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Sustainability in Managed Aquifer Recharge Projects: A Case Study of Three European Union Funded Projects

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ABSTRACT

Managed aquifer recharge (MAR) is presented as a water management approach that fits well within the broad sustainability agenda. Three European MAR projects' outcomes were analyzed to assess how these projects interpret sustainability. This article argues that MAR projects are pushed to a narrow interpretation of sustainability by funder requirements and the technical background of experts involved in MAR projects. This narrow interpretation is reinforced by the limited available resources for MAR projects. Pressing social and institutional issues are left unattended in these projects. This is likely to have implications for the long-term operation and maintenance of these MAR projects.

1 | Introduction

The concept of sustainability has gained increasing importance since the Brundtland (1987) report highlighted that [...] "the goals of economic and social development must be defined in terms of sustainability" (42). Despite its popularity, however, there does not appear to be a singular definition of what exactly sustainability encompasses (Caradonna 2017). Sustainability appears to be a "magic concept" (Pollitt and Hupe 2011). It is a broad concept, which, due to its normative attractiveness, has almost universal appeal and support, but that has no singular definition. Thompson (2011) even goes as far as suggesting that sustainability is "problematical" as "people have different and mutually irreconcilable ideas of just what is sustainable and what is not" (2).

To make things more complicated, the concept of sustainability is not static but is defined and redefined over time by different authors. Also, in relation to water governance, the concept of sustainability has evolved. Initially, the concept was defined narrowly by focusing on environmental and technical dimensions. This framing was largely promoted by engineers, hydrogeologists, and international water agencies seeking measurable outcomes (Dillon 2005; Pannell 2003). In recent years, however, sustainability has been redefined more broadly to also include social and institutional features. This expanded definition of sustainability reflects growing use of the concept of sustainability among water governance scholars (Conca and Weinthal 2018; Jakeman et al. 2016). Underlying the inclusion of social and institutional dimensions of sustainability appears to be the conviction that, for a water management activity to be lasting and maintained, adhering only to technical and environmental criteria is not enough (Gerlak 2007; Gleick 2000; Kemerink-Seyoum et al. 2019; Polonenko et al. 2020; Zwarteveen et al. 2021).

Social and institutional dimensions of sustainability seem to focus on questions of allocation and access to water, the rules that regulate this, the conditions under which water is allocated and accessed, the processes of decision-making, and the ultimate impact on water users. The wide spectrum of issues that the social and institutional dimensions of sustainability deal with also means that there is considerable divergence in what exactly these social and institutional dimensions of sustainability entail. Hellberg (2017) mentions that the "social sustainability literature has even been described as 'chaotic', 'messy' and even 'contradictory' and 'confusing'" (66). For example, the notion of institutional sustainability is often linked to both formal and informal rules, norms, and established practices (Hassenforder and Barone 2019). However, in the design and implementation of programs and projects, the emphasis tends to fall on formal institutions, frequently sidelining local practices and community-based norms (Cleaver 1998).

Without providing a generic definition of sustainability, in this article, we treat sustainability as a multidimensional concept. The concept of sustainability thus incorporates technical, economic, institutional, social, and environmental dimensions. In Table A1, we explain what this multidimensional approach to sustainability entails for managed aquifer recharge (MAR).

1.1 | MAR and Sustainability

MAR refers to a spectrum of water management practices aimed at purposefully allowing and enhancing the recharge of aquifers using diverse methods from different water sources (Dillon et al. 2010; Bouwer 2002). Over the past decade, MAR has frequently been presented and promoted as a sustainable water management strategy (Escalante et al. 2023; Szabó et al. 2023; Amanambu et al. 2020). The International Association of Hydrogeologists (IAH) refers to MAR as "a vital management tool in the sustainable use of the world's water resources." Similarly, a recent report published by UNESCO refers to MAR as "a showcase for resilience and sustainability" (Zheng et al. 2021).

Similar to the IAH and UNESCO, the European Union (EU) has also been at the forefront of promoting MAR as a strategy for sustainable water management practices. EU promotion of applied research on MAR has been done through various funding schemes such as Interreg and EU Horizon 2020, aimed at addressing the challenges posed by climate change, resource scarcity, and population growth. European funding for water projects is often tied to broader environmental, social, and economic goals that align with the EU's Green Deal, Climate Action, and the United Nations Sustainable Development Goals (SDGs) (REA 2024).

The presentation of MAR as a "vital tool" or "showcase" for sustainable water management is based on a number of arguments. Firstly, MAR is seen as mitigating climate change impacts on water resources by ensuring water availability for different uses and users (Escalante et al. 2023; Dillon et al. 2020; Escalante et al. 2019). Illustratively, it is noted that a core motivation for the EU to fund water projects is the conviction that these projects will "green" the European economy. MAR is argued to contribute to the EU's climate adaptation strategies by replenishing groundwater, mitigating droughts, and ensuring stable water supplies (Dillon et al. 2020). Secondly, MAR aligns well with the goal of achieving universal water access by linking groundwater conservation to universal access to safely managed water (HLPW 2018). Thirdly, MAR is advanced as an adaptable approach that incorporates a range of technical solutions that can be tailored to a variety of socioeconomic contexts (Fernández Escalante and López-Gunn 2021). Finally, in contrast to more controversial water management strategies such as the construction of dams and reservoirs, MAR is presented as a strategy that does "no significant harm" (Dillon et al. 2019; FAO 2016).

Sustainability in MAR projects incorporates a variety of dimensions. Apart from the technical sustainability, the economic dimension of sustainability in MAR projects centers on the financial viability, taking into account both the costs of the MAR project and the resulting benefits. The main focus is to ensure the financial sustainability of the project in its construction and its subsequent operation. A broad interpretation of economic sustainability may also include factors such as the creation of jobs and the cost of supply and demand of water. The environmental dimension of sustainability of MAR projects links water management to ecological impacts.

The institutional and social dimension of sustainability in MAR projects emphasizes aspects related to environmental justice, human health, participation, representativity, resource security, and community engagement (Fernández Escalante and López-Gunn 2021; Zheng et al. 2021). Particularly, MAR is increasingly recognized as the approach that pays attention to allocation and equity aspects of groundwater governance. It is argued that by recharging groundwater, MAR offers a way to manage water resources fairly (Ward and Dillon 2011).

It has been argued above that sustainability is a multidimensional concept. However, this does not necessarily mean that all dimensions are always of equal importance or that MAR projects always incorporate each dimension. Decisions about which dimensions are prioritized in MAR projects are not objective or neutral (Boulanger 2008). Emphasizing different dimensions of sustainability reflects a particular problem framing that is to be addressed by the MAR project. What dimensions are prioritized depends on who develops the projects, influenced by what aims, aspirations, values, worldviews, political opinions, personalities, and interests these decision-makers have (Boulanger 2008; Molle 2008). The dimensions that are prioritized in turn define how the concept of sustainability is understood (or operationalized) in practice.

In this article, we explore how "sustainability" is perceived and operationalized in MAR projects. The exploration of how sustainability is understood in MAR projects is done by focusing on three MAR projects financed by the EU. The selection of the EU projects is based on the EU's support for MAR as a sustainable water management strategy that aligns with the EU's Green Deal.

2 | Methodology

In determining how the concept of sustainability is defined and operationalized in MAR projects, the article employs an approach based on the work of Lazarsfeld (1958). The original framework of Lazarsfeld (1958) was designed as a tool for social scientists to select and/or develop indicators to "characterize the objects of empirical investigations" (100). The objects of empirical investigation were concepts that were to be "measured" by developing indicators or indices. In Lazarsfeld's framework, the indicators essentially operationalize the dimensions that are to be measured. For instance, a broad concept such as sustainability can be disaggregated into environmental, social, and economic dimensions, each measured through corresponding indicators or elements that represent those dimensions (e.g., CO_2 reduction, stakeholder participation, project costs, and infiltration rate).

In this article, we work backwards using Lazarsfeld's framework. Rather than starting with dimensions and selecting indicators that represent that dimension, we start by identifying the indicators used in MAR projects.

2.1 | Case Studies

Three MAR projects were selected as case studies: MARSOL, MARSoluT, and DEEPWATER-CE. These projects were selected because (a) they are all research projects funded through different programs of the EU and (b) the projects present MAR as a sustainable solution that can address real water problems of water users under limited water availability.

The MARSOL (2014–2019) project aimed to show that MAR presents a sound, sustainable solution to tackle problems associated with water scarcity and drought in southern Europe. The selected sites for this project were Lavrion, Greece; Algarve, Portugal; Arenales and Llobregat, Spain; Brenta and Serchio, Italy; Menashe, Israel; and South Malta, Malta. Funding was provided by the EU's Seventh Framework Programme for Research, Technological Development (EU FP7 Project) with €5.2 million over 3 years.

The MARSoluT (2019–2023) project was built on the same site selection used by MARSOL, except for Brenta, Italy, which was not included. The project had several deliverables, including a report on the performance of optimal MAR designs where new sustainable managed aquifer recharge technical solutions (SMARTS) are presented. Funding of close to €3 million was provided through the EU Horizon 2020 program.

DEEPWATER-CE (2019–2022) included five participating research organizations from different countries (Germany, Hungary, Poland, Slovakia, and Croatia). It is one of the most significant MAR initiatives in Eastern Europe in the last 5 years. This project's goal was to support the widespread adoption of MAR in various hydrogeological settings across the continent. The project was funded by the EU's Horizon 2020 research and innovation program.

2.2 | Materials and Resources Used

The selected projects were researched through different online databases such as CORDIS (cordis.europa.eu), the International Association of Hydrologists (recharge.iah.org), and Interreg CE (interreg-central.eu). Indicators were identified from relevant project deliverables. For each project, indicators developed in the project deliverables were analyzed to understand which dimension of sustainability they reflect (based on the sustainability dimensions and associated indicators presented in Table A1). Consequently, an indicator dealing with groundwater flow is allocated to the technical dimension, whereas an indicator that describes participation is assigned to the social dimension of sustainability. Indicators thus identify which dimensions of sustainability are prioritized or emphasized in the different MAR projects. This, in turn, allows for an assessment of how "sustainability" is defined and operationalized in practice.

In addition to project deliverables, indicators were also retrieved from the list of scientific peer-reviewed publications on the MARSoluT website for the MARSOL and MARSoluT projects. The analysis of indicators used in the DEEPWATER-CE project was based on project reports retrieved from the project website. These sources address a range of topics pertinent to MAR, spanning from technical aspects, such as design, operation, and maintenance, to regulatory considerations, including proposals for MAR regulatory frameworks, particularly emphasizing environmental impact assessment. Additionally, reports presenting economic analyses of the projects were reviewed. Table A2 presents the list of project deliverables and indicators for each MAR project.

To complement the secondary data of these projects, online interviews were carried out with a total of four respondents between October 2023 and September 2025. The aim of these interviews was to both validate the findings presented in the secondary data and gain deeper insights into these MAR projects. The four respondents were members of the research teams on the MARSOL and MARSoluT projects.[1] In addition to these four respondents directly involved with two of the studied MAR projects, 14 practitioners involved in implementing MAR projects in Europe were interviewed[2] (Table S1). Questions discussed with the respondents revolved around three main themes: (1) their view of sustainability in MAR projects, (2) the problems the pilot projects envisioned to address, and (3) the practical challenges that arose during the testing phase.

The respondents were selected through a snowballing process, where the first respondent indicated the next respondent that was relevant for the research goal. We also further used the interviews for triangulation in order to see to what extent the identified indicators representing a specific sustainability dimension were shared by the interviewees. This process of triangulation ensured that the categorization of indicators into sustainability dimensions was informed by both project deliverables and outputs and through interviews with practitioners.

By combining information presented in Table A1 with information in Table A2, we are able to make an assessment of the sustainability dimensions that the studied MAR projects focused on. This analysis is presented in Table A3.

3 | Results

In the three analyzed projects, various key indicators were used to assess the performance of the MAR projects. These indicators range from technical, economic, and ecological to social and institutional indicators. However, in all the projects, technical and economic indicators were noticeably prioritized (see Table A3).

3.1 | MARSOL

The MARSOL project primarily targets rural agribusiness by providing water for agricultural purposes. Technical and economic indicators were strongly prioritized. The prioritized indicators used in this project can be subdivided into five clusters of indicators. The first group of indicators measures the recharge volume and rate of water recharge into the aquifer. The second cluster of indicators focuses on the infiltration rate and hydraulic conductivity. This aspect is considered highly important for the technical performance of the project and is related to clogging. The purpose is to allow for mapping suitable "areas that have good characteristics for water to move through aquifer materials [...] without this there is no MAR" (MARSOL Contractor, personal communication, September 13, 2023). Infiltration rate is important as it talks about the aquifer productivity in terms of the speed at which water infiltrates the ground for each MAR method. The third type of indicators revolves around aquifer capacity and storage, which highlight the amount of water stored after recharge. The fourth set of indicators concerns water recovery efficiency, which highlights the percentage of recharged water that can be recovered for use (e.g., mean annual aquifer extraction). The fifth category of indicators relates to the water quality in the aquifer to ensure that no degradation occurs during MAR processes (before and after recharge).

The MARSOL project gave significant priority to the economic viability of MAR systems. This was particularly visible in the project deliverables entitled "Benchmarks Evolution, Pooling, and Practical Results, Work Package 13.4" and "Economic Analysis Report, Work Package 15."

These financial indicators were considered essential for showing that MAR could be a sustainable solution in the long term, both from a cost-efficiency standpoint and in terms of attracting private and public investment. Indicators such as infrastructural cost, cost per cubic meter of recharged water, and energy cost/saving were highlighted. Through benchmarking and cost–benefit analysis, the MARSOL project aimed to showcase the performance of each site/system, highlighting the achieved improvements and capabilities of each method of aquifer recharge. As emphasized by one of the respondents, "we want to create a spill-over effect … if farmers see it worthwhile, the news will spread around to other villages" (Communication Expert, personal communication, April 11, 2023). So, it was important for the project team to present deliverables that show the economic viability. Only when farmers are convinced about the return on investment and the economic feasibility for the long-term operation of aquifer recharge will they truly support MAR as a strategy for water management (MARSOL Contractor, personal communication, September 13, 2023).

When social issues were touched upon, they were translated into economic terms, for instance, through the use of Economic Net Present Value (ENPV). "Even though this is meant to evaluate the economic performance, it can be argued that the Economic Analysis as proposed in the EC's Guide can also serve as a sustainability check for a project" (MARSOL, Work Package 15). Although participation was included, only the Arenales (Spain) and Algarve (Portugal) MAR systems included stakeholder participation, meaning that six locations did not. Participation was predominantly operationalized through workshops and trainings with key stakeholders of the MARSOL project (one workshop/training per project site). These trainings/workshops were specifically dedicated to agribusiness farmers and MARSOL partners: "MAR4FARM and MARenales" (MAR Technical Solutions D13.1, 75). The limited attention given to the social dimension of sustainability is largely because these events "are very time-consuming and sometimes expensive to hold if one wants to fully capture the social challenges related to water distribution problems" (MARSOL Researcher, personal communication, March 13, 2023). As such, it was explained that "the main concern is not around how water will be distributed among different users, but it is to ensure the water is allocated and stored in the groundwater … the distribution issue is handled by whom take over the project" (MARSOL Researcher, personal communication, March 13, 2023).

3.2 | MARSoluT Project

For the MARSoluT project, the only focus was on technical considerations. By focusing solely on these technical indicators, MARSoluT aimed to optimize the effectiveness, reliability, and efficiency of MAR systems. The purpose of prioritizing this dimension was to build the capacity of MAR experts for future implementation of MAR projects (MAR Researcher, personal communication, October 2024). This, in turn, could then lead to long-term benefits associated with recharging aquifers and improving water security. The focus on technical indicators is also evident in the MAR models developed within MARSoluT publications (Lippera, Werban, and Vienken 2023; Muñoz-Vega et al. 2024; Pérez-Illanes and Fernàndez-Garcia 2024a, 2024b; Pérez-Illanes, Saaltink, and Fernàndez-Garcia 2024; Pérez-Illanes, Sole-Mari, and Fernàndez-Garcia 2024; Rudnik et al. 2022; Standen et al. 2022; Wang et al. 2023). The emphasis on technical indicators is reinforced by statements on the MARSoluT website, which note that the project contributes "significantly to increasing the market potential and access of MAR concepts in the water sector, raising European competitiveness in this important part of integrated water resources management".[3]

The indicators that received more focus for this project were grouped into three main categories: recharge quantity, water quality, and system design efficiency (MARSoluT, Work Package WP4: Optimizing Design). The importance attributed to these indicators was based on the assumption that technical improvements would drive long-term ecological and social benefits, to enable long-term ecological and social benefits (MAR Expert, personal communication, May 2024). In this sense, the indicators served not only to test technical performance but also to identify what the most cost-effective and sustainable designs for future implementation of agricultural water supply would be.

In the category of recharge quantity, indicators measured the volume of water by which the aquifer was recharged (Lippera, Werban, Rossetto, and Vienken 2023). By optimizing infiltration rates and increasing the aquifer's storage capacity, the project aimed to maximize the amount of water that could be recharged. Technical indicators such as the total recharge volume and the rate at which water infiltrates the soil were central to evaluating the effectiveness of the recharge processes. The water quality category was identified as a key priority based on the project deliverables of the three projects (Horovitz et al. 2024; Caligaris 2023). The focus was to ensure that the water being recharged meets high-quality standards. The main focus was on showcasing how to store good water quality (MAR Researcher, personal communication, March 13, 2023). This involved improving natural attenuation processes to filter and purify the water. Key technical indicators here included water quality parameters both before and after recharge, nutrient removal efficiency, and presence of harmful contaminants. These indicators helped assess how the recharge systems impacted water quality as it passed through the soil and into the aquifer. Finally, indicators for system design efficiency were considered important for the project team. The aim was to field-test different MAR design scenarios to identify which were most efficient in diverse environmental conditions. The efficiency of the system was measured in terms of how well it achieved recharge goals, the cost per cubic meter of recharged water, and the ease and cost of maintenance (see Sultana et al. 2024).

Regarding the institutional dimension of sustainability, comanagement through a partnership arrangement was brought in. Through a Public Private People Partnership (PPPP), private individuals would manage, operate, and benefit from the MAR system (Fernández Escalante and López-Gunn 2021). Although the project team does acknowledge the importance of participation, they largely attribute this limited focus on participation to the boundary conditions in which the project had to be implemented. “[P]articipatory and communication issues occupy less space because we need to keep with the project timeframe” (Communication Expert, personal communication, April 11, 2023). A different project member echoed this sentiment:

> I recognize that more emphasis should be put on social and institutional dimensions of MAR (...) we have conflicts that rises from different water users during the operations as communities' farmers still don't have the right to vote on the meetings (...) it is not easy to deal with in our time.
>
> (MARSOL Contractor, personal communication, September 13, 2023)

Similarly, as echoed by a panelist in a recent webinar on social aspects of MAR organized by the IAH MAR Commission, it was emphasized that social dimensions remain comparatively underrepresented in current practice. “[T]here are discussions on all areas but they are always reflected in the technical indicators” (Panelist, personal communication, September 17, 2025).

3.3 | DEEPWATER-CE

DEEPWATER-CE prioritized the analysis of surface geomorphology and cost analysis to optimize the operation and maintenance for MAR. Moreover, they underscore the economic viability of MAR initiatives. At the same time, attention given to the social dimension of sustainability is limited. This limitation is mainly a result of the specific focus on water companies. The benefits of MAR would first accrue to the water company, which is then, in turn, better able to service its consumers.

A central component of this project was the cost–benefit analysis developed in the common methodological guidance for DEEPWATER-CE MAR pilot feasibility studies (Deliverable D.T3.2.5). The cost side included detailed estimates of extraction, distribution, construction, land purchase, regulatory compliance, and environmental costs from aquifer overexploitation. On the benefit side, the analysis considered both private/market benefits, such as revenues for drinking water facilities and irrigation productivity, and socioenvironmental benefits, including willingness to pay for MAR water. These were to be assessed through contingent valuation methods and stakeholder surveys. Although the framework provided a comprehensive economic evaluation, the approach implicitly positioned social and ecological values within an economic lens, further highlighting the limited direct integration of broader social considerations into the project's assessment of sustainability.

4 | Discussion

There is a notable discrepancy between the concept of sustainability as discussed/promoted in literature and the practical implementation of the MAR research projects studied for this article. Below, we elaborate on this discrepancy and explain why this discrepancy exists.

4.1 | Promoting Success: Following the Funder

The narrow scope of sustainability promoted in these projects can be linked to the agendas of the funding entities. EU research programs frame MAR as a strategic component of the Green Policy,[4] and consortia vying for funds must align with this vision. As Brunsson (1989) has shown, applicants tailor their proposals and projects to reflect the values and norms of funders. In practice, this means that projects emphasize technical performance and economic viability to ensure alignment with funding priorities, whereas contentious issues of water allocation, access, and rights are left aside. This dynamic echoes observations from the water justice literature that equity concerns are often deferred or depoliticized when water is framed primarily in technical–economic terms (Molle 2008).

4.2 | Normative Isomorphism and Indicator Framing

The dominance of technical and economic framings is further reinforced by the professional background of the project partners. DiMaggio and Powell's (1983) concept of normative isomorphism helps explain the homogenization of practices across the MAR projects. Project consortia were largely composed of hydrogeologists, water engineers, and technical experts trained within similar educational traditions. These experts meet in recurring professional arenas, conferences, and EU research networks, where shared approaches are reproduced and reinforced (Communication Strategist, personal communication, October 21, 2024).

This homogeneity matters not only for project design but also for how sustainability is operationalized in MAR projects. As seen in the weighting of indicators, technical metrics such as recharge rates, storage capacity, and cost efficiency were privileged, whereas social and institutional indicators remained marginal as addressing these was "complicated and costly." Normative isomorphism thus helps explain why a narrow framing of sustainability was consistently reproduced across different projects, even when broader dimensions were acknowledged in principle.

4.3 | The Limits of Participation

The technical orientation of project partners also shaped the way participation was conceived. Stakeholder engagement in MARSOL and MARSoluT was primarily limited to informative workshops or training sessions aimed at demonstrating the benefits of MAR. Controversial questions of allocation, access, and rights were deliberately left outside the scope of the projects as a problem that will be solved later by other parties. The question is, however, how this problem will later be addressed by those needing to decide on water allocation and access. In very few cases, formal water allocation rules exist for water allocation, water distribution, and access to MAR water. In such settings, allocations often favor large-scale agribusiness farmers over small-scale farmers. These limited participatory practices reflect broader patterns in water governance, where participation often functions as a means of legitimization for funders rather than a mechanism for ensuring equality of access (Joy et al. 2014). Respondents themselves acknowledged these constraints, attributing the limited attention given to social and institutional sustainability to project timelines and resource limits. The result was a model of participation oriented toward informing and persuading stakeholders of MAR's technical and economic efficiency rather than engaging them in decisions about water allocation. This echoes critical water justice scholarship that underscores how social equity dimensions are sidelined when sustainability is reduced to questions of technical performance and economic feasibility (Rap 2006).

4.4 | Implications for Policy and Practice

The current configuration of MAR projects has a narrow targeting of beneficiaries that tends to favor specific types of users. Particularly those who can afford the technological, financial, and organizational demands for its implementation are favored. This typically includes larger scale agribusinesses or private actors with sufficient capital and institutional capacity or actors that are part of formal institutions such as a river basin organization or farmers' organizations. The vast majority of small farmers are not incorporated in the process of developing MAR projects, as seen with the idea of using the concept of PPPP to allow private individuals to manage, operate, and benefit from the MAR system, thus excluding the general water users. In doing so, MAR initiatives risk marginalizing smallholder farmers and other community members who may be equally dependent on groundwater resources but lack the means to participate in these schemes. This narrowing of user engagement not only creates blind spots in terms of social justice and equity but also threatens the inclusiveness and legitimacy of MAR as a sustainable water management approach.

A key implication of the technical nature of most MAR pilot projects is that these projects inform broader policy and implementation strategies. These pilots, although valuable in demonstrating technical feasibility, are often conducted in highly controlled environments. They are tailored to meet funder requirements and demonstrate success according to predefined technical and economic indicators. Consequently, such projects fail to reflect the messy, contested, and multiactor realities of real-world water governance. This means that policies derived from these pilot initiatives may be based on an overly linear view of MAR implementation and operation. If policymaking continues to be informed primarily by these top-down, techno-managerial approaches, it risks ignoring the critical complexities that emerge during long-term operation and maintenance. As shown by Rap (2006) and Pascual Sanz et al. (2013), such approaches often mask the real-world challenges of implementation in diverse and dynamic contexts.

4.4.1 | Institutional Readiness and Community Integration

Sustainability of MAR systems depends not just on technical success but on how well they are embedded within existing water governance structures (Kemerink-Seyoum et al. 2019; Cleaver 1998). This includes aligning MAR with organizations and established practices around aquifer recharge. It is only by addressing representation within water user associations (formal and informal), and clarifying how costs for operation and maintenance will be shared among diverse users, that a broader view of sustainability can be achieved. Without proper attention to these factors, MAR schemes risk institutional failure, particularly when project-based structures are withdrawn or external funding ceases. Interview data and prior studies (see Sprenger et al. 2017; Rivera-Vidal et al. 2025) highlight ongoing challenges related to stakeholder representation, transparency in decision-making, and equitable cost-sharing issues. To address these concerns, policies must actively support more socially embedded approaches that go beyond technical metrics and acknowledge the real, context-dependent negotiations around water access and governance (see also Kemerink et al. 2013; Peña 2011).

Sustainability as a guiding principle for MAR projects must be grounded in actual practice. This includes understanding how MAR functions in real-world settings across different social, political, and ecological conditions and making room for participatory governance mechanisms that are responsive to local needs. Drawing on insights from critical water governance literature (Mollinga 2008; Zwarteveen et al. 2017; Molle and Closas 2021), this implies that sustainability should be operationalized in ways that are attentive to issues of equity, legitimacy, and power. Promoting MAR as a sustainability solution requires more than proving its technical and economic viability. It also demands more engagement of funders with the institutional arrangements and community practices that shape how water is accessed, distributed, and governed.

4.4.2 | Trade-Offs and Sequencing Dilemmas in MAR Sustainability

MAR solutions, as implemented in relatively short research projects, seem to be characterized by an inherent sustainability dilemma. This dilemma arises because technical, economic, social, and governance dimensions cannot all be fully addressed within the limited timeframe of a project. At the same time, the hydrogeological and engineering expertise that dominates these project consortia tends to steer priorities according to their professional experiences. MAR solutions that overemphasize technical and economic dimensions may fail to adapt to local realities, overlook equity concerns, or exceed existing institutional capacities. Similarly, economically efficient designs may concentrate benefits among selected actors while excluding the broader group of farmers who depend on the same water resources.

The sustainability dilemma is also partially shaped by the goals that are prioritized by funding frameworks. As shown in the cases, projects are designed around specific target beneficiaries and implementation levels, especially at the EU scale, where goals, priorities, and actors often differ from those at national or local levels, where everyday water needs are articulated. Addressing this dilemma requires a shift in funding frameworks and transdisciplinary teams capable of integrating diverse forms of expertise and concerns across sustainability dimensions.

4.4.3 | Implications for EU Funding Frameworks

To better align MAR implementation with broader sustainability goals and better manage the trade-offs that eventually come with MAR projects, EU funding instruments should place greater emphasis on social and institutional dimensions. This can be done in three ways. First, indicator requirements in calls for proposals should better target social and institutional dimensions. Second, minimum social governance criteria should be established. Finally, the projects should have a timeline that allows for postproject institutional embedding.

Regarding indicator requirements in funding calls, emphasis should be placed on including disaggregated social indicators that are not limited to stakeholder participation. Relevant indicators could include dimensions of water justice, understood as the distribution of agency and authority to contest decisions related to water allocation, distribution, and access (Zwarteveen et al. 2017). This is operationalized through indicators such as the number and quality of established partnerships with local entities, community leaders, or customary authorities and their demonstrated role in decision-making processes. Further indicators can reflect inclusive codesign approaches that go beyond one-way information-sharing or consultative workshops. This includes early-stage engagement with local actors to jointly define needs, priorities, available resources, knowledge systems, and responsibilities (Hoque et al. 2026) related to MAR schemes. Education-related indicators could also move beyond unidirectional knowledge transfer from experts to users, instead valuing two-way learning processes in which local knowledge informs project design and operation.

Secondly, the EU funding framework should establish minimum social governance criteria. This includes social aspects that are not necessarily measurable but are defined through what users perceive as positive or negative impact (using a qualitative method approach). In this way, social governance includes both formal rules and informal institutions operating at the project or community level. Permit-granting processes should be based not only on sound technical risk assessments but also on considerations of distributive justice, ensuring that the costs of MAR are not socialized while benefits accrue primarily to project owners or a narrow group of users (Seidl et al. 2025). Inclusive institutional arrangements are equally critical. Inclusion means combining formal and informal governance mechanisms that are flexible enough to accommodate different forms of stakeholder consultation over time. Regular and publicly accessible reporting on project outcomes can further enhance accountability, transparency, and trust between actors.

Finally, EU funding schemes need to better support postproject institutional embedding to help in the transition, i.e., the handover of the MAR project to the community or third party. This requires a more realistic timeline and budget to account for the longer period of time needed to understand social and institutional dynamics. Similarly, human resources for postproject follow-up should be made part of such MAR projects. Such support can help in strengthening organizational capacities and create the enabling conditions necessary to operate, maintain, and adapt MAR systems beyond the project lifecycle. Without this support, MAR initiatives risk collapsing once external funding ends. Such collapses are visible in other water sectors where poor user engagement, unrealistic expectations by funders and implementers, limited workforce, and financial capacity undermine long-term project sustainability (Barrington et al. 2025; Hoque et al. 2026). Adding this support for postproject support would significantly improve the durability and societal value of MAR investments.

5 | Conclusion

Although the concept of sustainability is evolving and increasingly viewed as more multidimensional in nature, the studied MAR projects, financed by the EU, largely prioritized technical and economic indicators. This prioritization, it was argued, is largely the result of the educational background of MAR practitioners, the goals that funders of MAR projects want to achieve, and the resources (time and money) that were available for implementing these projects.

What makes this conclusion surprising is that most experts involved in the project acknowledge that a broader interpretation of sustainability is desirable in MAR projects. Several interviewees acknowledged the limited attention given to social aspects, noting that this has had tangible consequences, such as conflicts that arose during operations over water allocation and the conditions of access. In acknowledging this, they point to short and strict project timelines and limited resources as hindrances to projects that would adhere to a broader interpretation of sustainability.

As highlighted in the introduction, the argument for a multidimensional interpretation of sustainability lies in the importance of a broad set of sustainability issues, including questions around water allocation, regulation, and entitlement, alongside technical, socioeconomic, and environmental aspects. In the analyzed projects, these broader sustainability issues were largely side-stepped. The social sustainability dimension is largely restricted to rather procedural indicators of participation rather than adhering to a more outcome-based interpretation of social sustainability. In the studied MAR projects, social sustainability was limited to arranging a couple of information-focused stakeholders' workshops within each MAR application site. Such narrow attention to MAR sustainability may well promote the initial success of MAR projects in the narrow technical and economic sense, but it raises concerns about the long-term functioning and equitable benefits of these projects over time. Hence, ignoring the social and environmental dimensions of MAR sustainability and how to promote appropriate governance arrangements will not make pertinent long-term questions of water regulation, allocation, and access disappear. The strong emphasis on technical and economic aspects of sustainability in the analyzed MAR projects seems to suggest that the short-term goals of promoting the EU's Green Policy were prioritized over the long-term maintenance and operation of MAR systems. Consequently, more attention to long-term functioning and multidimensional sustainability outcomes of MAR would benefit both MAR research and practice.

Further research is needed to bring a broader understanding of the sociohydrological context encompassing institutional structures, decision-making processes, stakeholders' interests and conflicts, and affordability into MAR projects. Engaging this sociohydrological context allows for a more comprehensive development of MAR approaches.

Author Contributions

Helen Sundberg: conceptualization, data curation, formal analysis, writing – original draft, writing – review and editing. **Klaas Schwartz:** conceptualization, formal analysis, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available on request due to privacy and ethical restrictions. The data that support the findings of this study are available on request from the corresponding author, Helen Sundberg. The data are not publicly available due to the privacy of research participants. Basic data are available; share upon request.

Endnotes

[1] These four respondents are coded as C in this paper.

[2] These 13 respondents are coded as I in this paper.

[3] https://www.marsolut-itn.eu/.

[4] See also recent effort of creating the European MAR guidance titled "Common Implementation Strategy for the Water Framework Directive and the Floods Directive. Technical Document No. XX, Managed Aquifer Recharge (MAR) under the Water Framework Directive, September 25, 2024."

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** List of interview participants.

Appendix A

TABLE A1 | Dimensions of sustainability in MAR projects.

Dimensions/ benefits	Indicators representing this dimension	References
Technical	Recharge volume to a system (lake, aquifer, pond, wells, etc.); storage volume; hydraulic productivity; quality of water to the receiving medium and throughout the operation; rainfall pattern and frequency; soil thickness	(Escalante et al. 2019; Alam et al. 2020; Bouwer 2002; Rahbaralam et al. 2015; Scanlon et al. 2016; Soni et al. 2020; Szabó et al. 2020, 2023)
Economic	Ratio between investment cost and initial storage volume; through financial cost–benefit analysis; energy cost; socioeconomic survey	(Arshad et al. 2014; Vanderzalm et al. 2022; San-Sebastián-Sauto et al. 2018; Maliva 2014; Fernandez Escalante et al. 2014)
Institutional and regulatory framework	Regulation on water allocation; water entitlement (the right for a water user to benefit upon an agreed share, set by rules; distribution administration of entitlement vested with state or the community)	(Ward and Dillon 2011; Zheng et al. 2021)
Social	Resource security; human health and community participation; justice; data availability and protection; community involvement in the management of MAR; allocation and equity	(Zheng et al. 2021; Dillon et al. 2019; Fernández Escalante and López-Gunn; Ward and Dillon 2011)
Environmental	Water level; salt mass; heat; fluctuations in water quality and water quantity; ecosystem services; environmental stressors	(Zheng et al. 2023)

TABLE A2 | Identified indicators from the project deliverables of the MAR projects.

Project	Project deliverables	Indicators category derived from project deliverables	References
MARSOL	1. Managed Aquifer Recharge Technical Solutions (Design, Operation, and Maintenance) Guidelines, Work Package 13.1 2. Proposal MAR Regulatory Scheme, Work Package 17.1 3. Benchmarks Evolution, Pooling, and Practical Results, Work Package 13.4 4. Economic Analysis Report, Work Package 15.2	Groundwater flow model, groundwater/seawater dynamics, biofilm and microbial development, isotope dynamics, pharmaceuticals fate, climate change impact assessment, social value of MAR, emerging compound degradation, particle tracking	(Barba et al. 2019; Damigos et al. 2017; Ganot et al. 2017, 2018; Hugman et al. 2017a, 2017b; Pouliaris et al. 2022; Rahbaralam et al. 2015; Riva et al. 2014; Rodríguez-Escales et al. 2016; Rodríguez-Escales et al. 2017; Rossetto et al. 2020)
MARSoluT	1. Report on the Performance of Optimal MAR Design, Work Package WP4: Optimizing Design 2. Knowledge Transfer and Dissemination, Work Package WP6: Knowledge Transfer 3. Guideline for Regional Implementation of MAR, Work Package WP2: Improving Quality	Particle tracking, solute sorption, clogging prediction and distribution, reactive transport, regional groundwater flow, groundwater model optimization, conceptual models for regulations and type of climate change adaptation measure, climate change impact assessment	(Fernández Escalante et al. 2022; Henao Casas et al. 2021, 2022; Lippera, Werban, Rossetto, and Vienken 2023; Lippera, Werban, and Vienken 2023; Muñoz-Vega et al. 2024; Pérez-Illanes, Saaltink, and Fernàndez-Garcia 2024; Pérez-Illanes, Sole-Mari, and Fernàndez-Garcia 2024; Pérez-Illanes and Fernàndez-Garcia 2024a; Pérez-Illanes and Fernàndez-Garcia 2023; Pérez-Illanes and Fernàndez-Garcia 2024b; Rudnik et al. 2022; Standen et al. 2022; Wang et al. 2023)
DEEPWATER-CE	1. Collection of Good Practices and Benchmark Analysis on MAR Solutions in the EU, Work Package T1, Activity T1.1 2. Common Methodological Guidance for DEEPWATER-CE MAR Pilot Feasibility Studies, D.T3.2.5 (Data Requirement for CBA and Survey Template for Willingness to Pay for MAR Water) 3. Development of Policy Recommendations and National Action Plans, Work Package 4	Groundwater flow model, quantitative and chemical status of groundwater bodies, water demand determination, risk assessment and management, cost–benefit analysis, survey of willingness to pay for MAR water	(Patekar and Filipović 2020; DeepwaterCE 2020)

TABLE A3 | Analysis of the sustainability dimensions that the studied MAR projects focused on.

Project		**MARSOL**			**MARSoluT**			**DEEPWATER-CE**	
Indicator	Number of workshops held; number of farmers' participation; served population; proposed regulatory scheme	Type of water source; pumping time; air inflow; flow velocity of MAR water; water level; slope; hydraulic conductivity; infiltration rate; current irrigable area; mean annual aquifer extraction; electricity cost; energy savings; infrastructural cost; cost per unit of product; productivity per unit of time; amount of stored water; surface deposit area of materials; amount of silt deposit; effect of water from MAR in irrigation supply (m^3/ha)	Heat flux; volume of water diversion; restoration area; increased of water table after MAR	Farmers' income after the MAR scheme; participation of stakeholders	Precipitation rate; recharge rate; infiltration rate; hydraulic conductivity; aquifer storage capacity; type of water source; pumping time; flow velocity of MAR water; water table level; gas control; air inflow; maximum; mean annual aquifer extraction; electricity cost; energy savings; total dissolved solids; total suspended solids; turbidity; salt; mass; pH; temperature; monitoring frequency and data accuracy; model validation; performance benchmarking	Infiltration capacity; type of plant species used in the project for land restoration	Number of surveys/ willingness to pay; proposed environmental impact assessment	Hydraulic conductivity (K); aquifer thickness (M); volume of water supply; chemical, biological, and micropollutants; air inflow; storage flow capacity; precipitation; cost per unit of product; increased water availability for tourism and agriculture; number of new jobs	Decrease of the inflow of contaminated groundwater from the industrial zone; stable water level; creation of infiltration ditches; new ecological niches
Dimension	Social and institutional	Technical Economic	Ecological	Social N/A	Technical Economic	Ecological	Social and institutional	Technical Economic	Ecological