Response letter:

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

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(RC1) Referee 1:

The paper points out increasing conflicts between water demand and water availability (with "Day Zero" as the most extreme case) in regions facing water scarcity. This triggers extensive ground water (GW) extraction, to some extent, unsustainably. The authors choose central-north Chile as a testbed to unveil the phenomena, i.e., increasing water stress and unsustainable GW use. The authors also highlight the inadequate water management strategy and policies and give their recommendations.

The findings are practically important, but lack of scientific significance. The caveats in water management sections read informative and structured. However, the introduction is not organized in a balanced way and the conclusions are not well structured. See below for details:

R: We thank the reviewer for the recommendations to improve our manuscript, which is intended to be published as an "opinion article" -aimed at discussing a topical aspect- instead of a traditional research article. Please see below our responses to each of your comments.

Major comments:

RC1-1: The word "conceal" in the title and throughout the manuscript is confusing. I can not understand the meaning and the reasoning behind.

R: The word conceal refers to *"prevent something from being seen or known about" (Cambridge dictionary)*. We adopted this term to make the point that the unsustainable use of groundwater (GW) hides (or conceals) the fact that we are overusing renewable freshwater resources, which in turn obscure an alarming trajectory towards a day zero. By contrast, when only surface resources are available (e.g., dams), the time to reach a day zero is more clearly revealed and quantifiable.

RC1-2: The scientific significance needs to be well sharpened. I can not find out substantial new concepts or methods. In L15, the authors claim they based on "novel" estimates. However, I can not tell what the novel estimates are? Why they are novel? What problems previous studies have? The introduction is not in a balanced way, The author talk about the water scarcity condition with some local examples, GW extraction and consequences (with no details), and then skip to what this study do. No mention about current gaps or inconsistencies in the field.

R: Before answering this comment, we would like to recall that opinion articles should "*discuss a topical aspect of hydrology. These articles are not peer reviewed in the traditional sense, but they are discussed openly in HESSD so as to stimulate an open debate among peers on new ideas, views, or perceptions in hydrology. Opinion articles will be published under the heading "HESS Opinions" and are handled by the executive editors. Opinion articles are generally invited, but authors with ideas for an opinion paper are encouraged to contact one of the executive editors." (https://www.hydrology-and-earth-system-sciences.net/about/manuscript_types.html)*

Following these guidelines, we contacted a HESS editor before initial submission and received the approval to submit an opinion article showcasing how renewable freshwater is being overused at the expense of unsustainable withdrawals of GW and providing a view point of some of its causes and consequences. We differentiated the text from a traditional research article, in which research gaps are identified, hypotheses and research questions are elaborated based on the gaps, and a sound methodology is described and applied to address them.

Over the last three years, we have developed data products regarding water uses and availability that allows, for the first time, to make a consistent historical assessment of water stress conditions in Chile. These new data products are available at www.seguridadhidrica.cr2.cl. Our opinion piece aims at showing this evidence and highlighting an urgent message regarding the potential consequences of keep overusing renewable freshwater resources.

Having said that, we understand the comments made by the Reviewer and we addressed them by adding a new section where we explain the case study used to illustrate the argument proposed in the article. We moved some parts of the introduction to this section, which makes the reading clearer and more structured.

New Section 2 The dataset to illustrate the argument

Our argument is that when total water uses approach or surpass surface water availability within a basin, a D_0 scenario may be concealed by the overexploitation of GW. To illustrate this, we adopt Chile as a case study. In particular, we focus on the central-northern 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 change (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). 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.

We make use of novel water use and availability data products recently developed by the Center for Climate and Resilience Research (Alvarez-Garreton et al., 2023b). These datasets include the CR2MET product, containing daily time series of 5-km gridded precipitation (Boisier, 2023) and natural evapotranspiration (derived from undisturbed land cover) spanning the 1960-2020 period. The datasets also provide the derived water availability for each basin in Chile, calculated as the difference between annual catchment-scale precipitation and natural evapotranspiration. Regarding water uses, the dataset includes the CR2WU product, with annual time series (spanning the 1960-2020 period) of sectorial water usage at 5-km resolution for land-use-related sectors, such as agricultural and silvicultural activities, or at communal resolution for industrial and domestic sectors.
Some of the key novelties of the CR2WU product is that water uses are estimated based on actual anthropic-related activities (such as land cover changes, population growth and industrial production), and that land-cover water consumption estimates are consistent with the climatic data. In the absence of these type of data, previous studies generally assessed water uses based on water use rights (legal entitlements that allow users to extract water, see Sect. 5), which carries large uncertainties as they do not represent actual water uses but rather the fixed monthly (or annual) flows that are legally allowed to be used (e.g., Alvarez-Garreton et al. (2023a); Taucare et al. (2024); Barría et al. (2021a)). Therefore, the data used here fill a critical information gap in Chile, enabling consistent analyses between climate, water availability, and water usage. This, in turn, facilitates the assessment of the historical evolution of water stress and groundwater overexploitation, including an examination of its causes and consequences.

RC1-3: Some brief descriptions of data and methods are needed. For instance, what is the format, length and spatial-temporal resolution of the water availability and water use data? What's new about the data (e.g., first/better estimate water availability/use?)? How to calculate the trend of GW level in Figure 3 (linear regression? Sen's slope?).

R. Thanks for pointing this out. The data is now described in the new section 2.
The methodology for computing GW trend (linear regression) is specified in the Figure's revised caption.

RC1-4: The results are generally presented well but the conclusions are a bit lengthy and unstructured. I would recommend to make it more concise and well structed by firstly, briefly reporting main findings of this study, then implications, and giving recommendations to different authorities (researchers, government., etc.). Clearer ways would be a simple sentence at the start of each paragraph or give sequential numbers (like Section 4).

R. We thank the reviewer for this recommendation. We restructured the conclusions following the reviewer's suggestions, as follows:

Revised Section 6 Final Remarks:
This paper argues that 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 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 GW 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). To illustrate this argument, we present evidence for Chile and elaborate the following remarks:

1. ***The misconception of regarding GW savings as renewable water availability:***

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 from groundwater, rivers, channels or reservoirs. Drawing an analogy with a responsible fiscal budget, where permanent expenses are covered by permanent income, the intersection of water uses and availability reveals a structural imbalance. Here, the permanent water requirements are causing and relying on diminishing underground savings.

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 GW savings that are potentially non-renewable 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.

2. ***Water management must account for the risks of unsustainable GW use***

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.

Specific comments:

- L28: why "curve"? both water availability and demand are single values. Are there time series?
  R. Yes, we are referring to the evolution of water availability and water demands, which can be seen as curves. We specified this in the revised text:

  Revised L28: "In extreme cases, when the time series 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, (…)"

- L37: why desalinated water "non-drinkable"? Is this policy positive or negative? Here comes "conceal", does it mean "relief" or "save"?
  R. Thanks for pointing this out. What happened in Montevideo was that water supply freshwater stored in the main reservoirs was replaced by water from Rio de la Plata, which contains high concentrations of salt (not desalinated water). The levels of Sodium and Clorum were so high that authorities recommended to use tap water for sanitation and cooking, but not for drinking. If this policy was positive or negative is not clear, the policy did avoid water cuts in the city and thus the arrival of a day zero (can be seen as positive) however, this was at the expense of providing non-drinkable water (can be seen as negative).

  We clarified this in the revised text:

  Revised L40: "Due to low water reserves in the main reservoirs that supply drinking water to the city, the water supply was replaced with water from Rio de la Plata, which contains high concentrations of salt. As a consequence, the metropolitan area of Uruguay was receiving non-drinkable water from their taps. As a consequence, the metropolitan area of Uruguay was receiving non-drinkable water from their taps. Public opinion criticized that this measure concealed a D_0 situation by avoiding supply cuts at the expense of providing non-potable water (Gudynas, 2023)."

- L43: some exact number of withdrawal/natural recharge rate would be better.
  R. We agree with the reviewer that it would be better to provide exact numbers for these two variables. However, that is a highly challenging quantification, which depends on several

factors, including climate, terrestrial conditions, aquifer characteristics, human activities in the surface and associated water demands and the installed infrastructure to fulfill those demands. The cited studies provide estimations of GW uses and GW level variations, showing large differences across countries and large uncertainties in their estimates. The argument is that GW depletion (which can be observed from GW observation wells) is a result of having withdrawal rates above GW natural recharges.

We mentioned this in the revised text:

Revised L49: "Previous studies have raised alarm about the unsustainable GW use worldwide, highlighting the challenges of assessing the limits of its sustainable use, while emphasizing the risks to food security and aquatic ecosystems when water withdrawals surpass those limits (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, relying on underground water saving becomes precarious when GW ceases to be an accessible resource due to unsustainable extraction. Although assessing the limits beyond which GW extraction starts to be unsustainable remains an ongoing challenge, we know that pumping rates above GW natural recharge leads to long-term depletion of GW levels beyond those expected from climate (Bierkens and Wada, 2019). From that perspective, the evidence of long-term declines can be used to infer unsustainable GW use."

- L45: unsustainable GW use brings "challenges and risk", what exactly are they?
  R. We clarified this in the revised text:

  Revised L49: "Previous studies have raised alarm about the unsustainable GW use worldwide, highlighting the challenges of assessing the limits of its sustainable use, while emphasizing the risks to food security and aquatic ecosystems when water withdrawals surpass those limits (e.g., Gleeson et al., 2016; Schwartz et al., 2020)."

- L47: what "situation"?
  R. We clarified this in the revised text:

  Revised L52: "However, relying on underground water saving becomes precarious when GW ceases to be an accessible resource due to unsustainable extraction".

- L78: what is "water use right"?
  This was clarified in the revised Section 5.

  Revised L254: "Water management in Chile is primarily regulated by the Water Code, promulgated in 1981 and amended several times since then (Congreso Nacional de Chile, 1981, 2022, 2005). The Water Code defines water as a national asset for public use and defines its allocation by means of water use rights, which are entitlements specifying the quantity and *timing of water that can be used by private and public users. While these titles are granted free of charge by the State, once allocated, they represent property assets that can be traded by their owners. Currently, there is no market regulation for the buying and selling of these titles (further details regarding the water management system can be found in Alvarez-Garreton et al. (2023a); Taucare et al. (2024); Barría et al. (2021a)).”*

- L88: is “15 m” to identify surface and underground water a consensus or only in this paper? why “15 m”?
  R. The 15 m depth was used to classify the observations wells into shallow and deep wells. Both groups represent GW levels, although at different depth. Shallow wells are cheaper to construct and commonly used for accessing water for domestic use in rural areas, while deep wells are commonly used by productive sectors (such as large agricultural projects or sanitary industries). The 15 m threshold was adopted from the government “Manual for Small Irrigation Works in Family Farming Agriculture”. We added this reference in the revised manuscript:

  Revised captions Figure 2 and Figure A1: 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.

- L122: please be precise about “high” and “low” emission scenarios (RCP xx?).
  R. This was clarified in the revised text:
  Revised L148: “(...) an average of 10 to 30% less annual precipitation is projected by the end of the 21st century from climate models with high (SSP1-RCP2.6) and low (SSP3-RCP7.0) mitigation of greenhouse gas emission scenarios, respectively (...)”

- L107-108, L149-151 and L224-226 read very similar
  R. Agree. We revised and removed repetitions.

- Figure 2b: why use 1980-2010 as baseline period? Around 1980 there is little data, seems problematic.
  R. We adopted this period to avoid including the megadrought (2010-2022) in the anomaly computation. We clarified this in the revised text:

  Revised caption Figure 2: “(...) 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)”

- Figure 3b: for each basin, each well can have a GW level trend, then the bar can have ranges. Therefore, I would suggest adding error bars.
  Following the reviewer suggestion, we added error bars to Figure 3b in the revised manuscript.

Referee 2:

The manuscript presents “day zero” as a critical event of unsustainable groundwater use. As an opinion paper, the script identifies potential problems with water management and future planning. To a large extent, the document calls for quantifying groundwater recharge and withdrawals before aquifers dry up. "Day Zero" is considered a relevant topic for scientific research and public concern, but the framework should be explained further.

R. We thank the reviewer for the recommendations to improve our manuscript intended to be published as an opinion article. Please see below our responses to each comment.

Minor comments

Line 27. Is it possible that a decrease in water availability may cause "Day Zero” through climate change, keeping water demand stable?

R. This is an interesting point. The short answer is yes. For example, if current water use to availability ratio is high, a decrease in water availability driven only by climate change may solely cause the intersection of these variables, which represents a “day zero” condition if other water sources are not available. One of the main messages of this article is that water management should prepare and adapt total water uses within a basin based on the projected water availability under climate change scenarios. This is urgent to mitigate the short-term and long-term impacts of GW declines. The revised manuscript is more clear regarding this message.

Line 78. Why not include precipitation at the top of graph 2a to relate the reduction in precipitation since 2010?

R. We discussed this same idea the reviewer points out when we were elaborating the initial draft of the manuscript, and finally decided not to include precipitation in Figure 2, mainly to keep simplicity in a figure that already has many variables and information. The rationale was that precipitation is part of water availability (water availability = Precip – ET). Besides, precipitation is significantly larger than water availability so including it would require a secondary axis in panel Figure 2, panel a.

Line 88. Is there a reason for the 15 m threshold between shallow and deep wells?

R. The 15 m depth was used to classify the observations wells into shallow and deep wells. Both groups represent GW levels, although at different depth. Shallow wells are cheaper to construct and commonly used for accessing water for domestic use in rural areas, while deep wells are commonly used by productive sectors (such as large agricultural projects or sanitary industries). The 15 m threshold was adopted from the government “Manual for Small Irrigation Works in Family Farming Agriculture”. We added this reference in the revised manuscript:

Revised captions Figure 2 and Figure A1: 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.

Line 97. How was the D_0 time frame calculated?

R. To this end, we made a rough estimate of D_0 as a scale analysis considering the aquifer volume, a groundwater withdrawal and recharge rate. That is,

$D_0 = W / (U_S - R_N)$

with W representing the water volume of the saturated aquifer, U_S a groundwater extraction rate, and R_N a net recharge rate (water recharges minus springs). As mentioned in the manuscript, there are several uncertainties for all these quantities in the Maipo-Mapocho aquifer, but we considered the following values:

$W = 3\ 10^{10}\ m^3$ ($30\ km^3$), based on Araneda et al. (2010)

$U_S = 25$ to $50\ m^3/s$. This range corresponds to ~ 35 to 65% of total consumptive water uses in the basin. The upper bound roughly corresponds to actual ratio of groundwater to total water use rights (given the fewer limitations for the allocation groundwater rights, it is very unlikely that underground to total water use ratio will exceed the corresponding ratio for water use rights). The lower bound is considered to be slightly below independent estimates based on extraction wells in the watershed, totaling near 30 m^3/s (Daniela Riffo 2020).

$R_N = 10$ to $20\ m^3/s$. This range considers an imbalance between natural water recharge and springs (accounting for a positive net recharge), with values also based on Daniela Riffo (2020).

The combination of use and recharge estimates results in an aquifer decay rate ($U_S - R_N$) ranging from 5 to 40 m^3/s. We believe that the upper limit of this rate might be overestimated, particularly when considering decreased water springs as the water table descends. Consequently, we have narrowed the range of this decay rate to [5, 20] m^3/s, which lead to an estimated D_0 range between 47 and 190 years (rounded to 50-200 years).

We explained this procedure in the revised manuscript.

Revised L191: Determining that time frame requires a precise quantification of the water volume remaining in aquifers, GW recharges, and GW extraction rates. However, a rough estimate of the absolute D_0 can be estimated as $D_0 = W / (U_S - R_N)$, where W represents the water volume of the saturated aquifer, U_S the groundwater extraction rate, and R_N the net recharge rate (water recharges minus springs).
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 20 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 35 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.

Line 119. Why do permanent water uses rely on depleting GW storage? A reduction in surface water due to water management can also trigger overexploitation of groundwater. A cascade effect from surface to groundwater is observed.
R. We agree with the reviewer, GW overexploitation is the result of a cascading effect from climate, water availability, surface water use and GW water use. The idea with this line is to make an analogy to responsible economic budgets (permanent expenses must be covered with permanent income), and highlighting that in this case, permanent water requirements are relying on depleting savings rather than renewable incomes. We clarified this idea in the revised manuscript.

Revised L350: "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. Drawing an analogy with a responsible fiscal budget, where permanent expenses are covered by permanent income, the intersection of water uses and availability reveals a structural imbalance. Here, the permanent water requirements are causing and relying on diminishing underground savings.

Line 177. Is there any information about fossil groundwater flow within the aquifer?
R. We complemented this information in the main text.

Revised L325: The use of fossil water (i.e., resources that entered the aquifers centuries or millennia ago) would be an example of this intergenerational 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). Available evidence from a headwater section of the Maipo basin (Mapocho basin) have reported deep wells (water table below 112 m depth) characterized by low tritium concentrations (<0.8) and ^{14}C contents (70 pMC), indicating that such resources were likely recharged about 3,000 years ago (Iriarte et al 2006). These GW age tracers indicate that GW with modern and old fractions could also occur in the downstream area of the Maipo basin.

Line 186. With a neglected legal uncertainty about the economy, should the water management legal context (unregulated or weak) be explained?
R. We briefly described the water management legal context and refer to other papers for further details:

Revised L183: *Water management in Chile is primarily regulated by the Water Code, promulgated in 1981 and amended several times since then (Congreso Nacional de Chile, 1981, 2022, 2005). The Water Code defines water as a national asset for public use and defines its allocation by means of water* *use rights, which are entitlements specifying the quantity and timing of water that can be used by private and public users. While these titles are granted free of charge by the State, once allocated, they represent property assets that can be traded by their owners. Currently, there is no market regulation for the buying and selling of these titles (further details regarding the water management system can be found in (Alvarez-Garreton et al., 2023a; Taucare et al., 2024; Barría et al., 2021a)).*

Line 200: When does the irreversible impact occur?
R. This is not an easy question to address because it depends on the specific system under evaluation. An example of an ecological tipping point would be the death of groundwater-dependent ecosystems, such as peatlands and wetland vegetation. This, in turn, can create a cascading impact on the fauna depending on those ecosystems.

Some of these examples are mentioned in L281: *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., 2021b).*