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RESEARCH ARTICLE

Water allocation under climate change: A diagnosis of the Chilean system

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Chile is positioned in the 20th rank of water availability per capita. Nonetheless, water security levels vary across the territory. Around 70% of the national population lives in arid and semiarid regions, where a persistent drought has been experienced over the last decade. This has led to water security problems including water shortages. The water allocation and trading system in Chile is based on a water use rights (WURs) market, with limited regulatory and supervisory mechanisms, where the volume to be granted as permanent and eventual WURs is calculated from statistical analyses of historical streamflow records if available, or from empirical estimations if they are not. This computation of WURs does not consider the nonstationarity of hydrological processes nor climatic projections. This study presents the first large sample diagnosis of water allocation system in Chile under climate change scenarios. This is based on novel anthropic intervention indices (IAI), which were computed as the ratio between the total granted water volume to the water availability within 87 basins in north-central and southern Chile (30°S–42°S). The IAI were evaluated for the historical period (1979–2019) and under modeled-based climatic projections (2055–2080). According to these IAI levels, to date, there are 20 out of 87 overallocated basins, which under the assumption that no further WURs will be granted in the future, increases up to 25 basins for the 2055–2080 period. The results show that, to date most of north-central Chilean catchments already have a large anthropic intervention degree, and the increases for the future period occurs mostly in the southern region of the country (approximately 38°S), which has been considered as possible source of water for large water transfer projects (i.e., water roads). These indices and diagnosis are proposed as a tool to help policy makers to address water scarcity under climate change.

Keywords: Water management, Water market, Climate change, Hydrological modeling

1. Introduction

Water projections indicate that by mid-21st century, more than half the world population will live in regions under water stress conditions, either associated to the physical lack of water supply to meet the water demand (water scarcity; Van Loon et al., 2013) or to the inability of the water management systems to satisfy human and ecological demands for water (water access; UN, 2018). As population and economic development is projected to grow, the water demand is expected to increase worldwide up to 55% by 2050 (WWAP, 2014), exacerbating water scarcity in many areas of the world (Greve et al., 2018). These projections raise concerns about future global water security (Schewe et al., 2014) and the achievement of the Sustainable Development Goals (UN, 2015), most of which are strongly linked to water availability and quality (Vanham et al., 2018). This is particularly important in developing semiarid and Mediterranean climate regions of the world, such as north-central Chile, where general climate models (GCMs) consistently project decreases in rainfall over the following decades. These projected decreases highlight the need to revise current water management

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systems in order to adapt or transform them to manage the finite fresh water under an increasing demand (Polade et al., 2017).

In this context, there is a growing number of studies that propose large-scale water management strategies to deal with water scarcity (e.g., Kahil et al., 2015; Wada et al., 2016). Many of these studies propose guidance toward improving the operation or building new hydraulic infrastructure to increase the water supply based on informed decision making (e.g., Hoekstra, 2014; Zhang et al., 2019). The governmental investments in such large-scale strategies need to be founded on robust local information regarding water availability and climate projections at the regional scale (Greve et al., 2018). Studies on hydrology have stressed the need to start planning as viewing through a "cone of uncertainty" representing the multiple unknown affecting water supply (Waage and Kaatz, 2011), as current climatic trends are no longer valid (Milly et al., 2008). In this way, advancing the understanding of the physical limits of the resource (surface and groundwater availability) and water uses (Garrick and Hall, 2014) under different possible futures (Lempert et al., 2003; Kwakkel et al., 2016) should facilitate the design of resilient water security strategies (Ericksen et al., 2011; Fazey et al., 2011).

Chile is a narrow and long strip of land located between the high ranges of the Andes mountains and the Pacific Ocean, which provides an exceptional scenario for analyzing spatial and temporal variability of climate and water resources. In this territory, information on water availability and management is one of the main challenges toward addressing water scarcity (Mundial, 2013).

Chilean water management is ruled by the 1981 Water Code (WC81), which establishes that water allocation is based on a water use rights (WURs) system that grants a quantity of water to solicitor users. These can then be traded (or reallocated) through the water market, which theoretically would regulate the reallocation of the available water resources based on economic efficiency. However, the Chilean water market is constrained by severe limitations to provide responses to water conflicts and to reach environmental sustainability (Ríos and Quiroz, 1995; Hearne and Donoso, 2014; Rivera et al., 2016; Peña, 2018). Challenges as the lack of robust and updated databases of water availability (total precipitation and runoff), and existing total WURs and effective water use at the basin scale, highly debilitates the assumption of efficient reallocation (Donoso, 2018).

Furthermore, as water markets are driven by demand price set by relatively high-valued water uses (Donoso et al., 2014), the partly human-induced declines in water availability experienced in central Chile during the last 2–3 decades (Boisier et al., 2016; Boisier et al., 2018) have led to severe water-access problems, particularly for less profitable sectors such as subsistence agriculture or rural drinking water systems (Bauer, 2015; Muñoz et al., 2020). Considering the mounting evidence of climate change projections, there is still limited knowledge of how the hydrological regimes will evolve in the future decades (McPhee, 2018), and how well the existing water allocation methods will work under a changing climate (Barria et al., 2019).

In this context, to contribute into advancing toward a sustainable water management system that leads to water security under climate change scenarios, in this study, the historical and future performance of the Chilean water allocation system under nonstationary hydrology have been assessed. To do that, a hydrological model was implemented within 87 catchments in north-central and southern Chile to simulate water availability under historical and future climate change scenarios. Then, two indices were developed to facilitate the incorporation of current and future water availability states into a diagnostic of the national water allocation system. These indices, named the Indices of Anthropogenic Intervention (IAI), are computed at the catchment-scale and account for estimations of water availability and human intervention within the basin (granted WURs). The research questions here addressed are as follows:

1. What is the spatial-temporal variability of the anthropic intervention degree in the north-central and south Chilean region considering a large sample of catchments located in a wide latitudinal range?
2. How prepared is the current Chilean water management system to avoid the overallocation of basins under a nonstationary climate change scenario?
3. What are the implications of these results for large-scale projects aimed at increasing water supply?

1.1. Insights into the market-based Chilean water allocation system

As aforementioned, Chilean water allocation is based on a tradable WURs market originally granted by the *Dirección General de Aguas* (Chilean Water Directorate, DGA), and later traded by the owner as it is considered as immovable good which has to be registered in the Real State Title Offices and constitutes perpetual private property with high legal security (Bauer, 1998). However, this market-based system is limited by several failures regarding: water price, WURs hoarding (Bauer, 2004, 2015), and most importantly for this analysis, an incomplete information regarding the amount of WURs that is placed in the market. As it will be described in the following paragraphs, the latter is related with the official WURs database and the limited national water resources monitoring system that should support it.

Although much has been advanced in characterizing and understanding the Chilean hydrology over the last decades, from scientific perspectives (Alvarez-Garreton et al., 2018) and institutional perspectives (e.g., the Chilean Atlas Water by the DGA, 2016, and the National Water Balance project by the DGA, 2017), key challenges regarding water management still remain unaddressed, including the lack of robust and updated databases of (1) water availability (total precipitation and runoff), and (2) existing total WURs and effective water use at the basin scale (Donoso, 2018). The Chilean Water Atlas and Water Balance were efforts to improve the knowledge of the Chilean hydrology by systematizing the historical hydrometeorological records of the national territory at the basin scale, but continuous monitoring of hydrometeorological variables is still scarce and inexistent in many basins of Chile, especially glaciers monitoring (McPhee, 2018), key for snowmelt-dependent basins (Donoso, 2018). Glacier monitoring is crucial to have a good understanding of groundwater resources in Chile, especially in north-central semiarid and arid basins, where most of the groundwater recharge takes place in high elevations in the Andes Mountains (Suarez et al., 2021).

Regarding water use, several diagnoses (Mundial, 2011; Donoso, 2018; Fundación Chile, 2018; Barria et al., 2019) reported that the lack of reliable WURs records is one of the main problems of the Chilean water allocation system, which prevents a realistic quantification of the water balance within a basin and thus reliable water availability calculations. The main problems with the DGA WURs database reported by these studies are as follows: (1) contains WURs with different units of measurement or nonvolumetric units (*shares*); 2) as the databases aims to provide traceability of all the administrative processes that have affected WURs historically (purchases, sells etc.), there are several duplicates WURs, which are not identified in the database; (3) existence of pre-WC81 WUR granted during the agrarian reform (1970) that have not been systematized in the DGA databases; (4) existence of WUR that do not require to be registered in the databases, such as mining water use and the subsistence water uses (DS56); (5) information is not presented at the catchment scale, and location of the WURs is inaccurate in some cases, hampering the calculations of water balances to allocate further WURs; and (6) the database lacks information regarding effective water use, which means some granted WURs might not be currently used.

In addition to the aforementioned limitations in the water availability and use records, Barria et al. (2019) showed that the Chilean water allocation methodology disregards climate change impacts on water availability, which hinders a sustainable management of water and threatens long-term water security. Indeed, as stated by the WC81 (Articles 20, 22, 23, 57–60, 130, 141, 149, and 150), the DGA must grant any WUR requested if there is water availability in the basins. However, according to the methodology adopted by the DGA, that *water availability* (the available water volume to be granted via WURs) is determined based on statistical analysis of historical runoff information, and under the assumption of stationarity (DGA, 2008).

In the meantime, increased water consumption associated to the economic growth in agriculture and mining exports since the early 1990s (Anríquez and Melo, 2018), combined with the gradual decrease in precipitation during the last two to three decades (Boisier et al., 2016; Boisier et al., 2018), and exacerbated by the decade-long (2010–2019) precipitation deficits experienced during the so-called megadrought (MD; Garreaud et al., 2017, 2020), have pushed the proposition of large private and public infrastructure initiatives to increase water supply. These initiatives include a national dams plan that aims to build 26 dams in nine regions, desalination plants in coastal cities (Ministerio de Obras Públicas [MOP], 2018), and immense water transfer infrastructure of approximately US$10–20 million and over 1,000 km of distance, transporting water from the humid catchments located in southern Chile to the semiarid regions of the country. Currently, there are two long distance water transfer projects in pre-feasibility status, both pushed by noncorporations sponsored by farm and mining industry associations (e.g., Chilean fruit exporters association, National Agricultural Society, or the Mining Council, the trade association that brings together the largest mining companies producing in Chile). The more advanced project, named Hydric Road Project, plans to be constructed inland connecting existing infrastructure with new pipelines (Corporación Reguemos Chile, 2020), while the Aquatacama project is planning to submerge in the ocean a large pipeline using a new technology called SubmaFlex® (Aquatacama, 2020). Robust and reliable information are not only necessary for a strict enforcement of water use and water regulations (Vargas et al., 2020), but also to a deeper understanding of the trade-offs associated with such large-scale projects. Recent studies have stressed that these kinds of megaprojects require sound cost-benefit evaluations to assure sustainable water management (i.e., Vargas et al., 2020), incorporation of environmental impacts in the donor catchment (Albiac et al., 2006), as well as the long term projections of the opportunity cost of alternative water uses (Vargas et al., 2020).

In that regard, considering the current limitations of the Chilean water management system to deal with water scarcity problems during the MD (e.g., Alaniz et al., 2019; Muñoz et al., 2020; Barría et al., 2021), and the possible implementation of mega infrastructure strategies to search for new and distant water sources, it is urgent to revise and improve current water allocation mechanisms (Barria et al., 2019).

2. Study area and data

2.1. Study area

This analysis comprises from north-central to southern regions of Continental Chile, located between 30°S in the north and 42°S in the south. Following the Köppen-Geiger climate classification (Kottek et al., 2006), that region spans a variety of climates, from the desertic north (BWk) to the very wet rain-oceanic (Cfb) climate in the south, including the central sub-humid Mediterranean climate (Csb) region. These physiographic characteristics feature a large spatial variability of climate and result in a wide range of hydrological regimes within this region (McPhee, 2018). Indeed, as shown in **Figure 1a**, the mean annual precipitation ranges from around 240 mm/year in the northern basin (e.g., *Río Limarí en Panamericana*, -30.67°S) to around 1900 mm/year in the southern basin (e.g., *Río Rahue en Forrahue*, -40.52°S) of the study.

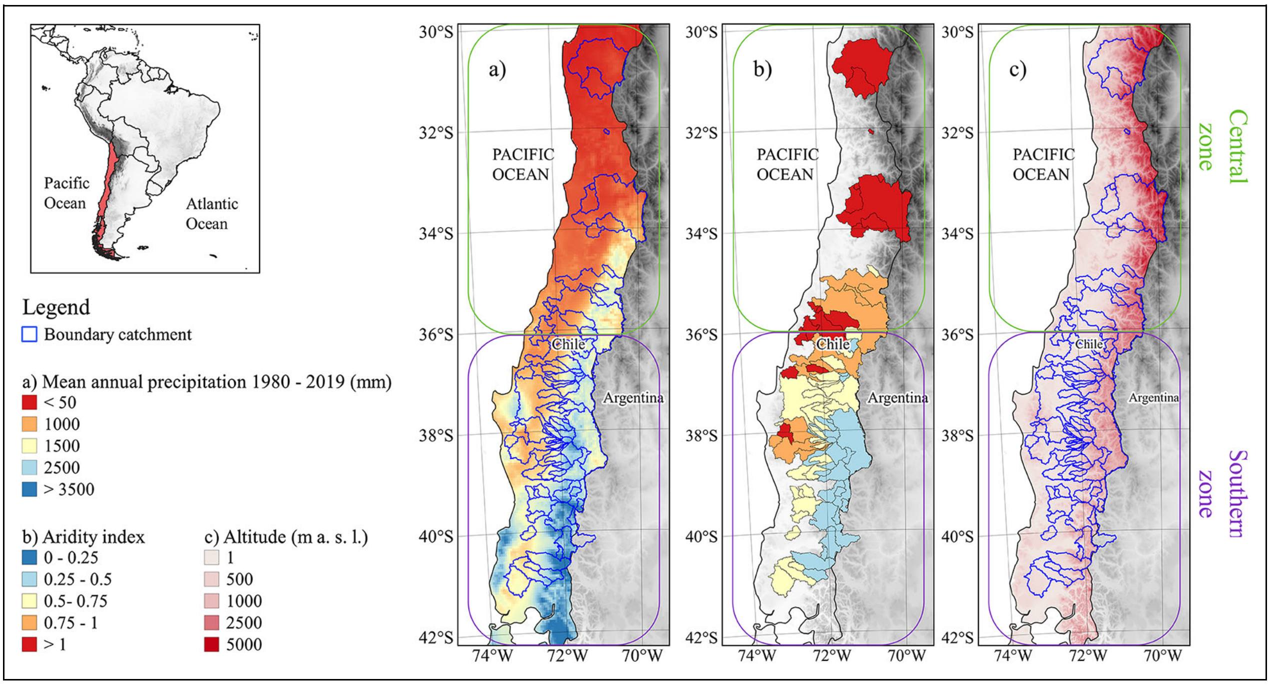

Figure 1. Location and characterization of the 87 study catchments. Mean annual precipitation (a), Aridity index (b), and elevation (c) of the study basins. DOI: https://doi.org/10.1525/elementa.2020.00131.f1

Furthermore, the study region concentrates more than 70% of the national population (INE, 2018), over 75% of the total irrigated agricultural activity of the country (INE-ODEPA, 2007) and more than 90% of the national forestry industry (INFOR, 2019). These activities are characterized by large and increasing water demands, which have propitiated substantial land use and land cover changes, and water use demands during the last three decades (i.e.- Schulz et al, 2010, Alaniz et al., 2019).

To assess historical and future performance of the Chilean water allocation system under a nonstationary hydrology, a modeled-based water balance of a large number of north-central and south Chilean catchments was obtained using historical, future climate change hydrometeorological data, and WURs information, all of them described below.

2.2. Observed hydrometeorological data

Monthly time series of streamflow, precipitation, and temperature data at the catchment scale were obtained from the CAMELS-CL (Alvarez-Garretón et al., 2018) database, which can be downloaded from the CAMELS-CL explorer (http://camels.cr2.cl). The database includes catchment boundaries, catchment-averaged hydrometeorological time series, and attributes characterizing the topography, geology, climate, hydrology, land cover for 516 basins across Chile, for the 1979–2019 period.

From the 516 CAMELS-CL catchments, a subset of 87 catchments that fulfilled the selection criteria described in Section 3.1 were used to calibrate and validate the water balance model. The subset of 87 catchments, feature diverse climatic (**Figure 1a** and **b**) and geographical conditions (**Figure 1c**), with areas ranging from approximately 81 km^2 to approximately 24,270 km^2 and mean elevations ranging from approximately 132 m a.s.l. to over 2,460 m a.s.l. Detailed information about the ensemble of basins is presented in Table S1. As presented in **Figure 1a**, precipitation within the study catchments generally increases southward. Also, the Andes mountains range is an important feature as it provides conditions for orographic precipitation enhancement (Viale and Garreaud, 2015). Because of the large climatic and geographical variability, the Chilean catchments encompass a wide range of hydrological regimes (McPhee, 2018) including pluvial, snowmelt, and mixed rainfall-snowmelt regimes. However, as illustrated in **Figure 2a**, the catchments analyzed in this study have predominantly pluvial hydrological regime, characterized by peak runoffs during austral winter months (June–July–August), with few pluvio-nival regime catchments.

2.3. GCM-based precipitation and temperature projections

Monthly temperature and precipitation data from the GCMs collated by the CMIP5 (Taylor et al., 2012) ensembles were used to analyze the projections of water availability within the study catchments under climate change scenarios. A list of the 75 simulations from the 41 CMIP5 GCMs used in this analysis, along with the GCMs characteristics, are presented in Table S2. CMIP5 GCMs were run under control forcing (preindustrial or representative of year 1900 conditions) for the period between 1900 and 2005 and transient forcing (time-varying concentrations of greenhouse gases) for the period between 2006 and 2100. The anthropogenic forcing Radiative Concentration Pathway (RCP) scenarios considered in this study are the RCP8.5 and RCP4.5 scenarios (Van Vuuren et al., 2011), which correspond to a more risk-averse and moderate

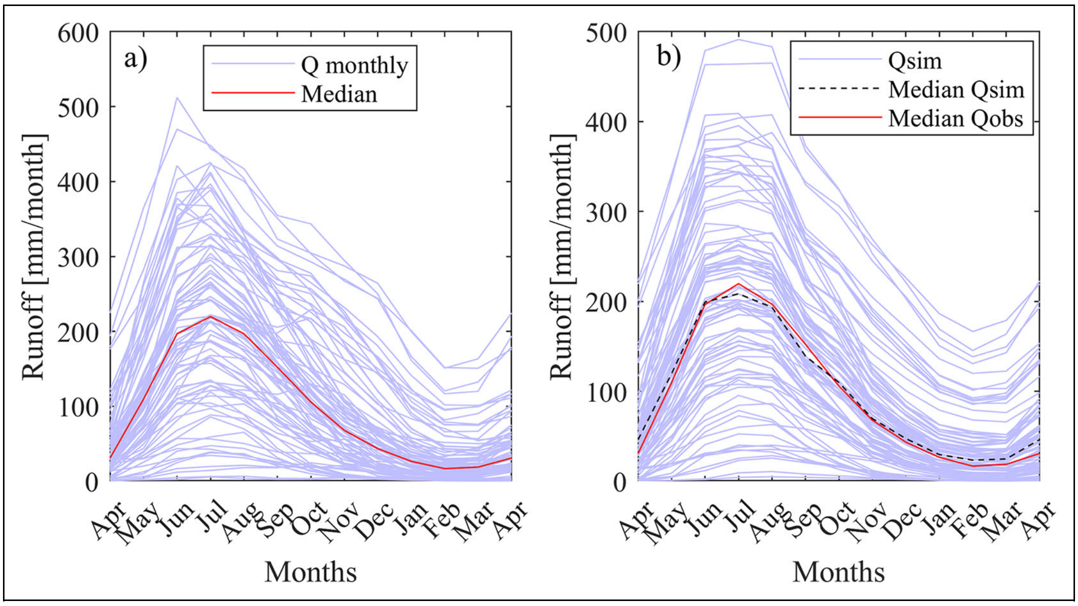

Figure 2. Streamflow seasonal variation of the 87 catchments for the 1980–2019. Calculations are based on (a) observed DGA runoff records, (b) simulated monthly runoff times series using the airGR GR2 M model. DOI: https://doi.org/10.1525/elementa.2020.00131.f2

perspective regarding future runoff reductions, respectively.

2.4. WURs

In this study, the official postprocessed (debugged) granted WURs database available at the Chilean Water Directorate was used. Although this information is not published in the DGA website, it can be requested through the Transparency Law website (Consejo para la Transparencia, 2020). As indicated in Section 1.1, the DGA WURs database is affected by several shortcomings regarding the location, amount, and type of WURs. Indeed, as presented in Figure S1, a preliminary assessment of the official DGA WURs database information within the administrative regions of the country where the 87 study basins are located was performed. According to that, from around 80,000 surface WURs and 110,000 groundwater WURs, a 58% and a 52% of the surface and groundwater WURs, respectively, lacks information to locate them at the basin scale. This problem is exacerbated in the basins located north of 36°S (north-central Chile), where the lack of geographical coordinates information affects to a 71% of the total WURs (Figure S1b and S1c), hampering the calculations of water balances.

As for the official WURs DGA database, in the debugged database here used, water entitlements are classified according to their use as either permanent or eventual water rights, and according to the source in surface or groundwater 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. It is important to mention that there are also nonconsumptive WURs, related with activities that in theory (according to the WC81) will not consume water and therefore will use it and return it somehow "intact" to the river channel, that is, for a hydroelectricity production. In this study, the same assumption was applied, then nonconsumptive WURs are diverted in the same catchment where they were captured, not affecting the basin scale water balance. Also, as the DGA database includes some WURs with nonvolumetric information (*water shares*), which are not presented at the basin scale, some postprocessing were required to include those WURs in the indices calculation (more information in Section 3.3.1).

3. Methods

The spatiotemporal variability analysis of water availability contrasted with the anthropic demands in terms of WURs was evaluated considering time-windows of 26 years length, following four stages. First, as detailed in Section 3.1, the airGR "GR2M" lumped hydrological runoff model was calibrated for the 516 catchments collated in CAMELS-CL data set, from which those that have good performances were selected to obtain runoff projections forced by climatic data under different climate change scenarios.

Second, two different approaches were proposed to calculate the theoretical available volumes of water to be granted as permanently exercisable surface and subsurface water rights on an annual basis (water availability): (1) based on the standard DGA procedure under scrutiny, using runoff records (see Section 3.2) and (2) considering the total water entering the basin, using the rainfall records. The water availability was calculated for three periods: (1) considering the data before the MD occurrence (1980–2005), (2) for the recent observed period including the last 10 years of MD period (1994–2019), and (3) considering future climate change scenarios (2055–2080).

Third, the indices of anthropic intervention within every catchment were calculated as the ratio between the annual surface and subsurface flow (groundwater flow) WURs allocated within every catchment plus the ecosystem requirements based on the ecological runoff, and the two theoretical water availability calculations here proposed (as it is calculated based on the DGA procedures; Section 3.3).

Finally, a spatiotemporal analysis of water availability, indices of anthropic intervention and granted WURs, was conducted for a variety of historical and future scenarios: the observed period before the MD (1980–2005), the recent historical period considering the MD (1994–2019), and the future period considering climate change projections (2055–2080).

3.1. Modeled-based hydrological projections

To obtain runoff projections for the large sample of catchments collated by CAMELS-CL, the airGR monthly lumped hydrological model (GR2 M) was used. The "GR2M" (Mouelhi, 2003) is an R-package (R Core Team, 2015), which simulates the monthly water balance at the catchment scale, forced with monthly rainfall and potential evapotranspiration. In this study, the Oudin et al. (2005) model was used to estimate the historical and future monthly potential evapotranspiration, from monthly temperature and solar radiation data, computed using the airGR package in R (R Core Team, 2015). The GR2 M airGR model considers two buckets: (1) Soil moisture, which has infiltration, evaporation, and percolation fluxes, and (2) Groundwater storage, where percolation is an inflow, superficial flows are outflows, and groundwater fluxes to other basins act either as inflows or outflows depending on the basin (Mouelhi et al., 2006).

The GR2 M model was implemented within the 516 CAMELS-CL catchments using catchment scale monthly precipitation, temperature, and runoff data from the CAMELS-CL database. However, only the catchments that fulfilled the following criteria were selected: (1) catchments with more than 75% of their monthly runoff data during the calibration period (1990–2019), (2) catchments with more than 50% of their monthly runoff data during the validation period (1979–1989), and (3) catchments with a Nash–Sutcliffe efficiency (NSE) greater than 0.5 in the calibration process, and coefficient of determinations above 40% during the validation process (R^2). These efficiency values are considered as satisfactory in runoff simulations (Moriasi et al., 2007).

Once the monthly water balance models of the 87 selected catchments were implemented for the historical period (1979–2019), bias-corrected future monthly temperature and precipitation data from the GCMs collated by the CMIP5 ensembles were used to obtain future projections of runoff within the studied catchments. To account for the uncertainties in climate change projections, 75 simulations from 41 CMIP5 GCMs were used in this analysis (GCMs list is presented in Table S2). As indicated in Section 2.2, the anthropogenic forcing scenarios considered in this study correspond to the risk-averse RCP8.5 and the moderate RCP4.5 scenarios (Van Vuuren et al., 2011). These GCMs data were bias-corrected using a delta change approach (Hay et al, 2000). The delta change approach consists of applying the changes simulated in the raw GCMs projections between a future and a historical period to the observed climate data. Thus, the observed precipitation series were multiplied by the change factor, and the temperatures were corrected applying an additive factor, both obtained from the raw GCM projections.

The calibrated GR2 M model for each catchment was run under bias-corrected monthly precipitation and temperature data (from the CMIP5 GCMs) to obtain evapotranspiration estimations and runoff projections for the long-term future 2055–2080.

3.2. Determination of the water availability at the catchment scale

According to the DGA procedures (DGA, 2008) and as governed by the Water Code, the available water supply in a catchment is determined from the observed runoff records on a monthly basis as follows:

$$Q_{\text{PEWR}_i} = Q_{85\,i} \tag{1}$$

where,

$Q_{\text{PEWR}\ i}$ = Runoff available for permanently exercisable water rights for month i

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

Based upon the DGA (2008) procedures, and according to the letter b of the Supreme Decree 14 of year 2014 (BCN, 2014), monthly ecological runoff is calculated from historical runoff records, as follows:

1. If 50% of the $Q_{95\ i}$ is less than 20% of mean annual runoff (Q_{annual}), then,

$$Q_{\text{ecol}\,i} = 0.5 \times Q_{95\,i} \tag{2}$$

where,

$Q_{95\,i}$ = 95% probability of exceedance runoff for month i

2. If 50% of the $Q_{95\ i}$ is greater than 20% of mean annual runoff, then,

$$Q_{\text{ecol}\,i} = 0.2 \times Q_{\text{annual}} \tag{3}$$

where,

Q_{annual} = Mean annual runoff in a period of interest

It is important to notice that considerable research has indicated the ecological flow calculations considered in the DGA methods do not necessarily comply with the ecosystem requirements associated with the surface source (i.e., Toledo and Muñoz, 2018). Moreover, the methods here described rule the calculations of water availability since year 2008, and the calculations of ecological runoff only affect WURs granted after year 2005. However, to accomplish the aims of this study, regarding estimating the anthropic intervention at the basin scale in a wide latitudinal range of Chile under historical and future climate scenarios, a conservative theoretical approach has been considered, applying the aforementioned expressions for all basins under all the climate scenarios.

In this study, empirical distribution functions were used to calculate different exceedance probabilities of runoff.

In addition, and as a proxy for estimating the theoretical available water for granting WURs without considering the effect of water withdrawals on the observed runoff, precipitation statistics for each basin were computed as follows:

$$P_{\text{PEWR}\ i} = P_{85\ i} \tag{4}$$

where,

$P_{85\ i}$ = 85% probability of exceedance precipitation for month i

The monthly amounts of theoretical available water for granting PEWR from runoff and precipitation data ($Q_{\text{PEWR}i}$ and $P_{\text{PEWR}i}$, respectively) were then processed on an annual basis considering the different analyzed time windows represented by the letter j (Q_{PEWRj}, P_{PEWRj}). Although according to Equations 2 and 3, the calculations of ecological runoff may vary according to the time-window implemented in the analysis, considering that the actual minimum ecosystem requirements do not decrease on time, and that the DGA estimations are not fully aligned to the actual ecosystem requirements, the annual Q_{ecol} was treated as a constant ecological runoff for the three periods here analyzed, based on the observed period before the MD (1980–2005). These data were then used to calculate the anthropogenic intervention indices.

3.3. Collection and systematization of granted WURs at the catchment scale

In this study, to know the water already allocated in each basin, geographical information systems were used to systematize the granted WURs obtained from the official debugged DGA databases at the basin scale, following these stages:

- The granted WURs database of all Chile was plotted and clipped within each catchment of CAMELS-CL database.
- The granted WURs with wrong or incomplete coordinates were associated to the gravity center of the subcatchment they belong to (which is an attribute of the database).
- The duplicated WURs were identified and eliminated from the database (changes in the coordinates, WURs bought or sold, etc.).
- The volumetric equivalent (in l/s) of WURs presented with qualitative information (shares) was estimated using the Water Use Associations share information (Universidad de Chile, 2018). For WURs which are not included in any of the Water Use Associations of Universidad de Chile (2018), an equivalent of 1l/s per one *water share* was considered.

More information regarding the DGA WURs database postprocessing is presented in Supplementary Material (Text S1).

3.4. Indices of Anthropogenic Intervention at the catchment scale

To characterize the level of anthropic intervention within the basins, two indices were defined, which account for the total allocated consumptive WURs as a function of water availability within the basin. Indices of anthropic intervention were defined as the ratio between the water use (granted WURs from the DGA databases plus the ecological runoff quantified from the historical runoff records) and the calculated water availability at the catchment scale. These indices correspond to a theoretical approach to assess the spatiotemporal variability of anthropogenic intervention, which are not entirely coincident to the administrative processes considered by the DGA to declare that a basin is depleted (Article 282 of the 81WC). Indeed, the Article 282 of the 81WC stipulates that the depleted basin declaration originates under a third-party request, aside from the fact that they could be physically depleted.

Two indices were calculated using the annual runoff data (IAI_Q), and the annual precipitation data (IAI_P) as water availability proxies. The first index is computed as the ratio of WURs granted within every basin and the ecological runoff to the Q85 (Equation 5), that is, representing water availability following the same approach than DGA uses for allocating WURs (Section 3.2). Given that the observed streamflow used to compute Q85 implicitly represents the volume of water already in use within the basin, we propose a second index, which represents water availability as the P85, that is, relying on the total water entering the basin (Equation 6).

IAI_Q and IAI_P were computed for the three-time windows used in Section 3.1: the observed period before the MD (1980–2005), the recent observed period including the last MD decade (1994–2019), and the future period considering climate change projections (2055–2080). In all the cases and as presented in Equations 5 and 6, the water use was quantified from the postprocessed consumptive, surface and groundwater granted WURs at the basin scale, from the DGA databases and the ecological runoff (Q_{ecol}), considered as an ecosystem water use. It is important to note that the granted WURs ($\text{Granted}_{\text{PEWR}j}$) change in time during the observed period, but as there is no information regarding future granted WURs, this study adopts a conservative criterion considering that the WURs of year 2019 remain constant in the future.

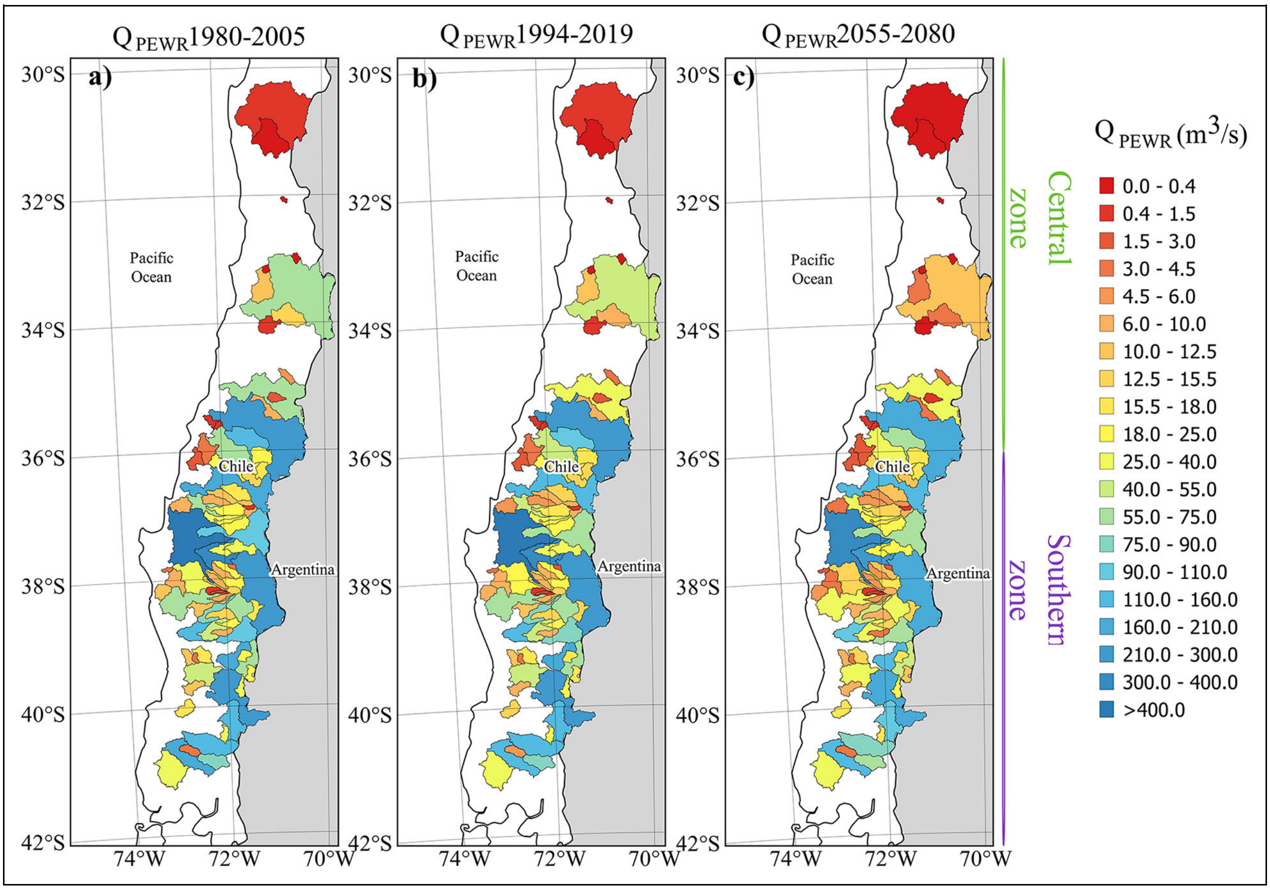

Figure 3. Water availability for granting permanently exercisable water use rights (Q_{PEWR}) and indices of anthropic intervention (IAI_Q). These calculated using annual runoff for (a) the 1980–2005 period, (b) the 1994–2019 period, and (c) the 2055–2080 period. DOI: https://doi.org/10.1525/elementa.2020.00131.f3

$$\mathrm{IAI}_{Qj} = \frac{\mathrm{Granted}_{\mathrm{WUR}j} + Q_{\mathrm{ecol}}}{Q_{\mathrm{PEWR}j}} \quad (5)$$

where,

IAI_{Qj} = Index of anthropogenic intervention using Q_{PEWR} calculated for time window j

$\mathrm{Granted}_{\mathrm{WUR}j}$ = Surface and groundwater granted WURs on time window j

and in terms of precipitation, the index is:

$$\mathrm{IAI}_{Pj} = \frac{\mathrm{Granted}_{\mathrm{WUR}j} + Q_{\mathrm{ecol}}}{P_{\mathrm{PEWR}j}} \quad (6)$$

where,

IAI_{Pj} = Index of anthropogenic intervention using $P_{\mathrm{PEWR}j}$ for time window j

$\mathrm{Granted}_{\mathrm{WUR}j}$ = Both surface and groundwater Granted WURs on time window j

Two IAI thresholds were then defined: (1) catchments with IAI over 1, meaning basins are already overallocated, therefore under large risk of water scarcity, as the calculated water availability is insufficient to satisfy the anthropic water demand and the minimum ecosystem requirements; and (2) catchments with IAI over 0.75, or at risk of future overallocation, especially considering that projections of IAI are based on the optimistic assumption that there will not be more WURs granted after year 2019. These thresholds are in accordance to the water scarcity analyses presented in Falkenmark (2013), which indicated basins with anthropic intervention degrees above 0.7 could be considered as basin at risk of water scarcity.

Finally, to assess the spatiotemporal variability of the water availability and the water use, the changes in the Q_{PEWR}, the P_{PEWR}, the IAI_Q, and the IAI_P for different time windows were quantified. Boxplots Kolmogorov Smirnov and *z* test of means were used to test the spatial patterns.

4. Results

4.1. Water availability based on observed runoff and precipitation data

Eighty-seven basins fulfilled the selection criteria presented in Section 3.1, where the implemented runoff models had a good performance to represent the hydrology of the catchments (NSE and R^2 of the models during the calibration and validation period are around 0.8, Figure S2), as revealed by the comparison of the observed and the modeled seasonal variation of runoff in **Figure 2a and b** respectively. The water availability for granting

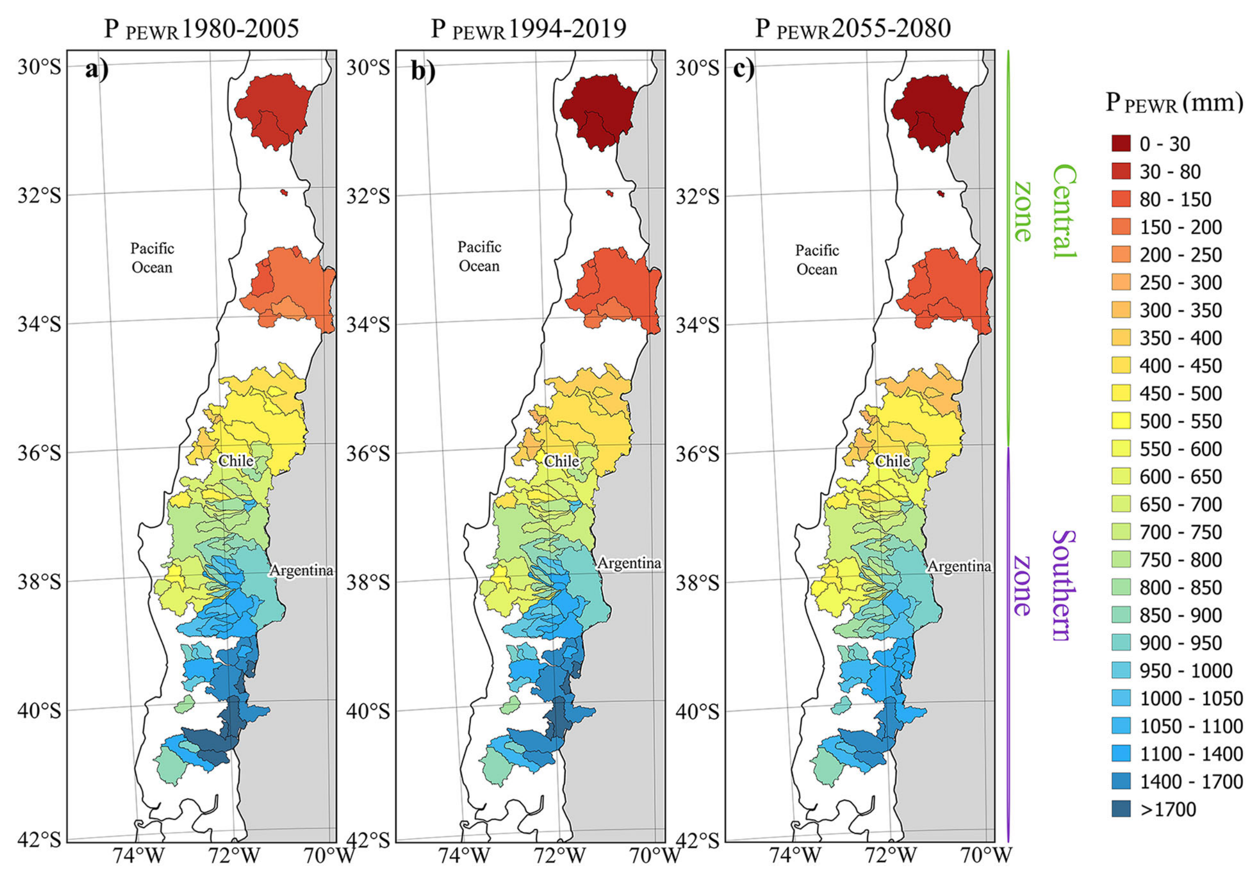

Figure 4. Water availability for granting permanently exercisable water rights based on precipitation (P_{PEWR}) calculated from annual rainfall data. These calculations are based on (a) the 1980–2005 period, (b) the 1994–2019 period, and (c) the 2055–2080 period. DOI: https://doi.org/10.1525/elementa.2020.00131.f4

permanently exercisable water rights estimated from runoff (Q_{PEWR}) data are presented in **Figure 3a–c** for the 1980–2005, the 1994–2019, and the 2055–2080 periods, respectively, while the available water for granting permanently exercisable water rights based on precipitation records (P_{PEWR}) is presented in **Figure 4a–c** for the 1980–2005, the 1994–2019, and the 2055–2080 periods, respectively. Considering the mean of all the 87 catchments, the Q_{PEWR} calculated from the 1980–2005 period is 13% larger than the Q_{PEWR} calculated for the 1994–2019 period. Similarly, the P_{PEWR} computed from the 1980–2005 precipitation records is about 4% larger than the P_{PEWR} computed for the 1994–2019 period, changes that are influenced by the effect of the MD. However, according to **Figure 3**, **Figure 4**, and **Table 1**, there is large spatial variability in the P_{EWR} calculations. This is a consequence of the unique natural and anthropic landscape characteristics of each catchment, which define the terrestrial part of the hydrological cycle. This spatial heterogeneity of natural and anthropic landscape characteristics and hydrologic propagation of precipitation leads to different challenges for achieving water security at the local scale.

Following the DGA definitions (DGA, 2016), and as presented in **Figure 1**, the boundary between north-central and south Chile was defined at the latitude 36°S (dividing central and south Chile macrozones). On average, the changes in the calculation of the Q_{PEWR} considering the 1980–2005 and the 1994–2019 periods is −32% in the central Chilean catchments and of −11% in the southern Chilean catchments. While for the $P_{PEWR,}$ the changes between the 1980–2005 and the 1994–2005 is of −18% and −3% for the north-central and south Chilean catchments respectively. These results indicate that the calculations of the water availability in the basins located in the north-central macrozone are more sensitive to the rainfall and runoff reductions of the MD period than the basins located in the southern macrozone. Also, the results show that elasticity of changes in runoff versus precipitation of the semiarid basins located in north-central Chile are lower than the elasticity of changes in southern, humid catchments (1.8 vs. 3.2 times).

The simulations of Q_{PEWR} under the RPC8.5 scenario for the long-term future (2055–2080) are presented in **Figure 3c**. According to **Table 1**, on average, the projected Q_{PEWR} for the 2055–2080 period for all the studied catchments is 30% lower than the Q_{PEWR} computed for the historical 1980–2005 period. This indicates WURs granted before the year 2005 considered a much larger water availability compared to what is projected for the second half of the 21st century under a severe climate change scenario (RCP8.5). A similar result was obtained under projections based on a moderate climate change scenario (RCP4.5). As illustrated in Figure S3 of the

Table 1. Runoff and rainfall for the 87 central-south Chilean catchments. DOI: https://doi.org/10.1525/elementa.2020.00131.t1

Statistic	Q_{PEWR} 1980–2005 (m^3/s)	Q_{PEWR} 1994–2019 (m^3/s)	$Q_{PEWR\ RCP4.5}$ 2050–2080 (m^3/s)	$Q_{PEWR\ RCP8.5}$ 2050–2080 (m^3/s)	P_{PEWR} 1980–2005 (mm)	P_{PEWR} 1994–2019 (mm)	$P_{PEWR\ RCP4.5}$ 2050–2080 (mm)	$P_{PEWR\ RCP8.5}$ 2050–2080 (mm)
Mean	51.69	45.12	39.61	34.35	837.38	828.62	783.01	724.10
5th percentile	0.69	0.42	0.04	0.03	120.16	94.03	96.12	88.87
95th percentile	246.38	227.85	190.13	168.45	1730.34	1737.19	1509.52	1409.91
Mean north of 36°	26.14	22.42	17.79	14.37	257.26	233.50	222.28	204.80
Mean south of 36°	57.46	50.23	44.53	38.86	968.12	962.73	909.37	841.12

Supplemental Material, the Q_{PEWR} for the 2055–2080 period, based on the RCP4.5 scenario, is 19% lower than the Q_{PEWR} computed for the 1980–2005 period. This indicates that even under a moderate climate change scenario, the calculations of the water availability considered during the 1980–2005 period are an overestimation of the future water availability for granting WURs.

According to **Table 1**, although the water availability is projected to decrease in all the analyzed catchments, the reductions are larger for catchments in the central macrozone. Considering the RCP4.5 scenario, the projections of Q_{PEWR} for north-central Chile catchments have reductions of about 47% compared to the historical period (1980–2005), while for catchments located in the south Chile macrozone, the reductions in Q_{PEWR} compared to the historical period are around 23%. Furthermore, the changes in the Q_{PEWR} calculations for the 2055–2080 and 1980–2005 period under the RCP8.5 scenario, indicate the north-central Chilean catchments will have reductions of around 65%, while south Chilean catchments present reductions of about 32%. Regarding precipitation, the projections of P_{PEWR} calculated for the 2055–2080 period under the RCP8.5 scenario are presented in **Figure 4**, and the projections of P_{PEWR} under the RCP4.5 scenario are presented in Figure S4 of the Supplementary Material. As shown in **Table 1**, on average, the P_{PEWR} calculated for the 2055–2080 period under the RCP8.5 scenario is 15% lower than the P_{PEWR} during the 1980–2005 period. Consistently with runoff projections, the water availability based on precipitation data also has large spatial variability. According to **Table 1**, the difference in the P_{PEWR} for the 2055–2080 and the 1980–2005 periods for north-central Chile macrozone catchments is about -27%, while the difference for southern catchments is about –12%.

4.2. Indices of anthropic intervention

The Indices of Anthropogenic Intervention (IAI) calculated from runoff and precipitation data (IAI_Q and IAI_P) for the two observed (historical) and the future periods are presented in **Figures 5** and **6**, respectively. As illustrated in **Figure 5a and b**, the number of catchments overallocated or with IAI_Q larger than one greatly increases between the 1980–2005 (**Figure 5a**) and the 1994–2019 period (**Figure 5b**). While 13% (11 basins) of the ensemble of catchments were already overallocated during the 1980–2005 period, they increased to about 23% (20 basins) in the 1994–2019 period. On the other hand, what is specially concerning is that even considering the IAI_P, calculated from precipitation records as a proxy for water availability (illustrated in **Figure 6**), the 4% (3 basins) of the catchments were already overallocated during the 1980–2005 period, which increased to about 6% (5 basins) in the 1994–2019 period.

As indicated in Section 3.4, the analysis of catchments under risk of overallocation with IAI_Q above 0.75 (panels a and b of **Figure 5**) shows an increase from 13% (16 basins) to 23% (23 basins) from the 1980–2005 (panel a) to the 1994–2019 (panel b) period. While according to the results presented in panels a and b of **Figure 6**, for the IAI_P, the percentage of basins under risk of overallocation increases from 8% (7 basins) to 14% (12 basins) during the 1980–2005 (panel a) and 1994–2019 (panel b) periods. This increasing risk of overallocation is partly associated with the decreases in water availability during the recently observed period (Section 4.1) and to the growing number of granted WURs (more detail is presented in Section 4.3).

Moreover, to further explore the implications of the overallocation, the information of urban and rural population (INE, 2018) and surfaces of the studied basins were also assessed (not shown). According to the IAI results during the observed period, a 43% of the national population is currently affected by overallocation ($IAI_Q > 1$ for the 1994–2019), which increases to 45% when considering the basins under risk of overallocation ($IAI_Q > 0.75$ for the 1994–2019). In the same line, around a 39% and a 48% of the total studied surface (123,808 km^2) is overallocated or under risk of overallocation, respectively.

The spatial pattern of IAI_Q and IAI_P calculations shows an increase in the percentage of overallocated catchments from 44% (7 basins) to 63% (10 basins) located in the north-central Chile macrozone for the 1980–2005 and the 1994–2019 periods, while the percentage of overallocated catchments located in the southern macrozone increases from 6% (4 basins) to 14% (10 basins) between the 1980–2005 and the 1994–2019 periods. The same spatial

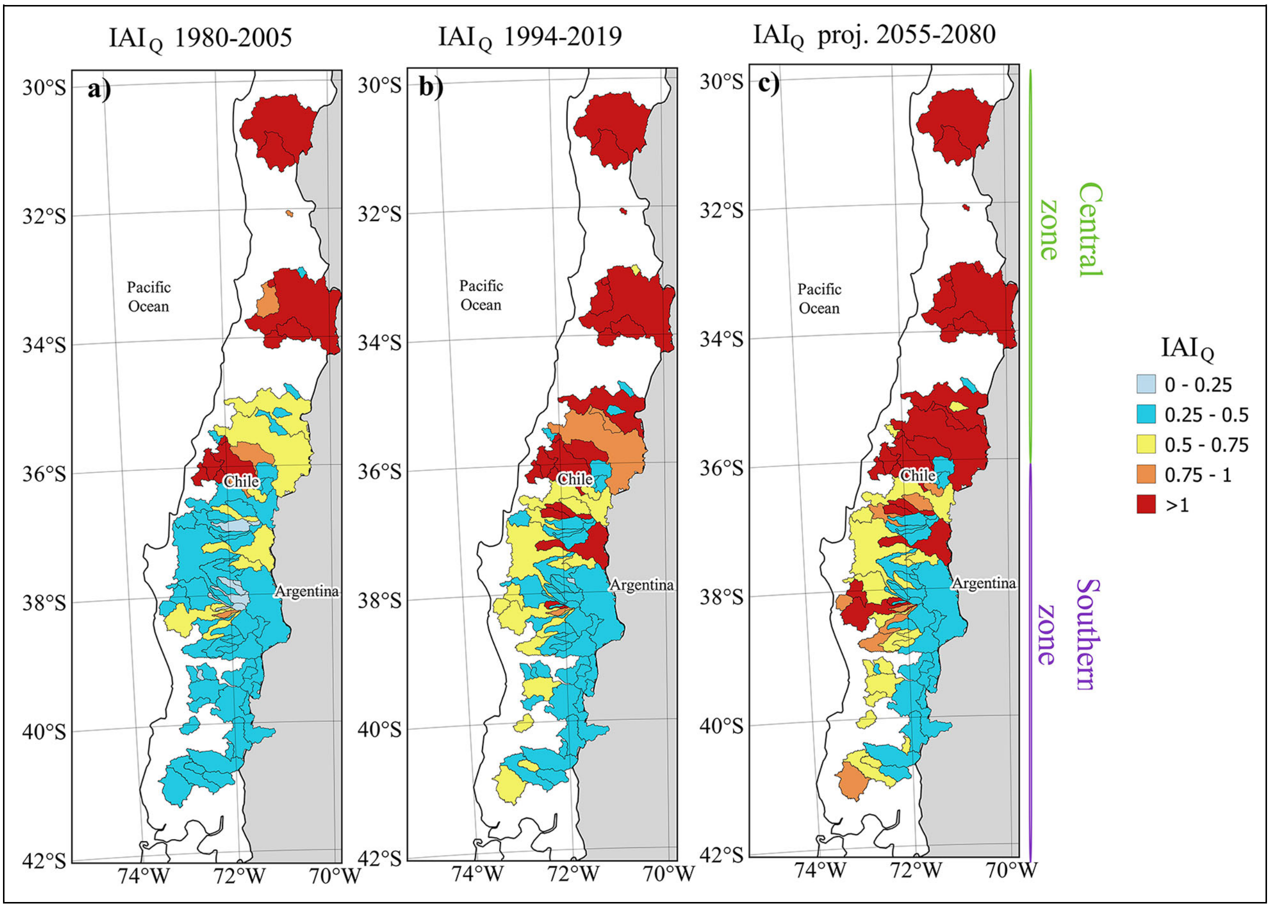

Figure 5. Indices of anthropic intervention (IAI$_Q$) calculated from annual runoff. These calculations are based on (a) the 1980–2005 period, (b) the 1994–2019 period, and (c) the 2055–2080 period. DOI: https://doi.org/10.1525/elementa.2020.00131.f5

pattern is observed from the IAI$_P$, where the percentage of overallocated catchments is larger in the region north of 36°S, but the new overallocated basins distribute equally between the northern and southern region. What is noteworthy is that even considering the IAI$_P$, computed from water availability based on rainfall records (which is an overestimation of the actual water availability at the catchment scale), around a 29% (4 basins) and a 1% (1 basin) of catchments located in the north-central and southern macrozones, respectively, are overallocated during the recent historical 1994–2019 period. This raises concern regarding how this IAI will evolve during the following decades considering the projections of drier futures under a climate change context (Boisier et al., 2018). As it will be presented in Section 4.3, this is a particularly important consideration for those costly and long-term impact infrastructures aiming at regionally redistribute "available water."

Figure 5c shows the IAI$_Q$ for the 2055–2080 period, calculated using the WURs granted until year 2019, that is, assuming there are not further WURs granted in north-central and south Chilean catchments. The results indicate that under the RCP8.5 scenario, by the second half of the century, 25 catchments will be overallocated in north-central and south Chile (IAI$_Q$ > 1), equivalent to a 29% of the total sample considered in this study and 14 more than the number of overallocated catchments during the 1980–2005 period. Considering the results presented in Figure S3 of the Supplementary Material, under the RCP4.5 scenario, 21 catchments are projected to be overallocated (24%), which considers 10 new basins compared to the 1980–2005 period. **Figure 6c** presents the IAI$_P$ obtained under RCP8.5, and Figure S4 of the Supplementary Material for the RCP4.5 scenario. For both scenarios, and under the assumption, there will be no more granted WURs in the future, four catchments will have a noticeable anthropic intervention (IAI$_P$ > 1) equivalent to 5% of the sample, with one new overallocated basins compared to the 1980–2005 period.

Again, there are significant differences between the percentage of basins that are projected to be overallocated in north-central and south Chile under the RCP8.5 scenario. As presented in **Figure 5c**, 81% (13 basins) of central Chilean catchments and 17% (12 basins) of south Chilean basins will be overallocated by 2055–2080 period (IAI$_Q$ > 1). Similarly, according to **Figure 6c**, central Chile has a larger number and percentage of overallocated basins (3 basins, 18%) computed from the precipitation records (IAI$_P$) than the southern macrozone (1 basin, 1%). These results mean that although south Chilean basins have larger water availability than central Chilean catchments, they will be increasingly affected by overallocation

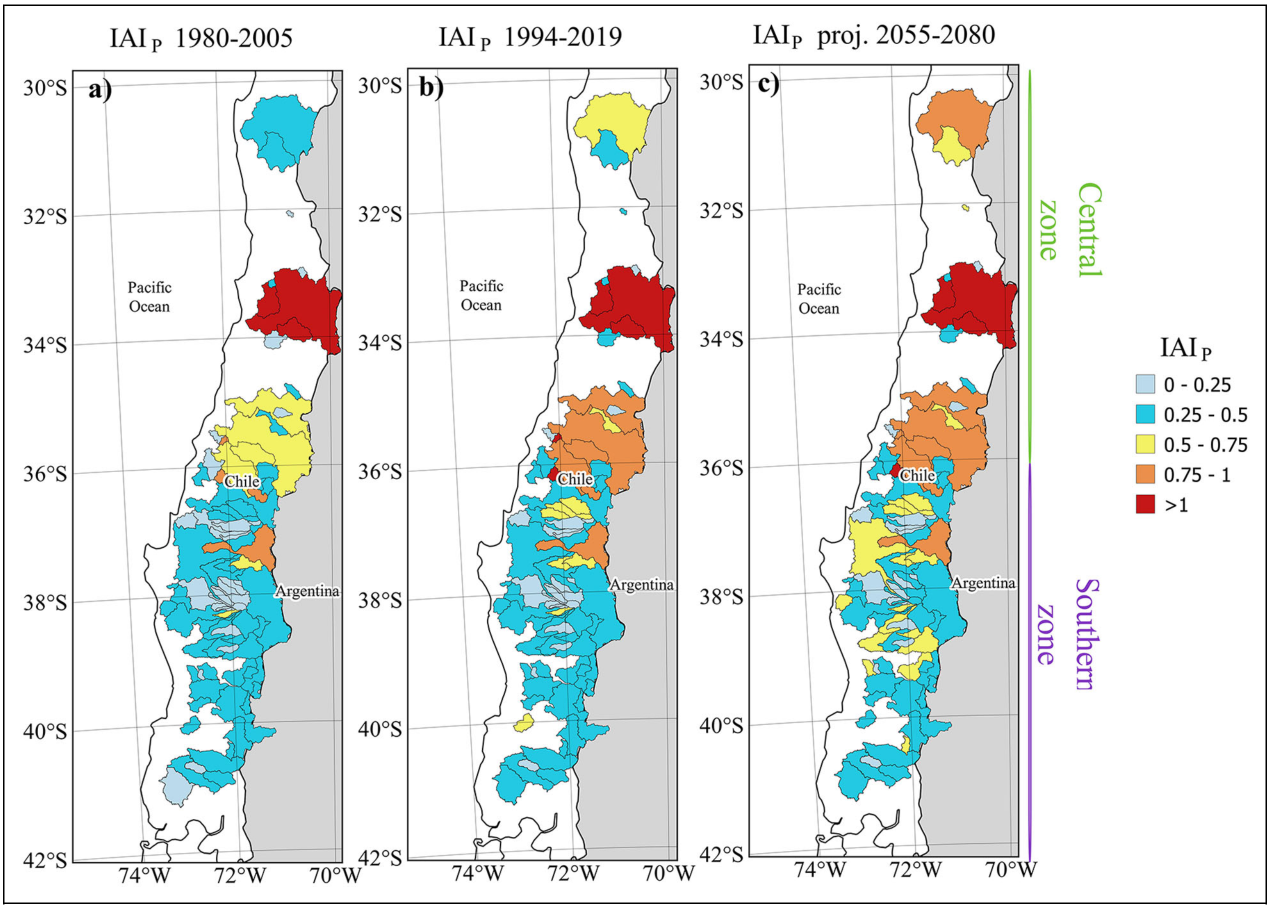

Figure 6. Indices of anthropic intervention (IAI_P) calculated using annual rainfall data. These calculations are based on (a) the 1980–2005 period, (b) the 1994–2019 period, and (c) the 2055–2080 period. DOI: https://doi.org/10.1525/elementa.2020.00131.f6

and water scarcity by 2055–2080 compared to the historical period (**Figure 7**).

Furthermore, considering the climate and runoff projections for the 2055–2080 period (under the RCP8.5 scenario), the basins under risk of overallocation ($IAI_Q > 0.75$) increase significantly compared to the 1980–2005 period. Around 81% of north-central Chilean catchments and 28% of south Chilean basins will be under risk of overallocation by 2055–2080 period (4 more basins compared to the 1980–2005 period). Finally, the analyses based on the IAI_P indicate that around 44% (7 basins) and 9% (6 basins) of the basins located in the north-central and southern macrozones respectively are projected to be under risk of overallocation for the 2055–2080 period (**Figure 6c**), which includes three more basins than for the 1980–2005 period.

Moreover, by considering the hydrological projections under the RCP8.5 high-emission scenario, a 45% of the national population will be in overallocated basins by 2055–2080 ($IAI_Q > 1$), which increases to 49% when considering the basins under risk of overallocation ($IAI_Q > 0.75$) for the same period. In the same line, around a 51% and a 62% of the total studied surface (123,808 km^2) will be overallocated or under risk of overallocation, respectively, when considering the water availability for the 2055–2080 period.

4.3. Assessments of long-term variability of anthropogenic intervention along a large north-central and south Chile latitude range, implications for water supply

To analyze the regions or macrozones that are under major risk of overallocation, the KS and the z test of means were used to identify spatial patterns, which indicated that there is a significant change in the IAI_P and IAI_Q around the latitude 36.5°S. This is also observed in **Figure 8**, where the cumulative IAI_P was plotted against the latitude of the catchments indicating there is a clear difference between basins located north and south of 36.5°S, with southern basins having a much more homogeneous behavior than northern basins (note that the jump in the curve around 33°S is explained by the lack of basins that comply the selection criteria in that area).

Figure 9a shows the distribution of the IAI_Q and the IAI_P for the three-time windows here evaluated for the catchments located north of 36.5°S, while **Figure 9b** shows the IAI_Q and IAI_P of the southern catchments. The catchments located north of 36.5°S have IAIs notoriously larger (two orders of magnitude) than for the southern catchments, with several catchments above one. According to **Figure 9a**, the median of the IAI_Q for catchments located north of the 36.5° during the 1994–2019 and 2055–2080 (under the RCP8.5) periods are overallocated.

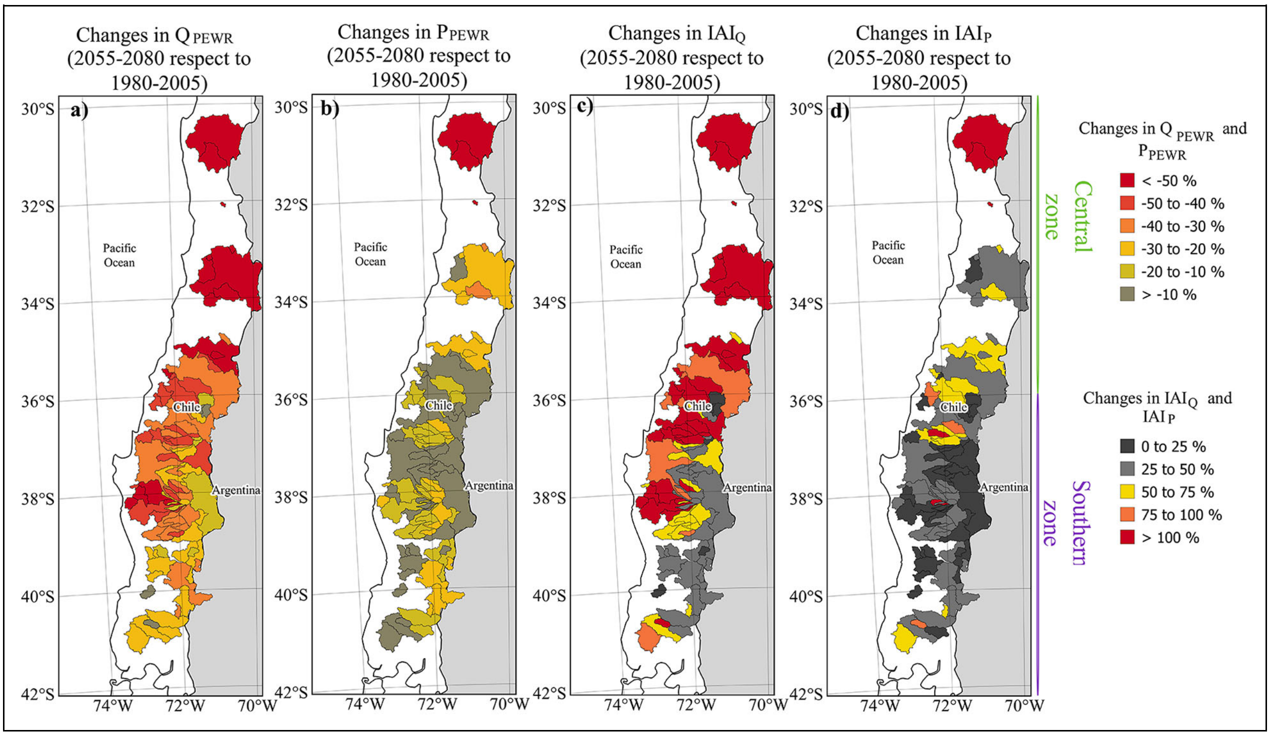

Figure 7. Projected changes of water availability and the indices of anthropic intervention. (a) Q_{PEWR} between the 2055–2080 and 1980–2005 period, (b) P_{PEWR} between the 2055–2080 and the 1980–2005 period, (c) IAI_Q between the 2055–2080 and the 1980–2005 period, and (d) IAI_P between the 2055–2080 and the 1980–2005 period. DOI: https://doi.org/10.1525/elementa.2020.00131.f7

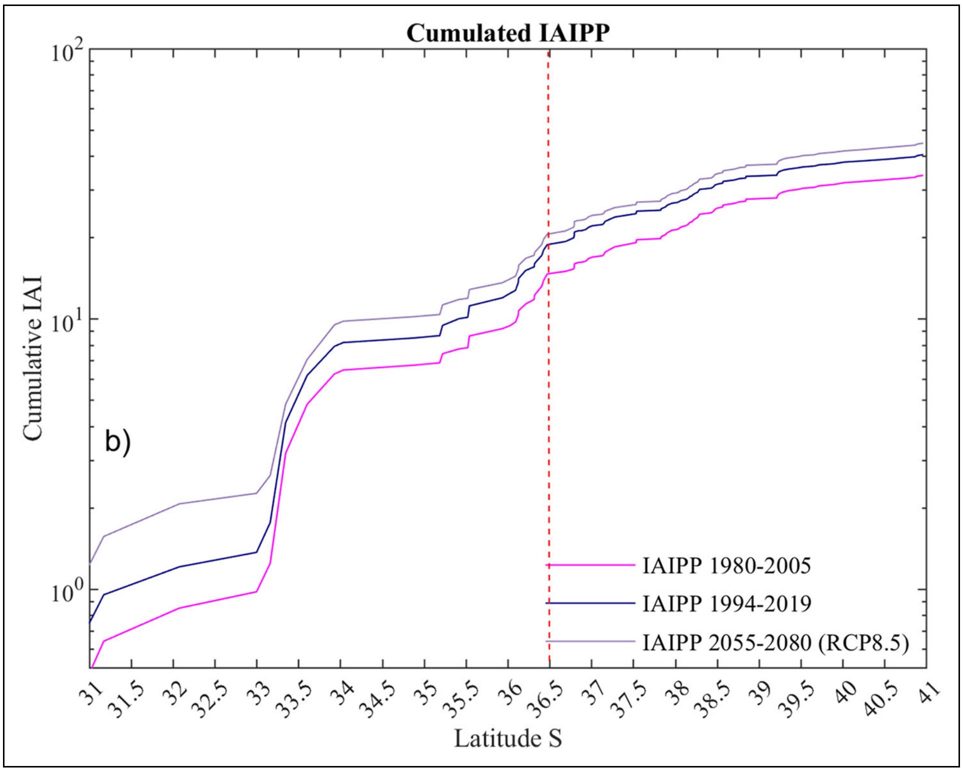

Figure 8. Cumulated indices of anthropic intervention compared to the latitude (IAI_P). DOI: https://doi.org/10.1525/elementa.2020.00131.f8

On the other hand, while the median of the IAI for southern catchments increases with time, they are still below one, with some catchments overallocated during the 1994–2019 and the 2055–2080 periods. These results provide important insights regarding the sustainability of the mentioned large-scale projects currently under

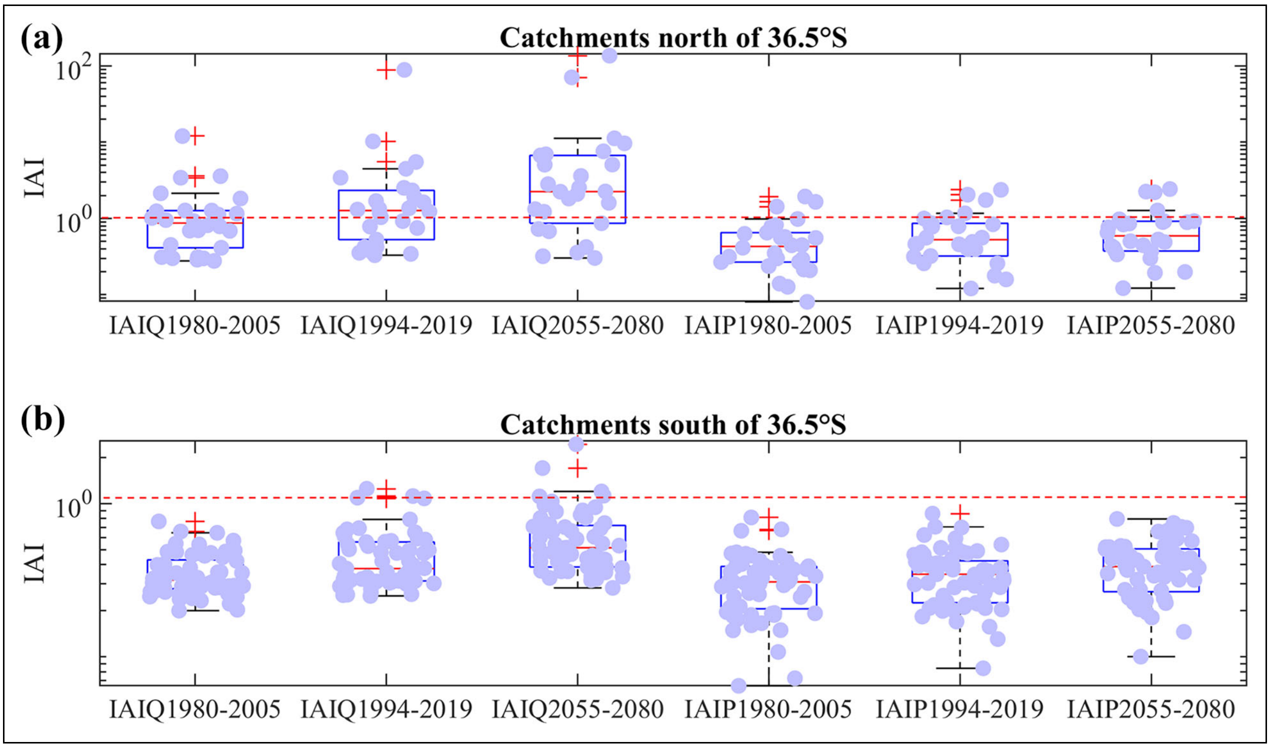

Figure 9. Indices of anthropic intervention. The IAI are presented by (a) catchments located north of 36.5°S and (b) catchments located south of 36.5°S. DOI: https://doi.org/10.1525/elementa.2020.00131.f9

evaluation, such as the construction of twenty six new dams distributed in nine regions of the country, recently announced by the Chilean Ministry of Public Works, desalinization plants in coastal cities (MOP, 2018), and "water roads" of over 1,000 km of pipeline aiming at transfer water from the humid catchments located in southern Chile to the semiarid regions of the country (Aquatacama, 2020; Corporación Reguemos Chile, 2020). According to these results, water supply is not assured under current circumstances, and it is projected to worsen under a climate change context. Indeed, as indicated in **Figure 9b**, there is increasing risk of overallocation and thus water scarcity in these basins, even without considering the transfer projects. These projections compromise the reliability and effectiveness of the mentioned large and long-term investments, as well as the foundations of the efficiency of tradable WURs under the water market paradigm, calling to rethink Chilean current water management approach to deal with scarcity.

Regarding surface and groundwater granted PEWR, a spatialization considering the boundary of 36.5°S was applied and plotted in **Figure 10**. Although there is large variability within the sample of catchments, there are clear differences in granted WURs between the northern compared to the southern catchments (**Figure 10a and b** compared to 10c and 10d, respectively). First, regarding surface granted WURs, both northern and southern basins had a large increase around the 1980s, with continuous increases since then. These growths are in concordance with the economic growth experienced in Chile during the 1990s (Anríquez and Melo, 2018). However, the surface WURs of basins located south of 36.5° are 2.1 times larger than basins located north of 36.5°S. On the other hand, there are noticeable differences between the granted groundwater WURs of the northern and southern basins of 36.5°S. The northern basins have 2 times more granted groundwater WURs than the southern basins. Also, according to **Figure 10b**, granted groundwater WURs of the northern basin had large increases since the mid-80s, while according to **Figure 10d**, southward basins started largely increasing since year 2000. Considering the granted groundwater WURs of southern catchments started increasing after year 2000, and its positive slope curve, it's very likely the granted WURs of this region will continue raising during the following decades. These results indicate that the assumption that no more WURs will be allocated in the basins during the following years may be an underestimation of the future water demand, and thus, the IAI projected for the period 2055–2080 in this study might also be higher than the estimations here presented.

Finally, to display the implications that the incomplete and limited DGA WURs database could have on the study zones water balances, Figure S5 shows the number of basins with IAI_Q (Figure S5a) and IAI_P (Figure S5b) larger than 1 (overallocated) obtained using the debugged database and the official DGA database. Based on those results (Figure S5a and S5b), by using the official DGA database, the number of overallocated basins increases on average by 3% and by 16% under the IAI_Q and the IAI_P indices, respectively, thus reinforcing that the analyses here presented are conservative and is very likely they are an underestimation of the actual overallocation.

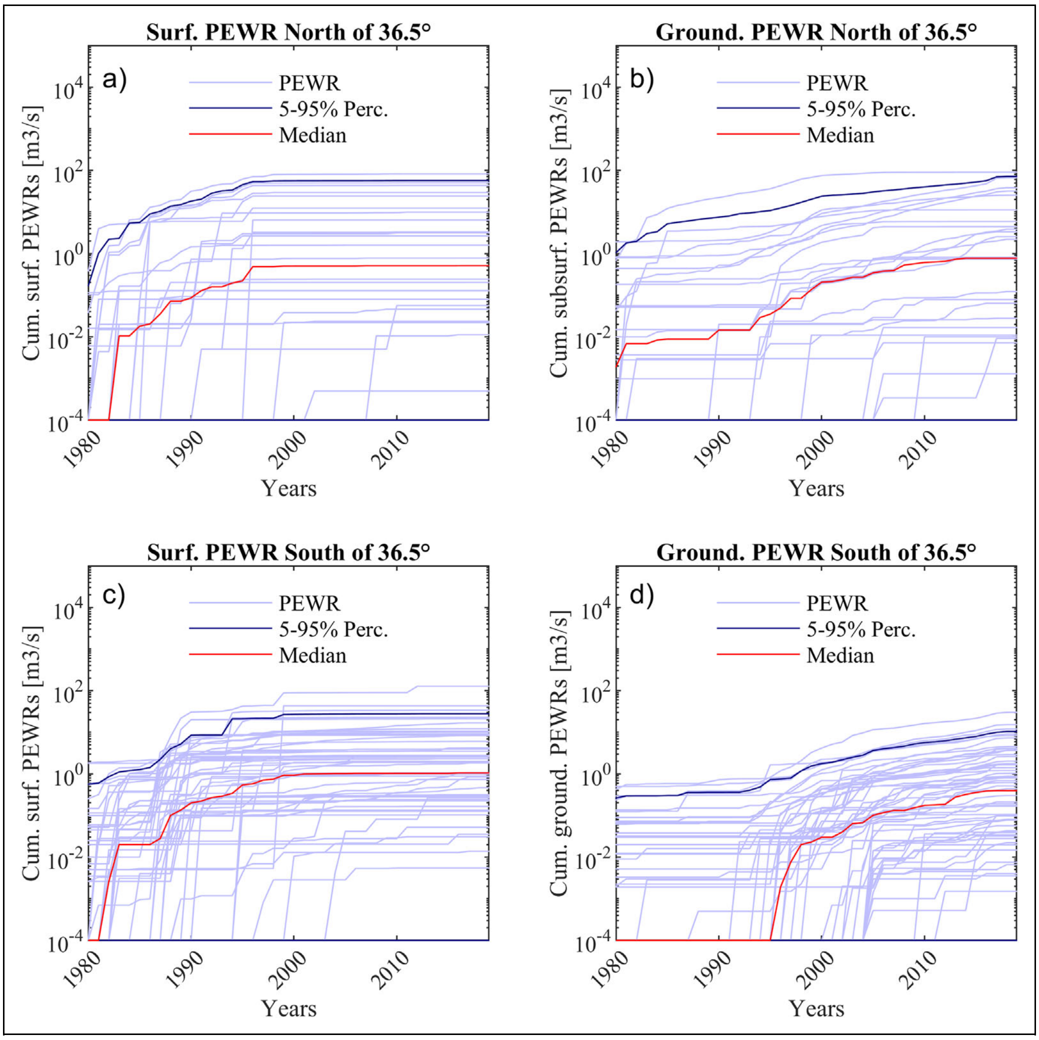

Figure 10. Analysis of cumulated WURs. These calculations are based on (a) surface granted WURs in basins located north of 36.5°S, (b) groundwater granted WURs in basins located north of 36.5°S, (c) surface granted WURs in basins located south of 36.5°S, and (d) groundwater granted WURs in basins located south of 36.5°S. DOI: https://doi.org/10.1525/elementa.2020.00131.f10

5. Discussion and conclusions

Although robust decision making needs to be based on reliable information, there are serious limitations in Chilean WURs databases and current State's capacity to improve in the near future the amount of monitoring information necessary for long-term investing and decision making over water resources allocation. A novel approach based on the indices of anthropic intervention was applied to 87 Chilean basins to get profound insights into one key process for water management under climate change uncertainty: water allocation under nonstationarity conditions. The methodology developed and applied in this study allows to assess the risk of overallocation, as well as the potential future water security risk in some of the currently nonthreatened basins as result of the market-based system prevailing in Chile.

Spatiotemporal variability of the anthropic intervention degree in the north-central and south Chilean regions indicates the water availability calculations in the basins located in the north-central Chile macrozone are more sensitive to the rainfall and runoff reductions of the MD period than the basins located in the south Chile macrozone. Also, the results show that elasticity of changes in runoff versus precipitation of the semiarid basins located north of 36°S are lower than the elasticity of changes in southern, humid catchments (1.8 vs. 3.2 times). In combination, the spatiotemporal analysis shows that percentage of overallocated catchments based on observed runoff records (IAI_Q) located in central Chile increases from 44% (7 basins) to 63% (10 basins) between the 1980–2005 and the 1994–2019 periods, while the percentage of overallocated catchments located in south Chile increases from 6% (4 basins) to 14% (10 basins) between the 1980–2005 and the 1994–2019 periods.

Results show that current Chilean water allocation system is not prepared for a nonstationary climate change scenario as WURs granted before the year 2005 considered a much larger water availability compared to what is projected for the second half of the 21st century under a severe climate change scenario (RCP8.5), and even a moderate climate change scenario (RCP4.5). Even if no more WURs are granted, under the RCP8.5 scenario, by the second half of the century, 25 catchments will be overallocated in central-south Chile ($IAI_Q > 1$), 14 more than the number of overallocated catchments during the 1980–2005 period, affecting the water security of around a 45% of the current national population.

The implications of these results for public and private initiatives pushing for large-scale projects aimed at increasing water supply by collecting water from upstream, or transferring water long distances, are that water is not assured in any basin today and is even projected to worsen under a climate change context. These results worry as they show future water availability may compromise the effectiveness of these investments and the foundations of the efficiency of tradable WURs under the water ruling market paradigm.

The overallocation of catchments have several legal, social, and environmental negative consequences that undermined the sustainability of the water resources and hampers the implementation of climate change adaptation plans. Water scarcity creates inefficiencies in the water market and diminishes legal certainty when, as shown in this study, WURs exceed the physically available water, and the latter significantly changes for different time windows. From a social–environmental perspective, water scarcity increases the competition, the social conflicts, and have detrimental consequences on the ecosystems. This is especially concerning as the ecological flow considered in the DGA methods is likely to underestimate the actual flow ecological requirements (Toledo & Muñoz, 2018). Moreover, as presented in the Results section, the scenario could be worse when considering the WURs of the official DGA database that have geographical information (around 50%), in which case the number of basins under high risk of overallocation increases up to 16% in comparison to the results under the debugged database, thus underlining the relevance of complete and robust information to estimate the water balances, which is fundamental to assess sound decision making on water management strategies.

This study provides a unique data set with information at the catchment scale of water use and water availability that can be used to assist decision making to diagnose the risk of water scarcity in different catchments for different periods of time and prioritize measures to deal with climate change and drought considering a climate change context. Although the local characteristics of the Chilean water allocation system were considered in this study, the methods and results can be adapted in other water allocation systems in regions with similar climates such as those spanned in central-south Chile.

Data accessibility statement

Precipitation and streamflow data for Chile are available at http://explorador.cr2.cl/. The CMIP5 data were acquired from the Earth System Grid Federation (https://esgf.llnl.gov). The time series processed at the basin scale and the catchment attributes introduced in this article are freely available at the CAMELS-CL explorer (http://camels.cr2.cl).

Supplemental files

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

Table S1. List of studied basins.

Table S2. List of CMIP5 models used to obtain climate and runoff projections.

Text S1. DGA WURs systematization.

Figure S1. Distribution of the Public DGA WURs database within the administrative regions of the study zone. (a) Map indicating the location of basins and administrative regions of the study zone, (b) Comparison of surface WURs with and without coordinates information, (c) Comparison of groundwater WURs with and without coordinates information.

Figure S2. Evaluation of the GR2 M model in the 87 catchments using the NSE and R2 coefficients.

Figure S3. Water availability under the RCP4.5 scenario for granting permanently exercisable water use rights (Q_{PEWR}) and indices of anthropic intervention (IAI_Q). The indices were calculated from model-based annual runoff projections considering: (a) Q_{PEWR} for the 2055–2080 period, (b) Changes in the Q_{PEWR} between the 2055–2080 and 1980–2005 periods, (c) IAI_Q for the 2055–2080 period, and (d) Changes in the IAI_Q between the 2055–2080 and the 1980–2005 periods.

Figure S4. Rainfall available under the RCP4.5 scenario for granting permanently exercisable water rights (P_{EWR}) and indices of anthropic intervention (IAIP). The indices were calculated using projected annual rainfall considering: (a) P_{EWR} for the 2055–2080 period, (b) Changes in the PEWR between the 2055–2080 and 1980–2005 period, (c) IAI_P for the 2055–2080 period, and (d) Changes in the IAI_P between the 2055–2080 and the 1980–2005 period.

Figure S5. Calculations of number of overallocated basins. The overallocated obtained using the debugged and the official WURs database considering the (a) IAI_Q and the (b) IAI_P indices.

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Competing interests

The authors have declared that no competing interests exist.

Author contributions

Contributed to conception and design: PB, IBS, CAG, CC, AOM.

Contributed to acquisition of data: PB, CAG, CG, RF.

Contributed to analysis and interpretation of data: PB, IBS, RDV, CG, CAG, CC.

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References

Alaniz, AJ, Carvajal, MA, Núñez-Hidalgo, I, Vergara, PM. 2019. Chronicle of an environmental disaster: Aculeo Lake, the collapse of the largest natural freshwater ecosystem in central Chile. *Environmental Conservation* **46**(3): 201–204. DOI: http://dx.doi.org/10.1017/S0376892919000122.

Albiac, J, Hanemann, M, Calatrava, J, Uche, J, Tapia, J. 2006. The rise and fall of the ebro water transfer. *Natural Resources Journal* **46**(3): 727–757.

Alvarez-Garreton, C, Mendoza, PA, Boisier, JP, Addor, N, Galleguillos, M, Zambrano-Bigiarini, M, Lara, A, Puelma, C, Cortes, G, Garreaud, R, McPhee, J. 2018. The CAMELS-CL dataset: Catchment attributes and meteorology for large sample studies – Chile dataset. *Hydrology and Earth System Sciences* **22**(11): 5817–5846. DOI: http://dx.doi.org/10.5194/hess-22-5817-2018.

Anríquez, G, Melo, O. 2018. The socio-economic context of Chilean water consumption and water markets growth: 1985–2015. In: Donoso, G ed., *Water policy in Chile*. Cham, Switzerland: Springer International Publishing: 53–63. DOI: http://dx.doi.org/10.1007/978-3-319-76702-4_4.

Aquatacama. 2020. Aquatacama. Available at http://www.aquatacama.com/. Accessed 22 July 2020.

Barría, P, Chadwick, C, Ocampo-Melgar, A, Galleguillos, M, Garreaud, R, Díaz-Vasconcellos, R, Poblete, D, Rubio-Álvarez, E, Poblete-Caballero, D. 2021. Water management or megadrought: What caused the Chilean Aculeo Lake drying? *Regional Environmental Change* **21**(1): 1–15. DOI: http://dx.doi.org/10.1007/s10113-021-01750-w.

Barria, P, Rojas, M, Moraga, P, Muñoz, A, Bozkurt, D, Alvarez-Garreton, C. 2019. Anthropocene and streamflow: Long-term perspective of streamflow variability and water rights. *Elementa: Science of the Anthropocene* **7**(1): 2. DOI: http://dx.doi.org/10.1525/elementa.340.

Bauer, C. 1998. Slippery property rights: multiple water uses and the neoliberal model in Chile, 1981-1995. *Natural Resources Journal* **38**(1): 109-155. DOI: http://www.jstor.org/stable/24888446.

Bauer, C. 2015. Water conflicts and entrenched governance problems in Chile's market model. *Water Alternatives* **8**(2): 147–172.

Bauer, CJ. 2004. Results of Chilean water markets: Empirical research since 1990. *Water Resources Research* **40**(9). DOI: http://dx.doi.org/10.1029/2003WR002838.

Boisier, JP, Alvarez-Garretón, C, Cordero, RR, Damiani, A, Gallardo, L, Garreaud, RD, Lambert, F, Ramallo, C, Rojas, M, Rondanelli, R. 2018. Anthropogenic drying in central-southern Chile evidenced by long-term observations and climate model simulations. *Elementa: Science of the Anthropocene* **6**(1): 74. DOI: http://dx.doi.org/10.1525/elementa.328.

Boisier, JP, Rondanelli, R, Garreaud, RD, Muñoz, F. 2016. Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile. *Geophysical Research Letters* **43**(1): 413–421. DOI: http://dx.doi.org/10.1002/2015GL067265.

Consejo para la Transparencia. 2020. Portal Transparencia. Available at https://www.portaltransparencia.cl/PortalPdT/. Accessed 22 July 2020.

Corporación Reguemos Chile. 2020. Corporación Reguemos Chile. Available at http://www.reguemoschile.cl/. Accessed 22 July 2020.

DGA (Dirección General de Aguas). 2008. Manual de Normas y Procedimientos para la Administración de Recursos Hídricos. Available at https://dga.mop.gob.cl/legistlacionynormas/normas/Reglamentos/proced_darh.pdf. Accessed 22 July 2020.

DGA (Dirección General de Aguas). 2016. Atlas del Agua Chile 2016. Available at https://snia.mop.gob.cl/sad/Atlas2016parte1.pdf. Accessed 22 July 2020.

DGA (Dirección General de Aguas). 2017. Actualización del balance hídrico nacional. Available at https://snia.mop.gob.cl/sad/REH5796v1.pdf. Accessed 21 July 2020.

Donoso, G. 2018. *Water policy in Chile*. Cham, Switzerland: Springer International Publishing: 197–207. DOI: http://dx.doi.org/10.1007/978-3-319-76702-4_13.

Donoso, G, Melo, O, Jordán, C. 2014. Estimating water rights demand and supply: Are non-market factors important? *Water Resource Management* **28**(12): 4201–4218. DOI: http://dx.doi.org/10.1007/s11269-014-0739-3.

Eriksen, S, Aldunce, P, Bahinipati, CS, Martins, RD, Molefe, JI, Nhemachena, C, O'Brien, K, Olorunfemi, F, Park, J, Sygna, L, Ulsrud, K. 2011. When not every response to climate change is a good one: Identifying principles for sustainable adaptation. *Climate and Development* **3**(1): 7–20. DOI: http://dx.doi.org/10.3763/cdev.2010.0060.

Falkenmark, M. 2013. Growing water scarcity in agriculture: future challenge to global water security. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **371**(2002). DOI: http://dx.doi.org/10.1098/rsta.2012.0410.

Fazey, I, Pettorelli, N, Kenter, J, Wagatora, D, Schuett, D. 2011. Maladaptive trajectories of change in Makira, Solomon Islands. *Global Environmental Change*

21(4): 1275–1289. DOI: http://dx.doi.org/10.1016/j.gloenvcha.2011.07.006.

Fundación Chile. 2018. *Radiografía Del Agua: Brecha y Riesgo Hídrico En Chile*. Available at https://fch.cl/wp-content/uploads/2019/05/radiografia-del-agua.pdf. Accessed 21 July 2020.

Garreaud, RD, Alvarez-Garreton, C, Barichivich, J, Boisier, JP, Christie, D, Galleguillos, M, LeQuesne, C, McPhee, J, Zambrano-Bigiarini, M. 2017. The 2010–2015 megadrought in central Chile: Impacts on regional hydroclimate and vegetation. *Hydrology and Earth System Sciences* **21**(12): 6307–6327. DOI: http://dx.doi.org/10.5194/hess-21-6307-2017.

Garreaud, RD, Boisier, JP, Rondanelli, R, Montecinos, A, Sepúlveda, HH, Veloso-Aguila, D. 2020. The Central Chile Mega Drought (2010–2018): A climate dynamics perspective. *International Journal of Climatology* **40**(1): 421–439. DOI: http://dx.doi.org/10.1002/joc.6219.

Garrick, D, Hall, JW. 2014. Water security and society: Risks, metrics, and pathways. *Annual Review of Environment and Resources* **39**(1): 611–639. DOI: http://dx.doi.org/10.1146/annurev-environ-013012-093817.

Greve, P, Kahil, T, Mochizuki, J, Schinko, T, Satoh, Y, Burek, P, Fischer, G, Tramberend, S, Burtscher, R, Langan, S, Wada, Y. 2018. Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability* **1**(9): 486–494. DOI: http://dx.doi.org/10.1038/s41893-018-0134-9.

Hay, LE, Wilby, RL, Leavesley, GH. 2000. A comparison of delta change and downscaled gcm scenarios for three mountainous basins in the United States. *JAWRA Journal of the American Water Resources Association* **36**(2): 387–397. DOI: http://dx.doi.org/10.1111/j.1752-1688.2000.tb04276.x.

Hearne, R, Donoso, G. 2014. Water markets in Chile: Are they meeting needs? in Easter, KW, Huang, Q eds., *Water markets for the 21st century: What have we learned*? Dordrecht, the Netherlands: Springer Netherlands: 103–126. DOI: http://dx.doi.org/10.1007/978-94-017-9081-9_6.

Hoekstra, AY. 2014. Water scarcity challenges to business. *Nature Climate Change* **4**(5): 318–320. DOI: http://dx.doi.org/10.1038/nclimate2214.

INE (Instituto Nacional de Estadísticas). 2018. Compendio Estadístico 2018. Available at http://webanterior.ine.cl/docs/default-source/publicaciones/2018/bookcompendio2018.pdf?sfvrsn=fae156d2_5. Accessed 22 July 2020.

INE-ODEPA (Instituto Nacional de Estadísticas – Oficina de Estudios y Políticas Agrarias). 2007. Censo nacional agropecuario y forestal 2007. Available at https://webanterior.ine.cl/estadisticas/censos/censo-agropecuario-y-forestal-2007. Accessed 22 July 2020.

INFOR (Instituto Forestal). 2019. Anuario forestal/chilean statistical yearbook of forestry 2019. Available at https://wef.infor.cl/publicaciones/anuario/2019/Anuario2019.pdf. Accessed 22 July 2020.

Kahil, MT, Dinar, A, Albiac, J. 2015. Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. *Journal of Hydrology* **522**: 95–109. DOI: http://dx.doi.org/10.1016/j.jhydrol.2014.12.042.

Kottek, M, Grieser, J, Beck, C, Rudolf, B, Rubel, F. 2006. World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift* **15**(3): 259–263. DOI: http://dx.doi.org/10.1127/0941-2948/2006/0130.

Kwakkel, JH, Haasnoot, M, Walker, WE. 2016. Comparing robust decision-making and dynamic adaptive policy pathways for model-based decision support under deep uncertainty. *Environmental Modelling & Software* **86**: 168–183. DOI: http://dx.doi.org/10.1016/j.envsoft.2016.09.017.

Lempert, RJ, Popper, SW, Bankes, SC. 2003. *Shaping the next one hundred years: New methods for quantitative, long-term policy analysis*. RAND Corporation. Available at https://www.rand.org/pubs/monograph_reports/MR1626.html. Accessed 21 July 2020.

McPhee, J. 2018. Hydrological setting, in Donoso, G ed., *Water policy in Chile*. Cham, Switzerland: Springer International Publishing: 13–23. DOI: http://dx.doi.org/10.1007/978-3-319-76702-4_2.

Milly, PCD, Betancourt, J, Falkenmark, M, Hirsch, RM, Kundzewicz, ZW, Lettenmaier, DP, Stouffer, RJ. 2008. Stationarity is dead: Whither water management? *Science* **319**(5863): 573. DOI: http://dx.doi.org/10.1126/science.1151915.

MOP (Ministerio de Obras Públicas). 2018. *Plan Chile 30/30. El Futuro No Se Espera Se Construye*. Available at http://www.dirplan.cl/planes/Documents/plan/plan_chile_3030.pdf. Accessed 22 July 2020.

Moriasi, ND, Arnold, GJ, van Liew, WM, Bingner, LR, Harmel, DR, Veith, LT. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **50**(3): 885–900. DOI: http://dx.doi.org/10.13031/2013.23153.

Mouelhi, S. 2003. Vers une chaîne cohérente de modèles pluie-débit conceptuels globaux aux pas de temps pluriannuel, annuel, mensuel et journalier [These de doctorat]. Paris, France: ENGREF. Available at http://www.theses.fr/2003ENGR0001. Accessed 22 July 2020.

Mouelhi, S, Michel, C, Perrin, C, Andréassian, V. 2006. Stepwise development of a two-parameter monthly water balance model. *Journal of Hydrology* **318**(1–4): 200–214. DOI: http://dx.doi.org/10.1016/j.jhydrol.2005.06.014.

Mundial, B. 2011. Chile: Diagnóstico de la gestión de los recursos hídricos. Available at https://dga.mop.gob.cl/eventos/Diagnostico%20gestion%20de%20recursos%20hidricos%20en%20Chile_Banco%20Mundial.pdf. Accessed 21 July 2020.

Mundial, B. 2013. Chile: Estudio para el mejoramiento del marco institucional para la gestión del agua. Available at https://research.csiro.au/gestion-copiapo/wp-content/uploads/sites/216/2018/01/010-Estudio-para-el-Mejoramiento-del-Marco-Institucional-para-la-Gestion-del-Agua-DGA-BM-2013.pdf. Accessed 21 July 2020.

Muñoz, AA, Klock-Barría, K, Alvarez-Garreton, C, Aguilera-Betti, I, González-Reyes, Á, Lastra, JA, Chávez, RO, Barría, P, Christie, D, Rojas-Badilla, M, Quesne, CL. 2020. Water crisis in petorca basin, Chile: The combined effects of a mega-drought and water management. *Water* **12**(3): 648. DOI: http://dx.doi.org/10.3390/w12030648.

Oudin, L, Hervieu, F, Michel, C, Perrin, C, Andréassian, V, Anctil, F, Loumagne, C. 2005. Which potential evapotranspiration input for a lumped rainfall–runoff model? Part 2—Towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling. *Journal of Hydrology* **303**(1): 290–306. DOI: http://dx.doi.org/10.1016/j.jhydrol.2004.08.026.

Peña, H. 2018. Integrated water resources management in Chile: Advances and challenges, in Donoso, G ed., *Water policy in Chile*. Cham, Switzerland: Springer International Publishing: 197–207. DOI: http://dx.doi.org/10.1007/978-3-319-76702-4_13.

Polade, SD, Gershunov, A, Cayan, DR, Dettinger, MD, Pierce, DW. 2017. Precipitation in a warming world: Assessing projected hydro-climate changes in California and other Mediterranean climate regions. *Scientific Reports* **7**(1): 10783. DOI: http://dx.doi.org/10.1038/s41598-017-11285-y.

R Core Team. 2015. R: The R project for statistical computing. Available at https://www.r-project.org/. Accessed 22 July 2020.

Rios, M, Quiroz, J. 1995. *The market for water rights in Chile*. The World Bank (World Bank Technical Papers). DOI: http://dx.doi.org/10.1596/0-8213-3307-0.

Rivera, D, Godoy-Faúndez, A, Lillo, M, Alvez, A, Delgado, V, Gonzalo-Martín, C, Menasalvas, E, Costumero, R, García-Pedrero, Á. 2016. Legal disputes as a proxy for regional conflicts over water rights in Chile. *Journal of Hydrology* **535**: 36–45. DOI: http://dx.doi.org/10.1016/j.jhydrol.2016.01.057.

Schewe, J, Heinke, J, Gerten, D, Haddeland, I, Arnell, NW, Clark, DB, Dankers, R, Eisner, S, Fekete, BM, Colón-González, FJ, Gosling, SN. 2014. Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences USA* **111**(9): 3245–3250. DOI: http://dx.doi.org/10.1073/pnas.1222460110.

Schulz, JJ, Cayuela, L, Echeverria, C, Salas, J, Rey Benayas, JM. 2010. Monitoring land cover change of the dryland forest landscape of Central Chile (1975–2008). *Applied Geography* **30**(3): 436–447. DOI: http://dx.doi.org/10.1016/j.apgeog.2009.12.003.

Suárez, F, Leray, S, Sanzana, P. 2021. Chapter 5, Water resources of Chile, in *Groundwater resources* Springer. DOI: http://dx.doi.org/10.1007/978-3-030-56901-3_5.

Taylor, KE, Stouffer, RJ, Meehl, GA. 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society* **93**(4): 485–498. DOI: http://dx.doi.org/10.1175/BAMS-D-11-00094.1.

Toledo, S, Muñoz, E. 2018. Determinación de un régimen de caudal ambiental para el río Ñuble considerando actividades recreacionales y requerimientos de hábitat de peces. *Obras y Proyectos* (24): 71–81.

United Nations. 2018. SDG 6 Synthesis Report 2018 on Water and Sanitation. Available at https://www.unwater.org/publication_categories/sdg-6-synthesis-report-2018-on-water-and-sanitation/. Accessed 21 July 2020.

United Nations (General Assembly). 2015. *Resolution adopted by the general assembly on 25 September 2015*. Transforming our world: the 2030 Agenda for Sustainable Development. Available at https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf. Accessed 21 July 2020.

Vanham, D, Hoekstra, AY, Wada, Y, Bouraoui, F, de Roo, A, Mekonnen, MM, van de Bund, WJ, Batelaan, O, Pavelic, P, Bastiaanssen, WGM, Kummu, M. 2018. Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 "Level of water stress." *Science of the Total Environment* **613–614**: 218–232. DOI: http://dx.doi.org/10.1016/j.scitotenv.2017.09.056.

Van Loon, AF, Van Lanen, HAJ. 2013. Making the distinction between water scarcity and drought using an observation-modeling framework. *Water Resources Research* **49**(3): 1483–1502. DOI: http://dx.doi.org/10.1002/wrcr.20147.

Vargas, CA, Garreaud, R, Barra, R, Vásquez-Lavin, F, Saldías, GS, Parra, O. 2020. Environmental costs of water transfers. *Nature Sustainability* **3**(6): 408–409. DOI: http://dx.doi.org/10.1038/s41893-020-0526-5.

Viale, M, Garreaud, R. 2015. Orographic effects of the subtropical and extratropical Andes on upwind precipitating clouds. *Journal of Geophysical Research: Atmospheres* **120**(10): 4962–4974. DOI: http://dx.doi.org/10.1002/2014JD023014.

van Vuuren, DP, Edmonds, J, Kainuma, M, Riahi, K, Thomson, A, Hibbard, K, Hurtt, GC, Kram, T, Krey, V, Lamarque, JF, Masui, T. 2011. The representative concentration pathways: an overview. *Climatic Change* **109**(1): 5. DOI: http://dx.doi.org/10.1007/s10584-011-0148-z.

Waage, MD, Kaatz, L. 2011 June 1. Nonstationary water planning: An overview of several promising planning methods. *JAWRA Journal of the American Water Resources Association*. Available at https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1752-1688.2011.00547.x. Accessed 21 July 2020.

Wada, Y, Flörke, M, Hanasaki, N, Eisner, S, Fischer, G, Tramberend, S, Satoh, Y, van Vliet, MTH, Yillia, P,

Ringler, C, Burek, P. 2016. Modeling global water use for the 21st century: The water futures and solutions (WFaS) initiative and its approaches. *Geoscientific Model Development* **9**(1): 175–222. DOI: http://dx.doi.org/10.5194/gmd-9-175-2016.

WWAP (United Nations World Water Assessment Programme). 2014. *The United Nations World Water Development Report 2014: Water and energy.* Paris, France: UNESCO (The United Nations world water development report; Vol. 5).

Zhang, K, Yan, H, Zeng, H, Xin, K, Tao, T. 2019. A practical multi-objective optimization sectorization method for water distribution network. *Science of the Total Environment* **656**: 1401–1412. DOI: http://dx.doi.org/10.1016/j.scitotenv.2018.11.273.

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