SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I6P101

Volume 13 Issue 6, 1-19, June 2026
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Review Article

Assessing the Role of Managed Aquifer Recharge Systems as a Mitigation Strategy Against Climate Change in Groundwater Resources: A Review Paper

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Received: 04 March 2026 Revised: 03 April 2026 Accepted: 02 May 2026 Published: 30 June 2026

***Abstract** - Managed Aquifer Recharge (MAR) has emerged as a significant strategy to protect groundwater from climate change impacts like flooding, droughts, water shortages, and saltwater intrusion. This literature review examines MAR's ability to shield aquifers, secure supply levels, and replenish aquifer systems that have been depleted, especially in semi-arid and coastal regions. Nevertheless, MAR's performance is very dependent on local hydrogeological conditions, water quality, and institutional and regulatory structures already in place at each site. There are several obstacles to implementing MAR, including: limited data; the cost of investment and operation; public perception; fragmented legislation; and lack of long-term monitoring of effects. The literature review illustrates that problems with economics, governance, and community involvement can pose as many challenges to MAR success as does technical feasibility. Integrated planning, adaptive management, and comprehensive monitoring are all essential, but MAR can still serve as an integral component of climate adaptability portfolios. Implementation of MAR must be done in a way that is contextual to specific sites, and included as part of broader, adaptable water governance structures to ensure both long-term sustainability and equitable outcomes.*

***Keywords** - Drought, Water scarcity, Water policy, Case-study, Artificial-recharge.*

1. Introduction

The amount of groundwater worldwide is being depleted at alarming rates due to a number of different factors, such as growing populations, changing climates, and general mismanagement of this limited resource. Droughts are becoming increasingly common and severe; thus, the unpredictability of rainfall has caused surface water supplies to become unreliable and has caused an un-sustainable reliance on groundwater abstractions (Wendt et al., 2020; Scanlon et al., 2012; Kuang et al., 2024). Most notably impacted are arid and semi-arid areas, as they primarily rely on groundwater to provide potable water for drinking and irrigation purposes (Sherif et al., 2023; Hayat et al., 2021). Threats to groundwater sustainability include overpumping, which causes land subsidence, saltwater intrusion, and degrades water quality (De Carlo et al., 2024; Dillon et al., 2019).

As groundwater depletion continues to worsen, Managed Aquifer Recharge (MAR) has emerged as a viable strategy for adapting to climate change impacts and enhancing groundwater resiliency to these impacts. MAR is an inter-disciplinary practice of intentionally increasing the natural groundwater recharge process using surface runoff, treated wastewater, and/or stormwater to recharge aquifers (primarily through infiltration basins, injection wells, and/or bank filtration) (Sufyan et al., 2024; Maliva, 2014; Sprenger et al., 2017). The primary goals of MAR are to recharge the aquifer, improve water quality, mitigate drought/flood events, and prevent saltwater intrusion to enhance sustainable water management and wetland ecosystem health (Escalante et al., 2019; Ajjur & Baalousha, 2021; Guyennon et al., 2017). Since the 1960s, MAR has been adopted worldwide, with an estimated 5% annual growth rate (Dillon et al., 2019). Although recharge volumes through MAR account for less than 2.5% of total groundwater withdrawals in countries utilizing MAR (Grinshpan et al., 2021; Dillon et al., 2019), multiple examples across various hydrogeologic and climatic scenarios demonstrate that MAR provides additional benefits to enhance groundwater storage, reduce vulnerability to extreme climate events, and ultimately enhance agricultural production (e.g., California’s Central Valley (Reznik et al., 2022; Dahlke et al., 2024); Mediterranean region (Henao Casas et al, 2022; Guyennon et al., 2017); Middle East and North Africa (Sherif et al., 2023); and South Asia (Hayat et al., 2021)). The success of MAR as an adaptive measure to climate change relies on a variety of interconnected processes related to hydrogeologic, technical, institutional, and socio-economic factors present at a specific site. Favorable hydrologic characteristics at a site include the presence of an aquifer that allows water to move through it easily, as well as sufficient quantities of high-quality water to recharge it. Additionally, the chosen recharge method itself, including its design and implementation, also plays a critical role in the success of MAR (Gonzalez et al., 2024; McCurry & Pyne, 2020; Reznik et al., 2022). Successful and cost-effective long-term MAR projects require institutions and stakeholders that will help support and implement them (Gonzalez et al., 2024; McCurry & Pyne, 2020; Reznik et al., 2022). An excellent example of the institutional impact of MAR can be seen in the recent passage of legislation in California regarding groundwater property rights to encourage the establishment of MAR-type arrangements (Reznik et al., 2022). Further, a supportive regulatory environment may be beneficial to facilitate the incorporation of MAR into local water management planning for Spain and Italy (Reznik et al., 2022; Sufyan et al., 2024; Escalante et al., 2019).

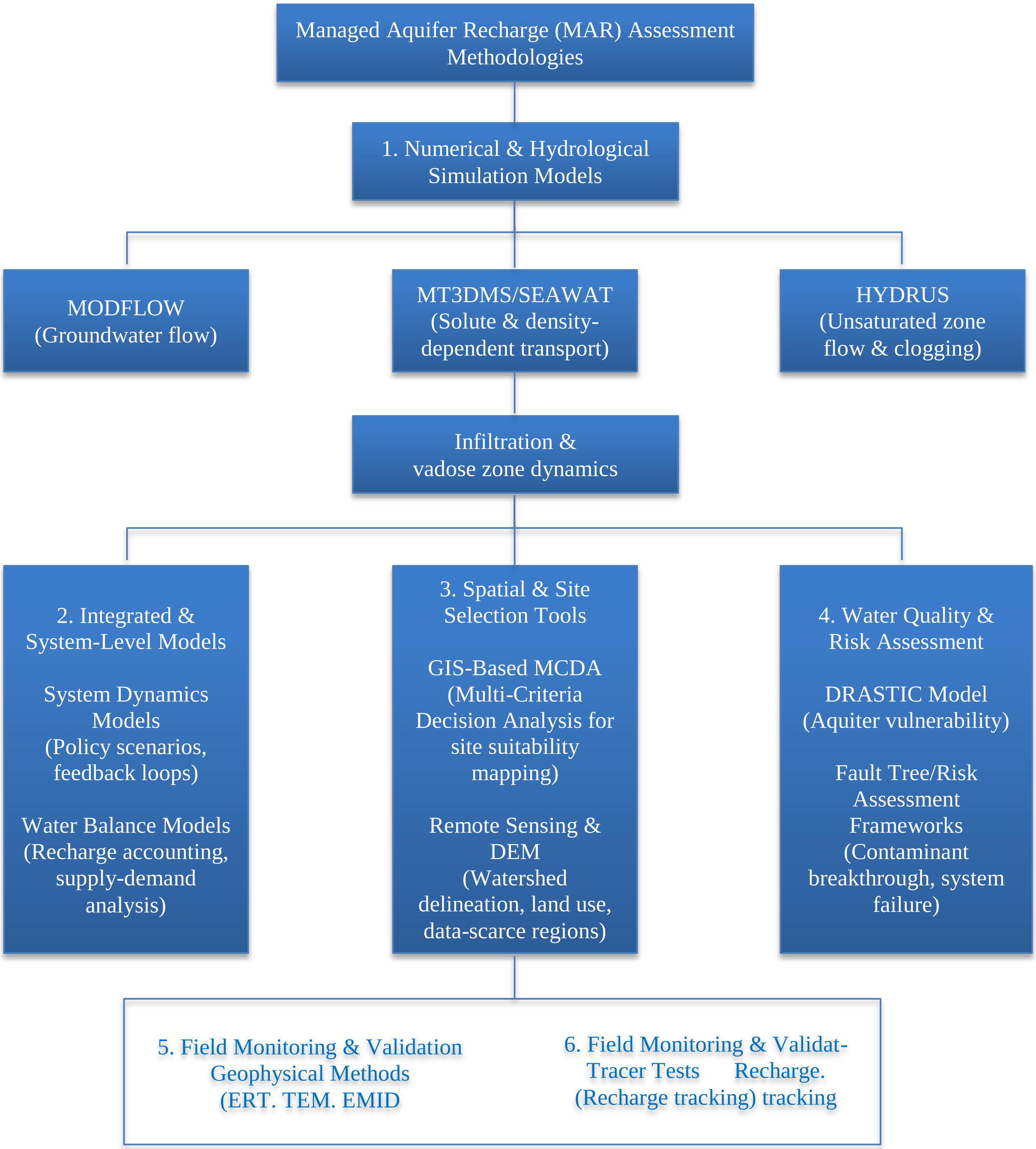

Fig. 1 MAR assessment methodologies

In addition to replenishing groundwater, MAR has many other co-benefits. MAR can help encourage natural attenuation processes, which can reduce the amount of global energy use and CO2 emissions associated with pumping groundwater. MAR can also restore ecosystem functions to promote flood mitigation or wetland restoration (Alelaimat et al., 2023; Bekele et al., 2018; Escalante et al., 2019; He et al., 2021; Henao Casas et al., 2022; Stefan & Ansems, 2017). However, while MAR has multiple benefits, it is not without challenges (i.e., it will need to be monitored beyond a pilot scale and evaluated using different criteria); achieve social acceptability (specifically concerning the use of reclaimed water); and develop cost effective and locally relevant MAR solutions (Sheik et al., 2024; Sherif et al., 2023; Sufyan et al., 2024).

There are many gaps in the existing literature regarding MAR that limit its utility as a climate change response mechanism. Many papers have focused solely on the technical and hydrological feasibility of MAR, generally neglecting socio-economic, institutional, and governance issues that are essential for successful implementation in the real world. The majority of documented MAR success stories have occurred in high-income, data-rich areas such as California, Australia, and Western Europe, thereby creating an overconfidence bias and limiting insight into MAR's potential in low-income, data-scarce regions such as Africa and some parts of Asia. In addition, there is a paucity of empirical evidence based upon long-term, large-scale monitoring of MAR systems, which limits the validity of many studies that rely upon either short-term pilot project experience or modeling assumptions that obscure the true impacts and sustainability of MAR. Given the above-identified critical gaps and the growing interest and recognition of MAR's potential, the primary contributions of this review paper are to provide a critical analysis of MAR as a strategy for mitigating climate-related impacts on groundwater resources. Using a comprehensive synthesis of recent literature and case studies from all corners of the globe, the paper demonstrates that MAR suitability should not only focus on the technical feasibility of MAR, so therefore the paper's central contribution is to rethink MAR as not simply a stand-alone technical fix, but rather as a context-specific, governance-intense component of adaptive water management portfolios, only viable if implemented within a robust set of institutional, economic, and monitoring frameworks.

2. Methodology

The review synthesizes methodologies used in MAR globally, and the flow chart shown below shows that these methods can be integrated. In order to assess the possibility of Managed Aquifer Recharge (MAR) as an adaptive response to lessen the stress that climate change is placing on groundwater resources, the review synthesised peer-reviewed literature. This review will discuss the most recent MAR best practice, building on previous research.

2.1. Literature Search and Selection

For the purpose of finding out more about managed aquifer recharge systems, a thorough literature search was carried out by using reputable scientific databases such as Web of Science, Scopus, and Google Scholar. The search centred around the following key terms and Boolean combination, "Managed Aquifer Recharge," alongside keywords like “groundwater”, “drought, " “climate change adaptation”, “sea level rise”, and “water policy”. Recent literature from 2015 onward was prioritised, but foundational studies and key reports were also considered for background information.

Inclusion Criteria: (1) Expert-reviewed journal articles, book sections, and authoritative technical reports. (2). Case studies documenting MAR in different hydroclimatic and policy settings (e.g., California, Spain, Mediterranean, MENA, Australia). (3). Modelling studies analysing MAR for drought mitigation, saltwater intrusion, or supply uncertainty (Guyennon et al., 2017; He et al., 2021). (4). Articles focused on combining policy/institutional, economic analysis, and challenges to MAR adoption (Kourakos et al., 2023; Sherif et al., 2023). Exclusion Criteria (1). Articles with primary focus outside groundwater, climate adaptation, or MAR. (2) Non-peer-reviewed opinion pieces unless containing essential technical overviews or data.

2.2. Data Extraction and Categorization

From each selected article, the following information was systematically extracted: Study location and hydroclimatic context, MAR technology, design, and operational features. Groundwater resource outcomes (e.g., changes in aquifer storage, quality, reliability), climate change impacts addressed (drought, sea-level rise, supply variability), modelling approach and key findings where applicable, socio-institutional and policy context, including success factors and challenges, quantitative results and qualitative judgments on MAR’s performance as a mitigation/adaptation strategy. This information was entered into a structured database for comparative analysis.

2.3. Thematic and Critical Analysis

A thematic approach was used to group evidence along the key dimensions for climate change adaptation:

(1). Effectiveness of MAR for drought resilience. (2). Performance of MAR in combating seawater intrusion under sea-level rise. (3). Capacity of MAR to buffer water supply variability. (4). Policy, regulatory, and economic frameworks enabling or constraining MAR implementation. (5). Environmental and social co-benefits, risks, or trade-offs. Qualitative synthesis was complemented by cross-case comparison, and where available, quantitative modelling results were summarized and contrasted. Particular attention was given to examining: Where and why MAR performance is maximized or limited. Uncertainties, knowledge gaps, and reported maladaptation risks-recurring institutional, financial, or technical barriers.

2.4. Quality Assessment and Bias Mitigation

To improve robustness, the review cross-checked multiple independent sources for all major conclusions, identified telling differences and uncertainties, and was careful not to overemphasize single case studies (Dillon et al., 2019; Imig et al., 2022; Sufyan et al., 2024).

The review contained specific limitations to context, and a broader whole of literature limitations, such as the limited reporting of failed MAR projects, and the lack of long-term monitoring.

The findings were put together in order to provide a multifaceted evaluation of MAR as a climate change mitigation and adaptation approach for groundwater resources. Strengths and weaknesses, context-specific factors, and policy implications were reported in accordance with state-of-the-art practice for groundwater/climate adaptation reviews (Dillon et al., 2019; Escalante et al., 2019; Sufyan et al., 2024).

3. Overview of Managed Aquifer Recharge (MAR) Technologies

The Table (1) below lists some of the relevant studies from the reviewed studies, detailing their MAR types, modelling techniques, parameters investigated, and main contributions.

Table 1. Overview of MAR studies

Reference	Year	MAR Types	Modelling Techniques	Parameters Investigated	Study Contribution
Hashemi, H. et al.	2015	Artificial Recharge (Floodwater spreading)	Coupled rainfall-runoff (Qbox) and MODFLOW groundwater flow model	Climate Scenarios (Rainfall, temperature, evaporation), Runoff, and recharge	Modelled adaptation scenarios showing groundwater decline reversal possible through abstraction decrease and recharge expansion in arid Iran.
Ringleb, J. et al.	2016	Well, spreading methods, ASR/ASTR, IBF, in-channel modifications	Groundwater flow, unsaturated flow, solute transport, reactive transport	Recovery efficiency, clogging, geochemical processes	Groundwater flow models were the most frequently applied tools for MAR assessment across various methods.
Guyennon, N. et al.	2017	MAR, Surface Reservoir Increase	Integrated modelling (unspecified details)	Groundwater overexploitation, climate change scenarios (RCP 4.5/8.5)	Assessed MAR effectiveness for climate adaptation in a semi-arid Mediterranean catchment, especially against groundwater overexploitation exacerbated by irrigation.
Rozman, D. et al.	2019	Infiltration ponds, recharge wells	BILAN (hydrological), MODFLOW (hydraulic)	Hydraulic conductivity, turbidity, recharge rates, and soil moisture storage	Demonstrated MAR via infiltration ponds and wells improves the water budget and acts as an effective drought mitigation strategy in Czech hard rock aquifers.
Alam, S. et al.	2021	Spreading methods (Ag-MAR, SAT)	GIS-based Multi-Criteria Decision Analysis (MCDA)	Soil type (clay loam C), water quality (metals, DOC, E. coli), land use	Proposed criteria framework linking MAR type selection to site conditions and assessed pollutant removal capability.

Zhao, M. et al.	2021	Infiltration area optimization (Implied spreading methods)	System Dynamics (SD) modelling	Infiltration rate, hydraulic conductivity, water rights, irrigation demand	Found MAR adoption drives a positive feedback loop, improving resilience against single and multi-year droughts by accumulating entitlements.
Wendt, D. E. et al.	2021	MAR operations in heavily stressed aquifers	Analytical method (SGI/SPI indices) on long-term data	Precipitation, Groundwater levels, MAR volumes	Showed long-term MAR operations alleviate groundwater droughts and cause a long-term rise in unconfined groundwater levels in California.
Henao Casas, J. D. et al.	2022	MAR systems (Los Arenales aquifer)	Groundwater statistical methods (SGI/SPI, trend analysis)	Groundwater levels, precipitation, and MAR operations	Concluded MAR effectively alleviates drought impacts, showing faster recovery and less susceptibility to drought compared to areas without MAR.
Pavelic, P. et al.	2022	Farm-scale pilots using dug wells, Roof/Field runoff recharge	Field monitoring, Numerical modelling (Pavelic et al., 2019)	Recharge volumes (5–530 m3/year), water quality, groundwater velocity	Found recovery of recharge water from wells was low (0%–39%) in high-velocity zones, but water was retained locally, improving security.
Ala'Alelimat, A. et al.	2023	GIS-based MAR, injection wells	MODFLOW (groundwater flow simulation)	Hydraulic Conductivity, Porosity, Recharge/Abstraction Rates	Demonstrated MAR with a 10% precipitation increase could raise water tables by 1.96% to 3.12% in Jordan's alluvium aquifer.
Abd-Elaty, I. et al.	2024	Rainwater Harvesting-MAR (RWH-MAR)	Watershed modelling System (WMS), SEAWAT modelling	Rainfall, Flood volume, Hydraulic conductivity, TDS, metals, pathogens	Showed RWH-MAR enhanced groundwater availability potential substantially, linking it to flash flood mitigation in arid regions.

Managed Aquifer Recharge (MAR) has grown from a minor hydrogeological intervention to a widely accepted approach in increasing aquifer resiliency as climate change and anthropogenic stresses grow. However, this has not been a uniform application either in the technologies or in the context of their use. A detailed inspection of the literature shows a gradual development in both technical complexities and conceptual context, but also uncovers a consistent gap in how MAR technologies are chosen, implemented, and assessed in widely differing socio-hydrological contexts. Earlier MAR applications mostly relied on surface spreading methods like spreading basins and percolation tanks, especially in arid and semi-arid areas. Hashemi et al. (2015) modelled the spreading of flood water in Iran as a way to reverse current groundwater depletion under climate stress, which showed the attractiveness of low-tech but land-intensive solutions in data-poor but runoff-rich regions. Along similar lines, Maliva (2019) and Ringleb et al. (2016) reviewed the global presence of surface spreading methods, which they identified, but indicated that the success of such techniques critically depended on the nature of the soil through which the released water passed and the sediment load that was carried. These two variables are well-known but generally ignored in applications of MAR in initial feasibility studies, but are of great concern. These spreading methods are often praised for their simplicity and for the filtration that they naturally provide (Dillon et al., 2019; Sufyan et al., 2024). They do, however, have drawbacks, in that they require a huge amount of land and are prone to the clogging of the surface bed, both in the case of an increased irrigational area, applied to affected areas with turbid source waters, which are also poorly pre-treated (Gaballah et al., 2024; Rozman et al., 2019).

In line with this ongoing land limitations due to urbanisation, subsurface techniques and well-based methods have become prevalent. Particularly in limited aquifers or highly populated areas, Aquifer Storage and Recovery (ASR) and its variant Aquifer Storage Transfer and Recovery (ASTR) have become viable land-efficient options (Dillon et al., 2019). Ala'Alelimat et al. (2023) used MODFLOW to simulate injection wells in Jordan's alluvial aquifers and showed water table recovery at modest but significant rates in moderate recharge situations. However, as warned by Sherif et al. (2023), such systems require much technical sophistication, very high water quality control programs, and they need frequent maintenance, all factors that are rarely evident in low-resource settings. Also, the very assumption that ASR/ASTR systems inherently provide greater water security ignores the fact that a degree of recovery inefficiency must be endured. Pavelic et al. (2022) showed that recovery rates might be as low as 0% to 39% in high-velocity aquifer situations, which, of course, leads to questions of the reliability of stored water recovery in times of greatest need.

In conjunction with such engineered recharge, indirect methods, including methods such as Soil Aquifer Treatment (SAT) and riverbank filtration, have been utilized for their dual benefits of increasing the water supply at the same time as improving water quality by means of natural attenuation. Bekele et al. (2018) cited SAT as highly successful in Israel, Australia, and the U.S., where water supply that was only partially treated would undergo further purification through the percolation process of groundwater storage. However, this again, “natural treatment” does not render the process foolproof. Abd-Elaty et al. (2024) warn that if attention is not paid to the examination of source waters, contaminants such as pathogens, heavy metals, and emerging micropollutants will exist or even change into still more dangerous compounds during the time they go through the aquifer material. The literature on these practices usually emphasizes the attenuation process, presuming it has worked efficiently, but without any supporting evidence of conventional experimentation and long-term monitoring (Sufyan et al., 2024).

Recently, interest has been shown in the urban and decentralized MAR approaches to recharge, as cities identified stormwater as an important resource to use to replenish aquifers. Methods such as the introduction of permeable pavements, rain gardens, and the installation of rooftop rainwater utilization systems have been increasingly incorporated into green planning strategies (Dillon et al., 2019; Moazzem et al., 2024). Sherif et al. (2023) indicate that there are possibilities for desert cities in water-scarce urban communities all over Asia and Africa to increase local water security through small-scale recharge methods. Nevertheless, they must face the paradox that while the recharge methods are decentralised in plan, their success depends on centralised methods of institutional backing, cleaning, maintenance, quality control, and training programs for local people, resources, and systems that are not always available when needed. (Basel et al., 2022).

Table 2. MAR technology types and applications

MAR Technology	Typical Applications	Pros	Limitations & Considerations
Infiltration basins/ponds	Rural; floodplain; stormwater	Simple, natural treatment, low-cost	Large land area; clogging risk
Percolation tanks, flooding	Seasonal/monsoon regions	High-volume recharge; agriculture link	Variable water availability, siltation
Check/sand/subsurface dams.	Ephemeral streams, arid zones	Water storage, evaporation reduction	Limited effect in impermeable strata
ASR/ASTR, recharge wells/shafts	Urban/confined/coastal	Space-efficient, high control	High technical/maintenance requirements
Bank/dune filtration, SAT	River/lake/coastal aquifers	Water quality improvement, dual-purpose	Requires suitable geology, quality control
Urban stormwater systems	Cities, peri-urban	Flood control, decentralized recharge	Source quality, urban contaminants
Rainwater harvesting	Urban/rural, community-scale	Low-cost, locally managed	Small-scale, maintenance, acceptance

The most significant aspect in current MAR literature is probably the prevalence of MAR convergence and integration in hybrid systems, combining different recharge techniques and water sources. Zhao et al. (2021) used System Dynamics modelling to show how dealing with the systems of water rights in California in a simple MAR system can induce positive feedback loops that progressively lead to a greater drought resilience over successive dry years. Henao Casaus et al. (2022) similarly showed in Spain that sustained Recharge through MAR resulted in more rapid recovery of aquifers, leading to a lesser degree of drought susceptibility than was the case with not implementing MAR. There is a gradual emerging realisation that MAR is not the sole mitigating factor, but should be used as a means of achieving a desirable end in water management.

Since improvements are constantly being made to address the growing issues of population growth, climate change, and water security in various situations, MAR systems are broad and flexible. The success and effectiveness of a MAR system depend on how well the system is suitable for the local aquifer, hydrological regime, water source, management objectives, while also mitigating technical, regulatory, and social barriers to feasible operation and positive outcomes for the site (Alelaimat et al., 2023; Dillon et al., 2019; Sherif et al., 2023; Sufyan et al., 2024).

4. Climate Change Impacts on Groundwater Resources

Scientists increasingly agree that climate change threatens groundwater sustainability, a concern gaining traction over the past twenty years. However, broad patterns do not always match what happens at specific local sites. Initially, early studies tended to treat groundwater as shielded from the surface climate changes. Now, new evidence alongside computer models demonstrates its vulnerability to rainfall, warming temperatures, rising seas, and, moreover, intense droughts or flood extremes (Green et al., 2011; Kuang et al., 2024; Taylor et al., 2013; Walker et al., 2021). This changing perception, however, is still new and not well integrated across disciplines, where hydrogeological technology is far ahead of institutional and policy responses.

A basic area of concern is that of precipitation variability and the uncertainty of recharge. Even though climate models predict that many dry and semi-arid regions would experience drier conditions with lower mean rainfall, the threat to subterranean water supplies is not the decrease in rainfall (Erler et al., 2019; Green et al., 2011; Sufyan et al., 2024). Indeed, how infiltration into the ground happens is not linear, often dramatically so (Taylor et al., 2013). Less rain means less groundwater recharge into the ground, particularly if the soil is degraded. However, current water plans often depend on old data, records from a time when the climate was different, as Walker and others pointed out in 2021. This assumption is now “hollow” in the face of rapidly accelerating climatic change. Pittock et al. (2016) have noted that this methodological inertia leads to an over-estimation of the resilience of underground aquifers in the future.

Diminished recharge capacity in most aquifers is associated with a reaction to increased temperatures and transpiration of water. Pittock et al. (2016) and Green et al. (2011) demonstrate how warming causes aquifers to experience double stress by reducing the amount of precipitation-derived water available for infiltration and water stressors brought on by agricultural needs for food production. Even under ideal circumstances, this twofold feedback causes over-extraction of groundwater in regions of intense farming in river catchments, such as those in the Mediterranean and South Asia (Walker et al., 2021).

Very few studies explicitly model the coupled effects of the human impact and climate stressor, but most treat the matter of abstraction to be static, thus not showing the dynamic vulnerability of the communities dependent upon groundwater (Sufyan et al., 2024). Sea level rise and salt intrusion pose serious risks to coastal ecosystems, posing existential risks to both the economy and the ecology. Sherif et al. (2023) and Green et al. (2011) show that even a small increase in sea levels will upset the freshwater and saltwater balance that exists in coastal aquifers, and the effect will be worse where this occurs in coastal aquifers subjected to pumping arising from stress caused by drought.

Low-lying deltas together with small island developing nations are acutely affected, where only small changes in head gradient cause serious salinisation of the groundwater (Pittock et al., 2016; Tarolli et al., 2023). While MAR is often considered a hydraulic barrier to mitigate this intrusion, these approaches are reliant on a continuous supply of freshwater, a resource that is becoming increasingly susceptible to climate change (Sufyan et al., 2024).

Likewise, the vast majority of investigations into saltwater intrusion are reactive, dealing with monitoring the phenomena rather than predictive governance, hardly engaging with compounding risks related to land subsidence or deteriorating groundwater quality (Sherif et al., 2023). Most often, the role played by extremes of hydrology, be it drought or flooding, is the one that is not underestimated. Not only is climate change increasing the frequency of prolonged periods of drought, but also the intensity of storm events (Green et al., 2011; Walker et al., 2021).

Droughts increase reliance upon groundwater supplies whilst reducing natural recharge, thus producing a “double deficit” that exhausts supplies sooner than they can be replaced (Pittock et al., 2016). Heavy rainfalls can present an episodic opportunity for recharge, yet as Taylor et al (2013) have indicated, much of this continues to be lost as runoff waters, especially in urbanized or degraded landscapes, whilst the pollutants from impervious surfaces are also dissolved and mobilized.

Importantly, existing groundwater management regimes remain ill-equipped to properly deal with such asymmetry. They are directed toward gradual fluctuations, rather than years of long droughts interrupted by flash floods (Walker et al., 2021). This mismatch demonstrates a systemic lack of adaptive capacity within the framework of groundwater management itself. To add to these physical stresses, the emergence of a range of threats to groundwater quality must be accounted for.

Since decreased recharge and increased abstraction bring an increased concentration of already present contaminants, while flooding waters can remobilise already accumulated pollutants (Green et al., 2011; Schwanen et al., 2023; Sherif et al., 2023). Salinization, as a variant of this phenomenon, operates independently of hydraulic considerations as it is a crisis of quality, rendering the affected groundwater unfit for consumption or irrigation (Sherif et al., 2023). Despite the threats posed, long-term and high-resolution quality studies of groundwater are rare on the whole, and in poor areas almost non-existent (Lall et al., 2020; Walker et al., 2021). Therefore, gradual but detectable degradation may go unnoticed until it is too late, significantly delaying early remediation solutions.

A deeper institutional and intellectual flaw is the heavy reliance on stationarity, the underutilisation of climate prediction in groundwater models, and the absence of long-term monitoring networks, which are at the heart of these obstacles (Green et al., 2011; Pittock et al., 2016). There are abundant case studies, even though they tend to be overwhelmingly location-specific, leading to more limited transferability of concepts while often ignoring instances of failure (e.g., interventions) (Sufyan et al., 2024). The result of this is fragmentation, which inhibits the delivery of generalized climate-resilient groundwater governance arrangements. Even worse is the likelihood of maladaptation, e.g., MAR that would worsen waterlogging, pollution, or inequalities that are unlikely to be subjected to systematic evaluation under deep uncertainty (Pittock et al., 2016; Sufyan et al., 2024).

A growing amount of research acknowledges that climate change jeopardises the stability of the entire socio-hydrological system in which aquifers are integrated, not just the amount of groundwater that is available. Responses, however, remain fragmented in highly localised technical studies that quantify losses of recharge, hydrogeologists map the movement of salinity fronts, and modelers simulate process extremes, but few weave these together into elegant, adaptive frameworks for governance that might unite them into a synthesis. Until interactions between climate and groundwater systems are treated as fluid and socially realised instead of as a hydrological problem, the management of groundwater through climate change will remain reactive, fragmented, and with unintended consequences.

5. MAR as a Climate Adaptation Strategy

Managed Aquifer Recharge (MAR), which can protect groundwater systems from the growing hydroclimatic extremes of the future, has been extensively hailed in recent research as a "low-regret" or "win-win" approach to climate adaptation (Dillon et al., 2019; Gonzalez et al., 2024; Sufyan et al., 2024). However, a close reading suggests that the element of optimism in this literature is neither uniform nor unchallenged. Rather, it can be observed that the discourse regarding MAR as adaptation has shifted from a decidedly techno-optimist narrative to a more wary, context-sensitive evaluation that majors in caveats pertaining to institutional arrangements, ecological dimensions, and equity matters. Here, there is a manifestation of a maturing field, yet one which still appears to be wrestling with the disjunction observed between modelled potential and rebellious on-the-ground feasibility.

Promoters of MAR were inspired to emphasize its potential to lessen the effects of drought by its ability to capture episodic surplus water like flood flows, stormwater, and the like, or excess surface releases from wastewater works, and store it underground for later application in times of need (drought). Modelled studies conducted of California’s Central Valley were taken as paradigmatic of the promise of MAR. Thus, Scanlon et al. (2016) and Kourakos et al (2023) have demonstrated it is possible, using model studies, to slow or even to reverse the groundwater declines associated with multi-year droughts, thus rendering agricultural and municipal withdrawals feasible.

Similarly, in Mediterranean basins, Guyennon et al. (2017) and Escalante et al. (2019) report that having MAR coupled with surface reservoirs has greater reliability and increased effective irrigation seasons. This confirmed to a material degree the “drought insurance” reputation subsequently acquired by MAR.

However, such conclusions often assume stable availability of recharge-related water inputs, the case under climate change, where wet periods can be increasingly rare and irregular (Kourakos et al., 2023; He et al., 2021). As Sufyan et al. (2024) later warned, many models overestimate MAR potentials by treating variables of flows above needs as constant and predictable, whereas consecutive dry years could show no availability of recharge whatsoever.

Alongside this drought mitigation role, MAR became attractive for saline management of coastal aquifers. Sea level rise and increased pumping are creating increasing risks to freshwater lenses, and MAR was advocated as a hydraulic barrier to resist saline intrusions. Evidence from Spain (Escalante et al., 2019), Malta (De Carlo et al., 2024), and the Arabian Peninsula (Sherif et al., 2023) suggested that prolonged injection of fresh water might consolidate or even reverse trends of salinisation. This, however, depended on a delicate equilibrium.

The volume of Recharge, therefore, must exceed that of extraction and high sea water levels. Under climate change, therefore, where droughts increase pumping and diminish recharge, this balance becomes at best precarious (Green et al., 2011; Kuang et al., 2024; Sufyan et al., 2024). When establishing, it should be noted also that most successful applications had occurred in settings where constant and reliable management and monitoring regulations were possible, which raises questions about the transference of findings to areas where poor governance or lack of data or costly field stations made such developments virtually impossible (Sherif et al., 2023). A variant in adaptation discourse has identified MAR as a balancer of supply variability in an epoch of hydrological whiplash, swinging between floods and droughts. Supplying sudden bursts of high magnitude, short in duration, MAR has the potential to “smooth” water availability and shift erratic surface bursts into regular groundwater outputs (He et al., 2021; Dillon et al., 2019). This function has particular appeal in arid and semi-arid climates, where conventional reservoirs suffer large evaporation losses.

Still, as Taylor et al. (2013) and Pittock et al. (2016) have observed, much of the floodwater is lost as Runoff before deflection takes place, especially in degraded or urban environments. The infrastructure necessary to catch and transport these flows, canals, diverging weirs, and infiltration basins, needs upfront capital and maintenance often absent in vulnerable communities (Sufyan et al., 2024).

In spite of these apparent strengths, a counter-narrative has emerged that questions the structural dependencies and hidden dangers of MAR. A recurrent criticism has been marshalled against MAR’s dependence on “surplus” water, the requisite not even implied in water-stressed basins already faced with conflicts of allocation (Dillon et al., 2019; Sufyan et al., 2024). Herein lies the potential for MAR to intensify inequities by conferring advantages on those having the capital and the rights to catch such “surplus”, who would thus eliminate it from ecosystems downstream or from smallholders using such water (Escalante et al., 2019). This tension manifests MAR not as a neutral technical fix, but as a socio-hydrological act of intrusion and (destructive) potential accountable to social and power relationships.

Of equal importance is the site-specificity of hydrogeological suitability. Not all aquifers lend themselves to recharge: low-permeable strata, complexity of layering, or molestation of natural salinity can prove MAR to be ineffective or positively destructive (Ajjur & Baalousha, 2021; Dillon et al., 2019; Sherif et al., 2023). Poorly conceived systems can result in waterlogging, mobilization of geogenic (e.g., arsenic) contaminants, or invulnerable hydraulic connections from sources of pollution (Sufyan et al., 2024). Nevertheless, as Sherif et al. (2023) see, the success, or at least conspicuous failure, of certain MAR projects is rarely catalogued, which leads to the incidence of publication bias that serves to exaggerate rates of success. The most serious drawback of MAR is likely the institutional and financial requirements that allow MAR to occur. For example, research in California, Australia, and Spain shows that there are several "enabling conditions" required for successful MAR, such as established water rights that include both surface and groundwater rights, streamlined permitting processes, dedicated funding, and multi-stakeholder coordination.

Conversely, many MAR efforts in low-income or institutionally fragmented areas cannot move forward because of unclear regulations, a lack of technical expertise, and an inability to secure long-term funding. These two examples illustrate an unfortunate trend: MAR is likely to work best in areas with the fewest amounts of water stress but is not able to function well in areas with high levels of water stress, which are more vulnerable to climate-related water scarcity.

Furthermore, some studies have noted that using treated wastewater and/or stormwater for recharge has social and environmental trade-offs, albeit researchers usually do not look closely at these trade-offs. For example, the public frequently opposes the use of treated wastewater for recharge because of the general dislike for using reclaimed wastewater (also known as "the yuck factor") and worries about the possible health effects of recharging reclaimed wastewater into aquifers (Dillon et al., 2019; Moesker et al., 2024; Sherif et al., 2023). This is despite the fact that the practice is highly efficient from a resource perspective.

Furthermore, if MAR is framed as a means to increase the available amount of water (i.e., the supply side), then this may detract from other options for managing water resources, including reducing the rate at which water is abstracted from aquifers and improving irrigation efficiencies (Kourakos et al., 2023). Therefore, MAR could become a techno-managerial "band aid" for addressing symptoms, while ignoring the root cause(s) of the problem.

Therefore, based upon the existing body of literature regarding MAR as a climate adaptation strategy, it is revealed that what was once viewed as a universally applicable solution to address climate-related water scarcity is now being viewed as having limited applicability. There appears to be a growing consensus among researchers that the potential of MAR as an adaptive response to climate-related water scarcity does exist, but only in certain contexts. These contexts require: 1) a reliable episodic source of water, 2) favourable geology, 3) a strong institutional structure, 4) an integrated system for monitoring the effectiveness of MAR, and 5) an understanding of how MAR will affect equity and ecosystems (He et al., 2021; Escalante et al., 2019). If key criteria are not met, managed aquifer recharge might offer help or even worsen issues (e.g., increased salinization, reduced aquifer storage capacity, etc.). MAR should therefore be viewed as a component of a flexible strategy to water management, with its performance linked to the larger system surrounding it, rather than as a cure-all.

Table 3. MAR barriers

Barrier Type	Example Issues	Representative Sources
Hydrogeological	Unsuitable aquifers, clogging	Dillon et al., 2019; Sufyan et al., 2024; Sherif et al., 2023
Water Source	Irregular supply, poor source water quality	Dillon et al., 2019; Escalante et al., 2019
Economic/Financial	High costs, unclear cost-benefit	Sufyan et al., 2024; He et al., 2021
Technical/Data	Lack of data, modelling/monitoring challenges	Dillon et al., 2019; Sufyan et al., 2024
Institutional	Fragmented institutions, regulatory gaps	Sherif et al., 2023; Dillon et al., 2019
Social/Stakeholder	Public resistance, coordination difficulties	Sufyan et al., 2024; Escalante et al., 2019
Environmental	Salinization, contamination, ecosystem impacts	Sherif et al., 2023; Sufyan et al., 2024
Knowledge/Capacity	Monitoring gaps, skills shortage	Dillon et al., 2019; Sufyan et al., 2024; Sherif et al., 2023

According to the literature, MAR must overcome a complicated web of interconnected technical, legal, financial, social, and environmental obstacles. Integrated planning, flexible management, strong governance, consistent investment in capacity and monitoring, and ongoing stakeholder involvement are all necessary to overcome these obstacles (Dillon et al., 2019; Sufyan et al., 2024; Sherif et al., 2023).

6. Modelling and Assessment Tools for MAR

6.1. Groundwater Flow and Solute Transport Models

The primary numerical model used for groundwater flow simulation in MAR in both confined and unconfined aquifer settings is MODFLOW. In MAR, MODFLOW has been used for many types of analysis, which include well drawdown analysis, well placement optimization, evaluation of recharge rates, measurement of water table rise and fall, and assessment of the aquifer storage capacity (Alelaimat et al., 2023).

Also, it is the standard model for scenario analysis, which we use when we look at changes in climate, hydrology, and water governance/management regimes (Dillon et al., 2019; Sufyan et al., 2024). To see the theory behind it and how it models groundwater response to dynamic conditions, the key partial differential equation (Equation (1)) is put forth.

This equation, which is the basis for mass conservation and Darcy's law, forms the basis of MODFLOW, which in turn is the basis for the model's ability to simulate transient groundwater flow in both confined and unconfined aquifers. Thus, it is very useful for the study of the effects of varying recharge rates, abstraction patterns, and boundary conditions in Managed Aquifer Recharge (MAR) planning.

$$\frac{\partial}{\partial x}\left(\rho K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(\rho K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(\rho K_z \frac{\partial h}{\partial z}\right) \pm W = \frac{\partial(\rho S_s h)}{\partial t} \qquad (1)$$

Where:

K_x,K_y,K_z = hydraulic conductivity along the x, y, and z axes (L/T)

h = hydraulic head (L)

W = volumetric flux per unit volume representing sources/sinks (1/T)

S_s= specific storage (1/L)

t = time (T)

Typically, MODFLOW is used in conjunction with the models MT3DMS and SEAWAT. MT3DMS simulates the three-dimensional transport of solutes (of any form of nutrients and contaminants) during and after recharge, whereas SEAWAT is essential for water flow and solute transport that is density-dependent (and thus aquifer management scenarios like saltwater intrusion in coastal MAR or the storage of treated wastewater and desalinated water at depth) (Dillon et al., 2019; Sherif et al., 2023). To clarify the mechanistic basis of this simulation and highlight the processes governing solute fate (e.g., advection, dispersion, and reactive transformations), the governing advection–dispersion–reaction equation (Equation (2)) is presented. This formulation is essential for evaluating water quality evolution, breakthrough risks, and the effectiveness of natural attenuation in aquifers, particularly when MAR involves recycled water, stormwater, or other non-traditional sources

$$\frac{\partial(\theta C)}{\partial t} = \nabla \cdot (\theta \mathrm{D} \nabla C) - \nabla \cdot (\mathrm{q} C) + \theta R \qquad (2)$$

Where:

C = Solute concentration (kg/m³)

θ = Porosity of the medium

D = Hydrodynamic dispersion tensor

Q = Darcy flux vector (m/s)

R = Source/sink term (reaction, decay, or injection)

The flow and solute transport in the unsaturated zone, especially in relation to surface spreading techniques, Soil-Aquifer Treatment (SAT), and problems with infiltration and clogging, are frequently studied using HYDRUS (2D/3D) models (Sufyan et al., 2024; Sherif et al., 2023). Equation (3) is used by HYDRUS models to simulate variably saturated flow in the vadose zone, a critical process in surface-based MAR techniques such as Soil-Aquifer Treatment (SAT) and infiltration basins. Including this equation underscores the physical representation of infiltration dynamics, capillary forces, and gravity-driven flow through unsaturated soils, which directly influence recharge efficiency, clogging potential, and contaminant attenuation during percolation (Sufyan et al., 2024; Sherif et al., 2023). By presenting the governing Richards' equation in its common form (Equation (3)), this review highlights the mechanistic basis for modelling transient water movement above the water table, an essential component in the integrated assessment of MAR performance and design.

$$\frac{\partial\theta}{\partial t} = \nabla \cdot [K(\theta)(\nabla h + \mathrm{e}_z)] \qquad (3)$$

Where:

θ = Volumetric water content (m³/m³)
t = Time (s)
K(θ) = Hydraulic conductivity as a function of water content (m/s)
h = Pressure head (m)
z = Vertical coordinate (positive downward)
e_z = Unit vector in the vertical direction (gravity term)

6.2. System Dynamics and Integrated Water Balance Models

In order to explore and evaluate the concurrent usage of surface and groundwater systems, user input, and policy scenarios, system dynamics models make it easier to integrate the assessment of MAR as a component of a water resources system (Guyennon et al., 2017; He et al., 2021). Water balance models are essential to characterize the fate of recharge water, change aquifer storage, and evaluate the effects of MAR in different supply and demand futures (Kourakos et al., 2023).

6.3. Multi-Criteria Decision Analysis (MCDA) and GIS Tools

MCDA, as well as spatial multi-criteria analysis, includes hydrogeologic, climate, topography, socio-economic, and infrastructure factors to rank or select optimal MAR sites. They are applied in GIS platforms to be spatially explicit and provide suitability mapping through an overlay analysis of land use, soil type, aquifer properties, slope, and source water availability, which helps to select a targeted MAR site at a regional or basin scale (Sufyan et al., 2024; Sherif et al., 2023).

6.4. Water Quality and Risk Assessment Frameworks

The DRASTIC model utilizes Equation (4) to quantify aquifer vulnerability to contamination, a critical consideration when implementing MAR with treated wastewater, stormwater, or other impaired source waters. Including this equation clarifies the structured, index-based methodology that integrates hydrogeological and environmental factors (e.g., depth to water, recharge, aquifer media, soil type, topography, impact of vadose zone, and hydraulic conductivity) into a composite vulnerability score. This transparency supports reproducibility and enables comparative risk screening across potential MAR sites, particularly in early-stage planning where data may be limited (Sherif et al., 2023). Presenting Equation (4) thus reinforces the systematic framework used to prioritize safe and sustainable MAR locations while accounting for intrinsic aquifer susceptibility to pollution.

$$DI = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r \qquad (4)$$

Where:

$D_w, R_w, A_w, S_w, T_w, I_w, C_w$ = Weight assigned to each parameter (from 1 to 5)
$D_r, R_r, A_r, S_r, T_r, I_r, C_r$ = Rating assigned to the parameter based on site-specific data
DI = DRASTIC index, higher values indicate higher vulnerability

6.5. Hydrological and Land Surface Models

The core equation governing soil moisture dynamics in the root zone over time (Equation (5)) is fundamental to hydrological models such as SWAT, which are widely used to estimate water availability for MAR, assess infiltration potential, and simulate catchment-scale water balances. Including this water budget equation clarifies how key hydrological fluxes, precipitation, surface runoff, evapotranspiration, deep percolation, and groundwater return flow, are integrated to track soil water storage changes at daily timesteps. This accounting is essential for identifying surplus water volumes that could be diverted to MAR, evaluating land-use impacts on recharge, and supporting integrated water resources management under varying climate and land-cover scenarios (Guyennon et al., 2017; Escalante et al., 2019; Sanchez-Gomez et al., 2025). Presenting Equation (5) thus provides the conceptual and computational foundation for linking surface hydrology to subsurface recharge opportunities in MAR planning.

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - ET - W_{seep} - Q_{gw} \right) \qquad (5)$$

Where:

SW_t = Final soil water content on day t(mm)
SW_0 = Initial soil water content at the beginning of the day (mm)
R_{day} = Precipitation on day t(mm)
Q_{surf} = Surface runoff on day t(mm)
ET = Evapotranspiration on day t(mm)
W_{seep} = Water percolation to the vadose zone (mm)
Q_{gw} = Return flow or groundwater contribution to streamflow (mm)

6.6. Economic and Policy Assessment Tools

Cost-benefit analysis and hydro-economic models to assess economic efficiency, comparing MAR to other forms of supply and demand management options and values under uncertainty, are coming into use (Gonzalez et al., 2024; He et al., 2021; Sufyan et al., 2024). Robust decision-making frameworks and typologies to assess decisions to invest in MAR under deep climate or policy uncertainty, with consideration given to institutional and infrastructure robustness, including (Dillon et al., 2019).

6.7. Field Assessment and Monitoring Tools

Geophysical methods, particularly electromagnetic induction, Time-Domain Electromagnetic (TEM) surveying, and Electrical Resistivity Tomography (ERT), are valuable for providing subsurface hydrogeological characterization.

These methods are leveraged for monitoring salinity changes, mapping saltwater intrusion, and delineating the advance of recharge fronts before, during, and after MAR operations (De Carlo et al., 2024; Roy et al., 2025; Sherif et al., 2023). Field tracer tests, as well as a distributed monitoring network, are also used for real-time validation of performance and to calibrate the system (Dillon et al., 2019).

Table 4. Schematic table of MAR modelling and assessment tools

Tool/Framework	Function/Application	Key Use Context / Source
MODFLOW	3D groundwater flow simulation	Dillon et al., 2019; Sufyan et al., 2024
MT3DMS, SEAWAT	Solute/density-dependent transport modelling	Dillon et al., 2019; Sherif et al., 2023
HYDRUS	Vadose/unsaturated zone, infiltration, clogging	Sufyan et al., 2024; Sherif et al., 2023
MCDA & GIS-based site selection	Site prioritization and suitability mapping	Sufyan et al., 2024; Sherif et al., 2023
System dynamics, water balance models	Integrated policy/system scenarios	Guyennon et al., 2017; He et al., 2021
DRASTIC	Pollution risk, aquifer vulnerability	Sherif et al., 2023
Economic/robust decision frameworks	Cost-benefit, risk, and investment feasibility	Sufyan et al., 2024; He et al., 2021
Geophysical and monitoring tools	Field validation, subsurface characterization	De Carlo et al., 2024; Dillon et al., 2019

The MAR literature offers a sophisticated set of tools for simulating, assessing, and optimising MAR from technical, economic, and policy viewpoints. These tools include numerical flow and transport models, GIS-based multi-criteria and risk analyses, system dynamics, economic models, and state-of-the-art field geophysics. The addition of remote sensing and in situ monitoring capabilities expands MAR assessment potential in data-sparse or otherwise complicated hydrogeographic environments (De Carlo et al., 2024; Escalante et al., 2019; Guyennon et al., 2017; Hayat et al., 2021; He et al., 2021; Sherif et al., 2023).

7. MAR Integration with Water Management Policies and Practices

Although it has gradually changed from being an afterthought to a deliberate objective, the gradual integration of Managed Aquifer Recharge (MAR) into the official institutional frameworks of water management varies greatly throughout regions and governance structures. Early MAR pilots were often arranged as isolated, technically driven experiments and suppliers disconnected from water planning and regulatory frameworks (Dillon et al., 2019; Sherif et al., 2023). Over time, however, a growing literature has pointed out that the prospect of long-term implementation of MAR does not depend predominantly on engineering, but rather on its embedding within supportive adaptive multi-scaled governance frameworks. This realisation has led to certain institutional innovations in regulation and exposed hard structural barriers in others.

The integration of MAR into conjunctive use regimes and Integrated Water Resources Management (IWRM) frameworks has been a significant shift. MAR is evolving from a sporadic intervention niche to an integrated component of basin-scale water security solutions in Australia, Spain, and portions of the western United States (Dillon et al., 2019; Escalante et al., 2019). California Sustainable Groundwater Management Act (SGMA), for example, aims to encourage MAR as a tool for the achievement of groundwater sustainability targets that give it a change of status from a voluntary exercise to a statutory expectation for the groundwater sustainability agencies (Kourakos et al., 2023; He et al., 2021).

Similarly, in Spain, MAR has found its way into the national drought resilience scheme, where it has been tied to surface reservoirs and demand management for the buffering of hydroclimate variability (Escalante et al., 2019; Mayor et al., 2023). These examples point to a growing maturity of the regime. Its importance is seen not as a mechanism for standalone water supply arresting measures, but as a crucial node in the mixed portfolio of an adaptive, diversified regime for the management of water.

However, establishing additional legal and regulatory frameworks is necessary for this. Uncertain or outdated water rights laws continue to be one of the major obstacles to entry with relation to MAR, according to a recurrent topic in the literature (Dillon et al., 2019; Sufyan et al., 2024). The legal regimes in many jurisdictions, particularly in parts of the Middle East, North Africa, South Asia, and Sub-Saharan Africa, generally do not address the fact that recharged water is a recoverable asset. As a result, they provide disincentives to the ownership structure of investments, whether collective or individual (Sherif et al., 2023; He et al., 2021). In the absence of coherent legal structures with reference to who owns the water, how it can be allocated, and on what conditions it can be abstracted, MAR pilot projects remain uncoordinated with legal instruments fit for purpose in terms of the legal backing for this structure. Conversely, regions with adequate MAR legislation in situ, like the groundwater banking provisions in California or Australia's systems of entitlement to water, have seen stronger and scalable forms of implementation (Kourakos et al., 2023; Nelson & Perrone, 2016; Sufyan et al., 2024). This dichotomy suggests a striking institutional divide. MAR works where property rights are clear and adaptive; it is stagnant where uncertainty prevails.

Beyond the legal aspects of integration, engaging stakeholders and institutionally coordinating have emerged from the literature as elements that cannot be negotiated away if MAR is to be successfully implemented. Dillon et al. (2019) and Escalante et al. (2019) offer examples from South Australia and Mediterranean Spain in which planning for MAR involved a kind of ongoing interplay in which farmers, utilities, regulatory bodies, and indigenous or local communities negotiated various interests in MAR products. The want of multiple perspectives served not only to align the various objectives of MAR (for example, ecosystemic baseflows, water by irrigation during drought, urban stormwater management) but also afforded legitimacy and ownership of MAR processes. Unfortunately, such a kind of governance is the exception rather than the rule. In situations where data are scant or institutional fragmentation is endemic, planning of MAR usually will be technocratic, with the marginal, small users of water omitted from the decision process and the factor of asymmetries of power neglected in the balancing of power for the users (Basel et al., 2022; Sherif et al., 2023). The literature then reflects on a paradox that results, namely, that while participatory processes of governance are endorsed in principle, the conditions of implementation remain in many instances not clearly documented and particularly sensitive to the contingencies of location.

Working with regulatory and participatory modes is the application of the instrument of the economy to the issues underlying MAR, so that elements for internalizing the value of MAR are to be found. Water banks, tradable rights systems, and targeted subsidies aimed at creating economic incentives for recharge have all been instituted. Water banks are to be found in action in the western USA, where they assist users of water to store surplus allocations in aquifers during wet years and draw them upon during dry seasons, thus changing effectively into institutions of a bank. Water basins that receive the stored waters and allocate funds available to the basins are changeable on demand during droughts (Kourakos et al., 2023). Also taking place are instances of rebate for installation of rainwater harvesting or use of permeable pavements in urban areas, which have increased the opportunities for decentralised MAR (Dillon et al., 2019; Sufyan et al., 2024; Wartalska et al., 2024). It must also be pointed out that these are instruments that presuppose functioning water markets with mutual understanding for accounting and the availability of administrative competence. Hence, they are not widely applicable to many parts of the low-income territories. It can thus be seen that such developments are confined mainly to the usages of the high-capacity jurisdictions. Economic instruments are then used operationally, relating to MAR, mainly confined to developed regions, with the machinery of resource development and availability effectively introducing a wide variance in the conditions for institutional viability of MAR globally.

Notwithstanding these advances, however, there remain major barriers to be crossed before it can be said that integrity is attained. Institutional fragmentation in the various mandates, whether surface water, groundwater, land usage, or environmental protection, resulting in pressures in different directions and imposed by different agencies, forms an obstacle to coordinated MAR (Adom & Simatele, 2024; Sherif et al., 2023; Sufyan et al., 2024). The tendency of organisms developed for bureaucratic purposes is to introduce delays, while the other typical phenomena of non-sharing of data and feelings of apprehension from established uses of water result in impediments to the installation of MAR (Dillon et al., 2019; Escalante et al., 2019). Further, in regard to the development of the political ambience, the introduction of MAR in a jurisdiction will take place at the sacrifice of developing policies for entrenched priorities, using, say, the groundwater subsidy or the large dam strategy for the establishment of political complacency and economic inertia. Even where the conditions are good for any hydrological or technical operation, the path dependencies related to institutional developments invariably find fixing by stalling or distorting effects on the processes of the institutional introduction of MAR.

The literature has then manifested a clear direction for its studies. MAR is increasingly seen as a process involving extensive governance whose effectiveness will depend on its harmonious working with legal evidential presentation, participative planning, economic incentives, and integrated water management. However, the position has not been translated into universality as regards practice. Such integrative process of MAR remains a privilege of the area where attitude to resource and structuring tends to place them among well financed and institutionally co-ordinated regions, where the areas low in data, powerlessness of governmental bodies in respect require to face full exclusion from access to benefits arising from recovery, with the result that MAR will show inequity of result according to locations, till more comprehensive approaches of an inclusive transferable nature may be in operation, increasing flexibility of the MAR policies (particularly with reference to institutional incapacity) before the MAR policy would appear a valid adaptation for climate resiliency reduction. Until they assume that shape, MAR as an adaptation based on recharging will be seen to give not an increasing availability of solutions but one that will tend to deepen the gulf of water availability, increasing inequities on the global scene.

Table 5. Integration of MAR with water management policies and practices

Integration Domain	Key Examples and Policy Mechanisms	Representative Sources
IWRM & Conjunctive Management	National and basin water plans; use of MAR in drought resilience and ecological flow objectives	Dillon et al., 2019; Escalante et al., 2019
Regulatory & Legal Frameworks	Specific legislation and permitting for MAR; clear water rights for recharged water (e.g., Australia, SGMA in California, Spain)	Dillon et al., 2019; He et al., 2021; Kourakos et al., 2023; Sherif et al., 2023
Stakeholder Collaboration	Multi-sector partnerships; active engagement of urban utilities, farmers, regulators, and NGOs	Dillon et al., 2019; Escalante et al., 2019; Sherif et al., 2023
Economic Instruments/Incentives	Water banking, trading, subsidies, rebates for recharge; pricing structures that support MAR	Kourakos et al., 2023; Dillon et al., 2019; Sufyan et al., 2024
Data, Monitoring & Capacity	Requirements for long-term monitoring, transparent data sharing, and technical capacity building	Sufyan et al., 2024; Dillon et al., 2019; Sherif et al., 2023
Barriers/Challenges	Fragmented governance; lack of permitting procedures; insufficient data; resistance from established users	Sherif et al., 2023; Sufyan et al., 2024; Dillon et al., 2019

8. Perspective on Main Findings in the MAR Literature

A field trapped between aspiration and evidence is suggested by a dogmatic analysis of the MAR literature. Declaring that Managed Aquifer Recharge may improve groundwater resilience in the face of climate change is one thing, but insisting on the long-term sustainability of recharged aquifers in terms of structural complexity, equality, and shared access is quite another. Tellingly, the literature celebrates technical feasibility and short-term success, while remaining oblivious to issues of longer-term sustainability, equity, and structural complexity. This section of the report qualifies dominant narratives in the MAR literature and describes six patterns of omission and overstatement that combine to form what can be called, for want of a better term, an “optimism bias”, a tendency to expound promise while explaining away failure, uncertainty, and structural constraints.

8.1. The Technical Feasibility Trap

The literature is full of studies that work through the technical minutiae of modelling recharge volumes, recovery efficiencies, aquifer responses under ideal conditions (Dillon et al., 2019; Sufyan et al., 2024But whereas these technical exercises regard MAR as a hydrogeological problem isolated from its socio-institutional embedding, later studies emphasising social acceptance, land tenure incompatibilities, ambiguities of water rights and burdens of maintenance etc. are relegated to footnotes or future considerations and are not regarded as co-determinants of success (Bennison & Claro, 2024; Escalante et al., 2019; Sherif et al., 2023). The consequence of this is that the literature presents MAR as a nearly universally applicable technology, whereas it is not, concealing the fact that technical viability is a necessary but not sufficient condition in the case of the real world.

8.2. The Geography of Success: A Preference Towards High-Capacity Regions

The “successful” MAR case studies cited most frequently appear to derive from data-rich, institutionally strong environments, such as California, Australia, Spain, and portions of Western Europe, where long-term monitoring, regulatory certainty, and funding are available (Dillon et al., 2019; Escalante et al., 2019; Seidl et al., 2023). These contexts provide the conditions that are lacking in many of the climate-vulnerable regions, particularly in Africa, South Asia, and parts of Latin America. By focusing disproportionately on high-capacity examples, the literature inevitably creates a false stereotype of MAR as an easily transferable solution, while at the same time downplaying the difficulties of implementation in low-resource, data-poor, or governance-weak environments (Sufyan et al., 2024). This geographic slant limits generalizability but also threatens to export models that are inappropriate for or even maladaptive in other institutional ecologies.

8.3. Superficial Approach to Water Quality Risks

The literature tends to downplay the introduction of new and complicated contamination hazards when discussing MAR as a solution to the water quality issue through natural attenuation (e.g., pathogen die off, nutrient uptake). The injection of treated wastewater, stormwater, or agricultural Runoff can provide a conduit for the introduction of trace organics, pharmaceuticals, PFAS, and micropollutants of industrial origin whose destiny is unknown (Dillon et al., 2019; Sufyan et al., 2024). Whereas geochemical changes wrought by recharge (notably redox) can, with the passage of time, facilitate the leaching of naturally occurring contaminants, like arsenic or manganese, studies addressing this aspect of unintended consequences created by MAR are few (Maliva, 2019; Sufyan et al., 2024). Where monitoring has occurred, it has generally been of a short-term nature and directed to commonly monitored parameters, thus rendering largely speculative the long-term quality trajectories of recharged waters.

8.4. The Monitoring Deficit and the Paradox of Pilot Projects

It is generally recognised that long-term monitoring is required, but empirical material from fully operational, full-scale MAR systems is rare, even though it is always advocated (Dillon et al., 2019). Except in the case of pilot studies and modelling exercises or risk analyses, there is little published case material that is relevant, resulting from long-term monitoring of full-scale MAR systems (Sheikh et al., 2023). The pilot studies give largely short-term conclusions based on short-term operations, whereas the cumulative impacts, rates of maintenance decay, and failure of systems appear over a period of years and possibly decades.

Hence, the material that is in the literature gives limited information about the durability of MAR, drying recovery return reliability, and less on the side effects of MAR, such as those on ecosystems depending on groundwater, which very few people study and value (Escalante et al., 2019).

8.5. Economic Over-Optimism, Hidden Costs

The economic studies dealing with MAR render a favourable impression with their very good C to B ratios, but in many cases tend to underplay, or ignore entirely, essential costs, such as the cleaning up of clogged systems, rehabilitation of wells in case of failure, treatment costs associated with treatment, or the co-operative technicalities which arise from a tendency to try to co-ordinate the user systems (He et al., 2021; Ross & Hasnain, 2018; Sufyan et al., 2024). There are the opportunity costs of foregoing investments in demand management, management of demand, conservation, or other sources of supply considered, which do not usually appear (Dillon et al., 2019). Also, the costs of development and of running a system are highly locally dependent and do not necessarily scale in a linear fashion, but the economic evaluations are often formulated on the assumption of homogeneity. Hence, there is a danger that MAR will be advocated as a strategy in systems, economic, and institutional contexts, where it is unsustainable in the end, or at best is inferior economically.

8.6. Governance as Afterthought

Although governance barriers (such as fragmentation of mandates, ambiguity of water rights, and low trust in stakeholders) are acknowledged, they are rarely analysed. Calls for “stronger institutions” or “inclusive participation” are common, and few studies suggest measures or approaches to effective institutional reform or how power relationships, historical inequity, or path dependency impact MAR (Sherif et al., 2023; Escalante et al., 2019). Without such analysis, governance becomes a rhetorical sleight of hand rather than a domain of strategic intervention.

8.7. Climate Uncertainty as Modelling Convenience

Although MAR is promoted as a climate resilience tool, most studies treat future climate conditions as a set of bounded, deterministic scenarios, usually using single GCM outputs or narrow RCP bands, instead of confronting the issues of deep uncertainty, non-stationarity, or compound extremes (He et al., 2021; Moure et al., 2023; Sufyan et al., 2024). This is likely to result in an underestimation of the risk that MAR systems designed to deal with historical variability can be overwhelmed by unprecedented patterns of drought or intensities of flood, thus compromising their reliability just at the time of greatest need.

The MAR literature presents a compelling situation of groundwater resilience, but one that is largely influenced by optimism in the efficacy of techniques, adequate capacity of situations, and the short term. To avoid this bias, it is essential that future research should concentrate on/analyse long-term empirical monitoring; compare governance approaches; integrate social sciences, and consciously engage with areas underrepresented.

Only then can MAR objectively be assessed not as a universal solution but as a circumstantial but situation-sensitive approach which is as dependent on institutions, equity, and adaptive learning as it is on hydrogeology and engineering.

9. Discussion

The literature synthesized in this review underlines the utility of Managed Aquifer Recharge (MAR) as a flexible, context-sensitive approach for enhancing groundwater resilience against climate change impacts, including drought, water scarcity, and coastal threats (Dillon et al., 2019; Sufyan et al., 2024). A key finding that separates this review from much of the existing research is the importance of how local hydrogeology, alongside governance, and real-world long-term monitoring, rather than just technical modelling, determine implementation success and scalability.

Many foundational studies, such as those conducted in the Murray-Darling Basin, generally assessed regional-scale recharge potential taken from climate models (Crosbie & Kumar, 2021); alternatively, some projects utilized modelling to improve specific site design, like in California or Iran (Hashemi et al., 2015; Reznik et al., 2022). While these modelling efforts progressed technical understanding, they frequently lacked connection to the real-world complexities of implementation (Ringleb et al., 2016).

The study obtained better contextual results because this review clearly integrated findings that link technical performance with institutional and economic practicality. For instance, studies in high-income and data-rich regions like California showed that MAR success, even when technically feasible, often hinges on legislative changes that clarify property rights for recharged water, thereby creating economic enticements (Reznik et al., 2022; Roberts et al., 2020). Even when the local community really wants to help, traditional ways of recharging groundwater do not always work. Research from places such as Bangladesh and Morocco shows that things like heavy clay soil or murky water can render these methods useless, despite enthusiastic local support (Hossain et al., 2021; Gouahi et al., 2024). This highlights that the "why" behind success is often institutional or economic, not purely hydrological, a nuanced conclusion often missed when focusing solely on technical model outputs.

California investigations reveal that successful managed aquifer recharge often hinges on laws solidifying ownership of replenished water, a financial boost. However, places such as Bangladesh and Morocco demonstrate that challenging geology or poor water quality can derail recharge efforts, even with enthusiastic locals.

Furthermore, the review noted that the focus on *potential* recharge in modelling studies often overlooks the "durability deficit" found in operational systems. Studies like those in Gujarat, India, revealed that high-density recharge structures failed to counteract increasing agricultural demand during dry years because they lacked sufficient carry-over storage and the context of demand management (Alam et al., 2022). Our synthesis emphasizes that frameworks incorporating economic feasibility and stakeholder participation, as seen in successful, mature systems in Australia and Spain, are vital for translating pilot success into long-term resilience (Walker et al., 2021; Escalante et al., 2019). Therefore, the improved contextual understanding in this review moves beyond simply validating if MAR can work, to detailing under which governance and economic structures it does work.

10. Conclusion

MAR has the potential to improve groundwater resilience to the growing threats of climate change, particularly in coastal, over-extended, and prone to drought, particularly in semi-arid and Mediterranean regions of the world, according to the literature review (Dillon et al., 2019; Sherif et al., 2023; Sheik et al., 2024; Sufyan et al., 2024). MAR can convert episodic surpluses (in flood flows, stormwater flows, or treated effluents) into stored subsurface resources that will buffer supply variability, prolong aquifer depletion, and reverse salinisation tendencies if applied strategically (Escalante et al., 2019; Guyennon et al., 2017). Nevertheless, this technical potential is thoroughly conditional. As the literature abundantly indicates, the effectiveness of MAR is not a result of intrinsic technical analysis but comes from the operation of factors such as hydrogeological suitability, institutional integrity, economic feasibility, and continued social legitimacy. The most successful and enduring MAR interventions have occurred, not in isolation, but in enabling governance regimes, places such as California, Australia, and the Mediterranean parts of Spain, where they feature explicit water rights for the recharged water, integrated basin-wide planning, and adaptive regulatory regimes (Dillon et al., 2019; Kourakos et al., 2023; He et al., 2021). In these contexts, MAR is not an adjunct non-intrusive engineering activity, but an explicit part of the conjunctive use of water policy active in such policies as they are essential for integrating surface and groundwater use, to incentivise recharge to aquifers, and to transparently distribute risks and rewards to the various stakeholders involved. In contrast, in data-scarce regions (notably in Africa, parts of South Asia, and parts of the Middle East), institutionally fragmented or weakly funded, MAR still remains aspirational. In these situations, barriers to scalability and sustainability are perpetuated by poor property rights, limited technical capacity, unreliable and/or degraded source water, and weakly functioning monitoring (Sherif et al., 2023; Sufyan et al., 2024).

Also, the field continues to grapple with a chronic under-provision of validation in the long term empirically. Despite an abundance of modelling and pilot-scale demonstrations of benefit, only a few studies document the performance of full-scale MAR systems over periods of decades (Sufyan et al., 2024; Sherif et al., 2023; Sheik et al., 2024). This kind of information skews researchers' perceptions of important issues like recovery reliability, cumulative effects on water quality, maintenance decay for resource replenishment, and unintended biophysical impacts (e.g., baseflow shifting to a groundwater-dependent ecological system, or if geochemical changes mobilise geogenic contaminants like arsenic in groundwaters with changing redox conditions) that must be understood for MAR decisions to be scientifically validated. Without it, estimates of the benefits of MAR for climate-related resilience are speculative, and the risk of maladaptation, where interventions cause unjustified increases in vulnerability, cannot be sufficiently established.

Likewise, of priority is that consideration of non-technical dimensions of failure might be required. A second continuing challenge has to do with human acceptance in terms of social acceptance, in particular, re reuse of reclaimed or stormwater sources. This remains a continuing challenge of social acceptance influenced by cultural features, risk functioning, and trust in institutions (Dillon et al., 2019; Steck, 2023; Sufyan et al., 2024). Thereafter, stakeholder coordination is reduced where power differentials exist, competing water uses, a lack of mechanisms or processes delivered, which enhance inclusiveness in terms of decision-making (Escalante et al., 2019). While at times, MAR could appear from economic costs analysis to produce a comparative advantage, it is at times overlooked as an implication of hidden costs, such as those attendant to clogging remediation, land opportunity costs, and those which might invigorate management in terms of demand-side management investment foregone (He et al., 2021; Sufyan et al., 2024). However, in the future, if the full potential of MAR as an adaptation strategy is effectively engaged, that will require not only technological improvements, but a systemic change in respect of the interaction of groundwater as a resource in terms of issues of governance. Four imperatives arise from this review. Beyond things such as changes in the use of MAR in a regional systematic sense, the following essentials are seen to emerge. System perspectives and approaches should work to enhance legal and policy frameworks to enhance clarity on the ownership of the recharged water, the suitability of the permitting processes, and ways that MAR could be included in adaptable plans/ideas of management at the basin scale. Long-term systematic, uniform monitoring processes and databases that not only monitor and assess the quantity of water, but also quality aspects, ecological effects, and social/statutory conditions will be essential. Economic instruments which relate to pricing factors, opportunities for inclusivity, and consideration of full life cycle economy, principles as factors will be required. Therefore, syntropic forms of interchange to build capability and co-production of knowledge in climate-vulnerable areas or less developed areas, so that MAR is not a matter of privilege of the elite, but a method or way towards sustainability, and resilience inclusively. In closing, MAR is not a panacea or peripheral form of management, but as indicated, an aspect of intervention looking at governance measures, so that there is an underpinning in the related management in exchange for the inclusive management of the entire resource with respect to its own augmentation. Clearly perceived, MAR can build towards some sustainability contemplatively in respect of climate resilience. At such a level, accessibility and social equity are critical. However, this is not something that is guaranteed by a technology-driven point of view. In this uncertain age, striking a balance necessitates humility in order to get closer to sustainability, social equality, and long-term care. How such interventions are measured and assessed must be based on the normative principles of social and environmental justice in all respects, especially when it comes to the biophysical and novel interventions of mind outside the resource itself. Insofar as MAR can fulfil its role as an operational fix, or an approach which acts as a facilitator in terms of water governance to watershed resilience and responsiveness, and responsibility related to management in climatic conditions managed in the era of climate stress and change.

Conflicts of Interest

"The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper."

Funding Statement

The publication of this paper was paid for by Ba Isago University.

References

[1] Salah Basem Ajjur, and Husam Musa Baalousha, "A Review on Implementing Managed Aquifer Recharge in the Middle East and North Africa Region: Methods, Progress and Challenges," *Water International*, vol. 46, no. 4, pp. 578-604, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] Ala'Alelaimat et al., "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*, vol. 23, no. 12, pp. 5136-5153, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[3] Britt Basel, Jaime Hoogesteger, and Petra Hellegers, "Promise and Paradox: A Critical Sociohydrological Perspective on Small-Scale Managed Aquifer Recharge," *Frontiers in Water*, vol. 4, pp. 1-14, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[4] Elise Bekele et al., "Water Recycling via Aquifers for Sustainable Urban Water Quality Management: Current Status, Challenges and Opportunities," *Water*, vol. 10, no. 4, pp. 1-25, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[5] Gabriella Bennison, and Edmundo Claro, *Managed Aquifer Recharge in Chile: A Promising Alternative to Enhance Water Security*, Managed Groundwater Recharge and Rainwater Harvesting, Springer, Singapore, pp. 151-178, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[6] Helen E. Dahlke et al., *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, Elsevier, pp. 215-275, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[7] Lorenzo De Carlo et al., "Mapping Saltwater Intrusion via Electromagnetic Induction for Planning a Managed Aquifer Recharge Facility in Maltese Island," *Acque Sotterranee - Italian Journal of Groundwater*, vol. 13, no. 1, pp. 7-15, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[8] Osvalda De Giglio et al., "The Aquifer Recharge: An Overview of the Legislative and Planning Aspect," *Annals of Hygiene: Preventive and Community Medicine*, vol. 30, no. 1, pp. 34-43, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[9] P. Dillon et al., "Sixty Years of Global Progress in Managed Aquifer Recharge," *Hydrogeology Journal*, vol. 27, pp. 1-30. [CrossRef] [Google Scholar] [Publisher Link]

[10] Andre R. Erler et al., "Evaluating Climate Change Impacts on Soil Moisture and Groundwater Resources within a Lake-Affected Region," *Water Resources Research*, vol. 55, no. 10, pp. 8142-8163, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[11] Enrique Fernández Escalante et al., "Sites and Indicators of MAR as a Successful Tool to Mitigate Climate Change Effects in Spain," *Water*, vol. 11, no. 9, pp. 1-18, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[12] Dennis Gonzalez et al., "The Potential for Water Banking in Australia's Murray–Darling Basin to Increase Drought Resilience," *Water*, vol. 12, no. 10, pp. 1-24, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[13] Dennis Gonzalez et al., "Estimating the Costs of Managed Aquifer Recharge under Uncertainty with Examples for Town Water Supply in Regional Australia," *Sustainable Water Resources Management*, vol. 10, pp. 1-19, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[14] Maayan Grinshpan et al., "From Managed Aquifer Recharge to Soil Aquifer Treatment on Agricultural Soils: Concepts and Challenges," *Agricultural Water Management*, vol. 255, pp. 1-16, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] Nicolas Guyennon et al., "Climate Change Adaptation in a Mediterranean Semi-Arid Catchment: Testing Managed Aquifer Recharge and Increased Surface Reservoir Capacity," *Water*, vol. 9, no. 9, pp. 1-18, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[16] Sikandar Hayat et al., "MAR Site Suitability Mapping for Arid–semiarid Regions by Remote Data and Combined Approach: A Case Study from Balochistan, Pakistan," *Acque Sotterranee - Italian Journal of Groundwater*, vol. 10, no. 3, pp. 17-28, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[17] Xiaogang He et al., "Climate-informed Hydrologic Modeling and Policy Typology to Guide Managed Aquifer Recharge," *Science Advances*, vol. 7, no. 17, pp. 1-12, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[18] J. D. Henao Casas, E. Fernández Escalante, and F. Ayuga, "Alleviating Drought and Water Scarcity in the Mediterranean Region through Managed Aquifer Recharge," *Hydrogeology Journal*, vol. 30, pp. 1685-1699, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[19] Jose David Henao Casas et al., "Managed Aquifer Recharge as a Low-Regret Measure for Climate Change Adaptation: Insights from Los Arenales, Spain," *Water*, vol. 14, no. 22, pp. 1-22, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[20] Anne Imig et al., "A Review on Risk Assessment in Managed Aquifer Recharge," *Integrated Environmental Assessment and Management*, vol. 18, no. 6, pp. 1513-1529, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[21] Xingxing Kuang et al., "The Changing Nature of Groundwater in the Global Water Cycle," *Science*, vol. 383, no. 6686, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[22] Upmanu Lall, Laureline Josset, and Tess Russo, "A Snapshot of the World's Groundwater Challenges," *Annual Review of Environment and Resources*, vol. 45, pp. 171-194, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[23] Elad Levintal et al., "Agricultural Managed Aquifer Recharge (Ag-MAR)—A Method for Sustainable Groundwater Management: A Review," *Critical Reviews in Environmental Science and Technology*, vol. 53, no. 3, pp. 291-314, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[24] Robert G. Maliva, *Surface Spreading System—Infiltration Basins*, Anthropogenic Aquifer Recharge: WSP Methods in Water Resources Evaluation Series No. 5, Springer Cham, pp. 469-515, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[25] Robert G. Maliva, *Anthropogenic Aquifer Recharge and Water Quality*, Anthropogenic Aquifer Recharge, Springer Cham, pp. 133-164, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[26] Shamima Moazzem et al., "A Critical Review of Nature-Based Systems (NbS) to Treat Stormwater in Response to Climate Change and Urbanization," *Current Pollution Reports*, vol. 10, pp. 286-311, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[27] Karen Moesker, Udo Pesch, and Neelke Doorn, "Public Acceptance in Direct Potable Water Reuse: A Call for Incorporating Responsible Research and Innovation," *Journal of Responsible Innovation*, vol. 11, no. 1, pp. 1-23, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[28] A. Reznik et al., "Institutions and the Economic Efficiency of Managed Aquifer Recharge as a Mitigation Strategy against Drought Impacts on Irrigated Agriculture in California," *Water Resources Research*, vol. 58, no. 6, pp. 1-28, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[29] Michael Roberts, Anita Milman, and William Blomquist, *The Sustainable Groundwater Management Act (SGMA): California's Prescription for Common Challenges of Groundwater Governance*, Water Resilience, Springer, Cham, pp. 41-63, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[30] Andrew Ross, and Sunail Hasnain, "Factors Affecting the Cost of Managed Aquifer Recharge (MAR) Schemes," *Sustainable Water Resources Management*, vol. 4, pp. 179-190, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[31] Dilip Kumar Roy et al., "A Review on the Applications of Machine Learning and Deep Learning to Groundwater Salinity Modeling: Present Status, Challenges, and Future Directions," *Discover Water*, vol. 5, pp. 1-34, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[32] Alejandro Sánchez-Gómez et al., "Modelling Water Management using SWAT+ : Application of Reservoirs Release Tables and the New Water Allocation Module in a Highly Managed River Basin," *Water Resources Management*, vol. 39, 2357-2399, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[33] Bridget R Scanlon et al., "Enhancing Drought Resilience with Conjunctive use and Managed Aquifer Recharge in California and Arizona," *Environmental Research Letters*, vol. 11, no. 3, pp. 1-15, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[34] Christina A. Schwanen et al., "Distribution, Remobilization and Accumulation of Organic Contaminants by Flood Events in a Meso-Scaled Catchment System," *Environmental Sciences Europe*, vol. 35, pp. 1-16, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[35] Constantin Seidl, Sarah Ann Wheeler, and Declan Page, "Understanding the Global Success Criteria for Managed Aquifer Recharge Schemes," *Journal of Hydrology*, vol. 628, pp. 1-18, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[36] Abdul Gaffar Sheik et al., "Machine Learning-based Monitoring and Design of Managed Aquifer Rechargers for Sustainable Groundwater Management: Scope and Challenges," *Environmental Science and Pollution Research*, vol. 32, pp. 31572-31605, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[37] Mohsen Sherif et al., "A Review of Managed Aquifer Recharge Potential in the Middle East and North Africa Region with Examples from the Kingdom of Saudi Arabia and the United Arab Emirates," *Water*, vol. 15, no. 4, pp. 1-34, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[38] Muhammad Sufyan et al., "Managed Aquifer Recharge for Sustainable Groundwater Management: New Developments, Challenges, and Future Prospects," *Water*, vol. 16, no. 22, pp. 1-28, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[39] Paolo Tarolli et al., "Saltwater Intrusion and Climate Change Impact on Coastal Agriculture," *PLOS Water*, vol. 2, no. 4, pp. 1-15, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[40] Ricarda von Krüchten et al., "Deep Learning for Accurate Tumour Volume Measurement and Prediction of Therapy Response in Paediatric Osteosarcoma," *European Radiology*, vol. 36, pp. 2458-2468, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[41] D.E. Wendt et al., "Managed Aquifer Recharge as a Drought Mitigation Strategy in Heavily-stressed Aquifers," *Environmental Research Letters*, vol. 16, no. 1, pp. 1-13, 2021. [CrossRef] [Google Scholar] [Publisher Link]