

Groundwater Depletion in a Changing Climate: Risks, Challenges, and Pathways to Sustainability

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Abstract:

Climate change is exacerbating groundwater depletion, a critical issue that threatens water security, ecosystems, and livelihoods worldwide. Rising temperatures, erratic precipitation patterns, and prolonged droughts are reducing natural groundwater recharge rates, while increasing demand for irrigation, industrial, and domestic use is accelerating extraction. This unsustainable exploitation of groundwater resources poses significant risks, including land subsidence, reduced streamflows, and the salinization of aquifers, particularly in arid and semi-arid regions. The interplay between climate change and groundwater depletion creates a feedback loop, where declining water availability further stresses communities and ecosystems, making them more vulnerable to climate impacts. To address these challenges, effective mitigation strategies are essential. These include promoting water-efficient agricultural practices, such as drip irrigation and crop diversification, implementing managed aquifer recharge (MAR) techniques to enhance groundwater replenishment, and adopting integrated water resource management (IWRM) frameworks. Policy measures, such as regulating groundwater extraction and incentivizing sustainable use, are equally critical. Additionally, leveraging advanced technologies like remote sensing, GIS, and AI can improve groundwater monitoring and management. Public awareness and community engagement are also vital to fostering conservation efforts. By combining scientific innovation, policy intervention, and stakeholder collaboration,

it is possible to mitigate the risks of groundwater depletion and build resilient water systems capable of withstanding the pressures of climate change, ensuring long-term water security for future generations.

Keywords: Climate change, groundwater depletion, water security, managed aquifer recharge, sustainable agriculture, integrated water resource management, land subsidence, mitigation strategies.

1. Introduction

Groundwater is the backbone of global freshwater supply, supporting domestic, agricultural, industrial, and ecological needs. It constitutes approximately 30% of the world's total freshwater resources and accounts for nearly 99% of accessible freshwater not locked in glaciers or ice caps (Davamani et al., 2024). Over 1.5 billion people rely directly on groundwater for drinking water, and up to 70% of global irrigation depends on groundwater withdrawals, underscoring its significance for food security and livelihoods.

However, the sustainability of groundwater resources is under increasing threat due to the compounded impacts of climate change and anthropogenic pressures. Over-extraction for agriculture, urbanization, industrial activities, and pollution have already strained aquifers, but climate-induced changes in precipitation patterns, temperature regimes, evapotranspiration, and land use further exacerbate groundwater depletion. According to the IPCC (2021), global temperatures are projected to rise by 2–4°C by the end of the 21st century, with significant implications for the hydrological cycle. These changes can reduce groundwater recharge, increase variability in discharge, alter groundwater temperature, and deteriorate water quality.

While surface water resources have received substantial attention in climate studies, groundwater—a more stable but less visible resource—has only recently become a focus of integrated climate-resilience planning. The complex interplay of hydrological processes under changing climate scenarios introduces significant uncertainties in groundwater management. Moreover, the indirect effects of climate change,

such as changes in vegetation, land cover, and socio-economic water demands, further complicate predictions.

Given the critical role groundwater plays in ensuring water security and climate adaptation, this review aims to synthesize existing knowledge on climate-groundwater interactions, highlight modelling innovations, and identify sustainable pathways for resource management. By integrating biophysical, technological, and policy perspectives, it seeks to offer a comprehensive understanding of the challenges and solutions related to groundwater depletion in a changing climate.

2. Climate Change and Groundwater Interactions

The interaction between climate change and groundwater systems is multifaceted, encompassing direct impacts such as altered precipitation patterns and increased temperatures, as well as indirect influences through changes in land use, vegetation, and water demand. Groundwater, which supports nearly 50% of global drinking water supplies and 70% of agricultural irrigation (Davamani et al., 2024), is highly sensitive to fluctuations in the hydrological cycle driven by climate variability.

One of the most direct consequences of climate change is the alteration of precipitation patterns—not just in quantity but also in intensity, seasonality, and type (e.g., snow vs. rain). In regions experiencing reduced rainfall or longer dry spells, recharge rates decline significantly, leading to falling groundwater levels. Conversely, areas receiving more intense rainfall events may still see limited recharge, as high-intensity precipitation often increases surface runoff rather than allowing infiltration (Kurylyk et al., 2014). Additionally, the shift from snow to rain in colder regions results in earlier and more rapid snowmelt, potentially reducing spring recharge and increasing winter recharge, thereby altering groundwater availability seasonally (Davamani et al., 2024).

Temperature rise is another critical driver. As global mean temperatures increase, evapotranspiration from soil and plants intensifies, reducing the amount of water that can percolate into the subsurface. This is particularly relevant in

tropical and arid regions, where higher evapotranspiration can drastically diminish recharge, even if precipitation remains constant (Liesch & Wunsch, 2019). Furthermore, climate-induced changes in vegetation, such as shifts in crop patterns or deforestation, also modify infiltration rates and water demand, creating complex feedbacks in groundwater dynamics.

The impacts on groundwater discharge are equally significant. Many rivers and streams rely on baseflow contributions from aquifers, and reduced groundwater levels diminish these flows, affecting surface water ecosystems. For instance, studies predict declining groundwater-fed spring flows in areas like the southwestern United States and the Himalayas due to prolonged dry periods and extraction pressures (Asoka et al., 2017; Russo & Lall, 2017).

In addition to quantity, groundwater quality is increasingly vulnerable. Warmer temperatures and variable recharge conditions facilitate the transport of contaminants such as nitrates and heavy metals from surface sources into aquifers. In coastal regions, saltwater intrusion—driven by sea-level rise and over-pumping—further degrades water quality, particularly in low-lying areas (Mustafa, 2019). Climate change can also intensify the leaching of pollutants during high recharge events, especially in agricultural zones with excessive fertilizer use (Alam et al., 2019).

Overall, the interaction of groundwater with climate systems is governed by a web of interdependent processes, including surface water exchanges, land cover dynamics, and socio-economic pressures. These complexities underscore the importance of integrated modelling approaches and vulnerability assessments to anticipate and manage groundwater sustainability in a warming world (Davamani et al., 2024).

3. Risks and Challenges of Groundwater Depletion

Groundwater depletion presents a multifaceted challenge to water security, environmental stability, and socio-economic development. The most immediate risk of excessive groundwater withdrawal is the reduction in water availability

for drinking, agriculture, and industrial use, particularly in arid and semi-arid regions where alternative water sources are limited (Davamani et al., 2024). This depletion threatens food security by undermining irrigated agriculture, which relies on groundwater for 60–70% of its supply globally (Velis et al., 2017).

One critical ecological consequence is the diminished groundwater discharge into streams, wetlands, and lakes, which sustains groundwater-dependent ecosystems (GDEs). Reduced baseflow alters aquatic habitats, impairs biodiversity, and contributes to the desiccation of wetlands and riverbeds, especially during dry seasons (Russo & Lall, 2017). Additionally, falling water tables force communities to drill deeper wells, escalating the energy and financial costs of water extraction. This creates a disproportionate burden on poor and marginalized populations, exacerbating social inequities (Asoka et al., 2017).

Another major concern is land subsidence, a phenomenon resulting from the compaction of aquifer systems due to long-term groundwater extraction. This has been observed in urban centers like Jakarta, Tehran, and regions such as California's Central Valley and northwestern India (Davamani et al., 2024). Land subsidence can damage infrastructure, compromise building foundations, and increase vulnerability to flooding, especially in low-lying areas.

In coastal zones, groundwater depletion accelerates saltwater intrusion, where seawater infiltrates freshwater aquifers. Rising sea levels due to climate change intensify this risk. Once salinized, aquifers become difficult and costly to remediate, posing long-term challenges for coastal agriculture and potable water supply (Mustafa, 2019).

Groundwater quality also deteriorates as aquifers are overexploited. Reduced recharge and fluctuating water tables increase the concentration of contaminants such as nitrates, arsenic, fluoride, and heavy metals. Agricultural runoff, industrial discharges, and poorly managed sanitation systems further compound this degradation, especially during high recharge events that mobilize pollutants into aquifers (Alam et al., 2019).

Overall, groundwater depletion is not merely a hydrological concern but a critical sustainability issue. It intersects with health, food, energy, and climate resilience, requiring integrated and adaptive management strategies that account for both natural and human-induced stressors.

4. Modelling Approaches and Groundwater Vulnerability Assessment

Simulation models are indispensable for assessing groundwater responses to climate stressors. Widely used models include MODFLOW, HYDRUS, and WetSpa, which integrate climate, land-use, and hydrogeological parameters (Scibek & Allen, 2006; Waikar&Somwanshi, 2014).

There are two broad categories of vulnerability assessment models: index-based (e.g., DRASTIC, GOD, GALDIT) and process-based or numerical models. Index-based models are simpler and require fewer data, making them suitable for rapid assessments. Process-based models provide more detailed outputs, including pollutant transport and recharge estimates, but require extensive data and computational power (Davamani et al., 2024).

Examples include:

Punjab, India: Predicted groundwater nitrate pollution to rise to 66% by 2040 (Sarkar et al., 2022).

Vientiane, Laos: Recharge projected to increase by 22–47% under future rainfall scenarios (Pham et al., 2019).

Arusha, Tanzania: Recharge may fall by 30–44% by 2050 due to increased evapotranspiration and reduced rainfall (Davamani et al., 2024).

5. Simulation Tools, Uncertainty, and Model Assumptions

Climate models used in groundwater assessments often include General Circulation Models (GCMs) under different Shared Socioeconomic Pathways (SSPs). However, these models are limited by coarse spatial resolution and assumptions regarding soil and aquifer properties (van der Knaap et al., 2015).

Key assumptions affecting accuracy include:

Use of lumped average slopes in topographic calculations.

Homogeneous aquifer characteristics across diverse geological settings.

Instantaneous sea level rise assumptions, rather than gradual trends (Golden et al., 2020).

Such oversimplifications may distort vulnerability estimates. Incorporating spatial variability through distributed models and high-resolution Digital Elevation Models (DEMs) is essential to enhance accuracy (Zume & Tarhule, 2011).

6. Hybrid Frameworks and Future Modelling Innovations

Hybrid approaches that combine index-based and process-based models offer promising advancements. For instance, integrating DRASTIC with MODFLOW allows spatial vulnerability mapping alongside predictive simulations (Aslam et al., 2019). These approaches leverage the strengths of both methodologies, reducing limitations related to data and scale.

Moreover, vulnerability assessments are increasingly incorporating exposure and sensitivity indicators, such as land use, evapotranspiration, slope, and groundwater depth. Adaptive capacity, a key IPCC vulnerability component, can be assessed using socio-economic indicators like income, education, and governance quality (Velis et al., 2017).

7. Artificial Intelligence, Machine Learning, and Quantum Computing in Hydrology

Recent years have seen growing use of AI and machine learning (ML) in groundwater modelling. Algorithms such as Random Forest, Boosting, and Neural Networks are used to predict groundwater levels, recharge zones, and contamination risks (Nyenje & Batelaan, 2012).

For example:

PERSIANN and its variants are leading ML-based tools for rainfall estimation.

Random Forests have been applied to model land subsidence due to over-extraction (Pham et al., 2019).

Quantum computing, though nascent, holds promise for solving complex inverse problems in hydrology. Algorithms like quantum annealing and inverse Laplacian solvers have been tested to accelerate groundwater simulations (Golden et al., 2020).

8. Policy Implications and Sustainable Water Resource Management

Addressing groundwater depletion requires multi-scalar, integrated policy responses. Key recommendations include:

Integrated Water Resource Management (IWRM): Encouraging basin-level planning that incorporates surface and groundwater, stakeholder participation, and ecological concerns (UNEP, 2021).

Adaptive Policies: Embedding flexibility into water governance to accommodate climate uncertainties.

Water Pricing: Reflecting the real cost of extraction and incentivizing conservation.

Infrastructure Investments: Supporting aquifer recharge projects, wastewater reuse, and monitoring systems.

Community Participation: Strengthening local governance and ensuring inclusive decision-making.

Healthy ecosystems must be protected to preserve natural recharge zones and maintain water quality. Policies should promote land-use regulations and restoration of wetlands and forests.

9. Conclusion

Groundwater depletion under the stress of climate change presents a formidable challenge to global water security and environmental sustainability. As climate variability alters precipitation patterns, intensifies evapotranspiration, and exacerbates extreme weather events, the pressure on already overexploited aquifers continues to grow. This review underscores the intricate and interdependent

dynamics between climate drivers and groundwater systems, highlighting both the direct hydrological impacts and the cascading effects on water quality, ecosystems, food production, and human livelihoods.

Advancements in hydrological modelling, particularly the integration of artificial intelligence, remote sensing, and uncertainty quantification, offer promising pathways for assessing and mitigating these risks. However, challenges remain in scaling models appropriately, addressing data limitations, and incorporating socio-economic variables into decision-making processes.

Sustainable groundwater management requires a paradigm shift—from reactive crisis responses to proactive, integrated water governance. Policies must embrace adaptive, inclusive, and science-informed frameworks, balancing ecological protection with human development needs. Collaboration among governments, researchers, local communities, and global institutions is essential to building resilient water systems.

Ultimately, safeguarding groundwater in a changing climate is not just a technical or environmental task—it is a societal imperative central to achieving the Sustainable Development Goals and ensuring long-term resilience for future generations.

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