Proceedings of the 3rd International Conference on Environmental Geoscience and Earth Ecology
DOI: 10.54254/2753-8818/94/2025.21675

Interactions Between Groundwater Use and Climate Change

Xiaowen Sun[1,a,*]

[1]South District, Huaihai Huafu, Xiangshan District, Huaibei City, Anhui Province, 235000, China
a. sun.sxw@foxmail.com
**corresponding author*

Abstract: Groundwater is a crucial resource for irrigation and domestic use, particularly in China and the United States. Nevertheless, climate change and excessive extraction threaten its sustainability. Over-exploitation not only accelerates climate change but also heightens groundwater's vulnerability to its effects. Declining water tables and disrupted aquifer recharge reduce long-term availability, while groundwater pumping releases dissolved carbon and nitrogen compounds, contributing to greenhouse gas emissions. Deeper extraction demands greater energy input, primarily from fossil fuels, further exacerbating emissions. These dynamics position groundwater depletion as both an environmental and climate challenge. This study reviews the effects of environmental change on groundwater availability and management, explores strategies for regulating its use in irrigation, and proposes effective measures to safeguard the long-term sustainability of this finite resource. By analyzing trends in major groundwater-dependent regions, the study advances understanding of how environmental changes influence groundwater availability and quality. The significance of this research extends beyond regional case studies, offering insights into the global implications of groundwater depletion. The findings underscore the urgent need for policy interventions, including regulated extraction, enhanced recharge methods, and energy-efficient irrigation practices, to safeguard this critical resource for future generations.

Keywords: Climate change, Greenhouse gas (GHG) emissions, Groundwater extraction, Energy efficiency, Sustainable groundwater management

1. Introduction

Groundwater is a vital resource supporting irrigation, drinking water, and industry worldwide. Excessive extraction and climate change, however, pose significant threats to its long-term viability and sustainability. Serving as both a source and sink of greenhouse gases, groundwater pumping releases dissolved carbon and nitrogen compounds, intensifying climate change [1]. Furthermore, declining groundwater tables increase energy-intensive pumping, further elevating greenhouse gas emissions [2]. Climate change, through altered precipitation patterns and rising temperatures, affects groundwater recharge, impacting availability and quality [3]. These challenges are particularly evident in high-use regions such as the United States and China, where groundwater extraction for irrigation significantly contributes to aquifer depletion [4].

This study investigates the environmental impacts of groundwater depletion, focusing on its contribution to climate change and the consequences of climate variability on groundwater availability. Specifically, it examines: (1) how groundwater extraction influences greenhouse gas

DOI: 10.54254/2753-8818/94/2025.21675

emissions, (2) the effects of climate change on groundwater recharge and storage, and (3) potential measures for sustainable groundwater management.

The significance of this research lies in its contribution to understanding groundwater's role in climate change and resource sustainability. By analyzing trends in major groundwater-dependent regions, the study provides insights into global water security challenges and offers recommendations for policy interventions, including improved irrigation efficiency, recharge enhancement, and energy-efficient water extraction. Addressing these issues is critical for mitigating environmental degradation, ensuring food security, and maintaining groundwater availability for future generations [5].

2. Impact of Groundwater Extraction and Use

Precipitation carries a carbon dioxide concentration comparable to that of the atmosphere. Whereas soil carbon dioxide levels are about 100 times higher than in the atmosphere due to the degradation of organic carbon to carbon dioxide by soil microbes and the additional carbon produced by water dissolving these microbes [6]. In the absence of external disturbances, carbon-rich groundwater would typically remain stored for hundreds to thousands of years before eventually discharging into surface water bodies such as rivers, lakes, and oceans [6] (Figure 1). However, the partial pressure of CO2 in groundwater is generally 10 to 100 times higher than in the atmosphere, making CO2 degassing an inevitable consequence of groundwater extraction [7]. Extensive global groundwater pumping has led to substantial discharges into non-aquatic terrestrial environments, while groundwater irrigation has altered and redistributed soil elements, disrupting natural cycles and increasing the risk of ecological and environmental degradation [8]. With groundwater being extracted at an unprecedented rate, this release of stored carbon contributes significantly to anthropogenic atmospheric carbon loads, exacerbating climate change.

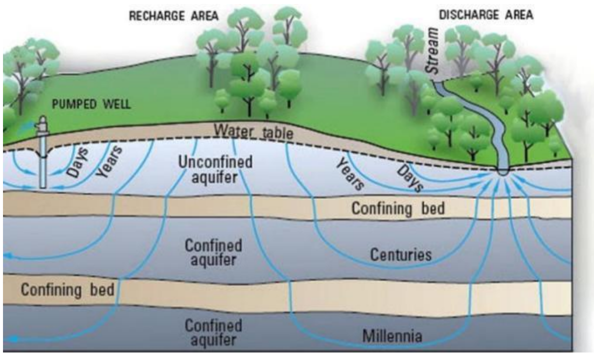

Figure 1: Aquifer recharge. Credit: USGS [9]

According to the USGS, groundwater extraction in the United States amounts to 25 cubic kilometers (6 cubic miles) annually, carrying approximately 2.4 million metric tons (5.2 billion pounds) of bicarbonate, with nearly half converting into atmospheric carbon dioxide [6]. This release—1.7 million metric tons (3.8 billion pounds) per year—surpasses the emissions from electricity use in 250,000 U.S. homes [6].

Beyond its atmospheric impacts, excessive groundwater extraction leads to severe environmental consequences, leading to the deterioration of ecosystem structures and functions, including land subsidence, saltwater intrusion, and chemical contamination, with recovery times significantly longer than those of surface water [10]. Furthermore, human-induced land use changes—such as deforestation for agriculture—alter hydrological cycles, affecting groundwater recharge and further diminishing available water resources [7]. Declining surface water availability, exacerbated by pollution and reduced river flows, has increased dependence on groundwater in many regions, often beyond sustainable levels [11]. The resulting depletion has already caused perennial river flows to

DOI: 10.54254/2753-8818/94/2025.21675

decline or vanish entirely in several areas. Over-extraction has also led to a severe decline in groundwater availability for both human consumption and commercial use, placing immense stress on water security [12]. In California, prolonged groundwater overdraft has not only undermined the state's long-term water supply but also caused extensive land subsidence, infrastructure damage, and degradation of groundwater-dependent ecosystems, raising serious concerns about the sustainability of the state's groundwater resources [13].

Effective groundwater management is essential to mitigate these cascading impacts. Without proactive intervention, continued overuse will further accelerate environmental degradation, disrupt ecosystems, and exacerbate climate-related challenges.

3. Impact of Climate on Groundwater

Increasing evidence suggests that human activities are driving an unprecedented period of climate change [14]. The IPCC indicates that global mean surface temperatures have risen by approximately 0.6°C since 1861, with forecasts predicting an additional 2°C to 4°C increase over the next century [15] (Figure 2). These shifts are expected to alter the hydrological cycle by modifying precipitation and evaporation dynamics [14]. Climate change promotes frequent and intense hydrological extremes, which affect groundwater recharge [16].

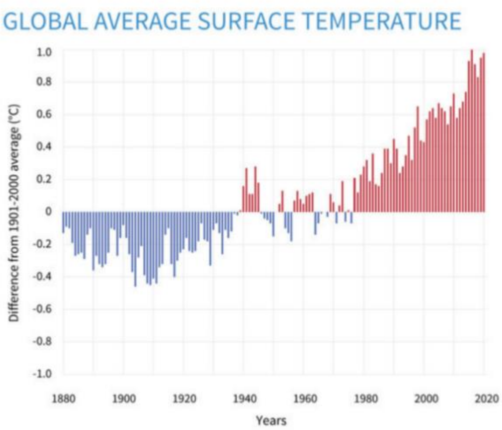

Figure 2: Yearly surface temperatures from 1880 to 2020 compared to the 20th-century average [17]
Note: Blue bars in Figure 2 represent years with lower-than-average temperatures; red bars denote years with higher-than-average temperatures.

In cold regions, permafrost significantly influences groundwater dynamics by restricting infiltration and subsurface flow, thereby shaping hydrological processes [18]. Glacial and snowmelt contribute significantly to groundwater recharge, with meltwater transported from high-altitude regions via streams and aquifers [19]. Permafrost is a key factor in groundwater dynamics, limiting infiltration and subsurface flow and thereby impacting the hydrological cycle in cold regions [18]. Its interactions with groundwater have significant implications for water management, infrastructure, biogeochemical cycles, and downstream water resources [19]. Permafrost shapes water flow patterns in polar regions, impacting stream discharge and thermal dynamics. Slope and upper permafrost aquifers capture precipitation across extensive areas, channeling it as surface runoff and shallow groundwater toward talus fans in foothills or hills, eventually replenishing aquifers in adjacent plains [19]. The transfer of carbon as well as nutrients to surface waters through groundwater in permafrost zones can alter the productivity of aquatic ecosystems, and changes in groundwater discharge associated with permafrost thawing may also alter surface water ecosystems [18]. Due to current environmental changes and global warming, permafrost is warming and thawing in many parts of the

DOI: 10.54254/2753-8818/94/2025.21675

world [19]. Groundwater is also becoming increasingly important as permafrost, an effective recharge barrier, continues to degrade. Snow-dominated systems provide water for one-sixth of the world's human population, and changes to snowpack, melt, and subsequent water allocation caused by climate and environmental change can reduce streamflow and control the sources and transport of hydrologic processes [20]. Streams partially infiltrate into aquifers as they flow through open plains and are recharged by groundwater as they flow through canyons [19]. Complex topography increases rain-to-snow ratios, and early spring arrival also reduces groundwater recharge in mountainous regions [21].

Future climate change and other developments may impact the availability of groundwater for drinking water supply [22]. Groundwater resources are often the preferred source of drinking water supply because they are considered less susceptible to contamination than surface water and because groundwater quality is relatively stable [22]. Climate change may lead to the deterioration of valuable groundwater-dependent ecosystems due to desiccation. In addition, climate change may directly lead to a reduction in base flows due to reduced groundwater recharge from, for example, melting snow.

Climate change is expected to intensify challenges in sustaining water supplies in arid regions. Rising temperatures and increased evaporation are likely to reduce surface flows in the southwestern United States. Nearly 30 percent of irrigated groundwater in the United States comes from the Ogallala Aquifer, the largest aquifer in the United States, which stretches across eight states in the Great Plains, including Colorado [23] (Figure 3). Yet, projections indicate a 10%–30% decline in Colorado River flows, with an 85% likelihood of reduced flows in the Salt and Verde River basins by 2050 [11]. As surface water sources become increasingly unreliable, greater dependence on groundwater extraction is likely, further depleting aquifers and exacerbating water scarcity. The combined effects of climate change—rising temperatures, prolonged droughts, and hydrological shifts—pose significant challenges for water management, necessitating adaptive strategies to ensure long-term groundwater sustainability.

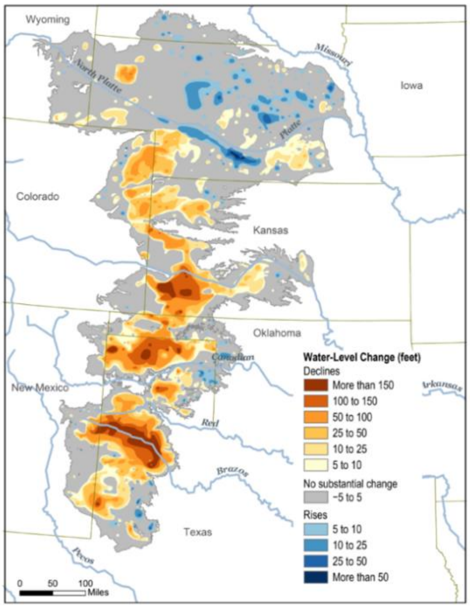

Figure 3: The change in water levels at Ogallala from before the aquifer was tapped to 2015 [23]
Note: Declining water levels are shown in red and orange, and rising water levels are shown in shades of blue. The darker the color, the greater the change. Gray indicates no significant change.

DOI: 10.54254/2753-8818/94/2025.21675

4. Strategies for Groundwater Sustainability and Policy Implementation

Despite the fact that comprehensive data on groundwater sustainability measures remains limited, various studies and policy initiatives have been implemented to mitigate depletion and ensure long-term water security. Researchers have explored strategies to balance groundwater use with conservation efforts, and a number of policies are actively being adopted to address these challenges.

One widely supported approach involves incentive-based water conservation programs for agricultural irrigation, which can enhance efficiency while reducing groundwater losses from runoff and evaporation. These programs allow farmers to adopt irrigation systems at lower costs, leading to higher profits while simultaneously promoting water conservation [24]. In the United States, particularly in states where groundwater serves as the primary water resource, conservation-focused subsidies for irrigation technologies and land retirement programs have been introduced to assess their effectiveness in limiting groundwater extraction. Since 1996, Kansas has enrolled an average of 2.7 million acre-feet of land annually in the Conservation Reserve Program, a federal initiative aimed at reducing excessive water withdrawals [24]. Additionally, Michigan State University has outlined a series of recommendations, including wellhead protection plans that involve historical land-use assessments, inventories of current land use, and proactive measures to prevent contamination [25]. Other strategies include zoning amendments for groundwater protection, municipal well regulations, police power ordinances, and public education campaigns to enhance groundwater management.

Notwithstanding these efforts, some conservation measures have yielded mixed results. For example, groundwater reduction initiatives in Kansas have not significantly curtailed extraction, as shifts in cropping patterns have inadvertently increased groundwater demand [24]. This highlights the need for comprehensive, adaptive management strategies that account for both economic and environmental factors.

In China, groundwater protection has become a national priority, with the government issuing a series of regulatory policies aimed at sustainable water resource management. The 2012 "Opinions of the State Council on Implementing the Strictest Water Resources Management System" outlined clear objectives for groundwater protection, focusing on rationalizing usage, limiting over-extraction, and improving long-term sustainability [26]. To support these efforts, the Chinese central government allocated approximately RMB 1.8 billion (US $265 million) to establish a nationwide groundwater observation network, designed to monitor thousands of wells and assess freshwater depletion trends [27]. While the full implementation of this project remains incomplete, notable progress has been made. By 2020, China successfully reduced national groundwater extraction to 89.25 billion cubic meters, meeting the policy target of keeping groundwater use below 100 billion cubic meters per year [28].

However, challenges remain, particularly in ecologically fragile regions, such as northwest China, where groundwater is essential due to scarce precipitation [29] (Figure 4). In these areas, groundwater serves as a critical resource for sustaining plant life and wetland ecosystems, yet extraction has only been partially reduced rather than fully controlled [26]. This underscores the need for more targeted policies that address regional disparities in water dependency and climate variability.

DOI: 10.54254/2753-8818/94/2025.21675

Figure 4: Spatial distribution of groundwater resources in China [29]

While efforts in both the United States and China have made strides toward more sustainable groundwater management, ongoing challenges demand further refinement of policies, stronger enforcement mechanisms, and integrated water resource planning to safeguard groundwater for future uses.

5. Conclusion

Groundwater is a fundamental freshwater resource essential for agriculture, industry, and domestic needs. Nevertheless, climate change and environmental degradation intensify stress on groundwater systems, reducing recharge rates and limiting availability. In regions like the United States and China, heavy reliance on groundwater has led to over-extraction, causing irreversible aquifer damage. Besides, groundwater pumping contributes to climate change by releasing greenhouse gases such as carbon dioxide. These interlinked challenges underscore the urgent need for sustainable groundwater management. Despite the severity of groundwater depletion, it remains an under-addressed issue, requiring further research, policy interventions, and international cooperation.

Looking ahead, effective groundwater governance must integrate environmental, economic, and energy considerations. Future efforts should focus on cost-effective policies, alternative water sources, and improved hydrological models for forecasting trends and informing adaptive strategies. Strengthening groundwater monitoring, addressing land subsidence, and promoting efficient agricultural practices can further support resource conservation and sustainable development.

Public engagement and education are also vital for long-term sustainability. Raising awareness about groundwater conservation and fostering collaboration among policymakers, researchers, and local communities can help balance economic growth with resource protection. Through informed decision-making, technological advancements, and collective action, it is possible to ensure groundwater sustainability for future generations while mitigating the broader impacts of climate change.

References

[1] *Minamikawa, K., Nishimura, S., Sawamoto, T., Nakajima, Y., & Yagi, K. (2010). Annual emissions of dissolved CO2, CH4, and N2O in the subsurface drainage from three cropping systems. Global Change Biology, 16(2), 796-809.*

[2] *Lal, R. (2004). Carbon emission from farm operations. Environnent International, 30(7), 981-990. https://doi.org/10.1016/j.envint.2004.03.005*

[3] *Aquilina, L., Vergnaud-Ayraud, V., et al. (2015). Impact of climate changes during the last 5 million years on groundwater in basement aquifers. Scientific Reports, 5(1).*

DOI: 10.54254/2753-8818/94/2025.21675

[4] *Portmann, F. T., Döll, P., Eisner, S., & Flörke, M. (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(2), 024023. https://doi.org/10.1088/1748-9326/8/2/024023*

[5] *Jia, X., O'Connor, D., Hou, D., et al. (2019). Groundwater depletion and contamination: Spatial distribution of groundwater resources sustainability in China. Science of The Total Environment, 672, 551-562. https://doi.org/10.1016/j.scitotenv.2019.03.457*

[6] *Wood, W. W., & Hyndman, D. W. (2017). Groundwater depletion: A significant unreported source of atmospheric carbon dioxide. Earth's Future, 5(11), 1133-1135.*

[7] *Macpherson, G. (2009). CO2 distribution in groundwater and the impact of groundwater extraction on the global C cycle. Chemical Geology, 264(1-4), 328-336.*

[8] *Stahl, M. O. (2018). Groundwater pumping is a significant unrecognized contributor to global anthropogenic element cycles. Groundwater, 57(3), 455-464.*

[9] *Groundwater and aquifers. (2019). Pinelands Preservation Alliance - Protecting the New Jersey Pinelands and Pine Barrens, April 25. https://pinelandsalliance.org/learn-about-the-pinelands/ecosystem/water/groundwater-and-aquifers/*

[10] *Zhou, Z., Wang, C., Bi, J., Zhao, Y., & Xiang, W. (2021). Simulation of underground freshwater exploitation and analysis of environmental impact in Hangzhou Bay new area, China. Natural Resources Research, 30(2), 1781-1794.*

[11] *Marshall, R. M., Robles, M. D., et al. (2010). Sustainable water management in the southwestern United States: Reality or rhetoric? PLoS ONE, 5(7), e11687.*

[12] *Eamus, D., Zolfaghar, S., Villalobos-Vega, R., Cleverly, J., & Huete, A. (2015). Groundwater-dependent ecosystems: Recent insights from satellite and field-based studies. Hydrology and Earth System Sciences, 19(10), 4229-4256.*

[13] *Ke, J., & Blum, H. (2021). A panel analysis of groundwater use in California. Journal of Cleaner Production, 326, 129357. https://doi.org/10.1016/j.jclepro.2021.129357*

[14] *Goodarzi, M., Abedi-Koupai, J., & Heidarpour, M. (2018). Investigating impacts of climate change on irrigation water demands and its resulting consequences on groundwater using CMIP5 models. Groundwater, 57(2), 259-268. https://doi.org/10.1111/gwat.12771*

[15] *Kumar, C.P. 2012. Climate change and its impact on groundwater resources. International Journal of Engineering and Science 1, no. 5: 43–60.*

[16] *Lall, U., Josset, L., & Russo, T. (2020). A snapshot of the world's groundwater challenges. Annual Review of Environment and Resources, 45(1), 171-194.*

[17] *Lindsey, R., & Dahlman, L. (2021). Climate change: Global temperature. NOAA Climate.gov | science & information for a climate-smart nation, August 12. https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature*

[18] *Sjöberg, Y., Jan, A., Painter, S. L., et al. (2021). Permafrost promotes shallow groundwater flow and warmer headwater streams. Water Resources Research, 57(2).*

[19] *Shaw, G. D., Conklin, M. H., Nimz, G. J., & Liu, F. (2014). Groundwater and surface water flow to the Merced River, Yosemite Valley, California:36Cl and Cl−evidence. Water Resources Research, 50(3), 1943-1959. https://doi.org/10.1002/2013wr014222*

[20] *Carroll, R. W., Bearup, L. A., et al. (2018). Factors controlling seasonal groundwater and solute flux from snow-dominated basins. Hydrological Processes, 32(14), 2187-2202.*

[21] *Ma, R., Sun, Z., Hu, Y., et al. (2017). Hydrological connectivity from glaciers to rivers in the Qinghai–Tibet plateau: Roles of suprapermafrost and subpermafrost groundwater. Hydrology and Earth System Sciences, 21(9), 4803-4823.*

[22] *Van Engelenburg, J., Hueting, R., et al. (2017). Impact of changes in groundwater extractions and climate change on groundwater-dependent ecosystems in a complex Hydrogeological setting. Water Resources Management, 32(1), 259-272.*

[23] *Karuga, J. (2017). Where is the Ogallala aquifer? WorldAtlas, April 25. https://www.worldatlas.com/articles/where-is-the-ogallala-aquifer.html*

[24] *Pfeiffer, L., & Lin, C. C. (2009). "Incentive-Based Groundwater Conservation Programs: Perverse Consequences?" ARE Update 12(6): 1-4. University of California Giannini Foundation of Agricultural Economics. https://giannini.ucop.edu/filer/file/1453327752/16814/*

[25] *Michigan State University. (2019). Local government strategies to protect groundwater. Government, October 8. https://www.canr.msu.edu/news/local_government_strategies_to_protect_groundwater*

[26] *Yu, L., Ding, Y., Chen, F., et al. (2017). Groundwater resources protection and management in China. Water Policy, 20(3), 447-460. https://doi.org/10.2166/wp.2017.035*

[27] *Qiu, J. (2010). China faces up to groundwater crisis | Nature, July 13. https://rdcu.be/cKM3H*

[28] *Ministry of water resources the People's Republic of China. (2020). https://www.mwr.gov.cn/english/*

DOI: 10.54254/2753-8818/94/2025.21675

[29] Liu, J., & Zheng, C. (2016). Towards integrated groundwater management in China. In Integrated Groundwater Management: Concepts, Approaches and Challenges (pp. 455–475). Springer International Publishing.