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# MANAGED AQUIFER RECHARGE SYSTEM IN GUJARAT REGION: A REVIEW

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**ABSTRACT**

Managed Aquifer Recharge (MAR) is animportant strategy for improving groundwater supply by redirecting surface water into aquifers, promoting future use and environmental sustainability. This approach uses various methods, including improvingbasin infiltration and employing injection wells, mainly in arid and semi-arid areas where water scarcity is evident. The effective design and operation of these wells are essential to optimize recharge rates and prevent clogging. In places like Gujarat, energy-efficient recharge wells provide promising solutions to sustainable water management. Successful implementation of MAR requires adherence to best practices in site selection, comprehensive hydrogeological assessments, and innovative well designs. Furthermore, research should focus on water quality, robust filtration systems, and pre-treatment methods to minimize contamination risks. Integration of real-time monitoring technologies, such as IoT and remote sensing, can further improve management by allowingappropriate injection rates based on aquifer conditions. The review examined global MAR practices, highlighted their advantages and challenges, especially in Gujarat, and examined the mechanisms and types of MAR barriersto provide insights into improving water management strategies.

***Key words*****:** Groundwater hydrology, Injection wells, Managed aquifer recharge, Recharge wells

## Introduction

Managed Aquifer Recharge (MAR) is progressively appreciated as one of the most effective strategies for addressing groundwater depletion and promoting sustainable water management (Richard-Ferroudji, Raghunath, and Venkatasubramanian 2018). This practice involves the strategic recharging of water to replenish subsurface storage, making it a key practice for sustainable groundwater management at the subbasin scale (Levintal *et al.*, 2023). In stressed aquifers, strategies such as MAR are vital for restoring and sustaining groundwater levels (Wendt *et al.,* 2021a). The effectiveness of MAR is evident in its ability to improve water quality and reduce electrical conductivity and total dissolved solids, provided that source water is uncontaminated and siltation is managed effectively (Standen and Monteiro 2020). In India, a manual on artificial recharge strategies for planning, designing, and monitoring recharge methods, including urban rainwater harvesting (manual on artificial recharge of groundwater, n.d.), Additionally, guidelines based on the United Nation's water safety planning approach, empower local communities to conduct visual assessments of water quality, emphasizing the need for enhanced government framework to ensure the sustainability of MAR practices (P. Dillon *et al.*, 2019). Managed Aquifer Recharge (MAR) systems, like riverbank filtration and soil-aquifer treatment, use natural subsurface mechanisms to improve the quality of recharged water-such as surface water, stormwater, and reclaimed water-before it is reused (Betancourt *et al.,* 2014).

As the world's largest user of groundwater, India has recognized MAR's potential to mitigate the adverse impacts of extensive groundwater use through multiple

**Table 1:** Report on dynamic groundwater resources of Gujarat state.

| Total No. of Assessed Units | Safe | | Semi- Critical | | Critical | | Over-Exploited | | Saline | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Nos. | % | Nos. | % | Nos. | % | Nos. | % | Nos. | % |
| 252 | 189 | 75 | 20 | 7.94 | 07 | 2.78 | 23 | 9.13 | 13 | 5.16 |

central and state government initiatives (Alam *et al.,* 2022). Due to over-extraction aquifers are under threat, thereby adopting MAR strategies is needed. These methods involve directly replenishing groundwater resources using techniques such as injection wells, recharge basins, and other approaches (Ulibarri *et al.,* 2021). The applications of MAR have been implemented since the 1950s for various purposes, such as to increase groundwater storage, improve quality, restore groundwater levels, prevent saline intrusion, and increase ecological benefits (Shubo, Fernandes, and Montenegro 2020).

Managed Aquifer Recharge (MAR) involves the decisive replenishment of aquifers with surplus surface water, using structures like check dams and recharge wells. This strategy boosts groundwater storage during dry seasons, aiding irrigation efforts and reducing resource depletion (Alam *et al.,* 2022). Drought and water scarcity severely hinder sustainable groundwater development, necessitating effective management strategies amid increasing climate change challenges (Henao Casas, Fernández Escalante, and Ayuga 2022). MAR systems aimed at achieving specific storage objectives are generally implemented in hydrological and engineering contexts where water shortages occur periodically and there are times when surplus water is available for aquifer recharge.(Maliva 2014). The goal of Managed Aquifer Recharge (MAR) is to inject water into partially depleted aquifers to improve the sustainable extraction of groundwater from these sources (Niswonger *et al.,* 2017). The Australian Guidelines for MAR define managed aquifer recharge as the purposeful recharge of an aquifer using a source of water (including recycled water) under controlled conditions, to store for later use or for environmental benefit while protecting human health and the environment(Peter Dillon, Page, *et al.,* 2020).

Gujarat has created a task force to explore large-scale MAR as groundwater storage is more effective than surface water for meeting the state's needs. Although groundwater represents just 30% of the total water resources, it supplies 82% of domestic needs, 65% of industrial demand, and supports 79% of irrigated agriculture (Shah 2014). MAR aims to mitigate the effects of groundwater overexploitation and climate change by recharging aquifers with excess surface water. It employs techniques like injection wells and infiltration ponds to improve both the quantity and quality of groundwater (Fichtner *et al.,* 2019). Gujarat's agriculture is heavily affected by its climate, especially the dependence on the southwest monsoon, with most rainfall occurring from July to September. This seasonal concentration creates challenges for crop cultivation during the other months, resulting in 13% increase in groundwater overdraft for irrigation from 2004 to 2009. In response, the Gujarat government has focused on improving irrigation systems and enhancing groundwater recharge through initiatives like rainwater harvesting, efficient irrigation methods, and educational programs for farmers on sustainable practices. Additionally, investments in infrastructure such as canals and reservoirs, along with regulatory measures to control groundwater extraction, aim to boost agricultural productivity while ensuring long-term water sustainability. (Chinnasamy *et al.,* 2015). The effectiveness of remote sensing and GIS inpinpointing suitable sites for various artificial recharge methods, aiding sustainable groundwater management (Aju *et al.,* 2021)

There is an alarming need for artificial recharge initiatives in semi-critical, critical, over-exploited, and saline regions. The report (Table 1), underscores the urgency of addressing unsustainable groundwater withdrawals and climate change impacts, which can lead to declining groundwater levels ("Report on Dynamic Ground Water Resources of Gujarat State as on March 2022" 2023).

Unsustainable groundwater withdrawals and climate change can lead to declining groundwater levels. Addressing these issues is crucial for maintaining water resources (Jasechko *et al.,* 2024a). Managed Aquifer Recharge (MAR) is essential for boosting agricultural productivity and water security in Gujarat by capturing excess surface water through various structures to replenish aquifers. Effective implementation requires collaboration among experts and thorough field and laboratory research to ensure resilience against water scarcity (Hossain, Bari, and Miah 2021).

This review paper aims to explore global MAR practices, focusing on their advantages and challenges, particularly in the context of Gujarat. It will also investigate the mechanisms and types of obstructions that can occur within MAR systems, providing valuable insights into how these challenges can be addressed. Ultimately, the goal is to leverage the potential of MAR to secure groundwater resources, ensuring sustainable development and resilience against water scarcity for future generations.

## Literature Review

This section reviews key research on Managed Aquifer Recharge (MAR) systems globally, incorporating case studies and academic literature. It highlights the crucial role of MAR in enhancing groundwater levels in Gujarat, as well as the associated challenges. Key regions (Fig. 1) include Saurashtra, which employs check dams to address groundwater depletion; Kutch, utilizing innovative MAR techniques; and North Gujarat, where intensive agriculture has led to significant groundwater declines. Recharge wells are vital for sustainable water management, improving aquifer resilience, and supporting agricultural productivity.

Gujarat covers 196,024 sqm. and has the longest coastline in India. It frequently faces droughts and consists of three physiographic regions with complex hydrogeological features. The state identifies 6,194.42 million cubic meters per year for artificial recharge planning, with a remaining surplus runoff of about 4,144.27 MCM after accounting for existing structures. An additional 315 MCM of surface water is also allocated for recharge, bringing the total available runoff for recharge to approximately 4,459.26 MCM, according ("Master Plan to GW Recharge 2020," n.d.). Gujarat's experience demonstrates the importance of community involvement and government support in the sustainability of recharge structures, as local engagement enhances effectiveness. Additionally, the Australian risk-based approach to Managed Aquifer Recharge (MAR) offers a valuable framework for maintaining groundwater quality,

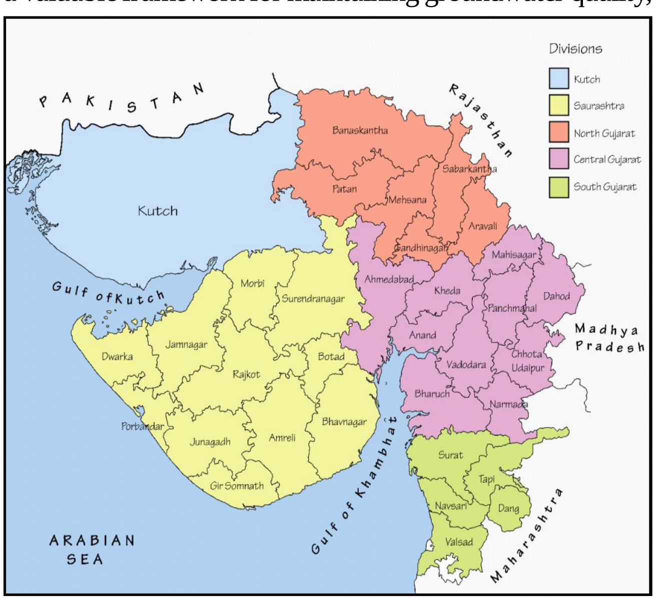


**Fig. 1:** Map of Gujarat region.

making it a relevant model for regions like Gujarat. (Zheng *et al.*, 2023).

Gujarat is characterized by arid and semi-arid conditions, with 64% of its land classified in these categories. The state relies heavily on agriculture, which severely depends on groundwater for irrigation, especially given the erratic and uneven patterns of monsoon rainfall. This dependence highlights the importance of sustainable groundwater management to support agricultural productivity and food security in the state (Chinnasamy *et al.*, 2015). Several studies have documented the increasing depletion of groundwater resources in Gujarat, noting a 13% rise in groundwater overdraft from 2004 to 2009. This over-extraction has resulted in declining water tables in many areas, particularly in Saurashtra, North Gujarat, and Kutch. Groundwater is an essential resource for the state, providing 82% of domestic water needs, meeting 65% of industrial water demand, and supporting 79% of the irrigated area. This highlights the urgent need for sustainable management practices to protect this vital resource (Shah 2014).

The comparative analysis of Managed Aquifer Recharge (MAR) techniques across regions highlights both similarities and best practices that can inform future efforts in Gujarat and beyond. The MAR strategies implemented in Gujarat closely resemble those utilized in other arid regions, such as Australia, Spain, and the southwestern United States (P. Dillon *et al.*, 2019). Groundwater resources support ecosystems and human livelihoods. However, unsustainable extraction practices have led to significant declines in groundwater levels, resulting in adverse consequences such as seawater intrusion, land subsidence, depletion of streamflow, and drying wells. Despite the significance of these issues, the global rate of groundwater decline remains poorly understood, largely due to a lack of synthesized in situ groundwater level data at a global scale (Jasechko *et al.*, 2024b).

The growing frequency of meteorological droughts and rising water demand are driving unsustainable groundwater use. In stressed aquifers, Managed Aquifer Recharge (MAR) techniques are essential for restoring depleted groundwater resources and managing brief dry spells. However, the broader effects of MAR as a strategy for mitigating drought still need a thorough evaluation. Understanding these impacts is crucial for refining MAR practices and enhancing its effectiveness in promoting sustainable water management (Wendt *et al.*, 2021b).

MAR is a crucialelement of integrated water resources management. It aids in restoring over-allocated or brackish aquifers, safeguarding groundwater-dependent ecosystems, and enhancing water supplies for both urban and rural communities. Furthermore, MAR helps reduce evaporation losses and bolsters overall water supply security, making it a vital strategy for achieving sustainable water management (Peter Dillon and Arshad 2016). Ongoing water resource crises emphasize the importance of better understanding hydrological processes and improving the technical and socioeconomic management of groundwater (Casanova, Devau, and Pettenati 2016).

Gujarat has its origins in the state's long history of water conservation, which includes traditional practices like village-level water harvesting structures. However, as groundwater depletion became increasingly severe, more formalized and large-scale MAR initiatives emerged. The Government of Gujarat, in collaboration with organizations such as the Central Ground Water Board (CGWB), began promoting MAR techniques, particularly following the establishment of a task force in 2008. This task force was tasked with exploring MAR's potential to mitigate groundwater depletion and enhance water security in the region. (Shah 2014)

A study by (Alam *et al.,* 2022), highlights the crucial role that Managed Aquifer Recharge (MAR) has played in stabilizing groundwater levels in Gujarat's water-scarce regions. The implementation of infrastructure such as check dams, percolation tanks, and recharge wells has effectively captured surface runoff and excess rainwater. This not only recharges local aquifers during monsoon seasons but also provides a buffer during dry periods, enhancing water availability and resilience in these areas.

A transdisciplinary approach and community involvement are crucial for effective village-scale groundwater management, as demonstrated in Gujarat and Rajasthan, India. By integrating diverse knowledge and empowering local communities in decision-making, these initiatives enhance management effectiveness and encourage a sense of ownership among residents. (Maheshwari *et al.,*, 2014),

Groundwater is essential for agriculture in Gujarat, leading to significant government investments in water infrastructure. Analysis of NASA's GRACE data shows an increase in water storage, alongside a 30% growth in cropped areas during the non-monsoon season. Overall, net water storage rose by 5,890 million cubic meters, demonstrating the effectiveness of these initiatives in enhancing agricultural productivity (Chinnasamy *et al.,* 2015). Artificial recharge can enhance groundwater quantity and quality, potentially freshening brackish water or lowering fluoride levels. However, it may also introduce contaminants or release harmful minerals like arsenic, posing health risks. Therefore, effective management is crucial, and Managed Aquifer Recharge (MAR) focuses on ensuring safe and sustainable groundwater for all uses (Peter Dillon *et al.,* 2014). A study of recharge wells in a coastal aquifer in Israel revealed that hydraulic parameters significantly decreased during injection compared to pumping tests, indicating challenges such as clogging. To mitigate these issues, it's important to keep the injection pipe filled with water, ideally using an orifice valve, though this may not entirely prevent clogging, highlighting the need for effective management protocols for water injection systems (Guttman, Negev, and Rubin 2017).

Managed Aquifer Recharge (MAR) is gradually valued for both underground water storage and its role in water treatment, especially for urban stormwater and treated wastewater. While it enhances water quality by reducing pathogens and organic chemicals, it can also introduce risks like arsenic mobilization. Despite its potential in sustainable urban water management, MAR's adoption has been slow, necessitating improved policies, transparent cost reporting, and better institutional coordination for effective integration into water management strategies. (Page *et al.,* 2018). Participatory groundwater management is crucial for promoting equity and sustainability, as demonstrated by the MARVI project in Rajasthan and Gujarat. In this initiative, local villagers, trained as BhujalJaankars (BJs), engaged in monitoring and managing groundwater resources. The project highlighted how capacity-building empowers BJs to share vital information within their communities, fostering sustainable practices and making them champions of groundwater management (Jadeja *et al.,* 2018).

The costs of Managed Aquifer Recharge (MAR) schemes can vary widely. Low-cost options include infiltration and spreading basins using untreated water, while recharge wells and more complex infrastructure incur higher expenses. Advanced water treatment further adds to costs. Factors influencing these expenses include the objectives of the scheme, how often it is used, hydrogeological conditions that impact infiltration rates and well yields, as well as the source and intended use of the recharged water. Future research should aim to provide a detailed breakdown of capital and operating costs and consider a wider variety of scheme types, water sources, and regional contexts(Ross and Hasnain 2018)

Integrating Artificial Intelligence (AI) into groundwater management presents transformative opportunities and challenges. AI can enhance predictive modelling, real-time monitoring, and data integration, significantly improving resource management. However, issues like model interpretability, the need for technical expertise, and data quality may hinder progress. Looking ahead, AI's potential to identify vulnerable areas and foster collaboration among stakeholders is crucial for advancing sustainable groundwater practices and evolving management strategies. (Mustaq Shaikh and Farjana Birajdar 2024).

To tackle the issue of decreasing groundwater levels in the Amaravathi aquifer system in southern India, researchers utilized remote sensing and GIS techniques to pinpoint ideal sites for artificial recharge structures. The analysis integrated eight thematic layers, including geology, geomorphology, and land use, using data from various sources to create thematic maps. The study classified the area into four feasibility zones for artificial recharge, finding that about 45% had high to very high feasibility. Existing recharge structures were mapped, and potential new constructions were proposed, including 166 masonry check dams, 155 nala bunds, 575 recharge shafts, and 716 percolation ponds. These initiatives are expected to increase annual water resources by approximately 198 million cubic meters (Senthilkumar, Gnanasundar, and Arumugam 2019).

Managed Aquifer Recharge (MAR) sites often face clogging issues mainly due to physical processes, which reduce infiltration capacity over time. Cleaning operations are needed to restore flow rates. This study reviews existing physical clogging models from engineering fields to enhance MAR design. It compares key assumptions and mathematical equations related to soil and particle interactions. The aim is to develop a process-based model suitable for surface spreading schemes and to improve clogging risk assessment, providing decision-makers with tools to plan effective MAR strategies. (Lippera, Werban, and Vienken 2023).

To prevent clogging in Managed Aquifer Recharge (MAR) systems, key strategies include careful aquifer selection, thoughtful design, and appropriate construction techniques. Implementing source control measures to divert water that doesn't meet quality standards is essential, along with treating source water before it enters the aquifer. Regular monitoring and maintenance, such as cleaning recharge basins and redeveloping wells, help minimize clogging risks. For significant clogging, more intensive treatments like acidization, biocide applications, vacuum pumping, and mechanical cleaning may be necessary ("MAR-Overview-and-Governance-IAH-Special-Publication-18 June 2022," n.d.). Clogging is a major challenge in artificial recharge systems (ARS), affected by various physio-bio-chemical factors that differ in porous and fractured media. It can block pore spaces, reducing permeability and flow to the aquifer. Poor-quality injected water often contains high levels of suspended solids (SS), BOD, nitrogen compounds, and grease, which contribute to clogging. Studies show that around 80% of aquifer recovery sites face clogging, mainly from physical SS infiltration (50%), followed by biological growth (15%) and chemical precipitation (10%). Other clogging causes include air entrapment (10%) and clay swelling (5%). Addressing these issues is crucial for developing effective, eco-friendly strategies. This paper reviews the mechanisms, types, and potential solutions for clogging in ARS. (Akhtar, Nakashima, and Nishigaki 2021).

An efficientrecharge well plays a crucial role in groundwater recharging, all well drilling methods inherently cause some borehole damage due to the infiltration of materials like clays, silts, and drilling fluids. Techniques such as flooded reverse circulation and casing advance are more effective at minimizing this damage compared to traditional methods. Choosing drilling fluids that can be fully removed is crucial, and while some polymers can decompose, they often require bentonite for effective cleaning, which needs careful management. Proper well development is essential for optimal performance, involving the removal of fines and drilling fluids to ensure a sand-free operation, ultimately leading to efficient well-functioning (Hanna, n.d.).

The article "Managed Aquifer Recharge: A Key to Sustainability" (Escalante *et al.*,, 2023), introduces the Monitored and Intentional Recharge (MIR) model, highlighting nine crucial components for effective Managed Aquifer Recharge (MAR): water source, hydrogeological factors, MAR technology, data collection, monitoring guidelines, intended water use, water quality analysis, risk assessment, and additional factors. It also presents innovative concepts like hydrodynamic monitoring and user participation. This framework encourages public involvement and strengthens oversight of water resources. While the MIR model serves as a comprehensive guideline for MAR practices, it promotes a flexible approach tailored to the unique contexts of various regions, making it an effective resource for developing relevant guidelines.

South Asia's heavy dependence on groundwater for irrigation plays a crucial role in supporting millions of smallholder farmers, but it faces significant challenges from overuse, growing demand, and climate change.

**Table 2:** Annual groundwater recharge and extraction for India (CGWB, 2022).

| Parameter | Value |
|---|---|
| Total annual groundwater recharge | 437.60 km³ |
| Annual extractable groundwater resources | 398.08 km³ |
| Annual groundwater extraction | 239.16 km³ |
| Stage of Ground Water Extraction | 60.08% |

Sustainable groundwater management is essential for maintaining resources and enhancing resilience to climate impacts. This study outlines strategies for improved management, highlighting the importance of managed aquifer recharge to increase groundwater supply, participatory approaches to regulate demand, and collaboration across different sectors. It also analyses the opportunities and obstacles present to identify practical steps for effective policy reforms and implementation initiatives (Sikka, Alam, and Pavelic 2021). Managed Aquifer Recharge (MAR) intentionally replenishes aquifers to secure water availability and environmental benefits, focusing on the quantity and quality of water. While traditionally termed "artificial recharge," MAR emphasizes quality assessment to protect public health, particularly in regions like India. Over the years, MAR has evolved to incorporate advanced techniques for enhancing water quality alongside increasing recharge volumes (P. Dillon *et al.,* 2019).

(Raj *et al.,* 2024), highlight a significant increase in attention toward artificial recharge in recent years. Government bodies have conducted pilot studies to demonstrate its effectiveness, raise public awareness, and build community expertise. This emphasis on enhancing artificial recharge infrastructure is driven by increasing pressure on groundwater resources illustrated in Table 2.

## MAR Techniques used in Gujarat

In Gujarat, various Managed Aquifer Recharge (MAR) techniques have been effectively implemented to address local hydrological and geological conditions. Key methods include check dams, which slow water flow to enhance infiltration and trap monsoon runoff; percolation tanks, shallow ponds that allow surface water to seep into aquifers; recharge wells for direct water injection into confined aquifers; and infiltration basins designed to capture and infiltrate surface water. These strategies have shown varying success, contributing to stabilized groundwater levels and improved water security in several regions (Chinnasamy *et al.,* 2015); (Shah 2014). Each of these techniques has been implemented with varying degrees of success, with studies showing that MAR systems have helped to stabilize groundwater levels and improve water security in some regions of Gujarat (Alam *et al.,* 2022). Managed Aquifer Recharge (MAR) employs various techniques (Table 3) to replenish aquifers, such as waterwell and borehole recharge, spreading infiltration methods, and induced bank filtration. These methods, along with stormwater storage modifications and rainwater harvesting, are adapted to local conditions for effective groundwater recharge (Ringleb, Sallwey, and Stefan 2016).

## Effectiveness of MAR in Gujarat

Various studies indicate the positive impacts of MAR in Gujarat. For instance, (Chinnasamy *et al.,* 2015) noted that check dams and percolation tanks built in Saurashtra and North Gujarat have significantly increased groundwater levels, thusreducing aquifer overexploitation. These structures have supported agricultural productivity by ensuring a steady supply of water during the dry months. Reports from the Central Ground Water Board and the Ground Water Resources Development Corporation, Gujarat state highlight that MAR structures, particularly check dams and recharge wells, have enhanced groundwater availability in critical and semi-critical regions. furthermore, a survey by (Shah 2014) in the Kutch region demonstrated that MAR has raised water tables, aiding farmers in this arid area.

As MAR gains wider acceptance, it provides benefits from higher-quality water sources, including treated recycled water. This process enhances groundwater quality through dilution of existing contaminants, addressing immediate concerns while contributing to long-term aquifer sustainability (Day and Senevirathna 2023). However, overexploitation and climate change lead to

**Table 3:** MAR classification system expressing five main methods and associated specific MAR methods, adapted from International Groundwater Resources Assessment.

| Techniques | Main MAR Methods | Specific MAR Methods |
|---|---|---|
| Technique referring primarily to getting water infiltrated | Well, shaft and borehole recharge | Aquifer Storage and Recovery (ASR) / Aquifer Storage, Transfer and Recovery (ASTR), Shallow well / Shaft / pit infiltration |
| | Spreading methods | Infiltration ponds & basins Flooding Ditch, furrow, drains, Irrigation |
| | Induced bank infiltration | River / lake bank filtration, Dune filtration |
| Techniques referring primarily to intercepting the water | In- channel modifications | Recharge dams, Subsurface dams, Sand dams, Channel spreading |
| | Runoff harvesting | Rooftop rainwater harvesting, Barriers and bunds Trenches |

significant issues such as aquifer depletion and groundwater quality degradation due to saline intrusion, adversely affecting water supply reliability and ecosystem health (Salameh, Abdallat, and van der Valk 2019). Moreover, utilizing floodwater for MAR (Flood-MAR) proves to be more cost-effective, sustainable, and adaptable to climate change compared to traditional surface storage methods (He *et al.,* 2021).

**Challenges and Limitations of MAR in Gujarat**

Despite its successes, Managed Aquifer Recharge (MAR) in Gujarat faces challenges such as variable rainfall, outdated infrastructure, and community resistance.

- Ensuring water quality and establishing a supportive regulatory framework are crucial for effective implementation. The state's varied hydrogeological conditions impact MAR effectiveness. In areas with hard rock aquifers, recharge rates are often low due to limited storage capacity, hindering the success of MAR initiatives (Shah 2014).
- Poor quality of recharge sources poses a risk of groundwater contamination. Studies (Dillon *et al.*, 2019), highlight the necessity of monitoring water quality before recharging aquifers to prevent long-term pollution.
- Clogging of recharge wells, primarily due to silt and clay particles in infiltration water, poses a major challenge to the sustainability of Managed Aquifer Recharge (MAR) schemes (Alam *et al.,* 2020). Clogging is a major challenge for MAR, whichrequires improving source water quality and monitoring. The approach includes initial problem avoidance, small cycle improvements, and long-term maintenance strategies for injection wells and infiltration basins.(Peter Dillon, Escalante, *et al.,* 2020)
- Effective MAR systems depend on active community involvement for maintenance. However, many structures fall into disrepair due to insufficient local engagement in their upkeep (Chinnasamy *et al.,* 2015).

**Policy and Governance Framework**

Establishing a State Ground Water Authority is essential for the sustainable management and conservation of groundwater resources. This requires strengthening institutions and building capacity for informed, equitable, and economical management practices. ("Report on Dynamic Ground Water Resources of Gujarat State as on March 2022" 2023). The Gujarat Water Resources Development Corporation (GWRDC) and the Gujarat government have developed policies to expand the use of MAR technologies across the state, focusing on groundwater sustainability. In addition, the Central Ground Water Board (CGWB) has issued guidelines on artificial recharge, which include detailed instructions on planning, designing, and monitoring MAR systems (CGWB, 2007).However, (Shah 2014) points out that while the government's policies on MAR are commendable, there is still a lack of coordination between various government agencies, as well as a need for better monitoring and evaluation of existing MAR projects. Managed Aquifer Recharge (MAR) presents challenges for regulators due to the numerous factors that must be taken into account. Effective implementation of any MAR project generally requires careful attention to both the quantity and quality of surface water and groundwater (Peter Dillon, n.d.).

## Conclusion

To enhance Managed Aquifer Recharge (MAR) in Gujarat, improving policy coordination, monitoring, and maintenance of recharge structures is imperative. Preliminary evidence indicates that grassroots initiatives are effective in addressing groundwater depletion (Shah *et al.,* 2003). The feasibility of MAR structures is influenced by local geology, rainfall patterns, and aquifer characteristics, necessitating regular monitoring to prevent contamination, silting, and clogging (Ganguly and Ganguly 2021). Injection wells facilitate targeted recharge with treated water, and integrating AI can optimize operations and enable real-time groundwater quality monitoring. Community engagement and supportive policies are essential for sustainable management.

The effectiveness and sustainability of Managed Aquifer Recharge (MAR) rely heavily on specific site characteristics. Integrating these factors and developing suitability maps is crucial for identifying optimal locations for MAR projects (Hussaini *et al.,* 2022). Overall, MAR is crucial for long-term water security in Gujarat, particularly in the context of climate change, with significant benefits derived from small-scale water-harvesting and artificial recharge efforts (Patel, Saha, and Shah 2020). This review presents strategies for better groundwater management, highlighting strategies for managing aquifers with excess surface water, participatory approaches to manage demand, and fostering synergies across sectors.

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