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Groundwater

Issue Paper/

Groundwater for People and the Environment: A Globally Threatened Resource

by Hugo A. Loaiciga[1,2] and Ryan Doh[3]

Abstract

The intensity of global groundwater use rose from 124 m^3 per capita in 1950 to 152 m^3 in 2021, for a 22.6% rise in the annual per capita use. This rise in global per capita water use reflects rising consumption patterns. The global use of groundwater, which provides between 21% and 30% of the total freshwater annual consumption, will continue to expand due to the sustained population growth projected through most of the 21st century and the important role that groundwater plays in the water-food-energy nexus. The rise in groundwater use, on the other hand, has inflicted adverse impacts in many aquifers, such as land subsidence, sea water intrusion, stream depletion, and deterioration of groundwater-dependent ecosystems, groundwater-quality degradation, and aridification. This paper projects global groundwater use between 2025 and 2050. The projected global annual groundwater withdrawal in 2050 is 1535 km^3 ($1\ km^3 = 10^9\ m^3 = 810{,}713$ acre-feet). The projected global groundwater depletion, that is, the excess of withdrawal over recharge, in 2050 equals 887 km^3, which is about 61% larger than in 2021. This projection signals probable exacerbation of adverse groundwater-withdrawal impacts, which are worsened by climatic trends and the environmental requirement of groundwater flow unless concerted national and international efforts achieve groundwater sustainability.

Introduction

Groundwater has contributed between 21% and 30%, with an estimated average of about 25%, of the total annual freshwater (i.e., surface water plus groundwater) use worldwide according to the most-recent (i.e., year 2020) AQUASTAT data on global groundwater and total freshwater use (Food and Agriculture Organization 2023). The contribution of groundwater to the total annual water use varies among the continents, the smallest being in South America and Europe (14%) and the largest in Asia (30%) (Margat and van der Gun 2013). Asia, North and Central America, Europe, Africa, South America, Australia and Oceania withdraw 64.5, 15.6, 7.1, 6.7, 5.4, and 0.7%, respectively, of the groundwater used worldwide on an annual basis (United Nations Educational, Scientific and Cultural Organization [UNESCO] 2022). Worldwide, 69% of withdrawn groundwater is destined for agriculture, and 31% is consumed by the municipal, industrial, and commercial sectors (UNESCO 2022). India, China, USA, Pakistan, Iran, Mexico, and Saudi Arabia, the seven largest groundwater users, withdrew 250, 125, 110, 80, 72, 42, and 25 km^3 in 2010 (Wada 2016), respectively, which amounted to about 74% of the worldwide use of groundwater (estimated to be 952 km^3) that same year. The data on groundwater use presented in this study demonstrate the importance of groundwater in meeting the global

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demand for water. This raises the question: can groundwater services to humanity be effectively delivered while preserving environmental quality in the decades ahead? This issue paper presents data and pattern analysis to answer this question, considering historical (global) water use, energy use, and population growth, coupled with projections of global water use, energy use, and population growth through 2050. Furthermore, this paper surveys a few adaptive strategies to preserve the services of groundwater to humanity.

Global Groundwater Recharge and Storage

It is insightful to compare global annual groundwater withdrawal with global average annual groundwater recharge. Global average annual groundwater recharge estimates vary considerably: 12,700 km^3 (Döll and Fiedler 2008), 14,000 km^3 (Cohen 1995), 14,400 km^3 (de Graaf et al. 2019), 15,200 km^3 (Wada et al. 2010), and 25,900 km^3 (Berghuijs et al. 2022), among other estimates reported in the literature. Approximately 5000 and 9000 km^3 of the average annual recharge are estimated to occur in uninhabited and inhabited/cultivated regions, respectively, according to Cohen (1995). The latter flux (i.e., 9000 km^3) replenishes aquifers tapped by humans for water-supply purposes.

It is pertinent to ponder how a worldwide average annual groundwater recharge in excess of 10,000 km^3, by most estimates, can threaten groundwater resources given that the global annual groundwater extraction was estimated at about 1200 km^3 in 2021 (see below). This dilemma takes heightened relevance in view of estimates of the global volume of groundwater storage, which are orders of magnitude larger than the volume of groundwater that is withdrawn annually. Specifically, Gleeson et al. (2016) estimated the volume of groundwater in storage in the upper 2 km of the continental crust (lithosphere) at 22.6×10^6 km^3. Other estimates of the volume of groundwater storage range between 1.1×10^6 and 60×10^6 km^3 (Margat and van der Gun 2013; Bierkens and Wada 2019). These estimates of global groundwater recharge and storage are inherently uncertain given (1) the large spatial and temporal variability of the climatic and hydrologic processes that govern recharge, (2) the heterogeneity of soils and rocks throughout the world's non-glaciated continental regions, and (3) the paucity of space–time hydroclimatic monitoring networks at a global scale (see, e.g., Döll 2009; Condon et al. 2021). It is noteworthy that the economics of groundwater withdrawal restrict the depth to which water wells can be installed and operated in a cost-effective manner (Glotfelty 2019). Most groundwater supply wells tap the top 1200 m of the lithosphere (Planert and Williams 1995) because of cost considerations and the natural increase of groundwater solutes with increasing depth (Sterret 2007), thereby rendering deep groundwater unsuitable for human and agricultural use without expensive treatment.

In spite of unavoidable errors of estimation the calculated global groundwater recharge and groundwater storage seem sufficient to meet the human use of groundwater without harm. The vast amount of groundwater storage is misleading from the perspective of global groundwater availability, however, because the aquifer-scale and not the global-scale water fluxes and groundwater storage controls the relevant availability of groundwater to meet human and environmental needs. The threat to groundwater resources materializes at the aquifer scale, primarily in semiarid and arid regions with naturally low recharge rates and high rates of groundwater withdrawal destined primarily to grow crops (Bierkens and Wada 2019; Masoudi et al. 2019; Bozorg-Haddad et al. 2020), although groundwater shortages may occur in humid areas, also (see, e.g., Hunt 2003). Examples of overdrafted regional aquifers can be found in Loaiciga et al. (2000), Custodio (2002), Scanlon et al. (2012), Margat and van der Gun (2013), Konikow (2013), Döll et al. (2014), and Kram et al. (2023), Bostic et al. (2023), but many others exist (see below).

Climate Change and Groundwater

Climate change poses a challenge to groundwater supply in many semi-arid and arid regions due to declining precipitation and rising surface-air temperature, which means reduced recharge to aquifers by the combined effects of reduced supply of surface water and rising evapotranspiration (which rises with rising surface-air temperature, see, e.g., Thornthwaite 1948; Budyko 1977; Hargreaves and Zamani 1985; Loaiciga 2003a, Portmann et al. 2013; Roderick et al. 2014; Yao et al. 2023). Hunt et al. (2013, 2016) have shown that a warming climate may reduce groundwater availability in humid regions, also. Evidence of rising surface-air temperature is shown in Figure 1, which displays the 1850–2022 global average annual surface-air temperature anomaly over land. The temperature time series exhibits a long-term linear trend of rising temperature that implies a rise of 0.94 °C per 100 years. The temperature data shown in Figure 1 indicate, also, that after 1970 the temperature rise has become more pronounced than that obtained from the long-term trend.

Groundwater Overdraft, Sustainability, and the Safe Yield

The condition of protracted groundwater withdrawal in excess of aquifer recharge that afflicts many aquifers is known as overdraft (see, e.g., Loaiciga 2017), which threatens groundwater sustainability in many regions of the world (see, e.g., Custodio 2002; Foster and Chilton 2003; Döll 2009; Wada et al. 2010; Margat and van der Gun 2013; Konikow 2013; Famiglietti 2014; de Graaf et al. 2019; Bierkens and Wada 2019; Gleeson et al. 2020, Liu et al. 2022). Groundwater pollution also threatens groundwater sustainability in many aquifers (see, e.g., Zektser et al. 2005). Sustainability is herein defined as the capacity of groundwater to provide beneficial services to humans while protecting the environment and groundwater-dependent ecosystems in perpetuity. See discussions of groundwater sustainability in Alley

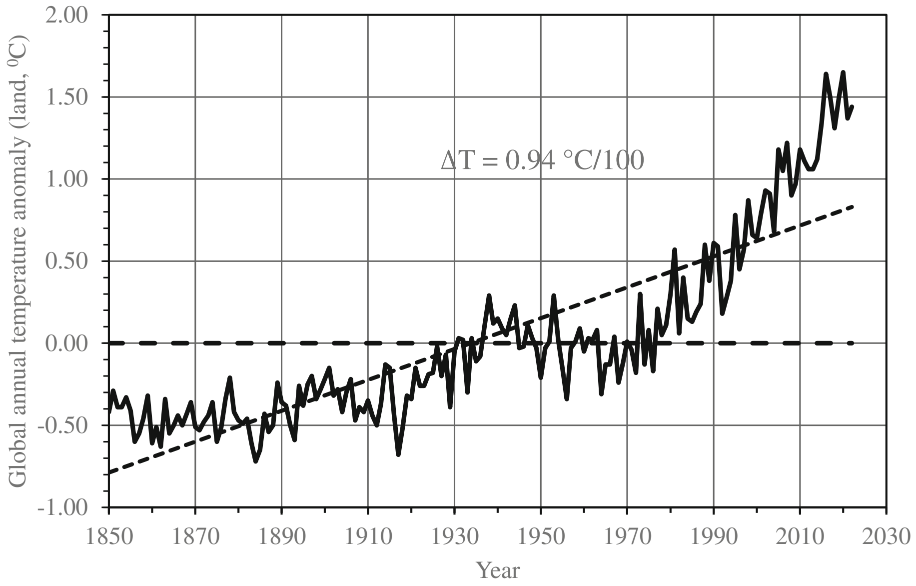

Figure 1. The 1895–2022 times series of global average annual surface-air temperature anomaly over land. The depicted trend is statistically significant with a p value <.01. The temperature anomaly is calculated with respect to the global average annual temperature over land in 1901–2000 (=8.5 °C) .(*Source*: National Oceanic and Atmospheric Administration 2022)

et al. (1999), Loaiciga (2003b), Alley and Leake (2004), Wada and Bierkens (2014), Gleeson et al. (2020), Konikow and Bredehoeft (2020), and Kram et al. (2023), which are a few examples in a growing literature on groundwater sustainability.

The safe yield of aquifers is a central to the question of groundwater sustainability. For background, the safe yield (or perennial yield, basin yield, sustainable yield) is defined as the maximum quantity of water that can be continuously withdrawn from a groundwater basin without adverse effects (California Department of Water Resources 2020, see also Alley et al. 1999; Reilly et al. 2008; Louwyck et al. 2023). The details written below further explain the roles of the safe yield, groundwater withdrawal, and the environmental flow requirements in the context of groundwater sustainability.

Global Population, Energy, and Water Uses

Figure 2 depicts the annual, historical, and worldwide annual consumptions of total freshwater water (i.e., surface water plus groundwater uses) and groundwater from 1950 through 2021, in addition to total energy use in the period 1965–2021 for which data were available. Moreover, Figure 2 shows the world population in the period 1950–2021, and projections of (1) population, (2) global total water use, (3) global groundwater use, and (4) global energy use from 2025 through 2050.

The population projection displayed in Figure 2 represents the United Nations' medium fertility scenario (see United Nations 2023). The United Nations' projection corresponding to the medium fertility scenario indicates that the world population will not stabilize until about 2090 with a population of approximately 10.4 billion people due to the momentum of population growth built in the world's predominantly young and rapidly growing population (see, e.g., Hardin 1993, Cohen 1995, Roser et al. 2013, for reviews of global population growth). Groundwater and total water uses, therefore, are likely to continue rising with the growing population during most of the 21st century.

Two key inputs to the world economy, namely, energy and water, are driven by population size, which has increased monotonically (as shown in Figure 2) and will continue to do so for most of the 21st century. Figure 2 shows that total energy use exhibits an overall increasing trend, but, unlike population, it displays noticeable temporary fluctuations, which are associated with economic recessions (notice that the scale for energy is on the right-and side vertical axis of Figure 2). The 2020–2021 economic downturn caused by the COVID crisis is a case in point, and is mirrored in the graphs of the total water and groundwater uses. The 2025–2050 energy projections do not show fluctuations because they are calculated with functions that have smoothed outputs corresponding to statistical trends (see the Data S1 for details on this matter). The global population and groundwater-use data presented in Figure 2 establish that the intensity of groundwater use rose from 124 m^3 per capita in 1950 (when the world population was 2.5 billion people and the groundwater use was 3.1×10^{11} m^3) and 152 m^3 in 2021 (when the population was 7.9 billion people and the groundwater use was 12×10^{11} m^3), or a 22.6% rise in the annual per capita use. The data displayed in Figure 2 imply that the intensity of energy use rose from about 13 GWh per person in 1965 to about 21 GWh per person in 2021, for a 61.5% rise in per capita energy use, which is well in excess of the 22.6% rise in per capita groundwater observed between 1950 and 2021. Evidently, the world's population has become much more "energivorous" than "watervorous" in the last decades

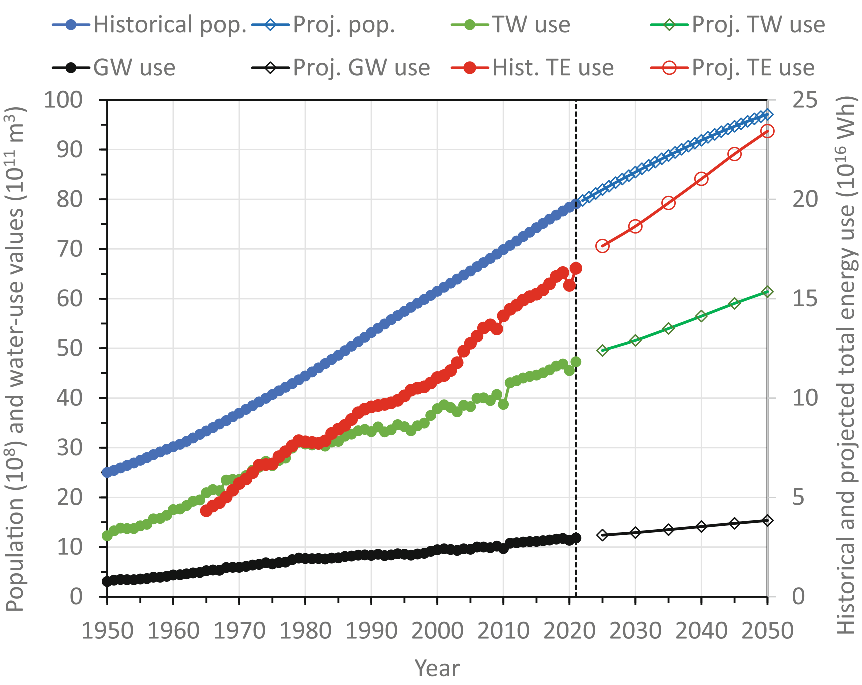

Figure 2. Historical (1950–2021) and projected (2025–2050) world population, and total energy, total water, and groundwater uses. Historical population (Historical pop.) and projected population (Proj. pop.) in 10^8 people ; TW use: total freshwater use (10^{11} m^3;); groundwater use (GW use, 10^{11} m^3;); historical total energy use (Hist. TE use 10^{16} Wh [watt hour];); see Data S1 for sources and calculations of projected total energy use (Proj. TE use, 10^{16} Wh), project total water use (Proj. TW use, 10^{11} m^3), and projected groundwater use (Proj. GW use, 10^{11} m^3).*Source*: U.S. Energy Information Administration 2023

(see Pitron 2023, for an insightful analysis of the ever-increasing energy consumption driven by information technologies). Water and energy consumptions have increased over time because the number of people and their intensity of use have risen.

The positive statistical association between energy use and water use stems from the use of the former in water withdrawal and conveyance, which are related to economic activity. This association was exploited in this paper by regressing the historical total water use on the historical energy use using data for the period 1965–2021, and applying the developed regression formula to project total water use based on the projected energy use through 2050 (see the Data S1 for details on this matter). Groundwater use (1950–2021) was estimated from historical data on global, total, water and groundwater use reported in FAO's AQUASTAT dataset (FAO 2023). Groundwater use was projected from 2025 through 2050 by using the historical relation (i.e., 1950–2021) between groundwater and total water uses and projecting that relation to 2025–2050 (see Data S1 for details).

The Environmental Flow and Groundwater Depletion

The increased reliance on groundwater has caused the overdraft of many aquifers (see, e.g., Loaiciga et al. 2000; Margat and van der Gun 2013; Famiglietti 2014; Pokhrel et al. 2015; Wada 2016; de Graaf et al. 2019; Liu et al. 2022). The most recent published estimate of global annual groundwater depletion, that is, the groundwater withdrawal in excess of the groundwater recharge, was for year 2010 and equaled 304 km^3 (Bierkens and Wada 2019). The northwestern Indian (India and Pakistan), the Arabian (Iraq, Jordan, Oman, Qatar, Saudi Arabia, UAE, Yemen), the northern Middle East (Iran, Iraq, Syria, Turkey), the High Plains (USA), and the north China Plain aquifer systems are the five most overdrafted aquifer systems with estimated average annual rates of depletion equal to 17.7, 15.5, 13.0, 12.5, and 8.3 km^3, respectively, according to Wada et al. (2010). The preceding estimates of regional aquifer depletion are approximate given that the Wada et al. (2010) estimate of global groundwater depletion for year 2000 was 283 km^3 (which is the sum of regional depletions), it was revised downward to 204 km^3 by Wada et al. (2010), and revised upward to 304 km^3 by Wada and Bierkens (2014) and Bierkens and Wada (2019).

The comparison of groundwater withdrawal to groundwater recharge for the purpose of calculating groundwater depletion does not fully capture the severity of depletion because it does not account for the discharge of groundwater that serves environmental functions, such as protecting groundwater-dependent ecosystems and preventing sea water intrusion into coastal aquifers (see, e.g., Foster and Chilton 2003; Zektser et al. 2005; Döll et al. 2014; Loaiciga and Schofield 2019; Herrera-Garcia et al. 2021). This beneficial discharge is called by some authors the environmental flow (see, e.g., de Graaf et al. 2019). In previous decades the safe yield was defined as the average annual groundwater extraction rate that equals the average annual recharge (see, e.g., Lohman 1972, for a discussion of the safe yield). This definition has been found in practice to be inadequate because it ignores the environmental flow and capture processes (see, e.g., Sophocleous 1997; Bredehoeft 2002; Alley and Leake 2004; Loaiciga 2017; Ferris and Porter 2021). Bredehoeft (2002) referred to the statement "the pumping must not exceed the recharge if the development is to be sustainable" as the water-budget myth (see, also, Alley 2007). Bredehoeft (2002) exemplified the complexities that arise when groundwater withdrawal alters the subsurface flow regime and captures discharge from the aquifer and induces seepage to an aquifer from a hydraulically connected water body (see also Theis 1940). In the more general case of regional aquifers whose natural replenishment stems from diffuse recharge and seepage from streams and lakes the calculation of recharge is complex, and must consider the balance of precipitation, evapotranspiration, and surface runoff (see, e.g., Loaiciga 2017; Döll and Fiedler 2008; Berghuijs et al. 2022). For these reasons the safe yield of an aquifer (Q_S) has been redefined from a computational viewpoint as the average annual recharge ($\overline{R}$) minus the average annual environmental flow ($\overline{D}$) $\left(\text{i.e., } Q_S = \overline{R} - \overline{D}\right)$ (Loaiciga 2017). Therefore, the calculation of the average annual groundwater depletion (Δ) must be based on the comparison of the average annual groundwater withdrawal ($\overline{Q}$) with the difference between the average annual recharge and the average annual environmental flow (i.e., $\Delta = \overline{Q} - (\overline{R} - \overline{D})$). Comparing the average annual groundwater withdrawal with the recharge underestimates the depletion of groundwater in a holistic sense because $\overline{Q} - \overline{R} < \Delta$. Studies of regional aquifers have shown that the environmental flow may be as high as 46% of the average annual recharge (Loaiciga and Schofield 2019).

A normalized value to rank the severity of groundwater depletion is herein named the groundwater stress index (GSI), which is calculated according to Equation 1:

$$\text{GSI} = \frac{Q}{R - E} 100 \tag{1}$$

in which E, Q, and R denote, respectively, the average annual environmental flow, groundwater withdrawal, and recharge (from which evapotranspiration from groundwater must be subtracted if it exists). The GSI is useful for comparing the severity of groundwater withdrawal impacts across basins, and, thus, may serve to prioritize restoration efforts. These authors recommend a classification of the GSI based on Table 1.

The GSI calculated for the Edwards Balcones Fault Zone Aquifer of south-central Texas based on data from 1934 through 2015, for instance, yields a GSI equal to 98%, which is critical. The impact of groundwater withdrawal on groundwater-dependent ecosystem led to the listing of several endemic species in the karst aquifer and its springs as endangered by the U.S. Fish and Wildlife Service (Loaiciga and Schofield 2019). This finding was followed by a Recovery Implementation Program and Habitat Conservation Plan (RIP-HCP) that Edwards Balcones Fault Zone Aquifer's stakeholders must implement (U.S. Fish and Wildlife Service 2013).

Table 1
The Groundwater Stress Index (GSI) and its Categorization.

GSI Range (%)	Stress Category
<10	Low
10–20	Low-medium
More than 20–40	Medium-high
More than 40–80	High
>80	Critical

Groundwater withdrawal in excess of the safe yield inflicts adverse impacts, which include lowering of the groundwater level to depths that render withdrawal uneconomical with current technology (Glotfelty 2019), cause land subsidence (Galloway and Burbey 2011; Herrera-Garcia et al. 2021), sea water intrusion (Loaiciga et al. 2012; Cao et al. 2021), loss of plant-community richness and aridification by declining groundwater levels (Chen et al. 2006; Masoudi et al. 2019), dewatering of streams and degradation of aquatic habitat (Barlow and Leake 2012; de Graaf et al. 2019), and deterioration of groundwater quality (Zektser et al. 2005). Our current understanding of the safe yield recognizes the necessity of applying an adaptive strategy for groundwater withdrawal. Such strategy accounts for the cycles of drought and wet periods that typify the climates of many regions and that account for the environmental flow (Loaiciga 2003a; Konikow and Bredehoeft 2020). Integrated water management has been proposed to achieve comprehensive and rational use of water resources (Jakeman et al. 2016).

Projection of Global Groundwater Depletion

The estimated global annual groundwater depletion in 2010 was 304 km^3, when the global groundwater use was 952 km^3 (Bierkens and Wada 2019). The projected annual groundwater withdrawal by 2050 shown in Figure 2 equals 1535 km^3, which compares with the 2021 groundwater use of 1200 km^3, and with 952 km^3 in 2010 (the 952 km^3 estimate compares closely with the 968 km^3 estimated in this paper). Assume that the global groundwater recharge in 2021 was equal to that of 2010 and that the recharge in 2050 will be the same as it was in 2021. Under this assumption the rise in groundwater withdrawal between 2010 and 2021 ($= 1200 - 952 = 248$ km^3) implies that the annual groundwater depletion would have increased by 2021 from 304 to $304 + 248 = 552$ km^3, and would rise to an annual $552 + (1535 - 1200) = 887$ km^3 by 2050. The projected annual groundwater depletion by 2050, which is about 61% larger than that in 2021, is plausible given the trend of population and economic growth, and the world's reliance on water that is required to support that growth. To compound matters, the projected groundwater depletion by 2050 most likely underestimates the actual impacts of declining groundwater storage because (1) climate change is reducing recharge in many aquifers where precipitation declines and surface temperature rises (see Figure 1), and (2) the 304 km^3 estimate of groundwater depletion in 2010 does not account for the environmental flow.

The projected rise in global groundwater use and depletion by 2050, when the world population is projected to increase to 9.7 billion people under the United Nations' medium variant (see Figure 2), would exacerbate the adverse impacts cited above. These impacts may force withdrawers to end groundwater extraction, as is already occurring in critically impacted regions due to (1) the pronounced decline in groundwater levels and the high cost of deepening wells and pumping groundwater from great depths (Bostic et al. 2023), (2) land subsidence, (3) seawater intrusion, (4) groundwater-quality deterioration, and (5) induced aridification.

Alternatives for Achieving Sustainability

Measures that counter groundwater overdraft are urgently needed, which from the water-demand perspective involves reducing the groundwater-use intensity by improving the water-use efficiency in the municipal, industrial, and agricultural sectors, and by increasing water recycling or reuse coupled with managed aquifer recharge (MAR). A glimpse of the extent to which water is wasted is revealed by data reported by Mexico's Comisión Nacional del Agua (CONAGUA 2006), which estimated that 40–60% of the water produced for irrigation use in Mexico is lost during conveyance or as runoff. Conveyance losses in Mexico's municipal sector range between 30 and 50% of the produced water (CONAGUA 2006). Hunt et al. (2010) reported cases of similar leakage losses in urban areas. Cohen (1995) estimated that 42% of the total water used globally is discharged after being used (i.e., as sewage and agricultural runoff). If that water were recycled or reused the water supply would be augmented by 72% (Loaiciga 2015).

The recharge of treated sewage, stormwater, and diverted surplus streamflow into aquifers for subsequent use by means of managed aquifer recharge constitutes an active effort to achieve sustainable groundwater use by means of managed aquifer recharge (Dillon et al. 2019). Other options available to combat groundwater depletion are strategically managing the trade of virtual water (i.e., water consumed in the production of goods, Delpasand et al. 2020, 2022), expanding alternative water sources such as seawater desalination powered by renewable energy (see, e.g., Gao et al. 2017) and protective of marine ecosystems (Sheibani et al. 2023), modifying cropping patterns and dietary customs in favor of foods that have a lower water footprint (Kheirinejad et al. 2022; Radmehr et al. 2022), metering water use and pricing water at its marginal cost to reduce wasteful use (Kiparksy et al. 2018; Maples et al. 2018), and developing a shared groundwater platform for groundwater monitoring and prediction (Condon et al. 2021).

Conclusion

The cited measures to achieve groundwater sustainability require time, investments in labor, capital, land, technology, and changes in social behavior towards resources use and consumption. They also must involve international cooperation in funding, technology transfer, trade, and must be driven by cultural and political/institutional shifts towards sustainable water and energy uses (Zareie et al. 2021; Abdi et al. 2023). The rise in population and groundwater-use in the decades ahead, and the intensification of consumption patterns signal worsening impacts that will be felt through the water-food-energy nexus unless corrective measures are taken on the local level, which can then culminate in meaningful change on a global scale.

Author Contributions

Hugo A. Loaiciga: Developed the method for groundwater use projection. **Ryan Doh**: Data analysis and paper writing.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Data S1. The supporting information explains the methods applied to project population, total water use, groundwater use, and total energy use from 2025 through 2050. Supporting Information is generally not peer-reviewed. Data used to prepare this paper can be made available from the corresponding author upon reasonable request.

References

Abdi, B., O. Bozorg-Haddad, and H.A. Loáiciga. 2023. International Water Comprehensive Organization (IWCO): Creating alliances for improved water management and solving water conflicts. *AQUA, Water Infrastructure, Ecosystems and Society* 72: 465–478. https://doi.org/10.2166/aqua.2023.181

Alley, W.M. 2007. Another water budget myth: The significance of recoverable groundwater in storage. *Groundwater* 45, no. 3: 251. https://doi.org/10.1111/j.1745-6584.2006.00274.x

Alley, W.M., and S.A. Leake. 2004. The journey from safe yield to sustainability. *Groundwater* 42, no. 1: 12–16.

Alley, W.M., T.E. Reilly, and O.L. Franke 1999. Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, Denver, Colorado.

Barlow, P.M., and S.A. Leake. 2012. Streamflow depletion by wells – Understanding and managing the effects of groundwater pumping on streamflow. U.S. Geological Survey Circular 1376. Reston, Virginia.

Berghuijs, W.R., E. Luijendijk, C. Moeck, Y. van der Velde, and S.T. Allen. 2022. Global recharge data set indicates strengthened groundwater connection to surface fluxes. *Geophysical Research Letters* 49: 1–9. https://doi.org/10.1029/2022GL099010

Bierkens, M.F.P., and Y. Wada. 2019. Non-renewable groundwater use and groundwater depletion: A review. *Environmental Research Letters* 14, no. 6: 063002. https://doi.org/10.1088/1748-9326/ab1a5f

Bostic, D., L. Mendez-Barrientos, R. Pauloo, K. Dobbin, and V. MacClements. 2023. Thousands of domestic and public supply wells face failure despite groundwater sustainability reform in California's Central Valley. *Scientific Reports* 13: 14797. https://doi.org/10.1038/s41598-023-41379-9

Bozorg-Haddad, O., B. Zolghadr-Asli, P. Sarzaeim, A. Aboutalebi, X. Chu, and H.A. Loaiciga. 2020. Evaluation of water shortage crisis in the Middle East and possible remedies. *Journal of Water Supply: Research and Technology-AQUA* 69, no. 1: 85–98. https://doi.org/10.2166/aqua.2019.049

Bredehoeft, J.D. 2002. The water budget myth revisited: Why hydrogeologists model. *Groundwater* 40: 340–345. https://doi.org/10.1111/j.1745-6584.2002.tb02511.x

Budyko, M.I. 1977. *Climatic Changes*. Washington, DC: American Geophysical Union.

California Department of Water Resources. 2020. California's groundwater update. California's Groundwater: Bulletin 118. Appendix B: Glossary. Sacramento, California.

Cao, T., D. Han, and X. Song. 2021. Past, present, and future of global seawater intrusion research: A bibliometric analysis. *Journal of Hydrology* 603: 126844. https://doi.org/10.1016/j.jhydrol.2021.126844

Chen, Y.N., N. Zilliacusb, W.H. Lia, H.F. Zhang, and Y.P. Chen. 2006. Groundwater level affects plant species diversity along the lower reaches of the Tarim river, Western China. *Journal of Arid Environments* 66, no. 1: 231–246.

Cohen, J.E. 1995. *How Many People Can the Earth Support?* New York: Norton.

CONAGUA. 2006. *Water in Mexico*. Mexico: Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT).

Condon, L.E., S. Kollet, M.F.P. Bierkens, G.E. Fogg, R.M. Maxwell, M.C. Hill, H.-J. Hendricks Fransen, A. Verboef, A.F. van Loon, M. Sulis, and C. Abesser. 2021. Global groundwater modeling and monitoring: Opportunities and challenges. *Water Resources Research* 57: 1–27. https://doi.org/10.1029/2020WR029500

Custodio, E. 2002. Aquifer overexploitation: What does it mean? *Hydrogeology Journal* 10: 254–277.

de Graaf, I.E.M., T. Gleeson, L.P.H. van Beek, E.H. Sutanudjaja, and M.F.P. Bierkens. 2019. Environmental flow limits to global groundwater pumping. *Nature* 574: 90–94.

Delpasand, M., O. Bozorg-Haddad, E. Goharian, and H.A. Loaiciga. 2022. Virtual water trade: Economic development and independence through optimal allocation. *Agricultural Water Management* 275, no. 1: 108022. https://doi.org/10.1016/j.agwat.2022.108022

Delpasand, M., O. Bozorg-Haddad, and H.A. Loaiciga. 2020. Integrated virtual water trade management considering self-sufficient production of strategic agricultural and industrial products. *Science of the Total Environment* 743: 140797. https://doi.org/10.1016/j.scitotenv.2020.140797

Dillon, P., P. Stuyfzand, T. Grischek, M. Lluria, R.D.G. Pyne, R.C. Jain, J. Bear, J. Schwarz, W. Wang, E. Fernandez, C. Stefan, M. Pettenati, J. Van der Gun, C. Sprenger, G. Massmann, B.R. Scanlon, J. Xanke, P. Jokela, Y. Zheng, R. Rossetto, M. Shamrukh, P. Pavelic, E. Murray, A. Ross, J.P. Bonilla Valverde, A. Palma Nava, N. Ansems, K. Posavec, K. Ha, R. Martin, and M. Sapiano. 2019. Sixty years of global progress in managed aquifer recharge. *Hydrogeology Journal* 27: 1–30. https://doi.org/10.1007/s10040-018-1841-z

Döll, P., H. Müller Schmied, C. Schuh, F.T. Portmann, and A. Eicker. 2014. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resources Research* 50: 5698–5720. https://doi.org/10.1002/2014WR015595

Döll, P. 2009. Vulnerability to the impact of climate change on renewable groundwater resources: A global-scale assessment. *Environmental Research Letters* 4: 035006. https://doi.org/10.1088/1748-9326/4/3/035006

Döll, P., and K. Fiedler. 2008. Global-scale modeling of groundwater recharge. *Hydrology and Earth Systems Sciences* 12: 863–885. https://doi.org/10.5194/hess-12-863-2008

Famiglietti, J. 2014. The global groundwater crisis. *Nature Climate Change* 4: 945–948.

Ferris, K., and S. Porter. 2021. *The Myth of Safe Yield: Pursuing the Goal of Safe Yield Isn't Saving Our Groundwater*. Arizona, USA: Kyl Center for Water Policy, Arizona State University.

Food and Agriculture Organization. 2023. https://tableau.apps.fao.org/views/AQUASTATDashboard/

Foster, S.S., and P.J. Chilton. 2003. Groundwater: The processes and global significance of aquifer degradation. *Philosophical Transactions of the Royal Society of London* 358: 1957–1972.

Galloway, D.L., and T.J. Burbey. 2011. Review: Regional land subsidence accompanying groundwater extraction. *Hydrogeology Journal* 19, no. 8: 1459–1486.

Gao, L., S. Yoshikawa, Y. Iseri, S. Fujimori, and S. Kanae. 2017. An economic assessment of the global potential for seawater desalination to 2050. *Water* 9, no. 10: 763. https://doi.org/10.3390/w9100763

Gleeson, T., M. Cuthbert, G. Ferguson, and D. Perrone. 2020. Global groundwater sustainability, resources, and systems in the Anthropocene. *Annual Review of Earth and Planetary Sciences* 48: 431–463.

Gleeson, T., K. Befus, S. Jasechko, E. Luijendijk, and M.B. Cardenas. 2016. The global volume and distribution of modern groundwater. *Nature Geoscience* 9: 161–167. https://doi.org/10.1038/ngeo2590

Glotfelty, M.F. 2019. *The Art of Water Wells*. Westerville, Ohio: NGWA Press.

Hardin, G. 1993. *Living Within Limits*. New York: Oxford University Press.

Hargreaves, G.H., and Z.A. Zamani. 1985. Reference crop evapotranspiration from temperature. *Applied Engineering and Agriculture* 1, no. 2: 96–99. https://doi.org/10.13031/2013.26773

Herrera-Garcia, G., P. Ezquerro, R. Tomas, M. Bejar-Pizarro, J. Lopez-Vinielles, M. Rossi, R.M. Mateos, D. Carreón-Freyre, J. Lambert, P. Teatini, E. Cabral-Cano, G. Erkens, D. Galloway, W.C. Hung, N. Kakar, M. Sneed, L. Tosi, H. Wang, and S. Ye. 2021. Mapping the global threat of land subsidence. *Science* 371, no. 6524: 34–36.

Hunt, R.J. 2003. A water science primer. *Wisconsin Academy of Sciences, Arts and Letters Transactions* 90: 11–21.

Hunt, R.J., S.M. Westenbroek, J.F. Walker, W.R. Selbig, R.S. Regan, A.T. Leaf, and D.A. Saad. 2016. Simulation of climate change effects on streamflow, groundwater, and stream temperature using GSFLOW and SNTEMP in the Black Earth Creek Watershed, Wisconsin. U.S. Geological Survey Scientific Investigations Report 2016–5091, Reston, Virginia. https://doi.org/10.3133/sir20165091

Hunt, R.J., J.F. Walker, W.R. Selbig, S.M. Westenbroek, and R.S. Regan. 2013. Simulation of climate-change effects on streamflow, lake water budgets, and stream temperature using GSFLOW and SNTEMP, Trout Lake Watershed, Wisconsin. U.S. Geological Survey Scientific-Investigations Report 2013-5159, Reston, Virginia. http://pubs.usgs.gov/sir/2013/5159/

Hunt, R.J., M.A. Borchardt, K.D. Richards, and S.K. Spencer. 2010. Assessment of sewer source contamination of drinking water wells using tracers and human enteric viruses. *Environmental Science and Technology* 44, no. 20: 7956–7963. https://doi.org/10.1021/es100698m

Jakeman, A.J., O. Barreteau, R.J. Hunt, J.-D. Rinaudo, and A. Ross (Eds). 2016. *Integrated Groundwater Management: Concepts, Approaches, Challenges*. Switzerland: Springer International Publishing AG.

Kheirinejad, S., O. Bozorg-Haddad, D. Savic, V.P. Singh, and H.A. Loáiciga. 2022. The effect of reducing per capita water and energy uses on renewable water resources in the water, food, and energy nexus. *Scientific Reports* 12: 7582. https://doi.org/10.1038/s41598-022-11595-w

Kiparksy, M., A.T. Fisher, W.M. Hanemann, J. Bowie, R. Kantor, C. Coburn, and B. Lockwood. 2018. Recharge Net Metering to Enhance Groundwater Sustainability. Issue Brief, University of California Water, Berkeley Law University of California, and University of California Santa Cruz. https://websites.pmc.ucsc.edu/∼afisher/CVpubs/pubs/Kiparsky2018˙CLEE˙ReNeM-IssueBrief.pdf

Konikow, L. 2013. Groundwater depletion in the United States (1900-2008). U.S. Geological Survey, Scientific Investigations Report 2013–5079, Reston, Virginia.

Konikow, L.F. and J.D. Bredehoeft. 2020. Groundwater Resource Development: Effects and Sustainability. The Groundwater Project, Guelph, Ontario, Canada. https://gw-project.org/books/groundwater-resource-development/

Kram, M., H. Loaiciga, M. Widdowson, E. Mendez, R. Solgi, and M. Lamar. 2023. Resolving the water crisis: there's a way, but is there the will? *Groundwater* 61, no. 5: 617–625. https://doi.org/10.1111/gwat.13310

Liu, P.W., J.S. Famiglietti, A.J. Purdy, K.H. Adams, A.L. McEnvoy, J.T. Reager, R. Bindlish, D.N. Wiese, C.H. David, and M. Rodell. 2022. Groundwater depletion in California's Central Valley accelerates during megadrought. *Nature Communications* 13: 7825. https://doi.org/10.1038/s41467-022-35582-x

Loaiciga, H.A. 2017. The safe yield and climatic variability: Implications for groundwater management. *Groundwater* 55, no. 3: 334–345.

Loaiciga, H.A. 2015. Managing municipal water supply and use in water-starved regions: Looking ahead. *Journal of Water Resources Planning and Management* 141, no. 1: 1–4. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000487

Loaiciga, H.A. 2003a. Climate change and groundwater. *Annals of the Association of American Geographers* 93, no. 1: 33–45. https://doi.org/10.1111/1467-8306.93103

Loaiciga, H.A. 2003b. Sustainable groundwater exploitation. *International Geological Review* 44, no. 12: 1115–1121.

Loaiciga, H.A., and M. Schofield. 2019. Climate variability and change and Edwards aquifer water fluxes. In *The Edwards Aquifer – The Past, Present, & Future of a Vital Water Resource, Chapter 19, Memoir 205*, ed. Brian A. Smith, and Brian B. Hunt. Boulder, Colorado: Geological Society of America.

Loaiciga, H.A., T. Pingel, and E. Garcia. 2012. Seawater intrusion by sea-level rise: Scenarios for the 21st century. *Groundwater* 50, no. 1: 37–47.

Loaiciga, H.A., D. Maidment, and J.B. Valdes. 2000. Climate change impacts in a regional karst aquifer, Texas, USA. *Journal of Hydrology* 227: 173–194. https://doi.org/10.1016/S0022-1694(99)00179-1

Lohman, S.W. 1972. *Groundwater Hydraulics. U.S. Geological Survey Professional Paper 708*. Washington, DC: U.S. Government Printing Office.

Louwyck, A., A. Vandenbohede, G. Heuvelmans, M. van Camp, and K. Walraevens. 2023. The water budget myth and its recharge controversy: Linear vs. nonlinear models. *Groundwater* 61, no. 1: 100–110. https://doi.org/10.1111/gwat.13245

Maples, S.R., E.M. Bruno, A.W. Kraus-Polk, S.N. Roberts, and L.M. Foster. 2018. Leveraging hydrologic accounting and water markets for improved water management: The case for a central clearinghouse. *Water*. 10, no. 12: 1720. https://doi.org/10.3390/w10121720

Margat, J., and J. van der Gun. 2013. *Groundwater Around the World*. Boca Raton, Florida: CRC Press.

Masoudi, R., G.H. Zehtabian, F. Jafary, and H.A. Loáiciga. 2019. Early warning system for desertification based on climatic and hydrologic criteria. *Desert* 24, no. 2: 183–195. https://doi.org/10.22059/JDESERT.2019.76359

National Oceanic and Atmospheric Administration. 2022. https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/

Pitron, G. 2023. *L'enfer Numérique*. Paris: Les Liens qui Libèrent.

Planert, M. and J. S. Williams. 1995. Groundwater atlas of the United States, segment 1: California Nevada. U.S. Geological Survey Hydrologic Investigations Atlas 730-B, Reston, Virginia. https://doi.org/10.3133/ha730B

Pokhrel, Y.N., S. Koirala, P.J.-F. Yeh, N. Hanasaki, L. Longuevergne, S. Kanae, and T. Oki. 2015. Incorporation of groundwater pumping in a global land surface model with the representation of human impacts. *Water Resources Research* 51: 78–96. https://doi.org/10.1002/2014WR015602

Portmann, F.T., P. Döll, S. Eisner, and M. Flörke. 2013. Impact of climate change on renewable groundwater resources: Assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. *Environmental Research Letters* 8, no. 2: 1–14. https://doi.org/10.1088/1748-9326/8/2/024023

Radmehr, A., O. Bozorg-Haddad, and H.A. Loáiciga. 2022. Integrated strategic planning and multi-criteria decision-making framework with its application to agricultural water management. *Scientific Reports* 12: 8406. https://doi.org/10.1038/s41598-022-12194-5

Reilly, T.E., K.F. Dennehy, W.M. Alley, and W.L. Cunningham. 2008. Groundwater availability in the United States. U.S. Geological Survey Circular 1323, Reston, Virginia. http://pubs.usgs.gov/circ/1323/

Roderick, M.L., F. Sun, W.H. Lim, and G.D. Farquhar. 2014. A general framework for understanding the response of the water cycle to global warming over land and ocean. *Hydrology and Earth System Sciences* 18: 1575–1589. https://doi.org/10.5194/hess-18-1575-2014

Roser, M., H. Ritchie, E. Ortiz-Ospina, and L. Rodés-Guirao. 2013. World Population Growth. OurWorldInData.org. https://ourworldindata.org/world-population-growth

Scanlon, B.R., C.F. Faunt, L. Longuevergne, R.C. Reedy, W.M. Alley, V.L. McGuire, and P.B. McMahon. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *National Academy of Sciences of the United States of America* 109, no. 24: 9320–9325. https://doi.org/10.1073/pnas.120031110

Sheibani, R., M. Sheibani, and M. Parandoust. 2023. Brine discharge disrupts Persian Gulf ecosystems. *Science* 380, no. 6645: 591. https://doi.org/10.1126/science.adh8179

Sophocleous, M. 1997. Managing water resources systems: Why "safe yield" is not sustainable. *Groundwater* 35, no. 4: 561.

Sterret, R.J. 2007. *Groundwater and Wells*, 3rd ed. New Brighton, Minnesota: Johnson Screens.

Theis, C.V. 1940. The source of water derived from wells: Essential factors controlling the response of an aquifer to development. *Civil Engineering* 10: 277–280.

Thornthwaite, C.W. 1948. An approach to a rational classification of climate. *Geographical Review* 38, no. 1: 55–94.

U.S. Energy Information Administration. 2023. https://www.eia.gov/totalenergy/data/browser/

U.S. Fish and Wildlife Service. 2013. Final environmental impact statement and record of decision on the Edwards aquifer recovery implementation program habitat conservation plan for incidental take of 11 species (8 federally listed) in 8 Texas counties. Federal Register 78, no. 32: 11, 11218–11220.

United Nations. 2023. https://population.un.org/wpp/Download/Standard/Population/

United Nations Educational, Scientific and Cultural Organization (UNESCO). 2022. *Eaux Souterraines: Rendre Visible L'invisible*. Paris: United Nations-Water.

Wada, Y. 2016. Modeling groundwater depletion at regional and global scales: Present state and future prospects. *Surveys in Geophysics* 37: 419–451. https://doi.org/10.1007/s10712-015-9347-x

Wada, Y., and M.F.P. Bierkens. 2014. Sustainability of global water use: Past reconstructions and future projections. *Environmental Research Letters* 9: 104003. https://doi.org/10.1088/1748-9326/9/10/104003

Wada, Y., L.P.H. van Beek, C.M. van Kempen, J.W.T.M. Reckman, S. Vasak, and M.F.P. Bierkens. 2010. Global depletion of groundwater resources. *Geophysical Research Letters* 37: L20402. https://doi.org/10.1029/2010GL044571

Yao, F., B. Livneh, B. Rajagopalan, J. Wang, J.F. Crétaux, Y. Wada, and M. Berge-Nguyen. 2023. Satellites reveal widespread decline in global lake water storage. *Science* 380: 743–749. https://doi.org/10.1126/science.abo2812

Zareie, S., O. Bozorg-Haddad, and H.A. Loaiciga. 2021. A state-of-the-art review of water diplomacy. *Environment, Development and Sustainability* 23: 2337–2357. https://doi.org/10.1007/s10668-020-00677-2

Zektser, I.S., H.A. Loaiciga, and J. Wolf. 2005. Environmental impacts of groundwater overdraft: Selected case studies in the southwestern United States. *Journal of Environmental Geology* 47, no. 3: 396–404.