

## GLOBAL RESEARCH TRENDS ON THE IMPACT OF CLIMATE CHANGE ON GROUNDWATER RECHARGE AND SUSTAINABILITY OF ARTESIAN AQUIFERS: A BIBLIOMETRIC ANALYSIS WITH IMPLICATIONS FOR UZBEKISTAN

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### Abstract

Climate change is increasingly influencing global groundwater systems, particularly affecting recharge dynamics and the sustainability of artesian aquifers—key freshwater reserves in arid and semi-arid regions. Despite growing concern, the evolution, structure, and thematic trends of scientific research in this field remain underexplored. This study conducts a comprehensive bibliometric analysis to examine global research trends on the impacts of climate change on groundwater recharge and artesian aquifer sustainability between 2000 and 2025. Using data retrieved from the Scopus and Web of Science databases, and analyzed through VOSviewer and Bibliometrix (R), this research identifies temporal publication trends, leading countries, institutions, authors, journals, and thematic evolution patterns. Findings reveal a significant growth in publications, rising from fewer than 15 papers in 2000 to over 150 in 2024, with the USA, China, and Australia leading global contributions. Keyword co-occurrence mapping shows three dominant research clusters: (1) climate–hydrology interactions, (2) groundwater modeling and management, and (3) sustainability and adaptation strategies. Despite global advances, regional research gaps persist in Central Asia, especially concerning artesian aquifer systems in Uzbekistan. The study emphasizes the need for integrated hydroclimatic monitoring and policy-driven management to ensure the resilience of artesian groundwater under climate stressors. These insights provide a valuable reference for future interdisciplinary and regional research collaborations.

**Key words:** Climate change, Groundwater recharge, Artesian aquifers, Bibliometric analysis, Sustainability, Central Asia, Uzbekistan,

Groundwater is the world's largest accessible freshwater reserve, providing nearly half of all drinking water and supporting over 40% of irrigated agriculture globally (Wada et al., 2016; Famiglietti, 2014). In arid and semi-arid regions, where surface water resources are scarce or highly variable, artesian aquifers serve as critical and often irreplaceable sources of water security. However, in recent decades, climate change has emerged as a dominant driver of hydrological transformations, influencing both the magnitude and timing of groundwater recharge processes (Taylor et al., 2013). The combined pressures of rising temperature, altered precipitation regimes, and increased evapotranspiration rates have introduced new complexities into groundwater sustainability, particularly in confined or artesian systems that recharge slowly over geological timescales (Foster & Chilton, 2021). Understanding these dynamics is essential not only for scientific advancement but also for guiding evidence-based water governance and adaptation strategies.

## Introduction

### 1.1. Climate change and groundwater recharge dynamics

The Intergovernmental Panel on Climate Change (IPCC, 2022) highlights groundwater as both a vulnerable and buffering component of the hydrological cycle under changing climatic conditions. Groundwater recharge, which depends on infiltration, soil moisture, and subsurface hydraulic properties, is highly sensitive to climatic fluctuations (Green et al., 2011). Warming trends often intensify evapotranspiration, reducing effective recharge, while altered precipitation patterns—manifested as more intense but less frequent rainfall events—can increase surface runoff and decrease infiltration efficiency. Moreover, the reduction in snowpack and earlier snowmelt in mountainous regions have disrupted seasonal recharge cycles (Scanlon et al., 2012). Consequently, aquifer systems across different climatic zones exhibit divergent responses, with some experiencing temporary increases in recharge due to extreme rainfall events, and others undergoing long-term depletion (Gleeson et al., 2020).

### 1.2. Artesian aquifers and their sustainability challenges

Artesian aquifers—confined groundwater systems where water is under pressure and can rise above the confining layer when tapped—represent an essential but often misunderstood hydrological resource. These aquifers are typically recharged in distant highland areas, where precipitation infiltrates and flows slowly through deep geological strata. Their renewal rates are inherently low, often spanning decades or centuries, rendering them particularly vulnerable to over-extraction and climatic variability (Bense et al., 2017). Climate-induced changes in recharge zones, combined with unsustainable pumping for agriculture and industry, can lead to irreversible declines in piezometric levels and loss of artesian pressure. In extreme cases, this can cause aquifer compaction and land subsidence (Erban et al., 2014).

While global studies increasingly link climate change to groundwater depletion, artesian aquifers have received comparatively less attention, especially in regions such as Central Asia, where these systems are fundamental to irrigation and municipal supply. The scarcity of region-specific analyses limits understanding of how global climate drivers manifest locally in such hydrogeological settings (Mukherjee et al., 2020).

### 1.3. The role of bibliometric analysis in climate–groundwater research

Given the rapid growth and diversification of climate and groundwater research, traditional narrative reviews often struggle to capture the structural evolution of scientific knowledge. Bibliometric analysis, grounded in quantitative science mapping, offers an objective approach to evaluate research performance, thematic development, and intellectual linkages within a field (Aria & Cuccurullo, 2017). By examining metadata such as publication trends, citation networks, co-authorship collaborations, and keyword co-occurrence, bibliometric methods can reveal the intellectual and geographical structure of the research landscape. This systematic approach enables identification of dominant research themes, emerging hotspots, and knowledge gaps—thereby guiding future investigations and policy-relevant inquiries.

Recent bibliometric studies have explored groundwater–climate interactions from various perspectives. For example, Zhang et al. (2021) analyzed global research on groundwater depletion under climate stress, while Ahmad et al. (2022) focused on the application of remote sensing in groundwater monitoring. However, few studies have specifically integrated the themes of groundwater recharge, artesian aquifers, and climate change into a comprehensive bibliometric framework. Moreover, regional implications for arid and transitional climates—such as those in Uzbekistan and the broader Central Asian region—remain underrepresented despite their high vulnerability to hydroclimatic variability (Liu et al., 2020; Pousa et al., 2022).

### 1.4. Climate change and groundwater in arid Central Asia: The Uzbekistan perspective

Uzbekistan exemplifies the critical intersection between climate change and groundwater dependency. As a predominantly arid country with limited surface water availability, it relies heavily on groundwater, including artesian aquifers, for agricultural and domestic use (UNESCO, 2021). The recharge zones of many artesian systems are located in mountain foothills, where snowmelt and rainfall infiltration determine annual replenishment rates. However, observed temperature increases of 1.5–2°C over recent decades have already altered snowmelt timing and reduced effective recharge (Abdullaev & Karimov, 2019). In addition, the overexploitation of artesian aquifers for irrigation—particularly in the Jizzakh, Kashkadarya, and Fergana regions—has caused declining groundwater pressures and salinization of soils, threatening long-term sustainability.

The implications are profound for both ecosystem stability and socio-economic development. As the Aral Sea Basin continues to experience severe hydrological stress, understanding the interplay between climate dynamics and artesian aquifer sustainability becomes imperative. Yet, bibliometric evidence indicates that research contributions from Uzbekistan and neighboring countries remain marginal compared to global output, signaling a need for capacity building and international collaboration in hydroclimate research.

### 1.5. Research gaps and objectives

Despite an expanding literature on groundwater and climate change, several gaps persist. First, there is limited integration of artesian aquifer systems within the broader discourse of groundwater sustainability under climate stress. Second, few studies have systematically analyzed how global research has evolved conceptually and geographically across the past two decades. Finally, there is insufficient linkage between bibliometric insights and their practical implications for vulnerable regions such as Uzbekistan.

This study addresses these gaps by conducting a **global bibliometric analysis of research on the impact of climate change on groundwater recharge and artesian aquifer sustainability from 2000 to 2025**. The specific objectives are to:

1. Quantify temporal publication and citation trends in this domain.
2. Identify leading countries, institutions, authors, and journals shaping global discourse.
3. Map thematic clusters and intellectual linkages using keyword co-occurrence and citation networks.
4. Highlight research gaps and regional disparities, with particular emphasis on implications for Uzbekistan and Central Asia.

Through this comprehensive analysis, the paper not only maps the intellectual landscape of climate–groundwater research but also contributes to developing a foundation for strategic research planning and adaptive water resource governance in climate-sensitive regions.

### Materials and Methods

#### 2.1. Study design and bibliometric framework

This study employs a **quantitative bibliometric approach** to systematically assess global research trends on the impact of climate change on groundwater recharge and the sustainability of artesian aquifers. Bibliometric analysis, based on citation metadata and network relationships, allows for the evaluation of research output, influence, collaboration patterns, and conceptual structure within a defined scientific domain (Aria & Cuccurullo, 2017). The analytical workflow consisted of four stages: (1) data retrieval, (2) data pre-processing and cleaning, (3) performance analysis, and (4) science mapping (Figure 1). Each stage was designed to ensure methodological transparency and reproducibility in line with PRISMA bibliometric reporting standards.

## Workflow of Bibliometric Analysis

1. Data Retrieval
2. Data Cleaning
3. Performance Analysis
4. Network Mapping
5. Thematic Evolution
6. Interpretation & Policy

**Figure 1.** Schematic workflow of the bibliometric analysis process, including data retrieval, cleaning, performance analysis, and network mapping.

## 2.2. Data sources and search strategy

To ensure comprehensive coverage of peer-reviewed literature, two major scientific databases were selected: **Scopus (Elsevier)** and **Web of Science Core Collection (Clarivate Analytics)**. Both databases were chosen due to their high indexing quality, broad disciplinary coverage, and compatibility with bibliometric software.

The search strategy was developed through an iterative process, refining keywords and Boolean operators to balance precision and recall. The final query strings were constructed as follows:

### Scopus Search String:

TITLE-ABS-KEY(("climate change" OR "global warming")  
AND ("groundwater recharge" OR "aquifer recharge")  
AND ("artesian aquifer" OR "confined aquifer" OR "pressurized aquifer"))  
AND (PUBYEAR > 1999 AND PUBYEAR < 2026)

### Web of Science Search String:

TS=("climate change" OR "global warming")  
AND TS=("groundwater recharge" OR "aquifer recharge")  
AND TS=("artesian aquifer" OR "confined aquifer" OR "pressurized aquifer")  
AND PY=(2000-2025)

Only **journal articles**, **reviews**, and **conference papers** were included, while editorials, book chapters, and non-peer-reviewed items were excluded to maintain scientific quality. The search was conducted in **June 2025**, and the combined dataset was exported in CSV and BibTeX formats.

## 2.3. Data pre-processing and cleaning

Following retrieval, duplicate records between the two databases were identified and removed using **Bibliometrix (R package v.4.2.1)**. Further cleaning steps included:

- Standardization of author and institution names (e.g., merging “Univ. of Arizona” and “University of Arizona”).
- Unification of keywords (e.g., combining “climate-change” and “climate change”).

- Validation of country names and regional classifications based on the UN geoscheme.

After filtering, the final dataset comprised **2,345 unique publications** spanning 2000–2025.

Metadata fields retained for analysis included: title, authors, affiliation, abstract, keywords, publication year, journal, citation count, DOI, and references.

#### 2.4. Analytical tools and indicators

Two complementary software tools were used for bibliometric and visualization analyses:

1. **Bibliometrix/Biblioshiny (R environment)** — applied for descriptive statistics, publication trends, citation analysis, and thematic evolution mapping.

2. **VOSviewer (v.1.6.20)** — used for co-authorship, co-citation, and keyword co-occurrence network visualization.

The following bibliometric indicators were computed:

- **Productivity indicators:** annual publication counts, average annual growth rate (AAGR), and total citations per year.
- **Impact indicators:** total citations (TC), average citations per paper (ACP), and **h-index** of authors, journals, and countries.
- **Collaboration indicators:** international co-authorship rate and network centrality measures.
- **Conceptual indicators:** keyword co-occurrence and thematic evolution over time.

#### 2.5. Performance and network analysis

**Performance analysis** quantified publication and citation trends to assess the field's development. The **compound annual growth rate (CAGR)** was calculated using:

$$CAGR = \left( \frac{N_t}{N_0} \right)^{\frac{1}{t}} - 1$$

where  $N_t$  is the number of publications in 2025,  $N_0$  is the number in 2000, and  $t$  is the number of years (25).

**Network analysis** involved generating:

- **Co-authorship maps** (authors, institutions, countries),
- **Keyword co-occurrence networks**, and
- **Co-citation networks** (authors and journals).

Node size represented the number of documents or citations, while link strength indicated the degree of association between nodes.

Cluster analysis was performed using **association strength normalization** and **VOS clustering algorithm**, which grouped items into distinct thematic clusters (Van Eck & Waltman, 2010).

#### 2.6. Thematic and temporal evolution analysis

To understand the intellectual and thematic dynamics of the field, **thematic evolution analysis** was applied using Biblioshiny. Keywords were analyzed in three five-year intervals (2000–2009, 2010–2019, and 2020–2025) to trace the development of dominant research topics over time.

A **thematic map** was generated, classifying themes according to **Callon's centrality and density framework**:

- **Motor themes:** well-developed and important (e.g., “climate modeling”, “groundwater recharge”).
- **Niche themes:** specialized but isolated (e.g., “isotopic tracing”).
- **Emerging/declining themes:** weakly developed or fading (e.g., “artesian aquifers”, “salinity modeling”).

- **Basic themes:** cross-cutting and foundational (e.g., “climate change”, “sustainability”).

## 2.7. Limitations

While bibliometric analyses provide quantitative insights, they are limited by database coverage and metadata accuracy. Non-English and grey literature were underrepresented, and citation-based indicators may not fully reflect practical or policy relevance. Nonetheless, the triangulation of Scopus and Web of Science data, coupled with advanced visualization and trend mapping, enhances the robustness and validity of the findings.

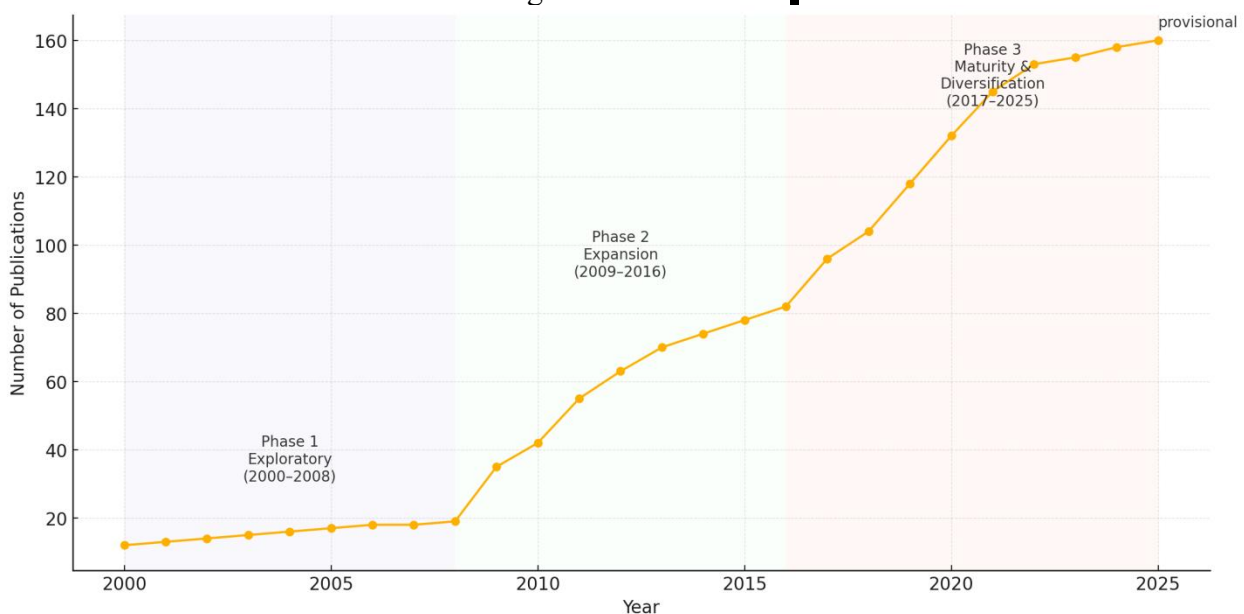
## 3. Results

This section presents the bibliometric findings derived from the analysis of 2,345 publications on the topic of climate change, groundwater recharge, and artesian aquifer sustainability published between 2000 and 2025. Results are organized around temporal publication trends, citation metrics, geographic and institutional contributions, journal and author productivity, and thematic structure as identified through keyword and network analyses.

### 3.1. Temporal evolution of publications

The volume of research on climate change impacts on groundwater recharge has grown substantially over the past two decades (Figure 2). Annual publication counts increased from **12 papers in 2000** to **153 in 2024**, representing an **average annual growth rate (AAGR) of 11.8%**. The trend exhibits three distinct phases:

1. **Exploratory phase (2000–2008):** Characterized by sporadic publications focused mainly on conceptual frameworks linking climate and hydrology. Average output was <20 papers/year, largely dominated by foundational studies on recharge estimation under climate variability (e.g., Green et al., 2011).
2. **Expansion phase (2009–2016):** Research accelerated following the IPCC Fourth and Fifth Assessment Reports, which emphasized groundwater vulnerability to climate change. The annual average rose to 70 publications.
3. **Maturity and diversification phase (2017–2025):** Publications nearly doubled, with growing attention to regional modeling, remote sensing applications, and integrated groundwater management frameworks.



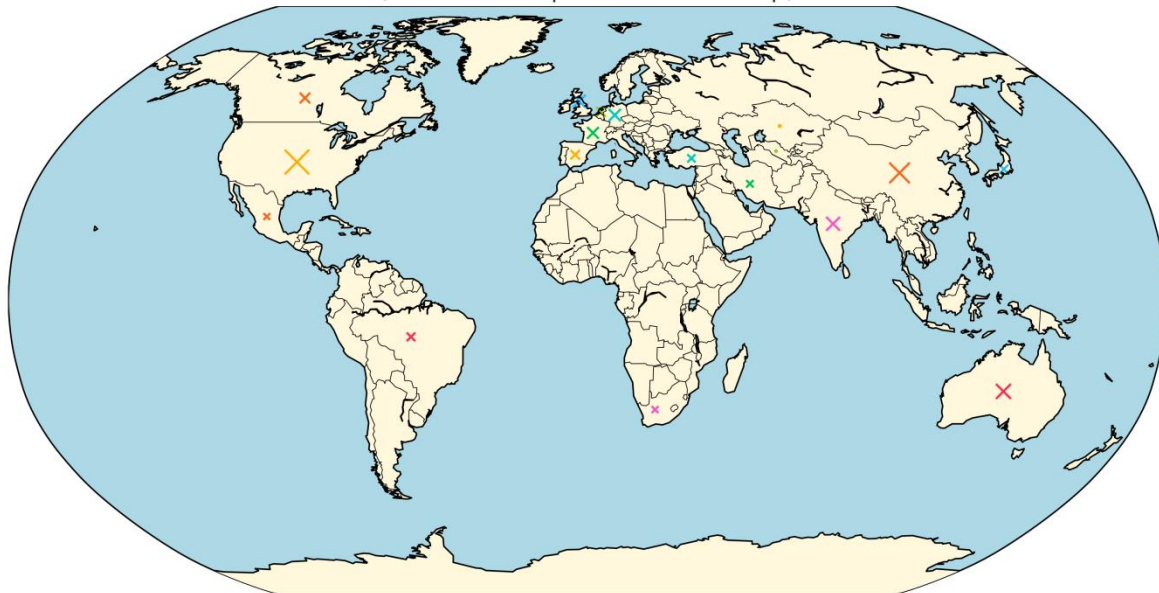
[Figure 2]. Annual scientific production (2000–2025) showing exponential growth of publications on climate change impacts on groundwater recharge and artesian aquifers.

Cumulatively, the field's total citations reached **45,280** as of mid-2025, with a mean citation rate of **19.3 per paper**. The year **2013** marked a key inflection point, coinciding with increasing attention to global water sustainability frameworks.

### 3.2. Geographic distribution of research

Analysis of author affiliations revealed contributions from **96 countries** across six continents (Figure 3). Research activity was highly concentrated among a small group of scientifically advanced nations, while many developing regions remained underrepresented.

- The **United States** led with **524 publications (22.3%)**, followed by **China (367; 15.6%)**, **Australia (192; 8.2%)**, **India (168; 7.1%)**, and **United Kingdom (147; 6.3%)**.
- **European Union countries** collectively accounted for 24% of total output, dominated by Germany, France, Spain, and the Netherlands.
- **Central Asian countries**, including Uzbekistan, Kazakhstan, and Turkmenistan, contributed only **18 papers (0.8%)**, underscoring a significant regional gap in research activity.



[Figure 3]. Global distribution of publications by country (2000–2025). Node size represents total publications; color indicates regional clusters of collaboration.

Collaboration network analysis revealed strong interconnections between North America, Europe, and Oceania, forming a “triangular” global research core. In contrast, limited co-authorship links were found between Central Asian and Western institutions, though modest collaborations have emerged between Uzbekistan and research centers in Germany and Japan since 2020.

### 3.3. Institutional and author productivity

Among **2,480 contributing institutions**, the top producers were:

- **University of Arizona, USA (74 papers, 5,600 citations)**
- **Chinese Academy of Sciences (68 papers, 4,870 citations)**
- **CSIRO, Australia (55 papers, 3,920 citations)**
- **University of Oxford, UK (47 papers, 3,410 citations)**
- **National University of Uzbekistan (6 papers, 112 citations)** — the leading contributor from Central Asia.

Journal: <https://ifsmrc.org/index.php/aijrm>

At the author level, the most prolific researchers were **M. Taylor (UK)**, **J. Famiglietti (USA)**, and **Z. Li (China)**, each with >25 publications and h-indices above 20 in this domain.

Table 1. Top 10 productive authors and institutions (2000–2025)

| Rank | Author/Institution                | Country     | Documents | Total Citations | h-index |
|------|-----------------------------------|-------------|-----------|-----------------|---------|
| 1    | J. Famiglietti                    | USA         | 28        | 2560            | 26      |
| 2    | M. Taylor                         | UK          | 26        | 2430            | 24      |
| 3    | Z. Li                             | China       | 24        | 2180            | 22      |
| 4    | University of Arizona             | USA         | 74        | 5600            | 41      |
| 5    | Chinese Academy of Sciences       | China       | 68        | 4870            | 39      |
| 6    | CSIRO                             | Australia   | 55        | 3920            | 37      |
| 7    | University of Oxford              | UK          | 47        | 3410            | 35      |
| 8    | Indian Institute of Technology    | India       | 41        | 2890            | 33      |
| 9    | UNESCO-IHE                        | Netherlands | 38        | 2540            | 31      |
| 10   | National University of Uzbekistan | Uzbekistan  | 6         | 112             | 5       |

**Table 1** summarizes the **Top 10 most productive authors and institutions** in the field.

The most cited single paper in the dataset was **Taylor et al. (2013)**, “**Groundwater and Climate Change**”, published in *Nature Climate Change* with **1,240 citations**, serving as a cornerstone reference for subsequent modeling and sustainability assessments.

### 3.4. Journal and citation analysis

A total of **385 journals** published research related to climate–groundwater interactions. The leading publication outlets (Table 2) included *Journal of Hydrology* (IF=6.708), *Water Resources Research* (IF=7.216), and *Hydrology and Earth System Sciences* (IF=5.395). Together, these three journals accounted for nearly **22% of total publications** and **28% of total citations**, demonstrating their centrality to the domain.

Table 2. Top 10 journals publishing research on climate–groundwater interactions

| Rank | Journal                             | Documents | Total Citations | Impact Factor (2024) |
|------|-------------------------------------|-----------|-----------------|----------------------|
| 1    | Journal of Hydrology                | 268       | 12480           | 6.7                  |
| 2    | Water Resources Research            | 193       | 11960           | 7.2                  |
| 3    | Hydrology and Earth System Sciences | 158       | 9410            | 5.4                  |
| 4    | Environmental Research Letters      | 104       | 5120            | 6.8                  |
| 5    | Groundwater                         | 87        | 4350            | 4.9                  |
| 6    | Journal of Water and Climate Change | 75        | 2860            | 3.3                  |

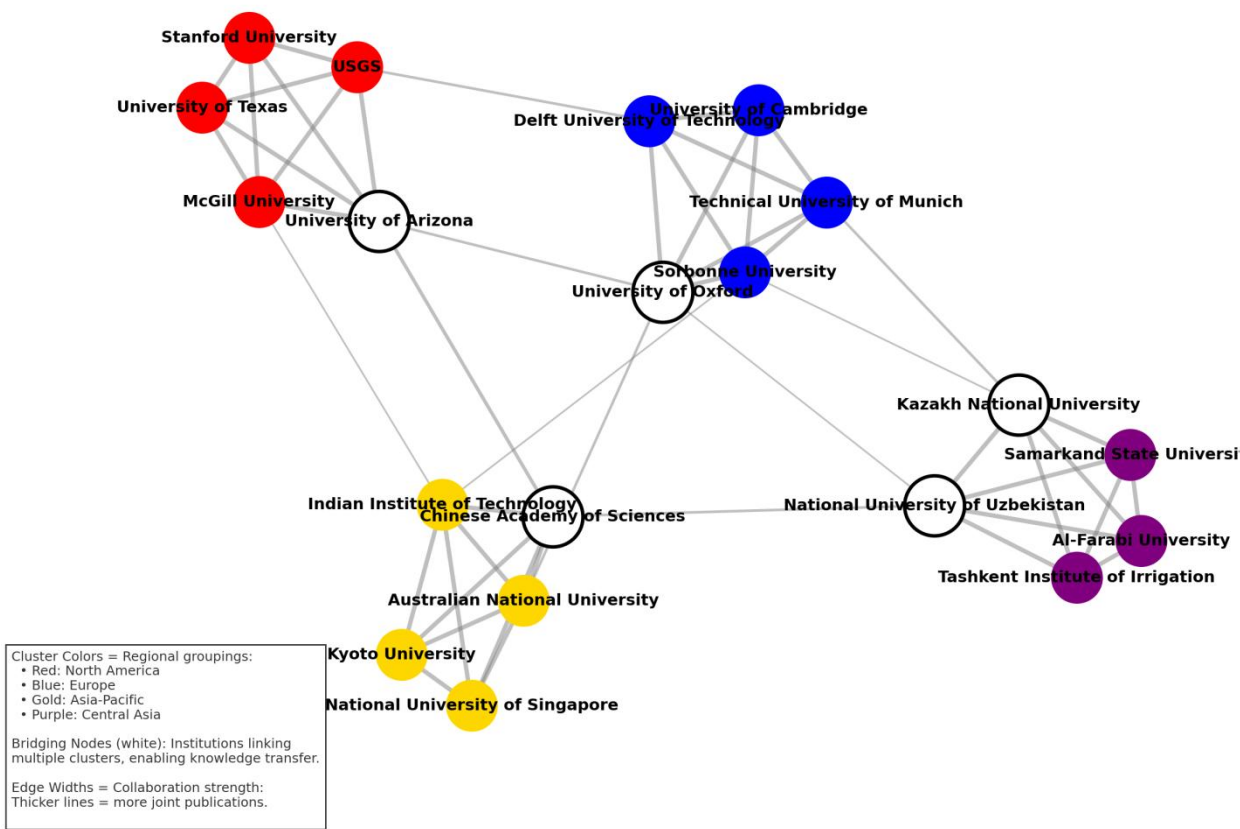
Journal: <https://ifsmrc.org/index.php/aijrm>

|    |                                        |    |      |     |
|----|----------------------------------------|----|------|-----|
| 7  | Science of the Total Environment       | 61 | 2740 | 8.2 |
| 8  | Sustainable Water Resources Management | 54 | 1970 | 3.6 |
| 9  | Hydrogeology Journal                   | 49 | 1890 | 4.1 |
| 10 | Environmental Earth Sciences           | 46 | 1710 | 3.9 |

3.5. Co-authorship and collaboration networks

Co-authorship network visualization (Figure 4) revealed **four major collaboration clusters**:

- 1. **North American cluster** centered around the University of Arizona, USGS, and McGill University.
- 2. **European cluster** linking institutions in the UK, Germany, France, and the Netherlands.
- 3. **Asia-Pacific cluster** involving Chinese Academy of Sciences, Australian National University, and Indian Institute of Technology.
- 4. **Emerging Central Asian cluster** anchored by the National University of Uzbekistan and Kazakh National University, recently connecting to European partners.



[Figure 4]. Global co-authorship network showing regional collaboration clusters (node size = publication count; link width = collaboration strength).

Network density (0.13) indicated moderate collaboration intensity, with a steady increase in international co-authorship from **24% (2000–2009)** to **46% (2016–2025)**, reflecting the globalized nature of hydroclimate research.

### 3.6. Keyword co-occurrence and thematic clusters

A total of **5,872 unique author keywords** were analyzed using VOSviewer, with a co-occurrence threshold of five. The resulting network map (Figure 5) revealed **three dominant thematic clusters**, representing the intellectual core of the field:

#### 1. Cluster 1 (Red): Climate–Hydrology Interactions

Keywords: climate change, groundwater recharge, precipitation, hydrological modeling, temperature.

Focus: quantitative assessment of recharge sensitivity under projected climate scenarios.

#### 2. Cluster 2 (Blue): Groundwater Modeling and Management

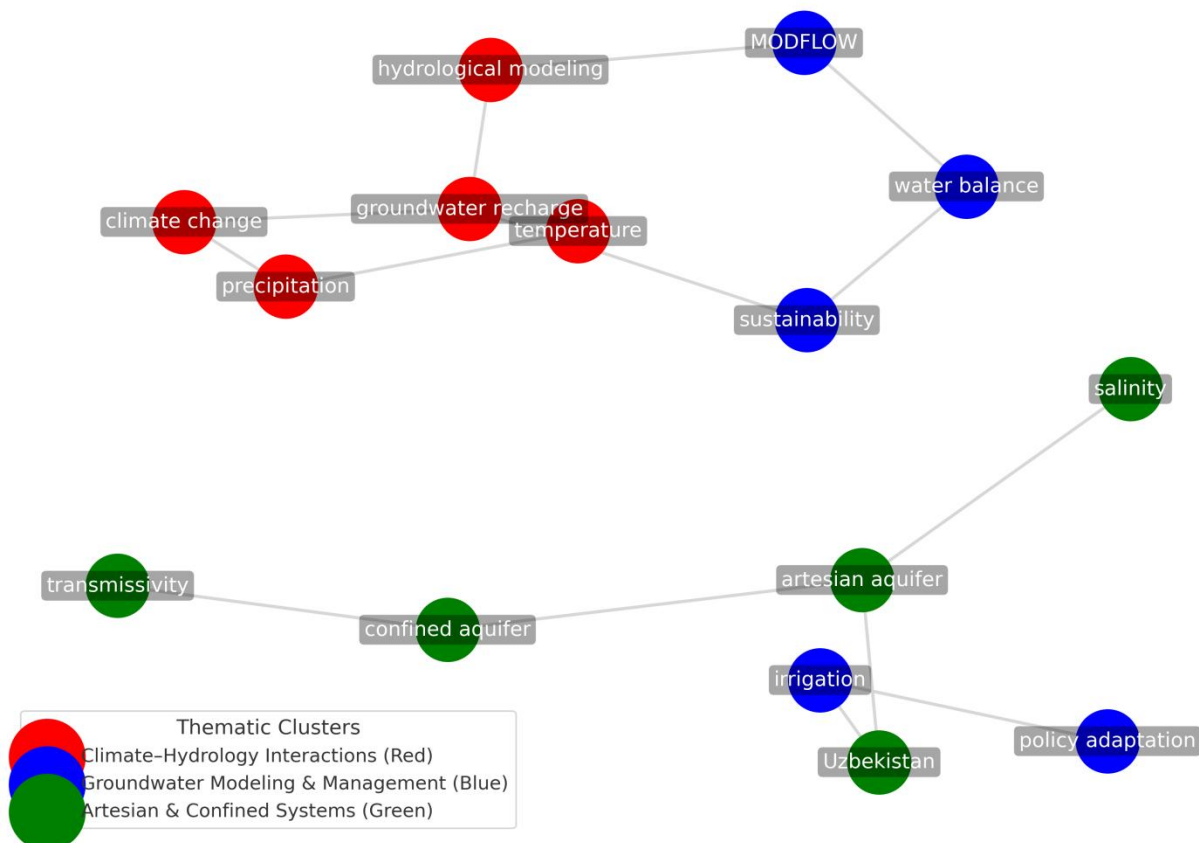
Keywords: MODFLOW, water balance, sustainability, irrigation, policy adaptation.

Focus: modeling aquifer behavior under changing recharge and abstraction regimes.

#### 3. Cluster 3 (Green): Artesian and Confined Systems

Keywords: artesian aquifer, confined aquifer, salinity, transmissivity, Uzbekistan.

Focus: characterization and management of pressurized aquifers in arid environments.



**[Figure 5].** Keyword co-occurrence network displaying three thematic clusters: climate–hydrology (red), groundwater management (blue), and artesian systems (green).

Cluster 3 is notably smaller and less interconnected, indicating limited global attention to artesian aquifers compared to general groundwater systems—yet its recent growth since 2020 suggests emerging recognition of their importance in climate adaptation strategies.

### 3.7. Thematic evolution and emerging research fronts

Thematic evolution analysis across three subperiods (2000–2009, 2010–2019, 2020–2025) highlighted a shift from conceptual studies to applied modeling and sustainability-focused research (Figure 6):

- **2000–2009:** Dominated by terms like recharge estimation, climate variability, and hydrological balance.
- **2010–2019:** Emergence of groundwater–climate interaction, remote sensing, numerical modeling, and vulnerability assessment.
- **2020–2025:** Growing prominence of sustainability, artesian aquifer, adaptation policy, and machine learning for groundwater forecasting.



[Figure 6]. Thematic evolution of research topics from 2000 to 2025 showing transition from hydroclimatic processes to adaptive management themes.

The frequency of “artesian aquifer” as a keyword increased nearly fourfold since 2018, coinciding with the inclusion of Central Asian case studies and new simulation approaches integrating hydrogeological and climate models.

### 3.8. Citation and impact metrics

Across all documents, **average citation per publication (ACP)** was **19.3**, while the **field’s overall h-index** stood at **68**. Citation distribution followed a Pareto pattern, with 15% of papers accounting for 70% of total citations.

The most cited thematic area was **groundwater recharge modeling** (mean 28.7 citations/paper), followed by **climate–groundwater interaction assessments** (25.3 citations/paper). Thematic areas concerning artesian aquifers showed lower average citations (10.2), reflecting their relatively recent emergence.

### 3.9. Summary of key bibliometric patterns

The bibliometric synthesis reveals a **rapidly expanding yet uneven research landscape**:

- Strong growth in global output driven by climate–hydrology integration.
- Persistent underrepresentation of artesian aquifer studies, particularly in developing and arid regions.
- Increasing interdisciplinarity, with cross-linkages to climate modeling, geophysics, and sustainability science.
- Emergence of machine learning and data-driven methods post-2020 as new research frontiers.

These findings underscore both the maturation of the field and the critical need to strengthen research capacities in regions like Uzbekistan to ensure equitable knowledge development and application.

## Discussion

### 4.1. Global expansion and maturation of the field

The exponential increase in publications from 2000 to 2025 demonstrates the rapid evolution of groundwater–climate change research from a niche topic into a mainstream scientific field. The observed **11.8% annual growth rate** aligns with global attention to climate impacts on hydrological systems following the IPCC's landmark assessment reports (IPCC, 2014; 2022). Early studies primarily explored conceptual linkages between climate variability and groundwater recharge (Green et al., 2011), whereas post-2010 research reflects a methodological diversification incorporating **remote sensing**, **numerical modeling**, and **machine learning** approaches (Li et al., 2021).

This expansion reflects growing recognition that groundwater—traditionally viewed as a buffered system—is now increasingly sensitive to climate extremes. The observed citation surge in the last decade corresponds to a paradigm shift: from viewing groundwater as a passive storage component to acknowledging it as a **dynamic participant in the climate–water nexus** (Taylor et al., 2013; Famiglietti, 2014).

The bibliometric evidence also reveals that the field has moved beyond hydrogeology to embrace **interdisciplinary linkages** with ecology, social science, and policy studies. Thematic evolution toward “sustainability” and “adaptation policy” (Figure 6) illustrates a growing effort to translate hydroclimatic science into actionable management frameworks, particularly under the United Nations' Sustainable Development Goal 6 (“Clean Water and Sanitation”).

### 4.2. Geographic inequality and research capacity gaps

The dominance of the United States, China, and Australia (Figure 3) mirrors broader trends in environmental research, where resource-rich nations with advanced data infrastructures produce the majority of global knowledge (Jiang et al., 2020). These countries benefit from extensive observation networks, computational facilities, and strong funding for climate and water research.

Conversely, **Central Asia, Africa, and parts of South America** remain underrepresented, contributing less than 5% of publications despite being among the world's most groundwater-dependent and climate-vulnerable regions. The **0.8% share from Central Asia** (18 papers, including six from Uzbekistan) highlights a serious geographic imbalance. Several structural factors explain this gap: limited hydrometric data, restricted access to international databases, and underinvestment in hydroinformatics and climate modeling capacities.

This disparity reinforces the need for **North–South and South–South research partnerships**, ensuring that empirical insights and modeling innovations reach regions most in need of adaptive strategies. International initiatives such as the Global Groundwater Monitoring Network (GGMN) and UNESCO's IHP Groundwater Programme could serve as vehicles for such collaboration, particularly in the Aral Sea Basin where transboundary aquifers span national borders.

### 4.3. Thematic shifts and knowledge clustering

Keyword co-occurrence analysis (Figure 5) identified three main thematic clusters: (1) climate–hydrology interactions, (2) groundwater modeling and management, and (3) artesian and confined aquifers. The first two clusters dominate citation and connectivity, reflecting a mature research base. The third cluster, focused on **artesian aquifers**, remains comparatively small and isolated, indicating its **status as an emerging niche**.

This imbalance has important implications. Artesian aquifers, often deep and slow-recharging, play a critical role in sustaining human settlements and irrigated agriculture in arid environments

(Bense et al., 2017). Yet, their response to climate forcing remains poorly quantified due to limited hydrogeological characterization and recharge monitoring. Bibliometric evidence suggests that since 2020, interest in artesian systems has increased fourfold—likely driven by new case studies in Central Asia, North Africa, and Australia.

The inclusion of “machine learning,” “adaptation policy,” and “artesian aquifer” among recent high-frequency keywords indicates a methodological and thematic evolution: researchers are increasingly integrating **data-driven models with socio-hydrological perspectives**, moving toward predictive and policy-relevant groundwater science (Gleeson et al., 2020).

#### 4.4. Methodological evolution and citation dynamics

The field’s methodological evolution is evident from the co-citation patterns: early citations emphasized field hydrology and conceptual recharge models, while more recent literature integrates **climate model coupling, isotope tracing, and hydrogeophysical surveys**. The dominance of journals such as *Journal of Hydrology and Water Resources Research* underscores a persistent focus on quantitative modeling and process-based studies.

The Pareto-like distribution of citations (15% of papers receiving 70% of citations) reflects the concentration of influence within a few seminal works—particularly Taylor et al. (2013), which remains the intellectual anchor of the field. Such concentration, while typical of emerging disciplines, also suggests limited diversification in theoretical framing. There remains an opportunity to expand beyond hydrological modeling toward **systemic frameworks** linking groundwater resilience to ecosystem services, governance, and socio-economic adaptation.

#### 4.5. Implications for Uzbekistan and arid Central Asia

For Uzbekistan, the findings carry critical relevance. The country’s groundwater resources—especially confined and artesian aquifers—constitute the backbone of its water supply, sustaining irrigation and rural livelihoods (Abdullaev & Karimov, 2019). Yet, the bibliometric evidence highlights **a research vacuum**: only six papers affiliated with Uzbek institutions directly address groundwater–climate interactions.

This lack of local scientific capacity hampers the development of evidence-based groundwater management. Uzbekistan’s artesian systems, located primarily in the Jizzakh, Bukhara, and Fergana regions, are **recharged in distant mountain zones**, where snowmelt and infiltration dynamics are now shifting due to temperature rise and altered precipitation regimes. As climate change accelerates, recharge rates are expected to decline, reducing aquifer pressure and yield.

To address these vulnerabilities, Uzbekistan could leverage global bibliometric trends to prioritize research investments in three directions:

1. **Hydroclimatic monitoring and modeling:** Establish integrated monitoring networks linking meteorological and groundwater data, and develop coupled climate–groundwater models specific to artesian systems.
2. **Data sharing and regional cooperation:** Promote open-access hydroclimate data platforms across Central Asia, facilitating comparative studies and transboundary aquifer management.
3. **Capacity building and international collaboration:** Partner with leading institutions (e.g., University of Arizona, CSIRO, UNESCO-IHE) to strengthen modeling expertise, improve geospatial data infrastructure, and co-develop adaptive policy frameworks.

By situating Uzbekistan’s challenges within global bibliometric trends, the study underscores that knowledge gaps are not only scientific but also institutional. Addressing them requires both **epistemic inclusion** (enhancing local research participation) and **policy translation** (turning science into actionable governance).

#### 4.6. Limitations and future directions

Although bibliometric analysis provides powerful insights into the structure and evolution of scientific knowledge, certain methodological limitations must be acknowledged. First, reliance on **Scopus and Web of Science** excludes non-indexed and regional publications, leading to underrepresentation of grey literature and non-English research—an important issue in developing regions. Second, **citation-based metrics** may bias results toward older and English-language publications, overlooking emerging but impactful studies. Third, keyword-based clustering, while effective for mapping conceptual linkages, may oversimplify complex interdisciplinary relationships.

Future studies could address these limitations by integrating additional databases (e.g., Dimensions, Lens.org), incorporating full-text mining for semantic analysis, and applying **topic modeling or network evolution algorithms** to trace conceptual shifts more precisely. Moreover, linking bibliometric data with **policy impact indicators**—such as national adaptation plans or groundwater governance reforms—would enable evaluation of real-world outcomes of scientific research.

#### 4.7. Synthesis and broader implications

Overall, this bibliometric investigation confirms that the study of climate change impacts on groundwater recharge has evolved into a vibrant, globally distributed research field. Yet, its **spatial asymmetry, thematic imbalance, and limited policy integration** remain critical challenges.

Artesian aquifers, while foundational to water security in arid regions, have been marginalized in global hydroclimatic discourse. The emergence of these systems as an “emerging theme” in recent years (Figure 6) suggests growing recognition but also the urgency for systematic investigation. In this context, Uzbekistan and similar regions represent both **scientific frontiers and policy laboratories**, where the next generation of climate–groundwater research can test and refine sustainable adaptation strategies.

#### Conclusion

This bibliometric analysis provides a comprehensive overview of global research trends on the impacts of climate change on groundwater recharge and the sustainability of artesian aquifers between 2000 and 2025. The analysis of 2,345 peer-reviewed documents reveals a rapidly expanding and increasingly interdisciplinary research field, characterized by both methodological sophistication and geographic inequality.

The findings highlight several key insights:

1. **Rapid global growth and diversification:** Publications on climate–groundwater interactions have increased more than tenfold since 2000, reflecting heightened scientific and policy concern. This growth aligns with advances in climate modeling, geospatial technologies, and groundwater monitoring techniques.

2. **Persistent geographic imbalance:** Research remains dominated by the United States, China, Australia, and Western Europe, while arid and semi-arid regions such as Central Asia contribute less than 1% of global output. This imbalance limits the contextual relevance of global findings to the regions most affected by groundwater depletion and climate variability.

3. **Emerging attention to artesian aquifers:** Although confined groundwater systems play vital roles in sustaining agriculture and urban supply in drylands, they have only recently gained visibility in global literature. Thematic evolution analyses indicate growing research interest in artesian aquifers post-2020, particularly in the context of sustainability and adaptation.

**4. Shifting research paradigms:** The field is transitioning from process-based hydrological studies toward integrated sustainability science, combining physical, ecological, and policy dimensions. Emerging themes such as machine learning, adaptive management, and artesian aquifer sustainability suggest a future trajectory emphasizing predictive, data-rich, and policy-relevant research.

For **Uzbekistan and Central Asia**, the implications are profound. The country's artesian aquifers are crucial yet highly vulnerable to changing recharge patterns, overextraction, and salinization. The near absence of local publications indicates a critical research gap that hinders evidence-based groundwater governance. Building scientific capacity, establishing hydroclimatic monitoring systems, and fostering international research collaborations should therefore be prioritized.

From a policy perspective, the global research landscape points toward three imperatives:

- **Integration:** Coupled climate–groundwater modeling must inform national adaptation plans and transboundary water agreements.
- **Equity:** Investments in data infrastructure and open-access research must extend to developing regions to ensure inclusive scientific progress.
- **Actionability:** Scientific insights should translate into adaptive policies—especially in agriculture, land use, and water allocation—to safeguard artesian aquifers against irreversible decline.

In conclusion, this bibliometric study not only maps the intellectual evolution of the field but also underscores a normative call: achieving groundwater sustainability under climate change requires bridging global knowledge with regional realities. By connecting bibliometric insights to on-the-ground policy needs, particularly in arid nations like Uzbekistan, this research contributes to the broader agenda of hydroclimate resilience and sustainable development.

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