



Research paper

A governance framework for managed aquifer recharge agreements in Mediterranean regions



Syrine Ghannem^{a,*}, Rafael J. Bergillos^a, Javier Paredes-Arquiola^a, Abel Solera^a, Joaquín Andreu^a, Teresa E. Leitão^b, Tiago N. Martins^b, Anis Chekirbane^c, Khaoula Khemiri^c, Constantinos F. Panagiotou^d, Anika Conrad^e

^a Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Valencia, 46022, Spain

^b National Laboratory for Civil Engineering LNEC, Portugal

^c Institut National Agronomique de Tunisie, University of Carthage, Tunisia

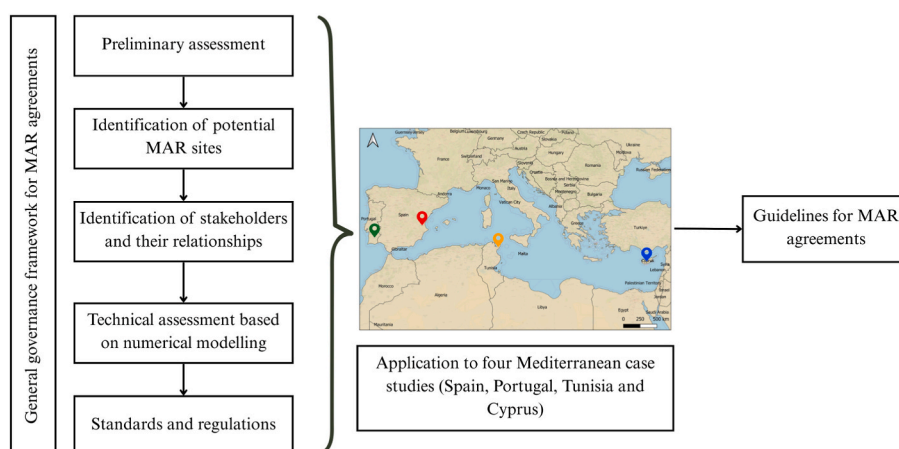
^d Department of Resilient Society, ERATOSTHENES Centre of Excellence, Cyprus

^e Adelphi Research GmbH, Germany

HIGHLIGHTS

- General Governance framework for Managed Aquifer Recharge (MAR).
- The framework includes technical, social, economic, and legal aspects.
- Six steps are proposed to guide MAR planning, design, and implementation.
- The framework is applied to four Mediterranean case studies.
- Proposal of guidelines for decision makers to implement MAR projects.

GRAPHICAL ABSTRACT



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ABSTRACT

With the intensification of global water scarcity issues, Managed Aquifer Recharge (MAR) has become an approach to improve groundwater resilience and promote long-term water sustainability. This study develops a general governance framework for MAR agreements that emphasizes the need for adaptability, public engagement and comprehensive regulations to effectively manage MAR systems. This framework takes into consideration different contexts and their impact on the design and feasibility of MAR agreements in four Mediterranean case studies in Spain, Portugal, Tunisia, and Cyprus. The framework demonstrates that successful MAR governance depends on the alignment between technical feasibility, stakeholder participation, regulatory integration

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* Corresponding author.

E-mail address: sghanne@upv.es (S. Ghannem).

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and financial sustainability. It guides managers from initial feasibility stages to the formalization of locally adapted MAR agreements highlighting common governance principles despite contrasting legal and institutional settings. The findings show the capacity of the framework to translate technical feasibility into functional governance roadmaps tailored to regional legal climates. Technical validation justifies these interventions by revealing localized potential benefits, including a projected 38% reduction in groundwater pumping in Spain, a lower-cost treatment in Portugal, groundwater level recovery of up to 23.6 m in Tunisia, and a 7.4 m groundwater rise in Cyprus. Furthermore, the framework identifies stakeholder engagement, adaptive monitoring, and flexible agreement structures as critical factors for long-term MAR implementation. Based on these findings, the proposed MAR governance framework has been able to adapt to different levels of institutional maturities leading to concrete outputs tailored to the local context, ranging from signed letters of intent for future management planning to formal institutional charter adapted to local governance maturity. This work provides decision-makers with a scalable, actionable model to overcome non-technical barriers a co-create accountable, socially accepted MAR implementation strategies. It also offers transferable lessons for the development of resilient MAR governance models in other regions facing similar governance challenges.

1. Introduction

As a limited natural resource, water plays an irreplaceable role in maintaining ecological integrity while sustaining human well-being and economic productivity (Flint, 2004; Karimi et al., 2024; Postel, 2003). The combined impacts of demographic expansion and changes in climatic patterns are intensifying pressures on water systems, which highlights the necessity for resilient water governance strategies (Dill et al., 2022; Hurlbert and Mussetta, 2016; Nguyen et al., 2024; Ongdas et al., 2026; Pereira et al., 2009; Wilby et al., 2010).

Water governance refers to the political, social, economic, and administrative systems that shape how water resources are developed, managed, and distributed across different levels of society. It involves designing and implementing policies and institutional frameworks that are technically sound, economically viable, and socially accepted and inclusive (Muenratch et al., 2022; Rogers and Hall, 2003; Samami-Foroushani et al., 2023).

The overexploitation of groundwater and contamination of aquifers have made water governance a critical issue. These pressures affect water availability, food security, public health, and ecosystem integrity, making it necessary to seek alternative strategies to replenish high-quality reserves (Closas and Villholth, 2020; Deng et al., 2026; Gajurel et al., 2024; Saqr et al., 2024; Romman et al., 2024; Taghilou, 2022; Taussi et al., 2024). Managed Aquifer Recharge (MAR) is one of these strategies. It is the intentional recharge of aquifers for future recovery or for environmental benefits (Dillon et al., 2009; Zhang et al., 2020). It involves directing various sources of water, such as stormwater, reclaimed water, or rainwater into the subsurface through adequate systems such as infiltration basins or injection wells (Alam et al., 2021; Henaou Casas et al., 2025; Page et al., 2018; Sallwey et al., 2019).

MAR has multiple objectives, including securing the water supply, preventing saltwater intrusion, and maintaining ecosystems (Dillon, 2005; Dillon et al., 2019; Panagiotou et al., 2024; Martins et al., 2024; Chekirbane et al., 2025). It serves as a technical measure and a strategic response to ensure future water supply needs (Dillon et al., 2009; Escalante, 2026; Escalante et al., 2023; Ringleb et al., 2016; Zhang et al., 2020). From a technical standpoint, the implementation of MAR systems generally involves four distinct stages: planning, investigation, design, and construction (Panagiotou et al., 2026; Zhang et al., 2020). But integrating it into water governance requires a multi-contribution approach.

A review of global experiences and theoretical perspectives on water governance, with an emphasis on MAR-specific challenges, shows how governance has been approached in MAR initiatives in terms of legal instruments, public participation, and risk-based assessments (Imig et al., 2022; Mankad et al., 2015; Seidl et al., 2026; Ward and Dillon, 2012). While these elements are important, a successful MAR system must also adapt to its specific hydrogeological, institutional, and cultural landscapes.

A well-structured MAR governance framework provides the

organizational structure required for MAR initiatives to succeed. It acknowledges the interdependent nature of technical considerations, governance dynamics, regulatory frameworks, and institutional roles, and encourages their coordination (Casanova et al., 2016; Dillon et al., 2022; Page et al., 2026). Within this framework, the development of MAR agreements represents a key milestone in MAR governance. These agreements, explicit or implicit, serve to clarify institutional arrangements, facilitate dialogue that aligns stakeholder interests, and distribute responsibilities in a transparent and equitable manner.

An agreement is a formal, legally binding document between two or more parties that outlines the roles and responsibilities of the stakeholders involved, including both the planning and implementation phases (Chekirbane et al., 2025; Fawcett, 1953; Martins et al., 2024; Mirumachi and Hurlbert, 2022; Panagiotou et al., 2024; Thorson, 2003). A good agreement should be clear, inclusive, and adaptable. It must define a shared roadmap towards a feasible, sustainable, and successful implementation. Effective agreements are built on mutual trust and shared goals, supported by scientific data and stakeholder participation. In line with these principles, it is essential to integrate stakeholder perspectives throughout all stages of MAR development, from feasibility assessment to governance design. Over the last few years, significant progress has been made in the analysis and modelling of MAR strategies; however, scientific advances in the governance of MAR systems remain comparatively limited.

The objective of this paper is to present a general governance framework to support the implementation of MAR systems. Based on recognizing the complexity of MAR, the framework aims to provide a structured and adaptable tool to assist those interdependencies. The adopted methodology unfolded in two interconnected steps: (1) the design of a general governance framework based on theory and practice and (2) its tailored adaptation across four Mediterranean case studies to identify common principles, contextual nuances, and practical considerations in order to generate a set of guidelines that can assist the design of regional MAR agreements, grounded in real experience.

2. Methodology

The proposed governance framework offers a structured approach for MAR implementation. It shows how the effective execution of MAR systems is dependent on a complex interplay of factors. Rather than treating key governance dimensions as separate layers, the framework suggests considering them as interdependent, constantly informing and reshaping one another (Fig. 1). From this perspective, MAR agreements are not simply formalized documents at the end of a linear process. Instead, they evolve from a dynamic system of technical feasibility, stakeholder negotiation, regulatory constraints, and economic possibilities.

The proposed framework aims to recognize the complexity between the different aspects and organize them to support coherent and well-grounded MAR agreements. Each component feeds on the others; no

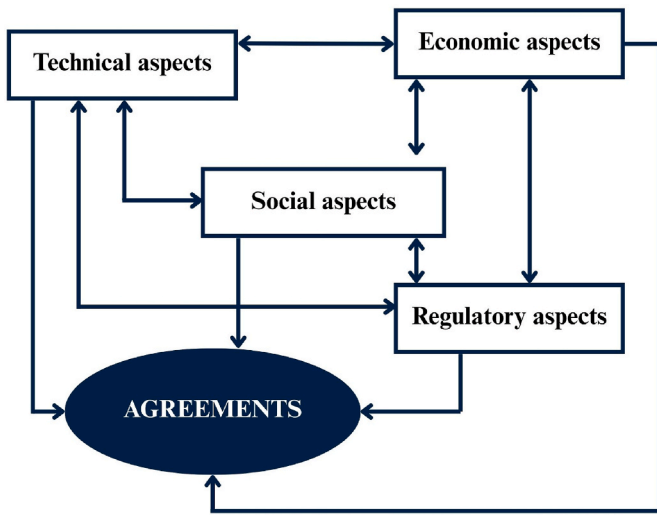


Fig. 1. Interrelation between the aspects to be considered when drafting MAR agreements.

single contribution is sufficient to support a credible MAR governance process (Fig. 2). For instance, while the technical component involves MAR feasibility, groundwater modelling and water allocation modelling, this assessment alone cannot support the entire process.

Instead, considering the social dimension makes the governance process more effective. This dimension includes stakeholder identification, roles, engagement, and the identification of direct and indirect MAR beneficiaries. It also involves building transparency through dialogue, allowing stakeholders to actively shape and refine technical choices. Economic considerations, such as costs and benefits, incentives, potential trade-offs, and cost allocation, intersect with these social dynamics, adding another layer of negotiation to MAR implementation. Regulatory frameworks based on analysis of existing regulations, institutional mandates, and legal feasibility can act as both enablers and constraints. They define what is legally possible, while exposing potential gaps in institutional willingness, reflecting deeper dynamics that must be addressed throughout the process.

The application of the general governance framework for MAR agreements is organized into six steps that integrate the four core aspects

(i.e., technical, social, economic, and regulatory). The first step consists of a preliminary assessment that requires an in-depth analysis of the intrinsic characteristics (geological, morphological and, most importantly, hydrogeological) to understand the suitability of MAR sites. This step must also incorporate environmental aspects, water availability for MAR and the assessment of the water needs of the region. The process may be built upon previous studies conducted at the site and expand the concept of MAR suitability into MAR feasibility. The second step is the identification of potential MAR sites using MAR feasibility maps (Chekirbane et al., 2025; Ghannem et al., 2024; Martins et al., 2024; Panagiotou et al., 2024). This step involves the selection, ranking, and weighting of various factors (biophysical, technological, social, economic, environmental, hydrological, institutional, and financial dimensions) with respect to three feasibility components (i.e., intrinsic properties, water availability for MAR, water demand). These dimensions serve as inputs into a multi-criteria decision analysis to identify the most feasible regions for MAR installation. The resulting feasibility maps serve as a first indication of possible sites for MAR. General and regional stakeholders participate in the mapping process, and then local stakeholders will be identified.

In parallel with the identification of potential MAR sites, the main stakeholders – which should be represented by promoters, beneficiaries, and decision-makers – must be identified along with their respective roles (e.g., engagement level, potential benefits, and influence) (Step 3). This step focuses on a participatory co-creation process via the integration of document analysis, stakeholder interviews, and workshops. The fourth step consists of a technical assessment based on a participatory process for local hydrogeological characterization, supported by numerical modelling. This step provides the scientific basis for the decision-making, design, and implementation of MAR systems to optimize MAR and assess its hydrological and ecological implications. Decision Support Systems (DSSs) and groundwater models play a crucial role in improving technical options, allowing the comparison of possible MAR solutions to select the suitable recharge technique and amount of water to be recharged. The developed outputs (e.g., feasibility mapping, hydrogeological study of the selected region, MAR system proposed) should be presented and discussed among technicians, stakeholders, and beneficiaries to reach a consensus and common vision for MAR implementation.

The fifth step addresses the economic considerations. This includes an examination of financial conditions and cost allocation to ensure that

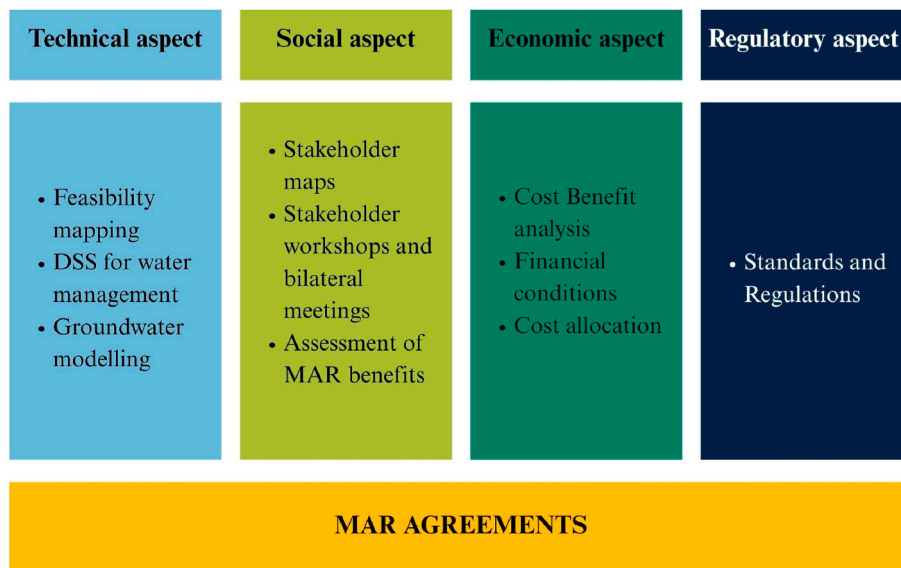


Fig. 2. Elements to be considered for drafting MAR agreements. All elements and tools are interrelated and collectively contribute to the formulation of robust MAR agreements.

resources are divided efficiently and fairly among beneficiaries. This phase involves analyzing investment priorities, financing strategies, and potential revenue models, directly contributing to the long-term sustainability of MAR systems. Finally, the sixth step focuses on standards and regulations to establish a legal framework for guiding the planning, implementation, and monitoring of the MAR system. Regulatory compliance ensures that the selected MAR project aligns with both national and international regulations governing groundwater recharge, environmental protection, and water resource management. The outcome of this proposed framework is the development of a set of guidelines that need to be considered for regional MAR agreements.

3. Application to the case studies

The general governance framework is applied to analyze and compare four Mediterranean case studies in the Mijares River Basin (Spain), Sado e Mira and Guadiana hydrographic regions (Portugal), Chiba River Basin (Tunisia) and Akrotiri region (Cyprus), each illustrating distinct approaches to the implementation of MAR (Fig. 3). The aim is to explore how the interaction of governance-related dimensions shapes MAR agreements and determines the viability and sustainability of MAR solutions. The comparison of the four case studies helps to illustrate the general applicability of the framework and its potential to be adapted to different contexts.

Across all four case studies, the implementation of the MAR governance framework followed a series of structured steps, as already discussed in section 2: a preliminary assessment of local hydrogeological and environmental conditions, a multi-criteria decision analysis and creation of feasibility maps to identify and evaluate feasible MAR sites, a stakeholder mapping and active engagement through meetings and workshops to ensure participatory governance, a technical assessment through groundwater modelling with INOWAS web-based platform (Glass et al., 2022; Stefan et al., 2017) and water allocation modelling with AQUATOOL (Andreu et al., 1991, 1996) to project the effect of MAR systems and optimize recharge strategies, in collaboration with

stakeholders, and an integration of legal and institutional frameworks. These shared processes are the tasks done to generate the guidelines for drafting MAR agreements for each case study.

3.1. Spanish case study

The Spanish case study, Mijares River Basin, is situated in the eastern part of the Iberian Peninsula (Fig. 4) and has a surface of 4818 km². The basin combines coastal plains susceptible to seawater intrusion with interior mountainous zones and sustains significant irrigation-dependent agriculture (CHJ, 2025). Groundwater has an important role in managing inland water resources within the Mijares River Basin. This importance is due to the presence of highly permeable geological formations, which facilitate recharge. As a result, aquifers function as natural reservoirs, helping to buffer variability and support the integrated management of both surface and groundwater. The coordination of these water sources is adapted over time to reflect temporal changes in water availability, such as seasonal variability and drought events, and to respond to environmental conditions (CHJ, 2022).

The MAR system in the Spanish case study involves the use of a storage pond (Belcaire Pond) to capture peak surface water flows, along with two infiltration wells to recharge the Rambleta aquifer.

Water governance system in Spain presents an example of environmental adaptability based on planning, public participation, technological development, and innovation. In response to the evolving challenges due to climate change, the country has taken steps to integrate strategic guidelines into water management through the Law 7/2021 of May 20, which outlines strategic orientations on water and climate change (MITERD, 2022). Also, the green book on Water Governance in Spain provides a foundational reference for strengthening collaboration with institutional actors and stakeholders (Gobierno de España, 2020). While Spain possesses a developed water governance system, with legally binding River Basin management plans and strong institutional coordination mechanisms, challenges persist (Schütze, 2023). Aquifer overexploitation, low reliability of water supplies in



Fig. 3. Study areas for the application of the MAR Governance Framework.

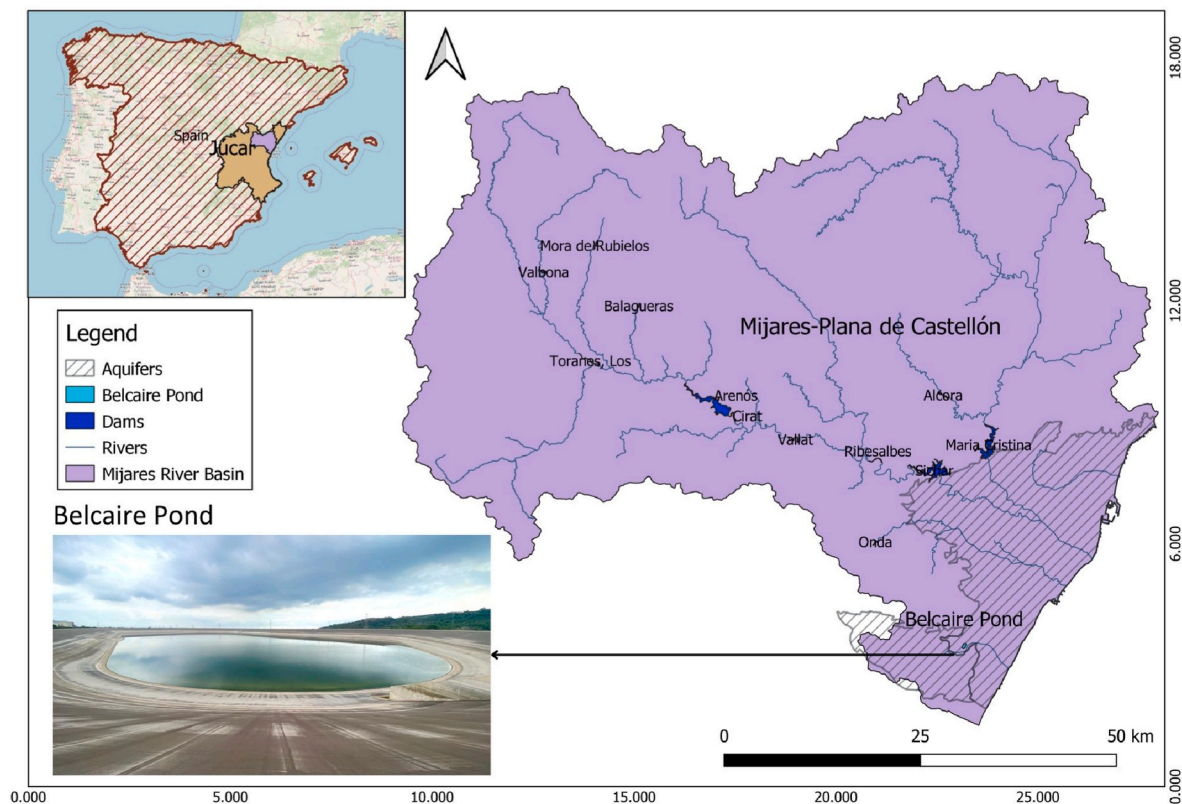


Fig. 4. Geographical location of the Mijares River Basin and Belcaire Pond.

drought years, and fragmented stakeholder interests place pressure on water managers to find innovative, collaborative solutions.

MAR agreements in Spain should articulate a clear and comprehensive framework that reflects both national legislation and the realities of local implementation. These agreements must explicitly define the scope of MAR activities, recognizing that MAR is not legally classified as discharge, and clarify authorization requirements to ensure that any intervention avoids groundwater contamination, aquifer overload, or incompatible extractions. They should also describe the range of MAR techniques to be considered, distinguishing between direct recharge methods, such as infiltration wells, and induced MAR strategies. In Spain, the most successful outcomes have resulted from combining direct and induced MAR approaches (Pulido-Velazquez et al., 2008; Henao-Casas et al., 2022; Sahuquillo et al., 2022).

The agreement should reflect the findings of the technical assessment based on numerical modelling, and using related indicators (environmental indicators, water demand reliability indicators, feasibility maps indicators, etc.). Legal and technical criteria must govern the selection of recharged water sources, and the use of modelling tools is essential to assess the availability of surplus water and potential impacts on basin water demands. Stakeholder roles should be mapped and differentiated, identifying their levels of engagement, benefits, and obligations. It is also essential to detail the roles of each stakeholder category, such as those involved in initiating, collaborating, informing, or consulting on MAR projects.

Requirements for feasibility studies and pilot experiments need to be included to identify suitable MAR sites and relevant stakeholders. This process confirms site viability through feasibility mapping and initiates stakeholder engagement, both of which require regulatory and institutional support. Agreements should outline detailed legal procedures, including technical documentation, environmental impact verification, recharge and extraction programs. Transparency and public participation are critical, along with reasonable timelines for processing MAR requests. Resulting authorizations should define operational conditions,

monitoring obligations, emergency response measures, and protocols for future revision. Regular reporting must document the system performance by tracking recharged and recovered volumes, groundwater level responses, and water quality indicators. Finally, economic considerations should be explicitly addressed, detailing how infrastructure and operational costs will be distributed among stakeholders to ensure financial sustainability without undermining the collective benefits of aquifer restoration.

This framework was applied through the involvement of the Technical University of Valencia (UPV) with direct participation of the Júcar River Basin Agency through its Water Commissary and the Hydrological Planning office. Other key participants are the state-owned company ACUAMED, and the irrigators community of Vall d'Uixó. At least 5 formal events were held, including a needs assessment workshop and meetings with stakeholders, a field visit and local stakeholders' meetings, an international symposium about conjunctive management of surface and groundwater in the Mediterranean region, a technical validation meeting, and a final civil assembly (Baumann et al., 2025).

The resulting agreement, referred to as the MAR charter, was initiated by the AGREEMAR project consortium (UPV and adelphi) in coordination with the Júcar River basin Agency. The process was documented through meeting minutes and detailed notes, which were compiled into reports. Workshops and meetings were based on structured group discussions among stakeholders. Decisions were reached through phased consultations, where initial seminars gathered broad perspectives before narrowing down to targeted technical dialogues. This process was based on consensus and finalized during the civil assembly, where the draft principles of the MAR charter were refined section by section. This adoption by the main regulatory water management entity in the region ensures that the implementation of this framework remains consistent with the Hydrological Planning Instruction and the Regulation of the Hydraulic Public Domain.

3.2. Portuguese case study

In Portugal, particularly in the water-scarce regions of Alentejo and Algarve, there is the need to adopt additional water storage strategies, enhanced by making a broader use of alternative water sources (e.g., treated wastewater). Climate change, coupled with tourism-related seasonal population surges, especially during the summer months, is intensifying water stress across both agricultural and urban sectors. In this context, the question of public and social acceptance of alternative water resources emerges as a key determinant in the transition toward more resilient water management. This acceptance is closely linked to the perceived benefits of such solutions, not only for protecting ecologically sensitive areas but also for sustaining local economic activities relying on water availability.

The Portuguese case study, which is situated in the southern region of mainland Portugal, comprises two River Basin districts – Guadiana (PTRH6) and Sado e Mira (PTRH7) with approximately 11 600 km² and 10 000 km², respectively, included in Alentejo and partially in the Algarve Administrative regions (Martins et al., 2024). The Comporta MAR site, located within the Sado and Mira River Basin districts, represents the first example of a SAT-MAR system in Portugal, and its running since October 1st, 2021 (Fig. 5). It is composed of four infiltration basins where the bottom of each basin is filled with gravel and separated from the sand below by a geotextile, with two basins having two new reactive organic layers to promote contaminants removal. It was presented as an alternative to the commonly implemented method of direct discharge of treated effluents into surface water bodies, therefore protecting Sado estuarine ecosystem, a sensitive area classified as a Nature Reserve located over the Margem Esquerda Tejo-Sado aquifer system. Due to the size of the Comporta system, its impact on regional scale is likely limited. However, its value lies in the water quality improvement and in its potential as a replicable MAR system model across Alentejo region.

The application of the general governance framework in Portugal requires careful coordination among project promoters, beneficiaries, and relevant stakeholders, and must be grounded in a robust set of preparatory hydrogeological studies and data. Agreements should

include a comprehensive description of the MAR project, detailing the infrastructure and operational aspects of the selected technique, such as infiltration basins, along with an environmental impact assessment, and an initial cost-benefit analysis. This analysis should weigh investment and operational expenses against anticipated ecological, agricultural, or socio-economic benefits, identifying which sectors may be positively impacted (e.g., tourism, industry, urban supply).

Legal compliance remains a complex but essential foundation in Portugal. Although specific MAR legislation is currently lacking, the Portuguese Parliament issued a resolution recommending that the Government encourages MAR to reinforce water efficiency (Resolução, 2026). Consequently, MAR projects must adhere to existing norms such as the Water Law (Law No. 58/2005 of 29 December, 2026) and the groundwater law (Decree-Law No. 208/2008 of October 28, 2026), which transpose the European Union (EU) Water Framework and Groundwater Directives. These regulations permit MAR in very restricted situations as long as it is proven that does not interfere with the groundwater body good status. Also, the Decree-law 152/97 (transposing the European Urban Wastewater Directive), does not recognize treated wastewater as a potential source for MAR, and therefore establishes quality standards that are limited and not tailored to support such applications (Decree-Law No. 152/97 of June 19, 1997).

At regional level, under the planning River Basin-level instruments, MAR implementation must align with the current established River Basin Management Plan cycle measures for improving water body status. This implies the necessity of hydrogeological characterization, environmental impact assessments, and the development of a groundwater monitoring plan. Impacts on groundwater quality is the most significant aspect in the Agreement, being one of the main concerns referred by the water authority when the Letter of Intent for the AGREEMAR project (AGREEMAR, 2026) was being discussed. This is related to the fact that groundwater is considered as a strategic reserve. Although not explicitly stated in the agreements, numerical modelling was identified as a relevant step, allowing to address suitability long-term viability, as well as establish the potential beneficiaries.

Stakeholder engagement should be informed by these technical findings, with clearly defined roles, obligations, and benefit-sharing

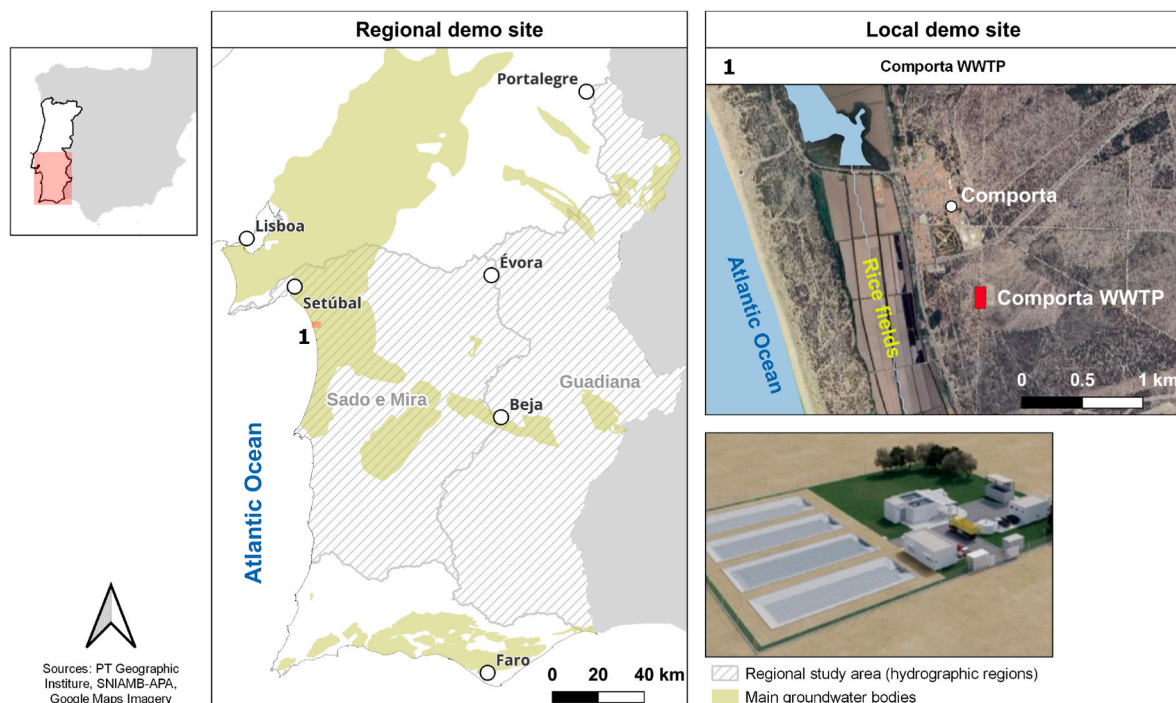


Fig. 5. Geographical location of Comporta case-study site and existing aquifer systems in Alentejo and Algarve region (Leitão et al., 2024).

arrangements. Transparency through public consultation is essential, not only for social legitimacy but to ensure inclusive decision-making. Furthermore, regular reporting on aquifer response, particularly in terms of groundwater quality and levels, should be embedded into the operational cycle of the agreement. Cost-sharing mechanisms must be addressed explicitly, outlining the financial structure for implementation, monitoring, and maintenance. Importantly, an agreement should clarify the permitting process, recognizing the authority of River Basin agencies to approve studies and grant operation licenses.

The application of the framework was an initiative of researchers from the National Laboratory for Civil Engineering (LNEC) and adelphi, as a development of the AGREEMAR project, and involved the two main actors, the Portuguese Environment Agency (APA), as the Water Authority and responsible for issuing the Permit for MAR, at both national and regional levels and the regional water utility Águas do Alentejo (AgdA) as the Comporta site owner. Four major events were held to prepare the agreement, including a field visit and stakeholders' meetings, a workshop on feasibility maps and constellation analysis, validation workshops, and a final civil assembly. The discussions were documented through detailed minutes and a visual constellation analysis conducted by the facilitator to map the interplay between institutional, technical, and legal elements. It included interactive exercises for stakeholders using digital tools such as word clouds and criteria assessments to identify the barriers preventing the implementation of MAR (Baumann et al., 2025).

The agreement development was initiated in the context of the AGREEMAR project by LNEC and adelphi as a strategic response to the lack of specific MAR legislation in Portugal. The agreement is referred to as a letter of intent. Decisions were reached through an iterative and collaborative review process in which stakeholders examined the draft letter of intent line by line to ensure full alignment with the expectations. The final agreement was signed by APA and AgdA. This initiative by APA allows the framework to serve as a legal blueprint for replicating MAR projects across the country, providing the institutional confidence

needed to expand the use of treated wastewater for MAR.

3.3. Tunisian case study

The Tunisian case study is situated in the Chiba River Basin, which covers the southeastern part of Tunisia, on the eastern side of the Cap-Bon peninsula. It covers an area of 204 km² characterized by forested upstream regions and mainly farmland downstream (Fig. 6). To address the ongoing degradation of groundwater resources in the region, water authorities proposed the Korba–Elmida artificial recharge site. Located approximately 1.5 km from the Mediterranean Sea and around 300 m north of the Korba wastewater treatment plant, the site is designed to use treated municipal wastewater as a source for MAR. The current system operates using a Soil Aquifer Treatment (SAT) process, consisting of three infiltration ponds, each covering 0.0015 km², with a targeted recharge capacity of 1500 m³/day. Despite this design, the site has faced persistent challenges such as clogging, limited availability of treated wastewater, and the relatively small size of the infiltration basins, which have constrained its effectiveness in restoring groundwater level (Gaaloul et al., 2012).

Coastal aquifers in Tunisia face increasing pressures, driven largely by overexploitation of groundwater, particularly for agricultural purposes. The region has witnessed a steady decline in groundwater levels accompanied by progressive salinization trends that have persisted over the past thirty years (Ennabli, 1980; Ben Hamouda, 2008; Chekirbane et al., 2013; Zghibi et al., 2019).

In Tunisia, the development of MAR agreements must balance institutional authority with stakeholder comfort regarding legal formality. Engagement activities revealed a clear preference among local actors for instruments with lower legal weight, such as memoranda of understanding or charters, rather than binding contracts (Ghannem et al., 2023). Nevertheless, the agreement document should remain structured and robust, beginning with a clear explanation of the authorization procedure. The General Directorate of Water Resources,

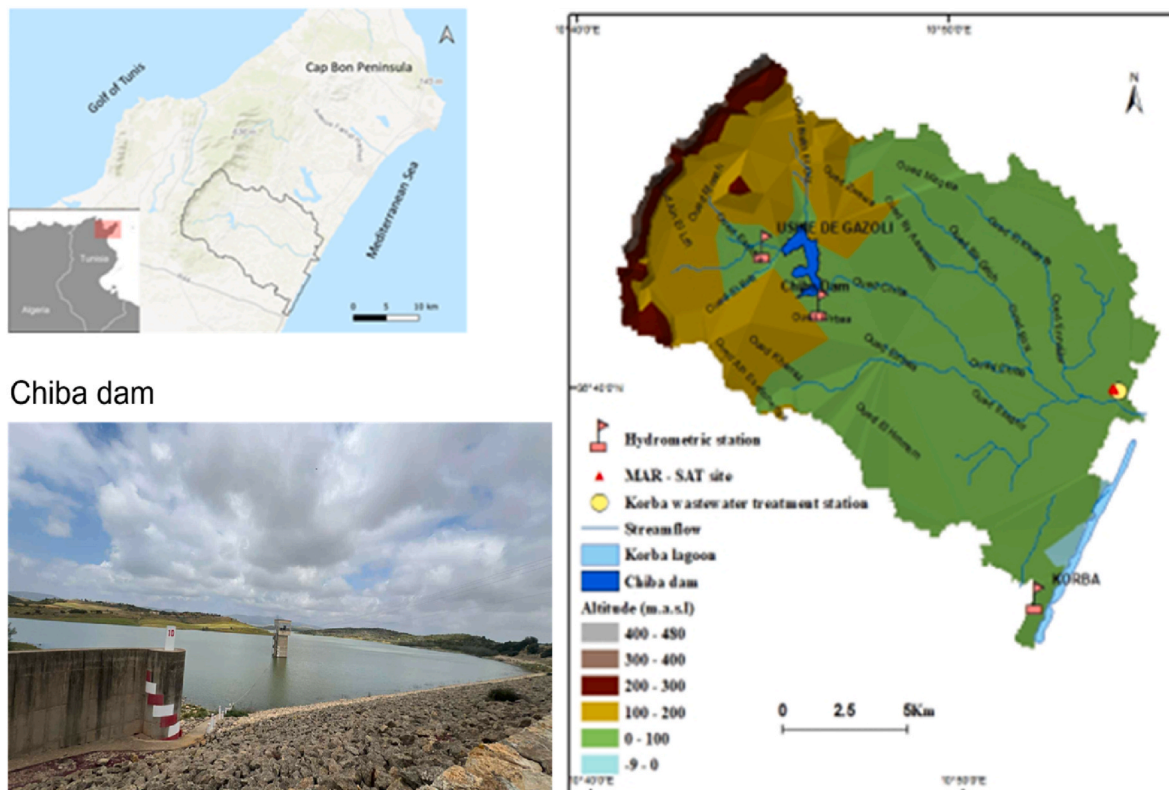


Fig. 6. Geographical location of the Chiba River Basin and the Chiba dam.

under the Ministry of Agriculture, Hydraulic Resources and Fisheries, is the designated authority to grant MAR permits, which must be preceded by an impact assessment of the quantity and quality of the aquifer. Numerical modelling is an asset in this evaluation, allowing for the simulation of aquifer responses to different recharge scenarios (Glass et al., 2022). The agreement should also specify the MAR typology, building insights from feasibility mapping to identify both appropriate locations and suitable recharge techniques. Source water considerations are important; beyond standard parameters like salinity, nitrates, and BOD/COD, the presence of suspended materials (which can cause clogging) and contaminants of emerging concern (CECs) should be assessed. The temporal reliability of water availability and potential conflicts with other uses must also be addressed.

Stakeholder roles, responsibilities, and anticipated benefits should be clearly stated, not only for transparency but to guide engagement and alignment throughout implementation (Conrad et al., 2022). Once the MAR scheme is defined, a detailed economic study must outline projected costs and propose a shared funding model, supported by documentation on infrastructure needs, operational demands, and maintenance requirements. Finally, the agreement should specify the time frame for project execution, ensuring that all parties operate within a clear and realistic horizon.

The framework was applied through a broad multidimensional collaboration, including the National Agronomic Institute of Tunisia (INAT), the General Directorate of Water Resources (DGRE), the Regional Commissariat for Agricultural Development (CRDA) of Nabeul, and the National Sanitation Utility (ONAS). A series of 5 key events were documented, including a field data collection, a participatory validation workshop, an NGO engagement meeting, a technical training course and a final civil assembly. The outcomes were documented via meetings minutes and the use of pinboards to capture brainstorming results. The agreement was initiated by INAT and adelphi in coordination with the DGRE in the framework of the AGREEMAR project, and it was named MAR charter. Decision-making was characterized by multidimensional collaboration and high-level political consensus, evidenced by the concluding summary and validation of the “MAR Charter” principles during a large-scale meeting. The implementation of this framework was reinforced by a decision taken by the State Secretary for Water, which made it possible to incorporate the results of this framework into the National Water Strategy 2050 (Baumann et al., 2025).

3.4. Cypriot case study

The island of Cyprus is situated in the south-eastern part of the Mediterranean basin, with total projected area of 9251 m² (Fig. 7). Cyprus is divided into six administrative districts, two of which are

located within the occupied territory of the Republic. Governance at the district level is coordinated through district offices, which serve as local extensions of the central government. These offices are responsible for aligning the activities of all Ministries within their respective jurisdictions, ensuring coherence in the implementation of national policies on the regional scale (Pericli, 2019).

Cyprus has the highest water exploitation index among EU member countries due to the combined pressures of prolonged periods of drought and intensive water extraction (EUROstat, 2024). The agricultural sector accounts for approximately 64% of total water use on the island, followed by the domestic sector, which represents 28.4% of the overall water consumption. Tourism and industry contribute smaller shares, with water demands of 4.7% and 2.9%, respectively (WDD Annual report, 2022). Cypriot water authorities promote the use of non-conventional water sources (desalination and treated wastewater) as an alternative to meet the growing demand. The total amount of treated wastewater is expected to increase over the next few years, intended to substitute for up to 40% of the freshwater currently used for irrigation by 2040 (Hadjigeorgiou, 2015).

In the Cypriot case study (i.e., Akrotiri region), a MAR scheme is operational since 2016 (Achiello et al., 2025), using tertiary-treated wastewater as the recharge source, whereas infiltration ponds are used to recharge the aquifer via soil-aquifer treatment (SAT). The primary recharge objectives of this system are a) the mitigation of seawater intrusion, and b) the storage of water for later use, primarily for irrigation purposes. The MAR facility is located near the urban area of Limassol city (southern part of the island) and is designed to recharge the Akrotiri aquifer during the winter season (October–March).

In Cyprus, the Water Development Department (WDD) is responsible for planning, implementing, and assessing MAR systems in accordance with the national priorities and EU water directives. Given the interdisciplinary nature of MAR, which requires collaboration and coordination among scientists from different disciplines (hydrologists, biologists, engineers, and economists), the development of agreements must integrate technical, institutional, and social dimensions. At the institutional level, the WDD is the lead coordinating entity among other relevant agencies, such as those involved in environmental assessment, public health, and infrastructure. The agreements should be grounded in a comprehensive baseline assessment that considers land use, population dynamics, ecosystem vulnerability, pollution pressures, seismic and hydrological risks, and, critically, the suitability of treated wastewater as a recharge source.

Numerical modelling must be used not only to optimize MAR design and evaluate aquifer responses, but also to predict how potential contaminants may behave under different recharge scenarios. Management and monitoring frameworks should cover both construction and

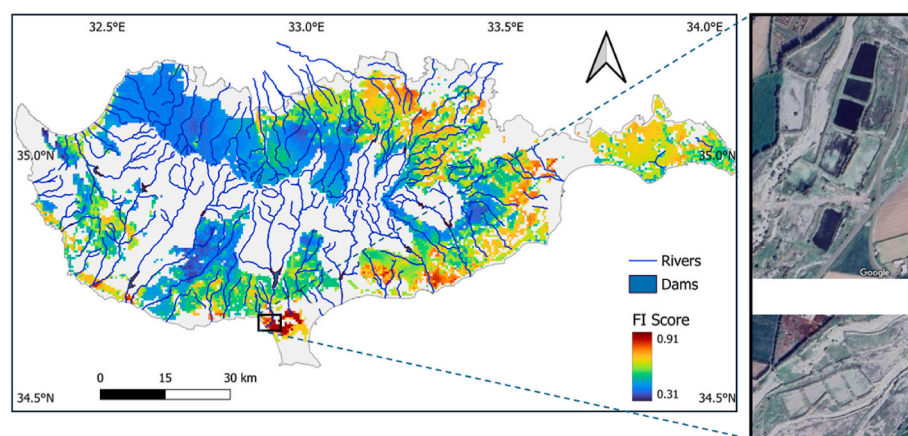


Fig. 7. Left: Spatial distribution of the feasibility indicator (FI score) covering the non-occupied part of the Republic of Cyprus. Cyan lines represent rivers, whereas blue polygons represent dams. Right: Satellite images of the infiltration ponds in Akrotiri MAR site.

operation stages, with special attention to water quality, ecological integrity, and system performance over time. Economically, MAR agreements must reflect the collective nature of MAR benefits of aquifer protection through public investment in infrastructure and operations. Finally, effective community engagement is essential: agreements should formalize communication links to build trust, provide clarity about risks and benefits, and ensure that public feedback informs decision-making and adaptive management.

The framework application was centered on the WDD, which is the unique authority responsible for water management in Cyprus (WDD, 2026). Four major events were conducted with key representatives of the national water authorities, together with the head hydrologist of the regional office where the MAR facility is located. The first meeting focused on presenting an overview of the proposed methodology for mapping MAR feasibility and the main results, followed by an extensive discussion that provided valuable feedback to the research team for further improvements and corrections. The second meeting focused on presenting the groundwater modeling of the Akrotiri aquifer to hydrologists and hydrogeologists from the WDD and the Department of the Geological Survey of Cyprus, which involved different scenarios of aquifer recharge via MAR. As in the first meeting, these scenarios were discussed, resulting in modifications to better address the current and future needs of water managers. The third meeting focused on presenting the final results of the technical assessments (feasibility mapping and groundwater modeling) and on compiling an initial draft of a non-binding agreement (referred to as a “Letter of Intent”) for use by the WDD in future revisions of its management plans. The last meeting focused on finalizing the agreement and the achievement of consensus between the research team and the representatives of the WDD. As a result, the final transcript was signed by the Director of the WDD, ensuring verified that the proposed MAR principles aligned with EU Water Framework Directive. All activities and discussions were documented through meeting minutes and reports. Since the WDD holds all jurisdictions over water resources, their involvement means that the framework is adopted into official planning for scaling up MAR across the island (Baumann et al., 2025).

4. Discussion

To address the need for a global applicable management structure, the general governance framework proposed in this work provides the essential structure for setting the scene for future implementation of MAR systems. This framework is not intended to be a one-size-fits-all model, but rather an integrative conceptual framework that identifies four key dimensions that need to be considered: technical, social, economic, and regulatory. The general governance framework delivers a roadmap designed to guide managers from the initial MAR technical feasibility stages to the formalization of strong, long-term MAR governance agreements. Even though the core pillars of the framework are global, its application is flexible and adaptable. Implementation in any given context will necessarily be different based on existing national legislation, socio-environmental context, the accuracy and availability of data, the specific project objectives, and the readiness of the institutions involved, among other aspects.

The diversity of geographic, legal, and hydrological contexts across the four Mediterranean case studies analyzed in this work reveals a set of converging elements and instructive contrasts in MAR governance, which were considered to make the tool more broadly applicable. Each case reflects a unique interplay between technical imperatives, institutional structures, stakeholder preferences, and socio-economic priorities. However, when analyzed side by side, common principles emerge (Table 1).

The four cases show the diversity of institutional frameworks, stakeholder dynamics and levels of readiness to implement MAR, yet they converge around basic MAR governance principles. In Spain, strong legal and institutional foundations allow for the deployment of MAR in targeted aquifers, particularly through induced recharge in over-exploited coastal areas, such as the Belcaire case study, where local stakeholders show a tangible willingness to participate. Portugal remains in the early stages of adopting MAR, hindered by a cautious approach to alternative water management solutions in the context of climate change, concerns about potential contamination, institutional ambiguity, and the absence of clearly defined beneficiaries. Tunisia offers a more flexible and context-sensitive model where institutionalized mandates coexist with local preferences for informal arrangements.

Table 1
Summary of the structure of the agreements for the four case studies.

Relevant subjects	Spain	Portugal	Tunisia	Cyprus
Identification of objectives	Yes	Yes	Yes	Yes
Relevant stakeholders to include	Water authority, agricultural communities	Water authority, local to regional stakeholders (Water Utilities, Farmers, Tourism sector)	Water authority, local stakeholders	Water authority, local communities
Pre-feasibility studies	Pre-feasibility studies must be conducted	Pre-feasibility studies must be conducted	Pre-feasibility studies must be conducted	Pre-feasibility studies must be conducted
Risk assessment methodologies	Environmental impact studies	Environmental impact must include risk analysis	Environmental and economic impact assessments	Environmental and economic impact assessments
Quality indicators to be considered	Should include water quality standards	Should be included for groundwater quality and treated wastewater quality	Should be included, especially for arid regions	Should be included, defined based on the MAR objective
Identification of beneficiaries	Yes	No	Yes	Yes
Regulatory framework alignment	Should be aligned with national and EU regulations	Should be aligned with national, EU regulations and River Basin Management Plan established measures	Should be aligned with national regulations	Should be aligned with national and EU regulations
Financial mechanisms for implementation	Government funding and stakeholder contributions	Government funding (national or EU mechanisms) and stakeholder or site owner contributions	Government funding	Government funding
Use of non-conventional water sources	Included	Included	Included	Included
Stakeholder communication and engagement	Regular meetings, consultations, workshops	Stakeholder consultations and coordination actions (specific platforms for that purpose), community meetings	Stakeholder workshops, community meetings	Stakeholder workshops, community meetings
Implementation of agreements	Through stakeholder consensus	Through stakeholder consensus and Environmental Agency (water authority) approval	Through stakeholder consensus and government Commitment for funding	Through stakeholder consensus

Stakeholder engagement in Tunisia is centered on practicality and trust-building. Cyprus demonstrates a centralized and technical approach supported by strong public investments. The interest expressed by stakeholders and the success of the pilot cases indicate the possibility for scaling up if critical knowledge gaps are addressed.

To address the complexities that vary from one case study to another, the framework adopts a tailored risk management approach. Risks are classified into technical (e.g., clogging in Tunisia and Portugal), environmental (e.g., seawater intrusion and groundwater pollution in Cyprus and Spain), and social (e.g., public mistrust regarding wastewater reuse). These risks are further classified by risk level based on existing guidelines and quality standards which are incorporated into the multi-criteria decision analysis for mapping MAR feasibility. Among environmental risks, special attention should be paid to groundwater pollution risk. Governance measures are accordingly categorized into prevention (via feasibility maps to avoid unsuitable hydrogeological zones), control (through groundwater modeling and water quality monitoring), and emergency/adaptive planning, where local MAR agreements allow changes in operating rules if piezometric levels or quality thresholds are exceeded.

The technical MAR validation of these cases provides evidence to justify these governance interventions. In the Spanish case study, there is a projected 38% reduction in groundwater pumping (from 11.45 to 7.15 hm³/year), which reduces the cost of energy for irrigation and mitigates the aquifer overexploitation. Similarly, the Portuguese case study highlights the cost-benefit efficiency of SAT-MAR, where current infiltration rates of 110–190 m³/day of secondary treated effluent provide a lower cost alternative to tertiary treatment and protect at the same time the Sado River estuary. The Cypriot case study shows that MAR leads to a 7.4 m rise in the groundwater mound, which successfully reverses a –4.3m sea-level depression and creates a hydraulic barrier against seawater intrusion. Moreover, preliminary results from particle tracking (MODPATH) originating at the infiltration ponds indicate that there is no risk of contaminating drinking wells located within the same aquifer according to the 50-days rule, which states that water recharged into an aquifer should take at least 50 days of subsurface travel time before reaching a drinking water abstraction point. In the Tunisian case study, the technical efficiency of the framework shows that replication of MAR sites could raise local piezometric heads by up to 23.6 m in depleted areas.

In all cases, the success of monitoring, assessment and risk communication initiatives is closely linked to the stakeholder engagement in all stages. They emphasize the importance of a formalized authorization process, although the degree of legal rigidity varies considerably. Spain and Portugal adhere to structured approval pathways governed by River Basin agencies. In Spain MAR can be integrated into existing water planning instruments. However, in Portugal MAR is not yet formally included in its water planning instruments, and the development of a MAR facility must undergo an Environmental Impact Assessment. Cyprus, under the leadership of its WDD, follows a centralized, institutionally embedded model that aligns closely with EU directives. Tunisia, in contrast, favors more flexible instruments reflecting both institutional pragmatism and stakeholder acceptance around legal formalization. These different legal cultures underline the need for MAR agreements to be adaptive, not only to regulatory frameworks but also to the degree of institutional awareness and local trust.

Water source quality and its assessment are another pillar shared across the cases. All four cases mandate some form of qualitative and quantitative evaluation of recharged water, often derived from treated wastewater. In parallel, to address pollution risks, the framework aligns with the environmental quality standards established under the EU groundwater directive (2006/118/EC) (European Parliament and Council of the European Union, 2006). Specific regulatory thresholds such as a strict European standard of 50 mg/L for nitrates (NO₃⁻) to target agricultural diffuse pollution, together with limits of 0.1 µg/l for each active substances in pesticides and 0.5 µg/l in total pesticides are

integrated to ensure that MAR supports the achievement of good chemical status of the aquifer. Tunisia and Portugal stand out for their detailed attention to emerging contaminants and suspended particles due to persistent clogging problems, enforcing strict thresholds tied to EU norms. Spain, Portugal and Cyprus integrate source evaluation within a broader modelling and scenario planning exercise that connects recharge potential to wider basin-scale planning and conjunctive use strategies while meeting the EU norms.

Stakeholder roles and engagement procedures were analyzed in every case, though with varying strategies and tools. Spain, Portugal and Cyprus provide highly structured schemes for stakeholder participation, based on institutional mandates and transparent procedures. Tunisia, while equally attentive to stakeholder dynamics, relies more on informal links and community trust-building. These differences suggest that stakeholder involvement must be tailored to the local scope of governance: formality where institutional legitimacy is rooted, and flexibility where informal consensus-building is more effective.

Technically, all four cases endorse the use of modelling tools, whether for aquifer simulation, contaminant transport, or scenario comparison. These tools form the analytical basis of MAR feasibility management and monitoring strategies for successful implementation. Spain highlights the value of regional modelling for differentiating between direct and induced MAR techniques and for determining operational thresholds. Cyprus integrates these tools into both planning and monitoring stages, with a strong emphasis on capturing long-term system behavior. Tunisia and Portugal use modelling to inform and ensure environmental compliance or to access the impacts of different recharge scenarios.

Monitoring and evaluation frameworks are another shared concern. Spain, Portugal and Cyprus prescribe regular reporting of recharge volumes, groundwater levels, and water quality metrics. Tunisia also recognizes the need for performance assessment, particularly considering technical challenges faced during past operations. This convergence underlines the fact that MAR must be treated as a dynamic system, requiring adaptive management rather than one-time assessment.

Finally, cost-sharing and financial sustainability appear across all cases, yet with distinct philosophies. Spain and Portugal integrate these elements within a cost-benefit approach, often tied to specific sectors (agriculture, tourism, urban supply). Tunisia adopts a more centralized approach, requiring detailed economic studies and proposing collective funding models, while Cyprus foregrounds public investment to distribute benefits equitably, particularly where aquifer protection serves the national interest.

Therefore, the general governance framework proposed in this paper shifts from a traditional MAR assessment, which usually identifies where recharge is possible from a hydrological point of view, toward creation of MAR agreements that define how regional stakeholders will implement and sustain the MAR project. Although the six steps of this framework are common to MAR project assessment, their application within this governance model is intentionally reoriented to serve as tools for building consensus and transparency. This framework serves as a scientific basis to demonstrate shared benefits to stakeholders, thus facilitating the collective commitment necessary to move from theoretical potential to a governance arrangement.

The focus on agreements transforms the outcomes of the framework from a technical report into an action plan for accountability and role definition. By integrating technical insights with social and economic aspects, the framework addresses the non-technical barriers, such as public mistrust or organizational ambiguity, that often cause MAR projects to fail despite successful technical assessments. The agreement-oriented approach ensures that the resulting management models are not only theoretical concepts but are also institutionally embedded and socially accepted, thereby providing the necessary legal and social infrastructure.

The MAR agreements developed within the general governance framework currently hold the status of finalized legally non-binding

institutional agreements tailored to the specific socio-legal maturity of each region. They were signed as letters of intent for use in future management plans in Portugal and Cyprus and established as formal MAR charters in Spain and Tunisia. To ensure transparency, the full text of these finalized charters and letters of intent has been made publicly available as official project deliverable (Baumann et al., 2025). To reach this stage, the process involved several preparatory meetings and large-scale civil assemblies where draft principles were reviewed, adapted to local legal frameworks, and validated. The final agreements were discussed and refined at civil assemblies with key stakeholders to ensure institutional commitment. During these meetings, it was agreed to establish dedicated follow-up committees for each site to ensure the sustainability of the agreements in the medium and long term. These committees are responsible for regular monitoring, validating technical and economic results, and guiding operational adjustments to maintain the long-term viability of MAR systems.

5. Conclusions

This study addresses the development and application of a general governance framework for MAR agreements that emphasizes how technical feasibility, regulatory framework, economic considerations, and stakeholder involvement shape successful MAR under different geographical and socio-economic contexts. It offers a guide to elaborate agreements for MAR.

The framework shows that a preliminary assessment of the case study is required to identify the specific provisions and potential MAR benefits. Then, potential MAR sites must be identified using feasibility maps to determine where MAR can be more effective. These maps serve as an initial tool for stakeholder communication and engagement. Identifying these actors and comprehending their interconnections is important for the elaboration of MAR agreements and the successful implementation of MAR. Furthermore, stakeholders should be actively involved in the technical assessment phase, which relies on numerical modelling to evaluate the effectiveness and productivity of the MAR system. This technical foundation also provides a basis for addressing economic aspects, such as the distribution of costs and benefits, which are crucial to support the feasibility, governance, and sustainability of MAR. Finally, all activities must be carried out in accordance with existing standards and regulations to avoid potential legal obstacles and ensure alignment with regional and national water management policies.

These aspects were analyzed for the four distinct Mediterranean case studies (Spain, Portugal, Tunisia, and Cyprus), each operating within different legal, hydrological, and cultural contexts. It has been demonstrated that there is no single template for MAR governance and that it should be seen as an iterative process. Guidelines for regional agreements were shaped in response to each case study, considering regional specificities and stakeholder involvement. Rather than offering fixed instructions, these guidelines are meant to serve as starting points designed to help water authorities create viable and resilient solutions for aquifer restoration.

The proposed framework is intended to be flexible and adaptable, providing a practical MAR governance tool applicable to MAR initiatives in different regions and institutional contexts. A key contribution of this framework is its ability to transform technical feasibility data into a functional governance roadmap. It offers a scalable model to overcome the institutional and social barriers by emphasizing good governance principles such as transparency, accountability, and equity. While standard technical assessments focus on intrinsic suitability, the proposed framework incorporates the thematic of water availability, and the specific water demands that can be partially or fully met through recharge. Furthermore, it provides social and legal infrastructure to ensure that MAR systems are successfully implemented and sustained over time. The stakeholder-adaptive approach facilitates the reduction of multi-actor conflicts by integrating diverse perspectives at every

implementation stage. Ultimately, by co-creating local MAR agreements, the framework defines the explicit roles, responsibilities, and benefit-sharing mechanisms that are often missing from purely technical reports.

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CRediT authorship contribution statement

Syrine Ghannem: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Rafael J. Bergillos:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Writing – review & editing. **Javier Paredes-Arquiola:** Conceptualization, Investigation, Methodology, Software, Validation, Writing – review & editing. **Abel Solera:** Conceptualization, Investigation, Methodology, Software, Validation, Writing – review & editing. **Joaquín Andreu:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Writing – review & editing. **Teresa E. Leitão:** Investigation, Methodology, Software, Validation, Writing – review & editing. **Tiago N. Martins:** Investigation, Methodology, Software, Validation, Writing – review & editing. **Anis Chekirbane:** Investigation, Methodology, Software, Validation, Writing – review & editing. **Khaoula Khemiri:** Investigation, Methodology, Software, Validation, Writing – review & editing. **Constantinos F. Panagiotou:** Conceptualization, Investigation, Methodology, Software, Validation, Writing – review & editing. **Anika Conrad:** Conceptualization, Investigation, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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