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Managed Aquifer Recharge (MAR) as a Tool for Sustainable Groundwater Management in Semi-Arid Regions

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Abstract

Groundwater serves as the principal source of water supply in many semi-arid regions. However, excessive extraction, contamination, and the impacts of climate change have rendered this resource increasingly unreliable. Managed Aquifer Recharge (MAR) has emerged as a viable strategy to enhance groundwater availability by enabling the intentional storage of water during wet periods for subsequent use during dry seasons. This review examines the role of MAR in promoting sustainable groundwater management in semi-arid environments through an analysis of field-based projects, modelling studies, and policy frameworks. It outlines the fundamental principles and techniques of MAR while addressing the associated technical, social, and regulatory challenges. Case studies from India, the United States, Australia, and Mediterranean countries are discussed to illustrate the practical applications and outcomes of MAR initiatives. Furthermore, the review highlights how improved planning, systematic monitoring, and active community participation can enhance the effectiveness of MAR interventions. Overall, the findings suggest that MAR represents a promising approach for strengthening water security and building climate resilience in semi-arid regions, particularly when integrated with sound governance and inclusive stakeholder engagement.

Keywords

Managed Aquifer Recharge, Semi-Arid Regions, Groundwater Management, Aquifer Storage, Water Security, Climate Resilience

1. Introduction

Semi-arid regions are areas characterized by low and highly variable rainfall, typically receiving between 250 and 500 millimeters of precipitation annually. These regions experience frequent droughts, high evaporation rates, and limited water availability, which significantly influence their ecosystems, agricultural potential, and socio-economic development. Given these characteristics, understanding environmental processes and sustainability challenges in semi-arid regions is essential for developing effective management and adaptation strategies.

Groundwater can play a central role in sustaining life in semi-arid regions, where surface water resources are not enough and highly variable. Groundwater, in many of these areas, forms the backbone of domestic supply, irrigation, and industrial activities. However, activities like unsustainable extraction, combined with climate variability and rapid socio-economic growth, have placed huge stress on these underground reserves. Declination of groundwater levels, aquifer depletion, seawater intrusion in coastal aquifers, land subsidence, and deteriorating water quality are now widely becoming documented because of this imbalance between recharge and extraction (Bouwer, 2002; Dillon, 2005). Addressing these crises requires strategies that not only increase groundwater availability but also ensure its long-term sustainability under changing climatic and hydrological regimes.

Managed aquifer recharge (MAR) is one such approach that has been used globally for many decades. MAR can be defined as the "injection of water into aquifers for subsequent recovery or for environmental improvement, using a variety of techniques (**Figure 1**) including infiltration basins, recharge wells, percolation tanks, and sand dams" (Bouwer, 2002).

While surface reservoirs lose water by evaporation, especially in arid climates, water stored in aquifers through MAR is safe from evaporation and also protected from contamination. In addition, the infiltration process provides an opportunity for filtration and improvement of water quality (Dillon et al., 2020). The practice of MAR has been conceptually expanded from the previously used term "artificial recharge" to a more comprehensive and all-inclusive concept of "managed aquifer recharge", which is more deliberate, strategic, integrated with water management policies, and participatory (Dillon, 2005).

MAR is especially relevant in arid and semi-arid areas, which are characterized by high seasonality in rainfall, high incidence of droughts, and infrequent recharge opportunities, resulting in a high vulnerability of groundwater resources to overexploitation. In these settings, MAR may help in smoothing climate extremes, providing more sustainable water supplies by storing excess rainfall or stormwater during wet periods and releasing it to cope with longer and more intense dry periods (Dillon et al., 2020), and in addressing various types of groundwater problems, such as saline intrusion in coastal aquifers, subsidence in overexploited groundwater basins, and water quality deterioration under falling water levels (Bouwer, 2002; Dillon, 2005). In general, MAR is increasingly considered as a form of adaptation to climate change and as a way to help in achieving various United Nations Sustainable Development Goals (SDGs), such as sustainable water supply, food security, and resilient cities (Dillon et al., 2020).

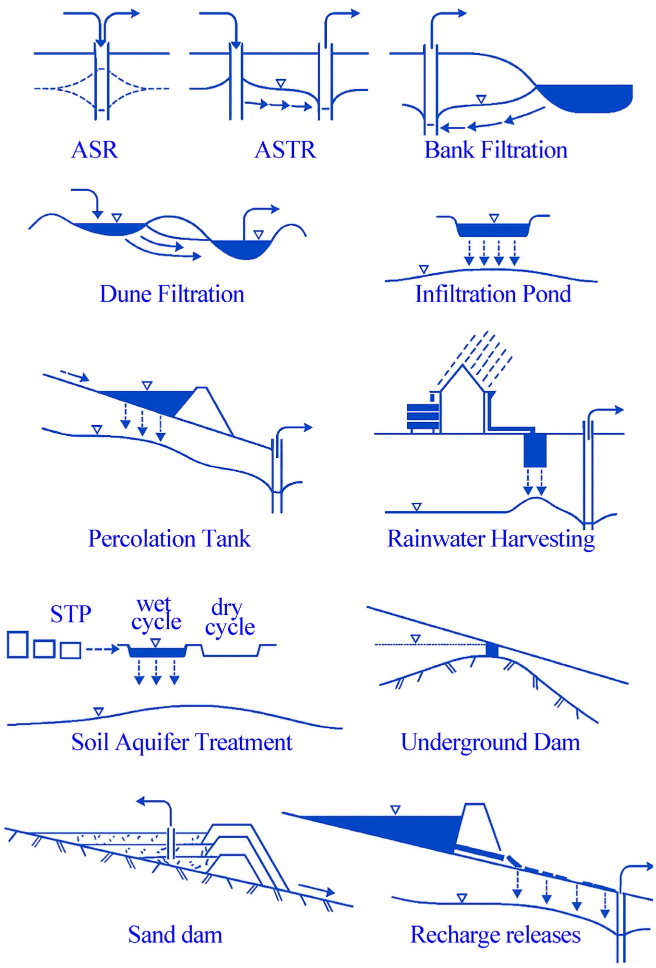

Figure 1. Schematic representation of Managed Aquifer Recharge (MAR) types, adapted from Dillon (2005).

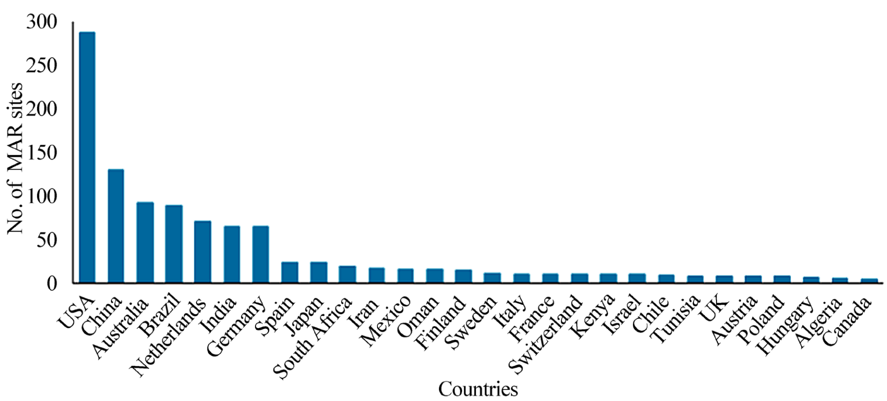

Figure 2. Global distribution of MAR sites (Sufyan et al., 2024).

Worldwide, thousands of MAR projects have been implemented, but their distribution is not even (**Figure 2**). Rather, it is clustered in those areas where governance is strong and technical capacity and institutional frameworks are available (Dillon et al., 2020). Many semi-arid regions of Asia and Africa lag behind because the regulatory framework is weak here, and technical expertise and investment are not available (Dillon, 2005). Further barriers to MAR implementation include proper site selection, aquifer suitability, infiltration structure clogging, and risks associated with the transport of contaminants (Bouwer, 2002; Fathi et al., 2020). Recently, GIS-MCDA—an integration between GIS tools and Multi-Criteria Decision Analysis—has been created to support systematic site selection. It is an especially promising pathway for complex semi-arid karst aquifers, where it can help unlock MAR for these environments (Fathi et al., 2020).

Apart from technical considerations, social and institutional issues are also very important to the ultimate success of MAR. Also, choosing the source of water to be used for MAR purposes is a key step in implementing MAR worldwide (**Figure 3**). In some cultures, it is a very big impediment, where treated wastewater is being used as the source for recharge, which has been identified as a potential impediment in areas with strong cultural sensitivities. Equally, some projects have identified that fragmented governance and a lack of integrated water management policies can constrain the effectiveness of MAR projects when working in transboundary aquifers, which are common in semi-arid zones (Dillon et al., 2020). Therefore, the future success of MAR lies not just in technological innovation but significantly more in governance reforms, stakeholder engagement, and capacity building at local as well as regional levels (Dillon, 2005).

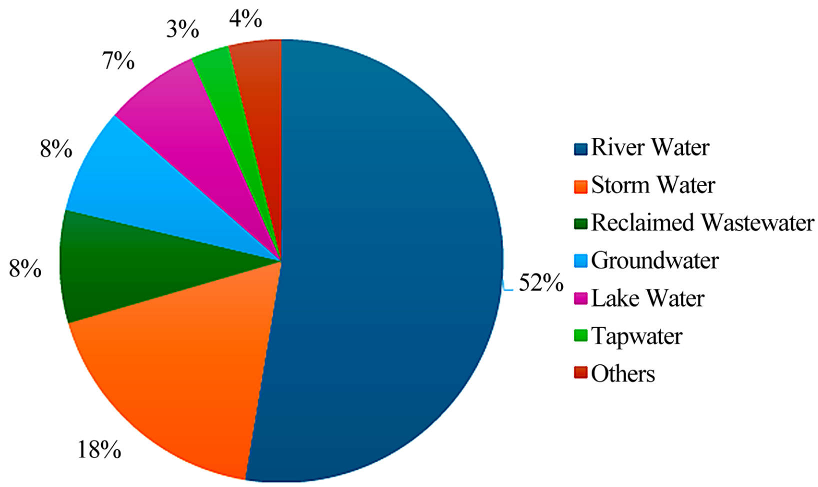

Figure 3. Water sources used worldwide in MAR applications (Sufyan et al., 2024).

The literature on MAR is enormous and growing rapidly with case studies, technical papers, and policy analyses, but a synthesis focused on how MAR relates to the management of groundwater systems in a sustainable fashion in semi-arid regions is scant. Reviews tend to treat managed aquifer recharge as a global issue, when what is needed because of differences in hydrogeology, climate, and socio-economics between the rest of the world and semi-arid areas is a much more narrowly focused analysis. This review paper undertakes an analysis of MAR as a tool for sustainable groundwater management in semi-arid regions by focusing on the principles and benefits of managed aquifer recharge, techniques and strategies of its implementation under semi-arid settings, challenges and risks associated with such environments, and finally on global experiences followed by future perspectives.

Drawing hydrology engineering, governance, and community perspectives together here provides evidence that signals toward a potential role for MAR in response to the escalating water crisis across semi-arid regions.

According to Sufyan et al. (2024), river water accounts for the majority of sources used in MAR applications worldwide (52%), with stormwater (18%) and reclaimed wastewater (8%) representing significant but smaller contributions. This distribution suggests a continued reliance on natural surface water sources despite growing interest in water reuse.

While numerous reviews of MAR exist, most adopt a global perspective, often focusing on engineering or water quality outcomes alone. There is a clear gap in the literature for a synthesis specifically focused on semi-arid regions, where hydrogeology, climate variability, and socio-economic contexts differ markedly from humid or temperate zones. This review addresses that gap by providing a comprehensive, interdisciplinary analysis of MAR for sustainable groundwater management in semi-arid regions. Specifically, it:

1. Examines the principles, techniques, and strategies of MAR implementation under semi-arid conditions.
2. Discusses the technical, social, economic, and governance challenges unique to these environments.
3. Synthesizes global experiences and lessons learned to inform future research, policy, and practice.
4. Provides integrated perspectives on future directions for MAR, emphasizing climate adaptation, sustainability, and equitable water management.

By linking hydrological engineering, governance, and community perspectives, this review highlights the potential role of MAR in mitigating the escalating water crisis in semi-arid regions, providing actionable insights for both research and implementation.

2. Principles and Concepts of Managed Aquifer Recharge

2.1. Evolution of the Concept

The idea of purposefully enhancing groundwater resources is by no means new. Primitive recharge systems like check dams, step wells, and infiltration ponds were developed by early communities in India, the Middle East, and Africa to meet dry-weather water demands (Bouwer, 2002). Over a large part of the 20th century, the term “artificial recharge” was used rather liberally, but it is often linked to large engineering works. "Managed Aquifer Recharge (MAR)" gradually replaced the term artificial recharge and more strongly underlined the importance of intentional, sustainable planning and integration into larger water policies (Dillon, 2005). MAR is, in this regard, different from uncontrolled or incidental recharge, such as seepage from irrigation or leaking canals. MAR is a term reserved for recharge that is conducted intentionally for storage and recovery over the long term, or for environmental benefits (Dillon, 2005; Dillon et al., 2020).

2.2. Definition and Scope

The International Association of Hydrogeologists (IAH) definition of MAR is "intentional recharge of water to aquifers for subsequent recovery or environmental benefit". The term "intentional" points to 1) planned and managed recharge, as opposed to incidental recharge, and 2) the fact that the purpose of MAR is not only to provide water supply but also to provide ecological/environmental services (Dillon et al., 2020).

MAR in semi-arid environments, on the other hand, tends to rely on the diversion of intermittent flood flow, storm water, or treated wastewater for aquifer infiltration. Rainfall in such areas can be very seasonally distributed, and MAR schemes can be used to store surplus water during wet seasons for consumption or irrigation during extended dry seasons (Fathi et al., 2020). MAR is also used to facilitate "water banking", where aquifers serve as a form of underground reservoir, protecting the stored water from the evaporative losses that can be significant in arid and hot climates (Bouwer, 2002).

2.3. Hydrogeological Basis of MAR in Semi-Arid Regions

The type of aquifer and geological setting mainly controls, or better relates to, the feasibility of applying MAR in semi-arid regions. Unconsolidated highly porous aquifers, compared to highly consolidated formations above the crystalline rock that can store only 1% (minimum) of their volume as groundwater. So generally, storage percentages are probably around 30% in unconsolidated against about 10% in consolidated (Bouwer, 2002). There is generally a combination of porous alluvial aquifers with either fractured or karstic systems, which are found in semi-arid regions; the latter provides favorable conditions besides posing challenges for implementing MAR (Fathi et al., 2020).

Karst aquifers, which predominate semi-arid Mediterranean zones, have high infiltration potential and vulnerability to rapid contaminant transport owing to their complex conduit networks (Fathi et al., 2020). GIS-based multi-criteria decision analysis (GIS-MCDA) has since evolved as a very important approach in such heterogeneous settings for the identification of suitable recharge sites through slope, lithology, soil texture, drainage density, and land use, among others (**Figure 4**) (Fathi et al., 2020). Thus, hydrogeological mapping and modeling are prerequisites for technically feasible and environmentally safe MAR interventions in semi-arid regions.

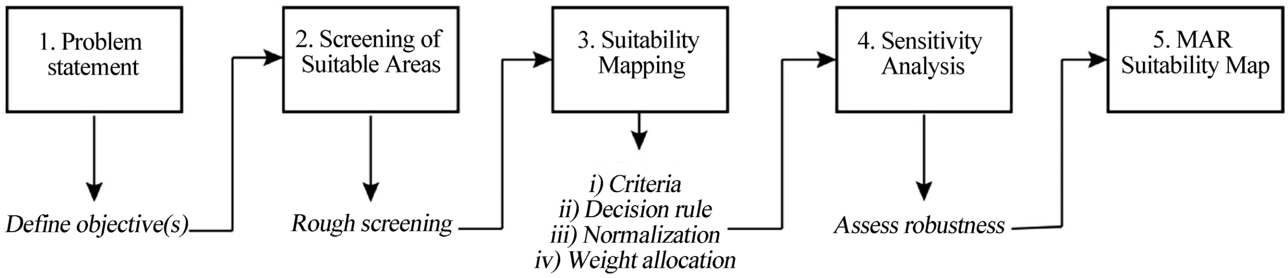

Figure 4. GIS-based suitability map (Fathi et al., 2020).

2.4. Key Principles of MAR

Managed Aquifer Recharge (MAR) is a deliberate process of augmenting groundwater resources by enhancing the natural replenishment of aquifers. A key principle underlying MAR is the integration of both hydrological and governance considerations to ensure sustainable water management. Dillon (2022) emphasizes that effective MAR schemes must account for aquifer characteristics, recharge water quality, and potential environmental impacts, while also embedding regulatory and institutional frameworks to guide operations and maintenance (Dillon, 2022).

Another foundational principle is the adaptation of MAR strategies to local hydrogeological conditions. Barquero Kamrath et al. highlight that infiltration capacities of spreading basins can vary significantly under different climatic conditions, necessitating careful assessment before implementation (Barquero Kamrath et al., 2020). Moreover, MAR projects should aim to enhance water resilience by balancing short-term recharge needs with long-term sustainability. Dillon et al. (2021) stress that maintaining aquifer health, preventing contamination, and optimizing recharge efficiency are essential components of sustainable MAR design.

Finally, governance and stakeholder engagement are critical. The European Commission Directorate-General for Environment (2025) underlines that clear regulatory framework, monitoring protocols, and community involvement are necessary to ensure MAR projects contribute effectively to water security while mitigating potential risks.

Several guiding principles underpin MAR practice, which are particularly relevant in semi-arid environments:

1. Recharge-Recovery Balance is important that the volume of recharge by far exceeds or at least matches the intended recovery, factoring in all losses-natural via seepage and evapotranspiration as well as lateral outflow. This shall go a long way toward ensuring aquifer sustainability over the long term (Dillon et al., 2020).
2. Water Quality Safeguards should be good enough to avoid groundwater degradation. Soil aquifer treatment can improve the quality of water due to natural filtration. However, the probability of conveying pathogens, nutrients and emerging contaminants which include pharmaceuticals, PFAS, and microplastics is high (Sufyan et al., 2024).
3. Clogging Management, the performance can be sustained if managed through

pretreatment and maintenance (Bouwer, 2002).

4. Adaptation to Climatic Variability—MAR as designed for storage from episodic storm flow and usage in long dry spells, hence resilience to climate as introduced by MAR (Dillon et al., 2020).
5. Integration with Local Water Management—the Managed Aquifer Recharge is best implemented when integrated within the broader system of integrated water resource management. Planning for surface water, demand management, and protection of the environment.

2.5. Benefits of MAR in Semi-Arid Regions

Semi-arid regions face persistent challenges related to groundwater depletion, seasonal water shortages, and increasing climatic variability. Managed Aquifer Recharge (MAR) has emerged as a practical approach to address these issues by capturing and storing excess water for future use. This section outlines the key benefits of MAR in such environments, including its roles in improving groundwater reliability, water quality, and overall climate resilience.

MAR's benefits are more than just improving groundwater storage. The most important advantages in semi-arid areas are the following:

- Reduction of evaporation losses: Underground storage has less water loss compared to surface reservoirs.
- Aquifer replenishment and drought buffering: these measures replenish depleted aquifers and offer supplies throughout dry seasons (Bouwer, 2002; Dillon et al., 2020).
- Water quality enhancement: Microbial and chemical quality are improved by soil-aquifer treatment.
- Control of land subsidence and saline intrusion: control of land Subsidence and saline intrusion is Important for overdrawn semi-arid aquifers along the coast.
- Flood mitigation and environmental benefits: By capturing flood waters, MAR structures like check dams and percolation tanks can decrease the damage downstream and replenish aquifers (Dillon, 2005).

2.6. Limitations and Knowledge Gaps

Despite its demonstrated potential, the application of Managed Aquifer Recharge (MAR) in semi-arid regions faces several limitations and knowledge gaps. Social acceptance remains a significant barrier, particularly in cases where treated wastewater or reclaimed water is used as a recharge source. Public concerns regarding health risks and water quality often limit the wider adoption of such practices. From a technical perspective, clogging of infiltration structures and wells can substantially reduce system performance and increase maintenance requirements.

Hydrogeological heterogeneity presents another major challenge, as variations in subsurface characteristics make it difficult to accurately predict recharge rates, storage capacity, and recovery efficiency (Dillon, 2005; Sufyan et al., 2024). Moreover, there is a persistent lack of long-term monitoring data to evaluate the sustainability and cumulative impacts of MAR projects in semi-arid environments. This is particularly evident in the limited understanding of ecosystem responses, groundwater quality changes, and potential geochemical alterations associated with long-term recharge (Dillon et al., 2020).

In addition, research on emerging contaminants—such as pharmaceuticals, personal care products, and microplastics—in MAR systems remains in its early stages and requires greater scientific attention. Addressing these gaps through integrated monitoring programs, community engagement, and interdisciplinary research will be essential to improving the performance, safety, and acceptance of MAR in semi-arid regions.

3. MAR Techniques and Implementation in Semi-Arid Regions

3.1. Overview of MAR Techniques for Semi-Arid Settings

Semi-arid regions face significant water scarcity, making MAR an essential tool for groundwater sustainability. Techniques commonly employed in these regions include surface spreading methods, such as infiltration basins and recharge ponds, as well as subsurface approaches like injection wells. Barquero Kamrath et al. (2020) note that the performance of surface spreading basins is highly sensitive to climatic variability, with infiltration rates influenced by seasonal rainfall patterns and soil characteristics.

Dillon et al. (2021) highlight that in arid and semi-arid areas, MAR can serve multiple functions: securing water supply during droughts, mitigating floods during extreme rainfall, and maintaining ecological flows. The design of MAR systems in these regions must therefore account for both the quantity and quality of recharge water, while considering potential evaporation losses and soil clogging issues.

El-Rawy and Negm (2024) provide insights into the MENA region, showing that effective MAR implementation requires integrated strategies combining engineered solutions with natural recharge processes. They stress that policy frameworks, continuous monitoring, and adaptive management are critical to address challenges such as water scarcity, salinity intrusion, and climate change impacts. Additionally, the European Commission emphasizes that harmonizing MAR techniques with regional directives and environmental goals ensures both legal compliance and sustainable outcomes.

Overall, MAR in semi-arid regions represents a balance between engineered intervention and natural processes, guided by careful planning, adaptive management, and stakeholder involvement to maximize water security and ecological resilience. Many of the MAR techniques have been developed worldwide (**Figure 1**), but whether they are suitable for semi-arid regions depends strongly on climate, hydrogeology, and socio-economic conditions. In areas with unconfined shallow aquifers and permeable soils, surface-based methods like infiltration basins and percolation tanks are used. But methods like aquifer storage and recovery (ASR), which is a well-based technique are more suitable for deeper, confined systems (Bouwer, 2002; Dillon, 2005). In semi-arid areas with short and intense rainfall specific MAR structures are built. They are designed to capture periodic flood flows or stormwater that would be lost to runoff otherwise (Dillon et al., 2020).

3.2. Surface Spreading Techniques

In MAR techniques, the surface spreading methods are the oldest and most widely used. The methods include infiltration basins, trenches, furrows, and percolation tanks (**Figure 5** and **Figure 6**). Percolation tanks and check dams are extensively used in semi-arid regions of India to improve the recharge during the monsoon, which in turn replenishes the local aquifers for agriculture and village water supply (Bouwer, 2002; Dillon, 2005).

Percolation Tank

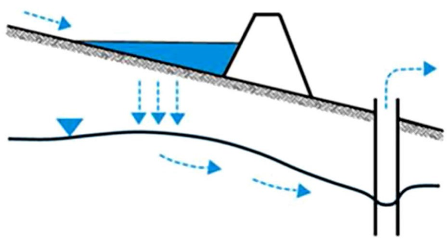

Figure 5. Schem of Percolation Tank (Sufyan et al., 2024).

Low cost, simple construction, and reliance on natural infiltration processes are some of the advantages of spreading methods. It also allows for the Soil-aquifer treatment, which improves the water quality. But there are some limitations that include land requirement, vulnerability to clogging, and a decrease in efficiency in areas with shallow impermeable layers or clayey soils. Maintenance is essential, for example, periodic removal of accumulated silt, to sustain infiltration rates (Bouwer, 2002).

Infiltration Pond

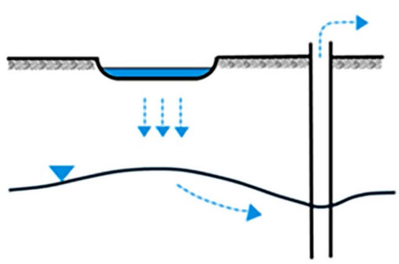

Figure 6. Schematic of Infiltration Pond (Sufyan et al., 2024).

3.3. Well- and Shaft-Based Techniques

Surface spreading is limited to land availability or soil permeability, which makes recharge wells and shafts a better alternative. These include Aquifer Storage and Recovery (ASR), water injected in wet periods and recovered in dry periods, and Aquifer Storage Transfer and Recovery (ASTR), which has recharge and recovery wells at different locations (Dillon, 2005)

In semi-arid zones where land for basins is limited. Well recharge is useful for urban water supply and industrial applications. It has been achieved in Arizona (USA) and parts of Australia where ASR was used to store and treat wastewater and storm water for reuse (Dillon et al., 2020). However, it requires high-quality source water and efficient pretreatment to avoid clogging and contamination of the aquifer. The method comes with a higher cost but better recovery efficiency.

3.4. Small-Scale and Community-Based Structures

Sand dams, subsurface dams, and rooftop rainwater harvesting, which is called small-scale MAR interventions, play an important role in water security (**Figure 1**). Sand dams trap coarse sediments and create storage zones from where water is slowly released to recharge aquifers in sub-Saharan Africa (Dillon, 2005). On the other hand, underground dams provide long-term recharge and minimize evaporation in semi-arid Japan and Africa. Rooftop rainwater harvesting is also a cost-effective technique, where water is directed to shallow wells and infiltration pits (Bouwer, 2002).

Such small-scale systems show the importance of MAR in Semi-arid zones, where centralized infrastructure is absent. However, their success depends on strong community participation and local maintenance (Dillon, 2005).

3.5. Soil Aquifer Treatment and Indirect Recharge

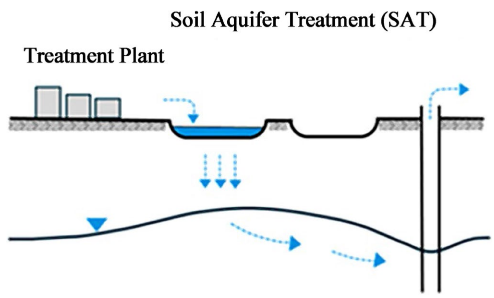

Figure 7. Soil Aquifer Treatment (SAT) (Sufyan et al., 2024).

Wastewater reuse is a very important source of MAR in some semi-arid cities. Soil Aquifer Treatment (SAT) (**Figure 7**) is a practice of spreading treated wastewater over infiltration basins, which in turn allows for further purification while passing through the unsaturated zone (Dillon, 2005). SAT has been used in countries like Isreal, USA, and Australia, the aquifers serve as both storage and treatment units. Moreover, riverbank and dune filtration which is a form induced recharge are being used in Semi-arid Europe and India to improve the municipal supply water quality.

3.6. Source Water for MAR in Semi-Arid Regions

In semi-arid regions, the availability and quality of source water play a decisive role in determining the feasibility and effectiveness of Managed Aquifer Recharge (MAR) schemes. Given the scarcity of perennial surface water, MAR projects often rely on opportunistic sources such as seasonal river flows, stormwater runoff, or reclaimed wastewater. Each of these sources presents distinct advantages and challenges related to variability, quality, treatment needs, and social acceptance. Careful evaluation and management of source water are therefore essential to ensure the long-term sustainability and safety of MAR systems.

The common sources of MAR include:

- Stormwater and Floodwater: largely used in semi-arid regions to capture periodic events of rainfall.
- River and Stream Water: It is only important where seasonal rivers exist, but are subject to variability.
- Treated Wastewater: it is significant in urban semi-arid regions, but requires pretreatment.
- Desalinated Water: A rare practice in the Middle East, especially, where the excess desalinated water is stored underground.

Fathi et al. (2020) have emphasized that the site selection for MAR depends on both source water proximity and aquifer suitability. Moreover, GIS-MCDA approaches which integrates hydrogeological and socio-economic factors provide a structured way to optimize source–site matching.

3.7. Engineering and Design Considerations

The success of Managed Aquifer Recharge (MAR) systems depends largely on appropriate engineering design and planning. In semi-arid regions, this involves adapting recharge structures to variable soil conditions, limited water availability, and potential clogging risks. Sound design ensures that MAR operations remain both technically effective and environmentally sustainable.

The design of the MAR system in semi-arid regions depends on the geological, hydrological, and engineering factors. It includes:

- Hydrogeology: it includes transmissivity of the aquifer, depth to the groundwater, and storage capacity (Bouwer, 2002).
- Soil and Lithology: it includes permeability, capacity of infiltration, and risk of clogging (Fathi et al., 2020).
- Topography: it basically means that slope and drainage density determine the potential of runoff capture.
- Distance from Source: determines transport costs, which influences the economic feasibility (Fathi et al., 2020).
- Water Quality Requirements: it requires pretreatment to manage sediments,

pathogens, and contaminants.

The numerical models (e.g., MODFLOW, SEAWAT, MT3DMS) are usually used to simulate MAR performance, to estimate the recovery efficiency, and to predict changes in the water quality (**Figure 8**). These tools are especially valuable in semi-arid regions where hydrogeological data is mostly unavailable, which enables more reliable planning and risk assessment.

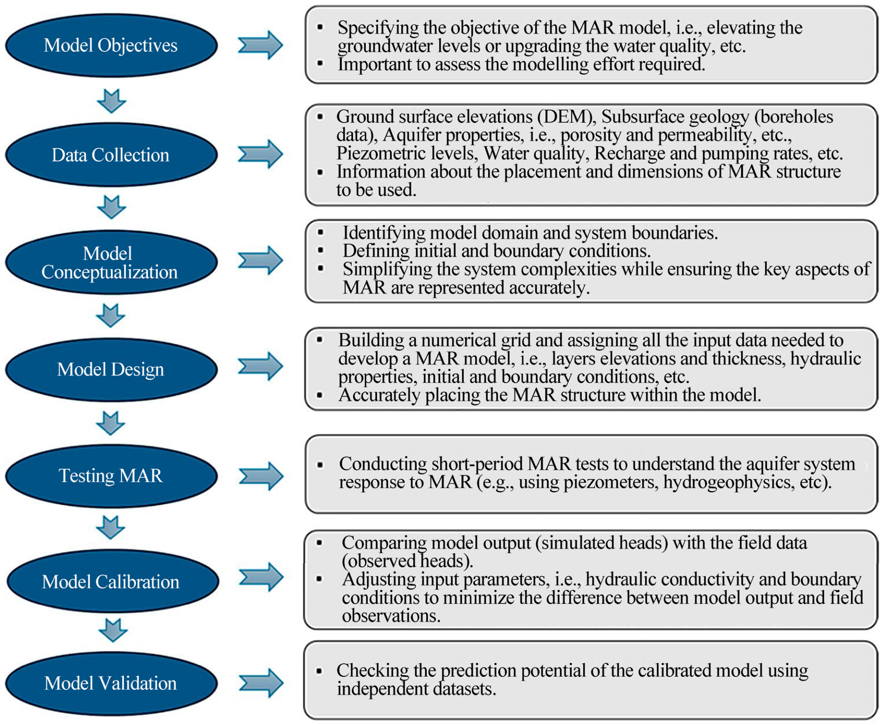

Figure 8. Steps involved in the numerical modeling of a MAR site (Sufyan et al., 2024).

Sufyan et al. (2024) describe a structured process for numerically modeling MAR sites, beginning with data acquisition and conceptualization, followed by model calibration, validation, and predictive simulations to evaluate system performance.

4. Challenges, Risks, and Governance Issues

4.1. Technical Challenges in Semi-Arid Regions

MAR techniques vary widely depending on local conditions. Surface spreading, in-channel recharge, and subsurface injection are commonly applied, with modeling supporting site selection and performance evaluation (Jadav & Yadav, 2023; Standen et al., 2020; Ringleb et al., 2016). Low-impact development strategies and hybrid approaches combining engineered and natural recharge have shown promise for improving efficiency and reducing environmental impacts (Job, 2022; Dillon, 2009). MAR in mining contexts also demonstrates potential for groundwater restoration and industrial water reuse (Sloan et al., 2023).

Performance evaluation of MAR is a recurring focus across global experiences. In the Nabogo Basin of Ghana, electrical resistivity tomography was used to assess infiltration rates and optimize recharge locations, highlighting the value of geophysical methods for site-specific assessment (Adam et al., 2023). Water reclamation technologies also play a critical role in ensuring safe recharge, particularly when using treated effluent or reclaimed water, as they allow both microbial and chemical risks to be managed (Kazner, 2012). Together, these approaches underscore the importance of combining technical monitoring with careful method selection to improve MAR outcomes.

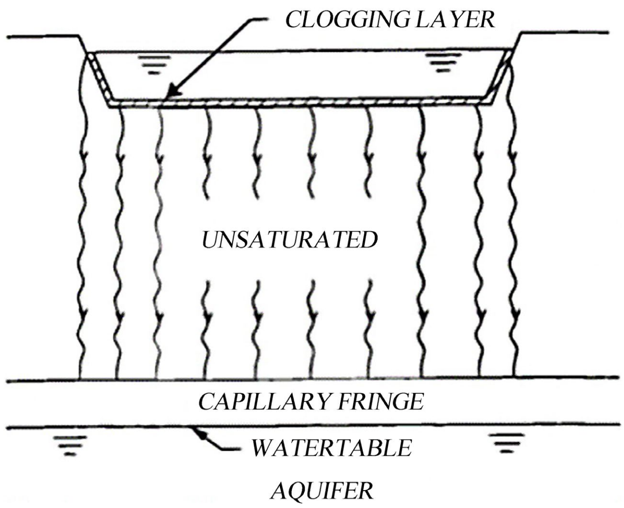

Figure 9. Section showing infiltration basin with clogging layer, unsaturated flow to aquifer, and capillary fringe above water table (Bouwer, 2002).

The risk of clogging is a serious limitation in MAR systems. Rainfall events that are intense but not frequent come with high sediment loads in semi-arid regions that can quickly reduce infiltration in basins and percolation tanks. Infiltration rates in arid and semi-arid basins are highly variable due to soil type, sedimentation, and floodwater availability (Steinel, 2012). The use of non-conventional water sources for MAR requires decision-support systems to optimize recharge efficiency and operational feasibility (Rahman, 2011). Strategic approaches to artificial recharge are necessary to address uncertainties in rainfall patterns, groundwater levels, and long-term sustainability (Kulkarni et al., 2024). Biological clogging that happens as a result of microbial growth and chemical clogging because of manganese, iron, or carbonate precipitation can complicate the maintenance (**Figure 9**). However, techniques like routine desilting, alternating recharge basins, and pretreatment of water can be helpful and are often necessary, but it comes with extra costs and operational complexity (Bouwer, 2002; Dillon, 2005).

Another technical issue that can make the recharge efficiency very unpredictable in karstic aquifers is aquifer heterogeneity, which is very common in Mediterranean semi-arid zones. It allows for rapid infiltration as well as rapid contaminant transport in conduits. It also reduces the effectiveness of natural filtration (Fathi et al., 2020). Also, fractured aquifers may store less water than actually predicted, or the release is not even, which in turn limits the recovery efficiency (Dillon et al., 2020). Recharge can also lead to waterlogging or the rise in water tables in some cases, which could damage infrastructure and agriculture if not managed carefully (Bouwer, 2002).

4.2. Water Quality and Environmental Risks

Water quality management is a central challenge in MAR implementation, particularly when using effluent or stormwater (Bahadori, 2024; Day & Senevirathna, 2023). Contaminant mobilization, including arsenic and pharmaceutical compounds, has been observed during recharge operations, highlighting the need for pre-treatment and monitoring (Maeng et al., 2011; Fakhreddine et al., 2021). Monitoring and modeling of recharge processes allow better prediction of water quality outcomes and inform adaptive management strategies (Achilleos et al., 2025; Glass & Stefan, 2015).

MAR could also contaminate the aquifer water quality through Soil Aquifer Treatment (**Figure 10**). Fluctuations in pollutants, including nutrients and microbial content, can pose risks to aquifers used for MAR (Augustin & Baumann, 2025). Soil clogging, chemical interactions, and pathogen infiltration are critical risks requiring mitigation through pre-treatment and monitoring (Mendez & Huhn, 2017). MAR can also impact local ecosystems by altering groundwater levels and affecting dependent vegetation and wetland habitats (Kulkarni et al., 2024).

Geochemical reactions that happen during the recharge could mobilize other contaminants. For example, changes in redox can produce or increase the concentration of arsenic, iron, or manganese in groundwater (Dillon et al., 2020). Also, saline intrusion could be worse if recharge changes pressure balances in the coastal aquifers (Bouwer, 2002). Because of such risks it's important to monitor both recharge water and the response of the aquifer.

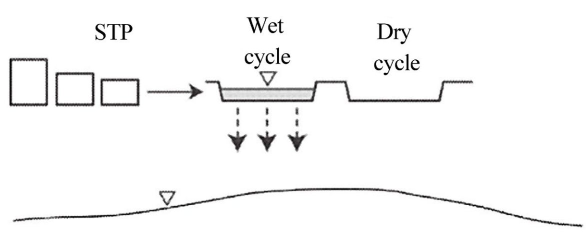

Figure 10. Schematic of Soil Aquifer Treatment (SAT) (Dillon, 2005).

The environmental impacts should also be considered when it comes to MAR. Systems with poor design may disturb the ecosystem. It can also change the flow and reduce water availability downstream. It is a challenge to balance human water needs and ecological sustainability in semi-arid zones (Dillon et al., 2020).

4.3. Economic and Operational Barriers

The capital and operational costs of Managed Aquifer Recharge (MAR) systems vary widely depending on the applied technique, local hydrogeological conditions, and project scale. Surface-spreading methods, such as infiltration ponds and basins, are relatively low-cost and technically simple but require large tracts of land, making them less feasible in densely populated or urban areas. In contrast, well-injection systems, such as Aquifer Storage and Recovery (ASR), offer higher storage efficiency and space savings but involve substantial costs for construction, operation, and maintenance (Bouwer, 2002).

Cost remains one of the principal barriers to MAR implementation. Although MAR can yield substantial long-term benefits, the high expenses associated with water pretreatment, clogging control, and post-operation monitoring often challenge financial sustainability, particularly in low-income or rural regions. Dillon (2005) noted that insufficient emphasis on operation and maintenance has led to the premature failure of many MAR projects. Securing investment and ensuring financial protection through government support or cost-sharing mechanisms remain persistent challenges.

Comprehensive economic assessments are therefore critical for evaluating MAR feasibility. Traditional cost-benefit analyses often underestimate the non-market benefits of MAR, such as enhanced drought resilience, groundwater-dependent ecosystem protection, and improved social well-being. When these co-benefits are accounted for, MAR frequently proves economically viable and socially beneficial (Ross, 2022). Incorporating ecosystem service valuation—such as reduced flood damage, sustained agricultural productivity, and improved water quality—provides a more accurate understanding of MAR's long-term return on investment.

Recent studies emphasize that integrating technical, environmental, and socio-economic dimensions into MAR planning yields more resilient and equitable outcomes (Bonilla et al., 2018; Shubo et al., 2020). Such holistic approaches can guide policymakers in prioritizing projects that deliver both financial efficiency and community-wide sustainability benefits. Developing standardized frameworks for evaluating these multi-dimensional benefits will be essential to justify MAR investments and to scale their implementation across diverse semi-arid regions.

4.4. Social and Cultural Acceptance

Understanding the willingness of the local community is important. Also, cultural norms and practices play an important role in the adoption of MAR. Experience in urban and peri-urban areas indicates that social and governance dimensions are as important as technical design for long-term sustainability (Palma Nava et al., 2022; Joseph & Venu, 2023). In many semi-arid areas, there is a dislike toward treated wastewater use for recharge. Even when it meets the prescribed health and safety criteria. For instance, in Middle Eastern and North African countries, religious and cultural issues have been barriers to the acceptance of wastewater-based

MAR projects.

4.5. Governance and Institutional Challenges

Governance frameworks play a crucial role in determining the success and sustainability of Managed Aquifer Recharge (MAR) initiatives. Effective MAR implementation requires not only technical feasibility but also institutional coordination, stakeholder engagement, and public acceptance (Mankad et al., 2014; Witt et al., 2025). Countries such as Australia and the United States provide valuable examples where clear regulations, well-defined responsibilities, and continuous monitoring have supported MAR development (Dillon et al., 2020). These frameworks ensure technical accountability and establish trust between agencies and the public.

In Australia, MAR governance operates under an adaptive management framework, where recharge projects are approved through staged licensing, ongoing performance evaluation, and transparent reporting. The National Water Initiative and the Australian Guidelines for MAR promote a risk-based approach, balancing water quality protection with operational flexibility. Similarly, in the United States, water banking policies in states like Arizona and California allow for the storage and exchange of recharged water rights, linking MAR to long-term groundwater management and drought resilience strategies. These mechanisms demonstrate how adaptive and market-based instruments can enhance MAR efficiency and accountability.

Table 1. Factors affecting technology choice for water supply (Dillon, 2005).

Method	Typical devolution/scale (m^3/year)	Typical unit cost (US$/$m^3$)	Limits	Relative investigation costs	Relative technical knowledge needed	Relative regulation difficulty
Purifying tablets/filters	Family: 10 - 10^2	<1	Treats only pathogens	–	*	*
Rainwater tanks	Family: 10^2 - 10^3	10	Fails in drought	*	**	*
MAR	Village/town: 10^3 - 10^6	1 - 10	Needs aquifer	****	***	***
Dam and treatment plant	Region: 10^7 - 10^9	10 - 100	Needs dam site	*****	****	***
Desalination	Town/region: 10^3 - 10^7	1 - 100	Needs power, brine discharge	***	*****	*

Note: Asterisks () indicate relative magnitude (more stars = higher level).*

In contrast, many semi-arid countries in Africa and Asia face governance challenges due to weak legal enforcement, fragmented institutional mandates, and limited community participation (Dillon, 2005). The absence of legal recognition of MAR, unclear water rights, and a lack of coordination among agencies hinder effective adoption. For example, until 2016, Italy lacked a defined legislative framework for MAR, delaying the implementation of technically feasible projects. Similarly, ambiguous groundwater rights in Mexico have discouraged investment in recharge schemes.

Beyond regulatory control, effective governance also depends on multi-stakeholder platforms that integrate local users, technical experts, and policymakers. Such collaborative structures facilitate transparent decision-making and equitable allocation of stored water, particularly for transboundary aquifers (Fathi et al., 2020). Strengthening these governance models through legal clarity, adaptive policies, and participatory management is essential for scaling MAR in semi-arid regions.

In **Table 1**, we can see the various factors that influence the choice of technology for water supply systems. These factors help determine the most suitable and sustainable options based on environmental, economic, social, and technical considerations.

The table illustrates key factors influencing the choice of water supply technologies, with asterisks indicating the relative importance of each factor (Dillon, 2005).

4.6. Knowledge Gaps and Capacity Limitations

Knowledge and technical capacity continue to be major bottlenecks in the semi-arid regions. Hydrogeological data are scanty, thus making it very difficult to model aquifer response to recharge. There is also a general limitation in capacity in terms of trained personnel, engineers, hydrogeologists, and regulators who are supposed to design, operate, and monitor MAR systems (Dillon, 2005).

Also, long-term results are not widely available. There are few projects in semi-arid regions with monitoring records longer than 10 - 15 years that leave gaps about aquifer sustainability, in the understanding of clogging behavior, as well as the fate of contaminants (Dillon et al., 2020). This is exactly what prevents moving MAR from an experimental project to a standard practice within water management strategies.

5. Global Experiences and Future Perspectives in Semi-Arid Regions

The challenges identified in Section 4, ranging from technical and economic barriers to governance and social acceptance, are not uniform across regions. However, global experiences demonstrate that many of these obstacles can be mitigated through context-specific innovations, institutional reforms, and community-based initiatives. This section examines how different regions have addressed these challenges, offering practical insights for scaling Managed Aquifer Recharge (MAR) in semi-arid contexts.

Global experiences suggest a move toward integrated MAR systems that combine monitoring technologies, efficient recharge methods, and socio-economic assessments to maximize benefits (Adam et al., 2023; Kazner, 2012; Ross, 2022). Advancements in geophysical assessments, water reclamation, and cost-benefit analysis are expected to improve decision-making, optimize performance, and support the wider adoption of MAR in water-stressed semi-arid and urban regions worldwide (Shubo et al., 2020; Bonilla et al., 2018).

Future MAR developments emphasize climate adaptation, sustainable urban water management, and resilience to droughts (Escalante et al., 2023; Alam et al., 2021). Advances in monitoring, modeling, and treatment technologies are expected to enhance recharge efficiency and mitigate contamination risks (Bahadori, 2024; Day & Senevirathna, 2023). International experiences underscore the importance of integrating MAR with water reuse, low-impact development, and ecosystem preservation strategies to maximize benefits in semi-arid and water-stressed regions (Joji et al., 2021; Bennison & Claro, 2024; Gouahi et al., 2024).

Managed Aquifer Recharge (MAR) has been implemented worldwide to enhance groundwater storage, improve water security, and mitigate the effects of climate variability (Escalante et al., 2023; Shubo et al., 2020; Bonilla et al., 2018). Experiences from Africa, Latin America, and Asia highlight that site-specific hydrogeological assessment and careful selection of recharge methods are critical for success (Gouahi et al., 2024; Ebrahim et al., 2020; Bennison & Claro, 2024). In semi-arid basins, such as Souss in Morocco, infiltration basins and check dams have proven effective in augmenting aquifer storage while managing seasonal variability (Gouahi et al., 2024; Renganayaki & Elango, 2013).

MAR has been successfully applied in diverse global contexts, including Brazil, Ghana, and Latin America, reflecting adaptation to local hydrology, climate, and socio-economic conditions (Shubo et al., 2020; Bonilla et al., 2018; Adam et al., 2023). In Brazil, urban and peri-urban MAR schemes focus on both groundwater replenishment and urban water management, demonstrating flexible approaches to different hydrogeological and regulatory conditions (Shubo et al., 2020). Similarly, an inventory of MAR initiatives in Latin America and the Caribbean shows that both small- and large-scale schemes have been implemented, often combining surface spreading and injection techniques to enhance recharge efficiency (Bonilla et al., 2018).

Managed Aquifer Recharge (MAR) has been increasingly applied in semi-arid regions worldwide to address water scarcity, climate variability, and groundwater depletion (Joji et al., 2021; Witt et al., 2025). Experiences from diverse countries highlight both successes and challenges in adapting MAR techniques to local hydrogeological and socio-economic conditions.

In **Table 2**, we present selected global case studies of Managed Aquifer Recharge (MAR) categorized by geographic zone. The table provides an overview of how MAR has been applied in various regions, illustrating differences in approaches, objectives, and local contexts.

In Cyprus, the Akrotiri MAR system demonstrates the potential of MAR to improve water security and maintain aquifer sustainability. Long-term monitoring of water quality and hydrogeochemical dynamics revealed that MAR can support aquifer replenishment without compromising water quality when properly managed (Achilleos et al., 2025). Similarly, Türkiye has implemented a range of MAR schemes over recent decades, combining infiltration ponds, recharge wells, and urban runoff capture to enhance groundwater storage. Historical and contemporary assessments indicate that integrating engineered solutions with natural recharge processes has proven effective in semi-arid contexts (Korkut et al., 2025).

Table 2. Representative global case studies of Managed Aquifer Recharge (MAR) by geographic zone.

Zone	Country	Location type (Urban/ Rural)	MAR Techniques/ Source Water	Scale/Volume	Key Challenges/Lessons
Africa	South Africa	Urban	Borehole injection	Drought-prone region	Water security, drought resilience
Africa	Kenya	Rural	Sand dams (in channel)	Village/farm scale	Seasonal water scarcity
Africa	Sub-Saharan Africa	Rural	Sand dams/small percolation structures	Community scale	Seasonal water scarcity, low infrastructure
Middle East & N. Africa	Jordan	Semi-rural	Floodwater infiltration/small dams	Semi-arid basin (~60,000 - 6,700,000 m^3/yr depending on site)	Site selection, siltation, turbidity, variable hydrogeology
Middle East & N. Africa	Cyprus	Coastal/ urban	Treated wastewater recharge	Pilot project	Saline intrusion, water quality, social acceptance
South & East Asia	China	Urban	Karst aquifer recharge	Semi-arid karst zone	Complex hydrogeology, quality monitoring
South & East Asia	India	Rural	Village ponds + recharge wells	Village-scale (~26,000 - 62,000 m^3/yr)	Community involvement, monitoring, small-scale governance
Europe & Mediterranean	Spain	Rural	Infiltration ponds	Alluvial aquifer/semi-arid inland	Nitrate pollution, rural water supply, and socio-economic feasibility
Europe & Mediterranean	Spain	Coastal	Coastal aquifer MAR	0.2 hm^3/yr	Salt intrusion mitigation, dual aquifer complexity
Europe & Mediterranean	Spain	Urban	Treated/reclaimed water recharge	Pilot/municipal scale	Urban integration, water quality, and cost
Europe & Mediterranean	Italy	Urban	Infiltration basins/ASR	Pilot & municipal scale	Legal framework delay, water quality, and institutional support
Australia/ Oceania	Australia	Urban/ Agriculture	Infiltration basins/ASR/ agricultural MAR	Cotton irrigation region/municipal	Integrating MAR with surface water, cost-sharing, and long-term sustainability
North America	USA	Urban/ Rural	Flood MAR/basin recharge	Semi-arid valley	Recharge efficiency, modeling, and regulatory clarity
Latin America & Caribbean	Brazil	Urban/ Rural	Various MAR techniques	Emerging region	Technical & regulatory gaps

Continued

Europe & Mediterranean	Italy (Friuli Venezia Giulia)	Semi-rural	Managed aquifer recharge with multi-sectoral use	Regional scale	Groundwater decline mitigation, stakeholder involvement, and multi-sector integration
Middle East & N. Africa	Saudi Arabia	Semi-rural	Recharge wells for desalinated water storage	Regional scale	Integration with desalination, governance, and operational costs

Note: This table presents selected illustrative examples of MAR implementation across different regions. Many additional projects exist worldwide; the cases included here highlight a diversity of techniques, scales, and governance contexts rather than providing an exhaustive inventory.

Global experiences also emphasize the need for robust governance, monitoring, and adaptive management. In developing countries, implementation challenges often arise due to limited technical expertise, inadequate regulatory frameworks, and resource constraints (Witt et al., 2025). Joseph and Venu (2023) highlight that risk management, including contamination control, aquifer clogging prevention, and stakeholder engagement, is critical to ensure the long-term success of MAR projects.

Future perspectives suggest that semi-arid regions will increasingly rely on MAR as a climate adaptation strategy. Joji et al. (2021) note that integrating MAR into broader water resource management plans can enhance resilience against droughts, urbanization pressures, and changing precipitation patterns. Advances in monitoring technologies, data-driven decision-making, and predictive modeling are expected to improve recharge efficiency and risk mitigation (Witt et al., 2025). Achilleos et al. (2025) further emphasize that understanding water quality dynamics and the interactions between recharge water and native aquifers will be central to optimizing MAR design in semi-arid regions.

Moreover, international experiences indicate that hybrid approaches—combining traditional surface spreading with subsurface injection methods—can maximize recharge while minimizing environmental risks (Korkut et al., 2025; Joji et al., 2021). Future MAR initiatives are likely to focus on integrating renewable energy sources, decentralized recharge systems, and multi-functional designs that support both urban water management and ecosystem preservation (Joseph & Venu, 2023).

5.1. MAR in Semi-Arid Italy

Italy is an important European example of MAR under semi-arid conditions because decreasing precipitation rates (**Figure 11**) and deepening underground water tables in Mediterranean regions raise issues of long-term water security. Before 2016, there was no clear legislative framework to significantly allow MAR implementation despite high technical potential. With the national guidelines' introduction and, finally, through an amendment to the water law where MAR was formally recognized, this has most recently been shown in a wave of projects that

EU and national funding are supporting.

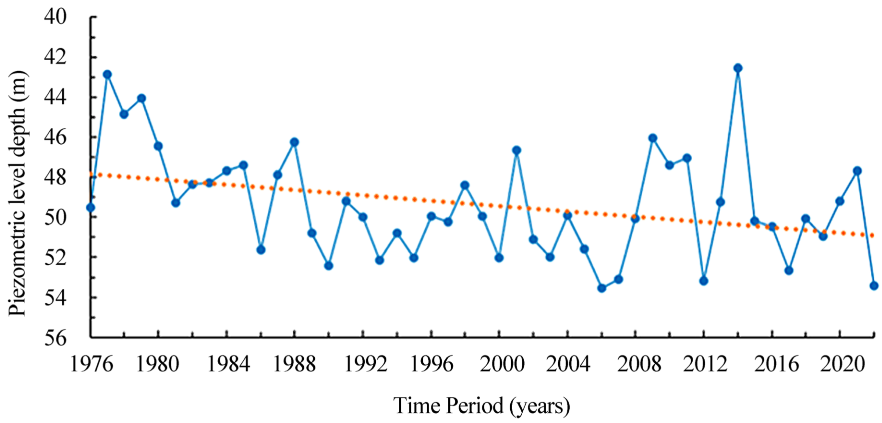

Figure 11. Trend of piezometric levels (1976-2022) in FVG region (Sufyan et al., 2024).

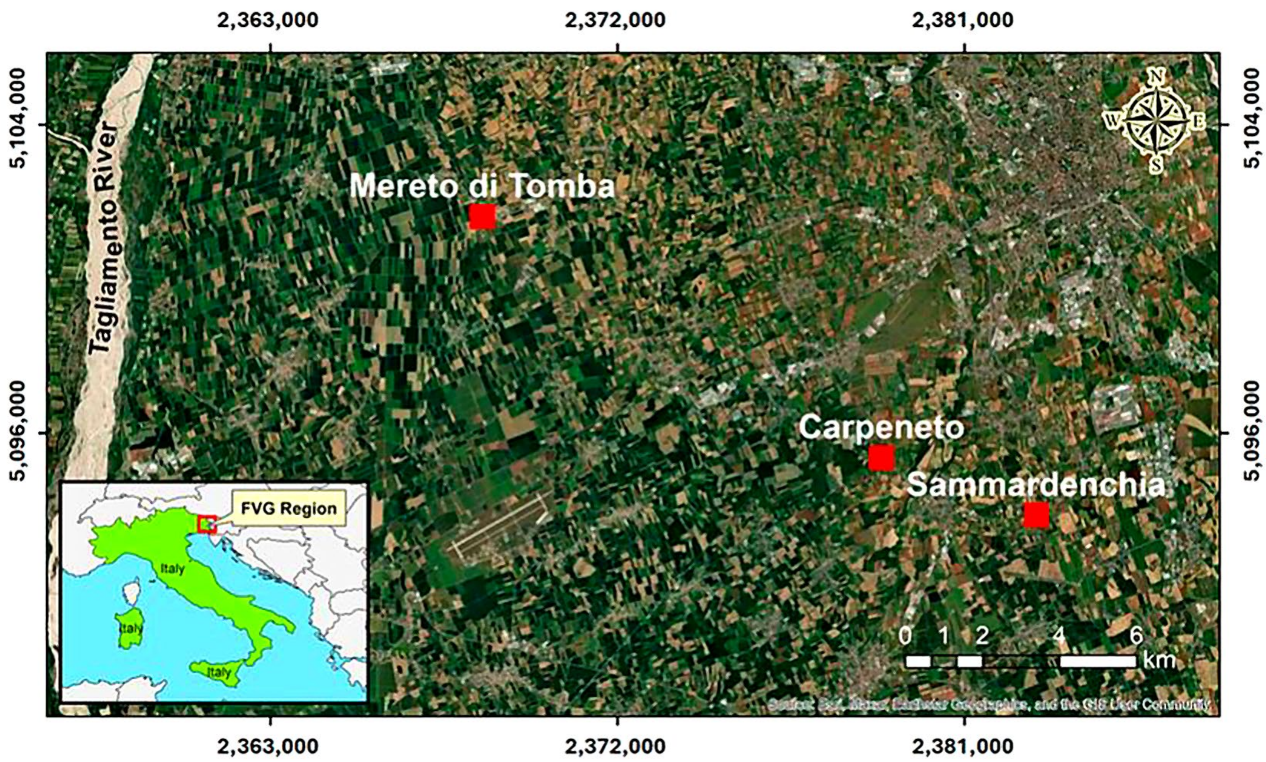

Figure 12. Map of upper Friuli plain, northern Italy, showing three recharge sites (Mereto di Tomba, Carpeneto, Sammardenchia) (Sufyan et al., 2024).

Projects TRUST, AQUOR, MARSOL, Life REWAT, and WARBO are a few of the efforts depicting this change that have tested and demonstrated MAR systems all over the country. In addition to fulfilling groundwater needs for human consumptive uses, Friuli Venezia Giulia (FVG) (Figure 12) has implemented managed aquifer recharge to mitigate falling groundwater levels by providing recharge when piezometric heads have declined approximately 3 m in recent decades because of decreased overall recharge coupled with increased extraction. Here, recharge would fulfill multi-sectoral water needs, from domestic supply to agriculture to fish farming thus illustrating how MAR can satisfy both human and environmental demands.

These projects put forward the urgent need to embed MAR into a wider policy on water and land management and into the process of elaborating a methodology for stakeholder involvement in order to guarantee effective operation and monitoring.

The Italian experience has perfectly demonstrated how legislative recognition and institutional support can fast-track the uptake of MAR in semi-arid European contexts by changing pilot studies into operational systems at the regional scale.

5.2. MAR in the Middle East and North Africa

In the Middle East, semi-arid and arid regions present some of the most severe groundwater problems in the world, with issues ranging from aquifer depletion to saline intrusion compounded by rapid urbanization. MAR has been tried as a supply augmentation scheme and also as a scheme for managing water quality. Treated wastewater recharge has been tried in Oman, Qatar, and Tunisia but actual implementation is very limited due to cultural resistance and also because it is perceived to pose health risks.

Saudi Arabia invested in recharge wells as storage of excess desalinated water to be used during a drought. Small dams and recharge releases in North Africa have also been used to capture the episodic flood flow for aquifer replenishment (Dillon, 2005). Therefore, these examples justify both optimistic and pessimistic views about obtaining MAR success in such regions that badly need water but pose governance and social barriers.

5.3. MAR in Sub-Saharan Africa

In rural sub-Saharan Africa, the sand dams and subsurface dams became leading MAR technologies. (**Figure 1**). Built across seasonal streams, these dams trap sediment but actually store water within them. It then percolates into the underlying aquifers. This system has been largely used in Kenya and Tanzania. It also ensures the security of village water supply to reduce vulnerability on seasonal droughts (Dillon, 2005).

5.4. MAR in the USA and Australia

The USA and Australia are good examples of the most advanced MAR implementation. In Arizona and California, surface water storage and treated wastewater have been used for groundwater recharge (**Figure 13**). Governance gaps discussed in Section 4.5, such as unclear water rights and poor regulatory enforcement, have been successfully addressed in countries like the USA through adaptive water banking policies and transparent licensing frameworks that link MAR operations with groundwater rights. Governance frameworks like state regulation and water banking policies are the reasons for the success (Dahlke et al., 2018; Dillon, 2005). Australia has adopted frequent use of MAR for the management of urban stormwater. Infiltration basins and ASR wells were used in Adelaide and Salisbury that store water from wet months for later use in irrigation, industry, etc. MAR in Australia has detailed guidelines at the national level. They present technical, legal, and environmental standards (Dillon et al., 2020). This kind of policy support, together with technical capacity, shows how the concept of integration of MAR with water resource management in semi-arid regions is realizable.

As noted in Section 4.3, high operational costs often threaten long-term sustainability. In Australia, however, strong government co-funding and cost-sharing models have reduced financial risks and ensured continuous operation of large-scale MAR schemes.

Figure 13. Application of storm water on an almond orchard for groundwater recharge in California, USA (Dahlke et al., 2018).

Collectively, these international experiences illustrate that the challenges identified earlier, technical, economic, institutional, and social, are not insurmountable. When supported by adaptive governance, adequate financing, and active community participation, MAR systems can deliver sustainable outcomes even under the demanding conditions of semi-arid regions. Linking local innovation with robust institutional frameworks is, therefore, key to replicating global success stories across diverse settings.

5.5. Future Perspectives for MAR in Semi-Arid Regions

Managed Aquifer Recharge (MAR) holds significant potential for enhancing water security in semi-arid regions, but its widespread adoption requires continued innovation and strategic planning. Future perspectives focus on integrating advanced monitoring technologies, optimizing recharge methods, and addressing emerging contaminants. Additionally, strengthening governance frameworks, promoting stakeholder engagement, and combining MAR with complementary water management strategies can improve system efficiency and sustainability.

Advancements in modeling, policy development, and community-based approaches are expected to play a pivotal role in expanding the applicability and resilience of MAR under changing climatic and socio-economic conditions.

Looking ahead, Managed Aquifer Recharge (MAR) is poised to play a central role in addressing water scarcity and climate challenges in semi-arid regions. The future of MAR depends on a holistic approach that integrates technological innovation, nature-based design, robust governance, and community participation. Together, these elements can transform MAR from a niche intervention into a mainstream tool for sustainable water management.

Integration with Nature-Based Solutions (NBS)—such as wetlands, green infrastructure, and sponge city concepts—can greatly enhance MAR performance. These hybrid systems not only increase recharge capacity but also regulate floods, improve water quality, and restore ecological balance in urban and peri-urban environments. Advances in monitoring and modeling technologies, including remote sensing, isotopic tracers, and real-time sensor networks, will further strengthen MAR design and management. In data-scarce semi-arid regions, tools such as GIS and numerical models like MODFLOW can become essential planning instruments for quantifying recharge rates and tracking contaminant pathways (Fathi et al., 2020; Dillon et al., 2020).

Future research must also focus on emerging contaminants—including pharmaceuticals, PFAS, and microplastics—that pose risks to both groundwater and public health. Developing advanced filtration media and bio-based treatment systems can help safeguard aquifer quality. Equally important is the scaling up of demonstration projects through regional centers of excellence and capacity-building hubs, which can facilitate technology transfer, standardize design practices, and reduce the failure of poorly planned projects (Dillon, 2005).

At the institutional level, policy and governance reforms will be pivotal. Clear legal frameworks, harmonized water rights, and transboundary aquifer management mechanisms can create an enabling environment for MAR implementation (Dillon et al., 2020). Finally, community engagement must remain at the heart of future MAR initiatives. Transparent communication, participatory planning, and risk-based regulatory approaches are essential to build public trust—especially in systems utilizing reclaimed or treated wastewater.

Taken together, these priorities form a comprehensive research and policy agenda for advancing MAR in semi-arid regions. By integrating nature-based designs, technological innovation, governance reform, and social inclusion, MAR can evolve into a resilient and equitable solution for long-term groundwater sustainability and climate adaptation worldwide.

6. Conclusion

Groundwater remains a critical resource in semi-arid regions, where surface water is scarce, rainfall is highly variable, and climate pressures intensify water insecurity. This review highlights the potential of Managed Aquifer Recharge (MAR) as a sustainable strategy to address these challenges. By using aquifers as subsurface storage, MAR improves water availability, reduces evaporation losses, enhances water quality through natural filtration, and mitigates land subsidence and saline intrusion. Its capacity to store episodic floodwaters makes it an effective climate adaptation measure aligned with global sustainability goals.

Despite its promise, MAR implementation faces technical, social, and institutional barriers. Issues such as clogging, aquifer heterogeneity, contaminant mobilization, and the presence of emerging pollutants like PFAS and microplastics require continuous research and monitoring. In addition, socio-cultural resistance to wastewater reuse, high initial costs, and weak legal frameworks constrain widespread adoption. Case studies from India, sub-Saharan Africa, Australia, and Mediterranean countries underscore the importance of local context, community participation, and supportive policy environments for successful outcomes.

The future of MAR in semi-arid regions lies in integration, innovation, and governance. Incorporating MAR within broader water management systems—alongside flood control, drought mitigation, and ecosystem preservation—can enhance resilience. Advances in modeling, sensor networks, and nature-based solutions offer opportunities to optimize recharge performance. Strengthening legal frameworks, building technical capacity, and engaging communities are equally vital to ensure responsible scaling. With science, policy, and public support working together, MAR can serve as a cornerstone of sustainable groundwater management in semi-arid regions worldwide.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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