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

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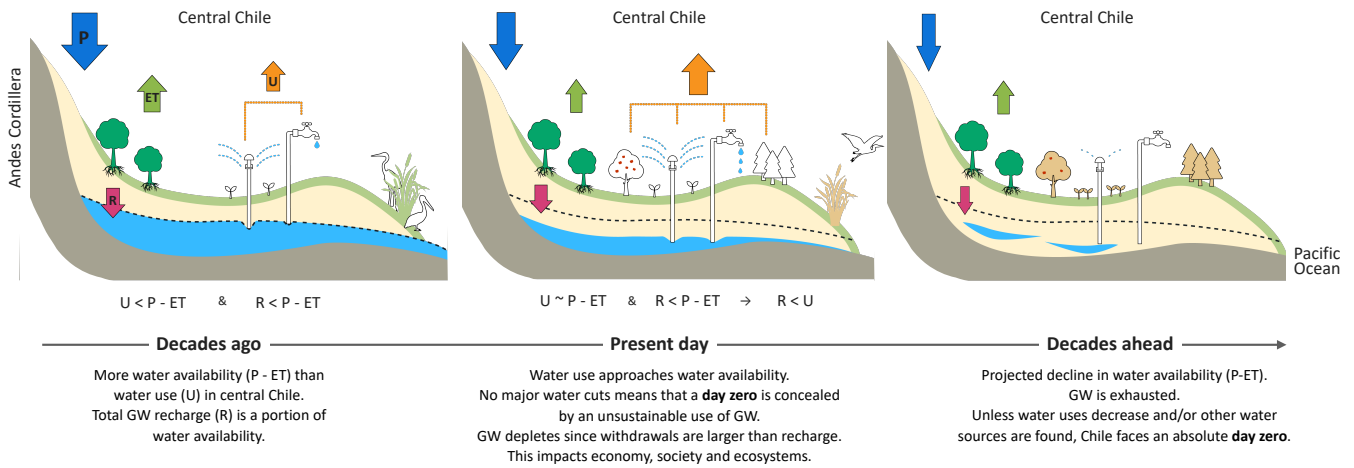
Abstract. Water scarcity is a pressing global issue driven by increasing water demands and changing climate conditions. Based on novel estimates of water availability and water use in Chile, we examine the challenges and risks associated with groundwater (GW) withdrawals in the country's central-north region (27−35ºS), where extreme water stress conditions prevail. As total water use 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 uncertain attributes 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

26   The risk of water scarcity in a basin increases as the water demand approaches the available renewable freshwater resources,
27   hereafter referred to as water availability. Water availability at the basin scale is represented by the difference between total
28   precipitation and natural evapotranspiration (ET), excluding land use-induced perturbations. When the ratio of total water uses
29   to water availability –the water stress index (WSI)– exceeds 40%, a basin is considered as highly water stressed (Oki and
30   Kanae, 2006). In extreme cases, when the time series of water availability and total water demands within a basin intersect or
31   get too close to each other (i.e., WSI = 100%), a "Day Zero" (D_0) may occur. During a D_0 event, water cuts are applied to
32   prioritize water access for human consumption and the ecological flows to maintain the well-being of ecosystems cannot be
33   safeguarded. The concept of D_0 has faced criticism from the scientific community (Warner and Meissner, 2021), attributing it
34   with a sensationalist use and lack of scientific robustness, among other concerns. Nevertheless, it generates a sense of urgency
35   that puts pressure on decision-makers to take actions.

36   A well-known D_0 event almost happened in 2018 in South Africa in the context of a severe multi-year drought, when Cape
37   Town was at risk of being the first major city worldwide to run out of drinking water due to the low dam levels. The
38   announcement of an imminent D_0 on a specific date (12 April 2018, estimated based on the remaining water stored in the
39   reservoir and the water use requirements from the city) triggered water saving strategies that –along with the arrival of winter
40   precipitation interrupting the drought– allowed the city to avoid drastic water cuts (Maxmen, 2018; Burls et al., 2019). Another
41   near D_0 situation occurred in July 2023 in Montevideo, capital of Uruguay. Due to low water reserves in the main reservoirs
42   that provide drinking water to the city, the supply was replaced with brackish water from Rio de la Plata. As a consequence,
43   the metropolitan area of Uruguay received non-drinkable water from their taps. Public opinion criticized this measure, claiming
44   it masked a D_0 situation by avoiding supply cuts at the expense of providing non-potable water (Gudynas, 2023).

45 Besides some well-known cases in metropolitan areas (Ahmadi et al., 2020), many basins around the globe are approaching

46 or have already reached the point where water uses intersects with or surpasses water availability, especially in water-limited

47 regions with intensive irrigation (Oki and Kanae, 2006). In those cases, water needs are usually met by exploiting groundwater

48 (GW) reservoirs at rates that exceed natural recharge, which is unsustainable in the long term (de Graaf et al., 2019). Indeed,

49 many societies have supported agricultural and population growth by pumping GW storage (Bierkens and Wada, 2019).

50 An increasing number of studies are raising the alarm on the unsustainable use of GW worldwide, highlighting potential threats

51 to water security and food security (e.g., Gleeson et al., 2016; Schwartz et al., 2020). These studies recognize that accessing

52 GW savings is crucial for addressing water scarcity, especially during droughts. However, depending on GW saving becomes

53 risky when over-extraction renders it a scarce or depleted resource. Although assessing the limits beyond which GW extraction

54 becomes unsustainable remains an ongoing research and technical challenge, we know that pumping rates exceeding the

55 natural GW recharge leads to long-term decline in reserves beyond those expected from climate variability (Bierkens and

56 Wada, 2019). From that perspective, the evidence of a long-term decline in water table can be used to infer or anticipate an

57 unsustainable GW use in a basin.

58 Here, we build upon the above evidence and emphasize that a D_0 scenario –which typically triggers alarms and immediate

59 management responses when is associated to surface reservoir depletions– may be concealed by an unsustainable use of GW.

60 To illustrate this, we focus on the central-north region of Chile, where GW overexploitation and its potential consequences

61 have recently been reported by Taucare et al. (2024) and Jódar et al. (2023). By following different approaches, those studies

62 assessed the effects of climate variability and GW withdrawals on GW level changes over the last four decades (1979-2020),

63 and drew similar conclusions regarding the dominant role of water withdrawals in GW declines. Water withdrawals in those

64 studies were computed based on allocated water use rights –the legal entitlements that allow users to extract water–, which is

65 a common approach adopted in water resources assessment studies in Chile due to the lack of actual water use estimates. A

66 caveat of this approach is that it may introduce large uncertainties as water use rights do not necessarily represent actual water

67 uses but rather the fixed monthly or annual flows that are legally permitted for use (see Sect. 5).

68 Our study complements these recent findings by making use of novel estimates of water use and availability developed by the

69 Center for Climate and Resilience Research (Alvarez-Garreton et al., 2023b), covering a large period (1960-2020). We reflect

70 on how the unsustainable GW use carries risks usually unforeseen or neglected, even before a D_0 is reached, and discuss how

71 this poses an intergenerational justice dilemma. Finally, we identify key water management limitations, from general

72 perceptions of GW to specific management instruments, that should be addressed to mitigate the impacts of GW

73 overexploitation. While the argument is framed using Chile as a case study, the approach and conclusions can be applied to

74 any region experiencing significant water stress and unsustainable GW usage.

2 A novel dataset to illustrate the case of Chile

The data products used here were developed by the Center for Climate and Resilience Research (Alvarez-Garreton et al., 2023b) to evaluate the long-term evolution of water availability, land use and water use across continental Chile, and are available for exploration at www.seguridadhidrica.cr2.cl. Time series of water availability were computed for each basin in Chile as the difference between catchment-scale annual precipitation and near-natural ET. Precipitation comes from the CR2MET meteorological dataset, which provides daily time series in a regular $1/20°$ grid ($\sim$ 5-km) for the period 1960-2020 (Boisier, 2023). The near natural ET, with the same temporal and spatial resolutions, is estimated from a simple 'bucket' water balance model. This model is driven by CR2MET meteorological inputs and a static land cover representative of the year 1950, assuming no irrigation. The model includes parameters related to the soil water holding capacity, root depth, canopy rainfall interception, maximum ratio of actual to potential evapotranspiration (akin to crop coefficients), and phenological cycle (leaf area index) across 61 natural and anthropic land cover classes.

The water use dataset provides annual time series for the period 1960-2020 of consumptive and non-consumptive sectorial water uses. For the LULUCF sector (Land Use, Land Use Change and Forestry), water uses were computed over the same grid and ET model previously described, but taking into account the changes in land cover and irrigation practices over the study period. Water consumption from industrial sectors and drinking water were estimated at the level of communal units, considering specific drivers (e.g., population, energy, or mining production) and water use coefficients, following a methodology similar to DGA (2017). Some of the key novelties of this product is that it is based on actual socioeconomic activities, including the evolution of LULUCF, industrial production and population, and that land use-related water consumption estimates are consistent with the climate data. It is important to note that these water use estimates are independent from the allocated water use rights, thereby addressing an important information gap in Chile and enabling a proper contrast of climate variability, water availability, and water uses. This, in turn, facilitates the assessment of the historical evolution of water stress and groundwater overexploitation, including an examination of its causes and consequences.

The variations in GW levels are obtained from the observation wells network maintained by the Water Directorate, which is publicly accessible from https://snia.mop.gob.cl/BNAConsultas/reportes.

To illustrate the relationship between water uses, water availability (with their corresponding WSI) and a concealed D_0 situation, we focus on 10 major basins in the central-north region of Chile (Fig. 1), where a number of water conflicts have been experienced due to rising demand and reduced water availability related to climate variability (e.g., Barría et al., 2021b; Muñoz et al., 2020), and where GW overexploitation has been recently reported (Taucare et al., 2024; Duran-Llacer et al., 2020; Jódar et al., 2023). We first discuss the case of the Maipo basin, which encompasses the extensive metropolitan area of

104 Santiago, and subsequently expand to the broader region of central-north Chile to illustrate the argument from a wider
105 perspective.

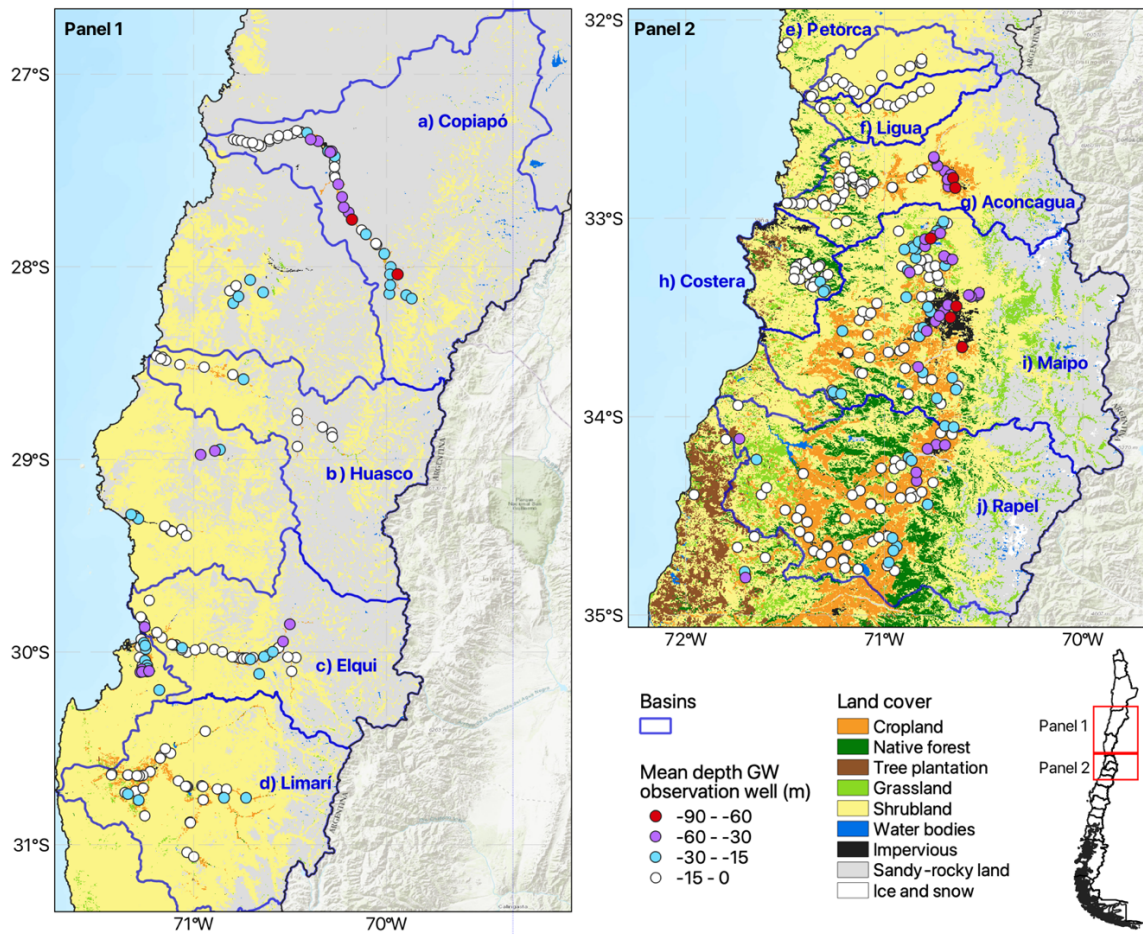



Figure 1: Location of the 10 major basins in central-north Chile. The land cover corresponds to (Zhao et al., 2016)**. The maps show the GW observations wells that have at least 10 years of observations since 1960. Each observation well is colored by their mean depth computed for their complete period of record. 3 A concealed "Day Zero" scenario in Santiago**

111 The metropolitan area of Santiago, located in the Maipo River basin in central Chile (Fig. 1), houses nearly six million
112 inhabitants (30% of the Chilean population). According to the water use dataset (Sect. 2), the Maipo basin's current total water
113 consumption is approximately 75 m³ s⁻¹, representing 15% of Chile's total consumptive water use. About 60% of the basin's
114 water consumption is attributed to the agricultural sector, while 35% is allocated for sanitation and drinking water.

115 Since the mid-20th century, total water use has continuously increased and, in the last decade, has approached water availability

116 in the Maipo basin (Fig. 2). These extreme water stress conditions (WSI close to 100%) emerge in the context of a protracted

117 drought spanning more than a decade since 2010, with precipitation deficits ranging between 20 to 70% (Garreaud et al., 2019,

118 2017). The so-called megadrought in central Chile is partially controlled by natural climate variability, but also weighted by a

119 long-term drying trend affecting the subtropical South Pacific region (Boisier et al., 2016, 2018). This trend, as an

120 anthropogenic climate change signal, is expected to persist in the coming decades, in line with global climate projections

121 (IPCC, 2022).

122 Yet, the causes of the extreme water stress in the Maipo basin are not solely attributable to climate variability and droughts.

123 The water demand, driven by the expansion of irrigated agriculture, has been maintained or even increased in central Chile

124 over recent decades, despite the diminishing water availability. To a large extent, water use in this region has been sustained

125 at the expense of GW resources, as indicated by the increasing allocation of water use rights for GW withdrawals (Fig. 2a).

126 Larger GW extractions and lower recharge rates are further evidenced by the ongoing depletion of GW levels (Fig. 2b).

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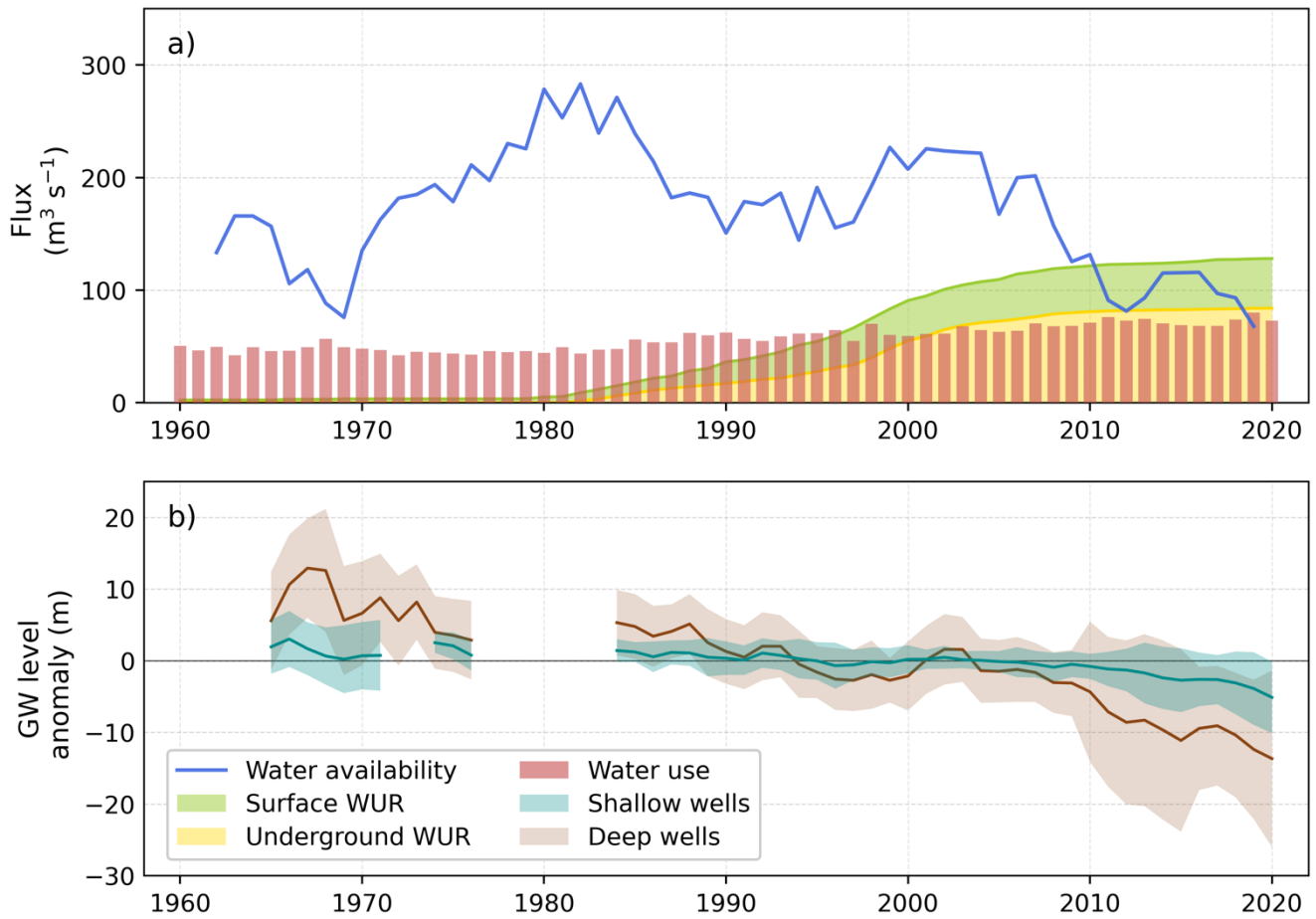
Figure 2: Panel a) shows the time series of water availability, water uses and water use rights (WUR) for the Maipo basin. Surface and underground WUR were obtained from CAMELS-CL dataset (Alvarez-Garreton et al., 2018)**. Panel b) shows the GW level anomalies of 89 observation wells located in the Maipo basin, computed as the difference between GW levels and the mean level for the 1980-2010 (baseline adopted to avoid including the megadrought period). The median (solid lines) and standard deviation (shaded area) of the GW level anomalies are plotted when at least five observations were available. Following well construction guidelines** (INDAP, 2010)**, observation wells were classified as shallow or deep wells if their mean annual GW levels (shown in Fig. 1) were above or below 15 m, respectively.**

135 Unlike estimating the time until a surface reservoir runs out, such as in the Cape Town and Montevideo cases, there is
136 significant uncertainty in estimating when a GW reserve will be exhausted or reduced to a state that is unrecoverable within
137 human time frames, leading to an absolute D_0 scenario. Determining that time frame requires a precise quantification of the
138 water volume remaining in aquifers, GW recharges, and GW extraction rates. However, a tentative estimate of the absolute D_0
139 can be derived as:

140 Eq. 1 $\qquad D_o = \frac{W}{U_{GW} - R_N},$

141 where W represents the water volume of the saturated aquifer, U_{GW} the groundwater extraction rate, and R_N the net GW recharge
142 rate (water recharges minus springs). Previous studies have estimated a volume of water of about 30 km^3 for the main aquifer
143 in the Maipo basin (Araneda et al., 2010; DGA, 2021) with net GW recharge rates (including springs) in the range of 10 to 20
144 m^3 s^{-1} (Döll and Fiedler, 2008; Riffo, 2022). If we consider present water uses of 75 m^3 s^{-1} and a ratio of underground to total
145 water uses ranging between 35 to 65% (upper bound corresponds to the ratio of GW to total water use rights in the Maipo
146 basin, Fig. 2), the absolute D_0 time frame would range between 50 to 200 years, depending on the values considered for
147 recharge and GW to total water use ratio.

148 These are rough estimates computed from variables that are challenging to accurately estimate and monitor, making it difficult
149 to assess the risk of overconsumption. However, they provide an order of magnitude of several decades to a few centuries to
150 deplete the GW sources in the Maipo basin and reaching an absolute D_0 in the capital of Chile. In contrast to the short time
151 frames associated to a D_0 caused by depleted surface reservoirs in some major cities (e.g., Cape Town, Montevideo), several
152 decades may seem like plenty of time to prepare for an absolute D_0 in Chile. However, such absolute D_0 is far more critical
153 than running out of surface reserves since GW reservoirs may take a much longer time to recover.

154 This situation poses an intergenerational justice dilemma as we are depleting the water savings of previous generations and
155 spending them in short-term economic activities whose benefits may not be perceived by future generations (Hiskes, 2009).
156 Conversely, limiting the current generation's use of GW to sustainable levels entails costs for today's society that cannot be
157 easily offset by the benefits that this sustainable use would have in future –and potentially wealthier– generations (e.g.,
158 Andersen et al., 2020).

159 The use of fossil water (i.e., resources that entered the aquifers centuries or millennia ago) would be a paragon example of this
160 intergenerational dilemma. The quantification of fossil water in arid and semi-arid Chile has not been fully addressed. Still,
161 there is evidence indicating that a part of GW reserves in several basins derive from late glacial climate conditions (Gayo et
162 al., 2012; Moran et al., 2019; Viguier et al., 2018). Available evidence from a headwater section of the Maipo basin (Mapocho
163 basin) have reported deep wells (water table below 112 m depth) characterized by low tritium concentrations (<0.8) and ^{14}C
164 contents (70 pmc), indicating that such resources were likely recharged about 3,000 years ago (Iriarte et al., 2009). These GW
165 age tracers indicate that GW with modern and old fractions could also occur in the downstream area of the Maipo basin.

166 In Santiago, a recent adaptive measure taken by governmental and water supply agencies to address water scarcity has been
167 the construction of deep pumping wells (reaching up to 300 m depth) to supply drinking water for human consumption. While
168 this measure is timely in the short term, helping to mitigate the risks of supply shortages in a highly populated region, it also
169 promotes the use of GW sources that might be, at best, very difficult to recover within human timescales. This, in turn, will
170 likely exacerbate GW depletion.

4 The non-sustainable GW use in central-north Chile

Like the Maipo basin, consumptive water uses in most basins located in central-north Chile (27-35°S, Fig. 1) are nearing or exceeding 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 use 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 precipitation and GW recharge. Current climate models project a reduction Click or tap here to enter text.of 10 to 30% in annual precipitation by the end of the 21st century under high (SSP1-RCP2.6) and low (SSP3-RCP7.0) greenhouse gas emission mitigation scenarios, respectively (Alvarez-Garreton et al., 2023b; IPCC, 2022). At the same time, water use will likely increase with population and economic growth (Meza et al., 2014).
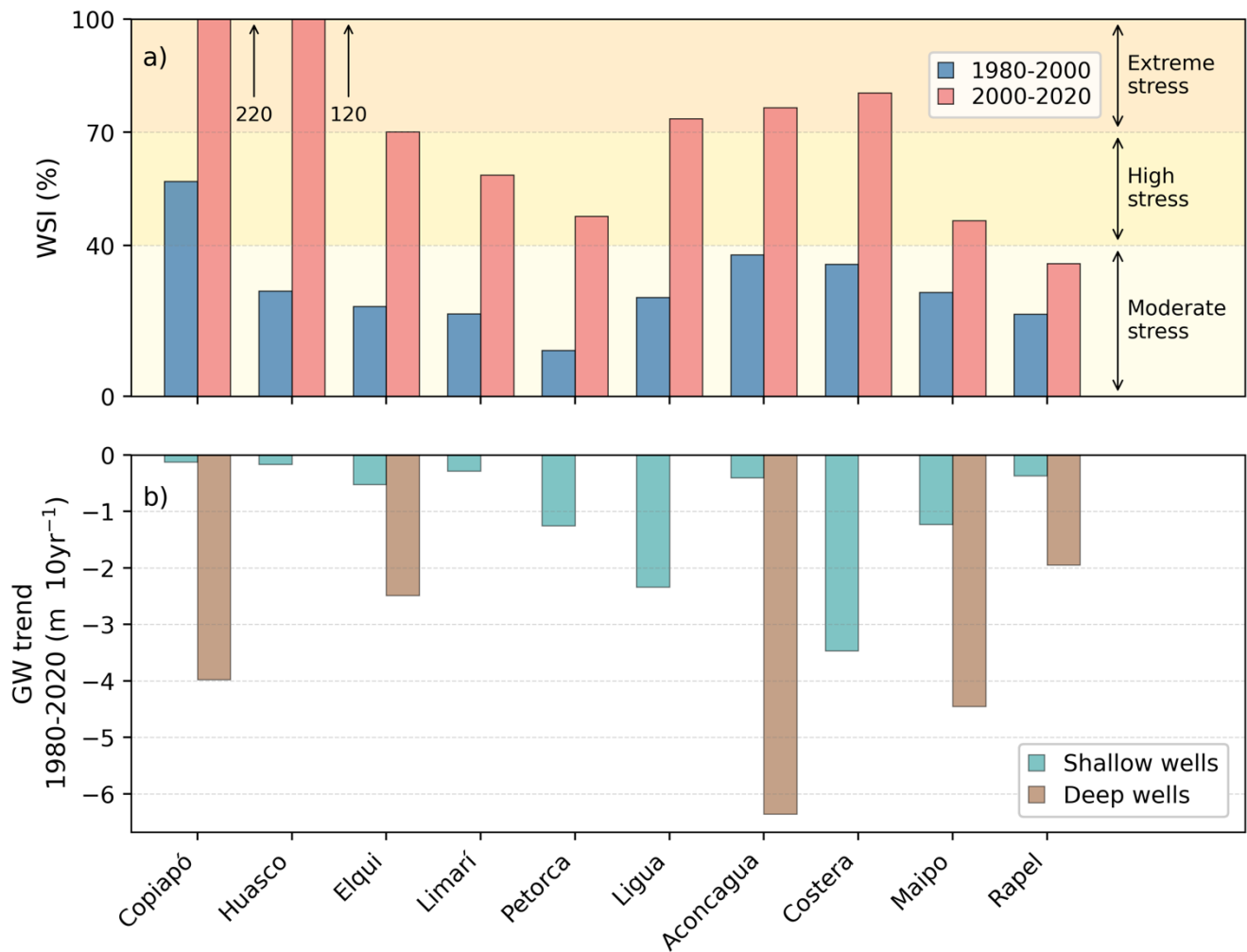
Figure 3: Panel a) shows the WSI of ten major basins of central-north Chile, computed as water use to availability ratio for the periods 1980-2020 and 2000-2020. The basins are sorted from north to south. The two most arid ones (Copiapó and Huasco) have WSI values above the upper WSI limit, so their 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.

Except for the most arid basin (Copiapó), all basins in central-north Chile maintained a moderate level of water stress during the 1980-2000 period (Fig. 3a). However, during the 2000-2020 period, 9 out of the 10 basins 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 has the largest water availability compared to the other eight basins (Fig. A1), which allows for sustaining large water uses (similar to those of the Maipo basin) at lower water stress levels. Furthermore, the water supply in the Rapel basin

193 relies less on GW sources, as indicated by the lower allocation of GW use rights in the basin, which would also explain its
194 lower GW declines in Fig. 3b.

195 For the rest of the basins, the large WSI values displayed in Fig. 3a align with the GW declines observed over the past four
196 decades (Fig. 3b), and the growing trend in the allocation of water use rights from GW sources (Fig. A1). The GW declines in
197 this region have been reported in previous studies (Pizarro et al., 2022; Valois et al., 2020; Duran-Llacer et al., 2020; Jódar et
198 al., 2023; Taucare et al., 2024). Within the study area, the most significant case is the mean reduction of up to 6 m per decade
199 in the Aconcagua basin (Fig. 3b).

200 Despite the current water stress levels observed in Fig. 3a, the decreased water availability driven by the megadrought over
201 the last decade has brought a relatively low direct cost to the Chilean economy (Fernández et al., 2023). This could be partly
202 explained by the extensive use of GW in the region and the country's robust infrastructure. However, when shifting from a
203 national to a local scale, the direct impacts of declining GW levels become more evident. For example, the need for deeper
204 wells to reach the water table has intensified social inequalities, particularly in rural areas where reliance on shallow pumping
205 wells is common. Here, the GW levels decline has led to interruptions in the water supply for basic needs and small-scale
206 agriculture activities, as reported by previous studies in Petorca and Ligua basins (Duran-Llacer et al., 2020; Muñoz et al.,
207 2020). Although this does not involve water cuts in a megacity, it represents a D_0 condition for those communities.

208 Furthermore, environmental impacts may also emerge well before reaching an absolute D_0 condition. Declining GW levels
209 have the potential to directly impact the ecological integrity of groundwater-dependent ecosystems and may cause a
210 disconnection between surface and GW sources (Jódar et al., 2023), potentially leading to the desiccation of rivers, wetlands
211 and lakes. This has been observed in the Ligua and Petorca (Duran-Llacer et al., 2022, 2020; Muñoz et al., 2020) as well as in
212 the Maipo basin (Barría et al., 2021b).

213 **5 Caveats in water management**

214 Water management in Chile is primarily regulated by the Water Code, promulgated in 1981, with several amendments since
215 then (Congreso Nacional de Chile, 1981, 2022, 2005). This Code defines water as a national asset for public use and regulates
216 its allocation by means of water use rights, which are legal entitlements specifying the quantity and timing of water that can
217 be used by private and public users. While these titles are granted free of charge by the State, once allocated, they represent
218 property assets that can be traded by their owners, with no water market regulations to their buying and selling transactions.
219 Further details regarding the water management system can be found in Alvarez-Garreton et al. (2023a), Taucare et al. (2024),
220 Barría et al. (2021a) and Alvez et al. (2020).

221 The estimates of total water use at present time shown in Fig. 2 and Fig. A1 indicate that, for most of the study basins water
222 uses are within the legal limits –i.e., they do not exceed the allocated water use rights. However, this evidence aggregated at
223 the catchment scale does not imply the absence of illegal water uses within the basins. In fact, previous studies have reported
224 unauthorized GW extraction in basins in central Chile, such as Maipo (Venegas-Quiñones, 2022), Petorca (Muñoz et al., 2020)
225 and La Ligua (Budds, 2008).

226 While no disregarding the potential occurrence of unauthorized water withdrawals at specific locations, our findings point out
227 that the problem at the basin scale is not due to illegal overuse, but rather to the current water allocation scheme being
228 inadequate to prevent water stress conditions. To elaborate on this, we highlight some aspects outlined in the Water Code that
229 help us to understand the causes of the current overallocation of water resources:

230   1. Since its amendment in 2005 (Congreso Nacional de Chile, 2005), the Water Code stipulates that the allocation of
231   surface water use rights must consider the protection of ecological flows. Nonetheless, the specified safeguarded flow,
232   set at a maximum of 20% of the mean annual streamflow, is not sufficient. This implies total water usage exceeding
233   80% of the water availability (i.e., WSI > 80%), which is associated to an extreme water stress condition (Alvarez-
234   Garreton et al., 2023a).
235   2. The allocation of GW use rights does not consider the interactions between the GW and surface systems, nor does it
236   consider the pre-existing surface water use rights within a given basin.
237   3. Surface and GW use rights are allocated as fixed absolute flows values and do not account for long-term, climate-
238   driven changes in water availability (Barría et al., 2021a).
239   4. Before the last Water Code modification in 2022, water use rights were allocated in perpetuity. After 2022, new
240   allocations may expire after 30 years only if the central authorities demonstrate they are not being used or are causing
241   water scarcity problems (Congreso Nacional de Chile, 2022). This modification does not apply to water rights granted
242   before 2022, which account for most of the water rights allocated in Chile.

243 The above dispositions of the Water Code entail an inadequate protection of ecological flows, a disconnected management of
244 surface and GW resources, and the failure to account for long term climate change. This allows for a tight balance between
245 water uses and availability that can become a structural condition of overuse in a basin. In combination to the drier climatic
246 conditions experienced in central-north Chile over the last decade, these water management caveats have led to unsustainable
247 GW withdrawals (Jódar et al., 2023; Taucare et al., 2024).

248 These water management limitations promote water overuse, as the main "signal" that current users have (besides natural
249 water scarcity by drought) is not the price of water extraction (owners of water use rights do not pay for water) but rather the
250 amount of water provided by the water use rights they own. Despite the evident shortcomings, addressing these issues is far

251 from straightforward. Segments of public opinion in Chile argue that revising already allocated water use rights, such as
252 limiting their perpetuity condition or adjusting their allocated volumes considering current and future water availability, may
253 introduce legal uncertainties that might harm the economy (Libertad y Desarrollo, 2019). The argument is that the owners of
254 water use rights need to plan their investments and revenues based on certain water volumes. Indeed, like private property, the
255 nature of water rights regulation allows owners to mortgage their water entitlements to obtain a loan from the bank (Muchnik
256 et al., 1997). Regardless of the various perspectives on this matter, it is important to note that such legal certainty become
257 physically unrealistic if the basin is not able to provide the amount of water stipulated by the allocated water use rights.

258 6 Water management recommendations

259 Climate projections for central Chile suggest that droughts such the one of the 2010 decade will become more frequent. With
260 current extraction rates (a conservative scenario), GW levels will likely continue to decrease, causing socio-economic and
261 environmental impacts, and bringing a major urban area such as Santiago closer to an absolute D_0. The large uncertainty
262 regarding D_0 estimates as those shown here (50 to 200 years) highlights the urgent need to improve the estimations of GW
263 volume and recharge rates and to account for its uncertainty in decision making.

264 Furthermore, long-term water management plans should consider the risks of GW overexploitation in order to achieve
265 sustainable development goals and water security. This involves revisiting the Water Code to address specific limitations, such
266 as those highlighted here. In particular, we recommend to consider the following recommendations:

267 - To update the formulae used to compute ecological flows and remove the upper threshold of 20% of mean annual
268   streamflow.
269 - To integrate the allocation of surface and GW use rights in such a way that the total flow granted within a basin does
270   not exceed the water uses associated to an extreme water stress level (i.e., WSI < 70%), while accounting for the
271   decreased precipitation expected for Chile.

272 7 Conclusions

273 This paper argues that access to GW savings is crucial for coping with water scarcity, particularly during droughts. However,
274 when water withdrawals are steadily greater than recharges, GW storage inevitably declines over time. The partial or complete
275 depletion of GW has present-day detrimental impacts on society and environment, plus potential negative effects that extend
276 beyond the time frame of this generation, concealing risks for water security that are often underestimated or disregarded.
277 These risks are analogous to those that would exist if water uses relied on a melting glacier or a depleting surface reservoir.
278 However, unlike surface resources, designing strategies to prevent an absolute D_0 is a challenging task due to the "hidden"

279 nature of GW resources. The road towards the absolute D_0 poses an intergenerational justice dilemma, while crossing several
280 tipping points beyond which social, economic and environmental impacts may become irreversible (Gleeson et al., 2020).

281 The capacity to access GW allows for tapping into large water volumes, often seen as an additional water source to the one
282 available on the surface, but the maintenance of GW savings is reliant on recharge rates from the surface. Given this constraint,
283 water consumption rates that approach or exceed fresh water availability will not be sustainable in the long term, whether the
284 access is from GW, rivers, channels or reservoirs.

285 To move towards a common perspective about the sustainable use of water resources, we recommend revisiting the definition
286 of water availability to explicitly include the sustainable use of GW. It is crucial to stop considering GW savings –which may
287 not be renewable within time frames of the generation that benefits from its use– as an additional and unlimited source of
288 water. This likely implies a change in regulations and the adoption of a set of rewards and sanctions that maintain the system
289 far from overuse tipping points (Castilla-Rho et al, 2017).

290 Natural water reserves in aquifers or in the form of snow and glaciers, along with artificial savings in reservoirs, primarily
291 contributes to water availability through temporal regulation. From an infrastructure perspective, increasing water availability
292 can also be achieved though water transfer between basins and desalination of seawater, both of which have socio-
293 environmental benefits and costs that should be considered in their evaluation.

294 The sustained declines of GW reported here, as well as those reported in several regions worldwide (de Graaf et al., 2019),
295 represent a critical situation that should trigger effective responses, just as they are triggered when the decline of a surface
296 reservoir indicates the arrival of a D_0.

297 **Data availability**

298 The water use and availability data was obtained upon request from the Center for Climate and Resilience Research website
299 at https://seguridadhidrica.cr2.cl (last access: 20 September 2023). The GW levels data were obtained from DGA website
300 https://snia.mop.gob.cl/BNAConsultas/reportes (last access: 20 January 2023). The water use rights were obtained from
301 CAMELS-CL dataset (Alvarez-Garreton et al., 2018), available at the Center for Climate and Resilience Research website at
302 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.

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Appendix A
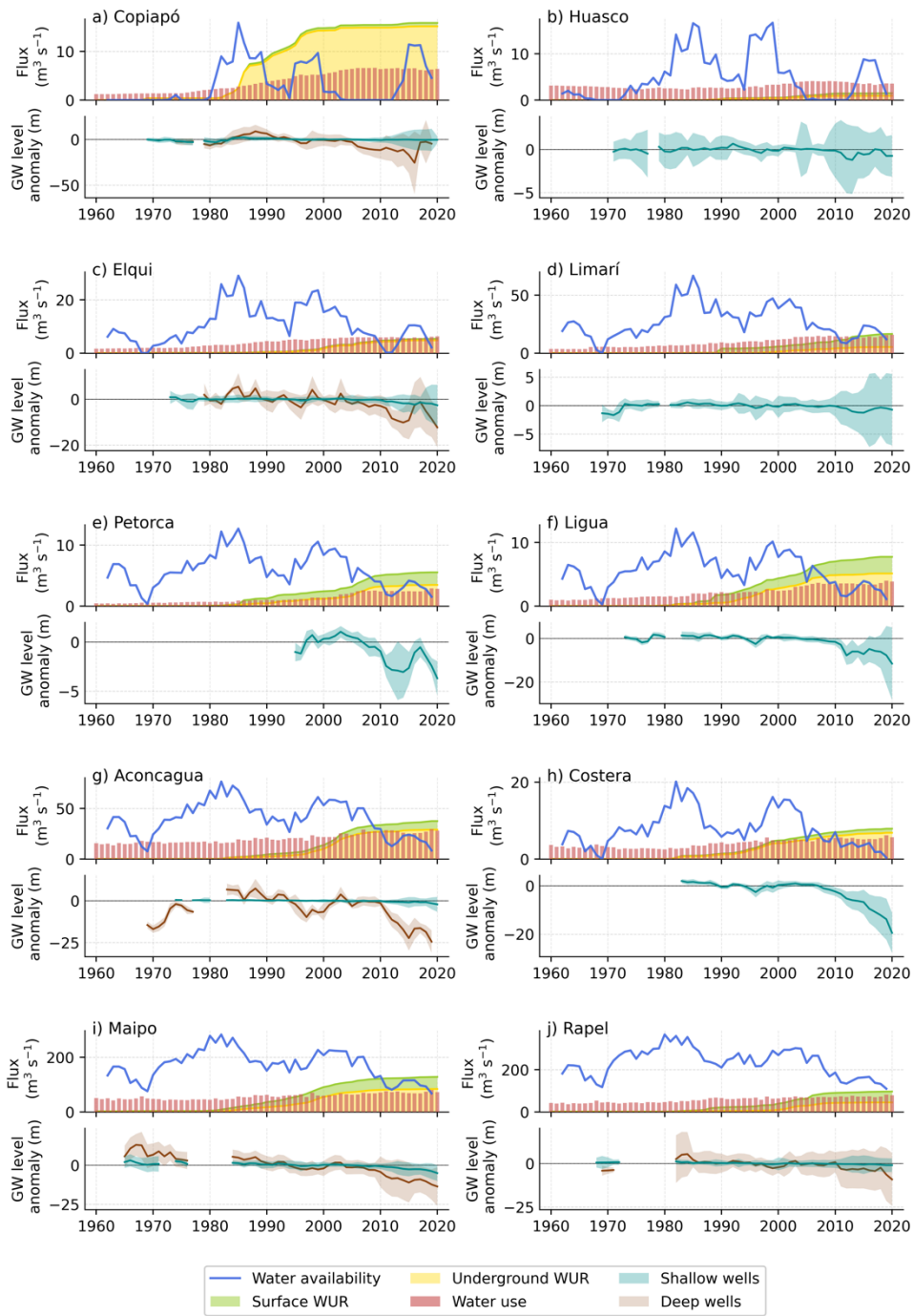
Figure A1: Panel a) shows the time series of water availability, water uses and water use rights (WUR) for the 10 major basins in central-north Chile. The water availability is computed as the difference between catchment-scale precipitation and total evapotranspiration from non-anthropogenic land cover 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. Following well construction guidelines** (INDAP, 2010)**, 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.**