For the above reasons, Barría et al., (2021) decided to use the official postprocessed (debugged) granted WURs database, which is not published in the DGA website but is the official information internally used by the DGA to estimate water availability and grant new WURs.

III. CONCLUSIONES

La información contenida en la base de datos nacional de DAA es de gran importancia para la cuantificación y gestión de los recursos hídricos en Chile. En este trabajo, dicha información se revisa y corrige con el fin de utilizarla para análisis de oferta y demanda de recursos hídricos. Su potencial aplicabilidad se ilustra para dos tipos de problemática: (1) predicción de caudales en cuencas sin control fluviométrico, mediante la implementación de un modelo estadístico, y (2) análisis temporal de DAAs otorgados en dos cuencas de Chile Central. Para la primera aplicación, se utilizan cuencas con información fluviométrica (88 cuencas en régimen natural, y 126 cuencas con niveles considerables de intervención humana) incluidas en la base de datos CAMELS-CL, mientras que el segundo ejemplo utiliza información de las cuencas de los ríos Petorca en Longotoma y Cachapoal en Puente Arqueado. Las principales conclusiones obtenidas son las siguientes:

- El análisis nacional de los DAAs otorgados muestra que el caudal medio anual asignado en la Región Metropolitana (~79%, y equivalente solo al ~8% del total de DAAs otorgados en Chile) es mucho mas alto que los volúmenes de agua asignados en el resto de Chile continental, lo cual es preocupante dada la creciente demanda de agua y las proyecciones de cambio climático para Chile Central. Este resultado también ilustra la alta desigualdad en la distribución de los DAAs otorgados en el país.
- La estimación del caudal real asignado como DAAs resulta desafiante porque requiere de algunos supuestos (e.g., punto de restitución de derechos no consuntivos, y equivalencia para la conversión de volúmenes de agua asignados bajo "acciones" a lt/s), y el grupo de DAAs que se tuvo que omitir debido a la falta de información. Además, la metodología de georreferenciación propuesta en este trabajo (i.e., para los DAAs no georreferenciados en la base de datos original y los que tienen coordenadas de captación incorrectas) provee resultados inciertos cuando se omite la información de las subcuencas en la que cada DAA se asigna, y sólo se dispone información de la cuenca completa. Asimismo, las extracciones reales pueden diferir considerablemente de las estimaciones del caudal debido a mecanismos de regulación y supervisión de DAAs otorgados deficiente, lo cual podría generar una no/sub/sobre utilización de un caudal asignado y extracciones no autorizadas.
- Los resultados obtenidos en ambas aplicaciones indican que los índices de intervención humana no pueden explicar la variabilidad espacial del caudal en cuencas intervenidas, pero sí su variabilidad temporal. No obstante, los índices de intervención humana permiten estimar el nivel de estrés hídrico dentro de una cuenca, y podrían servir como complemento del actual sistema de asignación de agua en Chile.

Estudios futuros deberían centrarse en mejorar la formulación de los índices de intervención humana, para lo cual se requiere de estudios más detallados que puedan determinar si la hidrología superficial y la subterránea están conectadas y, en caso afirmativo, si las extracciones de aguas subterráneas afectan al caudal y flujo de salida de la cuenca y en qué medida.

Por último, Barría et al., (2021) señalan otros problemas (obtenidos de varios estudios: Mundial, 2011; Donoso, 2018; Fundación Chile, 2018; Barría et al., 2019) con la base de datos de DAA de la DGA, que impiden una cuantificación realista del balance hídrico dentro de una cuenca y, por tanto, un cálculo fiable de la disponibilidad de agua: (i) el objetivo de la base de datos pública de la DGA es dar trazabilidad a todos los procesos administrativos que han afectado a los DAAs otorgados históricamente (compras, ventas, etc.), generando varios DAAs duplicados y no identificados dentro de la misma, (ii) existencia de DAAs anteriores al Código de Aguas de 1981, otorgados durante la reforma agraria (1970), que no han sido sistematizados en la base de dato de la DGA, y (iii) existencia de DAAs que no requieren ser registrados en la base de datos, como el agua de uso para minería y subsistencia (DS56). Por lo anterior, Barría et al., (2021) decidieron utilizar una base de datos de DAAs post-procesada (depurada), la cual no se encuentra publicada en su página web, pero es la información oficial utilizada internamente en la DGA para estimar la disponibilidad de agua y otorgar nuevos DAAs.

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V. ANEXOS

Anexo A

The following table contains a description of the 34 catchment attributes, from the CAMELS-CL database, considered to identify potential predictor variables:

Attribute class: Location and topography		
Attribute name	**Description**	**Unit**
area	catchment area	km^2
elev_gauge	gauge elevation (catchment outlet) obtained from the 30m ASTER GDEM elevation data and m a.s.l. the location provided by DGA	m a.s.l.
elev_mean	catchment mean elevation	m a.s.l.
elev_med	catchment median elevation	m a.s.l.
elev_max	catchment maximum elevation	m a.s.l.
elev_min	catchment minimum elevation	m a.s.l.
slope_mean	catchment mean slope	$m\ km^{-1}$
Attribute class: Geological characteristics		
Attribute name	**Description**	**Unit**
geol_class_1st_frac	fraction of the catchment area associated with its most common geologic class	-
geol_class_2nd_frac	fraction of the catchment area associated with its second most common geologic class	-
carb_rocks_frac	fraction of the catchment area characterised as "carbonate sedimentary rocks"	-
Attribute class: Land cover characteristics		
Attribute name	**Description**	**Unit**
crop_frac	Percentage of the catchment covered by croplands, level 1. Includes five types of level 2 classes: rice fields; greenhouse farming; other croplands; orchards; and bare croplands	%
nf_frac	Percentage of the catchment covered by forest (level 1) classified as natural broadleaf (level 2) or natural conifer (level 2).	%
fp_frac	Percentage of the catchment covered by forest (level 1) classified as broadleaf plantations (level 2) or conifer plantations (level 2).	%
grass_frac	Percentage of the catchment covered by grasslands, level 1. Includes three types of level 2 classes: pastures; other grasslands; and withered grasslands.	%
shrub_frac	Percentage of the catchment covered by shrublands, level 1. Includes five types of level 2 classes: shrublands; shrubs and sparse trees mosaic; succulents; shrub plantations; and withered shrublands.	%
wet_frac	Percentage of the catchment covered by wetlands and water bodies (level 1). Includes six types of level 2 classes: marshlands; mudflats; other wetlands; lakes; reservoirs/ponds; rivers; and ocean.	%
imp_frac	Percentage of the catchment covered by impervious surfaces (level 1). Urbanized areas are usually contained in this class.	%

Attribute class: Land cover characteristics		
Attribute name	**Description**	**Unit**
lc_barren	Percentage of the catchment covered by barren lands (level 1). Includes three types of level 2 classes: dry salt flats; sandy areas; and bare exposed rocks	%
snow_frac	Percentage of the catchment covered by snow and ice, level 1. Includes two types of level 2 classes: snow and ice.	%
lc_glacier	percentage of the catchment covered by glaciers.	%
fp_nf_index	forest plantation index: calculated as the ratio between fp_frac and the total forested area (fp_frac + nf_frac)	-
forest_frac	fraction of the catchment covered by forests, including native forest and forest plantation (fp_frac + nf_frac)	%
dom_land_cover_frac	fraction of the basin associated with dominant land cover class	%
land_cover_missing	percentage of the basin not covered by the land cover map	%
Attribute class: Climatic indices (computed for 1 April 1990 to 31 March 2010, using the CR2MET product)		
Attribute name	**Description**	**Unit**
p_mean	mean daily precipitation	mm day^{-1}
pet_mean	mean daily PET of pet_{har} product	mm day^{-1}
aridity	aridity, calculated as the ratio of mean daily PET (pet_mean) to mean daily precipitation (p_mean)	-
p_seasonality	seasonality and timing of precipitation estimated using sine curves to represent the annual temperature and precipitation cycles; positive (negative) values indicate that precipitation peaks in summer (winter); values close to 0 indicate uniform precipitation throughout the year.	-
frac_snow	fraction of precipitation falling as snow (i.e., on days colder than 0 °C)	-
high_prec_freq	frequency of high-precipitation days (≥ 5 times mean daily precipitation)	days yr^{-1}
high_prec_dur	average duration of high-precipitation events (number of consecutive days ≥ 5 times mean daily precipitation).	days
low_prec_freq	frequency of dry days (< 1 mm day^{-1})	days yr^{-1}
low_prec_dur	average duration of dry periods (number of consecutive days < 1 mm day^{-1})	days
p_mean_spread	standard deviation of p_mean from the four precipitation products, normalized by multi-product mean	-