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Review Article

A review of factors affecting the performance and impact of managed aquifer recharge projects: Insights from arid regions

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Abstract: Managed Aquifer Recharge (MAR) is a strategic approach to artificially replenishing groundwater supplies and has become an integral component of global water resource management. The number of MAR projects has steadily increased in recent decades, yet many have failed to achieved their intended outcomes, underscoring the complexity of project implementation. This review is dedicated to examine existing research and reports on MAR performance and impacts, aiming to establish objective criteria for gauging the success and identify key factors influencing the effectiveness of MAR project. Five critical performance factors have been identified as major determinants of MAR performance: aquifer transmissivity, vertical permeability, availability of recharge water, recharge water quality, and aquifer thickness, geometry and boundary conditions. These factors are directly related to project success and significantly shape MAR outcomes. In addition, this review explores research-based strategies to improve MAR success, including cutting-edge methodologies, technological innovations, and integrated management approaches to address key challenges. The ultimate goal is to foster more efficient, effective, and sustainable MAR practices, thereby enhancing the resilience and sustainability of water resource management.

Keywords: Groundwater Management; Artificial Recharge; Permeability and Clogging; Climate Change Adaptation; Flow Dynamics.

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Introduction

Managed Aquifer Recharge (MAR) is the intentional process of replenishing aquifers with surface water or treated recycled water, creating a sustainable resource for future extraction and use (Sherif et al. 2023; Parimalarenganayaki, 2021; Gruetzmacher and Kumar, 2012). This strategy is utilized to address various environmental and water management challenges, such as balancing seasonal discrepancies between water supply and demand (Standen et al. 2020; Spinoni et al. 2017; Hankin et al. 2017), providing strategic water storage for emergency (Alam et al. 2019; Maliva and Missimer, 2010; Pyne, 2005), elevating and stabilizing groundwater levels (Gruetzmacher and Kumar, 2012), mitigating land subsidence caused by excessive groundwater extraction (Casanova et al. 2016; Sheng and Zhao, 2015). Additionally, MAR enhances groundwater quality (Van Houtte and Verbauwhede, 2021; Parimalarenganayaki, 2021; Salameh et al. 2019; Alidina et al. 2014; Dillon et al. 2009; Rivett et al. 2008), provides ecological benefits (Ringleb et al. 2016; Dillon, 2005), reduces evaporation losses (Hartog and Stuyfzand, 2017) and facilitates the disposal of surplus water, such as in mining operations (Sloan et al. 2023). Various water sources can be used for MAR, including river water, stormwater, rainwater, excess desalinated seawater, and treated waste-

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water (Parimalarenganayaki, 2021; Zhang et al. 2020). As a vital component of global groundwater management, MAR projects have been steadily increasing in number (Dillon et al. 2019; Wolf et al. 2007; Bouwer, 2002). This growing trend underscores the recognition of MAR's potential of in addressing water scarcity, groundwater depletion, and the demand for sustainable water management strategies (Gale, 2006).

MAR is of particular importance in arid and semi-arid regions, where groundwater often serves as the primary, and sometimes the only, reliable freshwater source (Fallatah et al. 2019). In these challenging environments, MAR plays a crucial role in mitigating the severe impacts of arid conditions (Casanova et al. 2016; Dillon, 2005). However, the performance and challenges of MAR projects vary significantly between arid/semi-arid and temperate or humid regions. In arid regions, factors such as high evaporation rates, limited surface water availability, and salinity issues pose significant challenges to MAR efficiency. Additionally, variable rainfall patterns often lead to prolonged periods of low recharge in MAR systems (Sherif et al. 2023). Another critical issue is intensified erosion, which results in substantial sediment deposition during temporary flows triggered by rainfall events, reducing recharge efficiency and complicating MAR implementation (Al-Othman, 2011; Alhaj et al. 2017). In contrast, temperate and humid regions generally have greater water availability, lower sediment deposition, and reduced evaporation rates. However, these regions face their own challenges in implementing MAR systems, including competition for land use, risks of oversaturation, and a higher likelihood of water contamination from agricultural runoff, pesticides, and urban pollutants. These differences emphasize the need to tailor the designs and operational strategies of MAR to the unique hydroclimatic conditions of each region, ensuring their long-term effectiveness and sustainability.

Despite increasing investments in MAR, not all projects have achieved their intended success (Ajjur and Baalousha, 2021), highlighting the complexity of implementing. While quantifying the overall success rate is challenging, studies estimate that 20–30% of MAR projects face significant challenges, including operational inefficiencies and failure to meet performance objectives (Ajjur and Baalousha, 2021). In some regions, particularly those grappling with water quality issues, inadequate infrastructure, or weak water governance, failure rates can be even higher (Sherif et al. 2023; Salameh et al. 2019). MAR failure can range from reduced operational efficiency to complete facility shutdown. Partial failures involve issues that can be resolved in a short timeframe, allowing MAR operations to resume. In contrast, complete failures require substantial modifications or repairs, and in some cases, result in permanent facility closure. The reasons of MAR projects failure are diverse, including insufficient understanding of local hydrogeological context (Dillon and Arshad, 2016; Shah, 2014), inadequate stakeholder engagement, and lack of regulatory support (Daher et al. 2011). These failures carry significant financial, environmental and water management consequences (Maliva, 2014; Salameh, 2019).

Review objectives

This review provides a comprehensive synthesis of existing research and case studies on the performance and impacts of MAR projects. It focuses on identifying key environmental, hydrological, and operational factors that influence the success and sustainability of MAR initiatives at different stages of implementation. Particular emphasis is placed on arid and semi-arid regions, where MAR plays a crucial role in water security and sustainability despite challenges such as high evaporation rates, limited surface water availability, and salinity issues. The review evaluates both benefits and challenges of MAR, including its impacts on groundwater levels, water quality, flow patterns, clogging, and surface water dynamics. Case studies from diverse geographical regions are highlighted to illustrate the varying challenges and successes associated with different MAR applications. Furthermore, the review underscores the importance of detailed planning, continuous monitoring, and effective management practices in mitigating risks and optimizing MAR outcomes. It covers a range of MAR techniques, including recharge dams, Aquifer Storage and Recovery (ASR) systems, and direct injection methods. It also addresses persistent challenges such as clogging, deterioration of water quality, and sedimentation, offering practical solutions and actionable recommendations to enhance the outcomes of MAR project on a global scale.

In recent years, several reviews have explored different aspects of MAR projects. For example, Sherif et al. (2023) analyses of groundwater renewability and the effectiveness of recharge dams, while Alam et al. (2021) provides a frame-

work for selecting and implementing MAR types at a site based on water availability and quality, land use, source type, soil, and aquifer properties. Some reviews concentrate on MAR projects within specific regions, such as the Middle East and North Africa (MENA) (Sherif et al. 2023; Alam et al. 2021; Ajjur and Baalousha, 2021; Missimer et al. 2014), while others examine MAR applications in distinct contexts, such as surplus mine water management (Sloan et al. 2023) or specific MAR techniques (Parker et al. 2022).

This review distinguishes itself by focusing on critical factors influencing MAR outcomes, providing insights into long-term sustainability and project success. The paper begins with a detailed methodology for reviewing MAR literature, followed by an analysis of the key determinants of MAR performance and its impacts on groundwater. It concludes with discussion on potential future directions for MAR, summarizing key findings, practical implications, and recommendations for further research.

1 Review methodology

This review examines various research approaches used to evaluate the performance, impacts, and effectiveness of Managed Aquifer Recharge (MAR) projects. These approaches can be categorized as follows: (1) *Post-implementation performance and impact assessments*: Evaluations conducted after MAR projects are operational to measure their effectiveness and environmental impacts. (2) *Numerical groundwater and groundwater-surface water modeling*: Simulations designed to predict and analyze the effects of MAR on aquifer behavior, including changes in groundwater levels, quality, and flow dynamics. (3) *Water quality monitoring*: Systematic sampling and analysis performed before and after recharge activities to assess the influence of MAR on groundwater quality. (4) *Remote sensing and satellite data analysis*: Use of satellite imagery to monitor changes in land use, vegetation cover, and surface water bodies, providing information on MAR impacts over time. (5) *Tracer studies*: Application of environmental tracers and isotopes to track water movement, identify recharge pathways, and understand aquifer dynamics. (6) *Recovery efficiency evaluations*: Assessments comparing the volume of water injected into the aquifers with the volume recovered, considering aquifer properties and water quality factors.

These study categories are not mutually exclusive and often overlap in their objectives and methodologies. This review incorporates a mix of empirical research, both quantitative and qualitative, along with review articles, meta-analyses, and detailed case studies, to provide a comprehensive understanding of MAR projects. The information extracted from each study encompasses the project location, recharge technique used, project scale, and local groundwater and climate conditions. Assessment methods for project impacts are detailed, covering changes in groundwater levels, flow dynamics, recharge rates, and water quality metrics. In addition, this review examines MAR's impacts on surface flow, sedimentation, evaporation rates, and technical challenges such as clogging. Lessons learned, recommendations for future projects, policy implications, and suggested directions for further research are also compiled. To identify relevant studies, a keyword-based search strategy is employed, combining 'MAR' or 'groundwater recharge' with secondary term from a predefined list, including 'impact', 'effectiveness', 'environmental effects', 'ecosystem impacts', 'post-construction assessment', 'water quality improvement', 'technical challenges', 'policy implications', 'sustainability', 'climate change adaptation', 'long-term outcomes', 'lesson learned' and 'risk assessment'.

Grey literature, including government reports, company websites, and academic theses, is also considered valuable for its unique insights beyond peer-reviewed sources. These sources were systematically identified through searches in academic databases, government agency portals, institutional repositories, and credible organizational websites, using keywords aligned with the research objectives. For integration into the review, grey literature was evaluated based on relevance, credibility, and methodological rigor to ensure alignment with the standards applied to peer-reviewed sources. This review is confined to studies published in English.

1.1 Understanding manage aquifer recharge

Several types of MAR techniques are available, and selecting the most appropriate method depends on site-specific conditions. The key factors influencing this decision include the availability of surplus recharge water, which determines the feasibility and sustainability of the recharge process. Local geology plays a critical role in influencing aquifer permeability, storage capacity, potential barriers to water infiltration. The depth of the

groundwater table affects both recharge efficiency and energy requirements for water injection or extraction. In addition, groundwater quality must be evaluated to ensure compatibility with recharged water and to prevent contamination risks. Assessing site suitability for MAR requires hydrogeological surveys, field investigations, and numerical modeling to assess aquifer properties, water movement, and long-term recharge outcomes. Water quality assessments are essential to ensure chemical compatibility between recharge and aquifer water. Additionally, environmental and socio-economic factors—such as land availability, ecosystem impacts, regulatory requirements, and economic feasibility—must be considered. A multi-criteria assessment approach is often used to integrate technical, environmental, and socio-economic considerations, ensuring the selection of the most suitable and sustainable MAR technique for each site (Bailey et al. 2003; Rahman et al. 2012; Kaliraj et al. 2015).

For the effective selection of a MAR technique, several key criteria should be considered (Manual, 2007). First, recharge dams should be positioned upstream or upgradient of the target area to ensure efficient capture and utilization of recharge water. Second, groundwater levels must remain sufficiently below the streambed during recharge periods, with a thick unsaturated zone to accommodate recharge without causing excessive groundwater level rises or flooding. Third, the underlying strata must have adequate permeability to facilitate efficient recharge while minimizing evaporation losses. Low-permeability alluvial deposits should be avoided or mitigated during construction. Fourth, the storage capacity of recharge structures should align with catchment inflow patterns to optimize recharge volumes and maintain cost-effectiveness, especially during peak flow events. Fifth, river water quality must be assessed to prevent contamination, and areas affected by industrial discharges should be avoided, Additionally, sediment input must be carefully managed to prevent infiltration capacity reduction. Finally, MAR projects should incorporate water demand assessments and cost-benefit analyses to ensure that they address both community needs and economic viability. By integrating these criteria into a multi-criteria assessment framework, MAR projects can achieve greater technical efficiency, environmental sustainability, and long-term socio-economic benefits.

The scholarly discourse on MAR is well-established, with numerous studies categorizing MAR technologies based on their recharge and storage methodologies into five principal groups (Yang et al. 2021; Standen et al. 2020; Zhang et al. 2020). These categories are as follows:

1) Spreading Methods: These are among the most widely use MAR techniques that include infiltration ponds and basins, Soil Aquifer Treatment (SAT), controlled flooding, and surplus irrigation (Parimalarenganayaki, 2021; Missimer et al. 2014; Wang et al. 2014; Van Steenbergen, 2010; Parimala and Elango, 2014). Infiltration ponds or basins are excavated reservoirs or open land structures enclosed by an embankment (Van Steenbergen, 2010), designed to store and gradually infiltrate water—such as stormwater, rainwater, and dam runoff—into underlying aquifers. SAT systems utilize specialized ponds where intermittent infiltration enhances water treatment and aquifer recharge. Spreading methods are most effective in areas where unconfined aquifer lies near the surface, allowing water to percolate through permeable materials (Zhang et al. 2020).

2) Well, Shaft, and Borehole Recharge: This approach involves direct water injection into aquifers, bypassing surface infiltration barriers. It encompasses open wells, shafts, Aquifer Storage and Recovery (ASR), and Aquifer Storage, Transport, and Recovery (ASTR) systems. These techniques are particularly beneficial in areas with deep aquifers or low surface permeability, where spreading methods are ineffective. Despite well-based recharge can significantly enhance groundwater reserves, it requires considerable investment in pre-treatment processes, pumping, and maintenance to mitigate issues like well clogging and water contamination (Standen et al. 2020; Mohamedzein et al. 2016; Alam et al. 2021).

3) In-Channel Modifications: This method modifies waterways to boost vertical recharge, through structures such as check dams, percolation ponds, or subsurface barriers. In arid regions, in-channel modifications prove to be particularly valuable for capturing and storing floodwaters or seasonal flows that would otherwise be lost to runoff or evaporation. These interventions help with flood mitigation, groundwater replenishment, and erosion control. The effectiveness of in-channel modifications depends on local climatic, geological, and hydrogeological conditions (Sherif et al. 2023; Dillon et al. 2019; Alataway and El Alfy, 2019; Kacimov et al. 2021).

4) Induced Bank Infiltration: This method involves intentionally drawing water through riverbanks or dune systems to facilitate natural filtration and improve water quality. By drawing water near surface bodies, this method not only provides

indirect recharge but also enhances water quality. The efficiency of bank and dune filtration processes is dependent on the subsurface travel time of water, typically requiring more than a month to achieve significant purification (Maliva and Missimer, 2010).

5) Run-off/Rainwater Harvesting (RWH): RWH techniques focus on collecting and directing rainfall from urban surfaces into aquifers, serving as a cost-effective solution for flood prevention and urban water management. The impact of RWH on groundwater storage depends on regional factors like rainfall patterns and aquifer characteristics. While RWH can significantly contribute to water storage, its efficacy is contingent upon careful site selection and hydrological assessments to avoid water quality degradation during dry periods (Ajjur and Mogheir, 2021; Maurya et al. 2020; Dillon et al. 2019).

Table 1 provides an overview of the MAR classification along with examples of MAR technologies. The selection of a specific MAR technique depends on site-specific conditions, including geological and hydrogeological settings, aquifer type, depth to groundwater table, implementation costs, and groundwater quality (Sherif et al. 2023; Zhang et al. 2020). In many cases, multiple MAR options may be viable for a given aquifer, allowing for the choice of the most effective and efficient method based on these factors. Fig. 1 presents a schematic representation of diverse MAR techniques, illustrating their structural layouts and operational principles. While conceptual in nature, the figure provides insight into the design and function of each method. However, in practice, the scale and dimensions of MAR systems can vary significantly depending on site-specific factors such as hydrogeological condi-

Table 1 Classification and Examples of MAR Technologies

Principal Group	Sub-groups	Examples of projects	Applications
Spreading Methods	Infiltration ponds and basins	The Dan Region Sewage Reclamation Project, Israel (Goren et al. 2015); Atlantis, South Africa (Wright and du Toit, 1996)	Used for enhancing shallow unconfined aquifer recharge, increasing groundwater storage, and mitigating flood risks.
	Soil Aquifer Treatment (SAT)	The Baghmalek aquifer, southwest Iran (Kalantari et al. 2010); Dan region, Israel (Kanarek and Michail, 1996)	
	Controlled flooding	The Kuiseb River, Namibia (Morin et al. 2009); Kal-e-Shoor Rive, Iran (GHEZEL-SOFLOO)	
	Surplus irrigation	The Kothapally watershed, India (Sishodia et al. 2018)	
Well, Shaft, and Borehole Recharge	Open wells	The Wala Reservoir, Jordan (Xanke et al. 2021)	Directly recharges deep or clay-covered unconfined aquifers and confined aquifers, enhancing water availability.
	Shafts	The Arani River basin, India (Raicy and Elango, 2020); Recharge shafts project in the Village Anchalgao, India (Aher et al. 2015)	
	ASR	The Wadi Watir Delta, Egypt (Sallam, 2019); The Liwa Strategic Water Storage and Recovery (SWSR) Project, Abu Dhabi Emirate (Stuyfzand et al. 2017); The Merk River watershed in the Sirik region, Iran (Niazi et al. 2014);	
	Aquifer Storage, Transport, and Recovery (ASTR)	A pilot plant in the Samrak Park in the Nakdong River delta, Korea (Ji and Lee, 2022)	
In-Channel Modifications	Check dams	Check Dams in Chennai, India (Renganayaki and Elango, 2014)	Increases water storage and recharge potential in riverbeds and adjacent aquifers.
	Percolation ponds	The Cuddalore groundwater basin, India (Abraham and Mohan, 2019)	
	Subsurface barriers	The Kalangi River, Andhra Pradesh (Raju et al. 2013); The Shahrekord aquifer, Iran (Fakharinia et al. 2012)	
Induced Bank Infiltration	Riverbank filtration	The holy Ganga River, India (Essl et al. 2014)	Uses natural filtration processes along riverbanks to improve water quality and increase aquifer recharge.
	Dune filtration	The Damour River, Lebanon (Stuyfzand, 2023)	
Run-off/Rainwater Harvesting (RWH)	Urban surface runoff collection	The Gaza Coastal Aquifer, Palestine (Eshtawi et al. 2016)	Captures and uses urban runoff for groundwater recharge, reducing flood risk and improving water sustainability.
	Direct aquifer recharge	The Dharta watershed, India (Soni et al. 2020)	

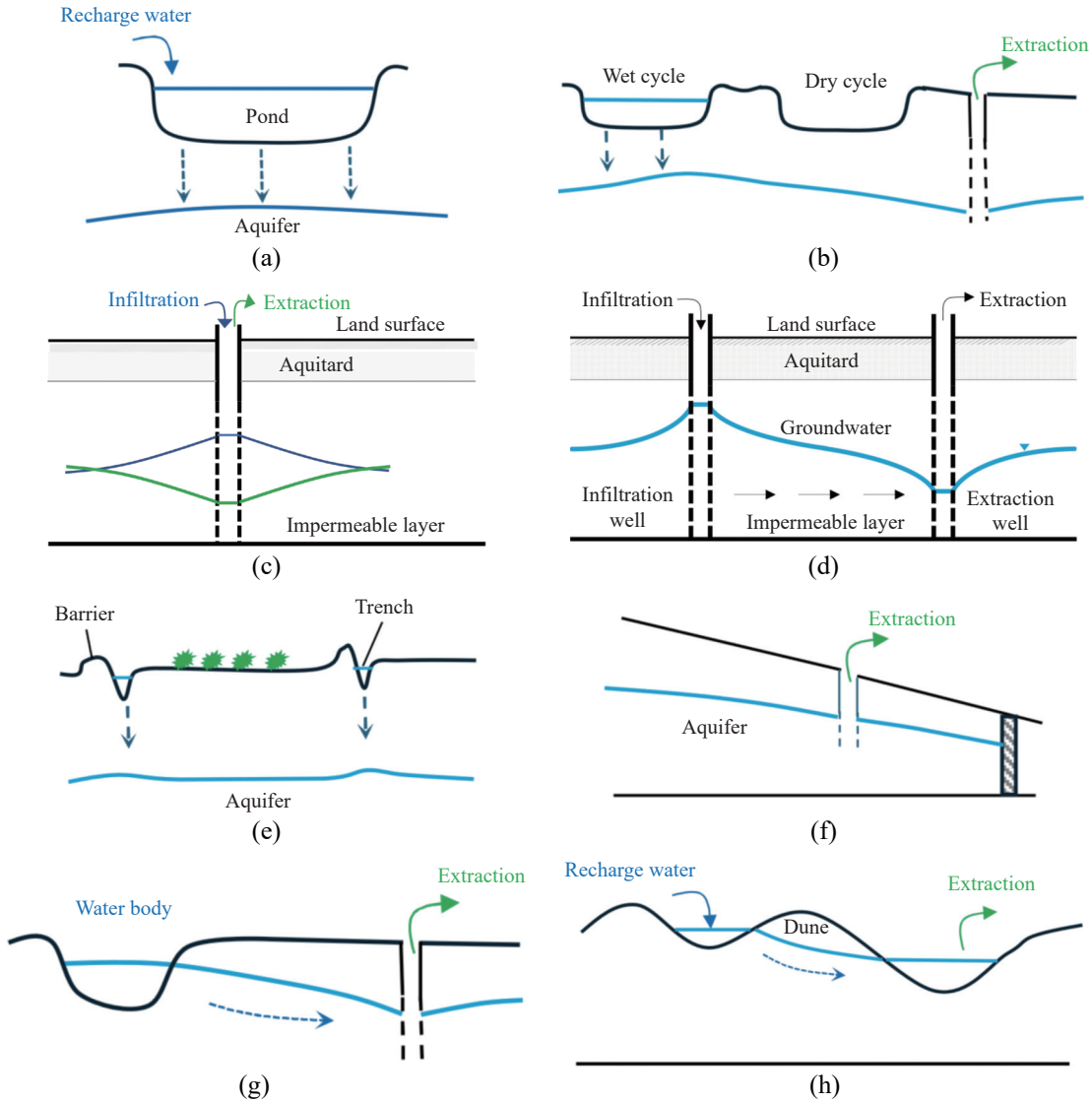

Fig. 1 Schematic illustration of various MAR techniques. (a) Infiltration ponds, (b) Soil aquifer treatment, (c) ASR, (d) ASTR, (e) Surplus irrigation, (f) Subsurface barriers, (g) Riverbank filtration (induced by groundwater extraction), (h) Dune filtration

tions, water availability, recharge objectives, and regulatory constraints. For example, infiltration ponds may range from small experimental setups spanning a few hundred square meters to large recharge basins covering several hectares. Similarly, ASR systems typically utilize deep wells, with depths ranging from tens to hundreds of meters, depending on the aquifer storage capacity and recharge requirements. Riverbank filtration systems, on the other hand, are generally located within a few hundred meters of riverbanks, with well depths tailored to aquifer characteristics.

2 Criteria for MAR success

This section introduces the key criteria used to assess the success or failure of MAR projects. These criteria are derived from established principles and widely accepted guidelines for the implementation of MAR and are summarized in Table 2. Although these criteria provide a robust foundation for evaluating MAR performance, it is essential to recognize that individual projects may require additional considerations or adaptations based on site-specific objectives, hydrogeological conditions, environmental constraints, and community needs. Therefore, the application of these criteria should remain flexible, allowing for adjustments to address the unique design parameters and goals of each MAR project. It is also important to recognize that MAR success or failure is not an absolute measure but rather exists along on a spectrum, influenced by varying degrees of success and occasional setbacks. Furthermore, MAR outcomes are dynamic, evolving over time in response to

Table 2 Summary of Criteria and Measures for Assessing MAR Success

Criteria	Quantitative measures	Expected outcome	Potential challenges
Groundwater Recharge	Rate of recharge [L/T], volume of infiltrated water [L^3], groundwater balance [L^3], net groundwater depletion [L^3].	To enhance groundwater recharge rates, aiming for a positive groundwater balance that contributes to reducing or reversing net groundwater depletion.	Insufficient recharge rates that fail to offset ongoing aquifer depletion under continuous or specific circumstances like significant climatic variations.
Groundwater Level	Depth to groundwater table [L], rate of level change [L/T].	To stabilize or raise groundwater levels, thereby reducing long-term stress on the aquifer	Failure to halt declines in groundwater levels, leads to potential aquifer stress and depletion. Excessively raising groundwater levels damages infrastructure and disrupts natural surface water-groundwater interactions.
Groundwater Flow	Velocity [L/T] and patterns [-] of flow, directional changes [-].	To maintain or intentionally alter groundwater flow patterns. Goals include averting significant and unpredictable shifts in groundwater flows on a regional level and devising induced flow patterns to combat seawater intrusion, prevent contamination, and improve groundwater availability.	Unpredictability or variability of groundwater flow patterns, might lead to undesirable flow paths that facilitate contamination spread or negatively impact water accessibility. Inadvertent changes in flow could disturb local ecosystems, affect groundwater recharge, or intensify problems such as seawater intrusion.
Groundwater Quality	Contaminant levels [M/L^3], biogeochemical indicators [- or M/L^3].	Enhance the overall quality of groundwater or, at the very least, maintain the current quality standards.	Degradation of groundwater quality and adverse effects on the quality of nearby surface waters
Clogging	Efficiency of wells [or%], rate of flow reduction [L^3/T], frequency of maintenance interventions [1/T]	Sustained the recharge performance with minimal intervention, ensuring long-term recharge efficiency	Accelerated clogging due to organic matter, mineral precipitation, or microbial growth, leads to reduced recharge rates and/or increased maintenance costs.
Surface Water Flow	Rates of streamflow [L^3/T], changes in water levels [L]	More uniform surface water flow rates by augmenting the consistency of base flow contributions.	Disturbance of ecological balance resulting from modifications in streamflow rates or patterns, including alterations due to seasonal variability.
Sedimentation	Levels of sediment accumulation [L], sediment concentration [M/L^3]	Decrease sediment presence in downstream water bodies	Alterations in sediment flow patterns lead to uneven sediment distribution, localized erosion, and excessive sediment deposition.

external factors such as climate variability, land use changes, and shifting water demand patterns (Faunt et al. 2016; Famiglietti, 2014; Gruetzmacher and Kumar, 2012; Tuinhof et al. 2011). In addition to their intended objectives, MAR projects can sometimes produce unintended negative impacts. These may include disruptions to natural surface flow regimes, leading to reduced river flows and ecological disturbances for species reliant on consistent water availability. Changes in sediment transport patterns can disturb aquatic and riparian habitats, affecting species dependent on specific sedimentation rates for key lifecycle processes. Furthermore, redirection of water flows can cause localized erosion or sediment deposition problems, potentially destabilizing riverbeds and banks, and creating imbalances in aquatic ecosystems. Although these unintended consequences are not part of the planned objectives, they are important considerations when evaluating the overall success and sustainability of MAR initiatives.

2.1 Groundwater recharge

Enhancing groundwater recharge is usually a primary objective of MAR initiatives, aimed at achieving a positive water balance and mitigating groundwater depletion. Quantitative assessments indicate that MAR can significantly increase recharge rates, often surpassing those of natural processes (Salameh et al. 2019; Page et al. 2018). For example, in Al Bih Dam in the UAE facilitated the recharge of approximately 28 Million Cubic Meters (MCM) of rainfall during 2015–2020, increasing aquifer recharge by 49% (Sefelnasr et al. 2022). Similarly, spreading methods applied in the Nile Delta Aquifer, Egypt, boosted recharge by about 50% (Nofal et al. 2019), while the Al-Fulaij Dam in Oman increased recharge rate from 0.4 m/d to 1.8 m/d (Mohamedzein et al. 2016).

MAR also plays a significant role in water

conservation by mitigating losses due to evaporation and transpiration. By channeling surface water into underground aquifers, MAR minimizes exposure to the evaporative forces, key advantage in arid and semi-arid regions, where high temperatures and dry weather accelerate water losses. Furthermore, by replenishing groundwater levels, MAR reduces the reliance on surface storage in reservoirs and dams, which are highly susceptible to evaporation.

The effectiveness of MAR varies across techniques applied and is influenced by site-specific conditions. Even though infiltration basins may recharge more slowly than direct injection methods, they can still substantially surpass natural percolation rates, especially when enhanced with soil amendments or artificial recharge techniques (Kourakos et al. 2019; Dahlke et al. 2018). However, the effectiveness of these methods heavily depends on soil texture and geological structure of the site, underscoring the need for thorough subsurface characterization (Maples et al. 2019; Cabalar and Akbulut, 2016). Selecting an appropriate site is crucial, with ideal locations having soils that facilitate rapid infiltration and substantial water storage while ensuring sufficient residence time for natural pollutant filtration (Alam et al. 2021).

2.2 Groundwater levels

Through deliberate introduction of water into aquifers, MAR seeks to elevate groundwater levels to their optimal state, mitigating water level declines caused by over-extraction or prolonged drought (Wendt et al. 2021; Kourakos et al. 2019). For example, the Al Bih Dam in the UAE facilitated a groundwater levle increase of up to 15 meters (Sefelnasr et al. 2022).

China has implemented large-scale MAR projects to combat groundwater depletion, particularly in urban and agricultural areas. For example, the Beijing Groundwater Recharge Project, designed to counteract severe groundwater overdraft caused by decades of excessive extraction, employes treated wastewater as a recharge source via infiltration basins and recharge wells. Long-term monitoring shows that MAR has increased groundwater levels by up to 1.5 meters per year in critical areas, improving water availability during droughts (He et al. 2021; Liu et al. 2022). Similarly, the Shijiazhuang MAR Project in Hebei Province was developed to address rapid groundwater declines from irrigation and industrial use. Using river water and treated wastewater, this project combines infiltration ponds and recharge wells, which has achieved an increase in groundwater levels of 2–5 meters over five years, significantly mitigating the impact of over-extraction (Lu et al. 2011). Beyond China, MAR has yielded positive results in other regions.in Jordan, the use of a recharge dam in an alluvial aquifer raised water levels by 1.96% to 3.12%, mitigating the adverse effects of climate changes on groundwater supplies (Alelaimat et al. 2023). A study in Wadi Araba, Jordan, identified eight potential MAR locations as viable solutions for improving water availability and climate adaptation (Alelaimat et al. 2023). In India, Raju et al. (2006) observed a 2-meter groundwater level rise downstream of a subsurface dam in the Swarnamukhi river basin, Andhra Pradesh.

Despite the successes of MAR, unintended consequences can arise if projects are not carefully planned and monitored. Excessive recharge can result in waterlogging, which degrades soil structure, reduces aeration, and negatively affects agricultural productivity and plant health. For example, in the Om Laksab-Sidi aquifer in North Africa, a recharge dam using treated wastewater paradoxically led to water level declines of 0.5 m to 10 m, indicating potential waterlogging issues (Hamed et al. 2022). Similarly, in Iran, the Meymand and Tangeriz recharge dams experienced groundwater level reductions due to high lateral recharge rates through vertical sidewall pits, illustrating the complex hydrological responses that can emerge from MAR projects (Mohammadzadeh-Habili and Khalili, 2020). These cases highlight the need for detailed site assessment and continuous monitoring to ensure MAR achieves its intended objectives without depleting groundwater reserves. In contrast, excessive recharge can also lead to infrastructure damage. Rising groundwater levels may compromise underground structure, including building foundations and sewer systems, by causing cracking and settlement (Hurst and Wilkinson, 1986). A notable instance occurred at the Al-Fulaij Recharge Dam in Oman, where over-recharge undermined the dam's foundation. Mohamedzein et al. (2016) attributed this failure to the presence of highly permeable alluvium and conglomerates containing cavities, exacerbated by the dissolution of the gypsum material. Furthermore, an insufficiently deep dam key led to seepage rates approximately twice as high as anticipated. In some areas, rapid groundwater level increases in can also triger saline water intrusion, increasing the risk of freshwater contamination and contributing to surface flooding (Bosserelle et al. 2022).

2.3 Groundwater flow patterns

MAR projects commonly affect groundwater velocity and flow patterns, either continuously or intermittently. For example, the introduction of MAR through recharge dams and ASR systems has been documented to dramatically change the direction and velocity of groundwater flow. Studies by Standen et al. (2020) and Yaraghi et al. (2020) highlight the capacity of MAR to create new hydraulic gradients, fundamentally reshaping local and regional groundwater flow patterns. Although these alterations are often inevitable, the overarching goal is often to avoid drastic regional-scale disruptions that could lead to unintended consequences, such as the alteration of surface-groundwater interactions. However, in certain cases, MAR is intentionally used to modify groundwater flow (Dahlke et al. 2018; Ward and Dillon, 2012). For instance, targeted intervention can redirect water to areas facing water scarcity or away from regiones vulnerable to salinization, contamination, or seawater intrusion (Cruz-Ayala and Megdal, 2020). By strategically manipulating groundwater gradients, MAR enhances the spatial distribution of groundwater resources, ensuring recharge efforts align with local hydrogeological conditions and water demand. Additionally, controlled flow modifications can optimize groundwater movement toward specific recharge zones, improving overall water availability and resource management.

2.4 Groundwater quality

MAR has significant implications for groundwater quality, with both beneficial and potentially adverse effects. On the positive side, MAR can improve water quality by diluting contaminants present in aquifers (Alam et al. 2021; Raicy and Elango, 2020; Moeck et al. 2017; Moeck et al. 2016). However, if the recharge water contains contaminants that are not adequately removed through natural filtration (Regnery et al. 2017), or if the recharge process mobilizes existing contaminants within the aquifer (Fakhreddine et al. 2021), groundwater quality can deteriorate. Chemicals, heavy metals or excess nutrients introduced through MAR can pose risks to both human health and the environment. For example, the use of reclaimed municipal wastewater for MAR requires a thorough evaluation of health and regulatory considerations (Asano and Cotruvo, 2004). Therefore, ensuring the quality of source water, implementing appropriate pretreatment processes, and understanding the geochemical interactions within the recharge site are essential to mitigate these risks and maximize the benefits of MAR for water quality enhancement (Alam et al. 2021).

Research from various countries and across different MAR techniques highlight the significant impact of MAR on water quality. In some cases, MAR has led to water quality deterioration. For example, in the Korba aquifer (Tunisia), a spreading project using poor-quality treated wastewater for recharge resulted in water quality deterioration, evidenced by a boron isotopic composition in recharged water samples that mirrored the signature of wastewater around the spreading basins (Comte and Bachtouli, 2019; Cary et al. 2013). Similarly, in the West Bank (Palestine), analyses of harvested rainwater used for MAR revealed significant contamination with total and fecal coliforms. Total and fecal coliforms were absent in fresh rainwater but were detected respectively in 100% and 86% of the tested harvested rainwater samples (Adbul-Hamid, 2008). Other studies in the West Bank area (Al-Khatib et al. 2019; Anabtawi, 2018) linked some local diseases, such as cancer, to high concentrations of heavy metals in collected rainwater. In Jordan, MAR sites where recharge water was affected by farming activities and human presence exhibited signs of groundwater pollution. A vulnerability assessment of the Wala catchment indicated that almost 96% of the area showed low, while about 4% fell in the range of moderate vulnerability. In contrast, in the Hidan catchment displayed varying degree of vulnerability: 42% low, 50% moderate, 6% high, and 2% extreme (Xanke et al. 2017). in the Tunisia's Grombalia aquifer, direct injection MAR led to changes in groundwater quality, particularly nutrient levels, highlighting the crucial role of hydrogeological and hydrogeochemical assessments in aquifer protection (Kammoun et al. 2018). On the positive side, MAR has been shown to improve groundwater quality in certain cases. In Oman, Bajjali (2012) reported that ASR in the Tanuf, Al Kabir and Ma'awil dams led to a freshwater increase in 19% to 57% of the watershed area, gradually diluting groundwater salinity. Similarly, in Kuwait, ASR resulted in recovered water with reduced Total Dissolved Solids (TDS). AlRukaibi and McKinney (2013) found that the injected water, treated to a TDS level below 500 ppm, yielded recovered water with a TDS of less than 1500 ppm in each well, which improved as the time interval between injection cessation and recovery initiation decreased.

2.5 Clogging

Clogging is a significant challenge in MAR projects, affecting both efficiency and long-term sustainability (Dillon et al. 2022; Zhang et al. 2020; Bouwer, 2002). It occurs when pore spaces in the aquifer or infiltration system become obstructed, reducing water infiltration rates and overall recharge efficiency (Bekele et al. 2018). Clogging arises from various processes: physical clogging results from the accumulation of suspended solids (Lippera et al. 2023; Barry et al. 2017; Hutchison et al. 2013; Martin, 2013); chemical clogging occurs due to the precipitation of minerals (Gruetzmacher and Kumar, 2012); and biological clogging results from the growth of microbial biofilms (Zhiteneva et al. 2023; Esfahani et al. 2020; Eom et al. 2020). These processes can significantly reduce recharge efficiency and overall effectiveness of MAR projects.

Several documented cases illustrate the impact of clogging in MAR projects. A case of physical clogging was observed at Malham Dam in Saudi Arabia, where silt accumulation reached depths of up to 120 cm on the reservoir bed (Stande et al. 2020). Similarly, the Al-Amalih Dam in Saudi Arabia faced challenges with reduced infiltration rates attributed to mud sedimentation, further demonstrating the impact of sediment accumulation on MAR efficiency (Al-Muttair et al. 1994). In the UAE, recent studies revealed that only 7-49% of the water stored in dam ponding areas successfully infiltrates the target aquifer, primarily due to clogging exacerbated by local physiographic conditions and variable precipitation patterns (Sherif and Sturchio, 2021; Sherif and Hussnain, 2017).

Beyond physical clogging, biological clogging has also been observed. In the Atlantis area of South Africa, recovery wells experienced biological clogging due to high levels of iron and sulfate in the groundwater, which facilitated microbial growth (Tredoux and Cain, 2010). Generally, clogging decreases the recharge capacity and can lead to system failure (Jeong et al. 2018). More broadly, research by Du et al. (2014) identified physical clogging as the most common type encountered in MAR projects, categorizing it into surface clogging, inner clogging, and mixed clogging (Rankgomo, 2020).

A large-scale example of clogging management can be found in the Yangtze River Managed Aquifer Recharge Project in Jiangsu Province, China. Designed to address seasonal water shortages and groundwater depletion, the project employs riverbank filtration, recharge wells and infiltration ponds. However, it has faced substantial physical and biological clogging, especially in infiltration basins, where suspended solids and microbial growth markedly reduced recharge efficiency. To combat these challenges, various measures were implemented, including pre-treatment techniques such as sand filtration and sedimentation basins, periodic backflushing of recharge wells, and targeted microbial biofilm control methods. These interventions ultimately improved infiltration rates by 30–50%, emphasizing the necessity of proactive clogging management in sustaining the efficiency of large-scale MAR systems (Zou et al. 2019).

Effective management of MAR systems requires proactive measures to anticipate and mitigate clogging, which often arises from blockages caused by artificial groundwater replenishment. This involves the selection of appropriate pretreatment processes for recharge water (Page et al. 2018; Gruetzmacher and Kumar, 2012; Bouwer, 2002), sediment removal techniques (Gruetzmacher and Kumar, 2012), regular maintenance and monitoring of recharge facilities (Alam et al. 2021), and system design that facilitate easy access and cleaning (Sloan et al. 2023). Pre-treatment methods, such as filtration, sedimentation basins, and chemical treatments help remove suspended solids and prevent mineral precipitation before recharge. Biological clogging can be minimized through disinfection, nutrient reduction, and bacterial control using techniques like UV radiation. For instance, a study at BHP Billiton's Mining Area C outlined measures to combat well-clogging in MAR trials, including targeted screening and injectivity tests (Sloan et al. 2023). Similarly, Cloud Break Iron Ore Mine utilized down-hole valves and a rotation system for bore usage, effectively reducing clogging risks (Windsor et al. 2012). At Cobre Las Cruces Copper Mine, reverse-osmosis treatment effectively prevented clogging, allowing recharge wells to function efficiently with minimal cleaning for over a decade (Sloan et al. 2023). Infiltration basin management, recharge shafts, and optimized well spacing can enhance MAR efficiency by reducing clogging risks. Vymazal (2018) found that using suitable porous filtration materials and maintaining pretreatment units significantly slow clogging process. Additionally, studies by Jeong et al. (2018) and Fernández Escalante, (2015) demonstrate that clogging can be physically removed through brushing or injecting compressed air or water, or chemically treated by injecting strong oxidizing agents such as acids.

Smart monitoring systems, including real-time sensors and machine learning models, play an increasingly vital role in detecting early signs of clogging and enabling proactive management strategies. These technologies help ensure the long-term sustainability of MAR projects by allowing operators to rapidly respond to clogging risks before they compromise recharge efficiency.

2.6 Surface water flow and sedimentation

MAR may have notable impacts on surface flow and sedimentation patterns. By increasing groundwater levels, MAR can lead to changes in groundwater-surface water interactions, potentially increasing base flows in rivers and streams. This enhancement can stabilize surface water ecosystems, support biodiversity, and improve habitat conditions. Furthermore, by altering how water infiltrates the ground, MAR can affect sedimentation rates and patterns. In areas where water is deliberately infiltrated through basins, trenches, or wells, MAR can reduce surface runoff velocity, thereby decreasing sediment transport to water bodies. This reduction in sedimentation can lead to clearer waterways and reduce siltation problems in reservoirs and dams, ultimately enhancing water quality and storage capacity.

Several case studies illustrate these impacts. At Wala Dam in Jordan, MAR reduced sedimentation from 9.3–7.7 Million Cubic Meters (MCM) due to increased dam capacity, reducing the need for sediment removal techniques such as dredging (Xanke et al. 2021). Similarly, in Iran, sedimentation control measures at Meymand and Tangeriz recharge dams resulted in the formation of a uniform low-permeability silt layer, significantly impacting both surface flow and sedimentation dynamics (Mohammadzadeh-Habili and Khalili, 2020). In Oman, strategies at the Al-Khoud Dam involved surface scraping used to combat sediment accumulation, which improved storage capacity and infiltration rates but also reduced dam capacity by 3.7 MCM (Al-Saqri et al. 2016). These cases highlighthow MAR can both mitigate sedimentation challenges and reshape local hydrological conditions.

However, these interventions can also have unintended consequences. Altering natural surface flow regimes may reduce river flows, affecting water dependent ecosystems. Changes in sediment transport can disrupt aquatic and riparian habitats, particularly for species reliant on specific sedimentation rates for lifecycle processes. Additionally, localized erosion or sediment deposition problems can arise due to water redirection, leading to imbalances that may affect riverbeds and banks and aquatic ecosystems. These potential negative impacts highlight the need for careful planning, implementation and monitoring of MAR projects to ensure that groundwater recharge benefits do not come at the expense of surface water ecosystems and sedimentation balance.

3 Factors affecting MAR performance

In Section 3, I explored the criteria and measures used to assess the success and failure of MAR projects, establishing a foundation for evaluating their outcomes However, a pivotal question remains: What distinguishes successful MAR projects from unsuccessful ones based onthese criteria?

To address this, this section analyzes the key factors that influence MAR performance, linking them to the criteria discussed early. Through a review of the literature, I have identified five key factors that profoundly influence MAR efficiency and long-term sustainability, as outlined in Table 3. These factors shape various aspects of MAR operations, from water absorption capacities to sustainable aquifer management, ultimately determining the feasibility and effectiveness of recharge efforts.

Real-world MAR projects further illustrate how

Table 3 Summary of Factors Influencing MAR Performance

Factors	Quantitative measures	Expected range/conditions	Potential problems
Aquifer transmissivity	Transmissivity [L^2/T]	High transmissivity for efficient recharge	Low transmissivity leads to slow recharge rates
Vertical permeability	Permeability [L/T]	Adequate vertical permeability	Insufficient vertical permeability hindering recharge
Water availability for recharge	Volume of Water [L^3]	Sufficient water availability for recharge	Limited water availability leads to low recharge
Recharge water quality	Contaminant concentration [M/L^3]	High-quality recharge water	Poor water quality compromising recharge efficacy
Aquifer thickness, geometry, boundary	Thickness [L], geometry [-], boundary condition [-]	Optimal aquifer characteristics for recharge	Inadequate aquifer properties impeding recharge

these factors interact and influence outcomes. For example, in the Al-Ahsa Oasis MAR Project in Saudi Arabia, early challenges with clogging due to water quality issues led to improvements in water quality monitoring and pre-treatment processes, significantly enhancing recharge efficiency (Aly et al. 2013). Similarly, the Gafsa MAR Project in Tunisia addressed high salinity concerns by implementing stricter water quality standards and localized hydrogeological studies to optimize recharge site selection (Ferchichi et al. 2018). In Marrakech, Morocco, MAR Projects initially struggled with poorly located recharge wells but overcame these challenges by employing advanced hydrogeological surveys and improved water treatment systems (Ait Brahim et al. 2017). These cases underscore the interconnected nature of MAR performance factors and demonstrate how the lessons from past challenges can guide future improvements in MAR design, implementation, and management.

To further illustrate these relationships, Fig. 2 illustrates the conceptual relationships between MAR factors and criteria through a Sankey diagram, where the width of each band represents the strength of a factor's impact on a given criterion. The diagram visually maps these influences, using color-coded factors to depict their significance in determining MAR success. By integrating these real-world insights, this section bridges the gap between theoretical frameworks and practical experiences, providing a comprehensive perspective on how critical factors collectively shape the success and sustainability of MAR initiatives.

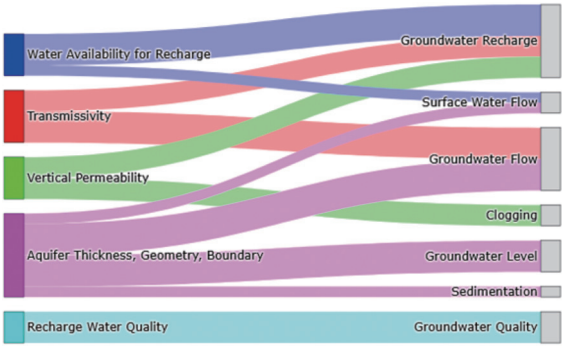

Fig. 2 The conceptual relationships between MAR factors and criteria through a Sankey diagram. The factors are positioned on the left, flowing towards the criteria on the right, visually depicting how each factor contributes to affects various criteria

3.1 Aquifer transmissivity

Transmissivity, a measure of how much water can move through an aquifer horizontally (Garba et al. 2018), is a critical factor in determining the success of MAR projects. It directly influences the capacity of an aquifer to accept, store and transmit injected or infiltrated water efficiently (Dhakate, 2020). For a MAR project to be successful, the aquifer must have appropriate transmissivity levels, typically from 100 m^2/d to 10,000 m^2/d. The exact value is dependent on the specific requirements and objectives of the project (Smith et al. 2018). If transmissivity is below this range, the aquifer may struggle to absorb and distribute recharged water effectively, leading to inefficiencies in water storage and potential over-saturation near the injection point (Perzan et al. 2023). Conversely, if transmissivity exceeds this preferred range, the aquifer may accept large volumes of water rapidly but could also lead to water dispersion away from the recharge zone, reducing the effectiveness of water storage and retrieval (Dillon et al. 2019).

Real-world examples highlight the challenges posed by transmissivity variations. In a Californian ASR project, Smith et al. (2018) found that low transmissivity resulted in aquifer over-saturation which restricted lateral water spread and reduced the efficiency of the recharge and recovery processes. This case emphasized the importance of thorough site characterization and hydrogeological assessments to optimize MAR outcomes. On the other hand, a study in Australia revealed that transmissivity levels exceeding the optimal range led to difficulties in managing the rapid spread of injected water, which compromised both water storage and retrieval efficiency.

To ensure an aquifer has sufficient transmissivity for MAR site selection, various methods are employed, including pumping tests (Utom et al. 2012; Butler, 1990; Sánchez, 1996), tracer tests (Oborie and Udom, 2014) and geophysical investigations (Parker et al. 2022). However, even with initial evaluations, several factors can still pose challenges to the success of MAR projects. The heterogeneity of an aquifer, along with the presence of fractures and conduits, can significantly affect the predictability and uniformity of water movement within the system. One such example occurred at the Al-Khoud dam MAR project in Oman, where infiltration ponds were used in an arid environment. Here, the variability in soil types and permeability across different layers significantly affected the recharge efficiency. Some areas experienced rapid water absorption, while others saw a decrease in permeability due to the movement of silt carried by the infiltrating water into the

coarser original alluvium (Al-Ismaily et al. 2015). This underscores the impact of heterogeneity on the effectiveness of MAR initiatives.

Fractures and conduits, on the other hand, can create pathways that allow water to move too quickly through the aquifer, bypassing intended storage zones. This can lead to the loss of recharged water to unintended areas (Maples et al. 2019; Holländer et al. 2009). A notable example is seen in ASR projects in the Karst regions of southeastern Europe, where extensive underground channels and fractures allowed injected water to travel significant distances from the recharge site. This not only reduced the efficiency of water recovery but also raised concerns about the potential contamination of distant water bodies. These examples highlight the need for detailed geological mapping and the development of predictive models to understand water movement in fractured aquifers. Such efforts are essential for ensuring that MAR initiatives enhance groundwater supplies while minimizing unintended environmental impacts.

3.2 Vertical permeability

The impact of vertical permeability on the performance of the MAR project varies depending on the techniques used. Infiltration basins rely on high vertical permeability in the unsaturated zone to facilitate effective water percolation from the surface to the aquifer (Standen et al. 2020). An optimal range of vertical permeability for infiltration basins is typically between 10^{-5} m/s and 10 m/s, ensuring efficient water infiltration (Masciopinto, 2013). Lower values can lead to surface pooling and runoff, reducing recharge efficiency and potentially causing erosion or localized flooding. For example, Su (2013) conducted an in-situ infiltration test on a reclaimed abandoned riverbed in Shijiazhuang City, China, which helped inform a tailored artificial recharge strategy. Furthermore, Yasa (2020) demonstrated the potential of infiltration wells to mitigate flooding by effectively reducing surface runoff. These cases highlight the importance of considering vertical permeability, among other factor, in the planning and execution of MAR projects.

For ASR systems, which primarily engage the saturated zone, vertical permeability is crucial for the injection, movement, and storage of water. The ideal vertical permeability range for ASR wells is typically between 10^{-4} m/s and 10^{-2} m/s. Excessively high vertical permeability might lead to rapid vertical dispersion of water, complicating recovery efforts, while low permeability may hinder the injection process, reduce recharge volumes, and can lead to clogging and higher maintenance costs (Masciopinto, 2013). These issues have been reported in several ASR studies examining across different regions (Smith et al. 2018).

The success of rainwater harvesting projects is closely related to the vertical permeability of the unsaturated zone, which should support rapid infiltration to prevent surface runoff during intense rainfall (Markovič and Vranayova, 2015). An ideal vertical permeability range is typically between 10^{-5} and 10 m/s (Sanford, 2017; Masciopinto, 2013). Insufficient vertical permeability can hinder the efficient infiltration of collected rainwater, leading to waste and reduce recharge capabilities. A case in point is Taking Murwani Dam, built in 2011 within the Wadi Khulays basin in western Saudi Arabia, aimed at capturing and storing stormwater (Lemaire, 2009). However, the dam's ability to recharge the Wadi channel into the underlying alluvial aquifer is limited. This limitation stems from several factors, including the swift onset of flood events, water losses due to evaporation and transpiration from the vadose zone, and the aquifer's heterogeneity, notably its low vertical hydraulic conductivity (Missimer et al. 2014). These challenges underscore the complex dynamics involved in managing stormwater recharge in arid regions.

Floodwater spreading benefits from high vertical permeability in both the unsaturated and saturated zones to manage large-scale recharge effectively during flood events (Smith and Jones, 2018). The desired vertical permeability ranges could vary depending on the project's goals but generally fall within 10^{-5} m/s to 10^{-3} m/s for unsaturated zones (Brown et al. 2010) and 10^{-4} m/s to 10^{-2} m/s for saturated zones (Garcia et al. 2020). Unsuitable permeability can result in inadequate recharge, flooding, or unintended rapid water movement away from the recharge area (Johnson et al. 2022).

Efficient transfer of water into the aquifer through bank filtration also requires adequate vertical permeability along riverbanks and adjacent saturated zones. Although primarily influenced by horizontal movement, suitable vertical permeability, possibly in the range of 10^{-4} m/s to 10^{-3} m/s (Jones and Smith 2018), ensures that water can infiltrate through riverbank materials into the aquifer. Too low vertical permeability could restrict water movement, reducing the effective-

ness of bank filtration and potentially leading to riverbank saturation or erosion (Garcia et al. 2020). This issue has been reported in several bank filtration projects across various regions (Patel and Nguyen, 2021; Brown et al. 2020).

3.3 Water availability for recharge

Accurate assessment of water availability is critical for the success of MAR projects, as these initiatives rely on precise estimates of both the quantity and the quality of water that can be sustainably recharged (White and Howe, 2004). Overestimating water availability can lead to the development of MAR systems that are too large or ambitious, resulting in inefficient use of resources, potential depletion of water sources, and ecological damage due to excessive water extraction (Parish et al. 2012). In contrast, underestimating water availability can result in underutilization of MAR facilities, missed opportunities to improve water security, and insufficient mitigation of water scarcity (Amarasinghe and Smakhtin, 2014). Miscalculations often arise from several factors, including inadequate assessment of hydrological cycles (White and Howe, 2004), changes in land use or climate patterns that affect water recharge and runoff (Nasonova et al. 2011), unforeseen increases in water demand (Sordo-Ward et al. 2016), and the variability in water yield due to seasonal fluctuations or extreme weather events (Gober et al. 2010). Accurate prediction of water availability is further complicated by the dynamics of surface-water-groundwater interactions (Haque et al. 2021; Rassam et al. 2013).

An illustrative example of the implications of recharge volume miscalculation occurred in a MAR project in the semi-arid region of Jordan, where an aquifer recharge scheme based on floodwater capture was established. Initial assessments overestimated the average annual floodwater volume due to insufficient analysis of long-term hydrological data and the failure to account for increased upstream water use. As a result, the MAR system was designed to handle water volumes that rarely occurred, leading to substantial underutilization of the recharge infrastructure. Additionally, the oversized infrastructure strained financial resources that could have been better allocated elsewhere. During years with minimal flooding, the overreliance on expected recharge volumes exacerbated local water scarcity, as alternative water sources were not adequately developed in anticipation of the MAR system's contribution.

3.4 Recharge water quality

Recharge water quality is a key factor in MAR projects. Regulations typically mandate that water introduced into aquifers through MAR must meet or exceed the quality of the receiving groundwater to avoid contamination and ensure the sustainability of the water source (Waterhouse et al. 2017). In many cases, water considered to be clean is directed to injection wellfields or infiltration structures without the need for pre-treatment (Regnery et al. 2017). However, when the recharge water is contaminated, treatment becomes necessary, contingent upon the quality standards set by relevant regulatory authorities (Alam et al. 2021). Water treatment can represents a significant financial burden, as it is often one of the costliest components of MAR projects (Ross and Hasnain, 2018). Although hydrogeological assessments can sometimes argue against the need for treatment, citing the natural dilution capabilities of the subsurface (Maliva, 2014), the reality of meeting quality requirements can significantly affect the feasibility and implementation of MAR initiatives.

3.5 Aquifer thickness, geometry, and boundary conditions

The thickness, geometry and boundary conditions of the aquifer play crucial roles in determining the performance of MAR projects, particularly in terms of water storage capacity and the potential for water loss from the system (Nicolas et al. 2019; Milanović et al. 2015). The thickness of an aquifer directly influences its storage capacity, with thicker aquifers typically offering greater volumes for water storage, thus facilitating larger recharge and extraction operations. Moreover, increased aquifer thickness not only enhances resource availability but also enables the installation of longer well screens (Abd-Elmaboud et al. 2024; Vouillamoz et al. 2015). The geometry of an aquifer, including its shape and spatial orientation, can affect how water is distributed within the system and its recharge or extraction efficiently (Yoshitaka and Makoto, 2021; Nury et al. 2009; Shahbazi et al. 1968). Complex or irregular geometries can lead to uneven recharge rates, posing challenges for water management (Behroozmand et al. 2017). Furthermore, aquifer boundary conditions, such as confining layers or hydrological connections to rivers or seas, significantly influence the potential for water to remain within the system or escape (Qian et al. 2020; Cau et al. 2002). Aquifers

with permeable boundaries may experience water loss through lateral flow, reducing the effectiveness of recharge efforts and potentially leading to contamination of adjacent water bodies (Jasechko et al. 2021; Nicolas et al. 2019). In contrast, aquifers with impermeable boundaries or well-designed artificial barriers are better equipped to retain recharged water, thereby improving MAR efficiency (De Giglio et al. 2018). Understanding these characteristics is essential for designing MAR projects that optimize water storage and minimize water loss, ensuring sustainable management of groundwater resources.

4 Future of managed aquifer recharge

Building on the key criteria for the success of MAR and the factors influencing the performance of MAR, this section explores actionable strategies within scientific research aimed at enhancing the success of future MAR projects. These strategies encompass advanced methodologies, innovative technologies, and integrated management practices that can effectively address the challenges posed by aquifer characteristics, climate variability, and water resource constraints. The overarching goal is to develop practical, sustainable solutions that optimize MAR efficiency while ensuring the resilience of groundwater systems amid increasing water scarcity and climate change.

4.1 Climate change adaptation

As climate change intensifies, adaptation strategies are becoming essential to the long-term success of MAR initiatives (Magnan et al. 2020). Arid and semi-arid regions are particularly vulnerable to rising temperatures, shifting precipitation patterns, and the increasing frequency and severity of droughts (Hu et al. 2023; Soares et al. 2021; Moreira et al. 2020). One of the most pressing concerns is the transition from snow to rain-dominated precipitation regimes, which leads to reduced snowpack and diminished water availability during peak demand periods in the dry season (Soomro et al. 2024; Asif et al. 2023; Alam et al. 2019). Failure to account for these climatic shifts can compromise aquifer management, reduce MAR effectiveness, and exacerbate water scarcity, particularly in already water-stressed regions (Kohlitz et al. 2024; Mukuhlani, 2023). Incorporating climate adaptation into MAR initiatives involves several strategic actions, including:

1) Employing regional climate change projection models to improve forecasts of precipitation and temperature fluctuations relevant to the MAR location (Christensen et al. 2020; Araya-Osses et al. 2020).

2) Utilizing advanced hydrological models to simulate the impact of varying climate scenarios on groundwater recharge processes is essential (Ngo et al. 2024). This helps in understanding how changes in precipitation and temperature may affect groundwater levels and recharge rates (Nourani et al. 2023; Epting et al. 2021).

3) Conducting sensitivity and risk assessments to gauge MAR systems' vulnerability to hydrological variability is vital. These assessments inform the development of contingency plans and adaptive measures, enhancing the resilience of MAR projects to unforeseen climatic shifts (Ajjur and Al-Ghamdi, 2022; Maliva, 2021).

4) Designing resilient MAR systems to withstand extreme weather events, including prolonged droughts and intense flooding (Pietersen, 2021). This includes identifying alternative sources for recharge during drought periods (Scanlon et al. 2023). Effective stormwater management requires facilities for rapid stormwater capture, conveyance, and pre-treatment to meet water quality standards before recharge (Noori and Singh, 2023; Hernández-Hernández et al. 2020).

5) For coastal MAR projects, planning for sea level rise is imperative to prevent saltwater intrusion into freshwater aquifers. Potential adaptation strategies include constructing physical barriers, optimizing recharge site placement, and developing aquifer replenishment techniques that counteract seawater encroachment (Stein et al. 2022; Logan, 2020).

4.2 Adaptive management

Adaptive management of MAR is paramount for long-term success of MAR projects, given the uncertainties posed by climate change and evolving socio-economic conditions, such as changes in land use (Subramanian et al. 2023; Wolka et al. 2023). This approach follows a systematic, iterative process that continuously refines MAR operations by learning from real-world outcomes, monitoring groundwater systems and assessing their interactions with ecosystems (Saccò et al. 2024; Huggins et al. 2023). Effective adaptive management involves several key components:

1) Flexible Infrastructure Design: Constructing MAR infrastructure with built-in adaptability to

accommodate fluctuating water availability and environmental conditions. This encompasses the use of adjustable structures such as weirs, gates, and modular recharge basins that can be dynamically altered to optimize recharge efficiency under varying hydrological scenarios (Alelaimat et al. 2023; Sikka et al. 2021).

2) Integrated Monitoring and Assessment: Establishing a comprehensive monitoring framework to track groundwater levels, water quality, and ecosystem responses in real time. Leveraging advanced technologies for data collection and analysis enhances decision-making, ensuring that MAR systems remain responsive to changing environmental conditions (Shaikh and Birajdar, 2024b; Ataei et al. 2024).

3) Iterative Decision-Making Process: Implementing a cyclical management approach that includes planning, execution, continuous monitoring, and evaluation. Refining MAR strategies based on empirical data ensures that management practices remain agile, evidence-based, and aligned with evolving environmental and and operational requirements (Rao et al. 2024).

4.3 Emerging technologies in MAR

Recent advancements in in MAR technologies have significantly enhanced water security, improved recharge efficiency, and increased adaptability to changing environmental conditions (Sabale et al. 2023). These advancements address key challenges such as climate variability, urbanization, and sustainability by optimizing recharge methods and integrating cutting-edge technologies (Mohammad-Hosseinpour and Molina, 2022). Some notable advancements include:

1) *Enhanced Infiltration Techniques*: The development of soil amendment practices and infiltration systems has improved the permeability of recharge areas (Snoussi et al. 2024; Mohammadzadeh-Habili and Khalili, 2020). This includes biochar amendment (Chen et al. 2023), the use of surfactants (Tiwari and Tripathy, 2023), and engineered soils designed to accelerate infiltration and minimize clogging (Poozan et al. 2024).

2) *Nature-Based Solutions* (*NBS*) *for MAR*: Incorporating NBS into MAR projects enhances recharge while providing ecological benefits. Examples include the restoration of wetlands and floodplains, which naturally increase groundwater recharge while supporting biodiversity (Szabó et al. 2023).

3) *Smart MAR Systems*: Leveraging Internet of Things (IoT) devices, real-time data analytics, and machine learning algorithms is transforming MAR operations (Senthilkumar et al. 2024). Automated recharge systems optimize water injection and extraction based on real-time monitoring of groundwater level and quality data, improving efficiency and resource management (Jones and Smith, 2018).

4) *Urban MAR*: Adapting MAR techniques for urban environments helps manage stormwater and reduce urban flooding. Innovative approaches include permeable pavements, urban recharge basins, and green infrastructure that facilitate rainwater infiltration and groundwater recharge (Johnson et al. 2022).

5) *Agricultural managed aquifer recharge* (*Ag-MAR*): Ag-MAR is gaining recognition as a sustainable groundwater management strategy, leveraging surplus irrigation water or seasonal runoff for recharge. While promising, further research is needed to address knowledge gaps and assess tradeoffs (Levintal et al. 2023).

6) *Advanced ASR Technologies*: Innovations in ASR focus on improving well designs and pumping strategies to optimize the storage and recovery of water in aquifers (Ma et al. 2024; Ismail and Gaganis, 2023). A notable advancement is the use of horizontal wells, which enhance recharge efficiency by distributing water across different aquifer layers, reducing clogging risks and enabling more effective water extraction (Al-Mudhafar et al. 2023; Stober et al. 2023). Compared to traditional vertical wells, horizontal wells offer improved control over water input and output, better matching demand fluctuations and minimizing aquifer disturbances (Zhang et al. 2024; Zekri et al. 2023).

4.4 Enhancing MAR initiatives with machine learning

Advancements in Machine Learning (ML) and deep neural networks offer significant potential to enhance MAR projects by improving accurate predictions, optimization, and real-time decision-making. These technologies can analyze vast datasets from various sources, including satellite imagery, climate models, soil and water quality sensors, and historical recharge data, to identify patterns and predict future conditions with high accuracy. For example, ML algorithms can predict changes in aquifer levels, water demand, and potential contamination risks, facilitating proactive management strategies (Shaikh and Birajdar, 2024a; Bai and Tahmasebi, 2023; Elzain et al. 2023). Deep neural networks, capable of modeling

complex nonlinear relationships, optimize recharge strategies by determining the most effective timing and locations for water injections, based on precipitation patterns, water availability, and usage trends (Chen et al. 2023; Masroor et al. 2023; Bhattacharyya et al. 2023). Additionally, ML-driven automation improves the efficiency of MAR systems by dynamically controlling gates and pumps in response to real-time data, ensuring optimal recharge rates and minimizing the risk of aquifer overexploitation or contamination. By integrating these cutting-edge technologies, MAR projects can achieve a higher level of adaptability and resilience, making them more effective in addressing the challenges of water scarcity and climate change.

5 Conclusions

This review critically examined the key factors that influence the performance of MAR projects, particularly in arid regions, with the objective of establishing success criteria and identifying key performance indicators. By synthesizing a broad spectrum of literature, we highlighted criticalfactors such as aquifer transmissivity, vertical permeability, water availability for recharge, recharge water quality, and physical characteristics of the aquifer. These factors are closely interlinked with key success criteria, including groundwater recharge rate, groundwater level, flow dynamics, water quality, and issues like clogging, surface water flow, and sedimentation control.

The interdependencies among these factors significantly shape MAR outcomes, often amplifying or mitigating each other's effects. For example, aquifer transmissivity and vertical permeability jointly determine water infiltration efficiency and lateral distribution, while recharge water must be compatible with aquifer properties to prevent mineral precipitation and pore clogging. As illustrated in Fig. 2, the Sankey diagram visually represents these complex relationships, reinforcing the need for integrated approaches in MAR design. Optimizing individual factors in isolation may not be sufficient, highlighting the importance of holistic planning. Looking ahead, MAR initiatives must incorporate advanced methodologies, cutting-edge technologies, and comprehensive management strategies to enhance efficiency and long-term sustainability. As global water scarcity intensifies, particularly in arid and semi-arid regions, the insights provided a roadmap for more resilient and adaptive MAR practices.

Based on the insights from this comprehensive review, specific recommendations for future MAR development are herewith proposed, with intention of promoting more effective and sustainable MAR practices.

First, a systems-based perspective should guide MAR planning, considering interactions among factors such as transmissivity, permeability, and recharge water quality. Conceptual models and Sankey diagrams can help map these interdependencies, ensuring holistic decision-making.

Second, real-time monitoring of recharge rates, water quality, and clogging dynamics should be prioritized to enable timely interventions. In addition, numerical models and machine learning algorithms can optimize recharge strategies by predicting long-term performance under varying conditions.

Third, in arid and semi-arid regions, unconventional recharge techniques such as treated wastewater reuse and stormwater harvesting should be explored. Aquifer storage and recovery (ASR) can further enhance operational flexibility and maximize resource utilization.

Fourth, recharge water should undergo pretreatment to minimize clogging and ensure compatibility with aquifer conditions. Regular monitoring of both recharge water and groundwater quality is essential to mitigate contamination risks and maintain long-term MAR sustainability.

Fifth, MAR systems must be designed to accommodate variability in water availability caused by extreme weather events. Scenario-based modeling can help assess climate impacts on recharge rates and aquifer storage, allowing for proactive adjustments in MAR operation.

Finally, training programs should equip practitioners and policymakers with expertise in cutting-edge MAR technologies. In addition, knowledge-sharing platforms should facilitate the dissemination of best practices and lessons learned from successful MAR project s worldwide.

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References

Adbul-Hamid M. 2008. Rainwater harvesting for domestic uses in tow Palestinian rural areas with emphasis on quality and quantity. Birzeit University.

Abd-Elmaboud ME, Saqr AM, El-Rawy M, et al. 2024. Evaluation of groundwater potential using ANN-based mountain gazelle optimization: a framework to achieve SDGs in East El Oweinat, Egypt. Journal of Hydrology: Regional Studies, 52: 101703.

Abraham M, Mohan S. 2019. Effectiveness of check dam and percolation pond with percolation wells for artificial groundwater recharge using groundwater models. Water Supply, 19(7): 2107–2115. DOI：10.2166/ws.2019.091.

Aher KR, Patil SM, Mane VP. 2015. Recharge trench cum recharge shaft new concept for groundwater recharge for sustainability of source: a case study. International Journal of Current Medical and Applied Sciences, 6(1): 17–21.

Ait Brahim Y, Saidi MEM, Kouraiss K, et al. 2017. Analysis of observed climate trends and high resolution scenarios for the 21st century in Morocco. Jounal of Materials Environmental Science, 8(4): 1375–1384.

Ajjur SB, Baalousha HM. 2021. A review on implementing managed aquifer recharge in the Middle East and North Africa region: Methods, progress and challenges. Water International, 46(4): 578–604. DOI：10.1080/02508060.2021.1889192.

Ajjur SB, Al-Ghamdi SG. 2022. Towards sustainable energy, water and food security in Qatar under climate change and anthropogenic stresses. Energy Reports, 8: 514–518.

Alam S, Borthakur A, Ravi S, et al. 2021. Managed aquifer recharge implementation criteria to achieve water sustainability. Science of the Total Environment, 768: 144992.

Alam S, Gebremichael M, Li RP, et al. 2019. Climate change impacts on groundwater storage in the Central Valley, California. Climatic Change, 157(3): 387–406. DOI：10.1007/s10584-019-02585-5.

Alataway A, El Alfy M. 2019. Rainwater harvesting and artificial groundwater recharge in arid areas: Case study in wadi Al-alb, Saudi Arabia. Journal of Water Resources Planning and Management, 145(1): 05018017. DOI：10.1061/(asce)wr.1943-5452.0001009.

Alelaimat A, Yusoff I, Nizar MK, et al. 2023. Groundwater management in the face of climate change: Enhancing groundwater storage in the alluvium aquifer of Wadi Araba, Jordan, through GIS-based managed aquifer recharge and groundwater MODFLOW. Water Supply, 23(12): 5136–5153. DOI：10.2166/ws.2023.316.

Alhaj M, Mohammed S, Darwish M, et al. 2017. A review of Qatar's water resources, consumption and virtual water trade. Desalination and Water Treatment, 90: 70–85. DOI：10.5004/dwt.2017.21246.

Alidina M Li D, Ouf M, et al. 2014. Role of primary substrate composition and concentration on attenuation of trace organic chemicals in managed aquifer recharge systems. Journal of Environmental Management, 144: 58–66. DOI：10.1016/j.jenvman.2014.04.032.

Al-Mudhafar WJ, Wood DA, Al-Obaidi DA, et al. 2023. Well placement optimization through the triple-completion gas and downhole water sink-assisted gravity drainage (TC-GDWS-AGD) EOR process. Energies, 16(4): 1790. DOI：10.3390/en16041790.

Al-Muttair FF, Sendil U, Al-Turbak AS. 1994. Management of recharge dams in Saudi Arabia. Journal of Water Resources Planning and Management, 120(6): 749–763. DOI：10.1061/(ASCE)0733-9496(1994)120:6(749).

Al-Othman AA. 2011. Enhancing groundwater recharge in arid region-a case study from Central Saudi Arabia. Scientific Research and Essays, 6(13): 2757–2762. DOI：10.5897/SRE11.173.

AlRukaibi D, McKinney DC. 2013. Conceptual designing and numerical simulation of the ASR technique operations-case study Kuwait. World Environmental and Water Resources Congress 2013. Cincinnati, Ohio. American Society of Civil Engineers, 2601–2613. DOI: 10.1061/9780784412947.258.

Al-Ismaily SS, Al-Maktoumi AK, Kacimov AR, et al. 2015. Impact of a recharge dam on the hydropedology of arid zone soils in Oman: anthropogenic formation factor. Journal of Hydrologic Engineering, 20(4): 04014053.

Al-Saqri S, Al-Maktoumi A, Al-Ismaily S, et al. 2016. Hydropedology and soil evolution in explaining the hydrological properties of recharge dams in arid zone environments.

Arabian Journal of Geosciences, 9: 1−12.

Al-Khatib IA, Arafeh GA, Al-Qutob M, et al. 2019. Health risk associated with some trace and some heavy metals content of harvested rainwater in Yatta area, Palestine. Water, 11(2): 238. DOI：10.3390/w11020238.

Aly A, Alomran A, Alwabel M, et al. 2013. Hydrochemical and quality of water resources in Saudi Arabia groundwater: a comparative study of Riyadh and Al-Ahsa Regions. Proceedings of the International Academy of Ecology and Environmental Sciences, 3(1): 42.

Amarasinghe UA, Smakhtin V. 2014. Global water demand projections: past, present and future, 156. IWMI. DOI: 10.5337/2014.212.

Anabtawi F. 2018. Heavy metals in harvested rainwater used for domestic purposes in rural areas: Yatta, Hebron as a case study. Ph. D. thesis.

Araya-Osses D, Casanueva A, Román-Figueroa C, et al. 2020. Climate change projections of temperature and precipitation in Chile based on statistical downscaling. Climate Dynamics, 54: 4309−4330. DOI：10.1007/s00382-020-05231-4.

Asano T, Cotruvo JA. 2004. Groundwater recharge with reclaimed municipal wastewater: Health and regulatory considerations. Water Research, 38(8): 1941−1951. DOI：10.1016/j.watres.2004.01.023.

Asif Z, Chen Z, Sadiq R, et al. 2023. Climate change impacts on water resources and sustainable water management strategies in North America. Water Resources Management, 37(6): 2771−2786. DOI：10.1007/s11269-023-03474-4.

Ataei P, Takhtravan A, Gheibi M, et al. 2024. An intelligent decision support system for groundwater supply management and electromechanical infrastructure controls. Heliyon, 10(3). DOI：10.1016/j.heliyon.2024.e25036.

Bachtouli S, Comte JC. 2019. Regional-scale analysis of the effect of managed aquifer recharge on saltwater intrusion in irrigated coastal aquifers: Long-term groundwater observations and model simulations in NE Tunisia. Journal of Coastal Research, 35(1): 91−109.

Bai T, Tahmasebi P. 2023. Graph neural network for groundwater level forecasting. Journal of Hydrology, 616: 128792. DOI：10.1016/j.jhydrol.2022.128792.

Bailey D, Goonetilleke A, Campbell D. 2003. A new fuzzy multicriteria evaluation method for group site selection in GIS. Journal of Multi-Criteria Decision Analysis, 12(6): 337−347. DOI：10.1002/mcda.365.

Barry KE, Vanderzalm JL, Miotlinski K, et al. 2017. Assessing the impact of recycled water quality and clogging on infiltration rates at a pioneering soil aquifer treatment (SAT) site in Alice Springs, Northern Territory (NT), Australia. Water, 9(3): 179. DOI：10.3390/w9030179.

Bajjali W. 2012. Spatial variability of environmental isotope and chemical content of precipitation in Jordan and evidence of slight change in climate. Applied Water Science, 2: 271−283. DOI：10.1007/s13201-012-0046-1.

Behroozmand AA, Teatini P, Pedersen JB, et al. 2017. Anthropogenic wetlands due to over-irrigation of desert areas: A challenging hydrogeological investigation with extensive geophysical input from TEM and MRS measurements. Hydrology and Earth System Sciences, 21(3): 1527−1545. DOI：10.5194/hess-21-1527-2017.

Bhattacharyya A, Nambiar SM, Ojha R, et al. 2023. Machine Learning and Deep Learning powered satellite communications: Enabling technologies, applications, open challenges, and future research directions. International Journal of Satellite Communications and Networking, 41(6): 539−588. DOI：10.1002/sat.1482.

Bekele E, Page D, Vanderzalm J, et al. 2018. Water recycling via aquifers for sustainable urban water quality management: Current status, challenges and opportunities. Water, 10(4): 457. DOI：10.3390/w10040457.

Bosserelle AL, Morgan LK, Hughes MW. 2022. Groundwater rise and associated flooding in coastal settlements due to sea-level rise: A review of processes and methods. Earth's Future, 10(7): e2021EF002580. DOI：10.1029/2021EF002580.

Bouwer H. 2002. Artificial recharge of groundwater: Hydrogeology and engineering. Hydrogeology Journal, 10(1): 121−142. DOI：10.

1007/s10040-001-0182-4.

Brown K, Clark R, Collins M, et al. 2010. UK Climate Projections Science Report: Climate Change Projections Summary. Exeter, UK: Met Office Hadley Centre.

Brown K, Lopez M, Zhang H. 2020. Performance variability in bank filtration: A review of case studies. Journal of Hydrology, 585: 124774.

Butler Jr, James J. 1990. The role of pumping tests in site characterization: Some theoretical considerations. Groundwater, 28(3): 394−402. DOI：10.1111/j.1745-6584.1990.tb02269.x.

Cabalar AF, Akbulut N. 2016. Evaluation of actual and estimated hydraulic conductivity of sands with different gradation and shape. SpringerPlus, 5(1): 820. DOI：10.1186/s40064-016-2472-2.

Cary L, Casanova J, Gaaloul N, et al. 2013. Combining boron isotopes and carbamazepine to trace sewage in salinized groundwater: A case study in Cap Bon, Tunisia. Applied Geochemistry, 34: 126−139. DOI：10.1016/j.apgeochem.2013.03.004.

Casanova J, Devau N, Pettenati M. 2016. Managed aquifer recharge: An overview of issues and options. Integrated Groundwater Management: Concepts, Approaches and Challenges. Cham: Springer International Publishing: 413−434. DOI: 10.1007/978-3-319-23576-9_16.

Cau P, Lecca G, Putti M, et al. 2002. The influence of a confining layer on saltwater intrusion under surface recharge and groundwater extraction conditions. Developments in Water Science, 47: 493−500. DOI：10.1016/S0167-5648(02)80100-9.

Chen L, Chen ZH, Zhang YB, et al. 2023. Artificial intelligence-based solutions for climate change: A review. Environmental Chemistry Letters, 21(5): 2525−2557. DOI：10.1007/s10311-023-01617-y.

Chen X, Xu XY, Wei YQ, et al. 2023. Constructing the active surface soil layer with ZVI-biochar amendment for simultaneous immobilization of as and Zn in both contaminated soil and groundwater: Continuous versus intermittent infiltration mode. Journal of Hazardous Materials, 445: 130518. DOI：10.1016/j.jhazmat.2022.130518.

Christensen OB, Kjellström E. 2020. Partitioning uncertainty components of mean climate and climate change in a large ensemble of European regional climate model projections. Climate Dynamics, 54(9): 4293−4308. DOI：10.1007/s00382-020-05229-y.

Cruz-Ayala MB, Megdal SB. 2020. An overview of managed aquifer recharge in Mexico and its legal framework. Water, 12(2): 474. DOI：10.3390/w12020474.

Daher W, Pistre S, Kneppers A, et al. 2011. Karst and artificial recharge: Theoretical and practical problems A preliminary approach to artificial recharge assessment. Journal of Hydrology, 408(3-4): 189−202. DOI：10.1016/j.jhydrol.2011.07.017.

Dahlke HE, LaHue GT, Mautner MRL, et al. 2018. Chapter eight managed aquifer recharge as a tool to enhance sustainable groundwater management in California examples from field and modeling studies. Advances in Chemical Pollution, Environmental Management and Protection, 3: 215−275. DOI：10.1016/bs.apmp.2018.07.003.

De Giglio O, Caggiano G, Apollonio F, et al. 2018. The aquifer recharge: An overview of the legislative and planning aspect. Annali Di Igiene, 30(1): 34−43. DOI：10.7416/ai.2018.2193.

Dhakate R. 2020. Distribution of aquifer characteristics in different geomorphologic units in a granitic terrain. Applied Water Science, 10(11): 231. DOI：10.1007/s13201-020-01313-0.

Dillon P. 2005. Future management of aquifer recharge. Hydrogeology Journal, 13(1): 313−316. DOI：10.1007/s10040-004-0413-6.

Dillon P, Pavelic P, Page D, et al. 2009. Managed aquifer recharge. DOI: 10.2166/wst.2010.444

Dillon P, Arshad M. 2016. Managed aquifer recharge in integrated water resource management. Integrated Groundwater Management: Concepts, Approaches and Challenges. Cham: Springer International Publishing: 435−452. DOI: 10.1007/978-3-319-23576-9_17.

Dillon P, Stuyfzand P, Grischek T, et al. 2019. Sixty years of global progress in managed aquifer recharge. Hydrogeology Journal, 27(1): 1−30. DOI：10.1007/s10040-018-1841-z.

Dillon P, Alley W, Zheng Y, et al. 2022. Managed

aquifer recharge: Overview and governance. IAH Special Publication: 90.

Du XQ, Fang YQ, Wang ZJ, et al. 2014. The prediction methods for potential suspended solids clogging types during managed aquifer recharge. Water, 6(4): 961−975. DOI：10.3390/w6040961.

Eftekhari M, Khashei-Siuki A. 2025. Evaluating machine learning methods for predicting groundwater fluctuations using GRACE satellite in arid and semi-arid regions. Journal of Groundwater Science and Engineering, 13(1): 5−21. DOI：10.26599/JGSE.2025.9280035.

Elzain HE, Chung SY, Venkatramanan S, et al. 2023. Novel machine learning algorithms to predict the groundwater vulnerability index to nitrate pollution at two levels of modeling. Chemosphere, 314: 137671. DOI：10.1016/j.chemosphere.2022.137671.

Eom H, Flimban S, Gurung A, et al. 2020. Impact of carbon and nitrogen on bioclogging in a sand grain managed aquifer recharge (MAR). Environmental Engineering Research, 25(6): 841−846. DOI：10.4491/eer.2019.373.

Epting J, Michel A, Affolter A, et al. 2021. Climate change effects on groundwater recharge and temperatures in Swiss alluvial aquifers. Journal of Hydrology X, 11: 100071. DOI：10.1016/j.hydroa.2020.100071.

Esfahani RA, Batelaan O, Hutson JL, et al. 2020. Combined physical, chemical and biological clogging of managed aquifer recharge and the effect of biofilm on virus transport behavior: A column study. Journal of Water Process Engineering, 33: 101115. DOI：10.1016/j.jwpe.2019.101115.

Eshtawi T, Evers M, Tischbein B. 2016. Quantifying the impact of urban area expansion on groundwater recharge and surface runoff. Hydrological Sciences Journal, 61(5): 826−843. DOI：10.1080/02626667.2014.1000916.

Essl L, Starkl M, Kimothi PC, et al. 2014. Riverbank filtration and managed aquifer recharge as alternative water supply technologies for India: Strengths–weaknesses–opportunities–threats analysis. Water Supply, 14(4): 690−697. DOI：10.2166/ws.2014.026.

Fakharinia M, Lalehzari R, Yaghoobzadeh M. 2012. The use of subsurface barriers in the sustainable management of groundwater resources. World Applied Sciences Journal, 19(11): 1585−1590. DOI：10.5829/idosi.wasj.2012.19.11.2365.

Fakhreddine S, Prommer H, Scanlon BR, et al. 2021. Mobilization of arsenic and other naturally occurring contaminants during managed aquifer recharge: A critical review. Environmental Science & Technology, 55(4): 2208−2223. DOI：10.1021/acs.est.0c07492.

Fallatah OA, Ahmed M, Cardace D, et al. 2019. Assessment of modern recharge to arid region aquifers using an integrated geophysical, geochemical, and remote sensing approach. Journal of Hydrology, 569: 600−611. DOI：10.1016/j.jhydrol.2018.09.061.

Famiglietti JS. 2014. The global groundwater crisis. Nature Climate Change, 4(11): 945−948. DOI：10.1038/nclimate2425.

Ferchichi H, Ben Hamouda MF, Farhat B, et al. 2018. Assessment of groundwater salinity using GIS and multivariate statistics in a coastal Mediterranean aquifer. International Journal of Environmental Science and Technology, 15: 2473−2492.

Fernández Escalante E. 2015. Practical management to minimize the effects of clogging in managed aquifer recharge wells at two sites in the Guadiana basin, Spain. Journal of Hydrologic Engineering, 20(3): B5014002. DOI：10.1061/(asce)he.1943-5584.0001047.

Faunt CC, Sneed M, Traum J, et al. 2016. Water availability and land subsidence in the central valley, California, USA. Hydrogeology Journal, 24(3): 675−684. DOI：10.1007/s10040-015-1339-x.

Gale IN. 2006. Managed aquifer recharge: Lessons learned from the agrar study. India. UNESCO G-WADI meeting on Water Harvesting, Syria.

Garba H, Norman S, Bayang F. 2018. Modelling the transmissivity of an aquifer using laboratory tests and vertical electrical sounding in Igabi Lga Kaduna State. International Journal of Science and Research.

Garcia M, Lee D, Chen Y. 2020. Permeability characterization in saturated subsurface environments. Environmental Geotechnics, 7(2): 120−133. DOI：10.1680/jenge.19.00025.

Gober P, Kirkwood CW, Balling RC Jr, et al.

2010. Water planning under climatic uncertainty in phoenix: Why we need a new paradigm. Annals of the Association of American Geographers, 100(2): 356−372. DOI：10.1080/00045601003595420.

Goren L, Castelltort S, Klinger Y. 2015. Modes and rates of horizontal deformation from rotated river basins: Application to the Dead Sea fault system in Lebanon. Geology, 43(9): 843−846. DOI: 10.1130/G36841.1.

Gruetzmacher G, Kumar PS. 2012. Introduction to Managed Aquifer Recharge (MAR)–Overview of schemes and settings worldwide. In Conference on Managed Aquifer Recharge: Methods, Hydrogeological Requirements, Post and Pre-treatment Systems.

Hamed MM, Nashwan MS, Shiru MS, et al. 2022. Comparison between CMIP5 and CMIP6 models over MENA region using historical simulations and future projections. Sustainability, 14(16): 10375.

Hankin B, Arnott S, Whiteman M, et al. 2017. Working with Natural Processes—Using the Evidence Base to Make the Case for Natural Flood Management. Environment Agency: Bristol, UK.

Hartog N, Stuyfzand PJ. 2017. Water quality considerations on the rise as the use of managed aquifer recharge systems widens. Water, 9(10): 808. DOI：10.3390/w9100808.

Haque A, Salama A, Lo K, et al. 2021. Surface and groundwater interactions: A review of coupling strategies in detailed domain models. Hydrology, 8(1): 35. DOI：10.3390/hydrology8010035.

He ZK, Han DM, Song XF, et al. 2021. Variations of groundwater dynamics in alluvial aquifers with reclaimed water restoring the overlying river, Beijing, China. Water, 13(6): 806. DOI：10.3390/w13060806.

Hernández-Hernández M, Olcina J, Morote ÁF. 2020. Urban stormwater management, a tool for adapting to climate change: From risk to resource. Water, 12(9): 2616. DOI：10.3390/w12092616.

Holländer HM, Mull R, Panda SN. 2009. A concept for managed aquifer recharge using ASR-wells for sustainable use of groundwater resources in an alluvial coastal aquifer in Eastern India. Physics and Chemistry of the Earth, Parts A/B/C, 34(4−5): 270−278. DOI: 10.1016/j.pce.2008.05.001.

Hu JY, Yang ZF, Hou CY, et al. 2023. Compound risk dynamics of drought by extreme precipitation and temperature events in a semi-arid watershed. Atmospheric Research, 281: 106474. DOI：10.1016/j.atmosres.2022.106474.

Huggins X, Gleeson T, Castilla-Rho J, et al. 2023. Groundwater connections and sustainability in social-ecological systems. Groundwater, 61(4): 463−478. DOI：10.1111/gwat.13305.

Hutchison A, Milczarek M, Banerjee M. 2013. Clogging phenomena related to surface water recharge facilities. Clogging issues associated with managed aquifer recharge methods: 34-49.

Hurst CW, Wilkinson WB. 1986. Rising groundwater levels in cities. Geological Society, London, Engineering Geology Special Publications, 3(1): 75−80. DOI：10.1144/gsl.eng.1986.003.01.07.

Ismail I, Gaganis V. 2023. Carbon capture, utilization, and storage in saline aquifers: Subsurface policies, development plans, well control strategies and optimization approaches—a review. Clean Technologies, 5(2): 609−637. DOI：10.3390/cleantechnol5020031.

Jasechko S, Seybold H, Perrone D, et al. 2021. Widespread potential loss of streamflow into underlying aquifers across the USA. Nature, 591(7850): 391−395. DOI：10.1038/s41586-021-03311-x.

Jeong HY, Jun SC, Cheon JY, et al. 2018. A review on clogging mechanisms and managements in aquifer storage and recovery (ASR) applications. Geosciences Journal, 22(4): 667−679. DOI：10.1007/s12303-017-0073-x.

Ji H, Lee S. 2022. Pilot-scale study of riverbank filtration performance in the Nakdong River delta, Korea. Journal of Water Supply: Research and Technology—AQUA, 71(2): 210−222.

Johnson TD, Belitz K, Kauffman LJ, et al. 2022. Populations using public-supply groundwater in the conterminous US 2010; Identifying the wells, hydrogeologic regions, and hydrogeologic mapping units. Science of The Total Environment, 806: 150618.

Jones A, Smith B. 2018. Vertical permeability

considerations in subsurface flow systems. Groundwater Journal, 56(4): 345−352.

Kacimov AR, Al-Maktoumi A, Obnosov YV. 2021. Seepage through earth dam with clay core and toe drain: The Casagrande–Numerov analytical legacy revisited. ISH Journal of Hydraulic Engineering, 27(sup1): 264−272. DOI：10.1080/09715010.2019.1633694.

Kalantari N, Rangzan K, Thigale SS, et al. 2010. Site selection and cost-benefit analysis for artificial recharge in the Baghmalek plain, Khuzestan Province, southwest Iran. Hydrogeology Journal, 18(3): 761−773. DOI：10.1007/s10040-009-0552-x.

Kaliraj S, Chandrasekar N, Magesh NS. 2015. Evaluation of multiple environmental factors for site-specific groundwater recharge structures in the Vaigai River upper basin, Tamil Nadu, India, using GIS-based weighted overlay analysis. Environmental Earth Sciences, 74(5): 4355−4380. DOI：10.1007/s12665-015-4384-9.

Kammoun S, Trabelsi R, Re V, et al. 2018. Groundwater quality assessment in semi-arid regions using integrated approaches: The case of Grombalia aquifer (NE Tunisia). Environmental Monitoring and Assessment, 190(2): 87. DOI：10.1007/s10661-018-6469-x.

Kanarek A, Michail M. 1996. Groundwater recharge with municipal effluent: Dan Region reclamation project, Israel. Water Science and Technology, 34(11): 227−233. DOI：10.1016/S0273-1223(96)00842-6.

Khadra WM, Stuyfzand PJ. 2023. Problems and promise of managed recharge in karstified aquifers: The example of Lebanon. Water International, 45(1): 23−38. DOI：10.1080/02508060.2019.1682910.

Kohlitz J, Grant M, Budhathoki RB, et al. 2024. Laying foundations for transformation: Insights from local government engagement on climate-resilient rural water services in Nepal. PLoS Sustainability and Transformation, 3(3): e0000081. DOI：10.1371/journal.pstr.0000081.

Kourakos G, Dahlke HE, Harter T. 2019. Increasing groundwater availability and seasonal base flow through agricultural managed aquifer recharge in an irrigated basin. Water Resources Research, 55(9): 7464−7492. DOI：10.1029/2018WR024019.

Lemaire P. 2009. Unfolding a chordate developmental program, one cell at a time: invariant cell lineages, short-range inductions and evolutionary plasticity in ascidians. Developmental Biology, 332(1): 48−60.

Levintal E, Kniffin ML, Ganot Y, et al. 2023. Agricultural managed aquifer recharge (AgMAR)—a method for sustainable groundwater management: A review. Critical Reviews in Environmental Science and Technology, 53(3): 291−314. DOI：10.1080/10643389.2022.2050160.

Lippera MC, Werban U, Vienken T. 2023. Application of physical clogging models to managed aquifer recharge: A review of modelling approaches from engineering fields. Acque Sotterranee - Italian Journal of Groundwater, 12(3): 9−20. DOI：10.7343/as-2023-681.

Liu SD, Zhou YX, Luo WJ, et al. 2022. A numerical assessment on the managed aquifer recharge to achieve sustainable groundwater development in Chaobai River area, Beijing, China. Journal of Hydrology, 613: 128392. DOI：10.1016/j.jhydrol.2022.128392.

Logan WS. 2020. Managed Aquifer Recharge and the US Army Corps of Engineers: Water Security Through Resilience. DOI：10.3389/frwa.2022.1024055.

Lu XH, Jin MG, van Genuchten MT, et al. 2011. Groundwater recharge at five representative sites in the Hebei Plain, China. Groundwater, 49(2): 286−294. DOI：10.1111/j.1745-6584.2009.00667.x.

Ma QS, Wu HJ, Ge WY, et al. 2024. Investigation of the emergency water supply schemes for youkou groundwater source field in Nanchang using a simulation–optimization model. Scientific Reports, 14: 2610. DOI：10.1038/s41598-024-52303-0.

Magnan AK, Schipper ELF, Duvat VKE. 2020. Frontiers in climate change adaptation science: Advancing guidelines to design adaptation pathways. Current Climate Change Reports, 6(4): 166−177. DOI：10.1007/s40641-020-00166-8.

Maliva R G, Missimer TM. 2010. Aquifer storage and recovery and managed aquifer recharge using wells: Planning, hydrogeology, design,

and operation. Houston, Schlumberger Water Services: Methods in Water Resources Evaluation Series. 2.

Maliva RG. 2014. Economics of managed aquifer recharge. Water, 6(5): 1257−1279. DOI：10.3390/w6051257.

Maliva R. 2021. Climate change and groundwater: Planning and adaptations for a changing and uncertain future: WSP Methods in Water Resources Evaluation Series No. 6. Springer Nature.

Manual ARS. 2007. Manual on Artificial Recharge of Groundwater Central Ground Water Board. Ministry of Water Resources, Govt. of India, New Delhi: 1–198.

Maples SR, Fogg GE, Maxwell RM. 2019. Modeling managed aquifer recharge processes in a highly heterogeneous, semi-confined aquifer system. Hydrogeology Journal, 27(8): 2869−2888. DOI：10.1007/s10040-019-02033-9.

Markovič G, Vranayova Z. 2015. Measurements of the quality of rainwater run-off and its potential for savings of potable water in TUKE campus. WSEAS Trans Environ Dev, 11: 302−311.

Martin R. 2013. Clogging issues associated with managed aquifer recharge methods. IAH Commission on Managing Aquifer Recharge, Australia: 26−33.

Masroor M, Sajjad H, Kumar P, et al. 2023. Novel ensemble machine learning modeling approach for groundwater potential mapping in parbhani district of Maharashtra, India. Water, 15(3): 419. DOI：10.3390/w15030419.

Maurya SP, Singh PK, Ohri A, et al. 2020. Identification of indicators for sustainable urban water development planning. Ecological Indicators, 108: 105691. DOI：10.1016/j.ecolind.2019.105691.

Masciopinto C. 2013. Management of aquifer recharge in Lebanon by removing seawater intrusion from coastal aquifers. Journal of Environmental Management, 130: 306−312. DOI：10.1016/j.jenvman.2013.08.021.

Milanović S, Dragišić V, Radulović MM, et al. 2015. Prevent leakage and mixture of karst groundwater. Karst Aquifers—Characterization and Engineering. Cham: Springer International Publishing: 531−599. DOI：10.1007/978-3-319-12850-4_16.

Missimer TM, Maliva RG, Ghaffour N, et al. 2014. Managed aquifer recharge (MAR) economics for wastewater reuse in low population wadi communities, Kingdom of Saudi Arabia. Water, 6(8): 2322−2338. DOI：10.3390/w6082322.

Moeck C, Radny D, Borer P, et al. 2016. Multicomponent statistical analysis to identify flow and transport processes in a highly-complex environment. Journal of Hydrology, 542: 437−449. DOI：10.1016/j.jhydrol.2016.09.023.

Moeck C, Radny D, Popp A, et al. 2017. Characterization of a managed aquifer recharge system using multiple tracers. Science of The Total Environment, 609: 701−714. DOI：10.1016/j.scitotenv.2017.07.211.

Mohamedzein YEA, Al-Hashmi SM, Al-Rawas AA. 2016. An investigation of excessive seepage from the Al-fulaij recharge dam, Oman. The Journal of Engineering Research, 13(2): 124. DOI：10.24200/tjer.vol13iss2pp124-136.

Mohammadzadeh-Habili J, Khalili D. 2020. Assessment of artificial recharge dams and improvement of their groundwater-recharge capacity. Journal of Hydrologic Engineering, 25(5): 04020011. DOI：10.1061/(asce)he.1943-5584.0001909.

Mohammad-Hosseinpour A, Molina JL. 2022. Improving the sustainability of urban water management through innovative groundwater recharge system (GRS). Sustainability, 14(10): 5990. DOI：10.3390/su14105990.

Moreira RP, Costa AC, Gomes TF, et al. 2020. Climate and climate-sensitive diseases in semi-arid regions: A systematic review. International Journal of Public Health, 65(9): 1749−1761. DOI：10.1007/s00038-020-01464-6.

Morin E, Grodek T, Dahan O, et al. 2009. Flood routing and alluvial aquifer recharge along the ephemeral arid Kuiseb River, Namibia. Journal of Hydrology, 368(1-4): 262−275. DOI：10.1016/j.jhydrol.2009.02.015.

Mukuhlani T. 2023. Making little go far in the context of climate change: Managing water demand in Bulawayo, Zimbabwe. In Climate Action in Southern Africa: 51-69. Routledge.

Nasonova ON, Gusev YM, Kovalev YE. 2011. Impact of uncertainties in meteorological forcing data and land surface parameters on global estimates of terrestrial water balance components. Hydrological Processes, 25(7): 1074−1090. DOI：10.1002/hyp.7651.

Ngo TML, Wang SJ, Chen PY. 2024. Assessment of future climate change impacts on groundwater recharge using hydrological modeling in the Choushui River alluvial fan. Water, 16(3): 419. DOI：10.3390/w16030419.

Niazi A, Prasher SO, Adamowski J, et al. 2014. A system dynamics model to conserve arid region water resources through aquifer storage and recovery in conjunction with a dam. Water, 6(8): 2300−2321. DOI：10.3390/w6082300.

Nicolas M, Bour O, Selles A, et al. 2019. Managed Aquifer Recharge in fractured crystalline rock aquifers: Impact of horizontal preferential flow on recharge dynamics. Journal of Hydrology, 573: 717−732. DOI：10.1016/j.jhydrol.2019.04.003.

Nofal S, Travi Y, Cognard-Plancq AL, et al. 2019. Impact of infiltrating irrigation and surface water on a Mediterranean alluvial aquifer in France using stable isotopes and hydrochemistry, in the context of urbanization and climate change. Hydrogeology Journal, 27(6): 2211−2229.

Noori AR, Singh SK. 2023. Rainfall assessment and water harvesting potential in an urban area for artificial groundwater recharge with land use and land cover approach. Water Resources Management, 37(13): 5215−5234. DOI：10.1007/s11269-023-03602-0.

Nourani V, Ghareh Tapeh AH, Khodkar K, et al. 2023. Assessing long-term climate change impact on spatiotemporal changes of groundwater level using autoregressive-based and ensemble machine learning models. Journal of Environmental Management, 336: 117653. DOI：10.1016/j.jenvman.2023.117653.

Nury SN, Nasrin S, Zhu X, et al. 2009. Three dimensional (3D) aquifer visualization for sustainable water management. Proceedings of the Environmental Research Event, Noosa, Queensland, Australia.

Oborie E, Udom GJ. 2014. Determination of aquifer transmissivity using geoelectrical sounding and pumping test in parts of Bayelsa State, Nigeria. Peak Journal of Physical and Environmental Science Research, 2(2): 32−40.

Page D, Bekele E, Vanderzalm J, et al. 2018. Managed aquifer recharge (MAR) in sustainable urban water management. Water, 10(3): 239. DOI：10.3390/w10030239.

Parimalarenganayaki S. 2021. Managed aquifer recharge in the gulf countries: A review and selection criteria. Arabian Journal for Science and Engineering, 46(1): 1−15. DOI：10.1007/s13369-020-05060-x.

Parimala renganayaki S, Elango L. 2014. Impact of recharge from a check dam on groundwater quality and assessment of suitability for drinking and irrigation purposes. Arabian Journal of Geosciences, 7(8): 3119−3129. DOI：10.1007/s12517-013-0989-z.

Parimalarenganayaki S, Elango L，Schneider M. 2019. Variations in stable isotopes of oxygen and hydrogen in surface and groundwater of a managed aquifer recharge site: A case study. Journal Geological Society of India, 93: 533−538. DOI：10.1007/s12594-019-1214-9.

Parish ES, Kodra E, Steinhaeuser K, et al. 2012. Estimating future global per capita water availability based on changes in climate and population. Computers & Geosciences, 42: 79−86. DOI：10.1016/j.cageo.2012.01.019.

Parker TK, Jansen J, Behroozmand AA, et al. 2022. Applied geophysics for managed aquifer recharge. Groundwater, 60(5): 606−618. DOI：10.1111/gwat.13235.

Patel R, Nguyen T. 2021. Challenges in bank filtration systems: A global review of operational issues. Water Resources Management, 35(3): 1021−1035.

Peng SY, Lu Z, Wu TT, et al. 2024. Research progress in integrated groundwater-surface water models. Hydrogeology & Engineering Geology, 51(6): 60−73. DOI：10.16030/j.cnki.issn.1000-3665.202401001.

Perzan Z, Osterman G, Maher K. 2023. Controls on flood managed aquifer recharge through a heterogeneous vadose zone: Hydrologic modeling at a site characterized with surface geophysics. Hydrology and Earth System Sciences, 27(5): 969−990. DOI：10.5194/hess-27-969-2023.

Pietersen K. 2021. Post-drought and emergency interventions: Towards higher water security (No. 3005/1, 21). Report.

Poozan A, Fletcher TD, Arora M, et al. 2024. The influence of spatial arrangement and site conditions on the fate of infiltrated stormwater. Journal of Hydrology, 630: 130738. DOI: 10.1016/j.jhydrol.2024.130738.

Pyne RDG. 2005. Aquifer storage recovery: a guide to groundwater recharge through wells/R. David G. Pyne.

Qian H, Chen J, Howard KWF. 2020. Assessing groundwater pollution and potential remediation processes in a multi-layer aquifer system. Environmental Pollution, 263: 114669. DOI: 10.1016/j.envpol.2020.114669.

Rahman MA, Rusteberg B, Gogu RC, et al. 2012. A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. Journal of Environmental Management, 99: 61−75. DOI: 10.1016/j.jenvman.2012.01.003.

Raicy MC, Elango L. 2020. Percolation pond with recharge shaft as a method of managed aquifer recharge for improving the groundwater quality in the saline coastal aquifer. Journal of Earth System Science, 129(1): 63. DOI: 10.1007/s12040-019-1333-0.

Raju N J, Ram P, Dey S. 2013. Hydrogeological and geochemical characterization of groundwater in the Kalangi River basin, Andhra Pradesh, India. Environmental Earth Sciences, 70(3): 1225−1246.

Rankgomo GT. 2020. Assessing the Potential of Artificial Groundwater Recharge: Case Study of Palla Road Wellfields, Botswana. MS. thesis. PAUWES.

Rassam DW, Peeters L, Pickett T, et al. 2013. Accounting for surface–groundwater interactions and their uncertainty in river and groundwater models: A case study in the Namoi River, Australia. Environmental Modelling & Software, 50: 108−119. DOI: 10.1016/j.envsoft.2013.09.004.

Raju NJ, Reddy TVK, Munirathnam P. 2006. Subsurface dams to harvest rainwater—a case study of the swarnamukhi river basin, southern India. Hydrogeology Journal, 14(4): 526−531. DOI: 10.1007/s10040-005-0438-5.

Rao RN, Pokkuluri Kiran S, Amena IT, et al. 2024. Enhancing rainwater harvesting and groundwater recharge efficiency with multi-dimensional LSTM and clonal selection algorithm. Groundwater for Sustainable Development, 25: 101167. DOI: 10.1016/j.gsd.2024.101167.

Regnery J, Gerba CP, Dickenson ERV, et al. 2017. The importance of key attenuation factors for microbial and chemical contaminants during managed aquifer recharge: A review. Critical Reviews in Environmental Science and Technology, 47(15): 1409−1452. DOI: 10.1080/10643389.2017.1369234.

Ringleb J, Sallwey J, Stefan C. 2016. Assessment of managed aquifer recharge through modeling—a review. Water, 8(12): 579. DOI: 10.3390/w8120579.

Rivett MO, Buss SR, Morgan P, et al. 2008. Nitrate attenuation in groundwater: A review of biogeochemical controlling processes. Water Research, 42(16): 4215−4232. DOI: 10.1016/j.watres.2008.07.020.

Ross A, Hasnain S. 2018. Factors affecting the cost of managed aquifer recharge (MAR) schemes. Sustainable Water Resources Management, 4(2): 179−190.

Sabale R, Venkatesh B, Jose M. 2023. Sustainable water resource management through conjunctive use of groundwater and surface water: A review. Innovative Infrastructure Solutions, 8(1): 17. DOI: 10.1007/s41062-022-00992-9.

Saccò M, Mammola S, Altermatt F, et al. 2024. Groundwater is a hidden global keystone ecosystem. Global Change Biology, 30(1): e17066. DOI: 10.1111/gcb.17066.

Sallam OM. 2019. Use of numerical groundwater modeling to assess the feasibility of aquifer storage and recovery (ASR) in the wadi watir delta, Sinai, Egypt. Journal of Water Resource and Protection, 11(12): 1462−1480. DOI: 10.4236/jwarp.2019.1112085.

Scanlon BR, Fakhreddine S, Rateb A, et al. 2023. Global water resources and the role of groundwater in a resilient water future. Nature Reviews Earth & Environment, 4(2): 87−101. DOI: 10.1038/s43017-022-00378-6.

Salameh E, Abdallat G, van der Valk M. 2019. Planning considerations of managed aquifer recharge (MAR) projects in Jordan. Water, 11(2): 182. DOI: 10.3390/w11020182.

Sánchez-Vila X, Carrera J, Girardi JP. 1996. Scale effects in transmissivity. Journal of Hydrol-

ogy, 183(1-2): 1−22. DOI：10.1016/S0022-1694(96)80031-X.

Sanford WE. 2017. Estimating regional-scale permeability–depth relations in a fractured-rock terrain using groundwater-flow model calibration. Hydrogeology Journal, 25(2): 405−419. DOI：10.1007/s10040-016-1483-y.

Sanford N. 2017. Self and society: Social change and individual development. Routledge. DOI：10.4324/9781315129112.

Sefelnasr A, Ebraheem AA, Faiz MA, et al. 2022. Enhancement of groundwater recharge from wadi Al bih dam, UAE. Water, 14(21): 3448. DOI：10.3390/w14213448.

Senthilkumar SA，Reddy B, Alphy A, et al. 2024. Mapping of groundwater availability in dry areas of rural and urban regions in India using IOT assisted deep learning classification model. Groundwater for Sustainable Development, 25: 101098. DOI：10.1016/j.gsd.2024.101098.

Şen Z, Al Alsheikh A, Al-Turbak AS. et al. 2013. Climate change impact and runoff harvesting in arid regions. Arab J Geosci, 6: 287−295. DOI：10.1007/s12517-011-0354-z.

Shah T. 2014. Towards a managed aquifer recharge strategy for gujarat, India: An economist's dialogue with hydro-geologists. Journal of Hydrology, 518: 94−107. DOI：10.1016/j.jhydrol.2013.12.022.

Shahbazi M, Zand S, Todd DK. 1968. Effect of topography on groundwater flow. International Association of Scientific Hydrology, 77: 314−319. DOI：10.3103/S0145875214010025.

Shaikh M, Birajdar F. 2024a. Artificial intelligence in groundwater management: Innovations, challenges, and future prospects. International Journal of Science and Research Archive, 11(01): 502−512.

Shaikh M, Birajdar F. 2024b. Advancing sustainable water management in solapur through continuous groundwater monitoring with piezometers and automatic water level recorders: Insights from the Atal Bhujal Yojana. International Journal of Innovative Science and Research Technology, 9(2): 230−239.

Sheng ZP, Zhao X. 2015. Special issue on managed aquifer recharge: Powerful management tool for meeting water resources challenges. Journal of Hydrologic Engineering, 20(3): B2014001. DOI：10.1061/(asce)he.1943-5584.0001139.

Sherif M, Hussnain S. 2017. Family Takaful in developing countries: the case of Middle East and North Africa (MENA). International Journal of Islamic and Middle Eastern Finance and Management, 10(3): 371−399.

Sherif M, Liaqat MU, Baig F, et al. 2023. Water resources availability, sustainability and challenges in the GCC countries: An overview. Heliyon, 9(10): e20543. DOI：10.1016/j.heliyon.2023.e20543.

Sikka AK, Alam MF, Pavelic P. 2021. Managing groundwater for building resilience for sustainable agriculture in South Asia. Irrigation and Drainage, 70(3): 560−573. DOI：10.1002/ird.2558.

Sishodia RP, Shukla S, Wani SP, et al. 2018. Future irrigation expansion outweigh groundwater recharge gains from climate change in semi-arid India. Science of the Total Environment, 635: 725−740. DOI：10.1016/j.scitotenv.2018.04.130.

Sloan S, Cook PG, Wallis I. 2023. Managed aquifer recharge in mining: A review. Groundwater, 61(3): 305−317. DOI：10.1111/gwat.13311.

Smith J, Kumar A, Lee M. 2018. Evaluating aquifer transmissivity for managed aquifer recharge (MAR) suitability. Hydrogeology Journal, 26(4): 1011−1024.

Snoussi G, Nasri B, Hamdi E, et al. 2024. Reuse of Tunisian excavated material into composite soil for rainwater infiltration within urban green infrastructure. Geoderma Regional, 36: e00748. DOI：10.1016/j.geodrs.2023.e00748.

Soares MO, Campos CC, Carneiro PBM, et al. 2021. Challenges and perspectives for the Brazilian semi-arid coast under global environmental changes. Perspectives in Ecology and Conservation, 19(3): 267−278. DOI：10.1016/j.pecon.2021.06.001.

Soni P, Dashora Y, Maheshwari B, et al. 2020. Managed aquifer recharge at a farm level: Evaluating the performance of direct well recharge structures. Water, 12(4): 1069. DOI：10.3390/w12041069.

Soomro SEH, Soomro AR, Batool S, et al. 2024. How does the climate change effect on

hydropower potential, freshwater fisheries, and hydrological response of snow on water availability? Applied Water Science, 14(4): 65. DOI: 10.1007/s13201-023-02070-6.

Sordo-Ward Á, Granados I, Martín-Carrasco F, et al. 2016. Impact of hydrological uncertainty on water management decisions. Water Resources Management, 30(14): 5535−5551. DOI：10.1007/s11269-016-1505-5.

Spinoni J, Naumann G, Vogt JV. 2017. Pan-European seasonal trends and recent changes of drought frequency and severity. Global and Planetary Change, 148: 113−130. DOI：10.1016/j.gloplacha.2016.11.013.

Standen K, Costa LRD, Monteiro JP. 2020. In-channel managed aquifer recharge: A review of current development worldwide and future potential in Europe. Water, 12(11): 3099. DOI：10.3390/w12113099.

Stein S, Shalev E, Sivan O, et al. 2023. Correction: Challenges and approaches for management of seawater intrusion in coastal aquifers. Hydrogeology Journal, 31(1): 187. DOI：10.1007/s10040-023-02593-x.

Stober I, Jägle M, Kohl T. 2023. Optimizing scenarios of a deep geothermal aquifer storage in the southern Upper Rhine Graben. Geothermal Energy, 11(1): 34. DOI：10.1186/s40517-023-00275-1.

Stuyfzand PJ, Smidt E, Zuurbier KG, et al. 2017. Observations and prediction of recovered quality of desalinated seawater in the strategic ASR project in liwa, Abu Dhabi. Water, 9(3): 177. DOI：10.3390/w9030177.

Subramanian A, Nagarajan AM, Vinod S, et al. 2023. Long-term impacts of climate change on coastal and transitional eco-systems in India: An overview of its current status, future projections, solutions, and policies. RSC Advances, 13(18): 12204−12228. DOI：10.1039/D2RA07448F.

Szabó Z, Szijártó M, Tóth Á, et al. 2023. The significance of groundwater table inclination for nature-based replenishment of groundwater-dependent ecosystems by managed aquifer recharge. Water, 15(6): 1077. DOI：10.3390/w15061077.

Tiwari M, Tripathy DB. 2023. Soil contaminants and their removal through surfactant-enhanced soil remediation: A comprehensive review. Sustainability, 15(17): 13161. DOI：10.3390/su151713161.

Tredoux G, Cain J. 2010. The Atlantis Water Resource Management Scheme: 30 years of Artificial Groundwater Recharge. Department of Water Affairs.

Tuinhof A, Foster S, van Steenbergen F, et al. 2011. Appropriate groundwater management policy for Sub-Saharan Africa.

Utom AU, Odoh BI, Okoro AU. 2012. Estimation of aquifer transmissivity using Dar zarrouk parameters derived from surface resistivity measurements: A case history from parts of enugu town (Nigeria). Journal of Water Resource and Protection, 4(12): 993−1000. DOI：10.4236/jwarp.2012.412115.

Van Houtte E, Verbauwhede J. 2021. Environmental benefits from water reuse combined with managed aquifer recharge in the Flemish dunes (Belgium). International Journal of Water Resources Development, 37(6): 1027−1034. DOI：10.1080/07900627.2020.1858035.

Van Steenbergen F. 2010. Guidelines on spate irrigation.

Vouillamoz JM, Lawson FMA, Yalo N, et al. 2015. Groundwater in hard rocks of Benin: Regional storage and buffer capacity in the face of change. Journal of Hydrology, 520: 379−386. DOI：10.1016/j.jhydrol.2014.11.024.

Vymazal J. 2018. Does clogging affect long-term removal of organics and suspended solids in gravel-based horizontal subsurface flow constructed wetlands? Chemical Engineering Journal, 331: 663−674. DOI：10.1016/j.cej.2017.09.048.

Wang W, Zhou Y, Sun X, et al. 2014. Development of managed aquifer recharge in China. Boletin Geologico Minero, 125(2): 227−233.

Ward J, Dillon P. 2012. Principles to coordinate managed aquifer recharge with natural resource management policies in Australia. Hydrogeology Journal, 20(5): 943−956. DOI：10.1007/s10040-012-0865-z.

Waterhouse J, Schaffelke B, Bartley R, et al. 2017. 2017 Scientific Consensus Statement: land use impacts on the Great Barrier Reef water quality and ecosystem condition.

Wendt DE, Van Loon AF, Scanlon BR, et al. 2021. Managed aquifer recharge as a drought mitigation strategy in heavily-stressed aquifers.

Environmental Research Letters, 16(1): 014046. DOI：10.1088/1748-9326/abcfe1.

White I, Howe J. 2004. The mismanagement of surface water. Applied Geography, 24(4): 261−280. DOI：10.1016/j.apgeog.2004.07.004.

Windsor S, C Rouhiainen, B Willis-Jones. 2012. Cloudbreak mine water conveyance infrastructure. Water Practice and Technology, 7(1). DOI：10.2166/wpt.2012.021.

Wolf L, Werz H, Hoetzl H, et al. 2007. Exploring the potential of managed aquifer recharge to mitigate water scarcity in the Lower Jordan River Basin within an IWRM approach. Proceedings of the 6th International Symposium on Managed Artificial Recharge of Groundwater, ISMAR6, Phoenix, AZ, 28.

Wolka K, Uma T, Tofu DA. 2023. The role of integrated watershed management in climate change adaptation for small-scale farmers in Southwest Ethiopia. Environmental and Sustainability Indicators, 19: 100260. DOI：10.1016/j.indic.2023.100260.

Wright A, du Toit I. 1996. Artificial recharge of urban wastewater, the key component in the development of an industrial town on the arid west coast of South Africa. Hydrogeology Journal, 4(1): 118−129. DOI：10.1007/s100400050101.

Xanke J, Liesch T, Goeppert N, et al. 2017. Contamination risk and drinking water protection for a large-scale managed aquifer recharge site in a semi-arid karst region, Jordan. Hydrogeology Journal, 25(6): 1795−1809. DOI：10.1007/s10040-017-1586-0.

Xanke J, Liesch T, Sawarieh A, et al. 2021. Case Study 27: Large-scale Managed Aquifer Recharge for drinking water production in a semi-arid karst region, Jordan. Managing aquifer recharge: A Showcase for Resilience and Sustainability: 331.

Yang YS, Wu YH, Lu Y, et al. 2021. Microorganisms and their metabolic activities affect seepage through porous media in groundwater artificial recharge systems: A review. Journal of Hydrology, 598: 126256. DOI：10.1016/j.jhydrol.2021.126256.

Yaraghi N, Ronkanen AK, Torabi Haghighi A, et al. 2020. Impacts of gold mine effluent on water quality in a pristine sub-Arctic river. Journal of Hydrology, 589: 125170. DOI：10.1016/j.jhydrol.2020.125170.

Yasa WI, Soekarno S, Dewa Gede Jaya Negera I. 2020. Efek sumur resapan terhadap pengurangan volume limpasan permukaan. Ganec Swara, 14(1): 537. DOI：10.35327/gara.v14i1.131.

Yoshitaka N, Makoto N. 2021. Clogging mechanisms and preventive measures in artificial recharge systems. Journal of Groundwater Science and Engineering, 9(3): 181−201. DOI：10.19637/j.cnki.2305-7068.2021.03.002.

Zekri S, Zeynali MJ, Channouf N, et al. 2023. Dynamic conservation of traditional irrigation systems: A Falaj case study. Arabian Journal of Geosciences, 16(3): 199. DOI：10.1007/s12517-023-11251-1.

Zhang ZY, Yang JB, Gong CC, et al. 2024. Enhancing predictions of remedial reagent transport via a vertical groundwater circulation well with high-resolution aquifer characterization. Science of The Total Environment, 921: 171041. DOI：10.1016/j.scitotenv.2024.171041.

Zhang H, Xu YX, Kanyerere T. 2020. A review of the managed aquifer recharge: Historical development, current situation and perspectives. Physics and Chemistry of the Earth, Parts A/B/C, 118: 102887. DOI：10.1016/j.pce.2020.102887.

Zhiteneva V, Mosher J, Gerba CP, et al. 2023. A new workflow for assigning removal credits to assess overall performance of managed aquifer recharge (MAR). Water Research, 235: 119836. DOI：10.1016/j.watres.2023.119836.

Zou ZK, Shu LC, Min X, et al. 2019. Clogging of infiltration basin and its impact on suspended particles transport in unconfined sand aquifer: Insights from a laboratory study. Water, 11(5): 1083. DOI：10.3390/w11051083.