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# Vulnerability of Groundwater Quality and Hydrology to Climate Change Induced Factors: Temperature and Precipitation

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ABSTRACT

Groundwater is a critical freshwater resource, supplying drinking water to billions of people and supporting agriculture, industry, and ecosystems worldwide. However, climate change poses significant risks to groundwater quality and hydrology through altered precipitation patterns, and rising temperatures. These changes lead to declining groundwater recharge, fluctuating water tables, and increased contamination risks, threatening water security and ecosystem health globally. Despite groundwater's natural buffering capacity, climate-induced factors such as temperature and precipitation exacerbate its vulnerability. This paper reviews climate-related impacts on groundwater quality and hydrology, focusing on precipitation and temperature factors influencing recharge and storage. It further explores adaptive strategies for sustainable groundwater management, including artificial recharge, enhanced monitoring, demand regulation, and integrated water resource management (IWRM). Mitigation measures, such as reducing greenhouse gas emissions, promoting sustainable land use, improving wastewater treatment, and adopting renewable energy, are crucial to safeguarding groundwater quality. Effective groundwater protection under climate change requires coordinated efforts to balance human needs with ecosystem preservation, contributing to Sustainable Development Goals on clean water, climate action, and biodiversity. This study highlights the importance of selecting appropriate vulnerability indicators and implementing adaptive management strategies to ensure groundwater resilience amid ongoing climate challenges.

**Keywords:** Groundwater Hydrology; Climate Change; Potential Impacts; Mitigation; Vulnerability; Induced Factors; Temperature; Precipitation; Groundwater Quality; Adaptive Strategies; Mitigation Measures.

## 1. Introduction

Over half of the world's population, about 4 billion individuals, lack adequate access to clean/safe drinking water for at least a month each year. According to another estimate, 57% of the world's population will reside in areas with severe water shortages by the year 2050 (Abbas, et al., 2022) as shown in Figure 1. Because groundwater provides for about 20% of water use globally and holds 70 times as much freshwater as surface water (Abu-Bakr, 2020; Ahmed et al., 2021), changes in temperature and precipitation brought about by climate change put significant pressure on water resource management worldwide by reducing both the quality of groundwater (Al Atawneh et al., 2021; Mafimisebi et al., 2024) as shown in Figure 2. Groundwater is a major source of water for the public and household in many parts of the world, sustaining agricultural and industrial economies, and supplying rivers, lakes, and wetlands with its flow, which aids in maintaining ecological equilibrium (Allan et al., 2020; Amanambu et al., 2020).

Groundwater can serve as a buffer against seasonal variations in rainfall patterns that climate change models predict because aquifers have a high-water storage capacity and use natural treatment methods. As a result, if managed effectively as a component of an integrated water resource management (IWRM) strategy to maximize its potential and assure its sustainability, it may contribute to climate change adaptation (Martins et al., 2024). By maintaining the baseflow of rivers and preventing land subsidence and seawater intrusion, groundwater helps achieve the Sustainable Development Goals (SDGs) by enabling the provision of clean water and sanitation for all (SDG 6), contributing to climate change adaptation (SDG13) by providing a reliable alternative resource that is less vulnerable to pollution and environmental shocks than surface water, and supporting terrestrial and underwater ecosystems (SDG 15) (Deshmukh et al., 2022).

As a result, groundwater protection is a top priority, and the problem is made worse by climate change. According to the Intergovernmental Panel on Climate Change (IPCC), climate change is the main factor affecting the sustainability of groundwater quality globally (IPCC, 2007; Benz et al., 2024).

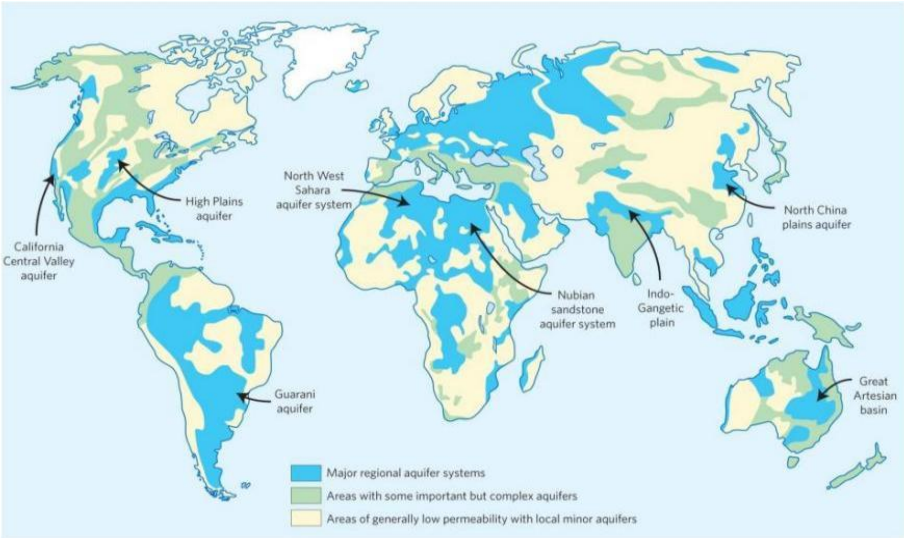


**Figure 1.** Global groundwater resources

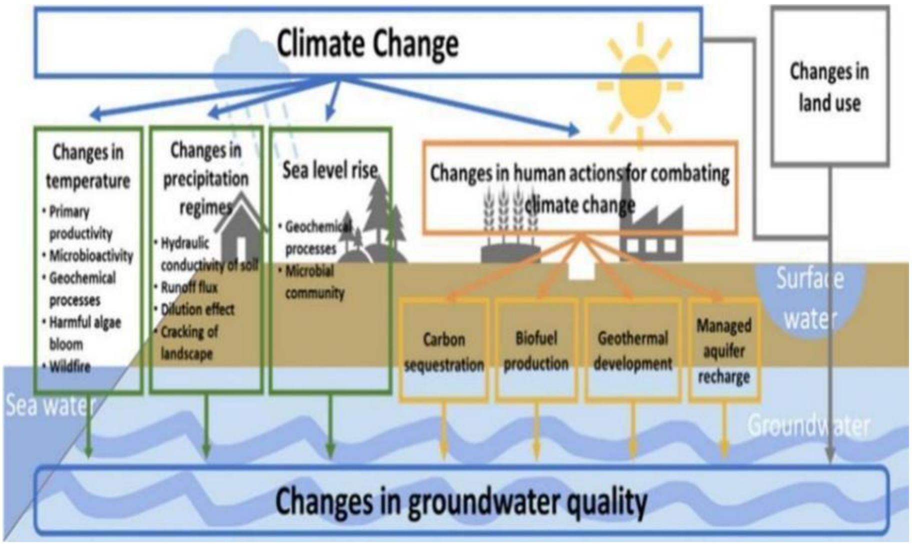


**Figure 2.** Factors affecting groundwater quality

### 1.1. Study Objectives

The aim of this study is to investigate the interaction between groundwater (its hydrology and quality) and climate change occurrences, as well as the importance of indicator selection in determining groundwater vulnerability.

Thus, the objectives of this study are as follows:

1) To assess the impacts of climate change on groundwater quality worldwide.

2) To analyse how changes in precipitation and temperature influence groundwater recharge (hydrology).

3) To evaluate indicators used to assess groundwater vulnerability to climate change.

4) To explore effective strategies for sustainable groundwater management and protection under changing climatic conditions.

5) To identify mitigation measures that can reduce the adverse effects of climate change on groundwater resources quality.

## 2. Groundwater Quality and Climate Change Factors

The water cycle has already changed due to climate change, and it will keep changing. The effects of climate change on hydrological processes are already apparent as shown in Figure 3. Climate change will also have an impact on the groundwater system, which is a component of the hydrological cycle (Swain et al., 2022; Rohde, 2023). Because groundwater formations are naturally shielded from the earth's surface by the geological environment, they are less susceptible to outside influences and more durable than surface water. As a result, groundwater is often only minimally and gradually impacted by climate (Nistor et al., 2016). Because of climate change, population expansion, the depletion of surface water resources, urbanization, industrialization, and agricultural development, the demand for groundwater is predicted to rise gradually (Barbieri et al., 2023; Egidio et al., 2022). By raising temperatures, causing erratic rainfall and drought, and resulting in lower groundwater levels and storage, climate change increases groundwater vulnerability (Egidio et al., 2022). Another consequence of climate change is flooding, which worsens groundwater contamination by carrying solid waste, such as sewage, into wells (Rohde, 2023). Groundwater contamination and these vulnerabilities have detrimental consequences for the health and survival of surface flora and fauna (Aslam et al., 2018; El Alfy et al., 2019).

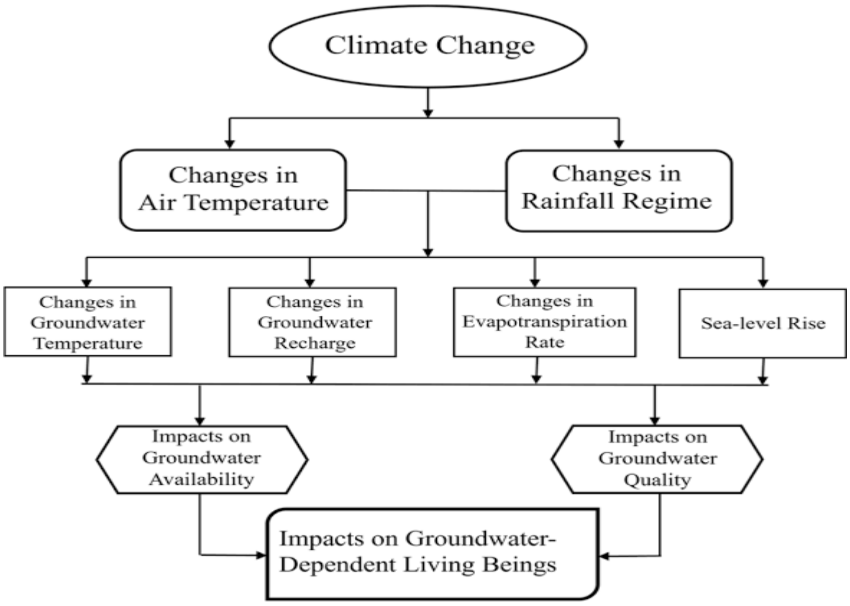


**Figure 3.** Impact of climate change on groundwater hydrology

### 2.1. Precipitation Effect on Groundwater

A change in precipitation patterns will have an impact on groundwater recharge rates and the depth of groundwater tables. In humid climates, higher precipitation variability may have a detrimental effect on natural recharge, as

Zeder et al., (2020) notes, since there is evidence that the ratio of runoff to precipitation rises with rainfall intensity. However, higher precipitation variability may lead to greater recharge in dry and semiarid areas since only intense rainfall can penetrate quickly enough before it evaporates (Nistor et al., 2016; Nnaemeka-Okeke et al., 2024). As a result, the overall effect on any location will depend on how both the amount and variability of precipitation changes. Due to rising temperatures and shifting precipitation patterns, increasing evapotranspiration will have a direct impact on groundwater systems, as shown by (Benz et al., 2024; Dao et al., 2024). In general, more precipitation will result in more surface runoff and groundwater recharge. However, groundwater infiltration will not rise in tandem with higher rainfall and runoff. According to Döll et al., (2005) prediction, the average rate of groundwater recharge worldwide will only increase by 2% in 2050, which is less than the anticipated increases of 4% and 9% in global annual precipitation and runoff, respectively. Furthermore, modifications to groundwater recharge will differ significantly from place to place around the world (Figure 4). Increased rainfall may sometimes result in lower groundwater recharge due to changes in rainfall intensity and distribution (Al Atawneh et al., 2021; Asoka et al., 2018; Liu et al., 2023).

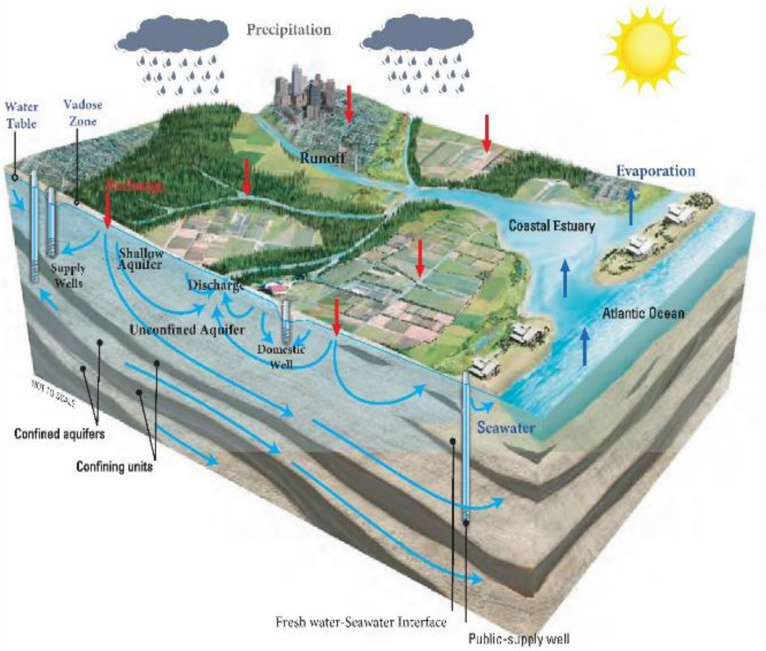


**Figure 4.** Groundwater recharge through precipitation process (Denver et al., 2015)

### 2.2. Temperature Effect on Groundwater

Higher temperatures will lead to a greater capacity for air moisture, which will ultimately result in more rainfall. Increased evaporation and plant transpiration rates will result from higher temperatures, which will cause soils to dry out more (Egidio et al., 2022). The availability of groundwater inside the exploitable limit may also change because of the effect of prolong temperature (Gumuła-Kawęcka et al., 2023). Variations in groundwater recharge throughout the seasons might result in significant fluctuations in groundwater level. As a result, a higher recharge rate may not be beneficial in raising the groundwater level throughout the year (Abu-Bakr, 2020; Ahmed et al., 2021; Jasechko, 2024). Groundwater level will drop even more during dry irrigation season because of an increase in the amount of its demand, according to (Swain et al., 2022). In several places throughout the globe, lower groundwater levels during dry months might result in more frequent and severe groundwater droughts (Büntgen, 2021; Bera et al., 2024) as shown in Figure 5 & 6.

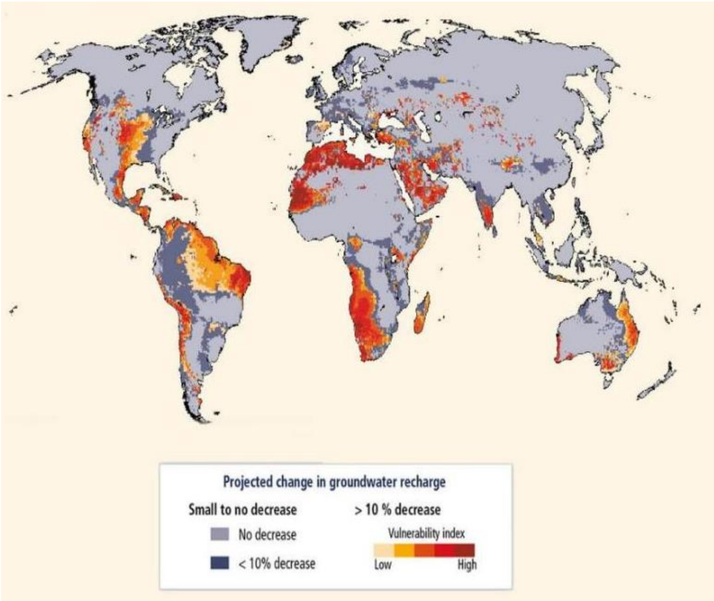


**Figure 5.** Impacts of climate change on groundwater globally

**Figure 6**. Impact of temperature on groundwater resources

### 3. Strategies for Managing Groundwater Quality in the Face of Climate Change

Groundwater is essential to maintaining global water security because it provides a consistent source of freshwater for drinking, farming, business, and environmental conservation. Climate change, however, poses a serious threat to the sustainability of these vital resources by jeopardizing groundwater recharge rates, availability, and quality (Saylor et al., 2013; IPCC, 2024). Dedicated efforts and intelligent management strategies are necessary to protect and increase the advantages of groundwater quality in a changing climate. To guarantee groundwater resilience in the face of climate change, these methods must be flexible, integrated, and long-lasting.

#### 3.1. Increasing Groundwater Storage and Recharge

Excess surface water during wet periods can be routed into aquifers via artificial recharge methods such as infiltration basins, recharge wells, and managed aquifer recharge (MAR) systems, which helps raise groundwater levels (Dillon et al., 2022). This helps keep groundwater accessible during droughts made worse by climate change. Maintaining and restoring wetlands, floodplains, and wooded catchments improves natural infiltration processes, promoting continuous groundwater recharge (Preciado et al., 2025). Rainwater collecting may be integrated at the community and household levels to complement groundwater recharge while lowering reliance on excessively taken aquifers (Riaz et al., 2025) as shown in Figure 7.

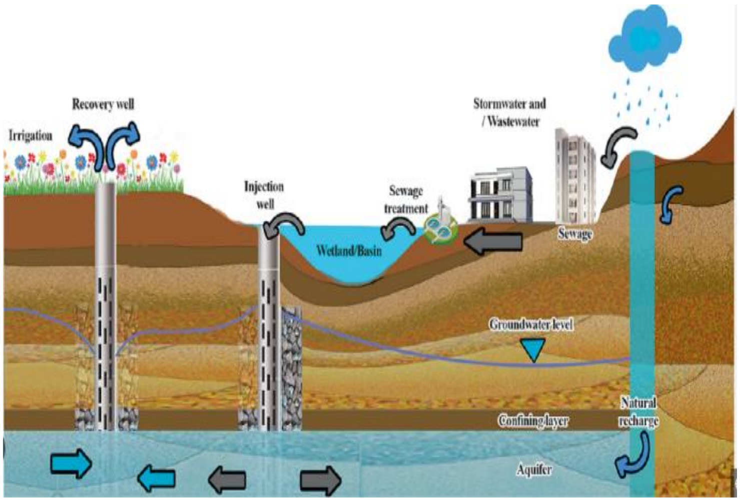


**Figure 7.** Groundwater recharge techniques

### 3.2. Enhanced Groundwater Monitoring and Data Management

Real-time information on groundwater levels, quality, and usage trends can be obtained using remote sensing, telemetry, and automated sensors to create complete groundwater monitoring networks, which enables early identification of depletion or pollution risks (Kumar, 2021). The creation of centralized groundwater databases that combine hydrological, climatic, and land-use data supports well-informed decision-making and climate-adaptive groundwater management (Barthel et al., 2021) as shown in Figure 8.

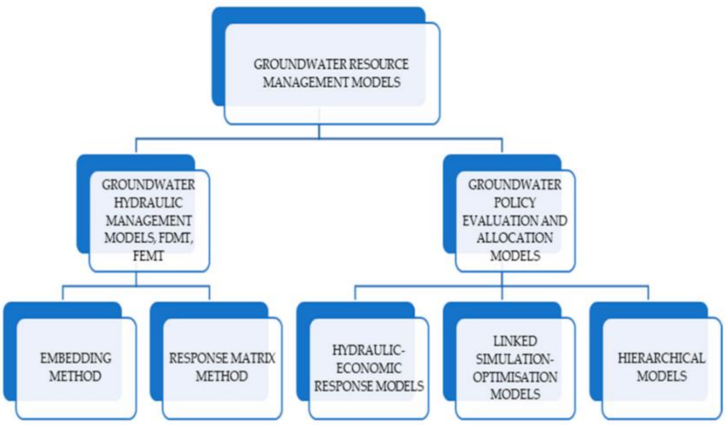


**Figure 8.** Groundwater Management Model (Gorelick, 1987)

Kisi et al., (2019) categorize groundwater management models into two groups: physical or process-based models and data-driven models. Physical-based models rely on the groundwater bed's physical parameters to assess water level changes, but they are challenging to implement, costly, and require partitioning for numerical data (Kisi, 2017). Although groundwater management models are crucial for evaluating the adverse impacts of human activities on groundwater dynamics, they depend on reliable data related to physical and hydrogeological conditions (Taormina et al., 2015; Xu et al., 2011; Mylopoulos et al., 2007). The physical groundwater management model includes factors like topography, soil, climate, and land use, which influence the aquifer. The hydrogeological surrounding involves groundwater movement and the characteristics of aquifer layers. This hydrogeological context changes over time and space (Xu et al., 2011; Fu et al., 2019). For precise modelling results, it is crucial to calibrate the model with accurate data, leading to better computation efficiency and accuracy.

### 3.3. Integrated Water Resources Management (IWRM)

Groundwater management must be integrated with surface water and ecosystem management to optimize overall water availability and quality under climate change (UNESCO, 2022). Involving local communities, water users, policymakers, and scientists ensures groundwater policies are socially acceptable, practically feasible, and scientifically sound (Smedley et al., 2017). Designing water infrastructure to withstand extreme weather events (e.g., floods, droughts) reduces vulnerabilities and enhances groundwater recharge and protection (Wang et al., 2022).

## 4. Measures of Mitigation to Climate Change on Groundwater Quality

Mitigation efforts aimed at climate change can play a crucial role in protecting and improving the quality of groundwater resources (Mary et al., 2018; Chambel et al., 2015). Since groundwater is vulnerable to contamination and depletion exacerbated by climate change impacts such as altered precipitation patterns and increased temperatures, mitigation measures can help reduce these pressures and preserve groundwater quality and its hydrological cycle (Motevalli et al., 2018; Yeh, 2015).

### 4.1. Reducing Greenhouse Gas Emissions from Agriculture and Industry

Agricultural activities and industrial processes are significant sources of both greenhouse gases (GHGs) and groundwater contaminants such as nitrates, pesticides, and heavy metals. Mitigation strategies that reduce emissions such as adopting precision agriculture, minimizing fertilizer use, and shifting to cleaner industrial technologies also reduce the risk of pollutants leaching into groundwater aquifers (Foster et al., 2013).

### 4.2. Promoting Sustainable Land Use and Forest Management

Forests act as natural carbon sinks and protect water recharge zones. Mitigation through afforestation, reforestation, and preventing deforestation helps maintain soil integrity and reduces erosion and sedimentation, which can degrade groundwater quality (IPCC, 2014). Healthy forest cover also enhances natural filtration of contaminants before they reach groundwater.

### 4.3. Enhancing Wastewater Treatment and Recycling

Improved wastewater treatment reduces the discharge of harmful contaminants into surface and groundwater systems. Mitigation measures that incorporate advanced treatment technologies (e.g., nutrient removal, membrane filtration) lower the risk of nutrient pollution, pathogens, and emerging contaminants infiltrating groundwater supplies (Martins et al., 2024; Kundzewicz et al., 2018).

### 4.4. Implementing Carbon Capture and Storage (CCS) with Groundwater Protection

CCS technologies capture $CO_2$ emissions from industrial sources and inject them underground. Proper site selection and monitoring ensure that injected $CO_2$ does not contaminate groundwater aquifers, thus safeguarding groundwater quality while reducing atmospheric greenhouse gases (Caretta et al. 2022).

### 4.5. Promoting Renewable Energy to Reduce Reliance on Fossil Fuels

Transitioning to solar, wind, and other renewable energy sources decreases fossil fuel extraction activities such as mining and drilling, which are often associated with groundwater contamination through chemical spills, acid mine drainage, and heavy metals. Mitigation through renewable energy adoption indirectly protects groundwater quality by reducing these pollution sources.

## 5. Conclusion

Groundwater is a crucial freshwater resource that sustains ecosystems, industry, agriculture, and drinking water supplies throughout the world. Changes in precipitation patterns and higher temperatures brought about by climate change, however, pose serious risks to the quality of groundwater. The threat to water security and ecosystem health comes from the increased risk of pollution, variable water tables, and decreased recharge caused by these alterations. Sustainable groundwater management must use adaptive methods like artificial recharge, improved monitoring, demand regulation, and integrated water resource management (IWRM) to overcome these issues. Just as vital are mitigation strategies such as lowering greenhouse gas emissions, encouraging sustainable land usage, enhancing and wastewater treatment. Successful groundwater protection in the face of climate change requires coordinated efforts from legislators, scientists, and communities to strike a balance between human demands and environmental protection. To achieve the Sustainable Development Goals pertaining to clean water, climate action, and biodiversity protection, such integrated strategies will be crucial for fostering groundwater resilience.

The following recommendations need to be considered for future purposes.

1) Enhance groundwater monitoring systems to provide accurate and timely data on groundwater quality and quantity, enabling early detection of climate change impacts.

2) Implement artificial recharge methods such as managed aquifer recharge and rainwater harvesting to sustain groundwater levels amid changing precipitation patterns.

3) Develop and apply integrated water resources management approaches that consider both groundwater and surface water under climate variability.

4) Use climate change projections to assess groundwater vulnerability and design adaptive management strategies that increase resilience.

5) Strengthen regulations to control groundwater extraction and prevent contamination, protecting critical recharge zones from human and climate-induced pressures.

6) Promote awareness and capacity building among communities, policymakers, and industries to encourage sustainable groundwater use and climate change mitigation efforts.

Further research is needed to improve our understanding of how climate change affects groundwater quality and its hydrological cycles and to develop effective mitigation strategies. Climate change alters precipitation patterns, and increases temperatures, all of which can degrade groundwater by promoting contaminant infiltration, reducing recharge rates, and intensifying pollutant transport. Research should focus on better assessing these impacts across diverse hydrogeological settings and improving predictive models that integrate climate data with groundwater flow and contaminant dynamics. Additionally, developing early warning systems based on chemical and microbial indicators will help detect groundwater quality decline promptly. On the mitigation side, studies on managed aquifer recharge, pollution control, and sustainable land-use practices are essential to enhance groundwater resilience. Furthermore, research into governance frameworks is crucial to implement adaptive groundwater management policies. Addressing these gaps is vital to safeguard groundwater resources, which are critical for drinking water, agriculture, and ecosystems, ensuring their sustainability in the face of ongoing climate change.

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**Competing Interests Statement**

The author declares no competing financial, professional, or personal interests.

**Consent for publication**

The author declares that he consented to the publication of this study.

**Authors' contributions**

Author’s independent contribution.

**Availability of data and material**

Supplementary information is available from the author upon reasonable request.

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**Informed Consent**

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