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# Global Trends and Research Frontiers of Water Harvesting and Groundwater Recharge: A Comprehensive Bibliometric Review

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**Abstract:** The intensifying global challenge of groundwater depletion driven by climate variability, urban expansion, and unsustainable extraction has elevated the strategic importance of water harvesting (WH) and groundwater recharge (GWR) as integral components of sustainable water resource management. This study presents a comprehensive bibliometric review of 587 peer-reviewed articles retrieved from the Scopus database and published between years 2019 and 2024. Employing VOSviewer and the bibliometrix *R*-package, the analysis mapped publication dynamics, co-authorship patterns, citation structures, and thematic evolutions in the WH and GWR research landscapes. The findings revealed four dominant thematic clusters, i.e., rainwater harvesting for climate adaptation, recharge estimation methodologies, geospatial and remote sensing applications, and interdisciplinary managed aquifer recharge (MAR) frameworks. India, China, and the United States emerged as the most prolific contributors in these topics although significant geographic and thematic imbalances persist, particularly in underrepresented yet water-stressed regions such as sub-Saharan Africa and Central Asia. Despite methodological progress in Geographic Information System (GIS) based modeling and tracer techniques, the integration of artificial intelligence, socio-hydrological modeling, and participatory governance points to future research direction. To advance global groundwater sustainability and resilience, this review highlights critical knowledge gaps and proposes a strategic research agenda emphasizing hybrid recharge systems, AI-enhanced decision support tools, and socially inclusive implementation pathways.

**Keywords:** Harvesting; Groundwater recharge; Bibliometric analysis; Sustainable water management; Rainwater harvesting

## 1. Introduction

Groundwater is a vital element of the global freshwater system, supporting domestic, agricultural, industrial, and ecological needs across diverse climates, with particular importance in arid and semi-arid regions. Globally, it provides at least part of the drinking water supply for nearly half the population and sustains around 43% of irrigation demand. In fact, more than 2.5 billion people depend entirely on groundwater for daily consumption (Barthel et al., 2021). However, escalating water demand driven by urban expansion, population growth, and climate change has intensified extraction rates, often in the absence of effective regulation. This overexploitation has resulted in declining water tables, reduced surface water flows, land subsidence, increased pumping costs, and degradation of both water quality and ecosystems. Such issues are particularly acute in water-stressed regions, including North Africa, the Middle East, South and Central Asia, Northern China, North America, and Australia, with localized depletion hotspots emerging worldwide (Lall et al., 2020).

In many developing nations, groundwater remains the primary drinking water source, particularly in sub-Saharan Africa. Countries such as Ethiopia and Kenya rely heavily on it, with roughly 30% of urban residents in the region drawing their drinking water from wells, springs, or other groundwater-fed systems (Chávez García Silva et al., 2020). This dependence stems from the limited reach of conventional water supply networks and the relative reliability and quality of groundwater, which often requires minimal treatment (Jebamalar et al., 2012).

Yet, urban development frequently disrupts natural recharge areas, further straining aquifers and, in some cases, exhausting them entirely (Anker et al., 2019). The challenge is particularly severe in arid and semi-arid zones covering over 40% of the Earth's surface where groundwater stress is already high (Priyan, 2021). Addressing this problem calls for proactive recharge strategies to counteract depletion and bolster resilience against climate variability (Barthel et al., 2021).

Enhancing groundwater recharge can be achieved through natural processes, such as rainfall infiltration, or through engineered interventions. Among the latter, rainwater harvesting (RWH) has gained traction in various African countries to supplement groundwater reserves (Yannopoulos et al., 2019). Yet, implementation faces obstacles, including irregular rainfall patterns, limited rooftop catchment areas, the high relative cost of infrastructure, and shortages of construction materials like cement and quality sand. Competition for water resources in the construction sector adds another layer of difficulty. Even so, both RWH and broader WH methods are expanding steadily (Ndeketeya & Dundu, 2019). WH refers to the capture, storage, and productive use of rainwater or surface runoff, often through systems such as rooftop collectors, small dams, or storage tanks. These systems enable households, farms, and communities to store water for later use in domestic supply, irrigation, livestock care, or aquifer recharge (Ertop et al., 2023).

By allowing captured runoff to percolate into the subsurface, WH directly supports aquifer replenishment, helping offset the effects of overextraction and improving groundwater levels (Huang et al., 2021). In addition, the relatively clean quality of harvested rainwater can help dilute contaminants within aquifers. When strategically integrated into groundwater governance, WH enhances sustainability, supports wetland and streamflow health, and contributes to long-term resource security. The effectiveness of WH in boosting groundwater recharge depends on local hydrogeological conditions, system design, and management practices (Sanil et al., 2024). Well-planned WH initiatives can thus play a pivotal role in integrated water resource management, especially in water-stressed environments.

To address the fragmented nature of existing reviews on WH and GWR, this study applies a bibliometric approach to systematically classify, visualize, and interpret global research trends, thematic clusters, and collaboration patterns. Previous reviews have typically examined isolated aspects such as specific recharge techniques or hydrological performance without integrating the technical, environmental, and policy dimensions into a unified analytical framework. By employing performance analysis and network mapping, this work aims to fill that gap, providing a holistic, data-driven synthesis of the field. The central question guiding this review is: What are the key research trends, dominant themes, and strategic directions in the global landscape of WH and GWR? To operationalize this aim, the study examines four sub-questions: (1) How has scientific output evolved over the past two decades? (2) Which countries, institutions, journals, and authors are most influential? (3) What are the most highly cited publications and their contributions to methodological or conceptual advancement? and (4) What innovation frontiers and thematic gaps define the future research agenda? This framing ensures the analysis moves beyond a general literature survey toward a targeted investigation capable of guiding future scholarly and policy efforts in sustainable groundwater management.

## 2. Advancement and Insights from Recent Literature

The accelerating demand for freshwater, compounded by pollution and unsustainable extraction, has intensified global concerns over groundwater security. As the most accessible freshwater source, groundwater remains central to domestic supply, irrigation, and industrial production across both developed and developing regions (Shemer et al., 2023). In response to mounting stress on aquifers, WH strategies have gained prominence, particularly in arid and semi-arid environments (Tamagnone et al., 2020; Umukiza et al., 2023). Techniques such as percolation tanks, check dams, and recharge wells have been widely implemented to enhance GWR and improve water quality in vulnerable catchments. Alataway & El Alfy (2019) highlighted the combined role of RWH and artificial recharge systems in alleviating water scarcity in desert regions, while Ertop et al. (2023) emphasized the potential of RWH in addressing urban water challenges linked to rapid development, climate change, and inadequate regulation.

RWH offers multiple advantages, including flood risk reduction, aquifer replenishment, cost savings, and agricultural sustainability. Decentralized RWH systems that draw on locally available materials and community knowledge can serve as viable alternatives to centralized supply networks (Al-Batsh et al., 2019). In urban contexts, recharge wells are effective for both stormwater management and groundwater (Hussain et al., 2019). Yet, as Gwenzi & Nyamadzawo (2014) observed, urban expansion often alters hydrological cycles reducing infiltration opportunities and increasing runoff particularly in water-scarce catchments of sub-Saharan Africa. This reinforces the need to embed WH measures into urban planning frameworks.

Recharge potential and system performance vary considerably by location. Environmental conditions such as climate, hydrogeology, land use, and data availability influence both the selection of recharge techniques and the methods used to estimate recharge (Guillaumot et al., 2022; Santarosa et al., 2021). Gee & Hillel (1988) noted that quantifying recharge in arid and semi-arid regions is particularly challenging due to highly variable rates driven by soil, vegetation, and topography. They also cautioned that broad-scale models may fail to capture rapid, localized infiltration events, advocating for complementary field-based methods.

A range of estimation approaches has since been applied, from tracer-based techniques like chloride mass balance to monitoring-driven methods such as water table fluctuation (WTF) analysis. Others employ hydraulic principles (Darcy's law), hydrological accounting through water balance models, or simplified techniques like base-flow separation. Each method carries trade-offs in terms of data requirements, resolution, and applicability. Mohammadlou & Zeinivand (2019) illustrated that selecting an appropriate method depends on aligning technical feasibility with regional hydrogeological realities. This reinforces the broader principle that effective groundwater management requires context-specific and adaptive strategies for both recharge implementation and assessment.

## 3. Classification and Application of Water Harvesting Approaches

Effective WH encompasses a range of techniques aimed at capturing and conserving rainfall and surface runoff for future use. These methods are particularly valuable in regions facing prolonged dry spells or water scarcity. WH can be applied at various scales from individual households to extensive municipal or watershed-level projects and serves multiple purposes such as drinking water supply, irrigation, and GWR (Ertop et al., 2023). Its benefits span water conservation, drought mitigation, flood control, soil protection, aquifer replenishment, and energy savings. A functional WH system typically consists of three interconnected components: the collection unit, where water is gathered (rooftops or catchments); the transportation network, which may include pipes or channels that move water to storage; and the storage system, such as tanks or cisterns, where water is kept until needed (Akter, 2022b).

Water harvesting practices fall into three primary categories: RWH, FWH, and GWH. Each category includes both surface-based and subsurface storage techniques. Depending on the context, structures may include temporary solutions like contour bunds and rock catchments or long-term systems like farm ponds, infiltration dams, and subsurface reservoirs.

### 3.1 Rainwater Harvesting: Capturing Precipitation at the Source

RWH refers to the intentional collection and storage of rainfall, typically from rooftops or open surfaces (Yannopoulos et al., 2019). The collected water is directed into containers or reservoirs using a network of gutters and conduits. This method is widely adopted to ensure a dependable water supply for domestic use, irrigation, and other needs, particularly in regions with irregular precipitation. RWH systems are usually tailored to capture smaller and more frequent precipitation events and to rely on proper storage design and filtration for maintaining water quality. Their adaptability makes them suitable for both rural and urban settings. In urban environments, RWH reduces dependency on centralized supplies and helps mitigate stormwater runoff. In rural areas, it improves agricultural resilience and year-round water availability. Importantly, RWH supports climate adaptation goals by reducing erosion, replenishing aquifers, and enhancing water security in drought-prone areas (Teston et al., 2022). These systems are increasingly promoted as environmentally friendly solutions to global water challenges (Nandi & Gonela, 2022).

RWH offers a range of environmental, economic, and infrastructural benefits that render it an essential component of sustainable water management strategies. One of the primary advantages is water conservation; RWH captures rainwater that would otherwise be lost as runoff, thus storing it for non-potable uses such as toilet flushing, laundry, and landscape irrigation. This significantly reduces dependence on municipal water supplies and preserves treated potable water for essential uses (Ahmad & Ashfaq, 2011). Additionally, utilizing harvested rainwater for these purposes lowers the energy demand associated with water treatment and distribution, thereby reducing greenhouse gas emissions and promoting energy efficiency in urban water systems (Wartalska et al., 2024).

Beyond conservation, RWH contributes to urban flood mitigation by intercepting stormwater runoff and this helps reduce surface water accumulation, erosion, and pressure on drainage infrastructure, particularly in flood-prone areas (Deitch & Feirer, 2019). From an economic perspective, RWH offers long-term financial savings by decreasing water utility bills and delaying or eliminating the need for new water infrastructure investments. To enhance water security at local and regional scales, it provides a dependable alternative water source during droughts or municipal supply shortages (Charlesworth et al., 2014).

RWH systems are widely applied across residential, agricultural, and urban sectors. In domestic settings, these systems can meet a substantial portion of household non-potable water needs. For instance, in the United Kingdom, an average RWH system installed in a four-bedroom house can supply approximately 60,000 liters of water annually (Johnen, 2006). In agriculture, especially in arid and semi-arid regions, RWH provides a vital water supply for irrigation, supporting crop productivity and resilience against climate variability (Oweis, 2022). Urban and industrial applications also benefit countries like Singapore and Japan with integrating RWH into high-rise buildings and commercial developments to reduce pressure on potable water systems and to manage wastewater flows more effectively (Sari & Suhendri, 2018).

Technological advancement has enhanced the performance of modern RWH systems, with features such as automated control units, submersible pumps, filtration systems, and integration with greywater reuse schemes. These innovations improve operational efficiency and water quality outcomes (Raimondi et al., 2023). From an environmental standpoint, RWH minimizes stress on freshwater ecosystems, reduces water extraction impacts, and plays a role in managing runoff-related pollution, hence ultimately improving downstream water quality.

Despite these benefits, several barriers limit widespread RWH adoption. High initial costs, technical complexity, and ongoing maintenance requirements can deter users, particularly in low-resource settings (Oweis, 2022). Addressing these barriers calls for a combination of financial incentives, public awareness campaigns, and accessible technical support. Furthermore, the development and enforcement of clear regulatory frameworks and design standards are essential to promote safe and effective implementation of RWH across diverse contexts (Raimondi et al., 2023).

### 3.2 Floodwater Harvesting (FWH)

FWH is designed to intercept and utilize excess runoff from intense precipitation events, river overflows, or seasonal floods. This method uses engineered structures such as check dams, recharge ponds, and percolation tanks to collect large volumes of water and gradually infiltrate it into the ground (Alam et al., 2021).

Unlike RWH, FWH systems, which often require more robust materials and structural designs, are built to withstand and regulate rapid inflows. For instance, check dams help decelerate water flows and promote infiltration whereas flood pits and tanks temporarily store water, so they could reduce erosion and infrastructure damage (Petpongpan et al., 2022). FWH is particularly beneficial in flood-prone regions or areas with erratic rainfall. Besides preventing flood damage (Jamali et al., 2020), it contributes to aquifer recharge, improves soil moisture for agriculture, and restores ecosystem balance (Hohne et al., 2021). As climate extremes become more frequent, FWH is gaining recognition as a viable climate adaptation measure that enhances water resilience at both local and regional levels (Fathy et al., 2021).

FWH can be implemented using a variety of systems tailored to specific environmental and land-use conditions. Micro-catchment systems, for example, are small-scale interventions that deliver floodwater directly to the root zones of crops, thereby enhancing water use efficiency and boosting agricultural productivity. In contrast, macro-catchment systems are designed to harvest runoff from larger areas and more suitable for broader agricultural fields or water storage needs at the community scale (Mekuria & Tegegne, 2023). In urban settings, FWH can be integrated with existing stormwater management infrastructure. A notable example is the use of stormwater retention ponds equipped with real-time control systems, which can dynamically manage water levels to increase storage capacity without compromising flood control capabilities (Rohrer & Armitage, 2017).

Despite its potential, the implementation of FWH systems is not without challenges. Key constraints include high initial construction costs, labour intensity, and ongoing maintenance demands, which can limit scalability especially in low-income regions (Mekuria & Tegegne, 2023). Effective and widespread adoption of FWH requires supportive policy frameworks and clear regulatory guidance, which could facilitate its integration into broader water management and urban planning systems (Farahbakhsh et al., 2009). Technological innovations such as web-enabled applications and real-time monitoring offer new opportunities for smarter control and adaptive responses to changing rainfall patterns, hence enhanced performance and reliability of FWH systems (Reidy, 2010).

The practical benefits of FWH have been clearly demonstrated in various global contexts. In the Sahelian regions of sub-Saharan Africa, the application of staggered half-moons has significantly decreased runoff and moderated flood impacts, thus underscoring the relevance of the system in dryland farming (Tamagnone et al., 2020). In urban environments, cities like Cape Town and South Africa have adopted stormwater ponds, which integrate real-time control mechanisms into harvest runoff. This approach not only mitigates flooding but also creates a cost-effective solution for augmenting non-potable water supplies (Rohrer & Armitage, 2017).

### 3.3 Groundwater Harvesting (GWH)

Groundwater harvesting involves tapping into subsurface water stored in aquifers through structures like wells, boreholes, and springs. This approach is vital in arid zones, where surface water is limited (Fathy et al., 2021). GWH also includes interventions aimed at boosting aquifer recharge, such as construction of subsurface dams, Qanat systems, and infiltration wells (Gil-Meseguer et al., 2023). Table 1 summarizes the main water harvesting approaches, such as RWH, FWH, and GWH alongside their descriptions, applications, advantages, and disadvantages.

Subsurface dams, typically built in seasonal streambeds, capture water in underground sediments, hence limiting evaporation and enabling long-term storage. Historically, qanats were used in North Africa and the Middle East to channel water via underground tunnels from high-elevation aquifers to lower-lying agricultural areas without mechanical pumping (Saha et al., 2024). Specialized structures like recharge wells allow rainwater or treated runoff to percolate directly into aquifers and help reverse the declining water tables in overexploited regions (Fuentes et al., 2020). Hussain et al. (2019) noted the usefulness of such systems in urban environments for both flood control and aquifer restoration

To address groundwater depletion and enhance water availability, various harvesting techniques are employed. These include conventional rainwater and floodwater harvesting methods as well as more advanced practices like MAR, which involves the artificial infiltration of water into aquifers to replenish groundwater reserves (Mekuria & Tegegne, 2023). MAR systems are widely applied in both rural and urban settings to stabilize declining water tables and improve groundwater quality (Gwenzi & Nyamadzawo, 2014). The integration of these practices contributes to a more sustainable and resilient water management framework.

**Table 1.** Summary of water harvesting approaches, applications, advantages, and disadvantages

| Water Harvesting Approach | Descriptions | Applications | Advantages | Disadvantages |
|---|---|---|---|---|
| RWH | Captures rainfall from rooftops or open surfaces for storage and use in domestic, agricultural, and urban settings. | Used in households, buildings, farms, and urban landscapes; supports irrigation, domestic use, and aquifer recharge. | Reduces reliance on potable supply, prevents runoff, saves energy, mitigates floods, and offers cost savings over time. | High initial costs, maintenance needs, technical complexity, and low adoption in resource-limited areas. |
| FWH | Intercepts and stores excess runoff from precipitation events, river overflows, and floods using structures like check dams and ponds. | Applied in flood-prone rural and urban regions for aquifer recharge, soil moisture improvement, and erosion control. | Controls flooding, promotes aquifer recharge, improves soil moisture, and supports agriculture in variable rainfall regions. | Labour-intensive and costly infrastructure, high maintenance, and challenges in low-income areas without regulatory support. |
| GWH | Taps and stores groundwater through wells, boreholes, or subsurface dams; includes techniques like MAR and Qanats. | Used in arid regions and urban recharge zones for enhancing aquifer storage, controlling floods, and stabilizing water supply. | Improves year-round water availability, prevents erosion, supports aquifer recovery, and enhances groundwater quality. | Risk of over-extraction, saline intrusion, high installation costs, and site-specific hydrogeological constraints. |

The benefits of GWH techniques are multifaceted. First, they significantly improve water availability by capturing surplus surface water and facilitating year-round access, even in arid and semi-arid environments (Rahaman et al., 2019). Second, by intercepting runoff, GWH systems contribute to flood mitigation and help reduce soil erosion (Mekuria & Tegegne, 2023). Additionally, the quality of groundwater can be enhanced through MAR systems, which filter recharged water and dilute contaminants within the aquifer (Rahaman et al., 2019).

Despite these advantages, several challenges hinder the widespread implementation of GWH. One of the most pressing issues is over-exploitation, which results in falling water tables, saline intrusion, and land subsidence in many parts of the world (Saha et al., 2024). Furthermore, the costs associated with construction, labour, and ongoing maintenance can limit the feasibility of GWH systems in low-income regions (Mekuria & Tegegne, 2023). Technological and environmental limitations, including complex hydrogeological conditions and potential clogging of infiltration systems, require careful site-specific assessment and planning (Karamouz et al., 2018).

Numerous case studies highlight the practical value and variability of GWH across different contexts. In Bangladesh, the integration of RWH and MAR has successfully enhanced groundwater recharge for both agricultural and domestic use (Rahaman et al., 2019). On Jeju Island of South Korea, the deployment of greenhouse-based RWH-MAR systems has proven effective in increasing groundwater storage in elevated terrains with favourable geological formations (Kim et al., 2024). Similarly, in the Middle East and North Africa (MENA) region, the implementation of recharge dams and MAR technologies plays a critical role in groundwater management, although their performance is sometimes limited by sediment buildup and system clogging (Sherif et al., 2023).

## 4. Groundwater Recharge: Mechanisms, Methods, and Assessment Approaches

GWR techniques can be broadly categorized into natural processes and artificial recharge methods. This classification reflects both the inherent hydrological mechanisms that replenish aquifers and the engineered interventions designed to enhance these processes, particularly in areas facing water scarcity or overexploitation.

### 4.1 Significance of Groundwater Conservation

Preserving groundwater resources is essential for ensuring a sustainable water supply, supporting agriculture, maintaining ecosystem health, and reducing vulnerability to drought. It also helps mitigate land subsidence, protect aquifer water quality, and enhance resilience to climate variability. GWR, either natural or artificial, is a pivotal technique for safeguarding aquifer sustainability (Shemer et al., 2023). Effective recharge sites are typically characterized by declining groundwater tables, poorly saturated aquifers, insufficient water supply from wells, or poor water quality. Recharge strategies that consider these factors can significantly enhance aquifer functionality and long-term water security (Fathy et al., 2021). Furthermore, such interventions support adaptation to changing climate regimes by stabilizing groundwater levels and preserving this resource for future use (Shemer et al., 2023).

### 4.2 Potential Water Sources for Recharge

Multiple water sources can be utilized for recharging aquifers, with selection depending on geographic, hydrological, and infrastructural considerations. These sources include (1) direct rainfall; (2) rooftop-collected rainwater; (3) seasonal stream and spring overflows; and (4) treated effluent from municipal and industrial origins. Rainfall percolation is the most direct natural recharge source. Its effectiveness is, however, governed by soil properties, topography, vegetation, and rainfall intensity. In urban environments, rooftop rainwater collection systems help redirect water to infiltration structures like recharge wells and trenches, which are crucial for urban aquifer replenishment and flood mitigation. In rural or riverine zones, surface water surpluses during peak flow can be diverted to recharge structures such as percolation tanks or infiltration ponds without disrupting downstream usage or ecological stability. Additionally, safely treated wastewater has emerged as a viable source for artificial recharge, particularly in water-stressed cities. This not only conserves freshwater but also promotes a circular water economy (Shemer et al., 2023).

### 4.3 Classification of Groundwater Recharge Techniques

GWR techniques can be broadly categorized into natural processes and artificial recharge methods (Figure 1). This classification reflects both the inherent hydrological mechanisms that replenish aquifers and the engineered interventions designed to enhance these processes, particularly in areas facing water scarcity or overexploitation.

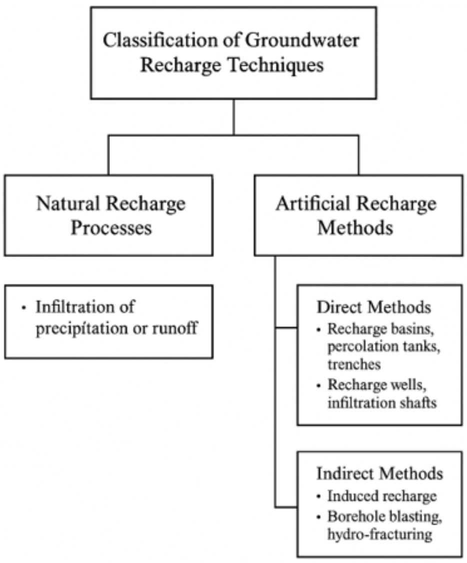


**Figure 1.** Classification of groundwater recharge techniques

4.3.1 Natural recharge processes

Natural GWR occurs as water infiltrates from precipitation or surface runoff into permeable layers beneath the surface (Akter, 2022a). Factors like soil type, land cover, topography, and vegetation play crucial roles in facilitating this percolation. However, urbanization, deforestation, and unsustainable agriculture can inhibit recharge by compacting soils, removing vegetative cover, and increasing impervious surfaces (Patel & Chaudhari, 2023). Groundwater overexploitation, along with climate change-induced shifts in rainfall patterns, further reduces the capacity for natural recharge. For instance, intense rainfalls may lead to increased surface runoff rather than infiltration, hence reducing effective aquifer replenishment. Pollutants in surface water can block infiltration paths and diminish recharge efficiency (Raimondi et al., 2023).

4.3.2 Artificial recharge methods

Artificial recharge refers to the deliberate and engineered enhancement of natural groundwater replenishment processes through various hydrological interventions. The primary objectives of artificial recharge include improving groundwater availability, maintaining aquifer pressure, and mitigating seawater intrusion in coastal regions (Chellamuthu Ranganathan et al., 2022; El Moneam, 2023) These interventions are especially crucial in areas facing significant groundwater depletion due to over-extraction, urbanization, and climate-induced variability in precipitation.

Artificial recharge techniques are typically categorized into two broad types: direct and indirect methods. Direct recharge methods involve the physical transfer of water to the subsurface through surface or subsurface systems. Common surface-based approaches include recharge basins, percolation tanks, and trenches, which allow water to infiltrate the soil and percolate into the aquifer. Subsurface techniques such as recharge wells and infiltration shafts, enable water to bypass surface layers and directly reach targeted aquifer zones (El Moneam, 2023) These methods are widely used in both rural and urban contexts, depending on land availability and hydrogeological suitability.

Indirect methods, on the other hand, aim to stimulate natural recharge processes by altering surrounding conditions or utilizing hydraulic gradients. Techniques such as induced recharge achieved by pumping wells near rivers or streams create a drawdown effect that encourages surface water to infiltrate into nearby aquifers. Other structural approaches, like borehole blasting and hydro-fracturing, are employed to increase permeability and enhance subsurface water movement (Muppidi et al., 2020). These methods are often applied in areas with limited surface area for recharge or deeper aquifer zones requiring targeted interventions.

### 4.4 Recharge Estimation Techniques

Estimating GWR rates is essential for the effective planning, management, and sustainability of aquifer systems. Accurate quantification allows informed decisions in water resource allocation, artificial recharge planning, and drought mitigation strategies. Various methods have been developed and applied across different hydrogeological settings, each with distinct data requirements, assumptions, and levels of complexity. One widely adopted method is the WTF approach, which estimates recharge by analyzing temporal variations at groundwater levels. This method assumes that changes in the water table primarily result from recharge, allowing direct estimation when combined with specific yield data (Healy & Cook, 2002). Another common approach is the Water Budget Method**,** which calculates recharge as the residual water balance by accounting for all inflows and outflows in each hydrological system (Graf & Przybyłek, 2014).

Darcy's Law, based on fundamental hydraulic principles, provides another pathway for recharge estimation. By analyzing water flow through porous media using known hydraulic gradients and conductivities, it allows spatially distributed recharge calculations in heterogeneous aquifer systems (Sun et al., 2024). Empirical models relying on statistical correlations between rainfall and recharge, offer simplified predictive tools especially useful in data-scarce regions as part of broader modeling efforts (Phankamolsil et al., 2022). More advanced techniques like tracer methods involve using natural or artificial isotopes and chemical markers to track water movement and infiltration pathways. These are particularly useful for understanding recharge dynamics, travel times, and aquifer connectivity (Wu et al., 2016). Lastly, numerical groundwater models which integrate hydrological, geological, and climatic data simulate aquifer behavior under varying input conditions. These models are invaluable for projecting long-term recharge trends and evaluating the impacts of land use or climate change on groundwater systems (Duque et al., 2022).

### 4.5 Water Table Fluctuation (WTF) Method

WTF method is among the most used techniques for estimating groundwater recharge. This method relies on observing changes at groundwater levels over time and linking these variations to the volume of recharge entering the aquifer. A fundamental assumption in this approach is that the rise in the water table is primarily caused by infiltration following precipitation events, assuming minimal influence from lateral flow or pumping during the observation period (Boumis et al., 2022; Delottier et al., 2018). The WTF method is particularly useful in unconfined aquifers where continuous groundwater monitoring is conducted. Recharge is calculated by multiplying the water table rise by the specific yield of the aquifer material. Despite its practicality and reliance on straightforward observational data, the method may overestimate recharge in areas with significant external influences such as pumping, evapotranspiration, and delayed drainage. In such contexts, corrections and combined methods are often necessary to improve accuracy (Penner et al., 2023). Although widely applicable in both humid and arid climates, the WTF method is sensitive to short-term fluctuations and is best suited for local-scale and short-duration studies. It remains a valuable tool when used with caution and in conjunction with other field-based or modelling approaches (Becke et al., 2024).

### 4.6 Water Budget Method

Water Budget Method (WBM) involves quantifying all inflows and outflows of water within a given hydrological unit to estimate recharge. The core principle is that groundwater recharge can be derived by balancing parameters such as precipitation, evapotranspiration, surface runoff, infiltration, and changes in soil moisture or storage capacity (Yun et al., 2023). This method requires extensive and accurate data to be effective. Factors like soil type, slope, land use, and vegetation cover influence infiltration rates and must be considered. In urban environments, built-up surfaces result in lower infiltration, whereas in natural or vegetated landscapes, infiltration rates are significantly higher. Calculating infiltration often involves applying empirical infiltration coefficients based on land cover type (Morque et al., 2019). A widely used model in surface runoff estimation within the water budget framework is the Soil Conservation Service (SCS) Curve Number method. This model assigns a runoff potential value based on land use, hydrologic soil group, and antecedent moisture conditions, enabling estimation of how much precipitation becomes runoff versus infiltration (Mohan & Pramada, 2023). Although robust and conceptually simple, the reliability of the water budget method depends on the accuracy of input data and assumptions, especially in complex or data-scarce regions.

### 4.7 Application of Darcy's Law

Darcy's Law provides a foundational principle for estimating groundwater movement through porous media and is often applied in recharge assessment, particularly for understanding lateral flow and hydraulic connectivity. The law relates the rate of groundwater flow to the hydraulic gradient and the hydraulic conductivity of the soil or rock (Alam & Farid, 2023; El Mezouary & El Mansouri, 2021). To apply Darcy's Law for recharge estimation, the necessary data include hydraulic head differences, cross-sectional area of the flow path, and the permeability of the aquifer material. It is particularly effective for confined aquifers or for evaluating seepage across boundaries under homogeneous and isotropic conditions and laminar flow, which may not always hold true in heterogeneous geological settings (Sun et al., 2024). Despite its limitations, Darcy's Law remains a reliable tool for calculating localized recharge or lateral groundwater flow, especially when paired with field measurements and proper aquifer characterization (Zhuang et al., 2021).

### 4.8 Empirical Estimation Methods

Empirical estimation methods establish mathematical relationships between recharge rates and variables such as rainfall, evaporation, and land use. These models are often developed through long-term observational studies and are calibrated to fit specific climatic and hydrogeological conditions (Islam et al., 2016). In many regions, empirical formulas link annual rainfall to recharge percentages, thus offering a quick estimate of potential infiltration. While these methods are advantageous for preliminary assessments or in data-scarce regions, their accuracy is limited by site-specific variability. Local calibration is essential, and empirical models must be cautiously transferred between regions with differing climatic or soil conditions (Jean Olivier et al., 2022). These approaches are particularly helpful in groundwater management plans, where a rapid estimation of recharge is needed to inform land-use decisions or infrastructure development.

### 4.9 Tracer Techniques for Recharge Assessment

Tracer techniques utilize natural or introduced substances such as isotopes or chemicals to track the movement of water and estimate recharge rates. In arid and semi-arid regions, where conventional methods often face challenges, tracers offer a direct approach to quantifying recharge (Paswan et al., 2024). Chloride Mass Balance (CMB) method, for example, is frequently used to estimate recharge by comparing chloride concentrations in precipitation and groundwater. Isotope hydrology techniques involving stable isotopes ($\delta^2H$, $\delta^{18}O$) or radioactive tracers (tritium, carbon-14, radon-222) allow dating groundwater, identifying recharge sources, and mapping flow paths (Jafari et al., 2019). Wilske et al. (2020) demonstrated the effectiveness of multi-tracer analysis in fractured aquifer systems and illustrated the ways to complement numerical modelling and overcome data limitations. While tracer techniques provide valuable insights, they can be cost-intensive and require specialized equipment and expertise.

### 4.10 Modelling-Based Recharge Estimation

Numerical groundwater models simulate aquifer behaviour under various hydrological, climatic, and land-use conditions, allowing dynamic recharge estimation. These models integrate data on soil characteristics, topography, precipitation, evaporation, and groundwater usage to evaluate recharge patterns over space and time (Zhang et al., 2020). Modelling tools like Modular Three-dimensional Groundwater Flow Model (MODFLOW) or Soil and

Water Assessment Tool (SWAT) are commonly used for regional assessments. They are especially useful in forecasting the impacts of climate change, land development, and policy interventions on groundwater systems. However, their accuracy depends heavily on model calibration, availability of reliable field data, and assumptions during simulation. Recharge estimation using models are crucial for strategic groundwater management, enabling decision-makers to identify recharge "hotspots" evaluate vulnerability, and plan interventions accordingly. Table 2 summarizes the major groundwater recharge techniques, their key features, advantages, and limitations, highlighting both process-based and estimation-based approaches.

**Table 2.** Classification of groundwater recharge techniques: processes, features, and limitations

| Recharge Technique | Category | Key Features | Advantages | Disadvantages |
|---|---|---|---|---|
| Natural Recharge | Natural Process | Infiltrates from rainfall/surface runoff, influenced by soil and land cover. | Low cost, self-sustaining, eco-friendly. | Affected by land use change, limited in urban settings. |
| Artificial Recharge | Engineered Process | Deliberates recharge via surface/subsurface structures; includes induced recharge and permeability enhancement. | High control over recharge process, suitable for urban/depleted areas. | Costly infrastructure, land requirement, maintenance needed. |
| WTF | Estimation Method | Estimates recharge from water table rise; best for unconfined aquifers. | Simple, uses observed data, suitable for short-term analysis. | Sensitive to external influences (pumping, ET); may overestimate. |
| WBM | Estimation Method | Estimates recharge as residual from hydrological balance using inflow/outflow data. | Conceptually clear, useful at watershed scale, includes land use effects. | High data demand; sensitive to input errors and assumptions. |
| Darcyâ€™s Law | Estimation Method | Uses hydraulic gradient and conductivity to estimate subsurface flow and recharge. | Accurate in well-characterized aquifers, useful for confined systems. | Detailed aquifer data required, assumptions may not hold in all settings. |
| Empirical Methods | Estimation Method | Uses statistical models based on rainfall-recharge correlations. | Quick and inexpensive for large-scale or data-poor regions. | Site-specific, needs calibration; limited transferability. |
| Tracer Techniques | Estimation Method | Uses isotopes or chemicals to trace and date water movement. | Direct evidence of recharge, source tracing possible. | Expensive, requires technical expertise and equipment. |
| Modelling-Based Estimation | Estimation Method | Simulates aquifer behaviour using tools like MODFLOW, integrating multiple data types. | Dynamic for scenario testing and long-term planning. | Complex setup, calibration needed, dependent on data availability. |

## 5. Methodology

This study employed a bibliometric analysis to systematically investigate and visualize the evolving research landscape surrounding WH and GWR. The goals were to identify key thematic trends, map knowledge clusters, and suggest future research pathways. Being a quantitative and computer-assisted literature review method, bibliometric analysis has been extensively used across disciplines to assess research productivity, track intellectual structures, and uncover underexplored domains (Aziminezhad & Taherkhani, 2023; Taherkhani & Aziminezhad, 2023).

By constructing bibliometric networks, this study was able to pinpoint influential authors, institutions, and countries while detecting emerging research fronts and gaps. Two standard counting techniques were employed: full counting was used to assign equal weight to each instance and fractional counting distributed weights among co-authors or sources proportionally. Full counting was chosen for its interpretive simplicity and relevance to mapping global trends.

The analysis was implemented with two established tools, including VOSviewer for building bibliometric maps, and the bibliometrix package in *R* to support advanced statistical and network evaluations (Rahman et al., 2023). These tools enabled the generation of co-authorship networks, keyword co-occurrence diagrams, and citation maps. In these visualizations, nodes represented entities such as keywords, authors, and institutions whereas links denoted collaborations and thematic relationships. The methodological workflow consisted of four main stages: (1) data collection from a comprehensive academic database; (2) performance analysis of bibliometric indicators; (3) visualization of co-occurrence and collaboration networks; and (4) strategic interpretation to guide future GWR and WH research.

### 5.1 Scope of the Study

The core objective of this research was to explore global scientific interest in the evolution of water harvesting and groundwater recharge as well as the emerging directions shaping the field. By reviewing a wide array of publications, the study also highlighted major themes, influential contributors, and knowledge gaps. The primary guiding question was: What are the dominant trends, thematic clusters, and strategic directions in global research on water harvesting and groundwater recharge?

### 5.2 Strategy for Literature Search and Preparation for Data

To ensure the breadth and reliability of bibliometric data, Scopus was selected to be the primary data source due to its extensive and reputable coverage of peer-reviewed literature in relevant domains such as environmental science, hydrology, engineering, and sustainability studies (Burnham, 2006). The search was conducted on 15 June 2025, covering publications from 1 January 2019 to 31 December 2024 to capture the most recent and relevant six years of global research activity in WH and GWR.

A carefully structured keyword search strategy was developed using Boolean operators to capture a wide and meaningful spectrum of literature. Keywords were organized into two major thematic categories. The first group focused on WH and GWR core terms, "water harvesting" or "RWH" or "flood water harvesting" or "stormwater harvesting" or "groundwater recharge" or "artificial recharge" or "recharge wells" or "infiltration pond" or "percolation tank". the second group reflected sustainability and resource management context terms, "climate change adaptation" or "water resource management" or "sustainable water supply" or "urban flooding" or "aquifer management".

This dual-category approach ensured that the retrieved publications encompassed both technical interventions and broader environmental or policy-driven aspects of WH and GWR. The initial Scopus search yielded 612 documents, which included journal articles and review papers across disciplines such as water resources, hydrology, civil engineering, and climate change adaptation.

To refine the quality and relevance of the dataset, a three-stage filtering process was applied. First, the scope was restricted to English-language, peer-reviewed journal articles and reviews, excluding conference proceedings, books, editorial materials, and notes. Second, manual screening of titles and abstracts was performed to verify thematic alignment with WH and GWR, ensuring the inclusion of studies with technical depth, environmental significance, and relevance to planning and management. This step removed irrelevant works that used the term "harvesting" in unrelated contexts, such as "energy harvesting" or "data harvesting". Third, full-text verification was conducted for borderline cases to confirm their inclusion.

Following this rigorous filtering, the dataset was narrowed to 587 unique and thematically relevant publications. Bibliographic records, including titles, abstracts, keywords, author affiliations, and citation data, were exported in BibTeX, a reference management software and Comma Separated Values (CSV) formats. Data deduplication and standardization, adhering to bibliometric data cleaning protocols, were carried out using R (bibliometrix package) to further ensure consistency and accuracy (Burnham, 2006). This process involved harmonizing authors' names and affiliations, formatting keywords like unifying "rainwater harvesting" and "RWH" and merging duplicate entries.

The complete bibliometric workflow is visually summarized in Figure 2, which outlines the sequential phases from database selection to data visualization. Figure 3 presents a conceptual framework that guides the logic of the study from analyzing historical development and identifying thematic knowledge clusters to formulating strategic directions for future research in WH and GWR.


**Figure 2.** Methodological workflow for the bibliometric analysis of WH and GWR

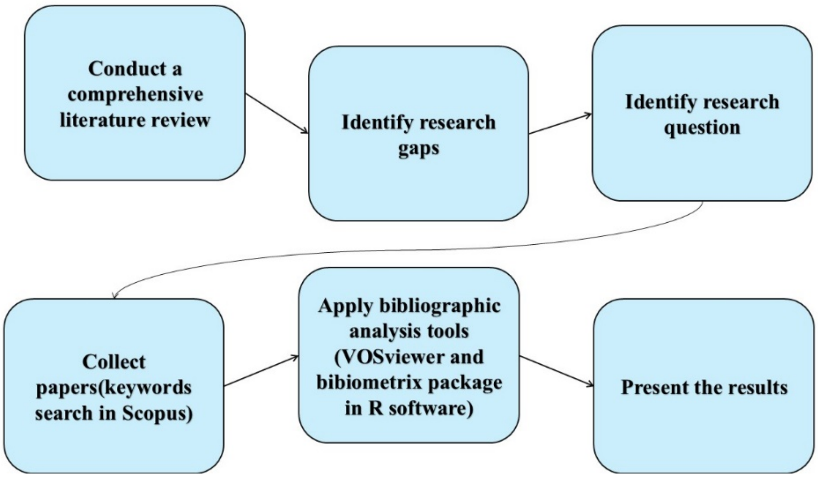


**Figure 3.** Conceptual framework guiding the study of WH and GWR

### 5.3 Analysis and Interpretation

The cleaned dataset was analyzed using VOSviewer and bibliometrix (*R*). These tools enabled the construction of bibliometric maps that revealed patterns in collaboration (co-authorship), thematic focus (keyword co-occurrence), and research impact (citation frequency). By examining these networks, the study identified core research communities, influential scholars and institutions, and prevailing themes across the WH and GWR literature.

This data-driven approach offered a clear and objective view of the scientific structure of the field, highlighting both its maturity and emerging frontiers. The combination of statistical evaluation and network visualization allowed strategic classification of thematic clusters and future directions for research related to water harvesting and groundwater recharge.

### 5.4 Extended Analytical Approach

To move beyond standard bibliometric mapping, this study incorporated thematic evolution analysis, country- and institution-level comparative mapping, and temporal trend detection using the bibliometrix *R*-package. Thematic evolution was conducted through longitudinal keyword co-occurrence networks, dividing the 2019-2024 dataset into two three-year periods (year 2019 to 2021 and year 2022 to 2024). This allowed the identification of emerging, declining, and persistent themes in the WH and GWR research. Country- and institution-level comparisons were generated by overlaying performance indicators (publications, citations, and *h*-index) with thematic specializations, hence highlighting geographic and institutional research priorities. Temporal keyword trend analysis further revealed shifts in focus, with recent years showing increased emphasis on interdisciplinary frameworks and advanced computational tools. Together, these analyses provided a richer picture of the intellectual structure and phases of development in the field.

## 6. Document Analysis

### 6.1 Trend Analysis

During the period 2019-2024, publication activity on WH and GWR has shown a steady rise, highlighting growing global concern over groundwater depletion. As depicted in Figure 4, both annual and cumulative outputs follow an upward trajectory, indicating not only sustained scholarly engagement but also expanding recognition of WH and GWR as central themes in sustainable water resource management. This consistent increase reflects the influence of climate variability, population growth, and water scarcity in driving research momentum and policy interest across regions.

Examining publication trends provides critical insights into the evolution and academic engagement of a research area over time. Figure 5 identifies India to be the clear global leader in the WH and GWR research by producing more than double the output of China and the United States, ranked second and third, respectively. This dominance further propels India to innovate in water resources, given its extensive coverage of water-stressed regions and reliance on groundwater for agriculture. The strong showing of countries like Australia and South Africa highlights the role of semi-arid climates in driving targeted research investment. Meanwhile, with a focus on technology, modelling, and integrated water management, contributions from European nations such as the UK, Germany, and France indicate the global relevance of WH and GWR even in water-scarce contexts. The data underscores a geographic imbalance, i.e., some of the most water-insecure regions, particularly in sub-Saharan Africa and Central Asia, remain underrepresented in research output, thus suggesting the need for capacity building and collaborative programs.

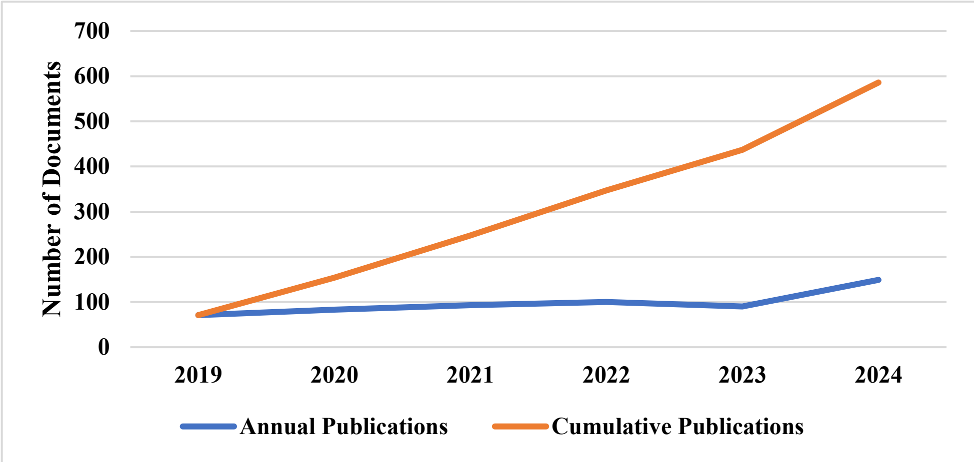


**Figure 4.** Annual and cumulative publications on the WH and GWR research (year 2019–2024)

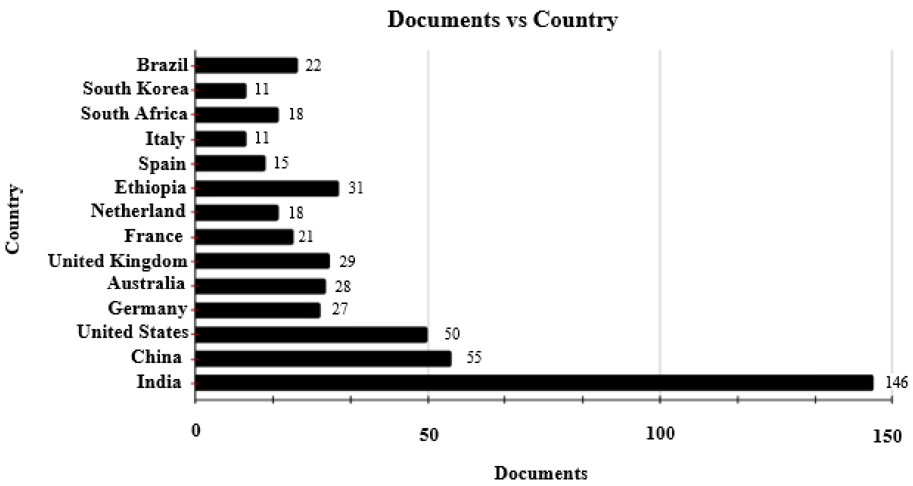


**Figure 5.** Document counts by country for WH and GWR publications

### 6.2 Research Activity and Global Distribution

Mapping the global landscape of research on water harvesting and groundwater recharge offers essential insights into the concentration of scholarly efforts and international collaboration. As depicted in Figure 5, India emerges as the leading contributor, accounting for the highest number of publications between years 2019 and 2024, with a total of 146 documents. China follows with 55 publications, and the United States ranks third with 50. Other notable contributors include Germany (27 publications), Australia (28 publications), the United Kingdom (29 publications), and France (21 publications). These results underscore a prominent academic presence in Asia and North America, hence reflecting regional concerns around water scarcity, climate resilience, and sustainable water infrastructure.

In terms of research influence, Figure 6 reveals that the impact of citations broadly aligns with the publication output, so India, China, and the United States are leading both in quantity and influence. However, high citation-to-publication ratios in countries such as Germany and Australia indicate a tendency toward fewer but more impactful studies, often centred on methodological advancement and high-visibility case studies. The relatively high citation count for South Africa suggests that research from water-scarce regions resonates strongly within the academic community, likely due to its relevance for challenges from global water scarcity. This distribution highlights the importance of not only producing research but also ensuring that it addresses globally significant gaps, integrates cutting-edge methods, and communicates important findings to a wide audience effectively.

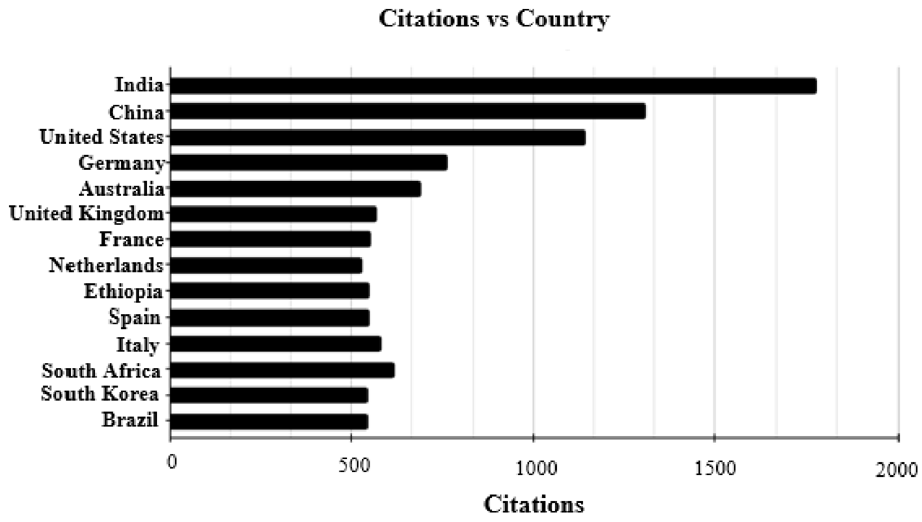


**Figure 6.** Citation counts by country for WH and GWR publications

Figure 7 reveals a highly interconnected global collaboration network in WH and GWR research, with India serving as the primary hub of co-authorship links, with China, Iran, the United States, Australia, and the United Kingdom in particular. This centrality indicates the dual role of India as both a high-output contributor and a key bridge between different regional research communities. The strong bilateral links between India-China and India-Iran suggest shared research priorities in arid and semi-arid water management, about which both technical and policy-driven solutions are being explored.

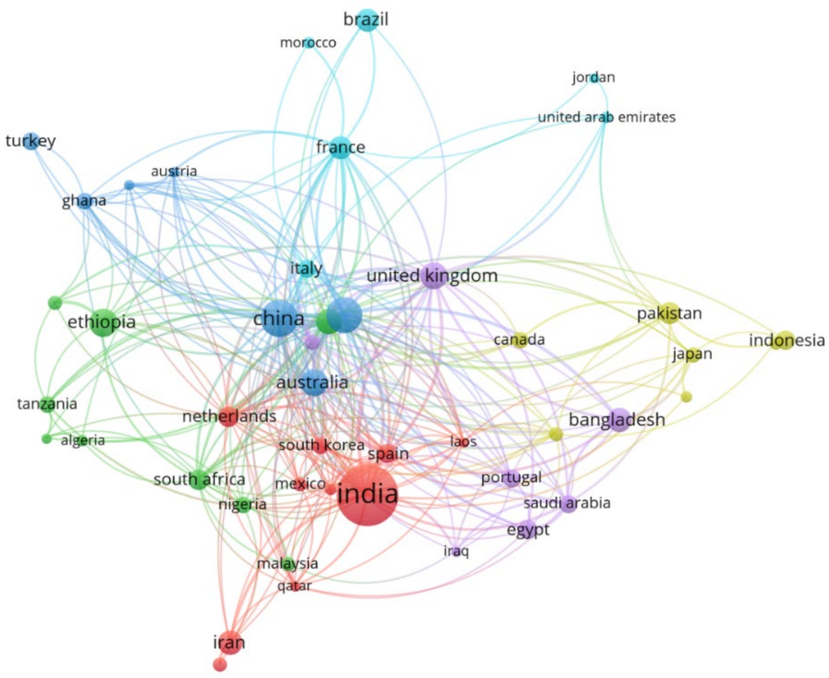


**Figure 7.** International co-authorship and research collaboration network

The map shows distinct regional clusters: European countries such as Germany, the Netherlands, and France form a dense collaborative bloc with strong internal linkages, reflecting their emphasis on advanced modelling, remote sensing, and integrated water management frameworks. In Africa, Ethiopia, South Africa, and Nigeria are visible nodes but their weaker interconnectivity with other regions highlights an underutilized potential for cross-regional knowledge exchange, especially critical given the acute groundwater stress of the continent.

The overall network structure suggests that while the WH and GWR fields are globally distributed, collaboration intensity is uneven. Well-connected hubs like India and the United States facilitate cross-pollination of ideas but peripheral regions with severe water scarcity such as parts of Central Asia and sub-Saharan Africa, remain relatively isolated in the co-authorship network. Addressing these gaps could enhance knowledge transfer, accelerate technology adoption, and lead to more context-specific solutions for underrepresented regions.

The visualization highlights several regional clusters, with prominent European engagement from countries like Germany, the Netherlands, France, and Italy, and strong Asian contributions from Bangladesh, Indonesia, Pakistan, and Japan. African nations such as Ethiopia, South Africa, and Nigeria also exhibit significant integration, thus reflecting growing regional efforts to address water security and sustainable groundwater management.

This collaborative landscape points to a highly interconnected and interdisciplinary research community. It encompasses themes ranging from recharge modelling and aquifer storage strategies to policy-driven water reuse systems and nature-based solutions. The global nature of these partnerships reinforces the shared urgency in tackling water-related challenges and emphasizes the role of collective knowledge generation in shaping resilient and adaptive water infrastructures worldwide.

### 6.3 Citation Analysis of Literature

An essential component of understanding scholarly progress in water harvesting and groundwater recharge research is identifying the most highly cited publications that have shaped the direction of academic inquiry and practical implementation. Citation analysis highlights pivotal studies, influential methodologies, and key thematic developments that serve as benchmarks in the field.

Figure 8 shows a relatively concentrated group of prolific authors, with leaders such as Saeid Eslamian and Kristine Walraevens contributing to diverse aspects of WH and GWR, from hydrological modelling to policy frameworks. The spread of author affiliations across multiple countries indicates that expertise in the field is geographically distributed, though high-output clusters tend to be associated with countries already dominant in publication output (India, China, and the USA). This distribution suggests that while global expertise is emerging, building new regional leaders particularly in Africa and Central Asia could diversify perspectives and approaches in the literature. The dominance of a small group of authors signals that future collaboration with early-career researchers could be essential for sustaining growth in the field.

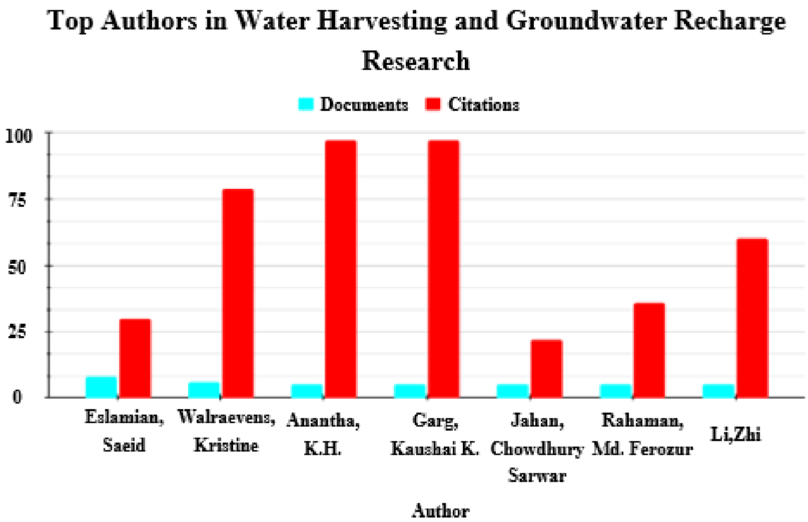


**Figure 8.** Leading authors in WH and GWR research (year 2019–2024)

Figure 9 highlights that the average years of publication vary across countries, hence suggesting different points of entry into WH and GWR research. Countries like Germany and Australia, for instance, show more recent average years; this implies increasing engagement in the last few years, possibly due to rising climate adaptation fundings. In contrast, nations like India and the United States display earlier average years so this indicates long-term involvement and established research programs. This temporal pattern reflects the dynamic nature of the field where mature contributors maintain steady output whereas new entrants bring fresh perspectives and innovative approaches. Such diversity in research maturity may encourage methodological cross-fertilization and adoption of globally relevant frameworks.

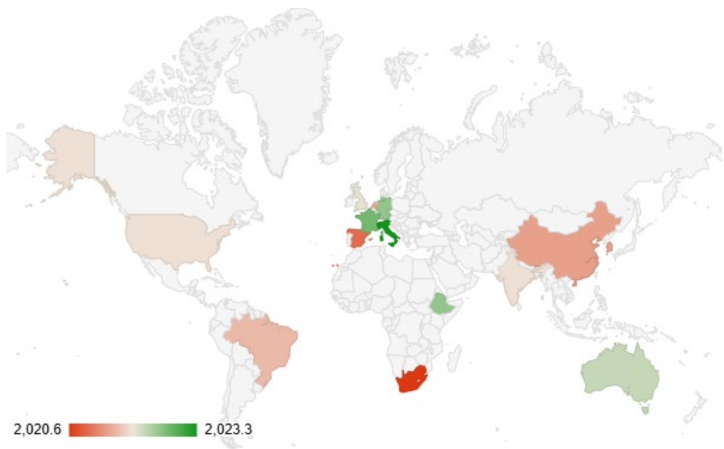


**Figure 9**. Global average publications on WH and GWR from 2019 to 2024

**Table 3.** Highly cited publications in water harvesting and groundwater recharge research

| Reference | Title | Year | Total Citations | Source |
|---|---|---|---|---|
| Dillon et al., 2019 | Sixty years of global progress in managed aquifer recharge | 2019 | 410 | *Hydrogeology Journal* |
| Mukherjee & Singh, 2020 | Delineation of groundwater potential zones in a drought-prone semi-arid region of East India using GIS and analytical hierarchical process techniques | 2020 | 181 | *Catena* |
| Amanambu et al., 2020 | Groundwater system and climate change: Present status and future considerations | 2020 | 173 | *Journal of Hydrology* |
| Marie et al., 2020 | Farmers' choices and factors affecting adoption of climate change adaptation strategies: Evidence from Northwestern Ethiopia | 2020 | 166 | *Heliyon* |
| Shammi et al., 2019 | Impacts of salinity intrusion in community health: A review of experiences on drinking water sodium from coastal areas of Bangladesh | 2019 | 116 | *Healthcare (Switzerland)* |
| Zhang et al., 2019 | Impacts of climate change on urban rainwater harvesting systems | 2019 | 97 | *Science of the Total Environment* |
| Kim & Song, 2019 | The multifunctional benefits of green infrastructure in community development: An analytical review based on 447 cases | 2019 | 76 | *Sustainability (Switzerland)* |
| Rajasekhar et al., 2020 | Identification of groundwater recharge-based potential rainwater harvesting sites for sustainable development of a semiarid region of Southern India using geospatial, AHP, and SCS-CN approach | 2020 | 75 | *Arabian Journal of Geosciences* |
| Singh et al., 2019 | An assessment of groundwater recharge estimation techniques for sustainable resource management | 2019 | 69 | *Groundwater for Sustainable Development* |
| Walker et al., 2019 | Insights from a multi-method recharge estimation comparison study | 2019 | 66 | *Groundwater* |

Table 3 showcases the most cited papers from the dataset, covering critical areas such as managed aquifer recharge, climate change adaptation, groundwater potential mapping, and RWH optimization. Heading the list is the article "Sixty years of global progress in managed aquifer recharge", which has 410 citations and was published in *Hydrogeology Journal* (2019). This work stands as a foundational reference for long-term global strategies for aquifer sustainability. “Delineation of groundwater potential zones in a hard rock terrain” (2020), which offers methodological insight into GIS-based groundwater zoning, is considerably influential with 181 citations. Another key study, “Groundwater system and climate change: Present status and future prospects”, has garnered 173 citations and this reflects its significance in linking climate variability with groundwater dynamics.

Notably, the article “Farmers’ choices and factors affecting adoption of rainwater harvesting practices”, with 166 citations, emphasizes socio-economic dimensions in technology uptake. Publications addressing urban water resilience such as “Impacts of climate change on urban rainwater harvesting systems” and “The multifunctional benefits of green infrastructure”, further underscore the interdisciplinary nature of this research domain. These highly cited works represent intellectual pillars that continue to inform best practices, strategic planning, and policy development in sustainable water resource management worldwide.

As shown in Figure 10, *Groundwater for Sustainable Development* also shows a marked upward trajectory by increasing from 2 to 10 articles in year 2019 and 2024, thus indicating growing attention to groundwater recharge frameworks and sustainable aquifer management. In contrast, *Environmental Earth Sciences* and *Journal of Hydrology* maintained consistent yet moderate output across the years, contributing to foundational knowledge in environmental geoscience and hydrological processes. *Sustainability (Switzerland)* reflects a steady commitment to interdisciplinary approaches, with notable peaks in years 2022 and 2023, aligning with broader sustainability discourses in water resource planning.

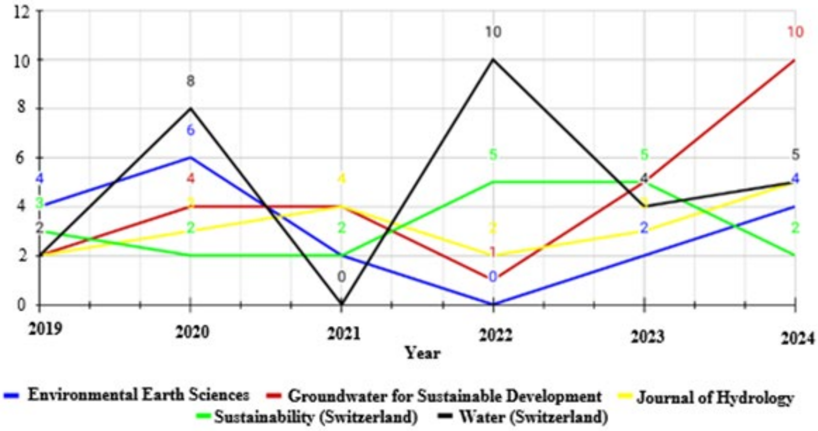


**Figure 10.** Distribution of research articles in the top 5 journals (year 2019–2024)

Overall, the figure highlights a clear pattern that peer-reviewed scientific journals are the preferred platform for publishing advancement in this domain. The increased visibility and citations of these journals suggest a maturing research landscape that values rigor, accessibility, and long-term scholarly impact in addressing global water challenges.

### 6.4 Keyword Analysis

The analysis of keyword co-occurrence provides critical insights into the thematic structure and emerging directions within water harvesting and groundwater recharge research. Figure 11 displays four distinct thematic clusters. The red cluster focuses on policy and climate adaptation, linking rainwater harvesting with broader sustainability goals. The green cluster, emphasizing recharge estimation techniques like chloride mass balance and hydrological modelling, is methodologically oriented. The blue cluster highlights geospatial and remote sensing applications to illustrate the integration of GIS, satellite data, and multi-criteria decision analysis (MCDA) in identifying recharge zones. The yellow cluster blends interdisciplinary approaches by combining flood management, water quality, and managed aquifer recharge. The dense interconnections among clusters suggest a shift toward integrated systems thinking, where technical interventions are increasingly evaluated within the socio-environmental and governance contexts. This integration signals a maturation of the field from single-focus studies toward holistic water resource management strategies.

The first cluster, shown in red, centres on themes related to water management, rainwater harvesting, climate change, and water conservation. This group, emphasizing adaptation strategies in response to increasing water scarcity, represents policy-driven and sustainability-oriented research. Studies in this cluster frequently explore decentralized water systems, public acceptance, and regional strategies to enhance water availability in drought-prone regions (Pan et al., 2020). The prominence of terms like harvesting and rainwater harvesting systems reflects the critical role of capture-based technologies in supplementing traditional water supplies under changing climate conditions. Interdisciplinary approaches incorporating environmental planning and social behaviour analysis are also evident in this cluster (Bai et al., 2022).

The second cluster, highlighted in green, emphasizes ground water recharge, recharge estimation, chloride mass balance, and hydrological modelling. This scientific stream is foundational in quantifying recharge rates through both direct and indirect methods. Chloride tracing, water balance models, and land use impact assessments are central methods in this group (Taloor et al., 2020). Studies often integrate spatial-temporal tools like SWAT and MODFLOW, the US Geological Survey modular finite-difference flow model, to simulate recharge under different hydrological and land use scenarios. Keywords such as runoff, catchments, and watersheds indicate the growing interest in watershed-level recharge interventions for long-term water sustainability (Jiang et al., 2020; Zhang et al., 2022).

The third cluster, shown in blue, focuses geospatial and remote-sensing tools such as GIS, remote sensing, aquifers, and artificial recharge. This cluster emphasizes the technical backbone of recharge research, in which multi-criteria decision analysis (MCDA), satellite data, and mapping techniques are applied to delineate potential recharge zones and prioritize intervention areas (Li et al., 2020). Keywords like managed aquifer recharge and infiltration reflect engineered solutions to augment groundwater reserves in overexploited aquifer systems. These tools are vital in creating decision-support systems for regional water planning and sustainable aquifer management.

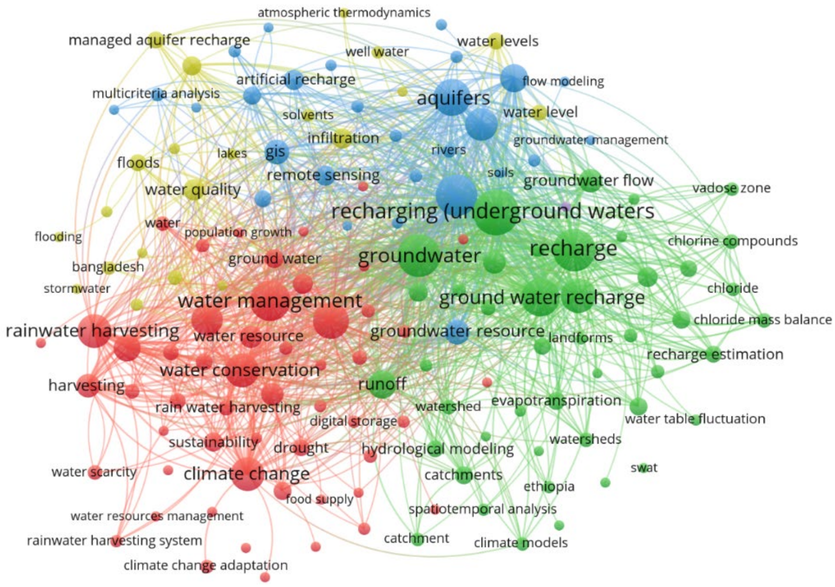


**Figure 11.** Keyword co-occurrence network map of WH and GWR research

The fourth cluster, marked in yellow, is a convergence of interdisciplinary techniques, integrating terms such as multicriteria analysis, managed aquifer recharge, floods, and water quality. This cluster bridges hydrological science with environmental and risk assessment approaches. It includes research on enhancing recharge through stormwater management, flood mitigation, and integrated urban water strategies (Evans et al., 2020). Tools like MCDA and analytical hierarchy processes (AHP) are frequently employed in this context to evaluate recharge suitability across multiple dimensions in hydrology, land use, soil texture, and socioeconomic conditions.

The co-occurrence network reveals the interconnected nature of water recharge research, with dense linkages between engineering, environmental, and planning-related terms. The integration of climate adaptation strategies with hydrogeological assessments highlights a systems-based approach to water sustainability. While substantial progress has been made, gaps remain in aligning technical solutions with policy, community participation, and long-term ecological outcomes. Future directions should emphasize hybrid recharge models, urban aquifer resilience, and AI-enhanced recharge monitoring systems, especially in regions vulnerable to hydrological extremes.

### 6.5 Thematic Evolution and Comparative Insights

Thematic evolution mapping revealed a clear transition in WH and GWR research priorities over the past six years. During the period of year 2019 to 2021, dominant themes were primarily technical and method-oriented, with clusters centred on “rainwater harvesting”, “groundwater recharge estimation”, and “GIS-based mapping.” These themes reflected a focus on foundational hydrological assessments and localized recharge interventions. In contrast, the period of year 2022 to 2024 showed a notable expansion into integrated and cross-sectoral approaches, with emerging clusters around “MAR”, “climate change adaptation”, and “urban water resilience”. This shift suggests a maturing research landscape that gradually integrates policy, governance, and socio-environmental dimensions alongside engineering solutions.

Country-level thematic specialization analysis indicated that India and China remain heavily invested in rainwater harvesting and artificial recharge infrastructure, whereas the United States and several European nations demonstrate stronger focus on remote sensing applications and climate-resilient water management frameworks. Institutions in Australia and South Africa have positioned themselves at the intersection of urban water security and nature-based solutions, while research centred in Japan and Singapore lead in technological integration, particularly the coupling of WH systems with IoT-based monitoring.

Temporal keyword trend analysis has further highlighted the rising prominence of terms such as “AI-enhanced recharge assessment”, “participatory governance”, and “hybrid recharge systems” since year 2022, thus reflecting growing interest in adaptive, data-driven, and socially inclusive approaches. Meanwhile, earlier high-frequency terms like “check dams” and “percolation tanks” have shown a relative decline in network centrality; this indicates a gradual shift from infrastructure-specific studies to broader system-level strategies.

### 6.6 Gap Analysis

Despite significant advancement in water harvesting and groundwater recharge research, several important gaps remain. One major limitation is the weak integration between hydrological models and climate adaptation strategies. While runoff, recharge, and climate change are commonly addressed topics, very few studies utilize dynamic and future-oriented tools that combine predictive climate modelling with localized recharge assessments. There is also a noticeable underuse of advanced technologies such as artificial intelligence, machine learning, and real-time remote sensing in identifying and managing recharge zones. Most current approaches rely on static parameters and conventional GIS tools, so they miss the opportunity for more adaptive and high-resolution planning.

Another critical gap lies in the limited focus on urban recharge systems and the social dimensions of water management. While the keyword network emphasizes technical and environmental aspects, issues like policy implementation, community participation, and socioeconomic factors remain underexplored. The application of multi-criteria analysis (MCA) is often confined to physical suitability mapping, without considering broader governance, equity, or long-term sustainability factors. There is also a geographic imbalance in research coverage, with many water-stressed regions, particularly Africa, Central Asia, and Latin America, lacking sufficient empirical and model-based studies. Figure 12 summarizes these four critical gaps and highlights the need for more holistic, interdisciplinary, and regionally inclusive research strategies that integrate cutting-edge technologies with socio-political and governance considerations to address the gaps.

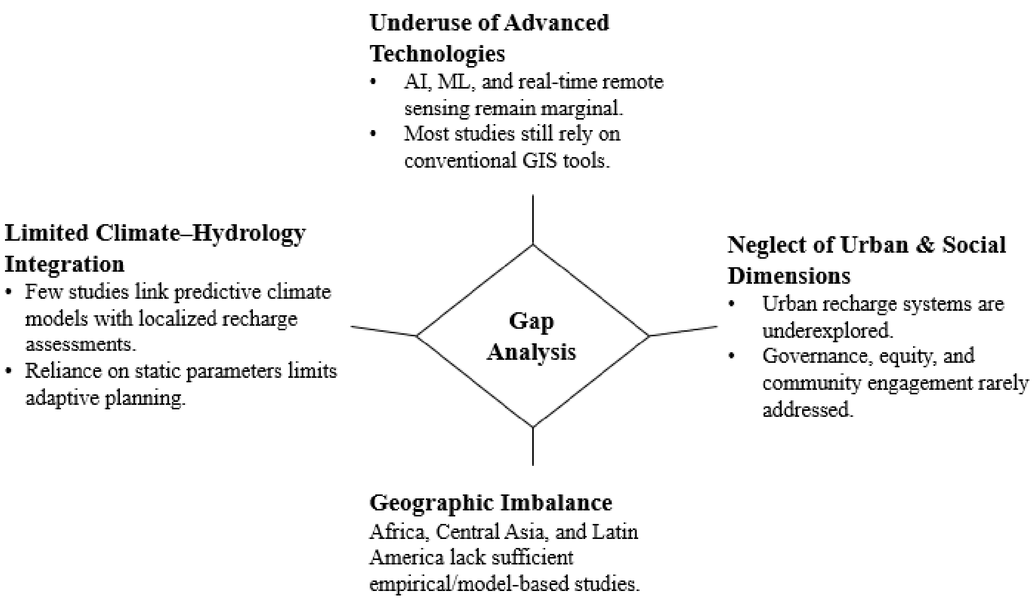


**Figure 12.** Gap analysis in water harvesting and groundwater recharge research

## 7. Discussion

The findings of this bibliometric review underscore the growing academic and policy-oriented emphasis on WH and GWR as essential components of sustainable water resource management. The upward trend in publication volumes from year 2019 to year 2024 reflects not only increased research interest but also a global recognition of groundwater depletion requiring urgent preventive measures, particularly in arid and semi-arid regions. This trend coincides with international water security challenges exacerbated by climate variability, population growth, and land use change.

The spatial distribution of research activity reveals a dominant contribution consistent with the acute groundwater stress and long-standing investments in hydrological research from countries such as India, China, and the United States. The prominent position of India in both publication output and citation metrics highlights its dual role as a research leader and a region grappling with groundwater overexploitation. However, the relatively limited representation of sub-Saharan Africa and Central Asia indicates a regional imbalance in both research production and application although these areas are facing severe groundwater scarcity. This discrepancy highlights a critical need for increased investment in localized and context-sensitive research in underrepresented regions.

The thematic structure identified through keyword co-occurrence analysis reveals four major research clusters: policy and climate adaptation via rainwater harvesting, recharge quantification methods, geospatial and remote sensing techniques, and MAR. This classification illustrates a maturing research landscape that is moving from purely technical investigations toward integrated and interdisciplinary frameworks that consider of policy, governance, and societal needs. Notably, the increasing adoption of tools such as GIS, remote sensing, and modelling platforms like MODFLOW and SWAT has enabled high-resolution analysis and improved recharge zone identification. However, the relative absence of artificial intelligence (AI) and machine learning (ML) in keyword clusters suggests that advanced computational tools remain underutilized in this domain and this represents an obvious opportunity for future innovation.

The review also points to a methodological shift from basic recharge estimation techniques such as the WTF and Water Budget Methods toward more complex and data-driven approaches including tracer techniques and numerical modelling. While traditional methods remain valuable, especially in data-scarce environments, the integration of multiple approaches offers enhanced reliability and decision-making power. Nevertheless, the effectiveness of these methods depends heavily on data availability, site-specific calibration, and the inclusion of socio-environmental variables, which are often lacking in current studies.

Moreover, the analysis reveals that while RWH remains the most extensively studied and applied technique, FWH and GWH are largely recognized for their potential in large-scale and urban contexts. Yet, the successful deployment of these methods is often hindered by high infrastructure costs, maintenance complexity, and weak policy frameworks. Addressing these barriers requires the development of cost-effective and modular systems alongside policy integration and community engagement strategies.

The citation analysis highlights several landmark studies that have shaped the field, particularly those focusing on managed aquifer recharge, GIS-based groundwater zoning, and the socio-economic factors influencing RWH adoption. These works serve as intellectual anchors, guiding both methodological development and practical implementation. However, the limited presence of socially grounded research within the most cited papers signals an ongoing gap in linking technical solutions with local behaviour, equity, and long-term community resilience.

Taken together, these findings suggest that while the field of WH and GWR has made significant strides, it must evolve toward a more holistic paradigm that fuses technological precision with adaptive governance, participatory planning, and climate foresight. The path forward lies in developing hybrid recharge systems, embedding predictive analytics, and fostering cross-sectoral collaborations that reflect the complexity and locality of water sustainability challenges.

## 8. Conclusions

This study provides a comprehensive bibliometric assessment of global research on WH and GWR techniques, highlighting significant trends, dominant research themes, and critical knowledge gaps. The analysis reveals a robust growth trajectory in publication output from year 2019 to year 2024; thus signalling an escalating global commitment to addressing groundwater depletion and enhancing climate resilience through sustainable water management. India, China, and the United States emerged as the most prolific and influential contributors although substantial regional disparities persist, particularly in underrepresented but water-stressed areas such as sub-Saharan Africa and Central Asia. The thematic mapping identified four major research domains, i.e., policy-oriented rainwater harvesting, recharge estimation methodologies, geospatial and remote-sensing approaches, and interdisciplinary MAR strategies; this demonstrates a gradual shift from foundational hydrological studies to more integrated and applied research frameworks in the field.

Despite methodological advancement, including the increased use of GIS, modelling tools like MODFLOW, and tracer-based recharge estimation techniques, the integration of advanced computational technologies such as artificial intelligence and machine learning remains limited. Furthermore, the adoption and scalability of WH and GWR systems are often constrained by high infrastructure costs, technical complexity, and weak institutional support, particularly in low-resource settings. Although the technical and environmental dimensions dominate the discourse in the field, the social, economic, and policy aspects of groundwater management remain underexplored.

From a practical perspective, the findings in this review have direct implications on water management, urban planning, and policy formulation. Urban planners could integrate WH and GWR strategies into stormwater management and green infrastructure designs to enhance urban resilience against flooding and drought. Policymakers in water-scarce regions should prioritize supportive legislation, incentives, and awareness campaigns to accelerate adoption. Engineers and environmental managers could enhance system performance by coupling technical design with socio-economic engagement so as to guarantee effective and locally accepted infrastructure. Finally, researchers should expand cross-regional collaboration and incorporate advanced analytical tools to address data gaps and support adaptive and context-specific solutions.

To translate these bibliometric insights into applicable strategies, Table 4 summarises the key recommendations and expected impact of implementing these measures for different stakeholders like researchers, urban planners, policymakers, practitioners/engineers, and international agencies. This structured synthesis bridges the gap between academic findings and real-world applications, thus offering a practical roadmap for promoting WH and GWR practices globally.

**Table 4.** Summary of recommended actions for key stakeholders based on the findings in the study

| Stakeholders | Recommended Actions | Expected Impact |
| --- | --- | --- |
| Researchers | • Conduct thematic evolution studies to track emerging trends.<br>• Integrate AI, ML, and real-time monitoring into WH and GWR assessments.<br>• Focus on underrepresented regions such as sub-Saharan Africa and Central Asia. | Improved global research coverage, enhanced prediction accuracy, and more context-specific knowledge. |
| Urban Planners | • Incorporate WH and GWR into green infrastructure and flood management plans.<br>• Design multifunctional systems that also provide urban cooling and biodiversity benefits. | Increased urban resilience, reduced stormwater runoff, and enhanced climate adaptation capacity. |
| Policymakers | • Develop clear regulatory frameworks for WH and GWR adoption.<br>• Provide subsidies or tax incentives for system installation.<br>• Promote public awareness campaigns. | Higher adoption rates, improved compliance, and greater public engagement. |
| Practitioners/Engineers | • Optimize designs for cost-effectiveness and local material use.<br>• Combine technical systems with community-based maintenance programs.<br>• Implement hybrid recharge models tailored to hydrogeological conditions. | More sustainable, affordable, and socially accepted WH and GWR projects. |
| International Agencies/NGOs | • Facilitate cross-country capacity building.<br>• Fund pilot projects in water-scarce developing regions.<br>• Support technology transfer initiatives. | Faster scaling of solutions and better knowledge transfer to vulnerable regions. |

## Data Availability

The data used to support the research findings are available from the corresponding author upon request.

## Conflicts of Interest

The author declares no conflict of interest.

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