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Research article

Protecting environmental flows to achieve long-term water security

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ABSTRACT

In this work, we propose a new approach to diagnose if a water allocation scheme is compatible with long-term water security at the catchment scale, and suggest steps to achieve such compatibility. We argue that when the remaining flow of a river after upstream withdrawals is not sufficient to safeguarding ecological river functions, the basin is at extreme risk of water scarcity, which indicates that the water management is failing. To test this, we analysed the water scarcity risks and the safeguarded environmental flows (e-flows) in 277 basins across a wide range of hydro-climatic conditions in Chile (17–55°S). For each basin, water scarcity risks were assessed based on water stress indices (WSIs, computed as the ratio of withdrawals to water availability), considering two water-use scenarios: (i) WSI_{max}, where total withdrawals correspond to the maximum consumptive water allowed by the law, i.e., where only the e-flows protected by law remain in the river, and (ii) WSI_{alloc}, where total withdrawals correspond to the actual allocated consumptive water uses within the basins. Further, we evaluated the adequacy of the water management system to protect ecological river functions by contrasting the e-flows protected in Chile with those safeguarded in six other countries.

The water allocation system in Chile incorporated the protection of minimum e-flows in 2005 and established that these do not exceed 20% of the mean annual streamflow, except in some exceptional cases. This upper limit is consistently lower than the e-flows safeguarded in other countries, where 20%–80% of the mean annual streamflow are protected. This turns out in WSI_{max} values between 80% and 100% in all basins, well above the threshold associated with over-committed basins under extreme risk of water scarcity (70% typically). When moving from the legally allowed to the actually allocated water use scenario, we found contrasting results: about 70% of the basins show low water scarcity risk (WSI_{alloc} <40%), while an 18% have WSI_{alloc} above 100%, indicating the allocation is going beyond current law limits and even beyond physical limits.

Our results reveal that the link between e-flows, water allocation and water security has not been adequately incorporated in the current law. E-flows stipulated by law are insufficient to fulfil environmental requirements, while placing the basins under extreme risk of water scarcity if the total allowed withdrawals were exerted. To move towards a system that can effectively achieve long-term water security, we recommend: (i) To define tolerable water scarcity risks for basins, considering environmental requirements. (ii) To translate those risks into measurable basin indices to measure water security, such as the WSI. (iii) To set maximum water use limits (or minimum e-flows) within the basins that are compatible to the water security goals. If, under current and projected water availability conditions, the existing withdrawals exceed these limits, water managers should be able to adapt total consumption to the required limits.

1. Introduction

Water security, defined as the capacity of a population to safeguard access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, socio-economic development and ecosystems, and to ensure protection against water-related hazards (UNESCO i-WSSM, 2019), is considered as one of the fundamental pillars of sustainable development and climate action. Indeed, water

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security corresponds to one of the seventeen sustainable development goals (Goal 6) recognized by the United Nations (UNESCO, 2019). To operationalize this complex systemic concept at the management level, narrower water security framings are usually adopted (Cook and Bakker, 2012). In most cases, the focus is on the quantity and availability of water, which can be assessed through use-to-availability metrics. This has been a practical approach adopted to inform the water management and policy communities since the 1970s (Falkenmark et al., 1976).

A common use-to-availability indicator is the water stress index (WSI), defined as the long-term ratio of water withdrawals to water availability (Rockström et al., 2009; Veettil and Mishra, 2018). The WSI has been used in several applications, including the definition of freshwater planetary boundaries (Steffen et al., 2015), as a measure of water scarcity risks at global to local scales (Falkenmark, 2013; Gosling and Arnell, 2016), and to assess when a basin should be closed to further withdrawals (Smakhtin, 2008).

In this work, we propose a novel use of metrics based on WSI as a straightforward way to diagnose if a water allocation scheme is compatible with long-term water security at the catchment scale, and suggest steps to achieve such compatibility. Our approach consists on analysing WSI from a water scarcity risk perspective (e.g., Falkenmark, 2002; Gosling and Arnell, 2016) combined with an ecological perspective. Given that the WSI includes the long-term flow at the basin outlet after upstream withdrawals, it can be contrasted to environmental flows (e-flows) requirements. E-flows, defined as “the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being” (Arthington et al., 2018), are an intrinsically related to water security in the long term as, when they are not properly maintained, rivers can in time become slower, narrower and shallower, and growingly unable to support human and natural needs (Dou et al., 2021; Liu et al., 2017).

This paper focuses on the current water allocation scheme in Chile —established by the Chilean Water Code (Congreso Nacional de Chile, 1981) and its subsequent reforms— as a case study, although the approach can be applied to any other scheme. As study area, Chile offers a wide range of hydro-climatic and topographic conditions, which modulate different hydrological regimes and water availability. Combined with these water availability characteristics, intensive water consumption in the country is exerted by industrial sectors, including mining, forestry and agriculture (Barria et al., 2021a). Previous studies have evaluated the Chilean water allocation scheme and found that it fails to incorporate variations in water availability, which prevents achieving effective adaptation strategies to climate change (Barria et al., 2019, 2021a). These studies have shown that, given the precipitation reduction in central and southern Chile over the last decades (Boisier et al., 2016, 2018a; Garreaud et al., 2017) and the projected drying trends under climate change scenarios over the region (Barria et al., 2019, 2021a; Bozkurt et al., 2018), the current allocation overestimates water availability, which in turn, can lead to over-allocating water uses.

These water management limitations are exacerbated during drought periods, such as the megadrought affecting central and southern Chile since 2010. The megadrought has led to water scarcity problems in several regions (Barria et al., 2021b; Garreaud et al., 2017; Muñoz et al., 2020). At present, 188 out of 346 communes in Chile are declared under water scarcity by the DGA, affecting 47.5% of the national population (DGA, 2002). To a large extend, the megadrought respond to anthropogenic climate change (Boisier et al., 2016; Garreaud et al., 2019) and precipitation in this region is projected to keep decreasing during the second half of the 21st century under severe to moderate climate change scenarios (Barria et al., 2019, 2021a; Bozkurt et al., 2018). The water scarcity problems experienced during the megadrought and the climatic projections for the region call for an urgent revision of the water management system.

Our work builds upon previous studies focusing on the water allocation scheme in Chile (Barria et al., 2019, 2021a), and complements them by providing an assessment of water security based on water scarcity risk and ecological perspectives. On this basis, we propose basic recommendations to advance towards a water allocation system that can effectively achieve water security —a main goal in the national Long-Term Water Strategy (MOP, 2020).

2. The water allocation scheme in Chile.

The water allocation scheme in Chile is primarily defined by the Chilean Water Code promulgated in 1981 (Congreso Nacional de Chile, 1981) and implemented through a series of complementary laws and decrees. Some specific articles from the Water Code have been amended during the last decades (Congreso Nacional de Chile, 2006; 2009, 2011, 2018) and the main text has been amended in 2005 (Congreso Nacional de Chile, 2005) and 2022 (Congreso Nacional de Chile, 2022).

The Water Code establishes water allocation through water use rights (WURs), which are entitlements defining the quantity and timing of the water that private and public solicitors can use. WURs can be allocated for consumptive (e.g., drinking water, irrigation) or non-consumptive (e.g., hydroelectricity) uses. Both kinds of entitlements, furthermore, are classified as permanent WURs, which can be used uninterruptedly, or eventual WURs, which can be used only when permanent WURs have been satisfied. Since the 2005 Water Code amendment, permanent and eventual WURs can be allocated only after a stipulated e-flow has been secured.

While the Water Code defines the overall use of water resources in Chile, the specific formulation for computing WURs and e-flows are provided separately in legal instruments and decrees, as presented in Fig. 1.

3. Study area, data and methods

The study area includes 277 basins that account for the contrasted hydro-climatic conditions in Chile, following a wide precipitation range (from about 0 to 4000 mm per year) and distinct hydrological regimes (e.g., rain- or snow-driven). Among other, these features control the mean streamflow and interannual variations of water availability in Chile (Fig. 2). For the analysis, we use monthly streamflow records from the Chilean Water Bureau (DGA), which were obtained from the CAMELS-CL dataset (Alvarez-Garreton et al., 2018).

Among the 516 catchments included in the CAMELS-CL dataset, we selected 277 which have at least 50% of monthly streamflow records in the period 1979–2005. This period was selected to fulfil the requirement of having at least 25 years of streamflow records for computing e-flows (Congreso Nacional de Chile, 2015), while using data prior 2005, where e-flows were included in the water allocation scheme (Fig. 1).

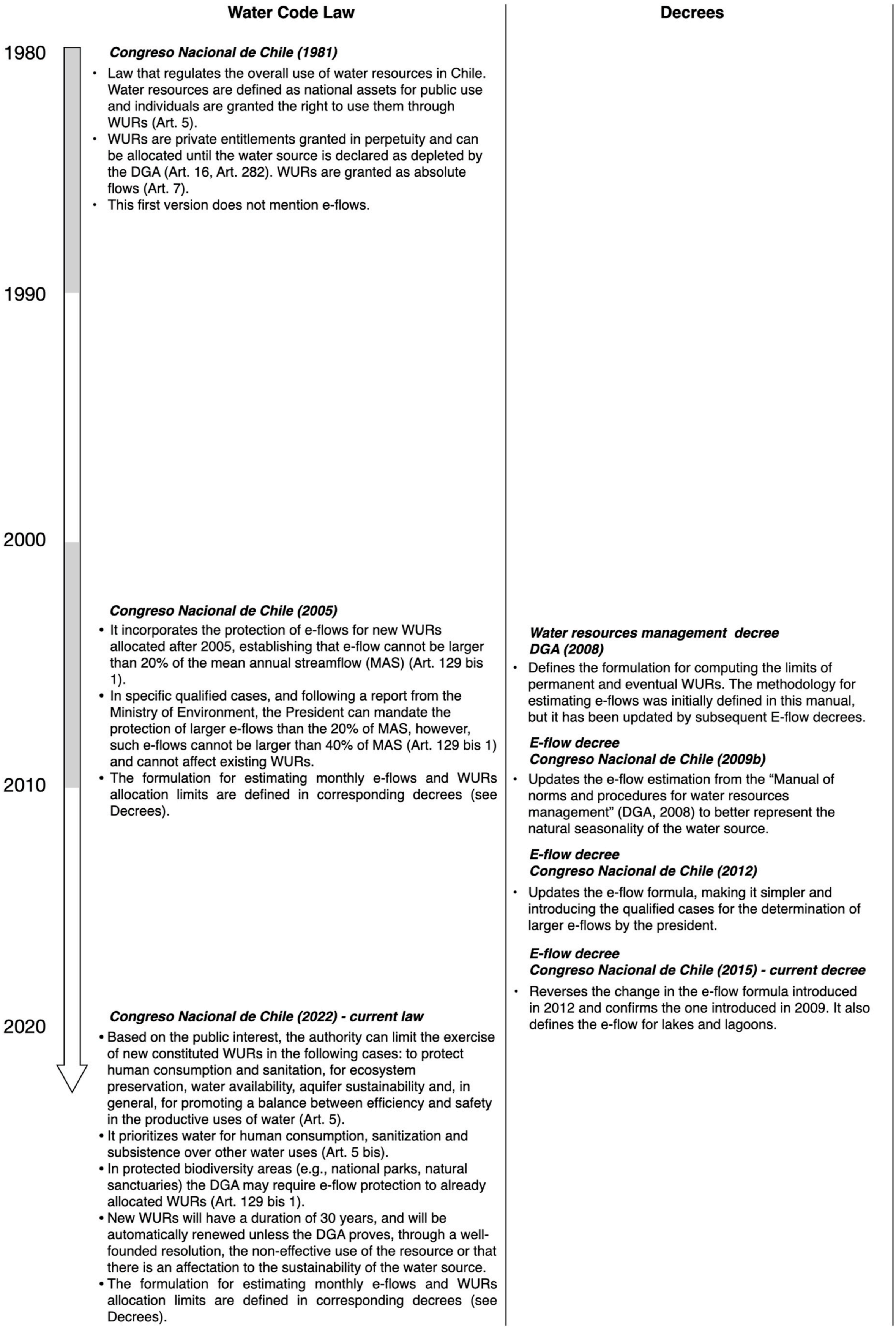
Our methodological approach has three steps. First, we computed WSIs in the 277 study basins under two water use scenarios: (i) an allowed scenario, where withdrawals correspond to the maximum consumptive WURs allowed by the current law (described in Sect. 3.1), and (ii) an allocated scenario, where withdrawals correspond to the actual allocated consumptive WURs within the basins (Sect. 3.2). Next, we assigned water scarcity risks to each basin based on the WSIs (Sect. 3.3). Finally, to assess the allocation scheme from an ecological perspective, we contrasted the e-flow stipulated by law with e-flows estimates computed with different methodologies (Sect. 3.4). We note that the analysis is limited to surface consumptive WURs, that is, excluding underground water and non-consumptive uses.

3.1. 1 Maximum allowed water use scenario

The maximum monthly flow allowed as permanent water use rights ($WU_{mon\_max}{}^{(P)}$) and as eventual water use rights ($WU_{mon\_max}{}^{(E)}$) for a given month are defined in current DGA decree (DGA, 2008) as follows:

$$WU_{mon\_max}{}^{(P)} = Q_{mon\_85} - Q_{mon\_eflow\_cl} \tag{1}$$

$$WU_{mon\_max}{}^{(E)} = Q_{mon\_05} - WU_{mon\_max}{}^{(P)} \tag{2}$$



Water Code Law

Congreso Nacional de Chile (1981)

- Law that regulates the overall use of water resources in Chile. Water resources are defined as national assets for public use and individuals are granted the right to use them through WURs (Art. 5).
- WURs are private entitlements granted in perpetuity and can be allocated until the water source is declared as depleted by the DGA (Art. 16, Art. 282). WURs are granted as absolute flows (Art. 7).
- This first version does not mention e-flows.

Congreso Nacional de Chile (2005)

- It incorporates the protection of e-flows for new WURs allocated after 2005, establishing that e-flow cannot be larger than 20% of the mean annual streamflow (MAS) (Art. 129 bis 1).
- In specific qualified cases, and following a report from the Ministry of Environment, the President can mandate the protection of larger e-flows than the 20% of MAS, however, such e-flows cannot be larger than 40% of MAS (Art. 129 bis 1) and cannot affect existing WURs.
- The formulation for estimating monthly e-flows and WURs allocation limits are defined in corresponding decrees (see Decrees).

Congreso Nacional de Chile (2022) - current law

- Based on the public interest, the authority can limit the exercise of new constituted WURs in the following cases: to protect human consumption and sanitation, for ecosystem preservation, water availability, aquifer sustainability and, in general, for promoting a balance between efficiency and safety in the productive uses of water (Art. 5).
- It prioritizes water for human consumption, sanitization and subsistence over other water uses (Art. 5 bis).
- In protected biodiversity areas (e.g., national parks, natural sanctuaries) the DGA may require e-flow protection to already allocated WURs (Art. 129 bis 1).
- New WURs will have a duration of 30 years, and will be automatically renewed unless the DGA proves, through a well-founded resolution, the non-effective use of the resource or that there is an affectation to the sustainability of the water source.
- The formulation for estimating monthly e-flows and WURs allocation limits are defined in corresponding decrees (see Decrees).

Decrees

Water resources management decree
DGA (2008)

- Defines the formulation for computing the limits of permanent and eventual WURs. The methodology for estimating e-flows was initially defined in this manual, but it has been updated by subsequent E-flow decrees.

E-flow decree
Congreso Nacional de Chile (2009b)

- Updates the e-flow estimation from the “Manual of norms and procedures for water resources management” (DGA, 2008) to better represent the natural seasonality of the water source.

E-flow decree
Congreso Nacional de Chile (2012)

- Updates the e-flow formula, making it simpler and introducing the qualified cases for the determination of larger e-flows by the president.

E-flow decree
Congreso Nacional de Chile (2015) - current decree

- Reverses the change in the e-flow formula introduced in 2012 and confirms the one introduced in 2009. It also defines the e-flow for lakes and lagoons.

Fig. 1. Time line with the main legal instruments defining water allocation in Chile. Only the contents and modifications relevant to this study were included.

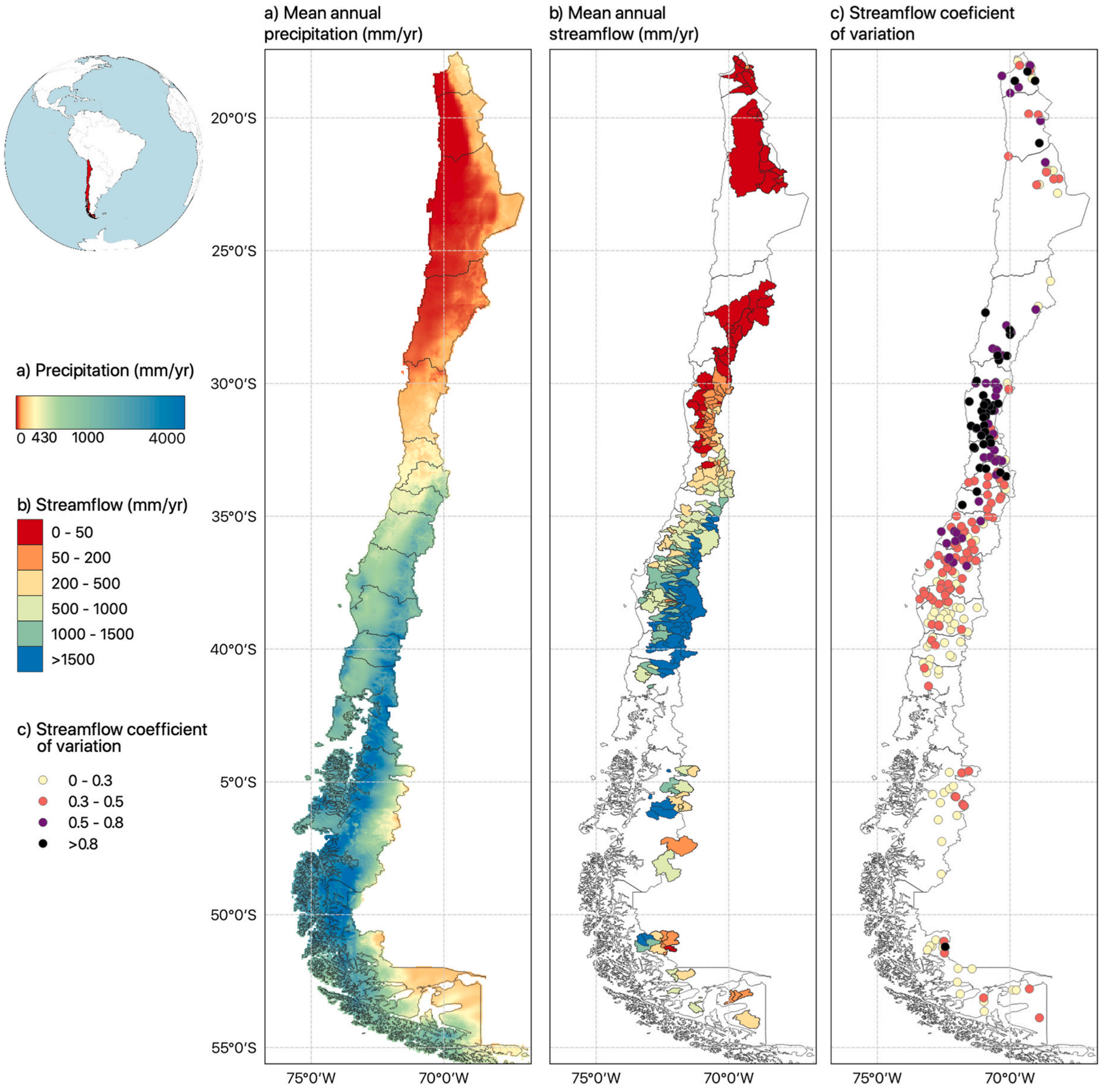


Fig. 2. Panel a shows the mean annual precipitation of the country computed from the CR2MET product (Boisier et al., 2018b). Panel b shows the study basins coloured by their mean annual streamflow expressed as mm per year. Panel c shows the study basins outlets coloured by their streamflow coefficient of variation (ratio of standard deviation to mean annual streamflow).

where Q_{mon_85} and Q_{mon_05} are the monthly streamflow associated to 85% and 5% probability of exceedances for a given month (i.e., the 15th and 95th percentiles, respectively). The environmental flow for the corresponding month ($Q_{mon\_eflow\_cl}$) is defined by the current e-flow decree (Congreso Nacional de Chile, 2015) as:

$$Q_{mon\_eflow\_cl} = \begin{cases} 0.5 \bullet Q_{mon} & if \quad 0.5 \bullet Q_{mon\_95} < 0.2 \bullet Q_{ann} \\ 0.2 \bullet Q_{ann} & if \quad 0.5 \bullet Q_{mon\_95} > 0.2 \bullet Q_{ann} \end{cases} \tag{3}$$

where Q_{mon} is the streamflow associated to a 95% probability of exceedance for a given month and Q_{ann} is the mean annual streamflow at the basin outlet, computed for the period 1979–2005.

Finally, the maximum monthly permanent and eventual water use rights allowed by the current law (WU_{mon_max}) within a basin for a given month correspond to:

$$WU_{mon\_max} = \min\left({WU_{mon\_max}}^{(P,E)}, Q_{mon} - Q_{mon\_eflow\_cl} \right) \tag{4}$$

where ${WU_{mon\_max}}^{(P,E)}$ is total monthly flow allowed as water use rights (${WU_{mon\_max}}^{(P)} + {WU_{mon\_max}}^{(E)}$) and Q_{mon} is the mean monthly streamflow. Hereafter, all results will be presented on annual basis and referred to current maximum allowed withdrawals as ${WU_{max}}^{(P)}$, ${WU_{max}}^{(E)}$ and WU_{max}, for permanent, eventual and total water use rights, respectively, and to annual e-flows defined by the current law as Q_{eflow_cl}. In this way, WU_{max} represents the maximum annual volume that can be granted for consumptive water uses within a basin according to the current law.

3.2. 2 Allocated water use scenario

Given that the maximum limits from the allowed water use scenario do not represent the actual water uses within the basin nor the water use rights that have been allocated historically, we also computed the actual allocated withdrawals (WU_{alloc}), which more closely resemble real conditions.

For each basin, WU_{alloc} was computed as the sum of the permanent and eventual consumptive water use rights (${WU_{alloc}}^{(P)}$ and ${WU_{alloc}}^{(E)}$, respectively) processed from the official national database by Barria et al. (2021a). It is worth noting that, if the current allocation scheme is respected, WU_{alloc} should be less than WU_{max}.

3.3. Catchment water security

For each basin, WSIs were computed considering both the currently allowed and the actual allocated water-use scenarios. Moreover, to explore the role of permanent and eventual water use rights on water security, we computed WSIs based on both types, as:

$$WSI_{max}{}^{(P)} = \frac{WU_{max}{}^{(P)}}{Q_{ann}}, WSI_{max}{}^{(E)} = \frac{WU_{max}{}^{(E)}}{Q_{ann}} \tag{5}$$

$$WSI_{alloc}{}^{(P)} = \frac{WU_{alloc}{}^{(P)}}{Q_{ann}}, WSI_{alloc}{}^{(E)} = \frac{WU_{alloc}{}^{(E)}}{Q_{ann}} \tag{6}$$

In both the current allowed and allocated scenarios, the total WSI (WSI_{max} and WSI_{alloc}, respectively) is the sum of permanent WSI and eventual WSI. These WSIs were used to classify the basins along three categories, ranging from a lower risk/restriction to a higher risk/restriction, according to Table 1.

3.4. 3 Environmental flow benchmarking

In response to the growing pressure on watersheds worldwide, the scientific and water management communities have developed several methodologies for e-flow quantification (Wineland et al.,). These methods vary in their complexity, data requirements, and suitability for representing ecological functions. Tharme (2003) identified 207 methodologies for e-flow estimation used in 44 countries, and grouped them into four categories: hydrological methods, hydraulic rating, habitat simulation and holistic methodologies. The simplest and most used in water management is the hydrological method, which uses hydrological data such as monthly or daily streamflow, usually under naturalized conditions, to estimate e-flow as percentages of mean flows or by look-up tables. More complex methods, such as hydraulic rating and habitat simulation methods are based on quantifiable relationships between river flow and river habitat. Holistic methods aim at representing the entire riverine ecosystem, including the preservation of habitat, geomorphology, groundwater connectivity and wetlands (Tharme, 2003).

Since the Chilean water allocation scheme defines e-flows following a hydrological approach, in our assessment we compared the $eflow_{cl}$ from Eq. (3) with some of the most widely used hydrological methodologies reported by Tharme (2003): (1) The Tennant method (Tennant, 1976), used in Australia, Canada, Italy, New Zealand and the USA; (2) the Tessman method (Tessmann, 1980), used in Canada; (3) the flow duration curve shifting method (FDC, Smakhtin and Anputhas, 2006), used in Denmark, South Africa and the USA. Monthly streamflow time series from the 277 study basins were used to compute $eflow_{cl}$ (Eq. (3)), as well as to derive the e-flows based on the Tennant, Tessman and FDC methods. The formula of each method can be found in Appendix A.

The Tennant and FDC methods define e-flows based on height and six conservation categories, respectively (see Appendix A). For the purpose of this comparison, we selected three of these categories, associated with high, medium and low conservation ratings. For the Tennant method, we used the categories Excellent, Good and Fair or degrading. For the FDC method, we used the categories C (moderately modified ecosystem), D (largely modified ecosystem) and E (seriously modified ecosystem).

Table 1
WSI classification based on water scarcity risks (Falkenmark, 2002; Gosling and Arnell, 2016; Rockström et al., 2009) and ecological perspectives (Falkenmark, 2002; Smakhtin, 2008).

	Water scarcity risk	Ecological perspective
$WSI<40\%$	Low risk	Open basin: the water supply is enough to meet the current withdrawals demands while maintaining the ecological functions of the river.
$40\% < WSI<70\%$	Medium risk	Closing basin: withdrawals begin to impinge on ecological needs.
$WSI>70\%$	Extreme risk	Closed basin: The basin is overcommitted and thus considered as closed, additional water commitments cannot be made.

4. Results

4.1. 1 WURs and water security

Fig. 3 presents the currently allowed and the actual allocated WURs within the study basins, highlighting those WURs allocated before and after 2005, the year in which the e-flow protection started (Fig. 1). Before 2005, 49 basins (18% of the sample) had permanent WURs exceeding the currently allowed by law (points above the 1:1 line in Fig. 3a). These basins sum up 8606 m^3/s allocated WURs, which largely exceeds the allowed limit of 250 m^3/s in those basins (computed as the sum of the allowed limits in each basin). Possible explanations of this overallocation include the lack of e-flows protection before 2005 and the use of a different reference period for computing the allocation volume (Eq. (1)), but these cannot explain all of it. The DGA official national database contains a WUR of 2714.879 m^3/s allocated in 1969 to the State in Estero Rungue (code UA-1301-807,179), which is a tributary of three of our study basins (gauge_id of 5734001, 5737002 and 5748001, according to CAMELS-CL), corresponding to the three highest points in Fig. 3a. This WUR largely exceeds the allowed limits and even the physical limits of the basins (the largest mean annual streamflow of these basins is 141.26 m^3/s). While this could be due to a methodological or even a transcription mistake when the WUR was registered, the Water Code does not allow to correct officially granted WURs.

Disregarding this particular case, there are still 46 basins above the 1:1 line in Fig. 3a, accumulating WURs of 142.44 m^3/s, which also exceeds the physical limits represented by an accumulated mean annual streamflow of 97.47 m^3/s within the 46 basins. Furthermore, and contrary to what would be expected, Fig. 3a shows that even after 2005, permanent WURs have been allocated beyond the allowed limits in other 15 basins, suggesting that e-flows or water availability were not adequately considered in those cases. In summary, at present, there are 64 basins (23% of the sample) with allocated permanent WURs beyond the currently allowed limits. When considering eventual WURs (Fig. 3b), problems are still evident, with 13 basins above the 1:1 line (the granted eventual WURs are larger than the availability based on theoretical calculations) when considering the allocated WURs prior 2005, and three additional basins with WURs beyond allowed limits after 2005.

Fig. 4a shows the $WSI_{max}{}^{(P)}$ and $WSI_{max}{}^{(E)}$ for each basin, that is, the WSI index based on the maximum WURs allowed by the current law. This figure describes a linear relationship between $WSI_{max}{}^{(P)}$ and $WSI_{max}{}^{(E)}$ that illustrates the current legal limits of water allocation. In basins with high streamflow variability (larger monthly streamflow coefficient of variation), most of the water resources can only be granted as eventual WURs (top left corner in Fig. 4a). This is the case of arid and semi-arid basins in central-northern Chile (25–35°S, Fig. 2). On the other hand, in basins with more steady flow regimes, the typical condition in southern Chile, most water resources can be granted as permanent WURs (bottom right corner in Fig. 4a).

The comparison of the WSI based on the actual allocated rights within the basins shows that the current allowed limits are exceeded in many cases (Fig. 4b), in line with the results illustrated in Fig. 3. Moreover, large flows have been allocated as permanent rights in basins with high streamflow variability (pink dots nearing the bottom right corner of Fig. 4b).

Fig. 5 presents the distribution of WSIs considering permanent water use rights ($WSI_{alloc}{}^{(P)}$) and total (permanent plus eventual) water use

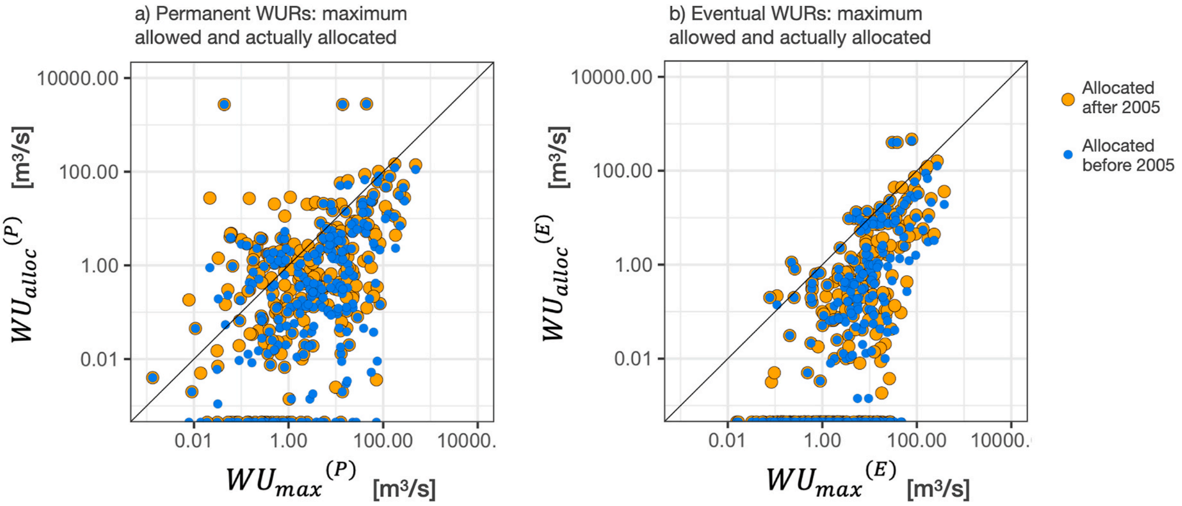


Fig. 3. WURs under currently allowed and actual allocated scenarios, considering permanent WURs (panel a) and eventual WURs (panel b).

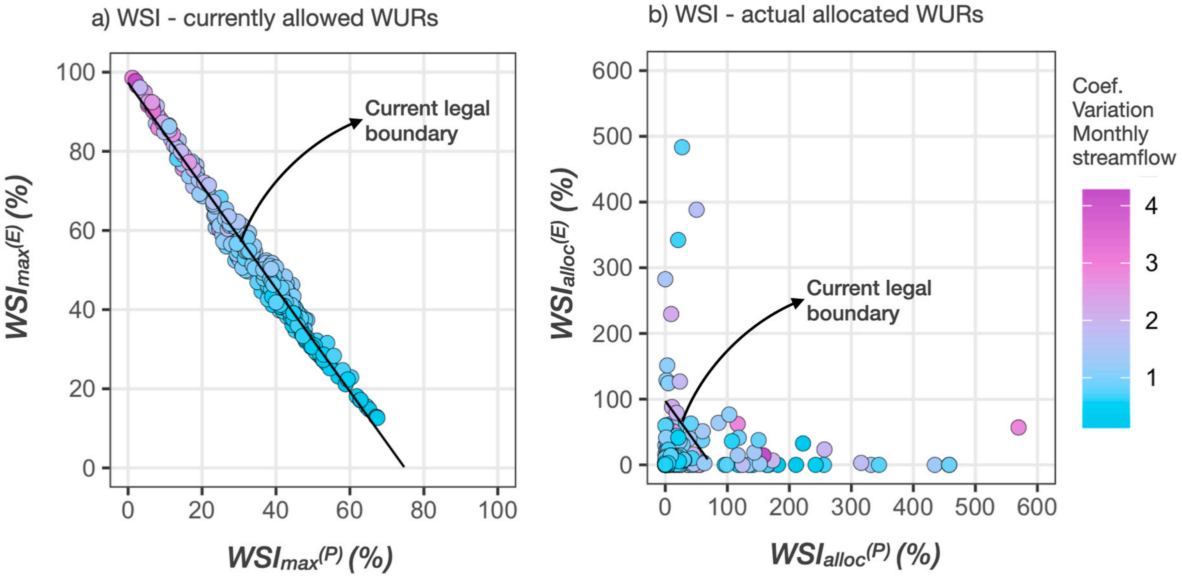


Fig. 4. WSI computed from permanent and eventual WURs, under currently allowed (panel a) and actual allocated scenarios (panel b).

rights (WSI_{alloc}), allowing to classify water security within the basins. Fig. 5a indicates that the currently allowed permanent withdrawals maintain all the basins below the extreme risk category, although a number of basins fall well within the medium level of water scarcity risk. However, when eventual WURs are considered, that is, when only e-flows defined by law are safeguarded, all basins move into an extreme water scarcity risk category. This indicates that the currently allowed water use limits, which are restricted by the protection of e-flows, do not prevent an extreme water scarcity risk. By construction, none of the basins falls beyond physical limits (see Eq. (4)).

When considering the allocated water use scenario (Fig. 5b), the distribution becomes bimodal: 71% of the basins feature a low risk of water scarcity (WSI$<$40%), both when considering total or permanent only WURs. These relatively low WSI values show that not all the currently allowed WURs have been allocated in the study basins, a situation that mostly happens in the southern regions where natural water availability is higher (35–55°S, Fig. 6) where water is more abundant. In an opposite situation, 18% of the basins have allocated WURs beyond physical limits (WSI$>$100%, Fig. 5b). A WSI value above one indicates that WURs cannot be guaranteed since the allocation has exceeded availability. In such cases, by definition, no e-flows will be maintained. Most of these basins are located in central-northern part of Chile (25–35°S, Fig. 6), the region that concentrates most of the population and where most agricultural activities take place in Chile (agriculture accounts for about 70% of consumptive water use in the country, (MOP, 2017).

4.2. 2 Environmental flows

Fig. 7 compares the e-flow defined by the current law in Chile (Q_{eflow_cl}) with e-flow computed for the study basins following the alternative methodologies described in Sect. 3.3. To facilitate the comparison, the different e-flow estimations are presented as annual values normalised by the mean annual streamflow (Q_{ann}) of each basin. The e-flows safeguarded by law in Chile, corresponding to $100 - WSI_{allow}$, are significantly lower than the alternative e-flow definitions analysed here. E-flows in Chile have an upper boundary of 20% of Q_{ann} (Eq. (3)), however, in most cases this upper threshold is not reached, with a median legal e-flow for the study basins corresponding to 14% of Q_{ann}.

The closest e-flow estimations are those from the FDC and Tennant methods in their lowest categories. The e-flow following Chile's regulation falls below the E category in FDC classification (Table A2), which

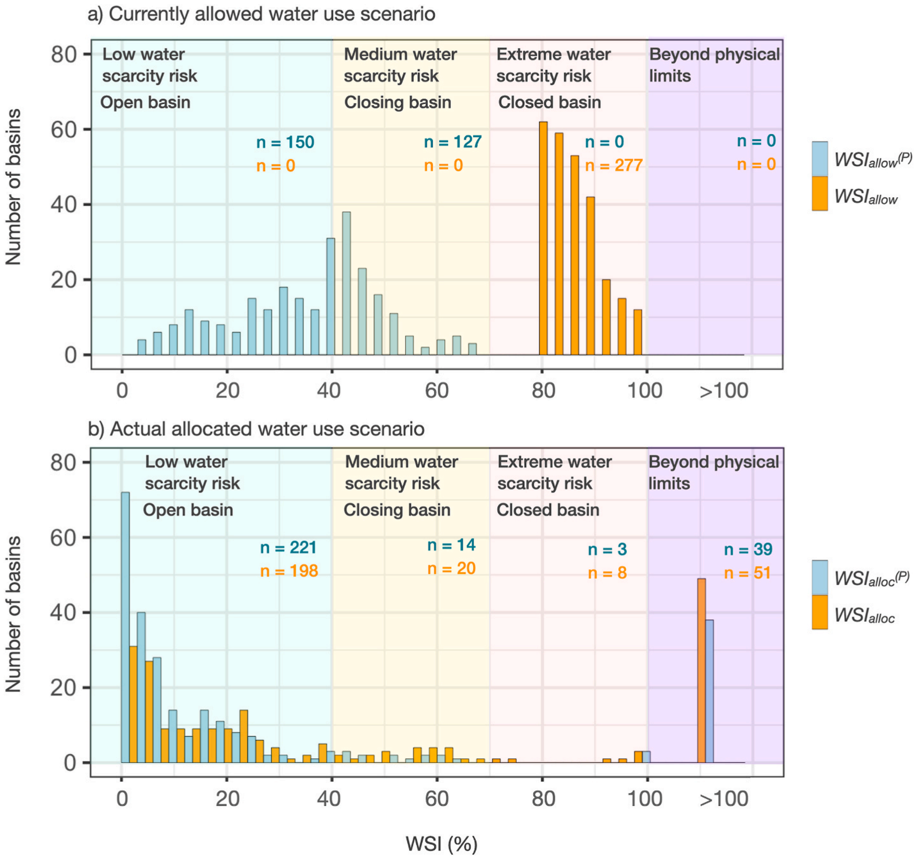


Fig. 5. WSI computed based on permanent and total withdrawals, under current allowed (panel a) and allocated water-use scenarios (panel b). The WSI values are classified following Table 1. The numbers of basins within in each WSI category are presented in blue and orange for permanent and total withdrawals, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

corresponds to seriously modified rivers, where water quality has degraded, habitat diversity and availability has declined, and where exogenous species have invaded the ecosystem and native species can no longer breed (Smakhtin and Anputhas, 2006). As indicated in the previous section, there are many basins in Chile —especially in the central-northern area— where the allocated rights exceed the maximum permitted by current legislation (Fig. 6), indicating that not even this minimum protection can be guaranteed throughout the country.

5. Discussion

The results described in Sect. 4 reveal critical structural flaws in Chile's water management system. In all basins, the current law allows potential consumptive water withdrawals up to limits that are not compatible with long-term water security. Permanent water uses are allowed into medium risk levels ($40\% < \mathrm{WSI} < 70\%$) in 46% of the study basins (Fig. 5a). According to the criteria of closing basins (Table 1), this indicates that no further uses should be allocated in the basins. However, the additional allowance of eventual WURs (allowed after permanent WURs and —since 2005— e-flows are secured) places all basins, independently of their hydrologic regime and initial risk level associated to permanent uses, at extreme risk of water scarcity (WSI >70%). This is because the e-flow to be safeguarded is, at maximum, a 20% of the mean annual streamflow, unless there is a qualified situation mandated by the President (Fig. 1). Therefore, if all water allowed by law is used, all basins would be classified as overcommitted, according to the criteria used in the literature (Table 1).

Moreover, the analysis on the actually allocated water use rights shows that the allocation in some basins goes even beyond physical limits (Fig. 5b). This creates serious legal uncertainties since WURs holders are not be able to use all the water that was legally allocated to them by the State. This is particularly critical considering that most of these overallocated WURs were granted as permanent consumptive entitlements (Fig. 3a). Eventual WURs can only be exerted after permanent and e-flows have been satisfied, hence, eventual WUR holders probably plan their use of water under higher uncertainty scenarios, but permanent WUR holders have a legal expectation to be able to use their rights, so permanent entitlements should have adequate certainty levels to promote investment by WURs holders, such as irrigation technology. Indeed, WUR holders frequently mortgage their water entitlements to access bank loans (Muchnik et al., 1997).

The lack of surface water to fulfil the uses has led to water scarcity problems that likely pushed several of these users to use underground sources (Muñoz et al., 2020; Prieto et al., 2019). Also, water scarcity rapidly accelerates the use of seawater in certain industrial sectors, however, the current desalinization regulation is fragmented and inadequate (the Water Code does not include seawater), which may carry critical social and environmental risks (Alvez et al., 2020).

The existing overallocation can be explained by limitations in the allocation system, including the following: i) Water availability (Q_{ann}) is computed considering a stationary climate, i.e., without accounting for present-day and projected drier conditions in central Chile. ii) WURs are defined as absolute volumes instead of as a fraction of the actual available water. iii) Before 2005, e-flows were not considered and thus WURs could be granted with volumes reaching all the available water computed at that time.

From an ecological perspective, the 1981 Water Code conceives water resources as assets that must be used without considering their ecological role. The subsequent Water Code amendments and the different versions of the e-flow decrees (Fig. 1) tried to reverse this,

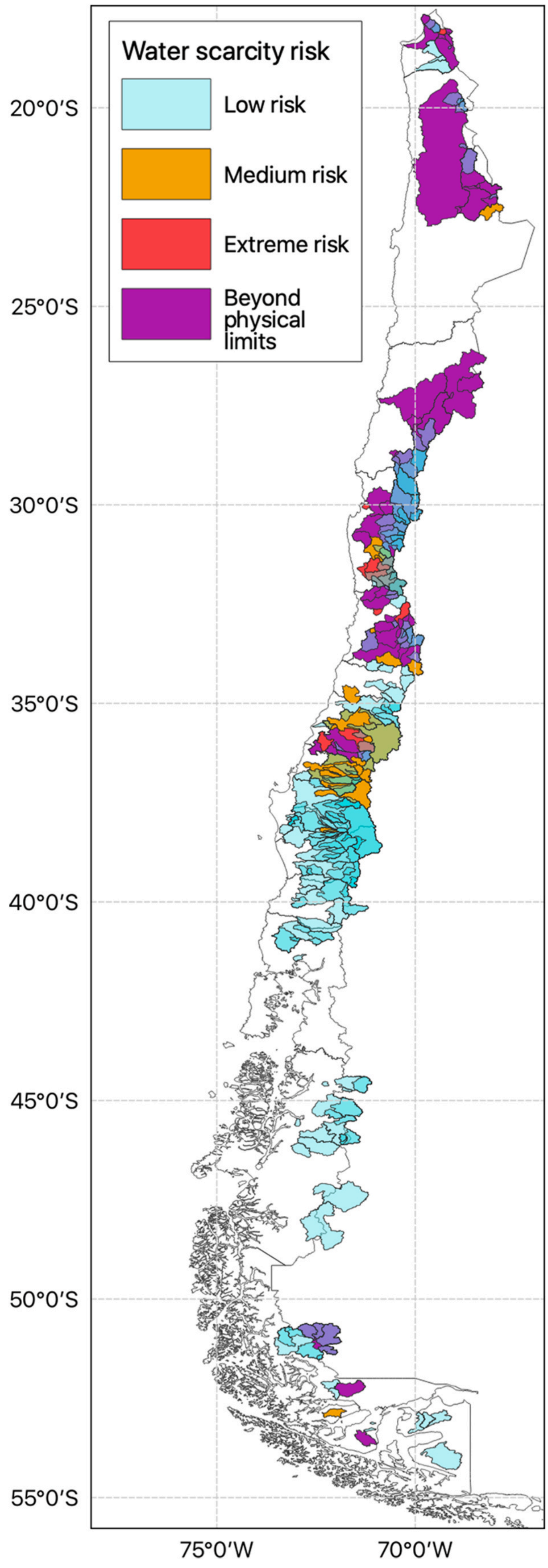


Fig. 6. Water scarcity risk classification for the study basins based on the WSI computed for total allocated withdrawals.

however, we identify two main caveats that prevent the effective protection of ecological functions: i) The e-flow stipulated by the current law is still below the minimal conditions to protect ecosystem functions (Fig. 7). ii) With the purpose of providing legal and economical certainties to WUR owners, the law stipulates that WURs allocated before 2005 (granted in perpetuity and without considering e-flows) cannot be modified unless some exceptional cases.

According to the official granted WURs database available at the Chilean Water Directorate, nowadays there exist 46,645 consumptive WURs allocated in perpetuity in Chile, corresponding to annual flows of about 2,250,000 L/s. From this total, about 1,770,000 L/s was given before 2005, i.e., 79% of the water volume allocated in Chile was assigned without considering e-flow restrictions. While the remaining 21% of surface flows have been allocated with the restriction of protecting e-flows, we also showed this protection is below recommended limits (Sect. 4.2) and that its implementation has failed in some cases (Sect. 4.1). Furthermore, e-flows are estimated based on streamflow records from a gauge in the river or in a nearby river (Congreso Nacional de Chile, 2015), which do not correspond to natural conditions since they account for the existing upstream withdrawals. Naturalized streamflow would likely result in larger Q_{ann} and, therefore, larger flows to be safeguarded as e-flow.

The recent 2022 Water Code amendment addressed the perpetuity condition of WURs, but to a limited extent (Congreso Nacional de Chile, 2022). The new law establishes a 30-year duration for WURs allocated after 2022, however, the term of these entitlements will be automatically renewed after the 30-year period unless there is a resolution from the Water Directorate requesting the end of the WUR term. Such legal resolutions must demonstrate that the owner is not effectively using his/her WUR or that the sustainability of the water source is being affected. Regarding e-flows, the 2022 Water Code amendment did not modify the upper limit established for e-flows, except for qualified cases mandated by the President, where e-flows in protected biodiversity areas may reach 40% of the Q_{ann}.

6. Conclusions and policy recommendations

This work proposes a new approach to diagnose if a water allocation scheme is compatible with long-term water security at the catchment scale. We focus on the water allocation scheme in Chile, although the approach can be applied to any other scheme. Our approach assesses water security by computing water stress indices and water scarcity risk levels in 277 basins considering a maximum allowed water use scenario and an actually allocated water use scenario. The water management scheme is further diagnosed from an ecological perspective by contrasting the e-flow safeguarded within the basins with those that would be legally protected in six other countries.

Based on our results, we conclude that all Chilean basins, independently of their hydrologic regime, would be at extreme risk of water scarcity and under e-flows threatening if all the consumptive WURs allowed by the current law were exerted. This reveals a structural contradiction to the water security goals declared in the Long-Term Water Strategy (MOP, 2020). To advance towards water security goals that can be effectively achieved, we recommend revising the current water allocation system by considering the following steps:

i. **Define tolerable water scarcity risks:** define tolerable water scarcity risks for basins in Chile that explicitly consider environmental requirements and their hydrologic regimes. Since basins within a low risk of water scarcity are more resilient to natural streamflow variability, basins prone to such conditions —such as semi-arid basins in central Chile— should probably target lower tolerable risks.
ii. **Compute water security indices:** to effectively guide public policy, water scarcity risks need to be clearly translated into measurable indices of water security, such as the WSI, based on robust data as representative as possible of natural conditions.

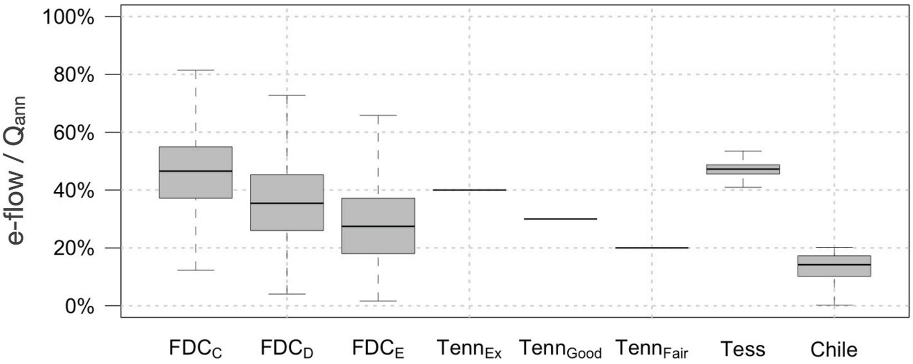


Fig. 7. e-flow comparison.

This is in line with Cook and Bakker (2012), stating that "discursively framing goals in terms of water security-related thresholds may be productive for water managers and policy makers, because this implies setting thresholds, which are actionable in governance processes (e.g. via indicators)."

iii. **Define water use limits:** set maximum withdrawals limits within a basin as a function of the tolerable water scarcity risks and their corresponding water security indices defined in the previous steps.

Based on the current legislation structure, these withdrawal limits could be achieved by: i) removing (or at least increasing) the upper e-flow limit indicated in the Article 129 bis 1 of the Water Code (defined as 20% of the mean annual streamflow) and ii) increasing the minimum protected e-flows in the current e-flow decree by following existing water management schemes that target higher levels of ecological protection.

If existing WURs —both the perpetuals or those that may expire after 30 years— have already exceeded the defined withdrawals limits, water authorities should be able to intervene and adapt total consumption to the defined water use limits. Such interventions may include withdrawals reductions and caps on irrigation.

In addition to limiting total water consumption, to achieve adequate water security levels, other sources of water availability could be explored, such as wastewater re-use or desalinization. Yet, these new water sources require a proper regulation that is still underdeveloped in Chile (Alvez et al., 2020).

iv. **Adaptation to climate change:** To achieve effective adaptation, withdrawals limits, e-flows and water security indices should account for projected water availability considering up-to-date climate change scenarios.

This work provides insights that can be used to improve the current water allocation system in Chile. The implementation of the latest 2022 Water Code reform implies the revision of current decrees and regulations. In this context, our diagnostic and recommendations are in line with the water security goals from the Long-Term Water Strategy (MOP, 2020), and also in good timing to inform the on-going public policy process.

Given the information gaps regarding actual water uses in Chile (in this work, water uses are represented by legally allowed and allocated water use rights), the water security diagnosis presented here is limited to the legal and structural aspects of the water management scheme, and do not necessarily represents actual water security levels of the study basins. Future work should advance towards a deeper diagnosis of water security in Chile, assessing and disentangling the impacts of climate variability, land use change and multiple water uses. Such diagnosis requires long-term estimations of water uses (actual uses, not allocated water rights) and naturalized water availability, as well as their projections under climate change scenarios. Great advances have been made regarding water availability estimations in Chile (DGA, 2017, 2018, 2019b, 2019a). However, to date, harmonized historical and projected estimations of water uses do not exist.

Credit author statement

Alvarez-Garreton, C.: Conceptualization of the study, Methodology, Writing - Original draft preparation. **Boisier, J.P.**: Conceptualization of the study, Methodology, Writing - Original draft preparation. **Billi, M.**: Conceptualization of the study, Methodology, Writing - Original draft preparation. **Lefort, I.**: E-flow benchmarking, Writing - Original draft preparation. **Marinao, R.**: E-flow computation, Writing - Original draft preparation. **Barria, P.**: Water allocation scheme review, Writing - Original draft preparation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. E-flow methods

A.1. Tennant method

This method uses mean annual streamflow (Q_{ann}) records and defines e-flows during wet and dry seasons as a percentage of the Q_{ann}, according to different conservation levels presented in Table A1. Given the precipitation seasonality in the study area, in this work the wet and dry seasons were defined as April to September and October to March, respectively.

Table A1
Categories in Tennant method. Retrieved from Table 3, Karakoyun et al. (2018).

Category	Dry season (% Q_{ann})	Wet season (% Q_{ann})
Flushing or maximum	200	200
Optimum range	60–100	60–100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	0–10	0–10

A.2. Tessman method

The Tessman method defines monthly e-flows ($Q_{mon\_eflow\_tess}$) based on mean annual streamflow (Q_{ann}) and mean monthly streamflow (Q_{mon}), as follows (Pastor et al., 2014):

$$If\ Q_{mon} < 0.4 \times Q_{ann} \rightarrow Q_{mon\_eflow\_tess} = Q_{mon} \tag{1a}$$

$$If\ Q_{mon} > 0.4 \times Q_{ann}\ \&\ Q_{mon} < Q_{ann} \rightarrow Q_{mon\_eflow\_tess} = 0.4 \times Q_{ann} \tag{2b}$$

$$If\ Q_{mon} > Q_{ann} \rightarrow Q_{mon\_eflow\_tess} = 0.4 \times Q_{mon} \tag{3b}$$

A.3. Flow duration curve method (FDC)

This method considers the following steps (Smakhtin and Anputhas, 2006): i) Estimating the monthly flow duration curve for the site where the e-flow needs to be computed. To avoid the effect of land use and water extraction from existing records, flows must be naturalized. ii) Defining a target class of environmental management, according to Table A2. In general, the classes from A to D are used for e-flow estimation since class E and F represent highly intervened water bodies. iii) Shifting the observed FDC according to the target of environmental management class and the lateral movements presented in Fig. A1. For example, for a target class “C”, the flow at 80% from the original FDC becomes the e-flow at 30%.

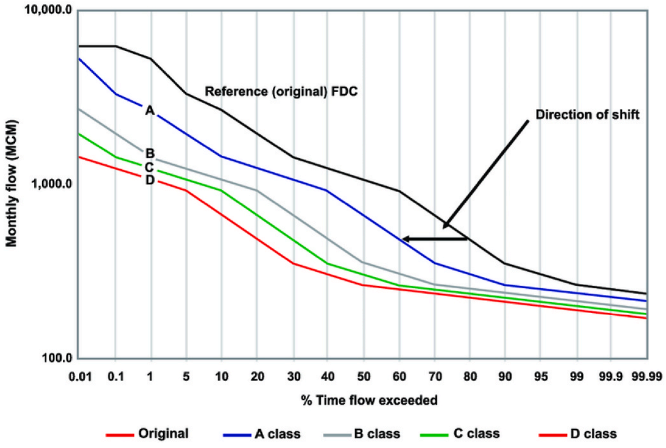

Fig. A1. Lateral movement of the FDC methodology. Retrieved from Smakhtin and Anputhas (2006) - copyright owner IWMI.

Table A2
Environmental Management Classes (EMC) and corresponding default limits for FDC shift. Retrieved from Table 3, Smakhtin and Anputhas (2006) - copyright owner IWMI.

EMC	Ecological description	Management perspective	Default FDC shift limits
A: Natural	Natural rivers with minor modification of instream and riparian habitat	Protected rivers and basins; reserves and national parks; no new water projects (dams, diversions) allowed	Lateral shift a reference FDC one percentage point to the left along the time axis from the original FDC position
B: Slightly modified	Slightly modified and/or ecologically important rivers with largely intact biodiversity and habitats despite water resources development and/or basin modifications	Water supply schemes or irrigation development present and/or allowed Multiple	Lateral shift a reference FDC one percentage point to the left along the

(*continued on next page*)

Table A2 (*continued*)

EMC	Ecological description	Management perspective	Default FDC shift limits
			time axis from the position of the FDC for A class
C: Moderately modified	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact; some sensitive species are lost and/or reduced in extent; alien species present	Multiple disturbances (e.g., dams, diversions, habitat modification and reduced water quality) associated with the need for socioeconomic development	Lateral shift a reference FDC one percentage point to the left along the time axis from the position of the FDC for B class
D: Largely modified	Large changes in natural habitat, biota and basic ecosystem functions have occurred; species richness is clearly lower than expected; much lowered presence of intolerant species; alien species prevail	Significant and clearly visible disturbances (including dams, diversions, transfers, habitat modification and water quality degradation) associated with basin and water resources development	Lateral shift a reference FDC one percentage point to the left along the time axis from the position of the FDC for C class
E: Seriously modified	Habitat diversity and availability have declined; species richness is strikingly lower than expected; only tolerant species remain; indigenous species can no longer breed; alien species have invaded the ecosystem	High human population density and extensive water resources exploitation; generally, this status should not be acceptable as a management goal; management interventions are necessary to restore flow pattern and to "move'' a river to a higher management category	Lateral shift a reference FDC one percentage point to the left along the time axis from the position of the FDC for D class
F: Critically modified	Modifications have reached a critical level; ecosystem has been completely modified with almost total loss of natural habitat and biota; in the worst case, basic ecosystem functions have been destroyed and changes are irreversible	This status is not acceptable from the management perspective; management interventions are necessary to restore flow pattern and river habitats (if stillpossible/feasible) to "move'' a river to a higher management category	Lateral shift a reference FDC one percentage point to the left along the time axis from the position of the FDC for E class

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