



MARCLAIMED

Co-creation report V1

Deliverable 3.2

WP3

**Author: Nouredine
Bouzidi. C. Dionisio Pérez-**



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RESPONSIBLE AUTHOR	Noureddine Bouzidi, C. Dionisio Pérez-Blanco		
CONTRIBUTIONS FROM	Sayed Mohammad Nazim Uddin		
ABSTRACT	The deliverable 3.2, Co-creation Report V1, methodologically guides and documents processes in which stakeholders actively contribute to developing and refining Alternative Water Resources (AWR) strategies (T3.2). This deliverable establishes a co-creation framework to facilitate knowledge exchange between stakeholders and scientists, enhance adaptive capacity, and foster collaborative experimentation. It outlines key processes, including co-designing scenarios, developing AWR strategies, refining models, and evaluating outcomes, to ensure solutions are context-specific, scientifically robust, and widely accepted. The report underscores the importance of structured collaboration to address local water challenges and achieve sustainable resource management.		

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EXECUTIVE SUMMARY

The MARCLAIMED project emphasizes the importance of a co-creation approach in developing sustainable Alternative Water Resources strategies. Co-creation refers to the collaborative development of solutions involving all relevant stakeholders, ensuring that their perspectives and expertise contribute to the final outcome. This approach involves stakeholders, including policymakers, researchers, local communities, and industry representatives, in every phase of designing, developing, and evaluating Managed Aquifer Recharge (MAR) and Alternative Water Resources (AWR) strategies. The co-creation process at three demo sites—Llobregat (Spain), Comporta (Portugal), and Waddenregio (Netherlands)—ensures that the strategies are tailored to the diverse conditions of each region, thereby enhancing the overall success of the project by addressing varied challenges such as water scarcity, pollution vulnerability, and saline intrusion.

The co-creation framework is structured into five main stages. First, it involves co-designing scenarios and co-designing AWR strategies to create context-specific approaches. Then, it includes co-developing models, co-evaluating results, and co-identifying resilient AWR strategies to ensure the effectiveness and adaptability of the solutions. Stakeholders actively participate in developing climate and socio-economic scenarios, designing AWR strategies, testing and refining tools, evaluating outcomes, and determining the most resilient strategies. This collaborative approach not only enhances the quality of the strategies but also ensures their acceptance and effectiveness, building trust and stakeholder ownership of the solutions.

The current situation in each demo site provides the baseline for these strategies. This baseline includes specific metrics such as water management and governance, pollution levels, stakeholder roles, regulatory conditions, and socio-economic factors. These metrics help define the starting point from which improvements are measured. In Llobregat, challenges include water scarcity, pollution vulnerability, and public resistance to the use of treated wastewater for MAR. In Comporta, frequent droughts, regulatory gaps, and financial barriers complicate the adoption of MAR and AWR. The Waddenregio site faces issues related to saline intrusion, water scarcity for agriculture, and the need for effective water retention methods. These challenges set the baseline scenario, highlighting the necessity of co-created solutions that balance environmental, social, and economic considerations.

1.0 Introduction

Water scarcity represents a significant challenge impacting numerous regions and nations globally (Kummu et al., 2016). The exacerbation of this issue is largely attributed to climate change and increasing water demand driven by socio-economic transformations (Zeeuw, 2024). The MARCLAIMED project addresses these challenges through the implementation of Managed Aquifer Recharge (MAR) and the utilization of Alternative Water Resources (AWR). MAR involves the deliberate enhancement of groundwater storage, with additional benefits including improved water quality and increased resilience against drought conditions. Techniques for MAR encompass methods such as infiltration ponds and injection wells (Hiscock et al., 2024). By replenishing groundwater resources, MAR ensures a more reliable water supply during periods of hydrological stress (Hiscock et al., 2024; Sitek et al., 2023). In parallel, AWR leverages non-conventional water sources—such as reclaimed wastewater, treated effluents, and agricultural drainage—for integration into MAR within the MARCLAIMED framework. The synergistic use of AWR and MAR enhances water availability, fortifying water systems against the pressures of scarcity and the adverse effects of climate variability (Birol et al., 2010; Hiscock et al., 2024).

The implementation of Managed Aquifer Recharge (MAR) and Alternative Water Resources (AWR) presents numerous challenges, necessitating rigorous technical, social, and economic considerations. A primary concern involves maintaining the quality of reclaimed and treated water to meet stringent regulatory standards, thereby minimizing the risk of groundwater contamination (Zheng et al., 2023). Public acceptance represents another significant barrier, as various stakeholders' express reservations regarding the use of reclaimed and treated water for aquifer recharge (Fielding et al., 2019; Verhoest et al., 2022). Therefore, fostering trust through transparent communication and dissemination of scientific evidence on the safety and benefits of MAR and AWR is crucial (Fielding et al., 2015). Moreover, MAR and AWR systems necessitate advanced technical capabilities, encompassing the design, construction, and maintenance of infrastructure such as infiltration ponds, injection wells, and water treatment facilities, which inherently require substantial financial investment (Zheng et al., 2023). Additionally, demonstrating the economic feasibility of MAR and AWR, both in present contexts and future climate scenarios, is complex and demands comprehensive economic analysis and long-term strategic planning (Birol et al., 2010).

The MARCLAIMED project endeavors to integrate Managed Aquifer Recharge (MAR) and Alternative Water Resources (AWR) into comprehensive river basin and drought management frameworks. This integration necessitates extensive data collection,

encompassing hydrogeological assessments to characterize aquifer dynamics, rigorous water quality monitoring to ensure compliance with safety standards, detailed water usage statistics, and climate projections to anticipate future variability in water availability. Engaging a broad spectrum of stakeholders is fundamental, including policymakers, direct beneficiaries, the public, academics, civil society organizations, and end-users such as agricultural producers and industrial sectors reliant on water resources. These stakeholders play a critical role in the co-design, co-development, and co-evaluation of AWR strategies within the MARCLAIMED initiative, fostering a collaborative approach to optimizing water resource management.

2.0 Co-creation Framework

The co-creation processes at the three MARCLAIMED demo sites, as delineated in Task 3.2 (Co-creation of Alternative Water Resource strategies), are designed to yield well-defined outcomes through a comprehensive and inclusive approach to addressing water management challenges. Stakeholders at these sites—including governmental bodies, local communities, industrial actors, environmental organizations, and end-users—collaborate closely with MARCLAIMED partners, bringing a wide array of perspectives and specialized knowledge to the process. Their active engagement in structured, iterative activities aims to enhance both the resilience and feasibility of the proposed strategies, thereby ensuring the sustainability and robustness of water resource management solutions.

The co-creation process is structured through five key steps: 1) constructing climate and socioeconomic scenarios that capture the status of AWR in the regions of study and potential future scenarios (used for modeling in Tasks 1.1-6). This involves the development of qualitative and quantitative scenarios that consider variables such as climate projections, demographic changes, economic growth trajectories, and land use dynamics, ensuring that a holistic view of future conditions is incorporated into the decision-making framework. Stakeholders are involved in scenario development workshops to provide local insights and validate assumptions, making the scenarios as contextually relevant as possible; 2) developing AWR strategies for these sites, encompassing financial planning, technical feasibility assessments, and partnerships to ensure their economic viability, with a specific focus on investments in MAR utilizing AWR (used for modeling in Tasks 1.1-6). This step integrates considerations related to resource allocation, governance structures, and long-term financial sustainability to ensure that AWR strategies could be effectively implemented; 3) co-developing the MARCLAIMED project tools to ensure alignment with the specific needs

of stakeholders, designed scenarios, and strategies (used for Tasks 1.1-6 and Task 2.1, and indirectly for all of Work Package 2). This includes iterative testing and refinement of tools to enhance their usability and relevance, informed by direct input from stakeholders who provide feedback on both the technical aspects and practical applications; 4) evaluating AWR strategies by employing modeling outcomes, stakeholder feedback, and logical analysis to assess their efficacy, including identifying strengths and weaknesses (based on results from Work Package 1 and stakeholder feedback to enhance model quality). This evaluation is multifaceted, combining quantitative model results with qualitative assessments from stakeholders to ensure a balanced view of each strategy's effectiveness, adaptability, and potential trade-offs; and 5) determining the AWR strategies that most effectively enhance the resilience of water systems against climate change. This final step involves synthesizing the findings from the evaluations to identify the strategies that offer the greatest potential for achieving resilience objectives while balancing social, economic, and environmental considerations.

Continuous engagement between stakeholders and MARCLAIMED partners facilitates the exchange of specialized knowledge, consensus-building, and informed decision-making processes (Figure 01). This collaborative approach enhances the quality and contextual relevance of the strategies developed, while also fostering stakeholder ownership and capacity-building, both of which are critical for the successful implementation and long-term sustainability of the project initiatives.

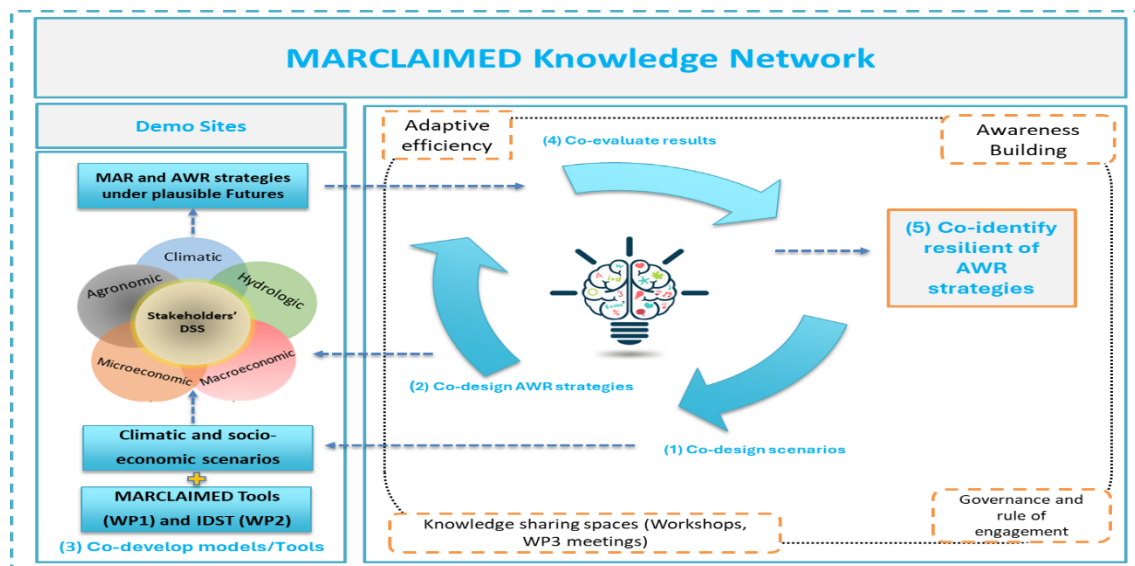


Figure 1: MARCLAIMED iterative 'stock-taking' co-creation process

2.1. Co-design scenarios

Scenario development plays a crucial role in the MARCLAIMED project, particularly in facilitating stakeholder engagement and guiding the development of project tools. These scenarios encompass potential future conditions, including climatic, socioeconomic, and technological changes that could affect the regions under study. By constructing these scenarios, the project adopts a systematic approach to anticipate and adapt to future shifts, while actively involving stakeholders to ensure that their perspectives are integrated into the decision-making process.

Key components include:

- **Climate:** Climate is a fundamental determinant of water resources. Climate scenarios serve as essential inputs for modeling and tool development, either directly or through comparisons with studies such as CMIP6 or ISIMIP. These scenarios include projections of temperature, precipitation, extreme weather events, and other climatic factors that could significantly affect water availability, quality, and demand.
- **External Economic and Technological Factors:** External drivers play a pivotal role in shaping regional development trajectories, presenting both challenges and opportunities. Key factors such as global economic trends, technological advancements, market dynamics, and regulatory changes significantly influence the broader context of water resource management. A comprehensive assessment of these elements allows for a more nuanced understanding of potential pressures and opportunities that may arise, thereby enabling more informed and adaptive management strategies.
- **Local Economic and Technological Innovation:** This approach underscores the importance of local solutions and innovations that foster regional adaptation and sustainable growth. By concentrating on localized economic activities, technological advancements, and social innovations, stakeholders can develop strategies tailored to the unique needs and challenges of each region. Examples of such strategies include the implementation of advanced water-saving technologies, optimization of irrigation efficiency, community-driven water management initiatives, and policy frameworks that promote sustainable water use at the local level.

The MARCLAIMED demo sites are designed to develop scenarios that are both accessible and intellectually engaging for all partners, including a diverse array of stakeholders. This is achieved by employing clear, precise language, visual storytelling techniques, interactive elements, and context-specific examples to foster comprehensive understanding and active engagement. These scenarios are communicated through a combination of narratives, visual aids, and innovative tools, such as mock press releases, during workshops and other stakeholder activities. Narratives serve to provide a cohesive storyline that contextualizes

the data, making it more relatable, while visual aids—such as charts, diagrams, and infographics—distill complex information into more comprehensible formats. Mock press releases, on the other hand, present key information in a familiar and accessible manner, enhancing stakeholder involvement by highlighting essential points. The primary objective is to render complex data, including hydrological models, socioeconomic forecasts, and climate projections, in a manner that is both transparent and relevant, thereby enabling stakeholders to grasp the potential implications of various future scenarios. These scenarios encompass major trends, key drivers, and transformative changes affecting factors such as population growth, urbanization, economic development, and land use dynamics.

To enhance the efficacy of scenario development, we propose employing the Intergovernmental Panel on Climate Change (IPCC)'s five Shared Socioeconomic Pathways (SSPs). These SSPs represent diverse future socio-economic conditions that influence greenhouse gas emissions and climate change impacts, and they will be adapted to the specific context of the MARCLAIMED demo sites. The SSPs are advantageous because they encompass critical climate variables, such as temperature increases, changes in precipitation patterns, and the occurrence of extreme weather events, as well as socio-economic factors, including GDP growth, income distribution, and technological advancement—all of which are pivotal for evaluating water resilience.

By customizing these SSPs, the scenarios will reflect both global trends and site-specific local and regional dynamics, including groundwater availability, land use practices, governance structures, and socio-economic inequalities. This approach will provide an in-depth analysis of the unique challenges and opportunities faced by each demo site. Moreover, these scenarios will address key water-related issues, such as severe droughts, flooding, pollution risks, and water scarcity, and will evaluate how these challenges may be mitigated or exacerbated by targeted investments or interventions, such as advanced water management technologies or conservation-oriented policies.

These scenarios will lay the groundwork for building the hydrological and socio-economic modeling framework and act as a starting reference. They will be refined iteratively with crucial stakeholder input—such as feedback from local water management authorities, community representatives, and agricultural stakeholders—and preliminary modeling results, including hydrological simulations and socio-economic impact assessments, ensuring they stay dynamic and adaptable to new data. By incorporating climate, socioeconomic, and technological factors into scenario planning, the MARCLAIMED project aims to create a solid foundation for water management strategies. These strategies are designed to be resilient, adaptable, and suited to each demo site's unique needs.

2.2. Co-design AWR strategies

This step focuses on co-developing Alternative Water Resources (AWR) strategies to achieve project goals. Scientists, tool developers, and stakeholders in the Community of Practice (CoP) will work together. Their collaboration will focus on creating actions addressing current water challenges and climate adaptation. This collaboration combines scientific expertise with local insights, such as traditional knowledge and community needs, to handle the complexities of water management. Strategies will be tested at demo sites with stakeholder involvement, allowing stakeholders to provide iterative feedback and actively participate in the refinement process, which is key to improving the solutions' practicality and effectiveness.

While AWR is often highlighted in policy and academic discussions, its practical implementation faces challenges like regulatory barriers (e.g., stringent permitting requirements and complex compliance processes), financial constraints (e.g., high capital costs for infrastructure and limited funding opportunities), and varying stakeholder engagement levels. One AWR strategy is reclaimed water, or treated wastewater, which can be used for agriculture (e.g., providing a reliable water source during droughts but requiring careful management to avoid soil salinity), landscaping (e.g., reducing the use of potable water for irrigation but facing public acceptance challenges), industry (e.g., offering cost savings for non-potable uses but requiring consistent quality control), or aquifer recharge (e.g., enhancing groundwater levels but needing rigorous water quality monitoring to prevent contamination). This approach aims to reduce freshwater demand and pollution. However, broad adoption requires attention to water quality standards and infrastructure needs. Additionally, public perception and economic viability must be addressed to ensure successful implementation. Early stakeholder engagement in the co-design process helps identify obstacles and collaboratively develop solutions acceptable to all parties. These stakeholders include local government authorities, community representatives, agricultural producers, industry partners, and environmental organizations, each contributing their expertise, concerns, and local knowledge to shape effective and inclusive solutions.

The co-design process comprises three principal steps:

1. **Identifying and Describing Strategies:** The MARCLAIMED team will brainstorm, conduct a comprehensive literature review, and gather stakeholder insights during workshops to identify potential strategies. This step involves an in-depth exploration of existing AWR practices, emerging technologies, and innovative approaches that could be applied to the demo sites. Stakeholder workshops will serve as platforms for sharing local knowledge, identifying specific needs, and discussing the feasibility of different options. The aim is to compile a diverse list of strategies that reflect both technical possibilities and local preferences.
2. **Selecting Strategies:** Identified strategies will be deliberated in workshops or smaller meetings to reach a consensus, or if necessary, through voting. The selection process will consider multiple criteria, including technical feasibility, cost-effectiveness,

environmental impact, and social acceptance. Stakeholders will play a pivotal role in evaluating each strategy's potential benefits and drawbacks, ensuring that the chosen strategies align with the community's values and priorities. The aim is to evaluate a range of strategies comprehensively before finalizing decisions, using decision-support tools, such as multi-criteria analysis, to facilitate transparent and inclusive decision-making.

3. Integrating Strategies: This step involves integrating the selected strategies and assessing their performance within broader scenarios. Visualization tools, such as charts, graphs, and scenario simulations, can facilitate comparisons of different strategies and their outcomes under various future conditions. By considering multiple scenarios—such as changes in climate patterns, population growth, and economic development—the MARCLAIMED team and stakeholders can better understand the resilience and adaptability of the selected strategies. This integration process also involves testing the strategies using models developed in other work packages to validate their effectiveness and identify potential areas for improvement.

Another crucial aspect is stakeholder mapping. Identifying stakeholders relevant to each strategy is vital for fostering connections and leveraging relationships within the system. Effective stakeholder mapping allows the MARCLAIMED team to understand the roles, interests, and influences of different actors involved in water management. These stakeholders include:

- Government Entities: Authorities responsible for formulating policies, setting regulations, and providing institutional support. Their role is critical for ensuring that the strategies developed are compliant with regulatory frameworks and are supported by enabling policies.
- Water Users: Including farmers, households, and industries that directly depend on water resources. Their participation is essential for understanding practical challenges, usage patterns, and potential benefits of AWR strategies.
- Third-Party Actors: Such as consultants, financial institutions, and insurance companies, who can provide technical expertise, financial resources, and risk management solutions. These actors can help address barriers related to funding and implementation.
- Group Organizations: Existing or newly formed collective entities, such as water user associations, community groups, and non-governmental organizations, which can facilitate community engagement, capacity building, and collective action.

The use of multiple timeframes, such as short-term, medium-term, and long-term, allows strategies to be modified or introduced over time through the Dynamic Adaptation Policy Pathways (DAPP) Framework. This approach enables adaptive planning that evolves with new information, such as updated climate data or technological advancements, and changing conditions, such as socio-economic shifts or policy changes. By building flexibility

into water management strategies, the MARCLAIMED project aims to ensure their effectiveness across various future scenarios, such as different climate conditions, economic trends, or policy changes. It also identifies "tipping points," such as reaching critical groundwater depletion levels or encountering unmanageable flood risks, where a strategy may no longer be viable, signaling the need for adjustments or alternative approaches. Such adaptive planning is essential to manage uncertainties from climate change, economic shifts, and social dynamics, helping stakeholders navigate complexity and make decisions that support long-term resilience.

2.3. Co-develop models

Through co-development, stakeholders at the demo sites, including local government, farmers, and community representatives, will play a key role in refining the tools created in Work Package 1, which will be integrated into the Integrated Decision Support Tool (IDST) in Work Package 2. This collaborative process ensures that the tools are not only technically sound but also relevant to each demo site's specific needs and conditions, such as local hydrological characteristics, socio-economic factors, and regulatory requirements. The goal is to adapt these tools, previously validated in other settings, such as agricultural water management projects in Southern Spain, to make them applicable, effective, and timely for the MARCLAIMED project. By engaging stakeholders directly in the development, the tools will more accurately reflect real-world conditions and practical challenges in water management, such as water scarcity, regulatory requirements, and community acceptance.

Stakeholders—including local government representatives, water user associations, and industry experts—will help identify key factors, such as water demand variability and infrastructure limitations, and knowledge gaps, such as insufficient data on groundwater recharge rates, in the models, strengthening their robustness across different future scenarios. This participatory approach is essential for capturing the full range of variables and conditions that could impact model performance, such as hydrological variability, economic shifts, and changes in land use. Co-development will involve iterative testing, uncovering tool deficiencies through practical use. This process will include adjusting enhanced functionality. Stakeholders will contribute valuable insights on local practices, such as traditional irrigation techniques, regulatory constraints, such as water use permits and quality standards, and socio-economic factors, all crucial for refining these tools.

Additionally, stakeholder mapping will help identify the right experts and participants for model development, based on criteria such as expertise in hydrology, local knowledge, or policy experience. This mapping will not only highlight key individuals and organizations but also encourage collaboration by connecting stakeholders with complementary expertise, such as local farmers and water quality scientists. The MARCLAIMED project aims to leverage the collective intelligence of the stakeholder community. This ensures that the tools are comprehensive, user-friendly, and effective for sustainable water management decision-

making. Ultimately, this co-development process will foster a sense of ownership among stakeholders through workshops, feedback sessions, and shared decision-making, increasing the chances of successful implementation and long-term use of the tools.

2.4. Co-evaluate results

The evaluation of AWR strategies under future scenarios will employ two main approaches:

- **Joint Evaluation with Stakeholders:** Workshops or surveys will be organized to collect stakeholder feedback, ensuring that local insights and perspectives from stakeholders such as local government, community groups, and industry representatives are fully incorporated into the evaluation. Techniques like weighting, ranking, and multi-criteria analysis will help manage complex scenarios and guide discussions. For example, weighting involves assigning importance to different factors based on stakeholder priorities, while multi-criteria analysis helps evaluate options by considering multiple aspects such as cost, sustainability, and social impact. Stakeholder involvement in the evaluation phase is key for understanding practical challenges. It also helps build support for specific strategies and fosters shared ownership. This collaborative process also enables stakeholders to contribute their experiential knowledge, such as insights into local water use practices and historical climate impacts, adding valuable context for assessing the feasibility and impact of each strategy.
- **Modeling Tools:** The MARCLAIMED team will use specific modeling tools to assess strategies, combining hydrological and economic models to forecast outcomes of different Alternative Water Resources (AWR) strategies across future scenarios. These tools will generate quantitative data to evaluate each strategy's technical performance (e.g., reliability, efficiency, and scalability), economic feasibility (e.g., cost-benefit analysis, return on investment, and affordability), and environmental sustainability (e.g., impact on biodiversity, carbon footprint, and resource conservation). Models will be refined iteratively using stakeholder feedback, such as insights on operational challenges and local water usage, and real-world data to ensure accuracy and relevance to each demo site's context. By simulating multiple scenarios, the models will help identify potential risks, trade-offs, and synergies for each strategy. For example, a trade-off might involve increased water supply at the cost of higher energy consumption, while a synergy could be the simultaneous improvement of water quality and agricultural yield.

Performance indicators will be co-developed with stakeholders, in alignment with the principles of Integrated Water Resources Management (IWRM), to ensure a comprehensive evaluation framework. These indicators will help measure the effectiveness, sustainability, and equity of the strategies being assessed. Key performance indicators include:

- **Water and Ecological Indicators:** Status of aquifers and conditions of water bodies. These indicators will provide insights into the environmental impacts of the strategies, such as

changes in water quality, recharge rates, and ecosystem health. By assessing these factors, stakeholders can determine whether the strategies contribute positively to the sustainability of water resources and overall ecological integrity.

- **Economic Indicators:** Revenue generation, income distribution, and the costs associated with implementing strategies. Economic indicators will help evaluate the financial feasibility of AWR strategies, including their potential to generate income for local communities, reduce costs associated with water scarcity, and promote economic resilience. These indicators will also consider the distributional impacts of the strategies, ensuring that economic benefits are equitably shared among different groups.

- **Social Indicators:** Inequalities, with an emphasis on how indicators change over time and across locations. Social indicators will assess the impact of AWR strategies on vulnerable populations, equity in water access, and social cohesion. Understanding the social dimensions of water management is crucial for ensuring that the strategies do not exacerbate existing inequalities but instead contribute to social well-being and community resilience. Indicators such as changes in access to water, public health outcomes, and community satisfaction will be used to capture these impacts.

- **Innovation Factors:** Elements that facilitate or hinder innovation, which are pivotal for improving strategies. These factors include the adoption of new technologies, the willingness of stakeholders to embrace change, and the availability of resources to support innovative practices. Evaluating innovation factors will help identify opportunities for enhancing the adaptability and effectiveness of AWR strategies, ensuring that they remain relevant in the face of changing conditions.

Stakeholders will be informed of uncertainties through modeling, with clear communication about the limitations of the models and the range of possible outcomes. This transparency is crucial for building trust and helping stakeholders understand the inherent uncertainties involved in long-term water management planning. Evaluating trade-offs among different strategies will facilitate an understanding of their strengths, weaknesses, and areas requiring adjustments. By highlighting the potential benefits and drawbacks of each strategy, stakeholders will be better equipped to make informed decisions that balance environmental, economic, and social objectives. This process aims to ensure that the selected AWR strategies are resilient, sustainable, and well-suited to the specific challenges faced by each demo site.

2.5. Co-identify resilient AWR strategies

The MARCLAIMED project supports stakeholders in identifying a resilient adaptation strategy at each demo site that aligns with Integrated Water Resources Management (IWRM) goals, such as equitable water allocation, improving water quality, and enhancing water use efficiency. MARCLAIMED is an advisory project, not a decision-maker, as these

responsibilities lie with local governments, regulatory agencies, and other relevant authorities beyond the project's scope. However, by assessing the impacts of various strategies across scenarios, MARCLAIMED provides critical mechanistic insights needed for resilient decision-making. These insights include detailed evaluations of hydrological parameters, socio-economic parameters, and environmental parameters, capturing the complexity of adaptation strategies. Effective stakeholder engagement is essential, ensuring that proposed strategies are scientifically robust, socially acceptable, and economically viable.

Resilience in water resources management refers to the capacity of water systems to absorb disturbances while maintaining their fundamental functions and structure. It encompasses preparedness for, response to, and recovery from water-related crises, such as droughts, floods, pollution, and the impacts of climate change, in a manner that ensures water security, protects ecosystems, and supports sustainable development. Achieving resilience involves not only addressing the immediate impacts of such crises but also building adaptive capacities to mitigate future risks, thereby enhancing the overall robustness of water systems. A resilient water resources management strategy emphasizes risk anticipation, impact absorption, and adaptation to and recovery from water-related challenges. This requires a comprehensive understanding of water systems, including the hydrological cycle, the dynamics of water demand and supply, and the socio-economic contexts within which water management operates. Moreover, it involves a recognition of the interconnectedness between water systems and other critical sectors, such as agriculture, energy, and urban development. Such interconnectedness necessitates a multidisciplinary approach that brings together hydrology, engineering, economics, policy analysis, and social sciences to craft effective solutions. Stakeholder engagement is also a key component, as resilience cannot be achieved without the involvement of all relevant parties, including policymakers, local communities, and industry stakeholders. Resilience-building measures might include infrastructural investments to enhance water storage and distribution, the development of early warning systems for extreme events, and the implementation of policies that promote efficient water use and equitable allocation. Such strategies are essential for developing water systems that are robust yet flexible, capable of withstanding shocks without causing long-term detriment to water availability or quality.

Implementing a resilient water management strategy necessitates a holistic approach that integrates environmental, economic, and social factors. Such an approach requires careful consideration of the interactions between natural ecosystems, human activities, and economic systems. It is an iterative process that involves continuous learning, monitoring, and adaptation to emerging challenges and opportunities. This iterative nature is essential for adjusting to the evolving conditions brought about by climate change, population growth, and shifting socio-economic dynamics. By fostering resilience in water management, societies can ensure the long-term availability of clean water, maintain healthy ecosystems, and support sustainable development. This includes not only securing water for human consumption but also ensuring adequate water availability for agricultural

activities, industrial processes, and the maintenance of biodiversity. Furthermore, resilient water management strategies must prioritize equitable access, recognizing the diverse needs of different communities and sectors, thereby promoting social equity and reducing vulnerabilities. By integrating advanced technologies, such as remote sensing and data analytics, and enhancing institutional capacities, water management systems can become more proactive in anticipating and mitigating potential risks. Ultimately, resilience-building in water management helps to create a more adaptable and robust system capable of withstanding both gradual changes and sudden shocks.

3.0 Llobregat demo site

The Spanish demo site is located in the Mediterranean coastal aquifer region of Barcelona, northwest Spain, due to its critical issues with water scarcity, pollution vulnerability, and its strategic importance in demonstrating MAR solutions in a heavily urbanized and industrialized area. This site uses a combined Managed Aquifer Recharge (MAR) approach, integrating Aquifer Storage Transfer and Recovery (ASTR), which involves moving water between different aquifers to improve quality before recovery, with Aquifer Storage and Recovery (ASR), which stores water in the same aquifer for later use. The main goal is to improve groundwater availability and quality to tackle the region's severe water scarcity issues. The MAR system uses reclaimed water infiltrated through ponds and a mix of surface and reclaimed water injected via deep wells. Using reclaimed water provides benefits such as reducing pressure on freshwater resources and promoting sustainability, but it also presents challenges, including the need for advanced treatment to meet quality standards and addressing public perception issues. Barcelona's Mediterranean climate, marked by recurrent droughts, exacerbates the water scarcity by reducing natural aquifer recharge rates and increasing the demand for limited groundwater resources. The Baix Llobregat aquifer, the area's main water source, is highly vulnerable to pollution from industrial and agricultural activities. This demo site was chosen to address these challenges by optimizing groundwater through MAR, reducing dependency on surface sources like the Ter River. The innovative MAR application aims to model sustainable water management for similar regions, such as the coastal aquifers in southern Italy, offering insights into enhancing water security, boosting groundwater availability, and building resilience against scarcity and climate variability.

The infrastructure at the Sant Vicenç dels Horts (SVH) MAR system includes infiltration ponds, injection wells, water treatment plants, and monitoring systems that track water quality, recharge rates, and piezometric levels, ensuring the effectiveness and safety of MAR activities. The main components of the MAR system are:

- **Infiltration Pond:** Capable of handling 3900 m³/day, used to enhance groundwater infiltration.
- **Injection Well:** Injection capacity of 1340 m³/day for a combination of water sources, including surface and reclaimed water.

- **Water Treatment Plants:** Sant Joan Despí Drinking Water Treatment Plant and El Prat Water Reclamation Plant, which provide treated water suitable for recharge.
- **Monitoring Systems:** Equipped to track water quality, recharge rates, and piezometric levels.

The available data at the demo site includes historical hydrogeological data, water quality data, climatic data, and usage data provided by stakeholders. This data has been shared with tool developers and will serve as essential inputs for all MARCLAIMED tools. Additionally, new datasets will be generated during the project to further enhance understanding and management capabilities.

Efforts are also underway to optimize the management of aquifer recharge with the highest possible efficiency. This involves a comprehensive approach that considers various factors such as water availability, optimal timing for recharge operations, and prioritization strategies based on diverse water demands. This ongoing research aims to establish best practices for sustainable aquifer management, ensuring long-term water security while balancing environmental and economic considerations.

The demo site ultimately aims to showcase how integrated approaches to water management, combined with stakeholder engagement and advanced technology, can effectively address the growing challenges of water scarcity in Mediterranean regions.

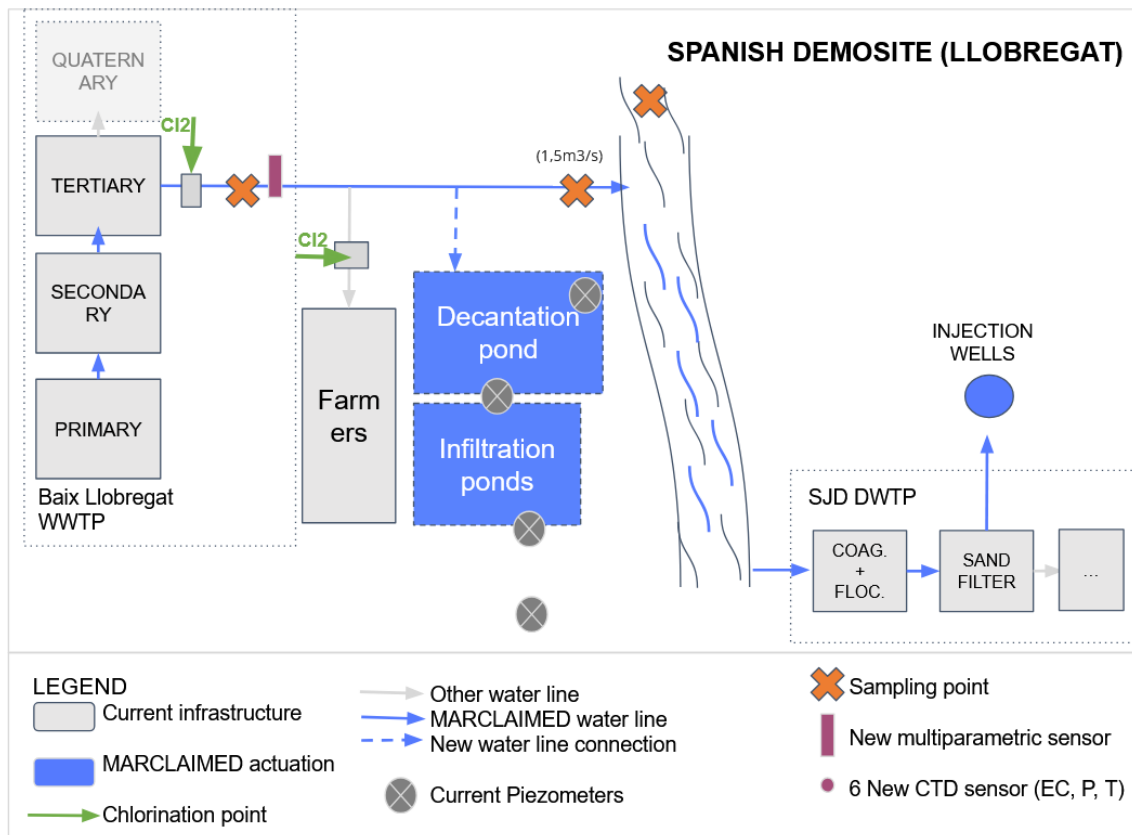


Figure 2: DS1 infrastructure (SVH infiltration ponds) diagram



Figure 3: DS1 infrastructure (P18 deep injection MAR system)

3.1. Water Resource Management and Adaptation

Quantitative and Qualitative Status of Water Bodies

The Llobregat River and its associated groundwater bodies are in poor condition. The "Llobregat River from SJD" surface water body and the "Vall Baixa i Delta del Llobregat" groundwater body (MAS39) are both classified in poor condition due to pollutants such as phosphates, ammonia, chlorides, nitrates, and sulfates. The increasing trend of saline intrusion further deteriorates the groundwater quality, particularly in the delta region, highlighting the need for measures to improve water quality and prevent further degradation.

Main Water User Sectors

The dominant water user in the Llobregat basin is urban supply, accounting for 66% of water use. Agricultural irrigation represents 27%, and industrial use accounts for 5%, while other uses, such as hydroelectric generation and aquaculture, make up 2%. The prioritization of

urban supply reflects the high population density in the region, placing pressure on available water resources and necessitating efficient allocation to balance urban and agricultural needs.

Impact of Climate Change

Climate change is projected to increase water demand in the Llobregat basin by approximately 1.1% by 2027 and up to 8% by 2039. Precipitation patterns are expected to become more variable, with significant reductions during summer months, particularly in coastal areas where reductions could reach 40%. These changes will reduce groundwater recharge and increase the number of water bodies with negative water balances. Such trends underscore the importance of implementing adaptive measures to ensure the sustainability of water resources in the face of growing demand and changing climatic conditions.

Water Rights and Regulation

Water resources in Catalonia are considered public hydraulic domains under Legislative Decree 3/2003. An administrative concession from the Catalan Water Agency is required for extracting both surface and groundwater. Concessions are issued for a maximum term of 75 years for public supply and 25 years for other uses. Priority is given to drinking water supply, followed by irrigation and industrial uses. Water rights are non-transferable, except in exceptional cases authorized by the Catalan Water Agency, emphasizing the public ownership and controlled management of water resources.

The regulatory framework for AWR in Spain is based on several legal texts. Key among these are the Texto Refundido de la Ley de Aguas (Real Decreto Legislativo 1/2001), consolidating water legislation; the Reglamento de la Planificación Hidrológica (Real Decreto 907/2007), guiding hydrological planning; and the Instrucción de Planificación Hidrológica (Orden ARM/2656/2008), offering methodological directives.

MAR with AWR requires approval from the river basin authority, which includes assessing the basin's hydrological balance, recharge water quality, and aquifer compatibility. A hydrogeological research that includes flow modeling, soil infiltration analysis, and the assessment of aquifer parameters such as hydraulic conductivity and transmissivity is essential for this process. Article 245.1 of the RDPH, Orden ARM/2656/2008, and articles 100 and later sections of the TRLA all regulate wastewater management. While Real Decreto 1514/2009 concentrates on groundwater protection, stressing pollution prevention, Real Decreto 1085/2024 governs water reuse within more comprehensive regulatory frameworks.

A monitoring plan is crucial, involving piezometric tracking, water quality assessments, and ecosystem impact evaluations. Compliance with Law 21/2013 mandates an Environmental Impact Assessment (EIA) to identify and mitigate adverse effects. Additional regulations

apply in protected areas like Natura 2000, requiring strict safeguards. A risk management plan is essential to prevent aquifer contamination and quality changes, ensuring MAR systems' sustainability within Spain's water management framework.

Managed Aquifer Recharge (MAR)

Several MAR systems are operational in the Llobregat region, such as the hydraulic barrier in the Delta del Llobregat and infiltration ponds at Molins de Rei. These systems use reclaimed water for recharge, aiming to address saline intrusion and enhance water availability. The integration of MAR into existing water management practices helps mitigate the impact of saline intrusion, particularly in coastal areas, and supports water supply resilience. The hydraulic barrier and other MAR initiatives contribute significantly to improving groundwater conditions and preventing further salinization.

Alternative Water Resources (AWR)

Reclaimed water is extensively used for MAR in the Llobregat region, including for recharging the Llobregat River. The region has also established monitoring and control plans as part of recharge permits issued by the Catalan Water Agency. The use of reclaimed water for MAR helps to reduce pressure on conventional water sources, particularly during periods of high demand or drought. However, concerns over groundwater quality and health risks pose challenges to the widespread adoption of AWR for recharge purposes, requiring robust monitoring and public engagement.

Economic Instruments

Water tariffs in Catalonia vary by municipality, while a regional water fee applies uniformly across the territory. Municipalities determine tariffs based on infrastructure costs, population density, and other local factors. The regional water fee serves as a specific income for the Catalan Water Agency, supporting its activities in managing and protecting water resources. Social tariffs are available to economically vulnerable groups, ensuring access to affordable water services. The differentiation between municipal and regional fees highlights the complexity of water pricing structures, which aim to balance cost recovery with equitable access.

Monitoring and Enforcement

The Catalan Water Agency provides open access to monitoring data for both surface and groundwater quality and quantity. This data is made available through a set of consultation applications to encourage transparency and public awareness. Unauthorized discharges are reported to the Agency, and sanctions are applied to ensure compliance. Monitoring relies on existing networks and technologies, which provide crucial information for managing water resources, assessing environmental impacts, and enforcing regulations. The

emphasis on transparency and public accessibility to data supports effective water management and stakeholder involvement.

3.2. Mapping of Actors, Roles and Power relations

Table 1: Overview of key stakeholders in Llobregat demo site and their role and influence

Key Stakeholder	Role	Power/Influence
Catalan Water Agency (ACA)	Regional water authority managing planning, quality, and supply	Regulatory power over water resources, compliance with Water Framework Directive
Metropolitan Area of Barcelona (AMB)	Manages urban water cycle and flood prevention in metropolitan areas	Administrative and operational power in urban water infrastructure management
Public Health Agency of Catalonia (ASPCAT)	Ensures water quality for public health	Regulatory power over water quality and health standards
City Councils	Local water management and infrastructure maintenance	Local administrative power in water policies and infrastructure
Associació Catalana de Comunitats de Regants (ACATCOR)	Advocates for efficient agricultural water use	Influence over irrigation practices and water allocation
University of Barcelona (UB) & UPC	Research and innovation in sustainable water management	Knowledge creation and technical innovation in MAR and water treatment
Consorci del Delta del Llobregat	Environmental conservation and habitat restoration	Power over environmental conservation and biodiversity protection
Grup de Recerca en Ciència i Tecnologia de la Sostenibilitat (UPC)	Research in sustainability, including MAR technologies	Influence through research and knowledge dissemination
CUADLL	Manages surface and groundwater distribution, recharging basins	Operational power in local water management and aquifer recharge

Irrigation Communities	Manages water rights for agricultural irrigation	Operational power over irrigation water distribution
Water Utilities (Aqualia, Sorea)	Operate water services for catchment, treatment, and distribution	Operational power over water supply systems and MAR investments
Catalan Water Partnership	Facilitates cooperation and innovation in the water sector	Networking power among companies, research centers, and public institutions
Companies (Damm, Cementos Molins)	Large industrial water users	Economic power and participation in MAR projects to offset water usage
Agrupacions de Defensa Vegetal (ADV)	Promotes sustainable agricultural practices	Influence in reducing water consumption and enhancing soil moisture retention
Water-related Civil Society Organizations	Advocacy for water conservation and sustainability	Advocacy power influencing public policy and awareness
Workers (CUADLL, Aigües de Barcelona)	Direct involvement in water management projects	Influence through operational expertise and labor representation
Meteorological Service of Catalonia (METEOCAT)	Provides climate and weather data for water management planning	Influence through climate data for drought forecasting and flood risk management

In Llobregat, the Catalan Water Agency (ACA) acts as the regional authority responsible for managing water planning, quality, and supply. ACA ensures compliance with the Water Framework Directive and holds significant regulatory power over water resources in the region. Its responsibilities include monitoring water quality, managing river basins, and implementing water use regulations to ensure sustainable water management. ACA collaborates with other regional and national entities to align water policies with broader environmental and sustainability goals, making it a central authority in water governance in Catalonia.

The Metropolitan Area of Barcelona (AMB) is a key actor in water cycle management and flood prevention across the metropolitan region. It holds both administrative and operational power, overseeing the infrastructure necessary for urban water management, including stormwater systems, wastewater treatment, and potable water supply. AMB works closely with local municipalities to develop strategies that enhance water resilience in urban areas. It plays a proactive role in integrating MAR practices into urban planning to mitigate flooding risks and ensure sustainable water availability for the growing population.

The Public Health Agency of Catalonia (ASPCAT) ensures that the water supply meets public health standards. ASPCAT holds regulatory power related to water quality, ensuring that all water used for human consumption is safe and complies with health regulations. ASPCAT works in tandem with water utilities and local councils to monitor water quality, identify health risks, and respond to emergencies, thereby safeguarding public health.

City Councils in the Llobregat region play a vital role in managing local water security and environmental protection. They hold local administrative power, enabling them to influence community-level water policies and oversee the implementation of water-saving initiatives. Councils are also responsible for maintaining local infrastructure, such as stormwater drains and small-scale irrigation systems, which contribute to effective water management at the grassroots level. They work with stakeholders like ACA and AMB to ensure that water management aligns with local development needs and sustainability goals.

The Associació Catalana de Comunitats de Regants (ACATCOR) is a regional entity that represents irrigators and advocates for efficient water use in agriculture. ACATCOR holds significant influence over irrigation practices and water allocation, ensuring that farmers have access to the water needed for crop production while promoting practices that minimize waste. The association also works on educating farmers about the benefits of MAR and other sustainable water management techniques, thereby supporting broader regional efforts towards water conservation.

The University of Barcelona (UB) and the Universitat Politècnica de Catalunya (UPC) are academic institutions that conduct research and develop innovative solutions for sustainable water management. These universities influence knowledge creation and technical innovation, particularly in the application of MAR techniques and other advanced water treatment methods. Their research projects often involve partnerships with government bodies, water authorities, and private companies, translating scientific findings into practical applications that benefit the region's water management systems.

The Consorci del Delta del Llobregat is an organization dedicated to protecting and managing the natural spaces of the Llobregat Delta. It holds power over environmental conservation and coordinates efforts among local authorities, farmers, and environmental groups to preserve the delta's biodiversity. The consortium is also involved in initiatives aimed at improving water quality and restoring wetlands, which are crucial for maintaining the ecological health of the delta. By working on habitat restoration and sustainable land use, the consortium helps to balance environmental conservation with agricultural and urban demands.

The Grup de Recerca en Ciència i Tecnologia de la Sostenibilitat (UPC) is a leading research organization that advances sustainability through innovative research projects. The group holds considerable influence through its work in knowledge dissemination and collaboration with industry and government stakeholders. Their research on MAR

technologies, climate adaptation, and resource efficiency provides valuable insights that shape water management policies and practices in the region.

The Water Users Community from Llobregat Valley and Delta (CUADLL) is responsible for managing both surface and groundwater distribution, recharging basins, and maintaining water infrastructure. CUADLL holds operational power over local water management, ensuring that water is distributed equitably among users, including farmers, industries, and urban areas. Their efforts to manage recharging basins are critical in preventing aquifer depletion and ensuring the sustainability of water resources in the Llobregat Valley.

Irrigation communities, such as Comunitat de regants de la Palma, manage water rights and are responsible for the operation of local irrigation activities. They hold operational power over the distribution of irrigation water and work to ensure that farmers have reliable access to water for their crops. These communities are also involved in promoting MAR practices to enhance groundwater recharge and maintain water availability during dry periods, thus contributing to the overall resilience of agricultural activities.

Water utilities, including Aqualia and Sorea, are responsible for the operation of water services, encompassing water catchment, treatment, and distribution. They hold operational power over the water supply system and play a critical role in ensuring the reliability and quality of water services for both residential and industrial consumers. These companies invest in MAR technology as part of their efforts to secure future water supplies, improve system resilience, and meet increasing water demand in the metropolitan area.

The Catalan Water Partnership is a non-profit association formed by companies, research centers, and public institutions involved in the water sector. It holds networking power that is crucial for fostering cooperation and promoting innovation within the industry. The partnership facilitates knowledge exchange between different stakeholders, helping to drive the adoption of sustainable practices and new technologies, including MAR, throughout the region.

Companies extracting water from the aquifer, such as Damm and Cementos Molins, are major industrial users that rely on groundwater for their production processes. These companies hold substantial economic power as they contribute significantly to the regional economy. Their activities, however, also present challenges for sustainable water management, as they require large volumes of water. As a result, these companies are encouraged to participate in MAR projects to help replenish the aquifer and offset their water usage, ensuring a more balanced and sustainable approach to industrial water consumption.

Agrupacions de Defensa Vegetal (ADV) are non-profit entities that collaborate with farmers on integrated pest management and other sustainable agricultural practices. ADV holds influence in promoting environmentally friendly farming techniques, including those that reduce water consumption and enhance soil moisture retention. Their efforts support the

adoption of sustainable practices that align with regional water conservation goals and contribute to the resilience of the agricultural sector.

Water-related Civil Society Organizations, such as Associació catalana amics de l'aigua, play a crucial advocacy role in promoting initiatives related to water sanitation, conservation, and sustainability. These organizations hold advocacy power and work to raise public awareness about water issues, influence policy decisions, and ensure that community voices are represented in water management discussions. Their involvement is key to fostering a culture of sustainable water use and encouraging public participation in water governance.

Workers, such as those employed by CUADLL and Aigües de Barcelona, are directly impacted by water management projects. They hold influence through their involvement in day-to-day operations and through labor representation, ensuring that their perspectives are considered in project planning and implementation. Workers' contributions are vital to the successful operation and maintenance of water infrastructure, and their expertise helps ensure that MAR and other water management initiatives are effectively executed.

The Meteorological Service of Catalonia (METEOCAT) plays an important role in climate change research and the dissemination of weather and climate information. METEOCAT holds influence through the provision of climate data, which is essential for planning water management strategies, forecasting droughts, and managing flood risks. Their collaboration with water authorities and local governments helps in developing adaptive measures to mitigate the impacts of climate change on water resources.

The power relations in each site involve complex collaboration between government entities (national, regional, and local), water authorities, end-users (farmers and companies), academia, and other stakeholders. All these actors work together towards sustainable water management through managed aquifer recharge (MAR) and improved water governance policies. These stakeholders hold varying levels of regulatory, operational, economic, technical, and advocacy power, which collectively contribute to the effective governance and implementation of water management practices in the region.

3.3. Pressures and Challenges for Implementing AWR and MAR

Socio-Economic Challenges: In the Llobregat region, the socio-economic impacts of water use restrictions during droughts are profound, particularly affecting agriculture and related economic activities. Agriculture is a significant sector in this region, and water restrictions directly impact crop yields, leading to financial losses for farmers and ripple effects throughout the local economy. The economic strain is further exacerbated by the unpredictability of drought conditions, which makes long-term planning difficult for both agricultural producers and other water-dependent industries.

Compliance and Conflict Management: Compliance and conflict issues also pose considerable challenges. Ensuring adherence to mandatory water restrictions during

drought periods is not straightforward, as different sectors compete for limited water resources. This competition can lead to conflicts between agricultural, industrial, and urban users. Managing these conflicts and dealing with non-compliance requires effective governance mechanisms, including monitoring systems and enforcement capabilities, which are often insufficient. The lack of effective coordination among stakeholders makes it challenging to implement equitable water management strategies during times of scarcity.

Public Acceptance and Health Concerns: Public acceptance of MAR is another significant challenge in the Llobregat region, largely due to concerns about potential health risks associated with recharging aquifers with treated wastewater. Despite the benefits of MAR in enhancing water availability, the local population remains wary of potential contamination risks, which creates resistance to its implementation. Addressing these concerns requires comprehensive public awareness campaigns to educate communities on the safety measures and benefits of MAR, as well as transparent communication about the quality control processes involved.

Financial Barriers: Additionally, the high initial economic investment required for MAR infrastructure presents a substantial barrier to implementation. Developing MAR systems involves considerable costs, including the construction of recharge facilities, pipelines, and advanced treatment systems to ensure water quality. These upfront costs are often beyond the reach of local governments and small-scale stakeholders without external funding or subsidies. The long-term nature of the return on investment further complicates financing, as stakeholders may be hesitant to invest in projects that do not provide immediate economic benefits.

Legal and Regulatory Challenges: Legal constraints, including complexities in water rights and regulatory frameworks, also hinder efficient MAR implementation in this region. Water rights in the Llobregat region are governed by a complex set of rules that can be difficult to navigate, particularly when it comes to reallocating water for MAR purposes. Regulatory frameworks may lack the clarity needed to support MAR projects, leading to delays in obtaining necessary permits and creating uncertainty for investors. Harmonizing water rights and establishing clear regulatory guidelines are essential to facilitate the effective deployment of MAR initiatives.

4.0 Comporta demo site

The Portuguese demo site is in Comporta, part of the Atlantic coastal aquifer system, which is crucial due to its role in regional water supply and its vulnerability to water scarcity and extreme droughts that pose significant risks. This site uses a MAR scheme with Soil-Aquifer Treatment (SAT), which involves the percolation of treated wastewater through soil to remove contaminants and enhance natural groundwater recharge, employing secondary treated wastewater to enhance groundwater recharge and improve water quality.

Comporta's water management is challenging due to frequent droughts. Additionally, its proximity to the Sado estuarine ecosystem, a Nature Reserve, prohibits the direct discharge of treated effluents into surface waters. This demo site highlights the role of MAR and Alternative Water Resources (AWR) in improving water security. The primary goal is to increase water availability by 20%, enhance groundwater quality by reducing contaminant levels by 30%, and reduce the impacts of climate variability by implementing adaptive measures to maintain water levels within a stable range. The Integrated Decision Support Tool (IDST) plays a key role in achieving these aims, helping stakeholders make informed water management decisions by providing real-time data analysis, predictive modeling, and scenario evaluations for optimizing water allocation and quality management.

The infrastructure at the Comporta demo site includes infiltration ponds, advanced wastewater treatment plants, and monitoring systems for tracking water quality and infiltration performance. The main components of the infrastructure are:

- **Infiltration Ponds:** Four ponds utilizing secondary treated wastewater with a capacity of 190 m³/day.
- **Treatment Plants:** Comporta Wastewater Treatment Plant with advanced treatment systems to ensure high-quality effluents for MAR.
- **Monitoring Systems:** Systems to track water quality and infiltration performance, complemented by three recently installed piezometers and six capsules in the vadose zone, as well as continuous online data gathering via CTD divers and scan probes.

Historical data, including hydrogeological data, water quality, climatic data, and usage data, has been provided by demo site leaders and shared with tool developers for use in the MARCLAIMED project tools. The continuous generation of new data will further aid in improving MAR strategies and achieving sustainable water management at the site.

The Comporta demo site showcases how MAR, in conjunction with AWR and advanced monitoring systems, can effectively improve water availability and quality in regions prone to extreme droughts, while balancing the needs of stakeholders and addressing the unique environmental challenges posed by sensitive ecosystems.

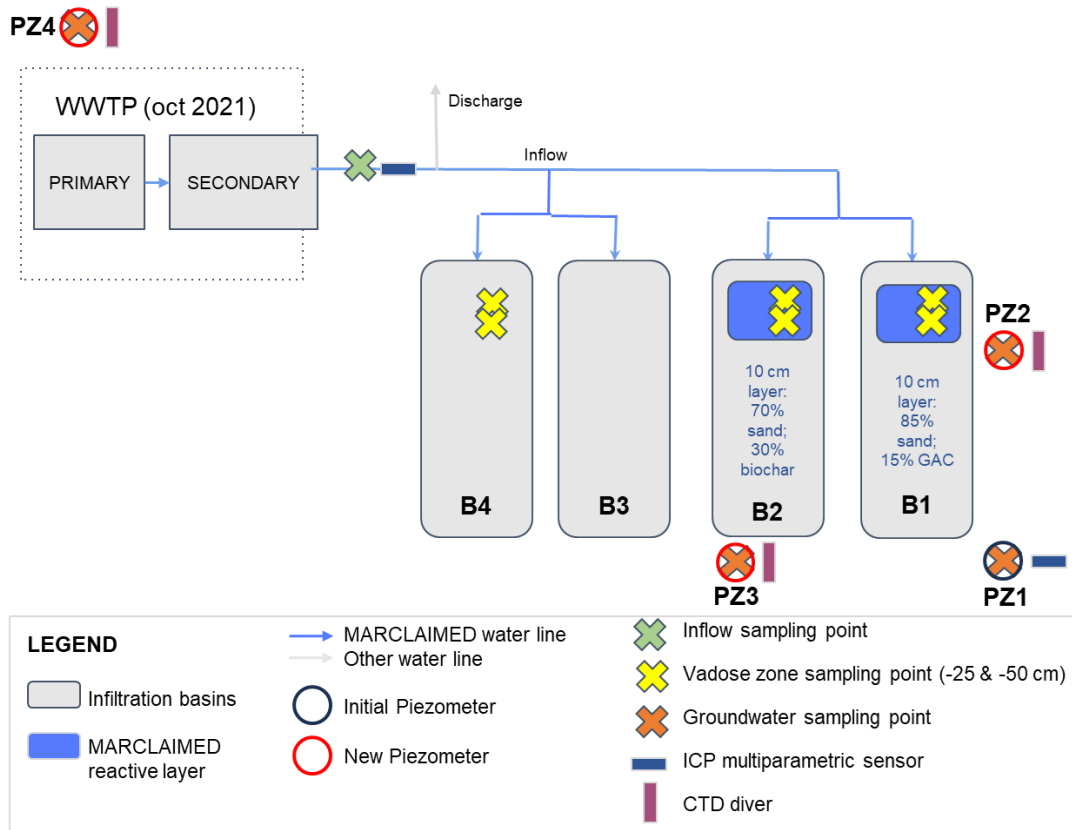


Figure 4: DS2 infrastructure diagram

4.1. Water Resource Management and Adaptation

Quantitative and Qualitative Status of Water Bodies

Groundwater bodies in Comporta, primarily in the Sado-Mira river basins, mostly exhibit good quantitative status. The aquifer systems considered in the study, such as Bacia do Tejo-Sado / Margem Esquerda (PTT3), Viana do Alentejo - Alvito (PTA6), Sines Zona Norte, Sines Zona Sul, and Bacia de Alvalade, all show good quantitative conditions. However, qualitative status varies. For example, Bacia do Tejo-Sado / Margem Esquerda is in a mediocre state due to high phosphate concentrations, while Sines Zona Sul faces issues with polycyclic aromatic hydrocarbons (PAHs). There is also no available data for Sines Zona Norte, indicating gaps in the assessment of water quality.

Main Water User Sectors

Agriculture is a significant user, accounting for 25.71% of water use, primarily sourced from surface water (64%) and some from groundwater (36%). Energy production is the largest

user at 65.03%, utilizing 100% surface water. Other sectors, such as industry (6.02%), urban consumption (0.88%), livestock (0.39%), and tourism (0.01%), also contribute to water usage. Urban water consumption relies on both surface water (56%) and groundwater (44%), while the tourism sector, including golf, depends entirely on surface water.

Impact of Climate Change

Climate change is projected to reduce rainfall significantly, especially under the more extreme RCP8.5 scenario. Rainfall reductions of 5.1%, 12.7%, and 24.8% are expected in the periods 2011-2040, 2041-2070, and 2071-2100, respectively. These reductions will exacerbate water scarcity, affecting groundwater recharge and overall water availability. Under the RCP4.5 scenario, the rainfall decreases are less severe but still significant, with reductions of 2.9%, 8.5%, and 9.9% over the same periods. These climatic shifts will directly impact water availability for agricultural and urban needs, demanding adaptive measures to ensure sustainable water use.

Water Rights and Regulation

Water rights in Portugal involve a permitting system managed by the Portuguese Environment Agency (APA). Managed Aquifer Recharge (MAR) is not explicitly regulated, but guidelines exist for using treated wastewater as a source of recharge. Natural recharge enhancement measures, such as infiltration basins, are generally accepted and not subject to Environmental Impact Assessments (EIAs). However, MAR systems using alternative sources, like treated wastewater, require an EIA and a permit from APA, specifying necessary studies and monitoring procedures. There are also two parliamentary resolutions recommending the encouragement of MAR and wastewater reuse to enhance water efficiency.

Portugal's legal framework for Managed Aquifer Recharge (MAR) includes the following regulations:

Lei da Água (Lei n.º 58/2005): Aligns national water management with EU standards, focusing on aquatic ecosystem protection, pollution prevention, and sustainable water use.

Decreto-Lei n.º 226-A/2007: Details water resource use, including groundwater protection, well drilling, and sanctions for unauthorized activities. Essential for MAR projects as it governs permits and operational conditions.

Lack of MAR-Specific Regulation: While no dedicated MAR regulation exists, Parliament resolutions (Resolução n.º 86/2022 and n.º 87/2022) encourage MAR use for water efficiency and wastewater reuse. Watershed plans reference MAR, but actions are unspecified.

Natural vs. Alternative Water Sources: Systems enhancing natural recharge face no restrictions. Treated wastewater used for MAR must meet Directive 91/271/EEC quality standards (transposed into Decreto-Lei 152/97).

Additional Norms:

- Decreto-Lei n.º 382/99: Defines groundwater protection zones.
- Lei n.º 54/2005: Governs public water resources.
- Decreto-Lei n.º 208/2008: Protects groundwater against contamination, establishing quality thresholds.
- Decreto-Lei n.º 151-B/2013: Regulates environmental impact assessments for projects.

Managed Aquifer Recharge (MAR)

MAR implementation in Comporta has included tertiary treated wastewater applications, but these are still in early stages and lack specific regulatory frameworks. The Comporta WWTP-MAR system is one example of MAR using treated wastewater, focusing on aquifer recharge to enhance groundwater resources. However, the lack of explicit MAR regulations creates uncertainties, particularly in defining environmental impacts and ensuring compliance with water quality standards.

Alternative Water Resources (AWR)

Treated wastewater is used in MAR systems in Comporta. Other potential AWR include collected rainfall water and road drainage. However, there are no specific subsidies for AWR projects, and acceptance by the Environmental Agency remains a barrier due to concerns over groundwater quality and the risks associated with using treated wastewater for recharge. The lack of clear regulatory support and financial incentives hinders the widespread adoption of AWR solutions.

Economic Instruments

The Water Resources Tariff (TRH) aims to compensate for the benefit from water use, cover environmental costs, and address the administrative expenses related to water management. The TRH applies to various water uses, including private use of public water resources, effluent discharges, and water extractions. However, water trading mechanisms are not implemented in Portugal. The tariff structure and lack of trading options indicate a need for more dynamic economic tools to facilitate efficient water use and promote conservation.

Monitoring and Enforcement

Water availability is monitored through the National Water Resources Information System (SNIRH), which includes data on surface and groundwater resources. Extracted volumes are reported by users to the Environmental Agency, which determines the applicable water tariff. Unauthorized abstractions are subject to fines, and wells or other extraction points must be registered. The SNIRH is crucial for ensuring compliance with regulations, assessing water availability, and supporting decision-making processes for sustainable water management.

4.2. Mapping of actors, roles and power relations

Table 2: Overview of key stakeholders in Comporta demo site and their role and influence

Key Stakeholder	Role	Power/Influence
Portuguese Environmental Agency (APA)	National water authority; manages river basins, issues licenses, oversees compliance	National and regional statutory power; implements policies, monitors water quality, enforces legislation
Águas Públicas do Alentejo (AgdA-AdP)	Regional water utility; manages water supply, wastewater treatment, MAR initiatives	Operational power over water infrastructure; treatment, distribution, and reclamation processes
Coordination and Regional Development Commission (CCDR-Alentejo)	Supports economic and social development through public financing for water projects	Allocates regional development funds, coordinates policies, and promotes MAR integration
Portuguese Farmers Confederation (CAP)	National body representing farmers; advocates for improved irrigation and MAR	Influences agricultural water use policies; promotes sustainable water management among farmers
Municipalities and Intermunicipal Communities	Ensures efficient local water distribution; promotes sustainability and public awareness	Local administrative power; implements MAR within municipal water systems
Local Irrigation Associations (ABORO, ABROXO, ARBCAS)	Manage irrigation infrastructure at the community level	Operational power over water allocation and dispute resolution for agricultural purposes
Alqueva Infrastructure and Development Company (EDIA)	Manages large water distribution systems, including the Alqueva Multipurpose Project	Oversees major irrigation infrastructure; key in regional water security and MAR implementation

Academic Institutions (UE, IPBeja, LNEC)	Conduct research on MAR and water management practices; support knowledge generation and innovation	Provide technical expertise, applied research on MAR, and collaborate with government bodies and utilities
Portuguese Water Partnership	Fosters collaboration across the water sector; promotes Portuguese expertise in water management	Networking power; facilitates knowledge exchange and cross-sector cooperation for sustainable water solutions
Tourism-related SMEs	Implement sustainable, environmentally responsible leisure activities benefiting from improved water management	Economic influence through tourism; supports the adoption of MAR and water conservation
Large Agricultural End-users (SOVENA, WESTFALIA)	Major farming companies; vested interest in MAR to ensure reliable water supply	Economic power to influence the adoption of MAR and water-saving technologies
Construction and Environmental Consultancy Companies	Conduct feasibility studies, environmental assessments, and ensure regulatory compliance for MAR projects	Expertise in project planning, design, and regulatory adherence for successful MAR implementation
Regional Board of Agriculture and Fisheries (DRAP-Alentejo)	Shapes agricultural policies; promotes sustainable water use and rural development	Regulatory power in agriculture; supports water conservation and MAR adoption

In Comporta, the Portuguese Environmental Agency (APA) acts as the national water authority, responsible for managing river basins, issuing water use licenses, and overseeing regulatory compliance to ensure sustainable water usage. APA holds statutory power at both the national and regional levels, granting it comprehensive authority over water management and regulatory control, which includes implementing policies, monitoring water quality, and enforcing water-related legislation. This agency is key in ensuring compliance with both national and EU water directives, making it a pivotal stakeholder in safeguarding water resources.

Águas Públicas do Alentejo (AgdA-AdP) is the regional water utility, tasked with managing water supply, wastewater treatment, and implementing Managed Aquifer Recharge (MAR) initiatives in the region. The company operates under a public partnership regime and has significant operational power over the water infrastructure, including the treatment, distribution, and reclamation processes. AgdA-AdP's role also includes ensuring that MAR techniques are implemented safely and effectively to augment groundwater resources, thereby enhancing water availability for both domestic and agricultural purposes.

The Coordination and Regional Development Commission (CCDR-Alentejo) is an important regional body that supports economic and social development through strategic public financing initiatives. CCDR-Alentejo coordinates various sectoral policies related to territorial planning, land use, and sustainable development. It plays a crucial role in promoting MAR practices, particularly by providing financial support to local authorities and other stakeholders involved in water management projects. CCDR-Alentejo's power extends to the allocation of regional development funds and policy coordination, making it a key player in ensuring the integration of MAR into regional water management strategies.

The Portuguese Farmers Confederation (CAP) serves as the national representative body for farmers, advocating for their interests, particularly regarding water usage and irrigation. CAP plays a significant role in promoting the adoption of improved irrigation practices and Managed Aquifer Recharge (MAR) as viable solutions to address water scarcity challenges. CAP actively engages in policy discussions, influencing agricultural water use policies and practices by lobbying government bodies and raising awareness among the farming community about sustainable water management solutions.

Municipalities and Intermunicipal Communities in the Alentejo region are responsible for ensuring that water distribution is conducted efficiently at the local level. They are pivotal in implementing environmental sustainability practices and promoting public awareness about responsible water use. These entities hold local administrative power, allowing them to influence community-level water management policies and oversee the integration of MAR practices within municipal water systems. Their collaboration with other stakeholders, such as water utilities and regional authorities, is crucial for ensuring the equitable distribution of water resources.

Local Irrigation Associations, such as ABORO, ABROXO, and ARBCAS, manage irrigation infrastructure at the community level, playing a key role in distributing water for agricultural purposes. They hold operational power over local irrigation systems, including water allocation and dispute resolution related to water availability. These associations ensure that farmers have access to adequate water supplies, especially during critical periods, thereby enhancing agricultural productivity while supporting sustainable water management through MAR.

The Alqueva Infrastructure and Development Company (EDIA) is a public enterprise that manages one of the largest water distribution systems in Portugal, the Alqueva

Multipurpose Project. EDIA's responsibilities include managing major irrigation infrastructure, operating the Alqueva dam, and distributing water for irrigation across the Alentejo region. EDIA plays a critical role in implementing integrated water management strategies, ensuring that MAR practices are effectively incorporated to complement existing surface water resources. Its authority over water allocation makes it a significant stakeholder in regional water security.

Évora University (UE), Beja Polytechnic Institute (IPBeja), and the National Laboratory for Civil Engineering (LNEC) are key academic and research institutions involved in water management initiatives in the Alentejo region. These institutions contribute by integrating project outcomes into their research and academic programs, thus supporting the development of innovative water management practices. They influence knowledge generation by conducting applied research on MAR techniques, providing technical expertise, and developing new technologies that enhance the efficiency and sustainability of water use in agriculture and other sectors. Their collaboration with government bodies and water utilities ensures that the latest research findings are applied in real-world scenarios to improve water management.

The Portuguese Water Partnership plays a pivotal role in fostering collaboration across the water sector in Portugal. This partnership involves professionals, institutions, and companies, aiming to project Portuguese expertise in water management onto the international stage. It holds significant networking power, enabling the exchange of knowledge and best practices between stakeholders, and catalyzing opportunities for innovation and sustainable development in the water sector. The partnership's efforts are essential for integrating MAR into broader water management frameworks and promoting cross-sectoral cooperation.

Tourism-related SMEs are companies within the tourism sector that aim to implement sustainable and environmentally responsible leisure activities, which are increasingly valued by tourists. These companies benefit from improved water management practices, including MAR, as they enhance the environmental quality of destinations. Their economic influence in the region supports the adoption of sustainable practices, making them a valuable stakeholder group in promoting MAR and water conservation initiatives.

Large end-users from the agricultural sector, such as SOVENA and WESTFALIA, are major farming companies in the Alentejo region. These companies are significant water consumers and have a vested interest in the successful implementation of MAR to ensure a reliable water supply for their operations. They hold substantial economic power, which they use to influence the adoption of MAR practices and other water-saving technologies that contribute to increased agricultural productivity and sustainability.

Construction and Environmental Consultancy Companies are crucial for the successful implementation of MAR projects. These companies are responsible for conducting feasibility studies, performing environmental impact assessments, and ensuring compliance with

regulatory requirements. Their expertise in project planning, design, and regulatory adherence influences the successful implementation of MAR and ensures that projects are environmentally sound and technically viable.

The Regional Board of Agriculture and Fisheries (DRAP-Alentejo) plays an active role in shaping agricultural policies, promoting rural development, and overseeing fisheries management in the region. DRAP-Alentejo holds regulatory power within the agricultural sector, which includes promoting sustainable water use practices, supporting the adoption of MAR, and ensuring that agricultural activities align with regional water conservation goals. Their involvement is key to integrating water management practices that support both agricultural productivity and environmental sustainability.

4.3. Pressures and Challenges for Implementing AWR and MAR

Legal and Institutional Barriers: In Comporta, significant legal and institutional barriers arise due to the lack of specific MAR regulations. The absence of well-defined regulatory frameworks creates uncertainty, making it challenging to obtain permits and proceed with MAR initiatives. Existing permits for MAR projects involve stringent environmental standards, which can be difficult for stakeholders to meet without adequate guidance and support. There is also a need for clearer legal frameworks to define the responsibilities of land and water rights holders, as this would help streamline the permitting process and provide greater clarity for all parties involved.

Public Acceptance and Awareness: Public acceptance of MAR is another key challenge in Comporta, primarily due to insufficient knowledge regarding its benefits and potential risks. The general population may be unaware of how MAR can contribute to water security and improve drought resilience, which affects overall acceptance. Misinformation and a lack of awareness about the safety of using treated wastewater for aquifer recharge further complicate public perception. To gain public support, it is essential to implement educational campaigns that explain the benefits of MAR, address safety concerns, and emphasize the rigorous quality controls that are in place to ensure water safety.

Socio-Economic Concerns: Socio-economic concerns are also prominent, particularly regarding water pricing and legal requirements that could exacerbate inequalities among different socio-economic groups. The costs associated with MAR, including infrastructure development and compliance with environmental regulations, may be prohibitive for small-scale farmers and other economically disadvantaged stakeholders. This financial burden creates disparities in access to water resources, leading to inequalities between different user groups. Resistance to change among small-scale farmers, who may be hesitant to adopt new technologies due to costs and unfamiliarity, further limits the widespread adoption of MAR in the region.

Technical and Financial Challenges: Technical and financial issues are significant barriers to MAR implementation in Comporta. MAR systems that use treated wastewater require comprehensive environmental impact assessments and stringent monitoring to ensure compliance with environmental standards. These requirements add to the cost and complexity of MAR projects. The financial investment needed for MAR infrastructure, including treatment facilities, recharge structures, and monitoring systems, is substantial, challenging the economic feasibility for many stakeholders. Without financial incentives or subsidies, the high costs deter potential investors and limit the scalability of MAR projects. Addressing these challenges will require innovative funding mechanisms, as well as technical assistance to ensure that MAR systems are both effective and affordable.

5.0 De Waddenregio demo site

The Dutch demo site is located in the Waddenregio, northwest Netherlands, near the Wadden Sea. The Waddenregio is significant due to its unique ecological value as a UNESCO World Heritage site and its economic importance, particularly in agriculture and fisheries. This site uses an Aquifer Storage and Recovery (ASTR) system, which involves storing excess water in an underground aquifer during wet periods and recovering it during dry periods, with agricultural tile drainage water to address water scarcity and pollution. The main goal is to boost freshwater availability for agriculture by 25% in an area affected by saline intrusion and limited high-quality freshwater access. The demo aims to enhance agricultural resilience to water shortages, supporting farming's economic sustainability in the region.

The Waddenregio faces unique challenges due to its low-lying landscape, vulnerability to saline intrusion, and reliance on agriculture, which depends heavily on freshwater. This site demonstrates the potential of storing freshwater from tile drainage during surplus periods. It also shows how this stored water can be accessed in dry spells to support agricultural needs. This approach eases pressure on limited freshwater resources, promotes sustainable farming, and mitigates the impacts of climate change and saline intrusion.

The primary objective is to improve freshwater availability for agriculture, enhance groundwater quality, and establish a sustainable water management solution that counters climate variability. The Integrated Decision Support Tool (IDST) will aid these efforts by equipping stakeholders with the insights needed for informed water management decisions in the region, such as optimizing irrigation schedules, predicting water demand, and assessing the impact of different climate scenarios.

The infrastructure at the Waddenregio demo site includes tile drainage systems, infiltration wells, and monitoring systems for tracking water quality and storage performance. The main components of the infrastructure are:

- **Tile Drainage System:** Collects excess water from agricultural fields for use in the ASTR system.

- **Infiltration Wells:** Used to inject the collected drainage water into the aquifer for storage, with a capacity designed to accommodate the volume of water collected during wet periods.
- **Monitoring Systems:** Systems to track water quality, storage levels, and the overall performance of the ASTR system. These include sensors to measure salinity, temperature, and water levels, providing continuous data for effective system management.

Historical data, including groundwater levels, water quality, and agricultural usage data, has been provided by regional stakeholders and shared with tool developers for use in the MARCLAIMED project tools. The ongoing collection of new data will further support the optimization of ASTR strategies and contribute to sustainable water management practices in the Waddenregio.

The Waddenregio demo site serves as an example of how MAR, through innovative ASTR techniques, can effectively improve water availability for agriculture in regions facing saline intrusion and freshwater scarcity. By leveraging agricultural drainage water and advanced monitoring systems, the site aims to provide a replicable model for sustainable water resource management in similar coastal regions.

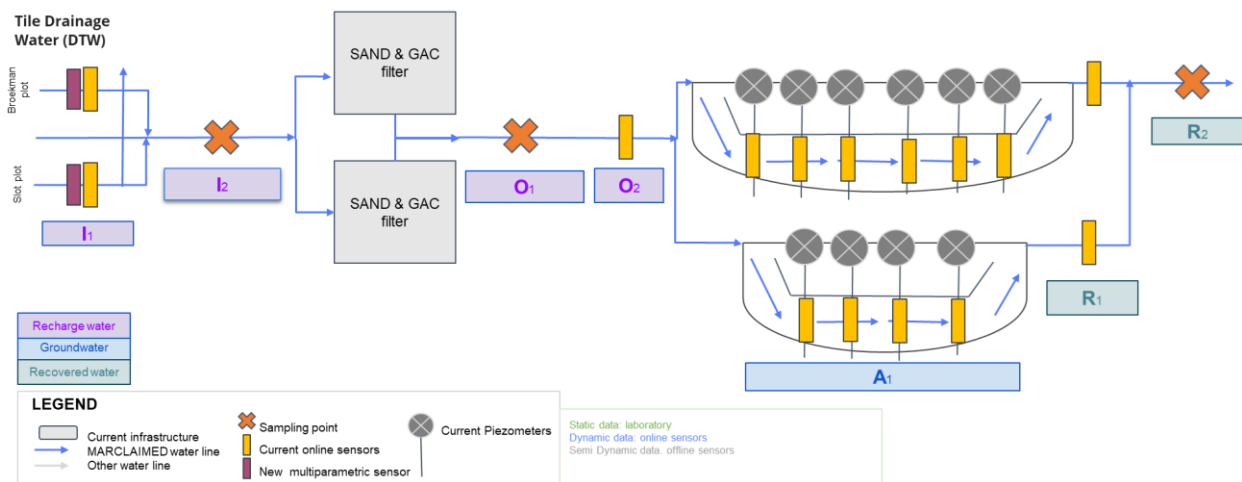


Figure 5: DS3 infrastructure diagram

5.1. Water Resource Management and Adaptation

Quantitative and Qualitative Status of Water Bodies

Groundwater bodies in the Waddenregio generally exhibit good quantitative status. The Salt Rhine North, Salt Rhine West, and Salt Meuse are in good quantitative condition. However, qualitative performance is poor in some areas, particularly concerning groundwater-

dependent terrestrial ecosystems. For example, the Salt Rhine West area has insufficient quality for groundwater-dependent ecosystems, affecting the N2000 area Botshol. The general quality of groundwater remains good, but ecological dependencies require additional attention to meet environmental standards.

Main Water User Sectors

The main user of groundwater in the Waddenregio is industry, which utilizes groundwater for cooling and processing purposes. Other users include agriculture for irrigation and modified groundwater level management. The extraction of water in this region is regulated to ensure minimal impact on vulnerable areas, with a specific focus on industrial and agricultural activities. The extensive use of groundwater for industrial purposes highlights the need for efficient water allocation, particularly during periods of scarcity.

Impact of Climate Change

Climate change is expected to lead to increased winter precipitation and decreased summer precipitation in the Waddenregio. Additionally, the frequency of high-water events is projected to rise. The region's artificial water management system, designed primarily for rapid drainage to the sea, poses unique challenges for drought adaptation. Dry summers may lower groundwater levels, although areas affected by seepage may retain more stable levels due to upward water flows. The system's inability to retain water effectively during dry periods necessitates adaptive measures to improve water retention and reduce vulnerability to climate extremes.

Water Rights and Regulation

Water rights in the Waddenregio are governed under the "Environmental Law." These rights are not bundled with land ownership, meaning that owning land does not automatically grant water extraction rights. Groundwater extraction outside protected areas requires permits, and specific volume thresholds determine the need for environmental assessments. During national water shortages, extractions are adjusted according to a prioritization system managed by the national drought council. This approach aims to balance the needs of various sectors, ensuring that critical uses, such as drinking water supply, are prioritized during scarcity.

In the Netherlands, Aquifer Storage and Recovery (ASR) is located near a polder and uses two injection wells with sandy low filtration and granular activated carbon. This requires meeting strict hydrogeological criteria.

Legal framework includes:

- WaterWet (Water Law): Governs water management, including groundwater.
- Wet milieubeheer (Environmental Management Law): Addresses contamination prevention.

- Besluit kwaliteitseisen en monitoring water 2009: Sets water quality standards essential for ASR.
- Wet bodembescherming (Soil Protection Law): Protects soil and groundwater from contamination.
- Meststoffenwet (Fertilizers Law): Relevant due to agricultural drainage.
- Waterschapswet (Water Board Law): Regulates regional water authorities (Waterschappen).

These laws form the legal framework for ASR, addressing water management, soil and water quality, and regional agricultural considerations.

A detailed aquifer characterization is essential, including pumping tests to determine transmissivity, storage, and hydraulic conductivity.

Numerical modeling is mandatory to assess injection bubble formation, flow effects, and seawater intrusion in coastal areas.

The injection system must meet water quality standards, focusing on turbidity, organic matter, and by-product formation. A monitoring program should track water quality, subsidence impacts, and head levels. Authorities must evaluate regional hydric balance, aquifer interactions, and long-term sustainability under climate change and sea-level rise.

Managed Aquifer Recharge (MAR)

MAR is widely used for drinking water extraction in the Netherlands, particularly in dune areas. However, small-scale MAR for agricultural purposes is still under development, with a few pilot projects currently operational. These projects aim to enhance groundwater reserves using drainage water from agricultural fields. The lack of a comprehensive regulatory framework for MAR beyond drinking water extraction limits the broader application of these techniques, particularly for farmers who need affordable and accessible solutions for water storage.

Alternative Water Resources (AWR)

Drainage water from agricultural lands is used for MAR, supported by subsidies from provinces and water authorities. The reuse of drainage water for MAR helps reduce reliance on conventional water sources, particularly during dry periods. Citizen engagement projects, such as "Boeren Meten Water" (Farmers Monitor Water), also contribute to monitoring efforts by involving farmers in assessing water quality, groundwater levels, and soil moisture. These initiatives help create awareness and promote sustainable water management practices at the local level.

Economic Instruments

Drinking water tariffs are determined by drinking water companies, while farmers pay for water indirectly through water authority taxes, typically based on land area. Water trading is uncommon, though informal water transactions from areas with excess availability are becoming more frequent. The lack of a formal water trading market and the reliance on regional taxes and tariffs highlight the need for more flexible economic instruments that could better address water scarcity and encourage efficient use.

Monitoring and Enforcement

The Waddenregio benefits from an extensive monitoring network for both surface water and groundwater, operated by Rijkswaterstaat, provinces, municipalities, water boards, and nature conservation organizations. Monitoring includes piezometers, telemetric systems, and flow measurements to track groundwater levels, water quality, and surface flow rates. Enforcement is handled by water boards, particularly during drought periods when extraction bans are issued. Unauthorized extractions are subject to fines, and strict measures are in place to ensure compliance, emphasizing the importance of a coordinated approach to monitoring and management.

5.2. Mapping of Actors, Roles and Power relations

Table 3: Overview of key stakeholders in De Waddenregio demo site and their role and influence

Stakeholder	Role	Power/Influence
Water Framework Directive (WFD)	Sets ecological standards for water quality and aquatic ecosystems in the EU.	Regulatory power over water quality standards.
Dutch National Government	Implements national water policies, including nitrogen norms, and ensures compliance with EU directives.	Legislative and regulatory power at the national level.
Province of Noord Holland	Promotes MAR implementation and supports sustainable development initiatives, aligning provincial planning with environmental sustainability goals.	Administrative power over regional planning and water governance.

Waterschap (Regional Water Authority)	Manages freshwater distribution, water infrastructure, and water quality; oversees MAR projects and flood control.	Operational power in regional water management.
Farmers	End-users in MAR practices aiming to secure water supply for irrigation and enhance climate resilience.	Economic power as key water users and influencers in local water management.
Acacia Water	Consultancy firm conducting MAR pilot projects and working with farmers to build climate resilience.	Technical expertise and operational power in pilot execution.
Deltares	Conducts research on delta and water systems, including MAR; provides science-based recommendations for water management.	Research and knowledge dissemination.
Ministry of Infrastructure and Water Management (MinIenW)	Shapes national water programs and climate adaptation strategies; oversees water infrastructure and resilience initiatives.	Policy-making and regulatory power.
Ministry of Agriculture	Regulates sustainable water use in agriculture, setting policies to promote water-saving techniques.	Regulatory power over agricultural water use.
Hoogheemraadschap Hollands Noorderkwartier (HHNK)	Manages dikes, water levels, and flood defenses, ensuring freshwater availability for agriculture and domestic use.	Operational and regulatory power over water management.
Seed Potato Traders & Flower Bulb Associations	Rely on stable water availability for irrigation; support MAR projects for water security.	Economic influence in water use and advocacy for reliable water supply.
Rabobank	Finances agricultural projects, emphasizing climate resilience and sustainability through water-efficient technologies like MAR.	Financial power through investment in sustainable farming practices.

Water Companies (e.g., Vitens, PWN)	Interested in MAR for securing drinking water supplies, reducing surface water dependency, and enhancing resilience against water scarcity.	Economic and operational influence in water supply services.
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In De Waddenregio, the Water Framework Directive (WFD) established by the EU sets ecological standards that all member states must comply with, particularly regarding water quality and aquatic ecosystems. The WFD holds regulatory power over water quality standards, making it a critical tool for ensuring sustainable water management. The Dutch National Government plays a pivotal role in implementing national water policies, including nitrogen norms and other regulations that impact agricultural and industrial sectors. The government holds legislative and regulatory power at the national level, and it is responsible for ensuring compliance with EU directives, as well as integrating these standards into national legislation to maintain ecological health and resilience.

The Province of Noord Holland is responsible for promoting Managed Aquifer Recharge (MAR) implementation and supporting sustainable development initiatives within the region. It holds administrative power over regional planning and water governance, working to align provincial development with environmental sustainability goals. This includes facilitating collaboration between municipalities, water boards, and other stakeholders to promote innovative water solutions such as MAR, ensuring that groundwater resources are effectively managed and protected against over-extraction and contamination.

Waterschap, the regional water authority, is tasked with managing fresh water distribution, maintaining water infrastructure, and ensuring the quality of water within the region. Holding operational power over regional water management, Waterschap plays a crucial role in overseeing the implementation of MAR projects, flood control measures, and water quality improvement initiatives. Its responsibilities include managing dikes, regulating water levels, and collaborating with farmers and municipalities to optimize water availability and quality for various uses.

Farmers in the region are private end-users who have a significant stake in MAR practices as they seek to enhance the resilience of their farming operations against climate variability. They hold considerable economic power as key water users and are instrumental in influencing local water management practices, especially in agricultural areas where irrigation is essential. Farmers' willingness to invest in MAR technologies not only helps secure their own water supply but also contributes to regional efforts to balance water demand and recharge aquifers, thereby promoting sustainability in agriculture.

Acacia Water is a specialized consultancy firm that executes pilot projects and works directly with farmers and local authorities to build climate resilience. With technical expertise and operational power in pilot execution, Acacia Water is involved in testing, demonstrating, and

refining MAR technologies to improve their effectiveness and scalability. Their work helps establish practical guidelines for MAR implementation, and their pilots serve as proof-of-concept for broader regional adoption, ultimately helping to develop resilient water systems in response to climate challenges.

Deltares, a renowned Dutch research institute, specializes in delta and water systems. It conducts research and impact analyses on MAR and other water management practices, holding influence through research and knowledge dissemination. Deltares collaborates with various stakeholders, including government bodies, farmers, and water authorities, to provide insights into the hydrological impacts of MAR and to develop science-based recommendations for policy and practice. Their research underpins decision-making processes, ensuring that water management solutions are both effective and environmentally sustainable.

The Ministry of Infrastructure and Water Management (MinlenW) plays a central role in shaping national water programs and climate adaptation strategies. It holds policy-making and regulatory power, overseeing major initiatives related to water infrastructure, climate resilience, and flood prevention. The Ministry of Agriculture also holds a significant role, focusing on sustainable water use in the agricultural sector. It holds regulatory power over agricultural water use, setting policies that encourage farmers to adopt water-saving techniques and improve irrigation efficiency. Both ministries work closely together to ensure that water management policies are cohesive and support national climate adaptation goals.

Hoogheemraadschap Hollands Noorderkwartier (HHNK) is a regional water authority with operational and regulatory power over water management. It is responsible for managing dikes, water levels, and flood defenses, as well as ensuring the availability of freshwater for agriculture, industry, and domestic use. HHNK collaborates with other stakeholders, such as municipalities and farmers, to optimize water distribution and ensure the safety and sustainability of water systems. Their work is vital for maintaining the delicate balance between water conservation, flood prevention, and agricultural productivity.

Seed Potato Traders and Flower Bulb Associations are important end-users in the region who rely heavily on irrigation and stable water availability. They hold economic influence in agricultural practices and water use, as their activities are closely tied to water security. These associations represent a sector that is both economically significant and vulnerable to water shortages, which drives their interest in supporting MAR projects and advocating for reliable water supply solutions.

Rabobank plays a traditional yet crucial role in financing the agricultural sector, with a growing emphasis on supporting initiatives that promote climate resilience and financial sustainability. The bank holds financial power through its investments in agricultural projects, which increasingly focus on innovations like MAR that enhance water security and ensure long-term viability for farmers. By providing loans and financial products tailored to

sustainable farming practices, Rabobank is helping to drive the adoption of water-efficient technologies in the region.

Water companies in the Netherlands, such as Vitens and PWN, are interested in MAR technology due to its potential to secure drinking water supplies. These companies hold both economic and operational influence in water supply services, as they are responsible for sourcing, treating, and distributing potable water. Their involvement in MAR initiatives reflects their commitment to securing future water resources, reducing dependency on surface water, and enhancing the resilience of the water supply system against periods of drought or water scarcity. These companies often work in partnership with regional authorities, research institutions, and other stakeholders to ensure that MAR is implemented effectively and contributes to the overall reliability of drinking water services.

5.3. Pressures and Challenges for Implementing AWR and MAR

Design and Capacity Challenges: In Waddenregio, the water system is primarily designed for rapid drainage, which significantly limits water retention capacity and makes it difficult to adapt to drought periods. The rapid drainage design, while effective in managing excess water during wetter periods, does not allow for efficient water storage, which is crucial during prolonged dry spells. This limitation in the system's capacity poses a serious challenge for water management, especially in the context of increasing climate variability and the need for greater resilience.

Cultural and Behavioral Challenges: Additionally, there is a cultural attitude in agriculture and industry that assumes water abundance, leading to inefficient water use. Water conservation has not been a traditional practice, and changing this deeply ingrained mindset is a significant challenge. The perception of water as an abundant resource results in practices that do not prioritize efficiency, and addressing this requires targeted awareness campaigns and education initiatives to promote the benefits of water-saving measures and sustainable usage.

Legal and Institutional Barriers: Legal and institutional barriers also exist, as inconsistent requirements and unclear permitting processes among water boards hinder effective MAR implementation. The water governance structure in Waddenregio involves multiple authorities, each with its own set of regulations and priorities, leading to confusion and delays in obtaining necessary permits for MAR projects. The lack of standardized procedures across different jurisdictions complicates the planning and execution of MAR initiatives, creating uncertainty for stakeholders.

Technical Issues: Technical challenges also play a significant role, particularly regarding purification requirements and the technical viability of MAR systems. Ensuring that recharged water meets environmental, and health standards requires advanced purification technologies, which may not always be readily available or affordable. Additionally, the

technical feasibility of implementing MAR varies depending on local geological and hydrological conditions, which can complicate project planning and increase costs. Addressing these technical issues requires investment in research and development, as well as collaboration between technical experts and local stakeholders to tailor solutions to specific site conditions.

Financial and Investment Concerns: Financial and investment concerns are another major hurdle, particularly due to the high costs related to monitoring requirements and infrastructure development. The financial burden associated with MAR projects include not only the initial capital investment but also ongoing operational and maintenance costs. These costs deter farmers and other potential investors, especially when the return on investment is uncertain or distributed over a long-time horizon. Securing funding for MAR requires innovative financing mechanisms, such as public-private partnerships and subsidies, to make these projects more economically viable.

Service and Implementation Challenges: Moreover, the lack of service providers and concerns about user-friendliness impede broader adoption of MAR. Many potential users, such as small-scale farmers, may lack access to the technical support and services needed to implement MAR effectively. Additionally, the complexity of MAR systems can be a barrier for users who are unfamiliar with the technology, making it essential to develop user-friendly solutions and provide adequate training and support to encourage adoption.

6.0 Conclusions

The MARCLAIMED project illustrates that a co-creation approach, engaging a diverse array of stakeholders—including policymakers, public entities, academic institutions, and end-users—throughout all phases of strategy development, is essential for addressing complex water management challenges. By customizing solutions to the specific conditions of each demo site and involving stakeholders at every stage, such as optimizing irrigation techniques at the Comporta site to mitigate drought-related issues, the project fosters trust, ensures the applicability of solutions, and enhances stakeholder ownership. This methodology not only enhances the adaptability and resilience of AWR strategies, but also effectively balances environmental, social, and economic considerations, thereby ensuring the long-term sustainability of these solutions.

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MARCLAIMED will support decision makers to integrate Managed Aquifer Recharge (MAR) with Alternative Water Resources (AWR) in River Basin and Drought Management Plans supporting the adaptation and resilience of structural supply systems in the context of climate change. The main outcome will be the MARCLAIMED Integrated Decision Support Tool (IDST) that will provide solutions to tackle existing and emerging threats and support decision making and adaptation policies.



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