https://doi.org/10.5194/hess-2023-245
Preprint. Discussion started: 19 October 2023

Hydrology and Earth System Sciences
Discussions

HESS Opinions: The unsustainable use of groundwater conceals a "Day Zero"

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Abstract. Water scarcity is a pressing global issue driven by increasing water demands and changing climatic conditions. Based on novel estimates of water availability and water use, we examine the challenges and risks associated with groundwater (GW) withdrawals, focusing on the case of central-north Chile (27−35ºS), where extreme water stress conditions prevail. As total water uses within a basin approaches the renewable freshwater resources, the dependence on GW reserves in unsustainable ways intensifies. This overuse has consequences that extend beyond mere resource depletion, manifesting into environmental degradation, societal conflict, and economic costs. We argue that the "Day Zero" scenario, often concealed by the hidden nature of GW resources, calls for a reconsideration of water allocation rules and a broader recognition of the long-term implications of unsustainable GW use. Our results offer insights for regions worldwide facing similar water scarcity challenges and emphasize the importance of proactive and sustainable water management strategies.

1 Introduction

The risk of water scarcity in a basin escalates as the water demand approaches the available renewable freshwater resources, referred as water availability hereafter, understood as the difference between total precipitation and natural evapotranspiration excluding land use-induced perturbations. When the ratio of total water uses to water availability, known as the water stress index (WSI) exceeds 40%, a basin is considered as highly water stressed (Oki and Kanae, 2006). In extreme cases, when the curves of water availability and total water demands within a basin are too close or intersect (i.e., WSI = 100%), a "Day Zero" (D_0) may occur, during which water cuts are applied to prioritize water access for human consumption, and where the ecological flows to maintain the well-being of ecosystems cannot be safeguarded. A well-known D_0 event almost happened in 2018, when Cape Town (South Africa) was at risk of being the first major city worldwide to run out of drinking water due to the low dam levels caused by a severe multi-year drought. The announcement that the D_0 would arrive on a specific date (12 April 2018, estimated based on the remaining water stored in the reservoir and the water use requirements from the city) triggered water saving strategies that –along with the arrival of winter precipitation that interrupted the multi-year drought– allowed the city to avoid drastic water cuts (Maxmen, 2018; Burls et al., 2019). Another D_0 scenario happened in July 2023 in Montevideo (Uruguay). Due to low water reserves in the main reservoirs that supply drinking water to the city, the water supply was replaced with desalinated water. As a consequence, the metropolitan area of Uruguay was receiving non-drinkable water from their taps. Public opinion argued that this measure concealed the critical D_0 situation, as it has avoided supply cuts at the expense of providing non-potable water (Gudynas, 2023).

Besides some emblematic cases in metropolitan areas, many basins around the globe are approaching or have reached the intersection between water uses and availability, especially in water-limited regions with intensive irrigation (Oki and Kanae, 2006). In those cases, water needs are usually met by exploiting GW reservoirs in unsustainable ways in the long term, i.e., with withdrawal rates above GW natural recharges (de Graaf et al., 2019). In fact, many societies have sustained agricultural and population growth by pumping GW storage (Bierkens and Wada, 2019).

Previous studies have raised alarm about the unsustainable GW use worldwide, highlighting the challenges and risks of this practice (e.g., Gleeson et al., 2016; Schwartz et al., 2020). These studies recognize that accessing GW savings is crucial for addressing water scarcity, especially during droughts. However, this situation becomes precarious when GW ceases to be an accessible resource due to unsustainable extraction.

Here, we built upon previous evidence and propose that a D_0 scenario, which typically triggers alarms and immediate management responses when is associated to surface reservoir depletions, may be concealed by the unsustainable use of GW. We reflect on how this situation carries risks usually unforeseen or neglected, even before a D_0 is reached, and discuss how this may pose an intergenerational justice dilemma. To illustrate this, we use recently developed water use and availability data products for Chile and present the case of the country's region experiencing a number of water conflicts due to rising demand and reduced water availability related to climate change. We first discuss the situation of the Maipo basin, which houses the large urban area of Santiago, and then move to a larger region in central-north Chile to illustrate GW use from a wider perspective. We relate the GW overuse to water management practices and provide recommendations to improve them. While the argument is framed using Chile as an example, the conclusions can be applied to any region experiencing significant water stress and unsustainable groundwater usage.

2 A concealed "Day Zero" scenario in Santiago

The metropolitan area of Santiago, home to nearly six million inhabitants, concentrates 30% of the Chilean population. The city is located in the Maipo basin in central Chile (Fig. 1). According to the water use dataset recently developed by the Center for Climate and Resilience Research (available at https://seguridadhidrica.cr2.cl), the Maipo basin currently has a total water consumption of around 75 m^3/s, accounting for 15% of the country's total water usage. About 60% of the basin's water consumption comes from the irrigated agricultural sector, while 35% is allocated for drinking water.

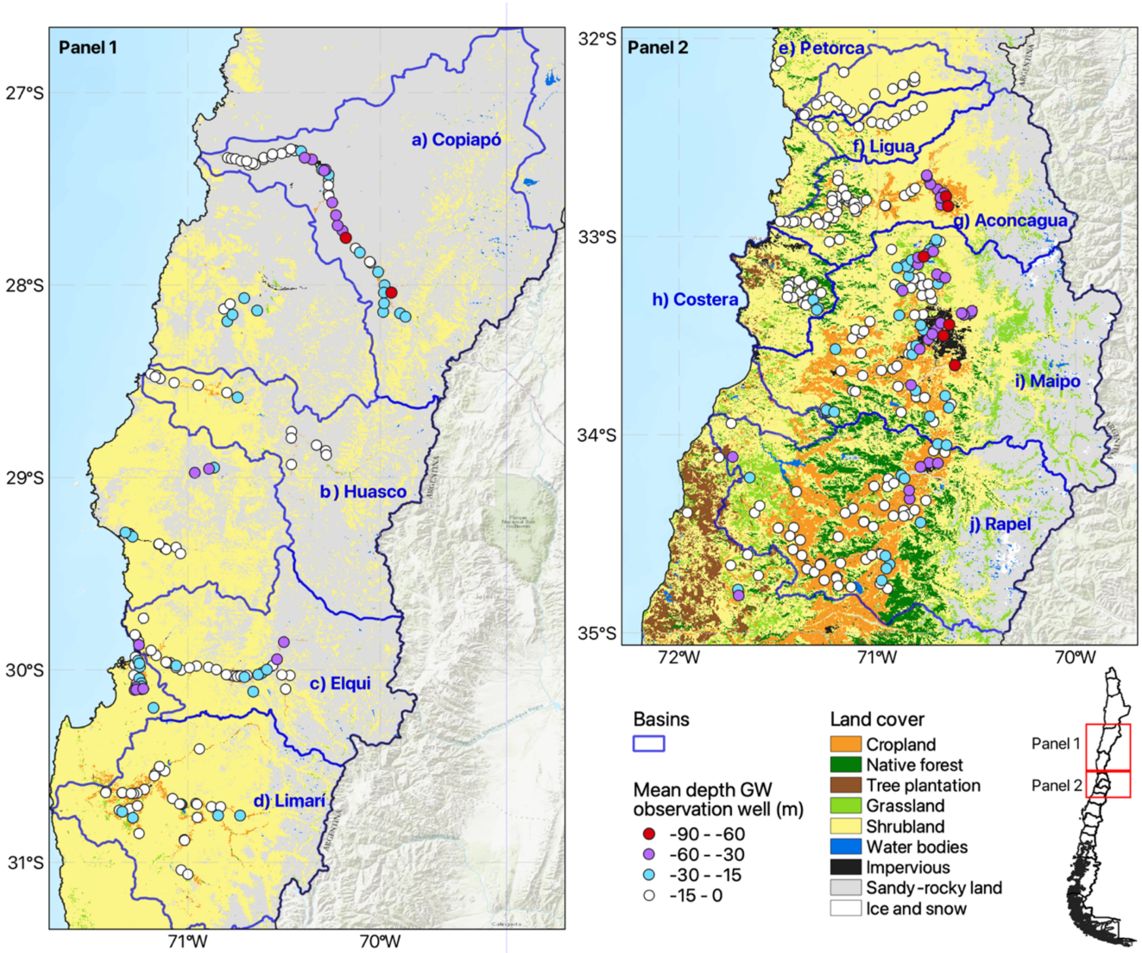

Figure 1: Ten major basins in central-north Chile and the land cover obtained from Zhao et al. (2016)**. The maps show GW observations wells that have at least 10 years of observations since 1960. Each observation well is colored by their mean depth computed for their complete period of record.**

Over the last decades, total water uses have continuously approached water availability in the Maipo basin (Fig. 2). These extreme water stress conditions (WSI close to 100%) emerge in a context of a protracted drought spanning more than a decade since 2010, with precipitation deficits ranging between 20 to 70% (Garreaud et al., 2019, 2017). The so-called megadrought in central Chile is partially controlled by natural climate variability, but also weighted by a long-term drying trend affecting the subtropical South Pacific region (Boisier et al., 2016, 2018). As an anthropogenic climate change signal this trend is projected to continue over the next decades along with global climate pathways (IPCC, 2022). Yet, the causes of the extreme water stress in the Maipo basin are not driven solely by climate variability and droughts. Driven by the expansion of irrigated agriculture, water usage in central Chile has been maintained or continued to rise over the last decades despite the diminishing water availability. To a large extent, water use in this region has been sustained at the expense of GW resources, as shown by the increasing water use rights allocation for GW abstractions, and further evidenced by the sustained depletion of GW levels (Fig. 2).

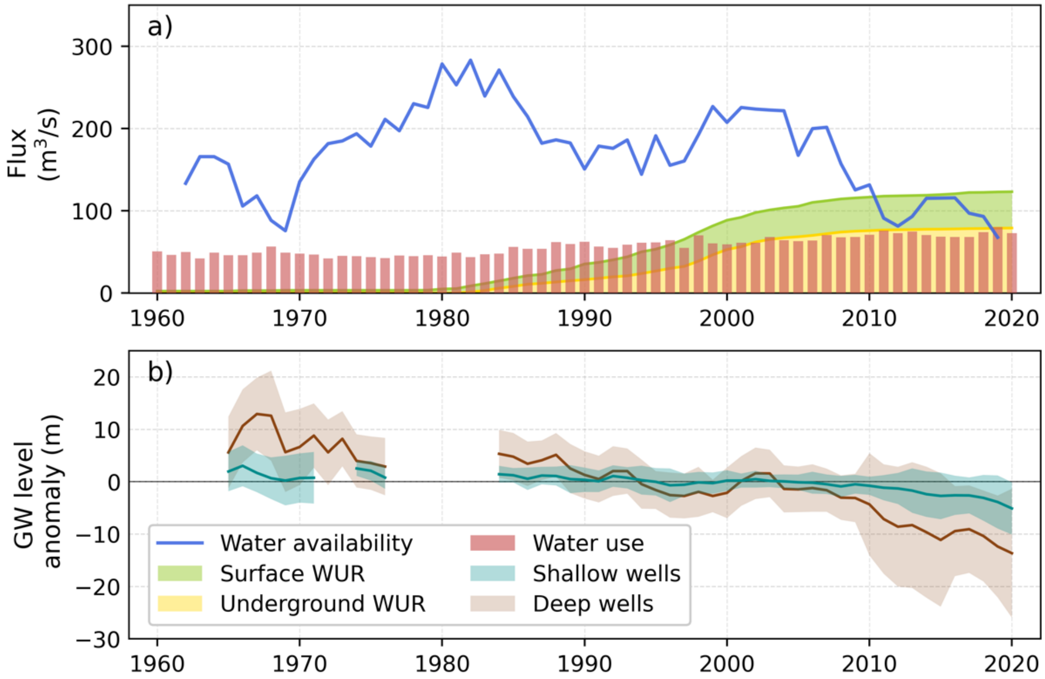

Figure 2: Panel a) shows the time series of water availability, water uses and water use rights (WUR) for the Maipo basin. The water availability is computed as the difference between catchment-scale precipitation and total evapotranspiration from non-anthropogenic land cover obtained from CR2MET product (Boisier, 2023)**. Surface and underground WUR were obtained from CAMELS-CL dataset** (Alvarez-Garreton et al., 2018)**. The water uses were obtained upon request from the CR2WU product available at https://seguridadhidrica.cr2.cl. Panel b) shows the GW level anomalies of 89 observation wells located in the Maipo basin, computed as the difference between GW levels and the mean level for the 1980-2010. The median (solid lines) and standard deviation (shaded area) of the GW level anomalies are plotted when at least five observations were available. Observation wells were classified as shallow and deep wells if their mean annual GW levels (shown in Fig. 1) were above or below 15 m, respectively. The GW observation data were obtained from the Water Directorate website https://snia.mop.gob.cl/BNAConsultas/reportes.**

Unlike estimating the time until a surface reservoir runs out, such as in the Cape Town case, there is large uncertainty in estimating the time remaining before a GW reserve is exhausted (or brought to a practical unrecoverable state within human timeframes), and an absolute D_0 is reached. Determining that time frame requires a precise quantification of the water volume remaining in aquifers, GW recharges, and GW extraction rates. Previous studies have estimated a volume of water of 30 km^3 for the main aquifer in the Maipo basin (Araneda et al., 2010) with net GW recharge rates (including springs) in the range of 10 to 30 m^3/s (Döll and Fiedler, 2008). If we consider present water uses of 75 m^3/s and a ratio of underground to total water uses ranging between 30 to 65% (upper bound corresponds to the ratio of GW to total water use rights in the Maipo basin, Fig. 2), the absolute D_0 time frame would range between 50 to 200 years, depending on the values considered for recharge and underground to total water use ratio. Consistent with this estimated range, another study for the Maipo basin forecasts a 33% reduction of GW storage for the 2020-2050 period in comparison to its 1990-2020 value (DGA, 2021). These are rough estimates computed from variables that are challenging to accurately estimate and monitor, making it difficult to assess the risk of overconsumption. However, they provide an order of magnitude of several decades to a few centuries to deplete the underground sources in the Maipo basin and reaching an absolute D_0 in the capital of Chile.

In contrast to the short time frames associated to a D_0 caused by depleted surface reservoirs in some major cities (e.g., Cape Town, Montevideo), several decades may sound like plenty of time to prepare for an absolute D_0 in Chile. However, such absolute D_0 is far more critical than running out of surface reserves since GW reservoirs take significantly longer time to replenish. Regardless of time frame for D_0, the depletion of GW levels, as observed in both shallow and deep wells (Fig. 2.b), cause environmental degradation, social conflict and economical. For example, wetlands may become disconnected from their groundwater source and deeper wells are required to access the water table, among other negative consequences. In Santiago, a recent adaptive measure taken by governmental and water supply agencies to face water scarcity has been the construction of deep pumping wells (up to 300 m depth in Santiago) for supplying drinking water for human consumption. While this measure is timely in the short term, helping to mitigate the risks of supply shortages in a region with nearly six million inhabitants, it also encourages the use of GW sources that might be, at best, very hard to replenish within human timescales. This in turn, will exacerbate GW depletion.

3 The non-sustainable GW use in Chile

Similar to the Maipo basin, water usage in most basins located in central-north Chile (27-35°S, Fig. 1) has reached or exceeded their water availability (Fig. 3 and Fig. A1). The definition of water availability entails the maximum potential of the integrated long-term fresh-water flow incoming to a basin, which could potentially be much higher than the long-term GW recharge. Therefore, the intersection of water uses and availability curves reveals a structural imbalance: permanent water uses rely more on depleting GW storage rather than on renewable sources. This situation will likely persist or worsen in the medium term due to the expected reduction in GW recharge resulting from the negative precipitation trends projected in this region (IPCC, 2022), where an average of 10 to 30% less annual precipitation is projected by the end of the 21st century from climate models with high and low greenhouse gas emission scenarios, respectively (Alvarez-Garreton et al., 2023a). At the same time, water usage will likely increase with population and economic growth (e.g., Meza et al., 2014).

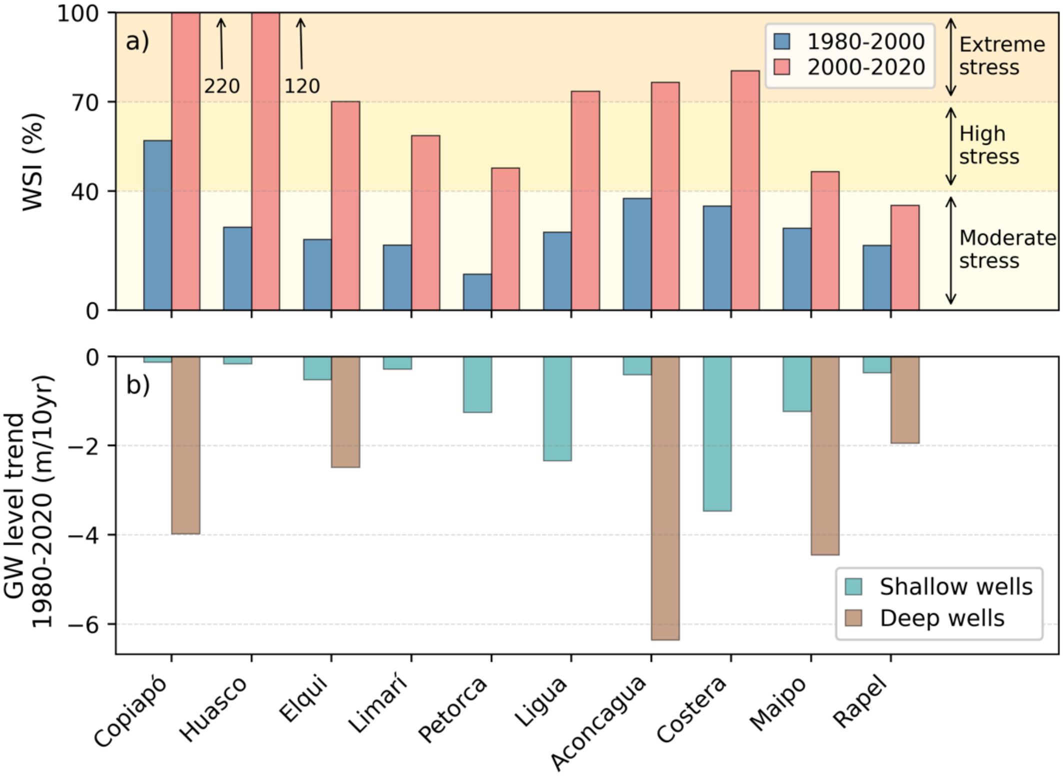

Figure 3: Panel a shows the WSI of ten major basins of central-north Chile, computed as water use to availability ratio for the periods 1980-2020 and 2000-2020. The basins are sorted from north to south. The two most arid ones (Copiapó and Huasco) have WSI values above the upper WSI limit, so their values are written beside the bars. The categories of water stress were obtained from Oki and Kanae. (2006). **Panel b shows the trend of GW levels of shallow and deep observations wells computed for the period 1980-2020.**

Before year 2000, all basins from Fig. 1, except for the most arid one (Copiapó), maintained a moderate level of water stress (Fig. 3a). However, during the 2000-2020 period, nine out of the ten basins shown in Fig. 1 moved towards a high or extreme water stress (Fig. 3a). The Rapel basin is the sole exception, maintaining a moderate stress level over the past two decades. This basin, as well as the Maipo basin, exhibit a Mediterranean-type climate and boast the largest water availability compared to the other eight basins (refer to Fig. A1). However, unlike the Maipo basin, the Rapel basin has a lower total water consumption, and its water supply relies less on GW sources, as indicated by the lower allocation of GW use rights in the basin. The large WSI values displayed in Fig. 3a align with the GW levels decline observed in these basins over the past few decades (Fig. 3b), and the growing trend in the allocation of water use rights from underground sources (Fig. A1). The GW declines in this region have been reported in previous studies (Pizarro et al., 2022; Valois et al., 2020; Duran-Llacer et al., 2020). Here, the most significant case is the mean reduction of up to 6 m/decade in the Aconcagua basin (Fig. 3b).

Despite the current water stress levels observed in Fig. 3a, the decreased water availability driven by the megadrought over the last decade has brought a relatively low direct cost to the Chilean economy (Fernández et al., 2023). This may be explained by the intense and widespread use of GW in the region, as well as the country's infrastructure capacity. When shifting from a national to a local scale, the direct impacts of declining GW levels become more evident. In particular, the necessity for deeper wells to reach the water table likely worsens social inequalities. In rural areas, where people rely on shallow pumping wells, the GW levels decline have led to interruptions in the water supply for basic needs and small-scale agriculture activities, as reported by previous studies in Petorca and Ligua basins (Duran-Llacer et al., 2020; Muñoz et al., 2020). This represents a D_0 condition for those communities.

Environmental impacts may also emerge well before reaching an absolute D_0 condition. Declining GW levels have the potential to directly impact the ecological integrity of groundwater-dependent ecosystems and may result in the disconnection between surface and underground water sources, which can lead to the drying out of rivers and lakes, as has been reported in the Ligua and Petorca (Duran-Llacer et al., 2022, 2020; Muñoz et al., 2020) basins and in the Maipo basin (Barría et al., 2021).

4 Caveats in water management

Water uses shown in Fig. 2 and Fig. A1 are within the legal limits (i.e., below the allocated water use rights), which indicates that the current water allocation scheme is failing to prevent water stress conditions, rather than being an issue of illegal overuse. To elaborate on this, we highlight some aspects outlined in the Water Code (Congreso Nacional de Chile, 2022), the regulatory framework for water management in Chile, that help us to understand the overallocation of water resources:

1. Since its amendment in 2005 (Congreso Nacional de Chile, 2005), the Water Code has stipulated that the allocation of surface water use rights must consider the protection of ecological flows. However, the streamflow value defined by the law is insufficient, as it sets an upper limit of 20% of the mean annual streamflow to be safeguarded as ecological flow. This implies total water usage exceeding 80% of the water availability (i.e., WSI > 80%), which is associated to an extreme water stress condition (Alvarez-Garreton et al., 2023b).
2. The allocation of GW use rights does not consider the interactions between the GW and surface systems, nor does it consider the pre-existing surface water use rights within a given basin.
3. Surface and underground water use rights are allocated as fixed absolute flows values and do not account for long-term, climate-driven changes in water availability.

https://doi.org/10.5194/hess-2023-245
Preprint. Discussion started: 19 October 2023

4. Before the last Water Code modification in 2022, water use rights were allocated in perpetuity. After 2022, new allocations may expire after 30 years only if the central authorities demonstrate they are not being used or are causing water scarcity problems (Congreso Nacional de Chile, 2022). This modification does not apply to water rights granted before 2022, which account for the majority of the water rights allocated in Chile.

The inadequate protection of ecological flows, the disconnected management of surface and GW resources, and the failure to account for long term and virtually irreversible climate change results in a tight balance between water uses and availability or a permanent overuse in a basin, which in turn could lead to unsustainable GW withdrawal. In addition to the risks discussed in sections 2 and 3, this situation represents an intergenerational justice dilemma since we might be using savings from previous generations and spending them in short-term economic activities whose benefits may not be perceived by next generations (Hiskes, 2009). Conversely, limiting the current generation's use of GW to sustainable levels, brings about costs for the present generation that cannot be easily offset by the benefits that this sustainable use would have in future—and potentially wealthier—generations (e.g., Andersen et al., 2020). The use of fossil water (i.e., resources that entered the aquifers centuries or millennia ago) would be an example of this dilemma. The quantification of fossil water in arid and semi-arid Chile has not been fully addressed. Still, there is evidence indicating that a part of GW reserves in several basins derive from late glacial climate conditions (Gayo et al., 2012; Moran et al., 2019; Viguier et al., 2018).

The water management limitations highlighted here promote water overuse, as the only "signal" that current users have (besides natural water scarcity by drought) is not the price of water extraction but rather the amount of water provided by their allocated water use rights. Despite the clear shortcomings of the water allocation system that make it prone to overallocation of water rights with respect to natural water availability, addressing these issues is far from straightforward. Segments of public opinion in Chile argue that revising already allocated water use rights, such as limiting their perpetuity condition or adjusting their allocated volumes considering current and future water availability, may introduce legal uncertainties that might harm the economy (Libertad y Desarrollo, 2019). The argument is that the owners of water use rights need to plan their investments and revenues based on certain water volumes. Indeed, like private property, the nature of water rights regulation allows owners to mortgage their water entitlements to obtain a loan from the bank (Muchnik et al., 1997). Regardless of the various perspectives on this matter, it is important to note that such legal certainty become physically unrealistic if the basin is not able to provide the amount of water stipulated by the allocated water use rights.

5 Final remarks

Accessing GW savings is crucial for addressing water scarcity, particularly during periods of drought. However, when water withdrawals are steadily greater than recharges, GW storage inevitably declines over time. The partial or total GW depletion has potential effects extending beyond generational time frames, concealing risks for water security that are often

https://doi.org/10.5194/hess-2023-245
Preprint. Discussion started: 19 October 2023

underestimated or disregarded. These risks are analogous to those that would exist if water uses relied on a melting glacier or a depleting surface reservoir, but unlike surface resources, designing strategies to prevent an absolute D_0 are challenging tasks due to the "hidden" nature of underground resources. Thus, research and monitoring efforts should focus on advancing our understanding of these systems. The road towards the absolute D_0 poses an intergenerational justice dilemma, while crossing several tipping points beyond which social, economic and environmental impacts may become irreversible (Castilla-Rho et al., 2017).

The capacity to access GW allows for tapping into large water volumes, often seen as an additional water source to the one available on the surface, but this volume is constrained by recharge rates. Given this constraint, water consumption rates that approach or exceed fresh water availability will not be sustainable in the long term, whether the access is underground, surface-based, or through reservoirs. To move towards a common perspective about the sustainable use of water resources, we recommend revisiting the definition of water availability to explicitly include the sustainable use of GW. It is crucial to cease regarding potentially non-renewable GW savings within generational timeframes as an additional water source. This likely implies a change in regulations and the adoption of a set of rewards and sanctions that maintain the system far from overuse tipping points (Castilla-Rho et al, 2017). Natural water reserves in aquifers or in the form of snow and glaciers, along with artificial savings in reservoirs, primarily contributes to water availability through temporal regulation. From an infrastructure perspective, there are other ways to increase water availability, such as water transfer between basins and desalination of seawater. These infrastructure solutions have socio-environmental benefits and costs that should be considered in their evaluation.

For the case of Chile discussed here, climate projections indicate that drought conditions such the one of the 2010s decade will be more frequent. With current extraction rates (a conservative scenario), GW levels will likely continue to decrease, causing socio-economic and environmental impacts, and bringing Santiago closer to an absolute but concealed D_0. The large uncertainty regarding D_0 estimates as those shown here (50 to 200 years) highlights the urgent need to improve the estimations of GW volume and recharge rates in central Chile and to account for its uncertainty in decision making. The aim of this opinion piece is not to fine-tune this calculation but to underscore that Chile should invest in advancing towards incorporating these principles in policy making. Also, we argue that, even before being able to tackle these challenges and forecast the arrival of an absolute D_0, the declining of GW levels will likely have impacts on society, local economy and environment well before reaching an absolute D_0, which calls for the implementation of measures to reach a sustainable use of water resources.

In addition to short-term strategies to secure water access, long-term water management plans should consider these risks in order to achieve water security goals. This includes revising the Water Code to address specific limitations, such as inadequate protection of ecological flows, the disconnection in managing surface and groundwater resources, and the failure to account for changing water availability over time in the water allocation scheme, all of which contribute to water scarcity and overuse.

Data availability

The CR2MET dataset were obtained from the Center for Climate and Resilience Research website at https://www.cr2.cl/datos-productos-grillados (last access: 20 September 2023). The water use data was obtained upon request from the Center for Climate and Resilience Research website at https://seguridadhidrica.cr2.cl (last access: 20 September 2023). The GW levels were data was obtained from DGA website https://snia.mop.gob.cl/BNAConsultas/reportes (last access: 20 January 2023). The water use rights were obtained from CAMELS-CL dataset (Alvarez-Garreton et al., 2018), available at the Center for Climate and Resilience Research website at https://camels.cr2.cl (last access: 20 September 2023).

Author contributions

CAG and JPB conceived the idea, perform the analyses and wrote an early draft of the manuscript. All the authors revised early manuscript drafts and wrote the final paper.

Competing interests

The contact author has declared that none of the authors has any competing interests.

Acknowledgements

This research has been developed within the framework of the Center for Climate and Resilience Research (CR2, ANID/FONDAP/1522A0001) and the research project ANID/FSEQ210001.

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Appendix A

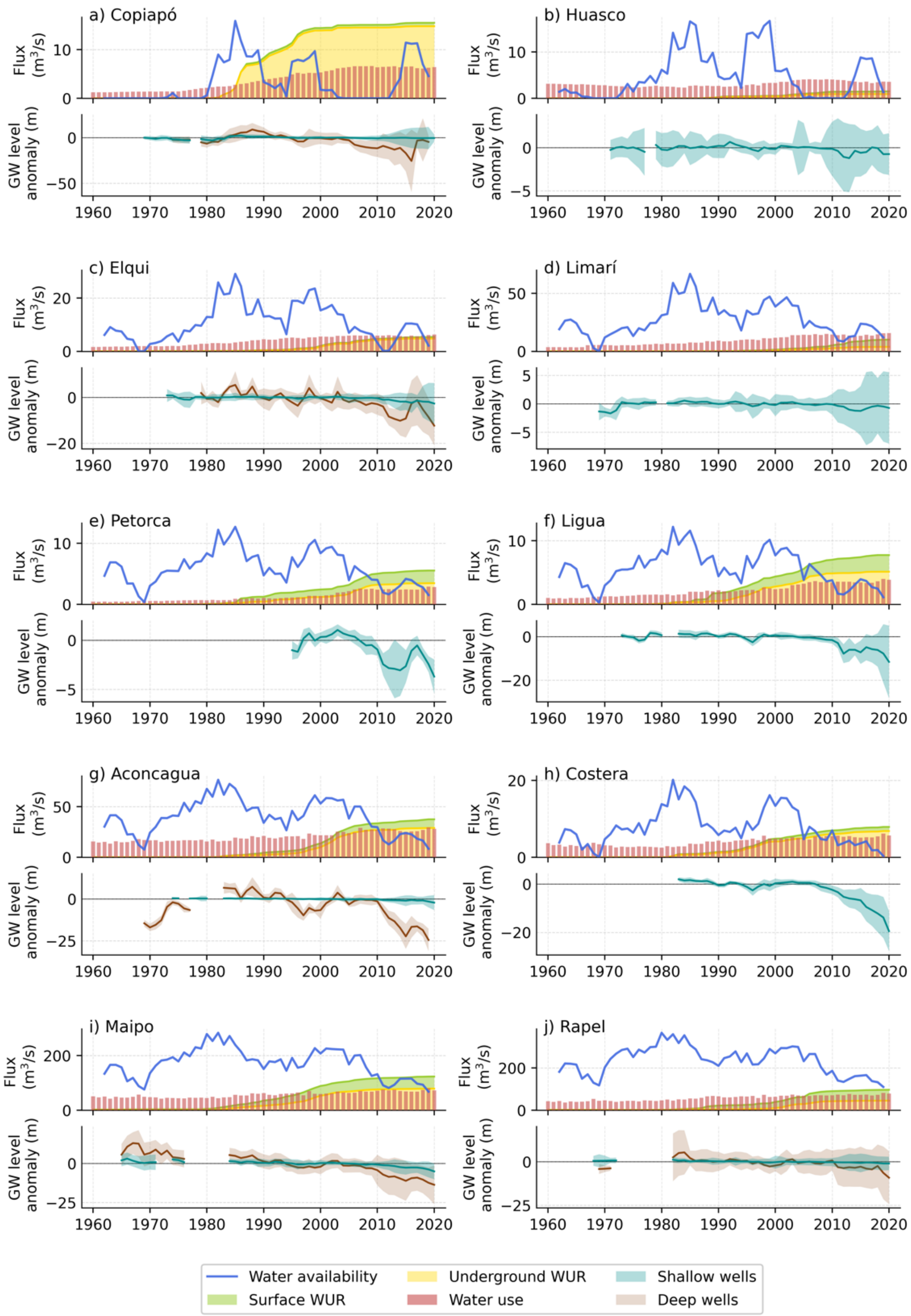
a) Copiapó
b) Huasco
c) Elqui
d) Limarí
e) Petorca
f) Ligua
g) Aconcagua
h) Costera
i) Maipo
j) Rapel
Flux (m^3/s)
GW level anomaly (m)
1960
1970
1980
1990
2000
2010
2020
Water availability
Surface WUR
Underground WUR
Water use
Shallow wells
Deep wells

Figure A1: Panel a) shows the time series of water availability, water uses and water use rights (WUR) for the ten major basins in central-northern Chile. The water availability is computed as the difference between catchment-scale precipitation and total evapotranspiration from non-anthropogenic land cover obtained from CR2MET product (Boisier, 2023)**. Surface and underground WUR were obtained from CAMELS-CL dataset** (Alvarez-Garreton et al., 2018)**. The water uses were obtained upon request from the CR2WU product available at https://seguridadhidrica.cr2.cl. Panel b) shows the GW level anomalies of the observation wells located in each basin, computed as the difference between GW levels and the mean level for the 1980-2010. The median (solid lines) and standard deviation (shaded area) of the GW level anomalies are plotted when at least five observations were available. Observation wells were classified as shallow and deep wells if their mean annual GW levels (shown in Fig. 1) were above or below 15 m, respectively. The GW observation data were obtained from the Water Directorate website https://snia.mop.gob.cl/BNAConsultas/reportes.**