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Groundwater Sustainability in Afghanistan: Challenges and Opportunities for AI-Enabled Management

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ABSTRACT

Groundwater is the most dependable freshwater source for much of Afghanistan, yet its sustainability is increasingly threatened by over-abstraction, declining recharge, contamination, weak monitoring systems, and fragmented governance. This article presents a critical narrative review of groundwater sustainability in Afghanistan, with particular attention to the Kabul Basin, where pressure on aquifer systems is especially severe. Rather than adopting a systematic review design, the study uses a transparent narrative-review approach to synthesize peer-reviewed studies, technical reports, and policy-relevant publications across five analytical dimensions: groundwater quantity, groundwater quality, hydroclimatic stressors, governance and monitoring capacity, and the emerging role of artificial intelligence (AI) in groundwater management. The review shows that Afghanistan's groundwater crisis is driven by the interaction of rapid urbanization, climate variability, inadequate sanitation, institutional fragility, and limited hydrogeological data. The article further argues that AI-based tools, when combined with remote sensing, community-centered monitoring, and institutional reform, can strengthen groundwater assessment and decision support in data-scarce environments. The paper concludes that sustainable groundwater management in Afghanistan requires technological innovation to be embedded within stronger governance, better data systems, and context-sensitive implementation.

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INTRODUCTION

Groundwater is a strategic component of water security because it supports domestic supply, agriculture, ecosystem stability, and economic production, particularly in arid and semi-arid regions [1],[2]. In countries where surface-water infrastructure is limited or unreliable, groundwater often becomes the default source of drinking water and irrigation, a condition that is especially pronounced in Afghanistan [3],[4].

Afghanistan's groundwater systems are under mounting stress. Existing studies point to declining water tables, deteriorating water quality, widespread bacteriological contamination, weak monitoring networks, and the cumulative effects of climate variability, rapid urbanization, and decades of conflict [5], [4]-[6] These pressures are most visible in the Kabul Basin, where demand growth, informal extraction, and pollution have converged into an acute urban groundwater crisis[7], [6].

The Afghan case highlights a broader research and policy challenge: how to manage groundwater sustainably in a conflict-affected, data-scarce environment. Conventional groundwater management depends on long-term monitoring, institutional coordination, and regulatory capacity—conditions that remain fragile in Afghanistan [4], [8],[9]. This makes

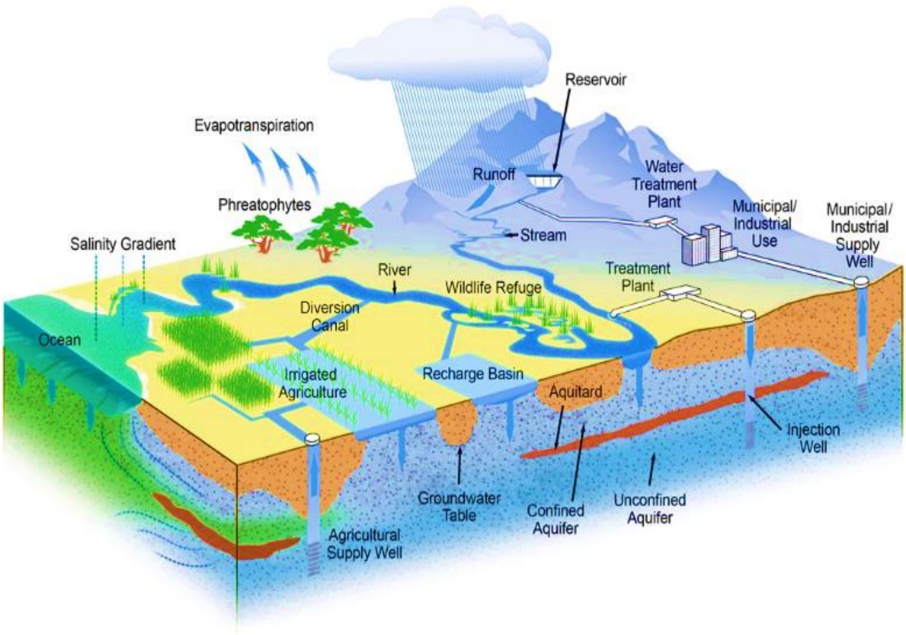

Fig. 1. Conceptual diagram of the groundwater cycle and recharge–discharge processes relevant to groundwater sustainability. Groundwater (ca.gov)

the country a compelling context in which to examine the potential of artificial intelligence (AI), remote sensing, and hybrid data strategies for groundwater assessment and decision support[10], [5],[11].

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This study has three objectives: (1) to synthesize current knowledge on groundwater sustainability in Afghanistan, with particular emphasis on groundwater quantity, quality, recharge, and governance; (2) to identify the major challenges affecting sustainable groundwater management, especially in the Kabul Basin; and (3) to evaluate the opportunities and limitations of AI-enabled approaches for groundwater monitoring, modelling, and policy support. The study adopts a narrative review approach rather than a systematic literature review. To enhance methodological transparency, the review draws on peer-reviewed articles, technical reports, and policy documents, which were selected and analyzed through a thematic synthesis focusing on groundwater resources, governance challenges, environmental pressures, and emerging AI applications.

CONCEPTUAL FRAMEWORK

This review is guided by an integrated conceptual framework in which groundwater sustainability in Afghanistan is shaped by the interaction of five dimensions: hydrogeological setting and recharge conditions; demand-side pressures, especially urban growth and irrigation; water-quality threats arising from sanitation deficits and waste mismanagement; institutional and monitoring capacity; and technological options for assessment, prediction, and governance support [4], [6],[7].

Within this framework, sustainability is understood not merely as maintaining groundwater availability, but as preserving the long-term quantity, quality, accessibility, and governability of aquifer systems [7],[12]. This broader interpretation is essential for Afghanistan because

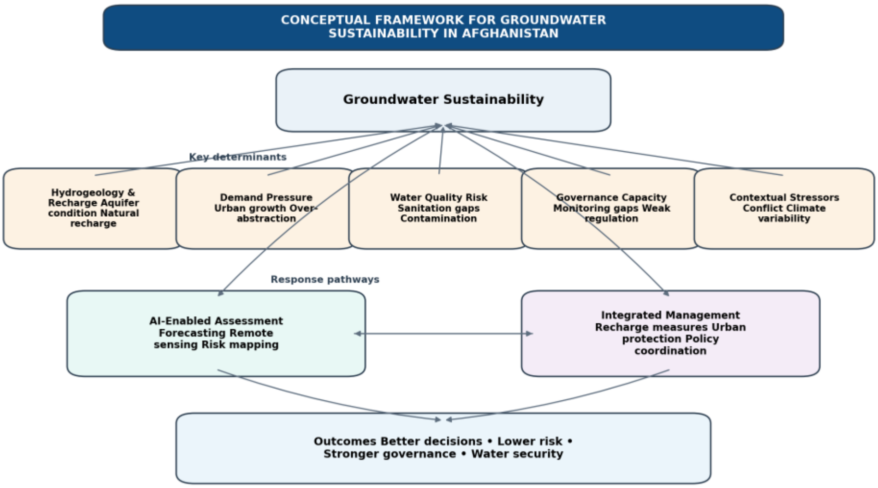

Fig. 2. Conceptual framework for groundwater sustainability in Afghanistan.

Groundwater failure is simultaneously a hydrological, public-health, governance, and development problem [3], [4].

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AI enters this framework as an enabling rather than stand-alone solution. It can strengthen groundwater management by improving forecasting, integrating heterogeneous datasets, identifying spatial patterns, and supporting early warning [10], [11], [13], [14]. However, AI cannot substitute for governance, regulation, public investment, and recharge enhancement; it is one component of an integrated strategy rather than a technocratic remedy in isolation.

METHODOLOGY

This study employs critical narrative review design. A narrative review is appropriate because the literature on groundwater in Afghanistan is heterogeneous in method, scale, and purpose, spanning hydrogeology, environmental management, remote sensing, public health, and AI applications [5], [4], [6]. The aim is therefore not statistical aggregation, but thematic synthesis and analytical integration of diverse evidence relevant to groundwater sustainability.

To improve transparency, the review was organized around five analytical dimensions: groundwater quantity and depletion; groundwater quality and contamination; hydroclimatic and recharge conditions; governance and monitoring systems; and AI-based opportunities for groundwater assessment and management. The source base consists of the references already compiled for the manuscript, including peer-reviewed journal articles, review papers, book chapters, technical studies, and policy-relevant reports focusing on Afghanistan, the Kabul Basin, groundwater sustainability, and AI in water management [10][14].

Sources were retained when they provided empirical or review-based evidence on groundwater quantity or quality in Afghanistan, discussed recharge, drought, climate variability, land subsidence, or urban growth relevant to groundwater sustainability, addressed governance or monitoring capacity, or examined AI, machine learning, remote sensing, or predictive modelling applicable to groundwater management [5], [4]-[6], [15], [16], [14]. Broad generic material with weak relevance to Afghanistan's groundwater problem was excluded or substantially condensed in the revised manuscript.

GROUNDWATER SUSTAINABILITY CONTEXT IN AFGHANISTAN

A. National Hydro-Environmental Context

Afghanistan is characterized by strong climatic and topographic contrasts, with much of its water originating in mountain systems and seasonal snowmelt [5], [2]. Although the country possesses substantial water resources at the basin scale, water availability is highly uneven in time and space. Groundwater is therefore indispensable, especially where surface-water access is limited, infrastructure is weak, or distribution systems are absent [3], [2].

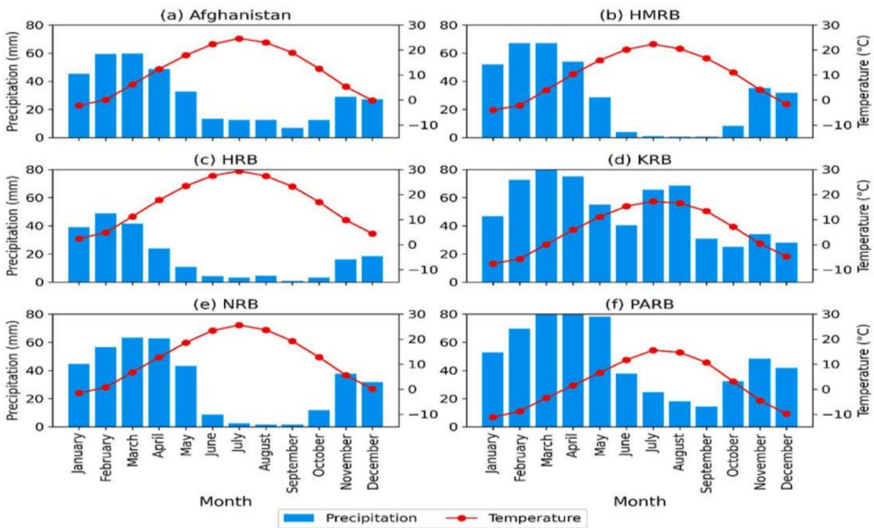
Groundwater dependence is shaped by both physical and institutional conditions. Rural communities rely on wells, springs, and karezes, while major cities increasingly depend on aquifers because piped surface-water systems are inadequate [2], [4]. Long periods of conflict have constrained hydrogeological data collection, weakened regulatory institutions, and reduced maintenance of monitoring infrastructure, producing severe informational uncertainty for groundwater management [4], [8].

Groundwater sustainability in Afghanistan must also be assessed in relation to sanitation, agriculture, and climate stress. In many cities, wastewater collection

systems remain underdeveloped, creating direct pathways for nitrate, fecal, and bacterial contamination [3], [4], [6]. In agriculture, groundwater functions as a drought buffer, but growing extraction without parallel recharge intensifies depletion risks [2], [4],[17].

Fig. 3. Map of Afghanistan showing the five major river basins and neighboring countries [7].

Fig. 4. Mean monthly precipitation and temperature patterns across Afghanistan and its five major river basins (2003–2022) [5].



B. Kabul Basin as the Critical Hotspot

The Kabul Basin is the most critical groundwater hotspot in Afghanistan because it combines high demand, limited recharge, rapid urban growth, and pronounced water-quality deterioration,[4] [6], [8]. Groundwater supplies most domestic water needs in Kabul, where population growth and informal abstraction have dramatically increased pressure on aquifer systems [4], [6].

The basin's hydrogeological vulnerability is intensified by urban expansion over recharge zones, the spread of impervious surfaces, and inadequate wastewater and solid-waste management [4], [6],[18]. As natural infiltration declines, aquifers are increasingly mined faster than they are replenished. Existing studies also document serious contamination problems, including nitrate pollution, fecal coliform contamination, and elevated concentrations of several chemical constituents in parts of Kabul [6], [18].

MAJOR CHALLENGES TO SUSTAINABLE GROUNDWATER MANAGEMENT

A. Groundwater Depletion, Aquifer Stress, and Land Subsidence

A central challenge is the persistent decline in groundwater levels, particularly in Kabul and other stressed urban and agricultural areas. Multiple studies indicate that extraction has exceeded recharge for prolonged periods, producing a pattern of aquifer mining rather than sustainable use [4]-[6]. Satellite-based analysis and well observations also indicate measurable land subsidence in some areas, signaling structural stress within aquifer systems and potential long-term loss of storage capacity [5],[19].

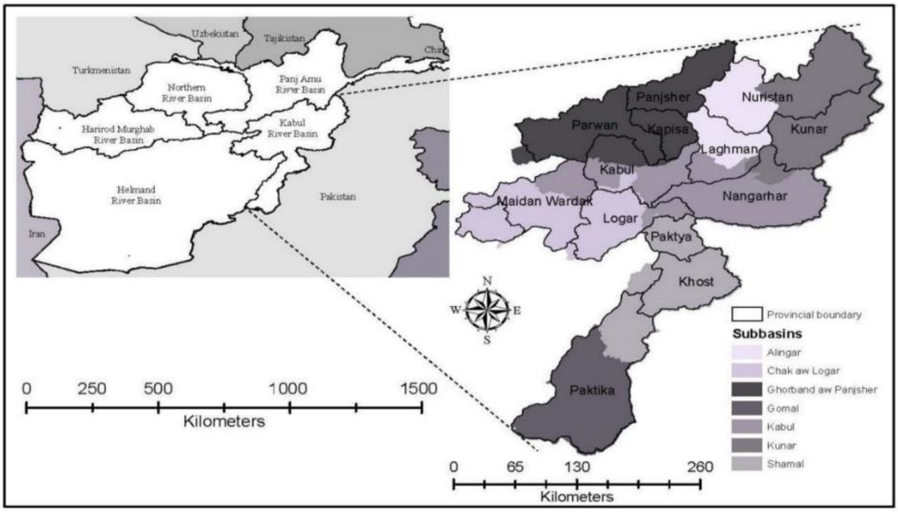


Fig. 5. Hydrogeological setting and groundwater sub-basins of the Kabul Basin [15].

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B. Loss of Recharge Under Urbanization and Climate Stress

Recharge conditions are deteriorating, especially in urban areas. The spread of roads, buildings, and other impervious surfaces reduces infiltration and diverts rainfall into runoff pathways rather than allowing it to percolate into aquifers. Climate variability compounds the problem: Afghanistan is highly sensitive to drought, changing snowfall patterns, and irregular precipitation, all of which affect the timing and reliability of groundwater replenishment [5], [4].

C. Groundwater Contamination and Public-Health Risk

Quantity decline is accompanied by serious deterioration in groundwater quality. In Kabul and other urban settings, the absence of centralized sewerage, widespread use of pit latrines and septic systems, unregulated waste disposal, and poor drainage have created pathways for bacterial and chemical contamination [3], [4], [6], [18]. Where groundwater serves as the main source of household water, contamination becomes a frontline human-security issue rather than a secondary environmental concern [3], [6].

D. Monitoring Collapse and Data Scarcity

Effective groundwater governance depends on time-series data on water levels, quality, recharge, abstraction, and aquifer response [7]. In Afghanistan, however, decades of conflict and institutional instability have weakened hydrometeorological and hydrogeological monitoring networks. This monitoring deficit makes it difficult to distinguish short-term climatic fluctuation from structural groundwater decline, to validate models, or to design evidence-based extraction limits [5], [4], [8].

E. Governance Fragmentation and Transboundary Vulnerability

Groundwater management in Afghanistan is institutionally fragmented. Responsibilities are distributed across multiple agencies, yet coordination, data sharing, and enforcement remain weak. A related challenge concerns transboundary water and aquifer systems. Afghanistan’s hydrological interdependence with neighboring countries raises important governance questions, yet formal cooperation over shared groundwater remains limited, increasing vulnerability in already fragile regions [2], [4].

F. Barriers to AI Adoption in Groundwater Management

Although AI offers promising analytical tools, its practical implementation in Afghanistan faces important constraints. Machine-learning systems require adequate data quality, metadata discipline, and technical expertise [10], [16], [14]. In settings where monitoring is sparse and institutional capacity is limited; the performance and interpretability of AI models may be compromised. Explainable and hybrid modelling approaches are therefore essential if AI-based systems are to support decision-making credibly [11], [13], [14].

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THE ROLE OF ARTIFICIAL INTELLIGENCE IN GROUNDWATER MANAGEMENT

AI is particularly relevant for Afghanistan because groundwater management must proceed under data scarcity, monitoring gaps, and rapidly changing environmental conditions. In such contexts, AI can help integrate heterogeneous datasets—including climate variables, satellite imagery, well records, land-use information, and Hydrochemical observations−to identify patterns that traditional methods may miss [10], [5], [11], [13].

For groundwater-level forecasting, recurrent models such as Long Short-Term Memory (LSTM) and Gated Recurrent Units (GRU) are promising because they capture temporal dependence in hydroclimatic series [10], [16]. Random Forest and other ensemble-learning models are useful for nonlinear prediction, classification, and variable-importance analysis [10], [5]. Convolutional Neural Networks and hybrid CNN–LSTM architectures can support spatial–temporal analysis when groundwater dynamics are linked to remote sensing and gridded environmental data [10], [14].

Remote sensing further expands the value of AI in Afghanistan. Satellite-derived products such as land-surface data assimilation outputs, deformation measurements, and land-use change layers can partly compensate for limited ground observations and support drought monitoring, recharge estimation, hotspot detection, and risk mapping [5], [19], [15]. In practice, the most useful AI for Afghanistan will not necessarily be the most complex model, but the one that is reliable, interpretable, and feasible under local constraints [11], [13], [14].

SYNTHESIS: CHALLENGE–RESPONSE FRAMEWORK

The reviewed evidence shows that groundwater sustainability in Afghanistan is shaped by multiple interrelated challenges, including depletion, contamination, weak monitoring, fragmented governance, and climate-related stress. To summarize these findings more clearly, this section presents a challenge–response framework that links the main groundwater problems with corresponding technological, institutional, and policy responses for integrated groundwater management in Afghanistan.

Table. 1. challenge–response framework for groundwater sustainability in Afghanistan

Challenge	Key Implication	AI-Enabled Contribution	Policy / Management Response
Declining groundwater levels	Long-term aquifer stress and reduced water security	Groundwater-level forecasting, trend detection, hotspot analysis	Abstraction control, managed aquifer recharge, basin-level monitoring
Urban recharge loss	Reduced infiltration and dependence on slow-renewal groundwater	Land-use change mapping, recharge-zone delineation, scenario modelling	Protection of recharge areas, urban planning, rainwater harvesting
Contamination	Public health risk and unsafe drinking water	Water-quality classification, contamination-risk mapping, anomaly detection	Sanitation infrastructure, landfill regulation, groundwater quality surveillance

Data scarcity	Weak evidence base for planning and regulation	Integration of sparse field data with remote sensing and machine learning	Rehabilitation of monitoring networks, data-sharing protocols, digital records
Governance fragmentation	Poor coordination and weak enforcement	Decision-support dashboards and early-warning systems	National groundwater policy, interagency coordination, local stewardship
Limited AI capacity	Low adoption and low trust in technical outputs	Explainable AI, hybrid models, transfer learning where appropriate	Capacity building, pilot projects, university–agency collaboration

POLICY IMPLICATIONS AND STRATEGIC PRIORITIES

The reviewed evidence suggests that groundwater sustainability in Afghanistan cannot be secured through a single intervention. A credible strategy must operate simultaneously on hydrogeological, institutional, technological, and public-health fronts [3], [4], [7]. First, Afghanistan needs a minimum national groundwater information system: restoring a core network of observation wells, harmonizing data standards, and digitizing available records would substantially improve management [4], [8], [7].

Second, groundwater protection must be integrated into urban governance. In Kabul and other expanding cities, sanitation planning, waste regulation, land-use control, and recharge-zone protection are inseparable from groundwater policy [3], [4], [6]. Third, AI should be adopted incrementally through problem-driven pilot projects—such as groundwater-level forecasting in the Kabul Basin, urban contamination-risk mapping, or drought-linked early warning—rather than broad rhetorical claims [5], [11], [13].

Fourth, groundwater governance must move toward institutional coherence and community legitimacy. This includes clarifying agency mandates, improving inter-ministerial coordination, involving local users in monitoring and stewardship, and developing policy instruments for sustainable abstraction and aquifer protection [4], [7]. Technology can strengthen governmental skills, but it cannot replace it.

CONCLUSION

Afghanistan’s groundwater crisis is no longer a localized or narrowly technical issue. It reflects the convergence of over-extraction, water-quality degradation, urban expansion, climate variability, weak monitoring, and institutional fragmentation. The Kabul Basin demonstrates these pressures most clearly, but the underlying sustainability challenge is national in scope.

This narrative review shows that groundwater sustainability in Afghanistan must be understood as a coupled environmental and governance problem. The evidence reviewed here indicates that aquifer depletion, recharge decline, and contamination are being intensified by inadequate infrastructure, limited regulation, and insufficient hydrogeological information. Under such conditions, business-as-usual management is unlikely to succeed.

AI offers important opportunities, especially in forecasting, data integration, and environmental monitoring but its value depends on being embedded within a broader strategy of institutional reform, monitoring recovery, recharge enhancement, and

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public-health protection. Sustainable groundwater management in Afghanistan will therefore require a balanced approach: technologically informed, institutionally grounded, and responsive to the realities of a conflict-affected and water-stressed setting.

Declaration of Competing Interests

The authors declare that there are no known financial interests or personal relationships that could have influenced, or be perceived to have influenced, the research reported in this paper.

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