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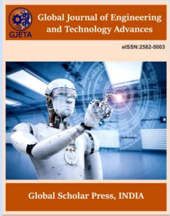

(REVIEW ARTICLE)

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Future challenges and climate change adaptation: Changes in precipitation patterns and their impact on coastal aquifers

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Abstract

Climate change is significantly modifying global precipitation patterns, generating direct impacts on the dynamics and sustainability of coastal aquifers. This study analyzes how alterations in rainfall amount, intensity, temporal distribution, and seasonality affect groundwater recharge processes and promote phenomena such as saltwater intrusion, groundwater level decline, and water quality deterioration. Based on recent scientific evidence and case studies from vulnerable coastal regions, the combined effects of prolonged droughts, extreme precipitation events, and sea-level rise on the hydrogeological balance of these systems are examined. Increased climatic variability reduces natural recharge efficiency due to greater surface runoff during intense rainfall and sustained reductions in water input during dry periods. Additionally, urban and agricultural overexploitation amplifies aquifer vulnerability to salinization. Adaptive management approaches—including advanced climate modeling, continuous hydrogeological monitoring, managed aquifer recharge, rainwater harvesting, and efficient water use—are essential to strengthen resilience. Ensuring the sustainability of coastal aquifers under climate change will require integrating public policy, technological innovation, and long-term climate-based planning.

Keywords: Climate change; Coastal aquifers; Precipitation patterns; Groundwater recharge; Saltwater intrusion; Water scarcity; Managed aquifer recharge; Climate variability; Water resource management; Hydrogeology

1. Introduction

Climate change represents one of the most significant environmental challenges of the 21st century due to its capacity to structurally alter physical, biological, and socioeconomic systems. Among its most evident manifestations are global temperature rise, sea-level increase, and modifications in precipitation patterns. These transformations directly affect the hydrological cycle, intensifying variability and impacting water availability, distribution, and quality [1,2].

Coastal aquifers are particularly vulnerable systems because they depend largely on precipitation-driven recharge and maintain a delicate hydraulic equilibrium between freshwater and seawater. Approximately 40% of the global population lives in coastal regions, where urbanization, agriculture, tourism, and industrial activities concentrate water demand [3]. Any alteration in precipitation quantity, intensity, or seasonal distribution can disrupt freshwater–saltwater balance, increasing the risk of saltwater intrusion and compromising drinking water supplies [4].

Recent studies demonstrate that climate change not only modifies annual rainfall totals but also alters their temporal distribution, increasing the frequency of extreme events such as torrential rainfall and prolonged droughts [2]. Intense rainfall often produces higher surface runoff and reduced infiltration, decreasing effective aquifer recharge. Conversely, extended dry periods significantly limit natural groundwater replenishment [1].

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In many coastal regions worldwide, groundwater extraction already exceeds natural recharge rates, leading to declining water tables and increased vulnerability to salinization [5]. The interaction between climate-driven recharge reduction and anthropogenic overexploitation creates compounded risks requiring multidisciplinary and adaptive management strategies.

This study examines the impacts of changing precipitation patterns on coastal aquifers, evaluates associated management challenges, and analyzes adaptation strategies aimed at ensuring long-term water resilience.

2. Impact of Changes in Precipitation Patterns

2.1. Alteration of Aquifer Recharge

Aquifer recharge strongly depends on precipitation volume and seasonal distribution. Intensified droughts and rainfall concentrated in short, high-intensity events reduce infiltration efficiency and groundwater replenishment [1]. In several coastal regions, including North Africa and Southeast Asia, increased rainfall variability has resulted in diminished recharge effectiveness and heightened groundwater stress.

In California's coastal basins, prolonged drought conditions have reduced recharge capacity and increased dependence on groundwater abstraction, exacerbating pressure on aquifer systems [6]. Insufficient recharge leads to groundwater level decline, affecting both quantity and quality of water resources.

2.2 Increased Climate Variability and Coastal Aquifer Vulnerability

Climate variability characterized by extreme events—prolonged droughts, storms, and heavy rainfall—further impacts coastal aquifers. Reduced freshwater recharge allows seawater intrusion into aquifer systems, compromising potable water supplies [3,4].

In low-lying island systems such as the Maldives, combined effects of sea-level rise and extended droughts have severely threatened freshwater lenses, forcing consideration of desalination technologies as alternative supply sources [7]. Meanwhile, intense rainfall events may overload drainage systems and reduce recharge efficiency while mobilizing contaminants into groundwater [4].

Table 1 Arrows indicate observed trends: ↑ increase, ↓ decrease.

Region / Country	**Change in Precipitation**	**Impact on Coastal Aquifers**	**Adaptation Strategies**
California, USA	↓ Annual total, ↑ extreme events	Declining groundwater levels, overexploitation	Sustainable management, artificial recharge, agricultural efficiency
North Africa	↑ Intense rainfall, prolonged droughts	Limited infiltration, increased runoff, risk of salinization	Rainwater harvesting, managed aquifer recharge (MAR), adaptive planning
Southeast Asia	↑ Seasonal variability	Urban aquifer overexploitation, saltwater intrusion	Extraction regulation, water conservation, climate modeling
Maldives	Longer droughts, ↑ sea level	Threat to freshwater lenses, saltwater intrusion	Desalination, MAR, aquifer protection
Northeast Brazil	Irregular seasonal rainfall	Reduced natural recharge, vulnerability to droughts	Large-scale rainwater harvesting, artificial recharge, water use efficiency

3. Future Challenges in Coastal Aquifer Management

3.1. Water Scarcity in Coastal Regions

Changes in precipitation patterns contribute to water scarcity, particularly in regions highly dependent on groundwater. The combination of drought intensification, extreme rainfall, and aquifer salinization may significantly reduce available freshwater resources [2].

In Southeast Asia and parts of India, rapid urban expansion and agricultural intensification increase groundwater demand, intensifying overexploitation risks under changing climatic conditions [2,8]. Without effective management, declining recharge rates could exacerbate conflicts over water resources.

3.2. Planning and Management Under Climate Uncertainty

Traditional water planning based on historical hydrological records is insufficient under evolving climate conditions. Advanced global and regional modeling of freshwater resources is required to integrate climate projections into groundwater management strategies [9].

In India, high reliance on coastal aquifers combined with altered rainfall regimes has increased extraction pressure, emphasizing the need for adaptive water governance frameworks [8]. Policymaking must integrate climate projections, hydrogeological modeling, and sustainable abstraction regulations to prevent irreversible aquifer degradation.

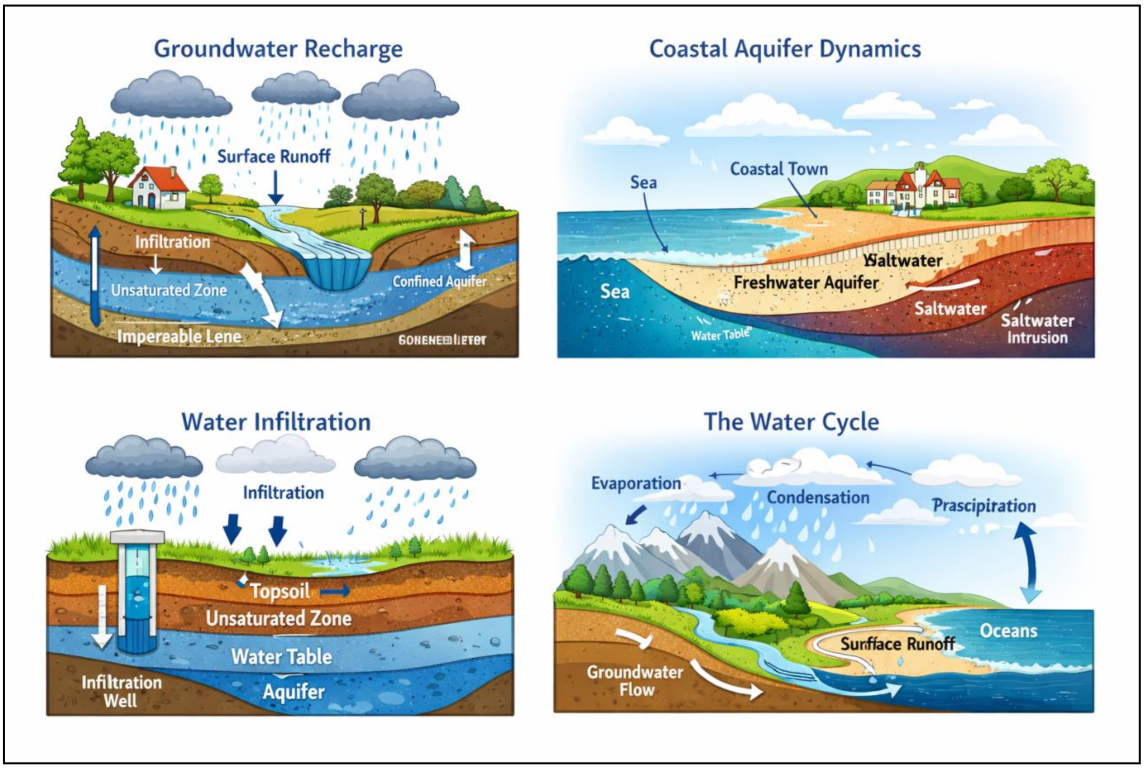

Figure 1 Schematically illustrates the processes of groundwater recharge and their relationship with the hydrological cycle **Figure 2 (**depicts the dynamics of a coastal aquifer and the process of saltwater intrusion associated with reduced recharge)

Table 2 Projected Changes in Precipitation and Impacts on Coastal Aquifers

Region / System	Precipitation Change Projection	Groundwater Trend / Observations	Saltwater Intrusion Projection
Global Coastal Average	Up to ±20% change in rainfall patterns by 2100 depending on region and emissions scenario (SSP2-4.5)†	~77% of global coastal watersheds likely to experience saltwater intrusion by 2100 due to reduced recharge + sea level rise‡	↓ Freshwater lens volume; intrusion inland expected in most coastal aquifers‡
California (USA)	Periodic increases in extreme rainfall but overall trend toward droughts with variable recharge[×]	Recent managed recharge added ~1.9 million acre-feet, but long-term groundwater remains in decline due to over-abstraction‡	Elevated risk where freshwater declines are persistent‡
Mediterranean / Arid Zones	Recharge rates may decline ~25–60% in many coastal systems due to reduced effective infiltration§	Groundwater levels projected to decline by ~14–16 m under high emissions scenarios with current abstraction rates§	High sensitivity to salinization; seawater intrusion more likely with decreased hydraulic gradients§
Pacific / Small Islands	Some western Pacific and Indian Ocean islands could see up to 120% increases in mean rainfall, but with high variability across years§	Potential for episodic recharge pulses, but overall vulnerability remains due to sea level rise and lens contraction§	Coastal fresh groundwater storage may decrease by ~22% due to erosion + SLR (modelled)§
South Asia / Southeast Asia (Coastal Deltas)	Model projections include regional increases in extreme rainfall events while dry spells lengthen[×]	Heavy demand + recharge variability increases aquifer stress and reduces sustainable yields	Saltwater intrusion under combined SLR + low recharge conditions likely

4. Adaptation Strategies

4.1. Managed Aquifer Recharge and Rainwater Harvesting

Managed aquifer recharge (MAR) is increasingly recognized as a viable adaptation strategy to enhance groundwater storage and counterbalance reduced natural recharge [10]. Controlled infiltration of stormwater and harvested rainwater can improve aquifer resilience in regions experiencing precipitation variability.

4.2. Sustainable Water Use and Conservation

Reducing excessive groundwater abstraction is critical to preventing salinization and long-term depletion. Global assessments indicate that groundwater depletion has accelerated in many regions, highlighting the urgency of sustainable management practices [5]. Technologies such as drip irrigation and improved urban water efficiency can significantly reduce pressure on aquifers.

4.3. Climate Modeling and Adaptive Planning

Improved climate models and integrated hydrological simulations enable more accurate projections of precipitation variability and extreme events [2,9]. Adaptive management frameworks should incorporate uncertainty analysis and stakeholder participation to enhance resilience.

5. Conclusion

Climate change–induced alterations in precipitation patterns pose substantial risks to coastal aquifers worldwide. Reduced recharge efficiency, increased climatic variability, and intensified saltwater intrusion threaten both water availability and quality. Overexploitation further compounds these risks.

Nevertheless, resilience can be strengthened through:

- Sustainable groundwater management
- Technological innovation, including managed aquifer recharge
- Climate-based predictive modeling
- Integrated water governance and community engagement

Ensuring long-term water security in coastal regions requires science-based planning, adaptive governance, and nature-based solutions capable of addressing growing climatic uncertainty.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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