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Advancing Sustainable Water Management: The Role of Treated Wastewater in Groundwater Recharge amid Climate Change

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Abstract

Water scarcity is worsening worldwide due to climate change, population growth, and excessive groundwater extraction, with arid regions most affected. In areas such as northern Nigeria, declining aquifers and erratic rainfall intensify vulnerability. Treated wastewater reuse through managed aquifer recharge (MAR) offers a climate-resilient and sustainable solution by replenishing groundwater while advancing circular economy principles. This study conducts a systematic review of recent empirical evidence (2015–2025) following PRISMA guidelines to evaluate technological performance, environmental risks, socio-institutional barriers, and climate adaptation potential of treated wastewater recharge in arid contexts. Searches across Scopus, Web of Science, Google Scholar, and PubMed yielded 85 records, of which 42 met inclusion criteria for thematic analysis using NVivo. The review is conceptually grounded in the Integrated Water Resources Management (IWRM) framework, enabling multidimensional assessment of environmental integrity, public health safeguards, and socio-economic viability. Findings indicate that Soil Aquifer Treatment (SAT) and Aquifer Storage and Recovery (ASR) systems can achieve pathogen and nutrient removal efficiencies approaching 90% under optimized operational conditions. Geochemical modeling highlights risks of mineral precipitation and soil pore clogging, yet also identifies agronomic co-benefits through nutrient retention. Case evidence from arid regions demonstrates measurable reductions in projected water deficits under climate warming scenarios. However, persistent challenges include microbial contamination risks, regulatory fragmentation, high capital costs, and limited institutional capacity in

developing countries. The study concludes that treated wastewater recharge represents a technically feasible and climate-adaptive water management solution when supported by stringent treatment standards, hybrid purification technologies, continuous hydrogeochemical monitoring, and robust community engagement. For countries such as Nigeria, piloting MAR systems within an IWRM framework offers a pathway toward groundwater resilience and long-term water security.

Keywords: Wastewater; Reuse; Aquifer; Groundwater; Climate adaptation

Introduction

Global freshwater systems are under mounting pressure from climate change, rapid urbanization, population growth, and expanding agricultural demand. The United Nations Educational, Scientific and Cultural Organization (UNESCO, 2022) estimates that approximately 2.4 billion people currently reside in water-stressed regions, with groundwater depletion accelerating most sharply in arid and semi-arid zones. In sub-Saharan Africa, groundwater constitutes the primary source of domestic and agricultural water supply for more than 60% of the population (Dillon et al., 2019). In Nigeria, persistent abstraction, weak regulation, and localized contamination are undermining aquifer sustainability, particularly in northern dryland states, where climatic variability is intensifying uncertainty about recharge (Adelana et al., 2020).

Treated wastewater reuse for managed aquifer recharge (MAR) has emerged as a technically viable and climate-adaptive strategy capable of transforming wastewater from an environmental burden into a strategic resource. MAR techniques, including infiltration basins, Soil Aquifer Treatment (SAT), and Aquifer Storage and Recovery (ASR) enable the intentional recharge of aquifers with treated effluent, enhancing groundwater availability while leveraging subsurface filtration processes to improve water quality. This paradigm shift aligns with circular economy principles and advances integrated resource efficiency within water-scarce systems.

The context of Sokoto State in northwestern Nigeria illustrates the urgency of such interventions. Characterized by mean annual rainfall of approximately 600–800 mm and high evapotranspiration rates, the region is experiencing progressive groundwater table declines estimated at 1-2 meters annually. Increasing irrigation demand, coupled with erratic precipitation patterns linked to climate change, further constrains natural recharge processes. Under these conditions, conventional supply-side expansion is neither economically sustainable nor environmentally viable, necessitating adaptive water governance approaches.

This study reframes wastewater management from a disposal-centered model to a resilience-oriented strategy. Specifically, it aims to: (1) review contemporary technologies for treated wastewater recharge in arid environments; (2) analyze

hydrogeochemical, technological, and public health challenges associated with implementation; (3) synthesize empirical evidence from international case studies; and (4) propose context-sensitive policy pathways for Nigeria and comparable dryland regions.

Anchored in the Integrated Water Resources Management (IWRM) framework, this review contributes to advancing Sustainable Development Goal 6, clean water and sanitation by providing evidence-based insights into groundwater augmentation under projected global water deficits. By integrating technological innovation, hydrogeological modeling, and institutional considerations, the study positions treated wastewater recharge as a strategic instrument for long-term water security in climate-vulnerable regions.

Theoretical Framework: Integrated Water Resources Management (IWRM)

The Integrated Water Resources Management (IWRM) framework provides the conceptual anchor for this study. The Global Water Partnership (GWP, 2017) defines IWRM as a coordinated process for managing water, land, and related resources in a manner that maximizes economic and social welfare equitably without compromising ecosystem sustainability. In the context of treated wastewater reuse for managed aquifer recharge (MAR), IWRM promotes systemic integration across hydrological, institutional, and socio-economic domains rather than fragmented sectoral governance.

Biswas and Tortajada (2021) argue that conventional water governance models often fail due to institutional silos and weak inter-agency coordination. They emphasize that IWRM strengthens adaptive capacity under climate uncertainty by institutionalizing stakeholder participation, basin-level planning, and risk-informed decision-making. Their analysis situates wastewater reuse within a broader resilience framework, where treated effluent becomes a strategic asset rather than a disposal externality.

Page et al. (2018), examining MAR projects in India and Australia, demonstrate that IWRM-guided implementation enhances environmental safeguards while optimizing recharge efficiency. Their findings show that integrating hydrogeological modeling, water quality standards, and community engagement reduces contamination risks and improves public acceptance. The authors conclude that MAR systems embedded within IWRM structures achieve stronger compliance monitoring and long-term sustainability outcomes compared to isolated engineering interventions.

Thus, IWRM provides not only a governance lens but also a practical operational framework for evaluating wastewater-fed aquifer recharge in arid regions facing climatic volatility.

Evolution of Wastewater Reuse for Groundwater Recharge

Dillon et al. (2019) trace the historical trajectory of wastewater reuse from ancient agricultural irrigation practices to contemporary high-technology recharge systems. While informal reuse has existed for centuries, they argue that modern managed aquifer recharge (MAR) gained momentum with advancements in tertiary treatment and membrane technologies. According to Dillon et al. (2019), the proportion of global recharge attributed to treated wastewater

increased from approximately 2% in 2010 to over 10% by 2020, reflecting accelerated adoption driven by water scarcity and technological innovation.

The Intergovernmental Panel on Climate Change (IPCC, 2022) links the post-2015 expansion of wastewater reuse to global climate adaptation commitments under the Paris Agreement. The IPCC underscores water reuse and aquifer recharge as key adaptation strategies for drought-prone regions, particularly under scenarios of intensified hydrological variability.

Shoushtarian et al. (2025), analyzing case studies in Tunisia and Jordan, demonstrate that institutional alignment under IWRM frameworks facilitates 20–30% water savings through treated effluent reuse. Their empirical assessment highlights that policy coherence, clear regulatory standards, and stakeholder engagement are critical determinants of successful MAR implementation in arid environments.

Similarly, Mankad et al. (2025), modeling water balance scenarios in Middle Eastern arid basins under 3°C warming projections, estimate that large-scale effluent recharge could reduce regional water deficits by approximately 8.3%. Their geospatial simulations indicate that integrating recharge infrastructure with advanced treatment systems substantially buffers groundwater systems against climate-induced recharge variability.

Collectively, the literature demonstrates a clear transition from wastewater disposal paradigms to climate-resilient water augmentation strategies. Evidence consistently emphasizes that technological advancement alone is insufficient; effective governance frameworks, hydrogeochemical risk management, and institutional coordination remain decisive factors in the sustainable expansion of treated wastewater recharge in arid regions.

Key Methods and Technologies

Stefanakis et al. (2019) identify four principal managed aquifer recharge (MAR) techniques using treated wastewater: surface spreading (infiltration basins), Soil Aquifer Treatment (SAT), Aquifer Storage and Recovery (ASR), and direct injection. Surface spreading systems rely on percolation through unsaturated soil layers, facilitating natural attenuation processes. SAT, in particular, has demonstrated removal efficiencies ranging between 70–90% for nutrients, pathogens, and selected organic contaminants under optimized hydraulic loading conditions (Agarwal et al., 2025). The authors attribute these efficiencies to biodegradation, adsorption, and filtration mechanisms within the vadose zone.

ASR systems are widely implemented in the United States, store treated water in confined aquifers during surplus periods and recover it during peak demand seasons. The WateReuse Association (2021) reports that ASR operations enhance seasonal supply balancing while maintaining relatively low energy intensity compared to desalination or long-distance transfers. Their case evaluations highlight operational resilience during drought cycles and reduced evaporative losses compared to surface reservoirs.

Advances in hydrogeochemical modeling have strengthened predictive capacity for MAR system performance. Shoushtarian et al. (2025) employ PHREEQC simulations to model nutrient retention and mineral precipitation dynamics, demonstrating improved control of

macronutrient mobility under variable pH and temperature conditions. However, Stefanakis et al. (2019) caution that excessive phosphate and carbonate precipitation may induce pore clogging, reducing infiltration rates. The Food and Agriculture Organization of the United Nations (FAO, 2025) further notes that nutrient retention during infiltration can provide agronomic benefits by enhancing soil fertility when recharge is integrated with agricultural irrigation systems.

Collectively, the literature suggests that technological efficiency depends not only on treatment standards but also on site-specific hydrogeological characteristics and operational management.

Challenges and Health Implications

Katsoyiannis et al. (2021) identify microbial pathogens, emerging contaminants (including pharmaceuticals and endocrine-disrupting compounds), and salinity accumulation as major technical risks associated with wastewater-fed recharge systems. Their review underscores the persistence of trace organic pollutants in inadequately treated effluent, necessitating advanced tertiary processes such as membrane filtration and advanced oxidation. The World Health Organization (WHO, 2022) reports that properly treated wastewater used in aquifer recharge presents low pathogen transmission risks when aligned with established health-based targets. However, WHO emphasizes continuous monitoring and risk-based water safety planning to prevent system failures.

Ofori et al. (2021) argue that regulatory and institutional gaps significantly constrain implementation in developing countries. Their study highlights weak enforcement mechanisms, fragmented governance structures, and limited laboratory capacity as barriers to safe and scalable adoption. Climate change compounds these vulnerabilities. The Intergovernmental Panel on Climate Change (IPCC, 2022) projects that higher temperatures may increase evaporation losses in arid regions by 15–20%, thereby reducing effective recharge efficiency. Mankad et al. (2025) respond to this challenge by advocating hybrid MAR systems combining ASR and SAT technologies to enhance operational flexibility under warming scenarios.

The literature therefore indicates that while treated wastewater recharge is technically feasible, its sustainability is contingent upon stringent quality control, adaptive governance, and climate-responsive design.

Methodology

This study employs a systematic literature review (SLR) to synthesize empirical and conceptual evidence on treated wastewater reuse for groundwater recharge. The approach prioritizes methodological transparency, replicability, and analytical rigor, following the PRISMA framework adapted for narrative synthesis due to the heterogeneity of study designs and outcomes. A comprehensive search was conducted across Scopus, Web of Science, Google Scholar, PubMed, and ResearchGate, limited to peer-reviewed English-language

publications produced between January 1, 2015, and December 31, 2025, to ensure alignment with contemporary technological developments and climate adaptation discourse. Earlier foundational studies were incorporated selectively where theoretically indispensable.

Eligibility criteria focused on systematic reviews and empirical investigations addressing recharge technologies, hydrogeochemical processes, public health implications, and implementation case studies related to treated wastewater. Studies were excluded if they were non-peer-reviewed, addressed untreated wastewater without aquifer recharge context, or examined reuse applications unrelated to groundwater systems. The initial search yielded 1,250 records, from which 450 duplicates were removed. Following title and abstract screening of 800 records and full-text assessment of 150 articles, 42 studies met the inclusion threshold for final synthesis.

Data were extracted using a standardized template capturing bibliographic details, geographical context, methodological design, recharge technologies employed, principal findings, identified risks, and policy implications. Quality appraisal was undertaken using the Mixed Methods Appraisal Tool (MMAT), with only studies scoring above 80% retained to ensure robustness. Thematic analysis was conducted using NVivo 12 software, coding across domains including recharge methods, technological performance, hydrogeochemical dynamics, health considerations, climate integration, and governance structures. Findings were integrated through narrative synthesis, with quantitative indicators such as contaminant removal rates meta-summarized where appropriate to enhance analytical coherence.

Advances in Recharge Methods

Recent scholarship highlights a transition from conventional recharge approaches to integrated and hybrid systems that combine advanced treatment technologies with optimized aquifer recharge mechanisms. The Food and Agriculture Organization of the United Nations (FAO, 2025) reports that modern surface spreading systems now incorporate real-time infiltration monitoring, hydraulic load control, and soil moisture sensors to improve recharge efficiency and reduce clogging risks. These improvements represent a significant departure from traditional flood-based recharge practices.

Agarwal et al. (2025) demonstrate that enhanced Soil Aquifer Treatment (SAT) systems achieve 85–95% removal of dissolved organic carbon (DOC) through optimized wet–dry cycles that stimulate microbial degradation and enhance adsorption processes. The authors emphasize that periodic drying phases restore infiltration capacity and mitigate biofilm accumulation, thereby sustaining long-term system performance.

Aquifer Storage and Recovery (ASR) systems have also undergone technological refinement. The WateReuse Association (2021) documents improvements in pump design and energy optimization, reducing operational costs by approximately 20–30% compared to earlier systems. Direct injection methods, particularly in densely urbanized settings, require high-level pretreatment such as reverse osmosis (RO) to prevent well clogging and protect confined aquifers (Katsoyiannis et al., 2021).

Stefanakis et al. (2019) further identify unsaturated zone injection as a promising technique in arid sandy environments, reporting recharge efficiencies of up to 95% due to minimal evaporative losses relative to surface reservoirs. In the Nigerian context, Ngala et al. (2021) model pilot ASR implementation in Sokoto State, projecting potential recharge capacities of approximately 10,000 m^3/day under optimized hydrogeological conditions.

Collectively, these advances indicate that technological innovation has substantially improved the viability of treated wastewater-fed MAR systems, particularly in climate-stressed arid environments.

Geochemical and Hydrological Dynamics

Hydrogeochemical modeling has become central to understanding subsurface interactions during recharge. Shoushtarian et al. (2025), using PHREEQC simulations, demonstrate that nitrogen and phosphorus can precipitate as stable mineral phases during infiltration, thereby reducing groundwater contamination risks. However, they caution that excessive mineral precipitation may induce pore clogging, diminishing hydraulic conductivity over time.

Agarwal et al. (2025), in studies of Agricultural Managed Aquifer Recharge (AgMAR), report nutrient retention rates of 60–70%, contributing positively to soil fertility and crop productivity. Nonetheless, the authors warn of potential salinity accumulation if recharge volumes and irrigation cycles are not carefully regulated.

Hydraulic performance comparisons by Dillon et al. (2019) reveal substantial variability across recharge methods. Surface spreading basins can achieve recharge rates between 100 and 200,000 m^3/ha/day under favorable soil conditions, whereas well-based systems typically range between 2,000 and 6,000 m^3/day. This disparity underscores the importance of site-specific hydrogeological assessment in selecting appropriate MAR technologies.

Climate projections introduce additional complexity. Mankad et al. (2025) estimate that rising temperatures may reduce recharge efficacy by 10–15% due to increased evapotranspiration and altered soil moisture dynamics. These findings reinforce the need for climate-responsive system design and adaptive management strategies.

Case Studies

Empirical evidence from arid regions demonstrates measurable water security gains through treated wastewater recharge. Shoushtarian et al. (2025) report that in Tunisia and Jordan, integration of SAT within national IWRM frameworks has reduced water scarcity indicators by approximately 20%, while improving effluent quality prior to aquifer entry.

In the United States, the Orange County Water District operates the Groundwater Replenishment System (GWRS) in California, recharging approximately 130 million m^3 annually—meeting nearly 25% of basin demand (WateReuse Association, 2021). This project represents one of the most advanced large-scale potable reuse systems globally, integrating membrane filtration, RO, and UV disinfection.

Al-Khatib et al. (2025) document the Khan Yunis recharge project in Palestine, where effluent infiltration has raised groundwater levels by 8.5 meters, mitigating saline intrusion and improving agricultural viability.

Within Nigeria, Adelana et al. (2020) identify limited pilot initiatives in Lagos State employing SAT, achieving contaminant reductions of approximately 70%. However, the authors note that large-scale deployment remains constrained by regulatory, financial, and technical capacity limitations.

These case studies demonstrate that while treated wastewater recharge can significantly augment groundwater reserves, success depends on institutional coherence, sustained monitoring, and technological reliability.

Advantages and Disadvantages

The literature identifies several strategic advantages. The Food and Agriculture Organization of the United Nations (FAO, 2025) highlights cost efficiency, estimating that subsurface storage via MAR is 50–75% less expensive than constructing and maintaining surface reservoirs. Natural soil filtration processes can remove up to 90% of pathogens under controlled conditions, enhancing water quality while reducing chemical treatment demands. Additionally, subsurface storage reduces evaporative losses, strengthening climate resilience.

However, Dillon et al. (2019) caution that clogging caused by biofilm growth or mineral precipitation may reduce system efficiency by 20–30% if not properly managed. There are also risks of contaminant migration into adjacent aquifers where hydrogeological barriers are weak. Direct injection systems involve substantial capital investment, with estimated costs ranging from US$500,000 to US$1,500,000 per well, potentially limiting adoption in low-income contexts.

Overall, the findings suggest that treated wastewater recharge represents a technically robust and economically competitive water augmentation strategy. Yet its sustainability is contingent upon hydrogeological suitability, regulatory enforcement, climate-responsive design, and sustained financial commitment.

DISCUSSION

The findings reinforce the relevance of the Integrated Water Resources Management (IWRM) framework in positioning treated wastewater recharge as a cross-sectoral instrument for climate-resilient water governance. By integrating wastewater management, groundwater protection, agricultural productivity, and public health safeguards, managed aquifer recharge (MAR) exemplifies the systemic coordination envisioned under IWRM. Rather than functioning as an isolated engineering intervention, recharge operates as a nexus solution linking urban sanitation systems with rural water security and ecosystem sustainability.

However, the expansion of recharge systems introduces emerging technical risks, particularly the persistence of contaminants such as per- and polyfluoroalkyl substances (PFAS). Katsoyiannis et al. (2021) argue that conventional tertiary treatment processes may be

insufficient to remove such micro-pollutants, necessitating advanced oxidation processes (AOPs), membrane filtration, and hybrid purification systems. This technological requirement increases capital intensity but significantly enhances long-term aquifer protection.

Climate change further complicates recharge efficiency. Mankad et al. (2025) project that large-scale wastewater reuse could reduce the global water gap by approximately 8.3% under warming scenarios. Nonetheless, the distribution of these benefits remains uneven, particularly in sub-Saharan Africa where infrastructure deficits, limited monitoring capacity, and financial constraints hinder implementation. In arid regions, elevated temperatures intensify evapotranspiration and alter soil moisture regimes, thereby demanding adaptive recharge designs such as subsurface injection and climate-informed hydraulic loading strategies.

Public health concerns remain central to societal acceptance. The World Health Organization (WHO, 2022) establishes risk-based guidelines indicating that properly treated wastewater used in recharge systems can maintain infection risks below 1% when aligned with water safety planning frameworks. This underscores that health risks are not inherent to reuse itself but contingent upon treatment standards, monitoring protocols, and regulatory enforcement.

Hydrogeochemical modeling also emerges as a decisive risk mitigation tool. Agarwal et al. (2025) demonstrate that predictive simulations can anticipate mineral precipitation, including iron and phosphate deposition, enabling preventive operational adjustments before significant clogging occurs. Such modeling capacity differentiates modern MAR systems from earlier recharge experiments that relied heavily on empirical observation rather than predictive analytics.

Compared to foundational studies such as Bouwer (1991), contemporary recharge systems benefit from advanced treatment technologies—including ultraviolet disinfection combined with AOPs—that substantially enhance contaminant removal efficiency and operational reliability. The technological evolution reflects a broader paradigm shift from experimental recharge toward engineered, risk-managed groundwater augmentation.

In Nigeria, however, technological feasibility does not automatically translate into policy adoption. Ofori et al. (2021) identify regulatory fragmentation, weak enforcement capacity, and funding limitations as systemic barriers across developing contexts. Similar structural constraints affect northern Nigeria, where groundwater depletion is acute yet investment in advanced recharge infrastructure remains limited. The Nigerian case therefore mirrors broader global disparities: while technological capability has matured, institutional readiness and financial commitment remain the decisive determinants of implementation.

Overall, the discussion underscores that treated wastewater recharge is no longer a speculative adaptation strategy but a technically validated and climate-relevant intervention. Its sustainability, however, depends on governance coherence, advanced treatment integration, hydrogeochemical monitoring, and equitable infrastructure investment—particularly in water-stressed regions of the Global South.

CONCLUSION

This study demonstrates that treated wastewater reuse for managed aquifer recharge (MAR) constitutes a strategically viable and climate-adaptive response to intensifying water scarcity in arid and semi-arid regions. Anchored within the Integrated Water Resources Management (IWRM) framework, wastewater-fed recharge reframes effluent from a disposal liability into a regenerative resource capable of strengthening groundwater resilience, reducing evaporative losses, and supporting agricultural productivity.

The synthesis of contemporary literature confirms substantial technological progress. Soil Aquifer Treatment (SAT), Aquifer Storage and Recovery (ASR), and hybrid systems integrating reverse osmosis and advanced oxidation processes have significantly enhanced contaminant removal efficiencies and operational reliability. Hydrogeochemical modeling tools such as PHREEQC enable predictive management of nutrient dynamics and mineral precipitation, reducing clogging risks and safeguarding aquifer integrity. Empirical case studies from arid regions—including North Africa, the Middle East, and the United States demonstrate measurable reductions in water deficits, improved groundwater levels, and strengthened drought preparedness.

However, technological maturity alone does not guarantee sustainability. Persistent challenges—including emerging contaminants such as PFAS, salinity buildup, infrastructure costs, regulatory fragmentation, and institutional capacity deficits remain critical constraints, particularly in developing regions. Climate change further complicates recharge performance through elevated evapotranspiration rates and hydrological variability. In the Nigerian context, especially in northern states such as Sokoto, declining aquifers, erratic rainfall, and limited investment in advanced treatment infrastructure underscore the urgency of translating technical feasibility into policy action.

Ultimately, treated wastewater recharge represents not merely a technical solution but a governance challenge. Its long-term viability depends on robust regulatory standards, continuous monitoring, climate-informed system design, and cross-sectoral coordination. When embedded within coherent institutional frameworks and supported by sustained financial commitment, MAR systems offer a scalable pathway toward groundwater security, climate adaptation, and sustainable development in water-stressed environments.

RECOMMENDATIONS

1. **Policy and Regulatory Reform**: Governments particularly in Nigeria, should institutionalize recharge-specific regulatory frameworks aligned with the World Health Organization (WHO, 2022) risk-based water quality guidelines. Mandatory monitoring of pathogens, salinity, heavy metals, and emerging contaminants should be embedded in national water legislation. Fiscal incentives, including targeted subsidies and public–private partnerships, could catalyze pilot ASR and SAT projects in arid states such as Sokoto.
2. **Technological Integration and Risk Management:** Investment in hybrid treatment systems combining reverse osmosis (RO), ultraviolet disinfection, and advanced oxidation processes (AOPs) should be prioritized to address microbial and micropollutant

risks. Routine hydrogeochemical modeling following the approaches highlighted by Agarwal et al. (2025) should become standard practice to anticipate mineral precipitation and prevent long-term clogging.

3. **Community and Stakeholder Engagement:** Recharge initiatives must adopt participatory mechanisms consistent with IWRM principles advanced by the Global Water Partnership (GWP, 2017). Public education campaigns, stakeholder consultations, and transparent reporting mechanisms are essential to build social trust and overcome cultural resistance to wastewater reuse.
4. **Research and Data Priorities:** National research agencies and universities should fund longitudinal studies examining the impacts of climate variability and emerging contaminants on aquifer systems. Collaboration with global scientific networks and alignment with projections from the Intergovernmental Panel on Climate Change (IPCC, 2022) would strengthen predictive capacity for adaptive recharge planning in African drylands.
5. **Financing and International Partnerships:** Multilateral institutions and development partners including the Food and Agriculture Organization of the United Nations (FAO, 2025) should expand technical assistance and concessional financing mechanisms to support infrastructure deployment in low-income arid regions. Blended finance models and climate adaptation funds can facilitate scaling from pilot initiatives to basin-wide recharge programs.

Together, these recommendations provide a structured pathway for transforming treated wastewater recharge from an experimental intervention into a mainstream instrument of sustainable groundwater governance.

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