REVIEW

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Systematic review of managed aquifer recharge in Brazil

Leonardo Capeleto de Andrade[1*], Ricardo Hirata[1], Leila Goodarzi[1] and Alexandra Suhogusoff[1]

*Correspondence:
Leonardo Capeleto de Andrade
leonardo.capeleto@usp.br
[1]Project SACRE | Integrated Water Solutions for Resilient Cities, Groundwater Research Center (CEPAS), Institute of Geosciences (IGc), University of São Paulo (USP), Rua do Lago 562, Cidade Universitária, São Paulo, SP 05508-080, Brazil

Abstract
Managed Aquifer Recharge (MAR) is an effective climate change adaptation strategy that can substantially increase water supply security. Regardless of the historical water crisis in Brazil, the extent of MAR utilization is relatively limited and considered a new technology in the region. This study aims to systematically review MAR practices in Brazil, as reported in published scientific articles. A Boolean search in seven electronic databases (PubMed, Redalyc, SciELO, ScienceDirect, Springer Link, Taylor & Francis Online, and Wiley Online Library) identified in 28 scientific articles on MAR in Brazil, which were verified and included in this review. The successful application of MAR in Brazil should anticipate future water crises as a tool for adapting to climate change. Public policies and regulations must take a proactive approach to support MAR adoption. More pilot studies should be conducted and widely disseminated to address resistance to MAR practices. Over the past three decades, nearly 30 articles on MAR in Brazil have been published. However, the application of MAR techniques remains limited, with most cases occurring in rural areas. These implementations are likely constrained by insufficient data publication and a lack of large-scale studies.

Keywords Artificial recharge, Water crisis, Water and sanitation, Water resources management

1 Introduction

Managed Aquifer Recharge (MAR) is a nature-inspired solution that intentionally recharges aquifers with surface water for later use or environmental benefits. MAR offers several advantages compared to surface water storage in dams and reservoirs, including lower costs, prevention of algae buildup and mosquito breeding, reduced evaporation loss, and ease of site selection near areas with high water demands [1]. MAR encompasses various recharge techniques, including spreading basins, infiltration ponds, wells, shafts, aquifer storage, and recovery (Fig. 1).

MAR's most significant goal and advantage is the enhancement of water security. Moreover, MAR can also be a climate change adaptation mechanism (a no-regret technique) for securing long-term groundwater availability [2]. MAR methods, serving as a water banking and treatment strategy in aquifers, address water resilience challenges by increasing water supply security, and potentially buffering water quality declines [2–4].

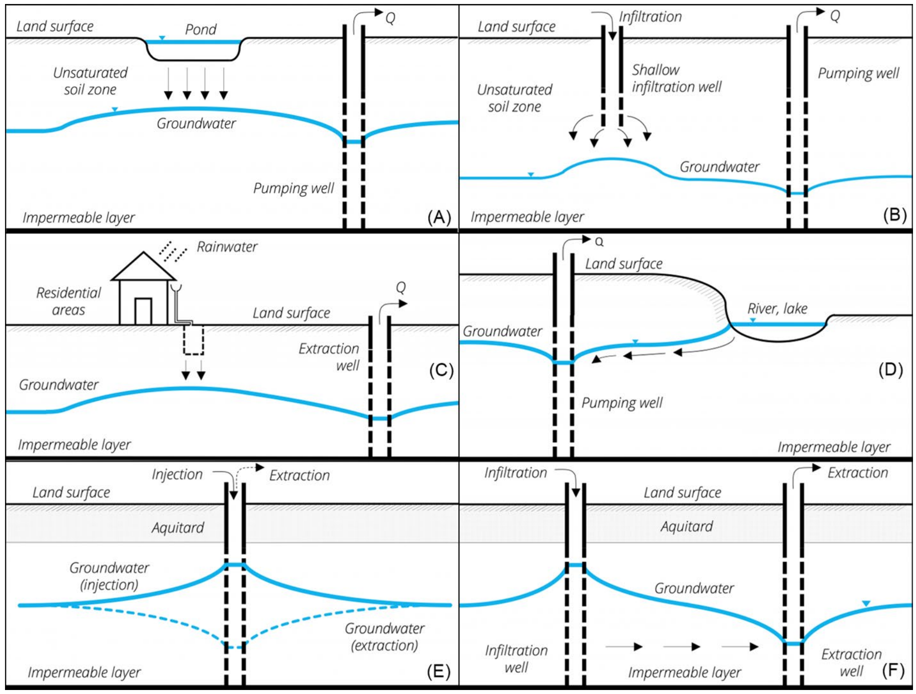

Fig. 1 Examples of Managed Aquifer Recharge (MAR) methods: **A** Infiltration ponds; **B** Shallow wells, shafts and pits infiltration; **C** Rooftop rainwater harvesting; **D** Induced bank filtration—RBF; **E** Aquifer storage and recovery—ASR; and **F** Aquifer storage, transfer, and recovery—ASTR [1]

MAR prototypes have been used for over 2,000 years on different continents, initially for agricultural irrigation. Since the 1990s, MAR has been adopted in many countries to combat water shortages resulting from climate variability and population growth, and to protect ecosystems and the environment [5].

Although Brazil has abundant water availability, it is not uniformly distributed across the country, and most water resources are concentrated in the Amazon region. The country has experienced hundreds of water crises since its colonization, especially in the Northeast region [6]. From 2019 to 2021, approximately 44 million people in Brazil were affected by droughts, which is about 14 times more than those affected by floods [7]. Most drought events in 2021 occurred in the Northeast region (67%), followed by the South (17%) and Southeast (15%) [7]. During the 2013–2017 water crisis, the number of private wells increased exponentially, followed by intense exploitation [8]. The federal capital, Brasilia, and the largest city, São Paulo, endured water rationing during this period [6].

Brazil increasingly relies on private wells as a self-supply strategy, as groundwater is considered an open-access resource [9]. Currently, 52% of Brazilian municipalities are totally or partially supplied by groundwater through approximately 2.5 million tube wells, 88% of which are irregular and unknown to the government. These wells, however, are essential to supplement the deficient public network in many cities and are crucial for rural water supply and agricultural production. Cities dependent on groundwater are twice as resilient to drought and better able to face global climate change than those supplied by surface water [8].

In a climate change scenario and with ever-increasing demand, MAR techniques can serve as an adaptation strategy for extreme events, such as droughts, and serve as a mitigation measure against future water crises [6]. The MAR concept has the potential to be an innovative approach to integrated water resources management in Brazil.

The impacts of climate change are expected to worsens water scarcity, especially in drought-prone regions of Brazil, with declining rainfall in the Northeast, Central, and Southwest [10]—further intensifying existing water stress. Erratic patterns and longer dry spells challenge traditional water sources, highlighting the need for alternative strategies like MAR as an adaptation measure. MAR could support communities by augmenting the availability of groundwater, which is often the primary source of water during droughts, and reducing reliance on unreliable surface water systems.

Despite the potential benefits of MAR as a solution for droughts and water shortages in Brazil, there is a lack of awareness and dissemination of these techniques, particularly to the international scientific community [11].

Thus, this study aims to conduct a systematic review of MAR practices in Brazil, as reported in published scientific articles. Our study highlights critical gaps in MAR research, focusing on the lack of scientific studies, technical aspects, and regulatory issues in Brazil.

2 Materials and methods

The systematic review applied the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) model [12]—a well-established methodology that enhances transparency by synthesizing literature and identifying key insights and research gaps [13–15].

2.1 Search strategy

The search was conducted in April 2023 across seven electronic databases: PubMed, Redalyc, SciELO, Science Direct, Springer Link, Taylor & Francis Online, and Wiley Online Library (Fig. 2)—extensively covering Brazilian scientific literature, particularly in environmental sciences and groundwater management.

Boolean search included the following terms in English, Portuguese, and Spanish languages: ("Managed Aquifer Recharge") OR ("Artificial Aquifer Recharge") OR ("Artificial Groundwater Recharge") OR ("Artificial Recharge") AND ("groundwater") AND ("Brazil"); ("Recarga Gerenciada de Aquíferos") OR ("Recarga Artificial de Aquíferos") OR ("Recarga Artificial") AND ("água subterrânea") AND ("Brasil"); ("Recarga de acuíferos administrados") OR ("Recarga artificial de acuíferos") OR ("Recarga gestionada de acuíferos") OR ("Recarga artificial") AND ("aguas subterráneas") AND ("Brasil").

Additional records were retrieved from the Brazilian journal's portal of the Coordination for the Improvement of Higher Education Personnel, the Periódicos CAPES (periodicos.capes.gov.br).

The search results were exported as a *Research Information Systems* (RIS) file, including Research articles, Review articles, and Short communications. For databases that did not allow filtering results by article type (such as Redalyc and Wiley), pre-screening was performed to eliminate other article types (such as Book chapters, Conference abstracts, Editorials, and Others).

A pre-screening and deduplication process was carried out using *Mendeley Desktop* software, and all article metadata was updated through *Update Details* function in the

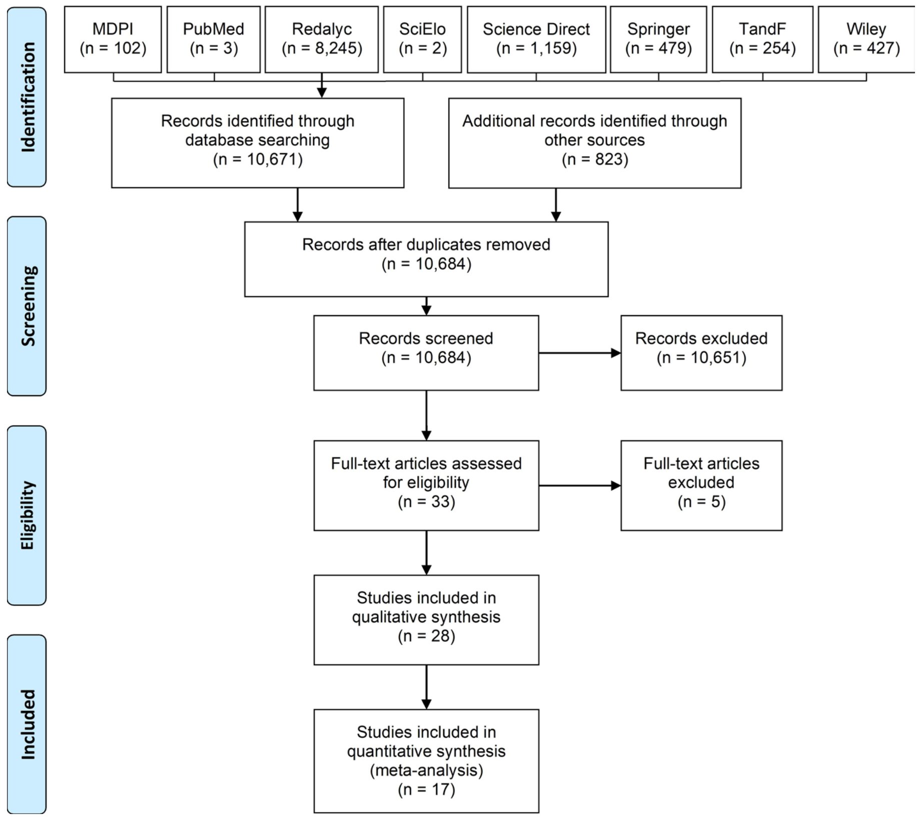

Fig. 2 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for Managed Aquifer Recharge in Brazil

same software. Subsequently, the records were imported into *Rayyan QCRI* [16] to manage the articles, repeating the deduplication process.

2.2 Screening and eligibility

The search terms were added as the *keywords for inclusion* in the *Rayyan QCRI* to highlight the metadata in the screening. Following the initial screening, *Rayyan's Compute Ratings*, a prediction feature based on near-match similarity [16], was eventually executed. Then, the records were evaluated through metadata, and the full texts were accessed when needed.

Articles were excluded from the evaluation if they did not mention the concepts, were unrelated to Brazil, or only included the search terms in the text.

2.3 Bibliometric mapping

Based on the RIS file, the graphical representations of bibliometric maps were generated using *VOSviewer software v1.6.16* [17]. These maps were created using co-occurrence (keywords) and co-authorship analysis, employing a full counting method.

For the co-occurrence analysis, a minimum of one keyword occurrence and a link strength of at least five were set. In the case of co-authorship Analysis, an author had to be associated with at least two documents. The resulting bibliometric map displayed the largest set of connected keywords and featured the maximum number of keywords and lines.

3 Results

A total of 11,494 papers were found through the search by the keywords, of which 810 records were removed through deduplication—and 10,651 (99,7%) were excluded for not dealing with the topic. After the screening process, 28 papers (0.24% of total) on Managed Aquifer Recharge (MAR) in Brazil were selected (Table 1), which involved a total of 90 authors, 14 of whom contributed to at least two publications, and nine authors had at

Table 1 List of 28 publications on Managed Aquifer Recharge in Brazil

Year	Authors	Journal	Local	Major themes	References
1994	Mendonça et al	*Environmental Geology*	DF, Brasilia	Theory	[18]
2001	Costa & Filho	*Águas subterrâneas*	PE, Recife	Theory / Case (Infiltration Ponds and Basins)	[19]
2002	Maurice & Lima	*Águas subterrâneas*	Nordeste	Theory	[20]
2003	Tubbs & Pereira	*Águas subterrâneas*	Brazil	Legislation / Theory	[21]
2003	Tubbs & Pereira	*Águas subterrâneas*	Brazil	Review	[22]
2004	Moura	*Águas subterrâneas*	-	Review	[23]
2004	Campos	*Revista Brasileira de Geociencias*	DF	Theory	[24]
2005	Costa & Barros Júnior	*Holos*	-	Review	[25]
2005	Cadamuro & Campos	*Revista Brasileira de Geociencias*	DF	Case (Open Well and Shaft / Rainwater harvesting)	[26]
2008	Diniz et al	*Águas subterrâneas*	SP, Taubaté	Case (Aquifer Storage/ transfer and Recovery)	[27]
2008	Diniz et al	*Ambiente & Água*	SP, Taubaté	Case (Aquifer Storage/ transfer and Recovery)	[28]
2013	Eichler & Serradourada	*Águas subterrâneas*	DF	Legislation / Theory	[29]
2018	Coelho et al	*Environmental Management*	PE, Recife	Case (Aquifer Storage/ transfer and Recovery)	[30]
2018	Coutinho et al	*Revista Brasileira de Recursos Hidricos*	PB, João Pessoa	Case (Infiltration Ponds and Basins)	[31]
2018	Stefan & Ansems	*Sustainable Water Resources Management*	Brazil / World	Review	[32]
2018	Bonilla Valverde et al	*Sustainable Water Resources Management*	Brazil / World	Review	[11]
2018	Petelet-Giraud et al	*Science of the Total Environment*	PE, Recife	Theory / Case (Infiltration Ponds and Basins)	[33]
2018	Mattos et al	*Environmental Monitoring and Assessment*	BA, Lençóis	Case (leakages)	[34]
2020	Escalante et al	*Acque Sotterranee*	Brazil / World	Review	[35]
2020	Nunes & Campos	*Geociencias*	DF	Case (Open Well and Shaft / Rainwater harvesting)	[36]
2020	Shubo et al	*Water*	Brazil	Review	[6]
2021	Campos et al	*Anuario do Instituto de Geociencias*	Biome Cerrado	Legislation / Theory	[37]
2021	Justino et al	*Revista Brasileira de Recursos Hidricos*	SP, São Carlos	Case (Open Well and Shaft / Rainwater harvesting)	[38]
2022	Bertrand et al	*Environmental Science and Health*	Brazil	Theory	[9]
2022	Bertrand et al	*Water Research*	PE, Recife	Theory / Case (River Bank Filtration)	[39]
2022	Freitas et al	*River Research and Applications*	PE, Recife	Case (River Bank Filtration)	[40]
2023	Costa et al	*Hydrogeology Journal*	CE	Case (interbasin transfers)	[41]
2023	Campos et al	*South American Earth Sciences*	RN	Case (leakages)	[42]

least two connections with others (Fig. 3). Of the included papers, 12 of them (43%) are written in Brazilian Portuguese (PT-BR), while the remaining (57%) are in English.

The high number of results retrieved in certain databases—1,159 from Science Direct and 8,245 from Redalyc (Fig. 2)—may be attributed to the platforms' processing of Boolean search expressions, favoring partial or generic keywords such as "[*ground*]water" ("*água* [*subterrânea*]") and "Brazil" over more specific MAR-related terms. This search behavior led to the initial inclusion of many records not directly aligned with the review topic.

Of the 17 theoretical or case studies focused on specific Brazilian cities or states (Fig. 4), the majority (53%) were conducted in the Brazilian Northeast region [20] and its states [19, 30, 31, 33, 34, 39–42]. Additionally, five studies focused are centered on the Federal District—DF [18, 24, 26, 29, 36], where the capital, Brasilia, is located (Fig. 4).

The most mentioned MAR techniques by the authors (Fig. 1) were the Infiltration Ponds and Basins (25%), Open Well and Shaft / Rainwater Harvesting (25%), and Aquifer Storage/Transfer and Recovery (ASR/ASTR; 25%), followed by Injection Wells (15%) and Riverbank Filtration (RBF; 10%).

For the Federal District (DF), it is recommended to employ artificial recharge through Open Wells and Shafts, combined with Rainwater Harvesting from rooftops [24, 26, 36]. Rainwater Harvesting has also been suggested for the state of São Paulo [27, 28], while for Recife (PE), the proposed techniques included Aquifer Storage and Recovery [20] and Aquifer Storage and Transfer and Recovery [30].

Three review papers citing MAR in Brazil focused on the world [32], Latin America [11], and Brazil [6]; and another four focused on the legal aspects of MAR and Brazilian legislation [21, 29, 35, 37].

In the bibliometric map of keywords co-occurrence, four distinct groups were formed around MAR (Fig. 5), related to: standards, guidelines, and regulations (in orange color); grain size and pollution (green); injection and infiltration (purple); and water security (yellow). The fifth group (blue), connected to the other through "Brazil", focused on governance and management.

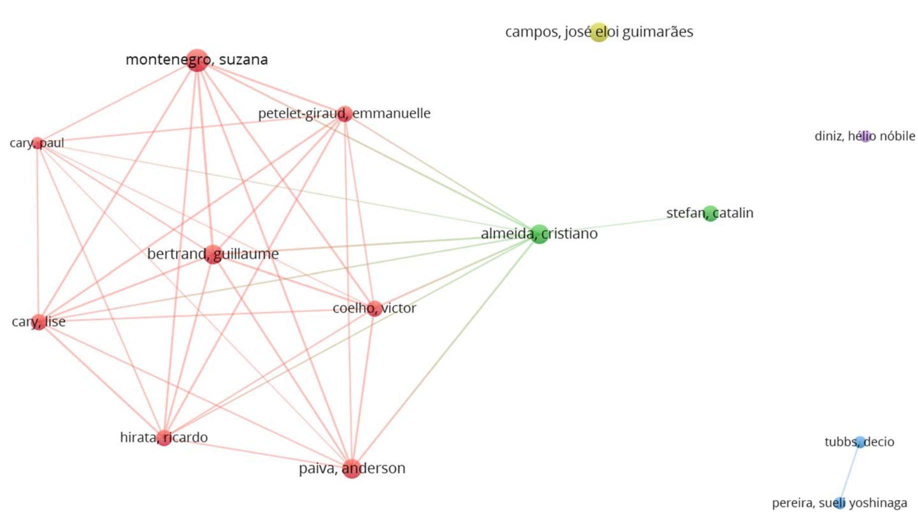

Fig. 3 Bibliometric map of co-authorship links on articles about Managed Aquifer Recharge in Brazil

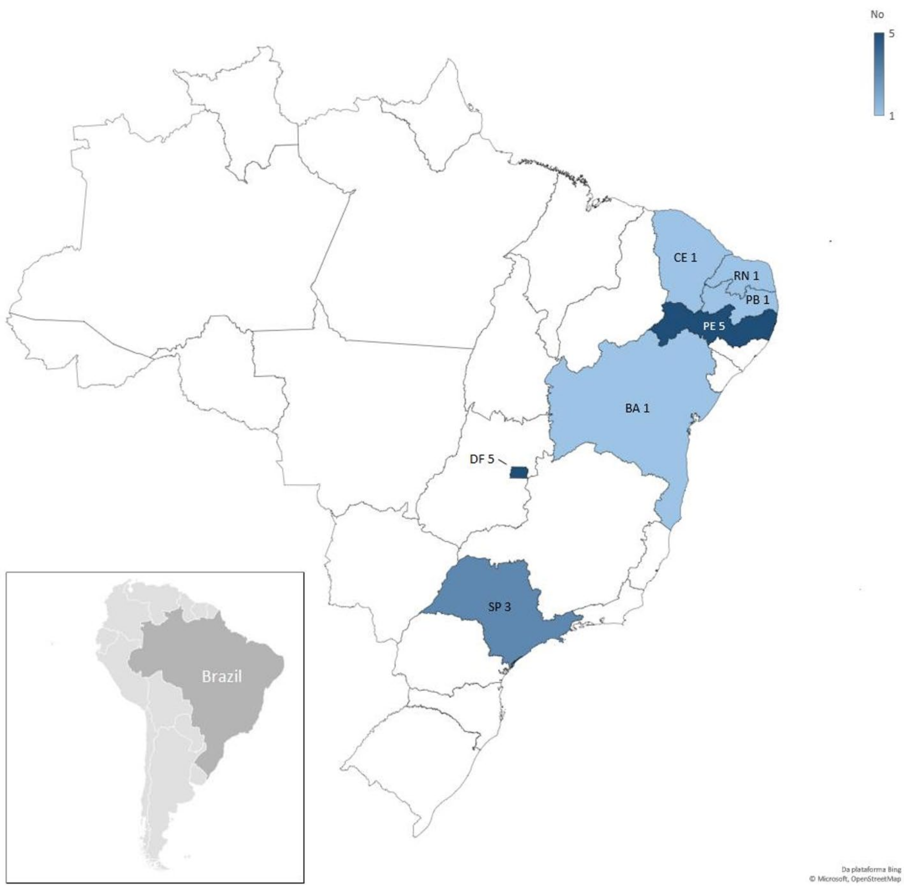

Fig. 4 Regional articles cases presented in the included articles on Managed Aquifer Recharge per Brazilian states (n = 17)

The eligibility criteria for this study primarily focused on the general MAR concept, allowing the inclusion of specific types of MAR studies depending on the searched terms—such as studies related to lake or riverbank filtration [40, 43, 44].

4 Discussion

4.1 MAR history in Brazil

The term "Managed Aquifer Recharge" was coined in 2005 [3], preceded by the expression "artificial recharge", which was the most commonly used [5]. In the articles included in this study, "artificial recharge" has been mentioned since the 1990s [18]. From 2001 to 2005, these references became more common as a recommended solution in the Brazilian Northeast (see Table 1). However, "Managed Aquifer Recharge" was first cited in Brazilian articles only in 2018 [30, 31].

According to [37], the pioneering work in applying "artificial recharge" techniques in Brazil was Cadamuro's thesis [26] on horizontal condominiums in the Federal District. However, Tubbs and Pereira (2003*b*) stated that the first systematic study on "artificial recharge" in Brazil was published in the *Águas Subterrâneas* Journal in the 1980s, focusing on water quality and clogging of injection wells in an aquifer [45].

A quarter of the papers (see Table 1) were published in *Águas Subterrâneas* Journal (aguassubterraneas.abas.org), a publication edited by the Brazilian Groundwater

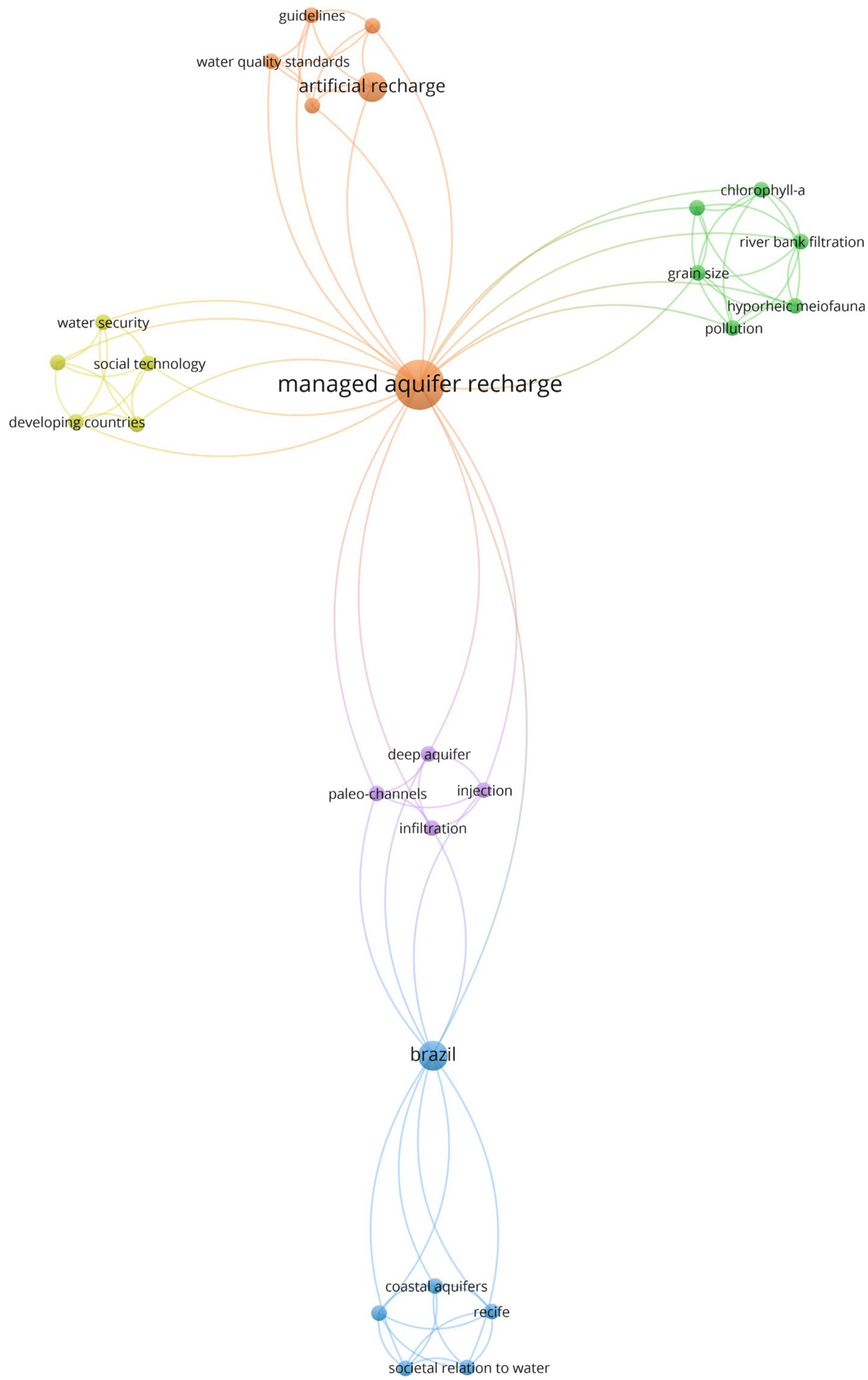

Fig. 5 Bibliometric map of keywords co-occurrence links in articles about Managed Aquifer Recharge in Brazil

Association (ABAS, the Brazilian Chapter of the International Association of Hydrogeologists—IAH-BR) since 1978.

Brazil currently accounts for nearly two-thirds of all reported MAR case studies in Latin America and the Caribbean, followed by Mexico with 13% of the reported cases.

Approximately 70% of the Brazilian reported final use of recovered water is for agriculture, while 20% is for domestic supply [11].

Half of the MAR techniques applied in Brazil are simple solutions (such as infiltration), with the other half involve more complex engineering and geotechnical approaches—including ASR/ASTR, injection, and RBF (see Table 1).

4.2 MAR cases in Brazil

The first initiatives to combat the drought in the semiarid Northeast of Brazil began in the early twentieth century, with the construction of dams and wells over time [46]. The challenge lies in effectively storing and utilizing rainwater in a region with irregular rainfall, high evapotranspiration, and limited storage capacity in fractured aquifers [41, 46].

Recife, the capital of the State of Pernambuco—PE [19, 30, 33, 39, 40], is the most studied city in these articles. This city has a history of water shortages, groundwater table reduction, well yield decline, and groundwater salinization [19, 39]. Recife is a water-stressed metropolitan region with nearly four million residents and a humid tropical climate surrounded by semiarid conditions inland [33]. Its water issues have worsened since the late 1990s, resulting in increasing number of irregular drilled wells [30]. To address water quality issues, some users have invested in private desalinization facilities or drilled deeper wells, which provide better short-term water quality but exacerbate seawater intrusion over time [39].

One of the earliest Brazilian studies on "artificial recharge" noted that in Recife, "the levels of the aquifers would only show recovery if the flow were reduced by half" and "the only viable solution to obtain a recovery of the aquifer will be artificial recharge", "with injection through deep wells [...] distributed along the coastline, acting as a recharge at the same time as constituting a barrier against salinization" [19].

The Federal District (DF), the second most studied region, is characterized by increasing surface runoff and a high population density in recharge areas [26]. Urbanization in the second half of the 1980s led to a threefold increase in deep tubular wells in the region [24]. Although the DF has an average annual precipitation of about 1,500 mm, rainfall is highly seasonal, with deficits from May to September, and nearly half of the annual rainfall occurring between December and March [24]—making it an ideal location for subsurface water storage during wet periods for later use in dry seasons.

Ninety MAR applications have been documented in Brazil [47], primarily concentrated in the semiarid Northeast region. Most of these applications (64%) involve "underground dams" [6, 32]. These subsurface dams store rainwater under temporary creek riverbeds during the rainy season, ensuring its availability during the dry season [6, 48, 49]. The second most common MAR application is the use of infiltration ponds, well-known in Brazil as *Barraginhas*—a widespread technique in Brazilian rural areas [6, 11]. *Barraginhas* are "small dams" reservoirs that capture runoff, enhance soil infiltration, and favor the water table increase. Since 1993, over 50,500 *Barraginhas* have been implemented, mainly in the Southeast region, providing environmental, social, and economic benefits to local populations [50].

Both underground dams and small dams are standard techniques for increasing natural water reserves, aiming to maximize natural storage for agricultural purposes [6]. These techniques are often considered social technologies and are frequently implemented through public policies, with thousands of applications in Brazil [11]. Most rural solutions devised to combat drought in Brazil are low-cost measures that focus on storing rainwater and stormwater in buried or semi-buried tanks to ensure water and food security for small farmers [6].

Despite their relevance, few studies have assessed the efficiency of MAR applications using small [51, 52] and underground dams [48, 53]. While small dams (*Barraginhas*) function as rainwater infiltration ponds, subsurface dams (underground dams) store water from ephemeral rivers [1]. Both techniques are mainly used to improve agricultural areas and can be classified as MAR, particularly when underground dams are connected to shallow well for water extraction [53].

4.3 MAR challenges in Brazil

Although Brazil has not yet implemented a MAR strategy, it has been warning for nearly three decades that there is an "Unmanaged Aquifer Recharge" in its territory, represented by leaks from water and sewage networks and failures in urban drainage [9, 18, 26, 33, 34, 42].

Being an incidental recharge, this is not MAR—which is intentional as opposed to the impacts of land clearing, wastewater losses, irrigation, and installing water mains which are incidental or unintentional recharge. However, it has been estimated that this incidental recharge (about 70% of which is due to the water supply and wastewater losses) is three times the natural recharge from precipitation in the Northeast State of Rio Grande do Norte (RN). If these losses were suspended entirely, groundwater levels would drop dramatically [42]. Therefore, measures to reduce losses must also address actions to avoid these declines.

MAR techniques could significantly contribute to local flood control, through infiltration wells or trenches, rain gardens, and even permeable pavements [6, 38]. For instance, dry wells are a compensatory (offset) technique for rainwater management that requires small areas for implantation and are easily integrated into urban environments, showing good efficiency in groundwater recharge, with twice the infiltration potential of a grassy area [38]. However, rainwater from public roads may introduce contaminants [54], potentially impacting groundwater quality if not effectively treated.

Adverse effects may occur if the aquifer recharge is not correctly managed, such as surface and underground structures flooding, soil instability and salinization, and soil and water contamination [3]. Also, chronic operational problems, such as clogging, can make MAR projects unsustainable, leading to failure in infiltration basins and injection wells [2]. This issue has been addressed in four Brazilian studies [31, 40, 43, 44].

Thus, the local assessment of aquifers, soil, and source water is necessary for MAR, with the evaluation of aquifer storage capacity, soil type, unsaturated zone thickness, infiltration rate, hydraulic conductivity and transmissivity, ecological flow, and the quality of source water [3, 55]. Furthermore, it is crucial to understand the surface and groundwater rights, land negotiation, drilling and environmental permissions and licenses needed for applying MAR. One should note that only local studies could support these concerns: with Brazil's vast size and heterogeneity, generating comprehensive state-level data remains a significant challenge.

Despite some MAR pilot projects and initiatives have been implemented in Brazil, especially in areas with water scarcity—such as infiltration ponds to aid small farming communities –, though on identifying optimal locations to enhance those ponds' performance remain limited. Underground dams face limitations, such as insufficient storage capacity for year-round use, particularly if extends beyond human consumption, and stored water may become unsuitable due to high salinity levels by the end of the dry season [6, 56]. These shortcomings highlight a critical gap: the lack of specific and comprehensive guidelines to support the proper design, implementation, and monitoring of MAR projects.

4.4 Legislation and regulations on MAR in Brazil

Discussions on MAR legislation in Brazil began over 20 years ago, when articles suggested that "the existing set of laws was sufficient to regulate artificial recharge practices in Brazil" [21, 22]. Despite these regulations and the subsequent legal updates, the official implementation of MAR techniques in Brazil remains limited to a few small-scale cases.

São Paulo was the first Brazilian state to develop MAR legislation, stating that recharge "depends on authorization" and must be supported by "studies demonstrating technical, economic, and sanitary feasibility while ensuring groundwater quality" [57].

In 2001, a resolution proposed that the National and the State Water Resources Management System should "encourage municipalities to protect groundwater recharge areas and adopt practices" such as "reuse and artificial recharge" to enhance water availability and quality [58]. In the current specific resolution, which "establishes criteria and guidelines for the implementation of Artificial Recharge of Aquifers in the Brazilian territory", such recharge must be authorized by the state water management agency, being subject to feasibility studies; possible implementation by an Entrepreneur; through infiltration or injection techniques; and not altering the groundwater quality [59].

Policies and legal frameworks for MAR are scarce and at an early stage, especially in developing countries [35]. In Latin America, three countries have guidelines or regulations on MAR: Colombia, Chile, and Mexico [11]. Although there are still no specific national quality guidelines on MAR in Brazil, the resolutions from the National Environment Council [60], which include almost a hundred parameters and contamination levels [61], can be used as a reference to comply with the requirement for maintaining groundwater quality—as the Special Class, "intended for the preservation of ecosystems".

At this moment, Brazil has legislation, but it needs more specific regulations for implementing MAR, such as detailing quality standards for different water sources and techniques. However, even though it is still incipient, Brazilian legislation related to MAR is sufficient for its development, and MAR application must adhere to current legislation [29]. In addition to national laws, complementary state laws exist, such as in the Federal District [37].

To ensure effective and sustainable MAR implementation in Brazil, comprehensive guidelines and regulations are essential. Establishing specific water quality standards can prevent contamination and inefficiency, while environmental impact assessments address risks, mitigate impacts, and protect ecosystems, ensuring projects' long-term viability. Regulations for site selection and recharge design are equally crucial, considering regional geology, hydrology, and climate to optimize efficiency and minimize environmental impacts [56]. Monitoring and reporting are necessary for tracking performance, maintaining compliance, and enabling adaptive management through regular assessments of water levels, quality, and recharge effectiveness. Additionally, a legal framework defining ownership, access rights, and responsibilities is necessary to ensure equitable resource distribution, prevent conflicts, and support long-term water security. Such frameworks are fundamental to making MAR projects scientifically sound, environmentally sustainable, and legally supported, addressing the country's growing water security challenges, particularly in the face of climate change.

4.5 Future expectative

Twenty years ago, [22] mentioned that "artificial recharge is not used on a large scale in Brazil", and the motivation for its implementation was to increase water supply security. As of 2023, MAR still has not been widely adopted in Brazil.

In many tropical areas with abundant surface water and rainfall, groundwater managers and consumers dismiss the possibility of water crises, which commonly occur simultaneously with the frequent use of irregular wells (drilled without permission)—especially where there is insufficient public investment in water supply [9, 33]. The implementation of MAR can incorporate a large number of private wells as a potential solution to water scarcity, through a "public–private opportunism" approach, converting part of the private wells into ASR injection wells, reintegrating the "open-access resource" into the "managed field" [9].

It is essential to assess the potential for MAR in different Brazilian regions, identifying the demands, opportunities, and the best sites for implementation. Brazilian regions with threatened water security, such as the semiarid Northeast and large cities, are potential locations for adopting MAR as an alternative to enhance integrated water resource management [6]. However, the semiarid geographical and climatic conditions limit this water storage, restricting its application to localized and smaller-scale cases, while also increasing the risk of groundwater salinization.

Several reasons explain the lack of official MAR implementation in Brazil. Due to insufficient studies on groundwater exploitation and aquifer contamination, the necessity of MAR practices in Brazil requires further justification. Furthermore, there is resistance to utilizing groundwater for public supply, which diminishes interest among public authorities. The lack of knowledge about MAR applications leads to uncertainty and hesitation, which may limit its use to private initiatives.

Resistance to MAR implementation arises from technical, behavioral, and institutional factors. Concerns include the risk of groundwater pollution from inadequately on treatment or monitoring of water source, lack of awareness among communities and decision-makers about MAR benefits, and fragmented governance with unclear responsibilities. Additionally, limited technical capacity or financial resources can make MAR seem complex and costly. Addressing these concerns requires inclusive dialogue, capacity-building, and clear guidelines to build trust in MAR as a viable water management solution.

The practical application of MAR in Brazil must anticipate future water crises as a tool for adapting to climate change. Public policies and regulations must be proactive in this regard. Additionally, conducting more pilot studies and widely sharing their findings is essential to overcoming resistance to using MAR.

5 Conclusions

Over the past thirty years, nearly thirty articles have been published on Managed Aquifer Recharge (MAR) in Brazil. Despite these studies, MAR techniques remain limited to a few cases, predominantly in rural areas. These applications are probably underreported due to the lack of data publication, particularly in indexed scientific journals.

The resistance to MAR practices in Brazil stems largely from a lack of understanding of its necessity. Hence, identifying regions experiencing critical groundwater situations, aquifer contamination, and the potential impact of climate change on future extreme events, such as extreme droughts, could help to mitigate this resistance. Concerns remain about groundwater quality risks from injection of contaminated surface water, underscoring the need for appropriate standards and guidelines for MAR to ensure sustainable groundwater management.

Significant gaps remain in research, knowledge, and data regarding the application of MAR in Brazil, including aspects such as legislation and permissions, regional assessments of water and aquifer availability for MAR practices, and academic studies—since many cases of effective implementation may not be officially recorded or published in indexed scientific articles.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s43832-025-00276-0.

Supplementary Material 1
Supplementary Material 2
Supplementary Material 3
Supplementary Material 4
Supplementary Material 5
Supplementary Material 6
Supplementary Material 7
Supplementary Material 8
Supplementary Material 9
Supplementary Material 10

Acknowledgements
The authors would like to express their gratitude for the financial support for the SACRE project from the São Paulo Research Foundation, FAPESP (Processes 2020/15434-0, 2022/00652-7, and 2022/05950-6), and the Brazilian National Council for Scientific and Technological Development, CNPq (423950/2021-5); and for the USPSusten program, from USP Environmental Management Superintendence, for the postdoc fellowship for the first author.

Author contributions
Author contributions: LCA designed the Conceptualization and Methodology and wrote the Original draft. RH, LG, and AS improved the review, analysis, and editing the manuscript. RH supervised the project. All authors reviewed the manuscript.

Funding
São Paulo Research Foundation, FAPESP (Processes 2020/15434-0, 2022/00652-7, and 2022/05950-6), and the Brazilian National Council for Scientific and Technological Development, CNPq (423950/2021-5); and USPSusten program (USP Environmental Management Superintendence).

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 3 February 2025 / Accepted: 5 August 2025
Published online: 31 August 2025

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