MARSoluT
Managed Aquifer Recharge ITN

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MARSoluT

Managed Aquifer Recharge Solutions Training Network

A Horizon 2020 MSCA ITN

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Author(s) [1]	J.D. Henao Casas (Tragsa, UPM), E. Fernández Escalante (Tragsa), F. Ayuga Téllez (UPM); K. Standen, L. Costa, J.P. Monteiro (UAlg); A. Vlassopoulou, A. Kallioras (NTUA); E. Caligaris, R. Rossetto (SSSA); G. Rudnik, D. Kurtzman (ARO); M. Sapiano (EWA); A. Wefer-Roehl (TUDa)
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[1] ARO: The Agricultural Research Organization of Israel - Volcani Center, Israel; EWA: Energy and Water Agency, Malta; NTUA: National Technical University of Athens, Greece; SSSA: Scuola Superiore Sant'Anna, Italy; TRAGSA: Empresa de Transformación Agraria S.A, Spain; UAlg: Universidade do Algarve; UFZ: Helmholtz-Zentrum für Umweltforschung GmbH, Germany; UPM: Universidad Politécnica de Madrid, Spain; TUDa: TU Darmstadt, Germany.

[2] PU: Public, RE: restricted to a group specified by the consortium, CO: Confidential, only for members of the consortium; Commission services always included

[3] Draft, Revised, Final.

Contents

Executive Summary

Managed Aquifer Recharge (MAR) is a promising technique for water management. It comprises a group of technologies that enhance the infiltration of various water sources into aquifers. The water stored underground can serve different uses, such as irrigation, industrial and drinking water supply, and the recovery or preservation of environmental assets. The uptake of MAR is rapidly increasing worldwide under the threat of multiple pressures, including climate change, the decline in aquifer storage and environmental degradation. The present report is part of the Horizon 2020 MSCA "*Managed Aquifer Recharge Solutions Training Network*" (MARSoluT ITN, 2019-2023), which aimed at training experts in MAR (https://www.marsolut-itn.eu/). Report D4.4 deals with the objectives of work package 4 (WP4) and seeks to evaluate the performance of MAR sites across the Mediterranean using monitoring data. D4.4 continues a line of research started in the FP7 project "*Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought*" (MARSOL, 2013-2016) through MARSOL work package 13 (WP13) and its Deliverables D13.1 and D13.3, which provided technical solutions for MAR.

The performance of six MAR sites across the Mediterranean was evaluated, namely, The Algarve, Portugal (UAlg); The Los Arenales MAR sites, Spain (TRAGSA); the Suvereto MAR site, Italy (SSSA); the Pwales MAR site, Malta, (EWA); the Argolis Field, Greece (NTUA); and the Menashe streams MAR site, Israel (ARO). The performance was evaluated in terms of seven categories: yearly recharge volumes, impacts on groundwater levels, impacts on water quality, infiltration rates and clogging, site upgrade, financial aspects, and other aspects. The site performance evaluation involved research conducted primarily within the framework of the MARSoluT project. In general, the sites show satisfactory performance after several years of operations. In the Algarve, MAR could help to palliate some of the current issues, but other measures are also required.

In addition, a calculation for the unintentional recharge of groundwater caused by transversal structures (dykes and dams) has been conducted as a starting point for a future more accurate estimation. The volume infiltrated from the about 27,600 in-river structures ranges between 800 and 1,200 Mm^3/year for the Spanish territory, representing a starting point for this new line of action about (un)managed aquifer recharge at a large scale. The obtained figures will be fine-tuned in the future of this initial figure.

The site performance evaluation research involves multiple tools and diverse approaches, including numerical groundwater modelling, analytical hydrochemical characterisation, field and laboratory experiments, and geospatial analysis. A total of 20 technical solutions were added to the list that started in MARSOL with Deliverable D13.1. These technological solutions are related to multiple aspects of MAR, such as operation, planning, maintenance, and site upgrade. The advances in MAR sciences and engineering reflected in this report showcase successful MAR experiences and provide technical solutions that can support the market penetration of MAR in the Mediterranean region and beyond.

1. Introduction

The MARSoluT Interactive Training Network (ITN) is a Marie-Skłodowska Curie doctoral network aiming to train 12 highly skilled doctoral fellows in Managed Aquifer Recharge (MAR). This goal materialises through PhD theses developed with member and partner institutions. The main objective of all the PhD candidate's research is to provide scientific and technical solutions for MAR.

The PhD candidates' research has also been grouped into four work packages (WPs) which focus on different aspects of MAR, including sustaining high infiltration rates (WP1), or improving water quality for MAR (WP2). The results of the WPs are presented as deliverables that are submitted to the European Commission. The WPs and PhD researches give answers to knowledge gaps detected by the consortium and, in some cases, continue active lines of research started in previous projects, notably the FP7 MARSOL project.

This deliverable (D4.4) is part of WP4 and deals with MAR design and construction criteria. It is a continuation of MARSOL's WP13, which resulted in various Deliverables (D13.1 and D13.3[1]) and showcased technical solutions for MAR. WP4 has a pragmatic and innovative character. Specific objectives are the following:

1. Implementation of monitoring systems and development of a flow model for Malta South.
2. Development of a regional river basin model for scenario analyses.
3. Enhancing water quality by optimising MAR design at active MAR sites in Spain.
4. Statistical analysis and evaluation of long-term monitoring data and site upgrade of identified hotspots.

D4.4 titled "*Report on the performance of optimal MAR designs*" concerns the fourth objective of WP4, namely, the statistical analysis and evaluation of long-term monitoring data and site upgrade of identified hotspots. Consequently, this report aims to provide optimal design and construction criteria by assessing the performance of MAR sites through monitoring data. To this end, five hotspots across the Mediterranean where MAR operations have taken place were evaluated.

The performance of the MAR system can be assessed from various perspectives. From the impact of the artificial recharge operations on groundwater levels and quality to the state of the infiltration infrastructure and economic indicators. Hence, multiple aspects were considered for the evaluation of MAR site performance:

1. Yearly recharge volumes: yearly volume of water artificially recharged into aquifers during MAR site operation.
2. Impacts on groundwater levels: evaluation of the effects of the MAR site operation on groundwater levels and aquifer storage.
3. Impacts on water quality: evaluation of the effects of MAR systems on groundwater quality.

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[1] Available at www.https://dinamar.tragsa.es/ (accessed 19/01/2023)

4. Infiltration rates and clogging: evaluation of how infiltration rates have evolved with a view to clogging issues and how they have been managed.
5. Site upgrade: description of any engineering or infrastructure upgrade of a MAR site.
6. Financial aspects: indicators of financial performance or financial factors that could be of interest to the MAR community, given the relatively little literature in this regard.
7. Other aspects: other aspects that are key to the performance of the MAR system (e.g., water governance).

The performance evaluation of some of the addressed MAR sites does not include all of these aspects since not all of them may have been researched in the framework of MARSoluT.

The evaluation of dykes as sources of recharge for aquifers in Spain is also included in this report. These dykes have contributed to groundwater recharge for many decades. Helping in understanding their role would help to decrease uncertainty in hydrological balances. Although dykes in Spain are, in most cases and unintended sources of groundwater and, therefore, not MAR systems, they resemble the situation in India, where ubiquitous check dams have been built to feed aquifers. Hence, any conclusion in Spain could be relevant for MAR performance at the regional level in other parts of the world.

Technical solutions result from the assessment of MARSoluT’s MAR site performance. These solutions are conceptualised and summarised in the present report, giving continuity to MARSOL’s WP13 and Deliverable D13.1.

The present deliverable follows this structure: the first section provides the objectives, followed by a background on the MAR sites focusing on the improvements and the research conducted during the previous project MARSOL, MARSoluT´s precedent. Section two evaluates MAR site performance for six hotspots in the Mediterranean region from east to west (**Figure 1**). These sites are their corresponding responsible institutions are i) The Algarve, Portugal (UAlg); ii) The Los Arenales MAR sites, Spain (Tragsa), iii) the Suvereto MAR site, Italy (SSSA); (iv) the Pwales Valley MAR Site, Malta (EWA); (v) the Argolis Field, Greece (NTUA); and (v) the Menashe Streams MAR site, Israel (ARO). Performance is evaluated in terms of the seven factors described above, preceded by an introduction to the site. Section 3 studies the long-term indirect infiltration of water in Spain through dykes. Subsequently, the technical solutions drawn from MARSoluT’s MAR sites are presented (section five). The report finishes with conclusions (section six), references (section seven), and the annex.

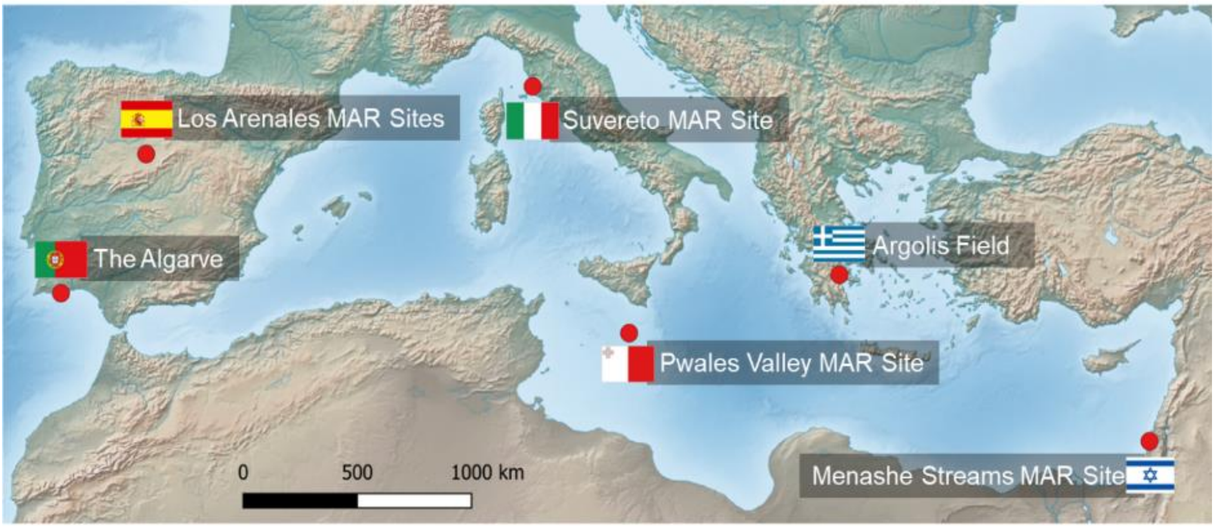


Figure 1. *Location of MAR sites evaluated in the current MARSoluT deliverable.*

2. Objectives

The main objective of deliverable D4.4 is to conduct statistical analysis and evaluate long-term monitoring data and site upgrades of identified hotspots. This objective is linked to a MARSOL project's line of research concretised in deliverables D13.1 and D13.3.

The following are the specific objectives that allow achieving the main objective:

- Reviewing the main accomplishment of Deliverables D13.1 and D13.3.
- Reporting on the performance of MARSoluT's MAR sites through the analysis of monitoring data.
- Conceptualising new technical solutions for MAR based on the progress at MARSoluT's MAR sites.

3. Background on MARSOL Site Upgrades

Several lines of research developed in MARSoluT WP 4 began in MARSOL (FP7 Water-Inno-demo call, 2013-2016), especially in WP13, which provided technical solutions for MAR design and construction criteria. MARSOL's deliverables D13.1 and D13.3 (accessible at https://www.dinamar.tragsa.es/) accomplished the following results:

- Examined the implemented technical solutions at the MARSOL demonstration sites to define a baseline.
- Developed new designs, technologies and construction criteria.
- Guidelines for selecting appropriate MAR technical solutions and construction under diverse environmental conditions.
- The proposition of effective strategies to integrate MAR techniques to expand the water supply capacity.
- Analysis of best MAR practices and technical solutions at the MARSOL demonstration sites through benchmarking.
- Demonstration that MAR is, in some cases, the only strategic solution to face water scarcity and extreme weather events, especially droughts ("the key is the storage").

Key information from these deliverables is presented below, constituting a baseline for many of the solutions and analyses provided in the present report (D4.4).

3.1 MARSOL Deliverable D13.1: "*MAR Technical Solutions Review and Data Base*" - main outcomes

MARSOL's D13.1 report (Fernández Escalante et al. 2015) described in detail the state of the art of MAR technical solutions at MARSOL demo-sites. These solutions included operative and management aspects, criteria for the design and construction of MAR facilities, and a set of problem-solution binomials.

The technical solutions (TS) were distributed among five groups according to the main component or aspect of the MAR system. Each group was further subdivided in various thematic categories. A total of 73 TS were identified.

3.1.1 Source water – quantity

1. Preselecting: define criteria for selecting MAR source water when several sources are available.
2. Temporary storage of MAR water in surface reservoirs.
3. Control of the flow velocity of MAR Water (e.g., dykes).
4. Manage/avoid operations during specific events/periods (e.g., freezing conditions and heat waves).
5. Install security structures to prevent overflow, such as run-off tramps, spillways, etc.

3.1.2 Source water – quality

3.1.2.1 Pre-treatment

6. Pre-treating the water for MAR at the origin. Various technologies are applicable: WWTP, membranes, mud lines, filters, packets, etc.
7. Pre-treating the water for MAR at the beginning of the MAR scheme. Various technologies are applicable: filtering beds, decantation/stagnation structures, deaerating, etc.
8. Including multiple barriers along water conveyance structures to improve water quality, e.g., controlling the pH through mudstone gravel filters.
9. Utilising various procedures and products for disinfecting, such as Cl, I, O3, H2O2, UV rays, etc.
10. Using chemical additives to eliminate clogging layers (specify).
11. Combining different methods to improve MAR water quality, e.g., a "triplet scheme" which involve wastewater treatment plants (WWTPs), green biofilters, and artificial wetland.

3.1.2.2 Surface facilities

12. Designing durable slopes (e.g., rubble works, gabions, etc.).
13. Controlling hydraulic heads.
14. Considering denitrification processes/additives (e.g., annamox).
15. Employing mechanisms to mix vertical water layers, such as stopping devices.

3.1.2.3 Injection

16. Employing anticorrosive materials.
17. Changing pumping depth.
18. Reduce fertiliser and pesticide input in nearby areas.

3.1.2.4 Receiving medium

19. Employing mechanisms to avoid aeration of MAR water, e.g., communicating vessels, open/buried structures, velocity control, etc.
20. Using deaerating techniques, for instance, through piezometers or increasing distance between injection-extraction points.
21. Maintain the system as closed as possible from the atmosphere to avoid air bubbles in the recharge water and algae blossom.
22. Avoid seawater intrusion by installing hydraulic barriers.
23. Considering groundwater flows in complex systems.

3.1.2.5 Other

24. Using fish species to reduce clogging (e.g., medaka).

3.1.3 Receiving medium (saturated and unsaturated zones)

3.1.3.1 Previous studies

25. Improving as much as possible the knowledge about the receiving medium.
26. Using natural structures on the site can contribute to avoiding water losses from the system.

3.1.3.2 Surface facilities

27. Improving the design of the surface facilities, by including, for instance, furrows at the bottom of an infiltration basin.

28. Using geo-fabrics at the bottom and slopes.
29. Injecting water in wells and pits close to the MAR infiltration infrastructure.
30. Maintaining geo-fabrics, membranes, and filters through backwashing.
31. Using water jet-type cleaning techniques.
32. Using chemical products such as additives to conduct cleaning.
33. Conducting operations at the bottom of infiltration basins such as algae drying, natural bed drying, cryo-treating, and cake cracking (cake).
34. Mechanical cleaning (scarification or silting zones and cleaning /replacement) (specify).

3.1.3.3 Injection facilities and piezometers

35. Alternate normal and inverse pumping and change their frequency.
36. Employing chemical cleaning (use of chemical additives) techniques for the regeneration of recharge wells.
37. Selecting casing materials for wells according to groundwater characteristics (pumping quantity, water quality, and expected durability).
38. Employing automatic systems to control water levels.
39. Employing clogging preventive procedures, e.g., cathodes protection.

3.1.3.4 Operative aspects

40. Using multiple infiltration systems that allow cleaning in one of them while the rest operates.
41. Cleaning the vegetation in the MAR facilities.
42. Utilising plant roots to increase infiltration rates.
43. Changing the frequency of cleaning techniques.
44. Using basic cleaning vehicles (BCVs).

3.1.4 Operation, maintenance, decision support systems, management, and reuse

3.1.4.1 Operation

45. Considering ex-situ management practices, such as water governance.
46. Selecting the most appropriate period and place to deviate water for MAR considering previous concessions.
47. Initiating MAR operation progressively.
48. Measuring and controlling (automatic or manual) the water flow volume and velocity.
49. Using multiple infiltration systems that allow cleaning in one of them while the rest operates.
50. Considering alternative sources of water for MAR.
51. Monitoring chemical properties of the source water during recharge cycles

3.1.4.2 Maintenance

52. Developing a specific protocol to control clogging.
53. Developing a protocol for the proper functioning of hydro-mechanical, e.g., the pressure inside the conveyance pipes.
54. Designing programs for cleaning and maintenance and leaving room for decisions "on the go".

3.1.4.3 Decision support systems

55. Integrating all the elements in the system properly.
56. Promoting the participation of farmers and other decision agents in water management.
57. Limiting fertilisers’ use.

58. Decreasing untreated water spills in the area.
59. Creating a protection perimeter around the MAR facilities to avoid vandalism.
60. Including safety measures for humans and fauna in MAR facilities.
61. Regulate the public use of the facilities, if any.

3.1.4.4 Management

62. Adopting at an early stage the best available techniques.
63. Designing and adopting proper watching and control programmes.
64. Constructing dams specifically designed for MAR.
65. Constructing WWTP specifically designed for MAR.
66. Considering financing mechanisms to give continuity to R&D projects.
67. Consulting existing operative guidelines.
68. Utilising surface and underground sensors to monitor MAR operations.

3.1.4.5 Reuse

69. Reuse abandoned wells and facilities that were intended for other purposes, such as River Bank Filtration (RBF) systems.
70. Using existing natural previous elements to improve MAR efficiencies, such as dolines and sinkholes.
71. Using pre-existing elements for MAR, e.g., rivers, dams and meander scarfs.

Detailed explanations of the technical solutions are available in MARSOL’s deliverables D13.1 and D13.3.

As part of this deliverable, a movie about the Los Arenales MAR demonstration site was created and titled "*Arenales Movie: Technical solutions for Managed Aquifer Recharge at Los Arenales aquifer, Castile and Leon (Spain)*". This movie is intended for technicians and students and explains site conditions and the MAR technical solutions applied. The video is available on the Water Channel (http://thewaterchannel.tv/media-gallery/6139-managed-aquifer-recharge-at-los-arenales-aquifer-castille-and-leon-spain), and on YouTube (https://youtu.be/Dw22rcEQdiw).

The most relevant conclusions drawn from the study of the entailed technical solutions are:

- Before implementing MAR, it is necessary to choose the most appropriate method. Surface infiltration systems can have the advantage of pollutant attenuation in the vadose zone.
- In most demonstration sites, water availability for MAR is not guaranteed during long droughts. Consequently, alternative sources such as reclaimed water should be considered.
- Although many MAR sites have been operating for several years, there is always room to improve design, operation and maintenance.
- Detailed technical studies before MAR facility construction can help considerably reduce or avoid problems.
- Most of the MAR demonstration sites show a good performance and, in some cases, even beyond expectations despite some drawbacks. However, conducting MAR in areas with unfavourable or difficult conditions (e.g., karstic and fractured aquifers) can lead to larger failures.

- Water treatment and reuse (sometimes through MAR) can help satisfy growing water demand. For instance, in coastal areas with a significant seasonal demand variation, jointly using systems for water storage and regeneration is having great success in supplying drinking water and counteracting seawater intrusion.
- Depending on the local conditions, design parameters and management practices must be created "a la carte".
- The process of improving MAR sites is never ending. Each improvement comes with a new research line.

3.2 MARSOL Deliverable D13.3: "*MAR Design and Construction Criteria*" - main outcomes

MARSOL's D13.3 deliverable includes and inventory of the 25 MAR types available. It consists of a update of the inventory developed in the DINA-MAR project (2010). The 25 typologies, omitting those redundant, are the following:

1. Infiltration ponds/wetlands.
2. Infiltration canals (= channels) and ditches.
3. Ridges/soil and aquifer treatment techniques.
4. Infiltration fields (flood and controlled spreading).
5. "Accidental" recharge by irrigation return.
6. Reservoir dams and dams.
7. Permeable dams and gabions.
8. Drilled dams.
9. River bed scarification.
10. Qanats (underground galleries).
11. Open infiltration wells.
12. Deep wells and well-boreholes.
13. Boreholes.
14. ASR.
15. ASTR.
16. River Bank Filtration (RBF).
17. Inter-dune filtration.
18. Underground irrigation.
19. Rainwater harvesting in unproductive.
20. Sustainable Urban Drainage Systems (SUDS).

Figure 2 shows the existing MAR types, visual representation, and picture of an actual site. The figure also indicates whether a type is present at a MARSOL demonstration site.

The recommendations for each typology of the inventory are developed in the deliverable. Some specific items are under improvement during MARSoluT progress.

The following are the most important conclusions from this report:

- An environmental impact assessment at MAR sites shows that MAR schemes can solve problems and create new ones. Fortunately, most negative impacts can be mitigated by considering site-specific conditions.
- Not all MAR types were applied in the MARSOL MAR sites.
- It is necessary to design SMARTS (Sustainable Managed Aquifer Recharge Technical Solutions) that involve expertise gained in previous projects.
- New facilities incorporate updates and state-of-the-art technology that are based on previous experiences, resulting in a constant process of improvement. The same applies to SAT techniques at a smaller scale, in which every new recharge cycle becomes an opportunity to improve.
- Even if the overall performance is satisfactory, every MAR scheme is improvable.
- In the future, the need for a reliable water supply will force a move away from natural resources and towards water reuse, which can often supply recharge water 24/7.
- Optimal MAR facility designs must come along with wise operation and sound planning, management, cleaning and maintenance.
- MAR techniques can leverage previous infrastructure (quarries, mines, sand pits, and old ditches) to decrease costs and building times.
- Perhaps the major issue in MAR operation is clogging. Preventive measures are paramount to deal with it.
- Modifying the receiving medium (e.g., bottom of and infiltration basin) can be advantageous to increase infiltration rates and lengthen the facilities’ lifespan.
- In terms of water quality, the most important measure to achieve great MAR performance is pre-treatment. The better the quality of the original water, the better the results.
- It is imperative to consider the experience of specialists and strengthen links between technicians, farmers and regulators.
- Showcasing a successful experience with MAR is vital to improving confidence in the technique.
- It is essential to use multiple approaches for technological watching (e.g., web alerts) to be updated on the best available technologies.
- Conducting previous studies carefully can help avoid inconveniences during MAR facility construction and operation.

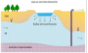
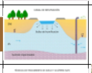
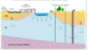
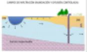
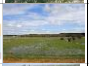
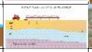
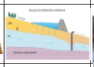
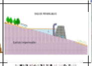
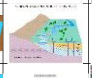
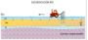
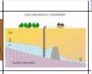
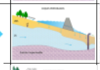
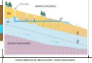
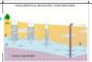
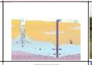
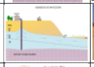
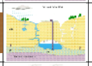
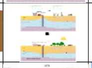
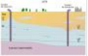
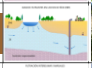
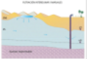
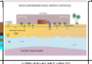
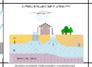
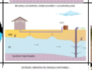
N	SYSTEM	MAR DEVICE	LOGO	FIGURE	PHOTO	LEGEND	1: Lavrion, Greece	2: Algarve and Alentejo, Portugal	3: Los Arenales, Spain	4: Llobregat River, Spain	5: River Brenta, Italy	6: Serchio River, Italy	7: Menashe, Israel	8: South Malta, Malta
1	DISPERSSION	INFILTRATION PONDS/ WETLANDS				Artificial wetland to recharge in Sanchón, Coca, Arenales aquifer		✓	✓	✓				
2		CHANNELS AND INFILTRATION DITCHES				Artificial recharge channel of the Basin of Santiuste, Segovia, Spain, operative since 2002.			✓					
3		RIDGES/ SOIL AND AQUIFER TREATMENT TECHNIQUES	SAT			Furrows at the bottom of a infiltration pond in Santiuste basin (Arenales)	✓	✓	✓	✓	✓			
4		INFILTRATION FIELDS (FLOOD AND CONTROLLED SPREADING)				Infiltration field in Carracillo, Arenales aquifer	✓		✓		✓			
5		ACCIDENTAL RECHARGE BY IRRIGATION RETURN				Artificial recharge by irrigation return. Extremadura, Spain. Photo: Tragsa		✓			✓			
6		BOFEDALES WETLANDS				Bofedales (Colombia)								
7	CHANNELS	RESERVOIR DAMS AND DAMS				Artificial recharge dam in Arenales. Segovia, Spain.			✓					
8		PERMEABLE DAMS				Permeable dam in Huesca, Spain. Photo: Tragsatec.								
9		LEVEES				Levees in Santa Ana river, Orange County, California, USA. Photo: A. Hutchinson.								
10		RIVERBED SCARIFICATION				Scarification at Besós riverbed, Barcelona, Spain. Photo: J. Armenter.								
11		SUB-SURFACE/ UNDERGROUND DAMS				Sub-surface dam in Kitui, Kenya. Photo: Sander de Haas.								
12		DRILLED DAMS				Drilled dam. Lanjarón, Granada, Spain. Photo: Tragsatec.								
13	WELLS	QANATS (UNDERGROUND GALLERYS)				Qanat at Carbonero el Mayor, Segovia, Spain. Photo: E.F. Escalante			✓					
14		OPEN INFILTRATION WELLS				Passive infiltration well. Santiuste basin		✓	✓					
15		DEEP WELLS AND BOREHOLES				Artificial recharge well. Menashe. Israel. Photo: EFEscalante								✓
16		BOREHOLES				Borehole in Israel. Photo: EFEscalante								
17		SINKHOLES, COLLAPSES...				Sinkhole called"El Hundimiento". Alicante, Spain. Photo: DINA-MAR								
18		ASR	ASR			ASR device in Scottsdale, Arizona, USA. Photo: DINA-MAR					✓		✓	
19		ASTR	ASTR			ASTR device in California, USA.				✓				
20	FILTRATION	RIVER BANK FILTRATION (RBF)	RBF			MAR RBFsystem in Villeguillo, Arenales, Spain		✓				✓		
21		INTERDUNE FILTRATION				Interdune filtration in Carracillo Eastern site. Arenales, Spain			✓					
22		UNDERGROUND IRRIGATION				Underground irrigation in Andalucía, Spain. Photo: Tragsa.								
23	RAIN	RAINWATER HARVESTING IN UNPRODUCTIVE				Rainwater harvesting in unproductives for MAR techniques.			✓					
24	SUDS	ACCIDENTAL RECHARGE PIPES AND SEWER SYSTEM				Artificial recharge from sewer system in Arenales, Spain			✓					
25		SUSTAINABLE URBAN DRAINAGE SYSTEMS				SDUS. Gomeznarro park. Madrid, Spain. Photo: E.F. Escalante.								

Figure 2. *MAR types and their presence at the MARSOL demonstration sites.*

4. Evaluating the Performance of MAR Systems Across the Mediterranean

4.1 The Algarve (Portugal)

4.1.1 Introduction

It is worth to notice that most of this chapter's contributions proceed from MARSoluT's Early Stage Researcher (ESR) Kathleen Standen and her tutors during the project's development.

The studies referenced within D4.4 in the Algarve focus on the Campina de Faro aquifer (formerly designated as M12 for its groundwater body´s designation), which is now divided into two regions for management purposes, based on the different pressures in each area. The eastern sector (M19) has been subject to historical and on-going nitrate contamination from agricultural activities, whilst the western sector (M18) is facing aquifer levels below sea level across much of the aquifer and consequently is at risk of seawater intrusion (SWI). The aquifer is shown on **Figure 3**.

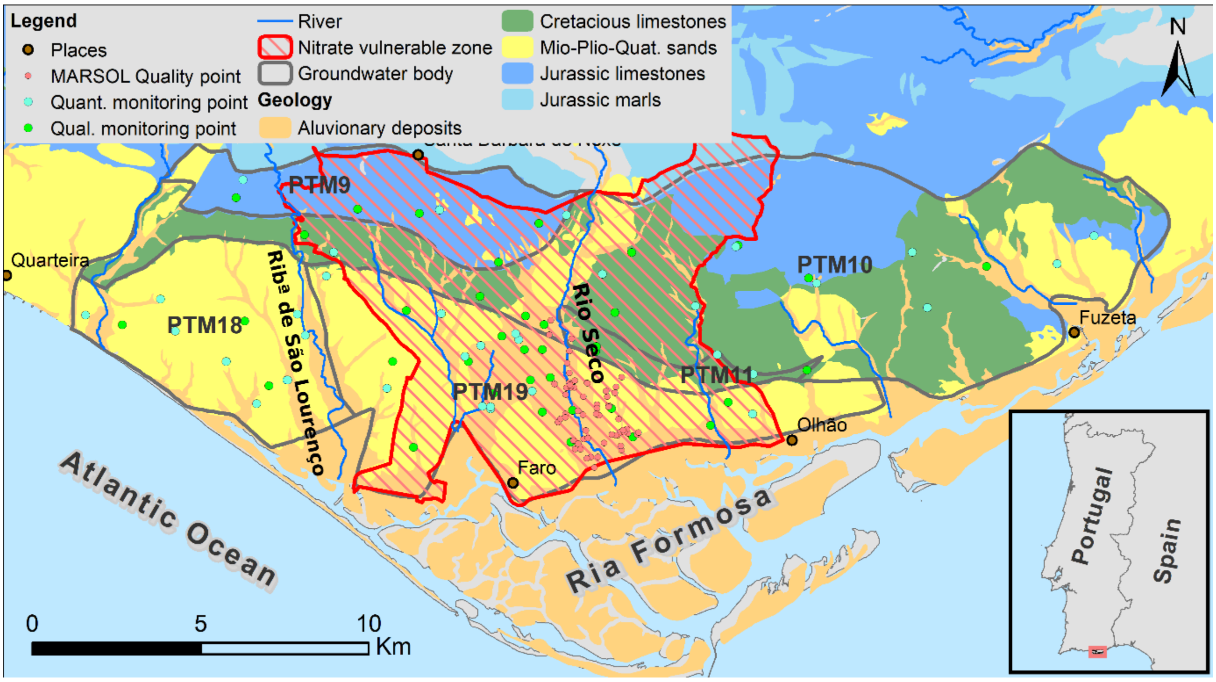


Figure 3. Study area, main groundwater bodies, simplified geology, designations and monitoring network. From Costa et al. (2020).

Previous MAR investigations have mainly focussed on the eastern part of the Campina de Faro aquifer (M19). These included the EU-funded GABARDINE (Diamantino 2009) and MARSOL projects (Leitão et al. 2017), where infiltration basins were excavated into the Rio Seco, the main surface water drainage that crosses M19 from north to south as shown in **Figure 3**.

During MARSoluT, a feasibility study of MAR potential across the whole of the Algarve River Basin District (RH8) was undertaken (reported as MARSoluT Deliverable D4.2, 2023). A detailed numerical modelling study was also undertaken to investigate the potential of MAR to mitigate seawater intrusion (SWI) in the western part of the Campina de Faro aquifer, the Vale do Lobo sub-system (Standen et al. 2022). Several recent studies have also been completed that investigated the potential of greenhouse runoff recharge (Costa et al. 2020) and assessing the impact of management changes on groundwater nitrate concentrations (Costa et al. 2021).

This extensive body of evidence means that we are now able to identify and quantify the water sources for MAR in the area, determine whether these are sufficient to achieve improvement in the groundwater status alone, and identify if and where further measures are required.

4.1.1.1 Water management challenges

In Europe, the Water Framework Directive (WFD) legislation requires EU member states to achieve "Good" status for all groundwater and surface water bodies by 2027. Where this status is not met, measures must be included in the River Basin Management Plan (RBMP) Program of Measures to achieve these objectives. In Portugal, good quantitative status was defined where annual abstraction is <90% average annual recharge for the first and second cycles of the RBMP, whilst the draft RBMP for consultation for the third cycle now defines 'good' status based on abstraction <80% of historical recharge (APA 2022). In the third cycle in the RH8 region (Rivers of the Algarve), 5 of the 25 groundwater bodies fail to meet good status, including both the Vale de Lobo and Faro subsystems of the Campina de Faro primarily due to golf course irrigation, and agricultural irrigation respectively.

In the draft RBMP of the third cycle, there are 20 groundwater bodies with 'good' chemical status and 5 with a 'mediocre' chemical status including nitrate in M11 (Chão de Cevada – Quinta João de Ourém) and in M19 (Campina de Faro – Subsystem Faro); and chloride in M18 (Campina de Faro – Subsystem Vale de Lobo).

Groundwater is used in the Campina de Faro aquifers for the golf, tourism, and agriculture sectors, with current abstraction in M18, M19 and M11 estimated at 12.80 Mm^3/year, whilst long term annual recharge for these aquifers is estimated to be significantly lower at only 8.83 Mm^3/year. Consequently, the annual water balance deficit in the Campina de Faro is large, with M18 (4.10 Mm^3/year), M19 (1.35 Mm^3/year) and M11 (0.29 Mm^3/year) affected (APA 2020), leading to declining water levels and SWI in places.

4.1.1.2 Campina de Faro nitrate contamination

Aquifer contamination by fertilizers has been of concern for aquifers in South Portugal since the 1980s, particularly for the Campina de Faro aquifer system, where nitrogen fertilizers used in agriculture represent the largest diffuse pollution threat to groundwater quality (Stigter et al. 2013). The Nitrate Directive and WFD resulted in the implementation of measures by the regulatory agency, such as encouraging good agriculture practices to achieve 'good' chemical status. However, groundwater quality has not improved significantly since the implementation of these measures, and well-defined nitrate contaminant plumes are slowly heading towards the Ria Formosa coastal lagoon (an EU-designated special site), with evidence of decreasing concentrations of nitrates in the northernmost region and increasing concentrations in the southern part of the region (Stigter 2005; Diamantino 2009; Stigter et al. 2011, 2013; Lobo Ferreira et al. 2016).

The observed nitrate concentrations in 2016 at the 91 groundwater quality monitoring points (from APA official network and MARSOL project) are presented in **Figure 4**. Of these, 65 exceed the threshold value of 50 mg/l (Costa et al. 2020).

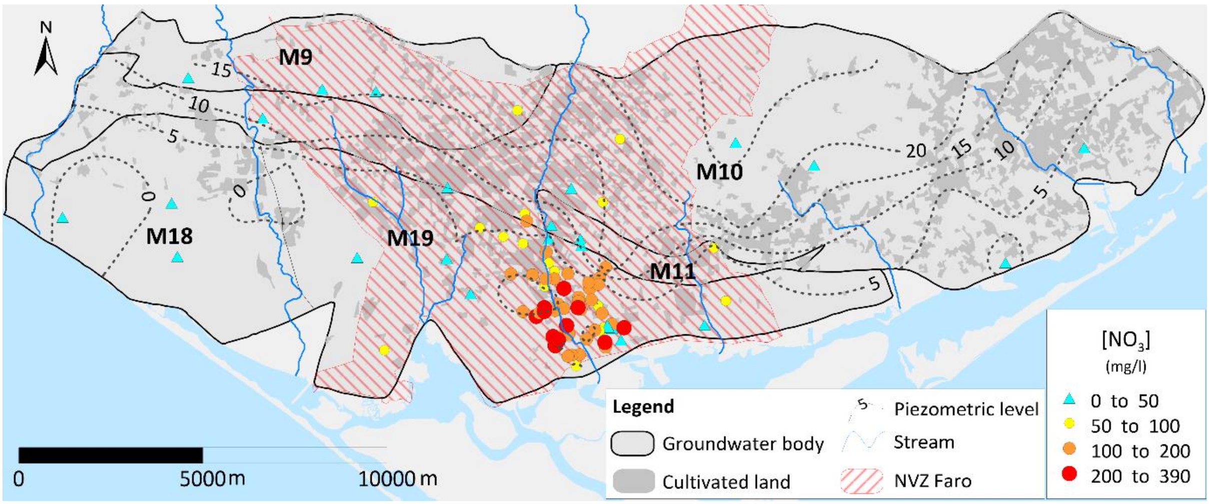


Figure 4. *Observed nitrate concentrations and piezometric levels from May 2016 according to observation points from the Environmental Protection Agency and the MARSOL sampling campaigns. From Costa et al. (2020).*

4.1.1.3 Risks of seawater intrusion

Current groundwater extraction is estimated at 6.45 Mm^3/year (APA 2020) in the Vale do Lobo sector (M18), whilst long term recharge is 3.46 Mm^3/year. Groundwater from this coastal aquifer has been used extensively for irrigation over the last 50 years, for golf, tourism, and agricultural purposes. Consequently, hydraulic heads are now well below sea level across much of the aquifer as shown in **Figure 5** (A), and several boreholes can no longer be used due to high chloride concentrations. Time series from three boreholes with the longest period of record are shown in **Figure 5** (B), indicating that hydraulic heads were already declining during the 1980's, possibly reaching a new equilibrium since the late 1990's with higher seasonal variation.

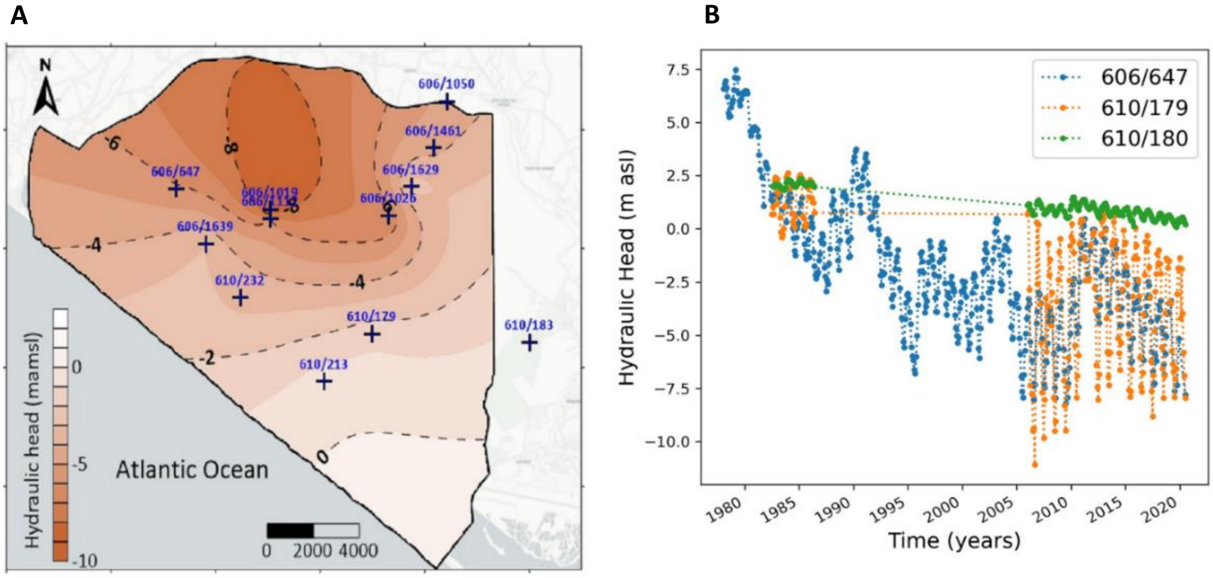


Figure 5. *Hydraulic head contours from semi-confined aquifer, October 2018 (A); Selected hydraulic head time series at piezometer locations 606/647 (semi-confined), 610/179 (semi-confined), and 610/180 (phreatic) (B). From Standen et al. (2022).*

Time series measurements of chloride concentrations over time are only available at 4 locations in the Vale do Lobo sector, with 2 of these exhibiting increasing trends. A monitoring program during 2019/2020 encountered chloride concentrations up to 2,200 mg/l in extraction boreholes, with land managers reporting that several boreholes are no longer used as their chloride concentrations are too high for irrigation (Fernandes et al. 2020).

4.1.1.4 Previous MAR installations

In-channel infiltration basins were developed on the Rio Seco, Algarve region, Portugal, during the EU funded GABARDINE (Lobo Ferreira & Leitão 2014), and MARSOL (Leitão et al. 2017) projects with the purpose to increase the Campina de Faro aquifer recharge to mitigate historical and current nitrate concentrations. Three infiltration basins were excavated to a depth of 6 m, to remove a low permeability clay layer, before being filled with clean gravels. The infiltration basins' effectiveness does not appear to have changed over time and clogging with fine sediments does not appear to be a significant issue (Oliveira et al. 2015).

However, achieving aquifer-scale water resource benefits from these pilot infiltration basins is not possible. With limited surface area (300 m^2), infiltration rates of 1 m/d, and Rio Seco flows for 60 days/year, only an average of ~18,000 m^3/year additional recharge is achieved. However, a larger, potentially off-line infiltration basin, or reusing existing shallow wells for recharge could result in a much higher proportion of the Rio Seco flow being captured (1.5 Mm^3/year of the 4.4 Mm^3/year annual average flow), as detailed in MARSoluT's Deliverable D4.2.

Re-using shallow wells (known as "noras") for recharge could be more practical than in-channel MAR. The well inventory indicates that there are over 60 noras in M19 alone, and a recharge test reported in Costa et al. (2020) indicated that for a typical construction (4.5 m diameter, 20 m deep, rest water level 10 m below ground level), a recharge rate of 2,500 m^3/d could be achieved for a rise in groundwater levels of around 8 m. Therefore, 1.5 Mm^3/yr recharge could be achieved using only 10 suitable noras, based on the water availability from the Rio Seco, providing issues such as ownership and protection from historic / potential future contamination can be resolved.

4.1.1.5 Other MAR-related studies

A recent study identified the potential water available for recharge from intercepting greenhouse roof runoff and recharging the Campina de Faro aquifer (Costa et al. 2020) for the purpose of reducing groundwater nitrate concentrations by dilution. Only the greenhouses that are totally within or intercept the M18/M19 aquifer limits were considered in this study, and their total surface area accounts for 2.74 km^2 (in-use greenhouses only). Assuming an annual average rainfall of 570 mm (Nicolau 2002), a total rainfall interception of 1.63 Mm^3/year was calculated. The study identified greenhouses located within 150 m of an existing large diameter well (to recharge the aquifer), concluding that 1.51 Mm^3/year of rainwater could be harvested from a total greenhouse surface of 2.21 km^2 and recharged by existing wells.

Numerical modelling results show improvement in nitrate concentrations in the study area, in certain locations decreasing up to 70 mg/l by 2027. However, this MAR option is insufficient on its own to resolve the groundwater nitrate contamination, predicting a decrease in the number of nitrate threshold exceedances in observation points, from 33 to 30 by 2027 and 14 to 9 by 2040 (Costa et al.

2020). Despite this, there is a water resource benefit slightly greater than the estimated annual deficit for M19 (1.35 Mm^3) if this scheme could be implemented at scale.

4.1.2 Site upgrade

New MAR facilities were not developed during MARSoluT, however numerical modelling was carried out to determine whether MAR could result in an aquifer-scale benefit to the Vale do Lobo sector and protect the aquifer from SWI. The modelling is described briefly below and presented fully Standen et al. (2022).

4.1.2.1 Modelling rationale

It is clear the current rates of extraction from the Vale do Lobo sector are unsustainable and meeting the water balance requirement of the WFD will not prevent SWI. MAR has been identified as a potential mitigation measure. Before committing to further investment in investigating MAR options, decision-makers need to understand whether it is likely to prevent SWI in this aquifer. Therefore, a decision-support groundwater model was developed during the MARSoluT project.

Two types of water are locally available for MAR in this area:

- Ephemeral river flow, highly variable with an average annual flow of 1.25 Mm^3/year; and
- Treated wastewater, from three treatment works in the area: Quinta do Lago (0.76), Vale do Lobo (0.16) and Faro Noroeste (1.50 Mm^3/year).

Recharge is proposed by boreholes into the Miocene, at locations close to the water sources, as shown in **Figure 6**.

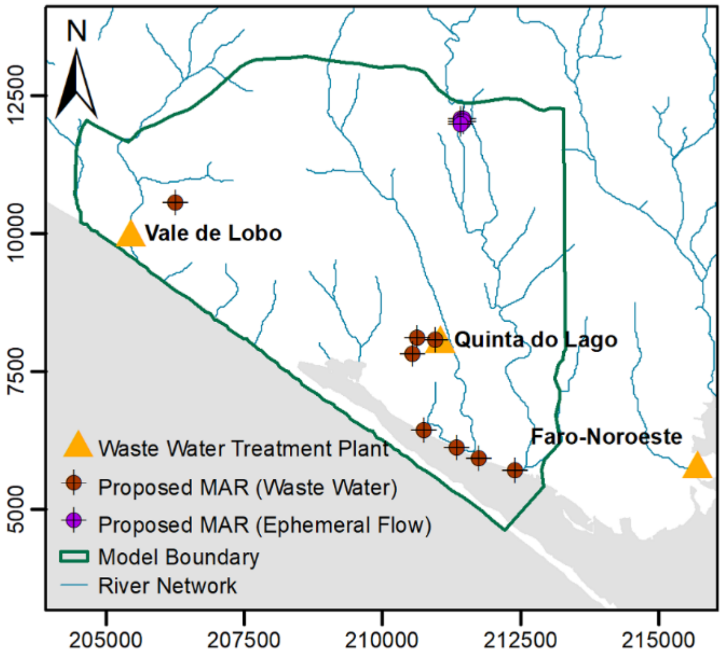


Figure 6. *Locations of wastewater treatment plants, and proposed MAR borehole locations. From Standen et al. (2022).*

4.1.2.2 Groundwater model development

A groundwater model was developed specifically to determine whether these sources of water could resolve the problem at an aquifer scale, an ambitious, but important aim. To account for parameter and structural uncertainty, and allow quantification and reduction of predictive uncertainty, a fast and stable numerical model was required.

The groundwater model was constructed using MODFLOW6 (MF6) (Langevin et al. 2017), using the open source Flopy environment (v.3.3.4) (Bakker et al. 2016). The lumped parameter recharge model, LUMPREM (Doherty 2020a) was used to estimate both recharge and groundwater abstraction for irrigation, based on daily rainfall and potential evapotranspiration. The sea boundary was defined with a general head boundary, where the head and conductance values were defined by the method by Hugman & Doherty (2022) accounting for the offshore extent with a complementary model.

Using a constant density model meant that the prediction was based on hydraulic heads to determine if MAR could raise hydraulic heads sufficiently at existing abstraction boreholes for them to be protected from SWI (based on the Ghyben-Herzberg relationship).

For the combined model (LUMPREM + MF6) a solution of minimum error variance (MEV) was sought using PEST_HP (Doherty 2020b), employing a highly parameterized approach. A unique solution was obtained using Tikhonov (preferred value) regularization. This was followed by history-matching and uncertainty quantification (and reduction) using PESTPP-IES (White 2018).

4.1.2.3 Model results

The resulting MEV parameter set achieved a good fit to measured observations of both hydraulic heads and groundwater extraction. In general, a better fit was obtained for heads in the semi-confined aquifer compared to the phreatic (as shown in **Figure 7**).

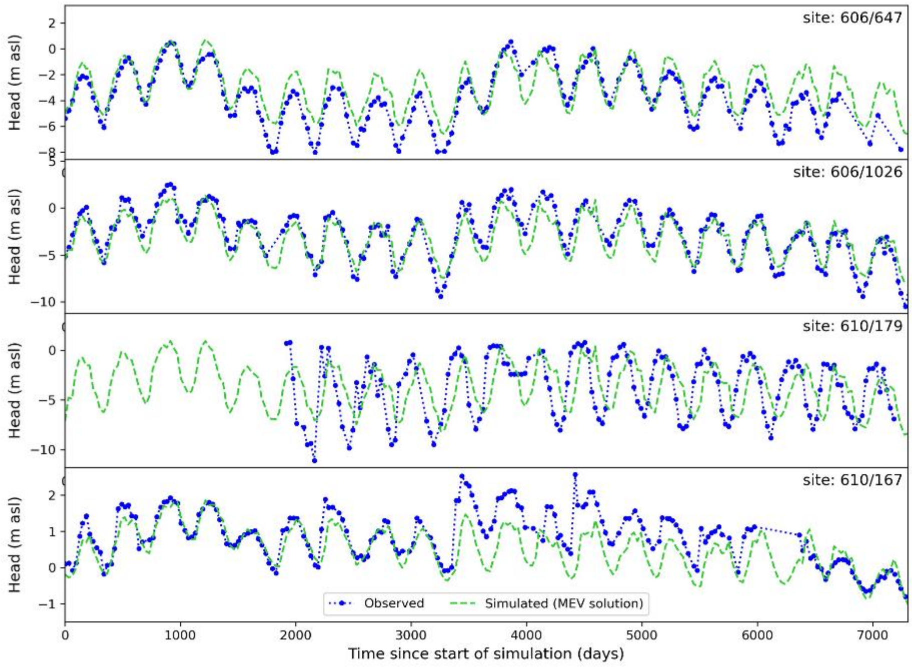


Figure 7. *Measured and simulated hydraulic heads for 606/647, 606/1026 and 610/179 from the semi-confined aquifer, and 610/167 from the phreatic aquifer. From Standen et al. (2022).*

The impact of MAR at the locations denoted Marsl (Ribeira da São Lourenço), Marww1 (Quinta do Lago), Marww2 (Vale do Lobo) and Marww3 (Faro Noroeste) is shown in **Figure 8**, where the ensemble of predicted heads is plotted against the minimum head required at each location.

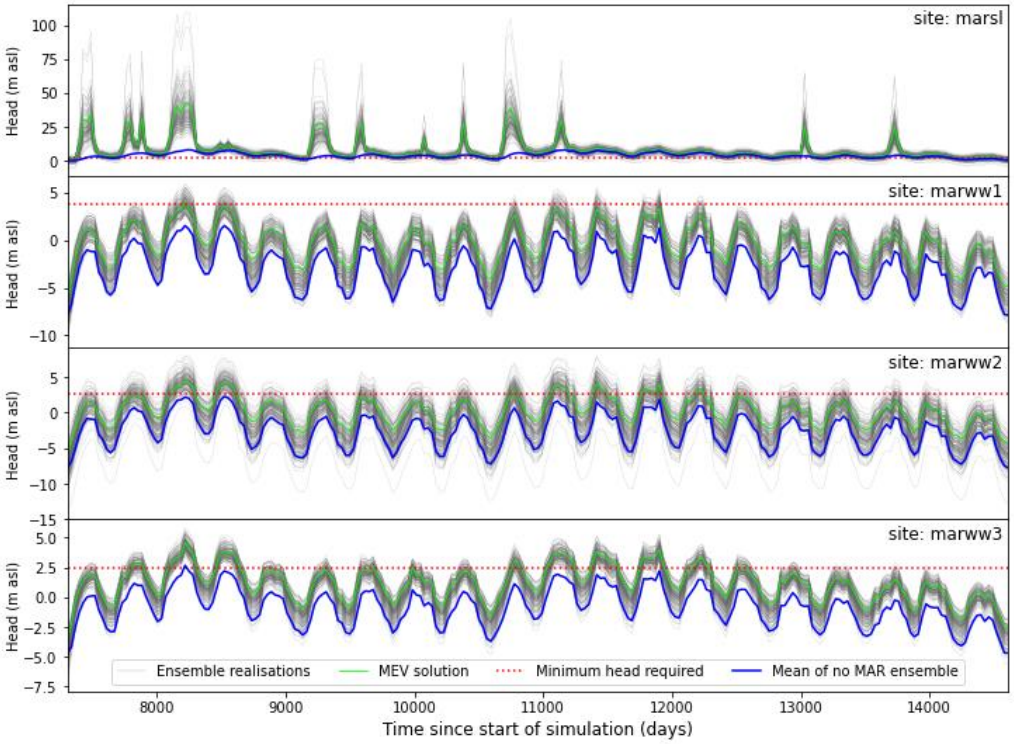


Figure 8. *Predicted hydraulic heads at MAR locations, showing MEV model results (green), each ensemble member (grey), mean of ensemble (blue), and the minimum head requirement at that location (red dashed). From Standen et al. (2022).*

At Marsl, the heads are highly dependent on the variability of ephemeral flow, with large increases occurring during recharge periods. However, these are short-lived, falling rapidly to levels similar to the minimum head requirement when additional recharge is not occurring. This indicates that MAR is probably not necessary at this location; a location further downstream would be more beneficial. At the other MAR locations, the minimum head requirement is only met during limited times and for some realisations.

4.1.2.4 Modelling conclusions

This case study demonstrates the development of a decision-support groundwater model to assess the effectiveness of MAR to prevent seawater intrusion in a coastal aquifer system, whilst allowing reduction of prediction uncertainty through data assimilation in a highly parameterized framework.

Evaluating MAR by the ability to achieve minimum heads that prevent the seawater interface encroaching above the base of the current extraction boreholes is pragmatic. It permits a preliminary, aquifer-wide assessment, and allows regulators and stakeholders to understand the benefits and limitations of MAR with a simple metric. The results demonstrate that MAR cannot increase the hydraulic heads sufficiently to attain the minimum heads required, even locally. Therefore, the proposed MAR schemes cannot prevent the interface from reaching the base of the existing extraction boreholes, and SWI the Vale do Lobo cannot be mitigated by MAR with the locally available water sources alone.

The minimum heads can be met for most locations in a 'no-extraction' scenario, the exception being deep boreholes close to the eastern boundary. Here heads are not sufficiently high enough to prevent SWI, indicating that the Vale do Lobo sector cannot be entirely protected from SWI under this scenario without concurrent management action in the eastern part of the Campina de Faro.

This modelling, in conjunction with that of Hugman & Doherty (2022), identifies for the first time, the true scale of the problem in this area, and how difficult it will be to resolve. A significant reduction in extraction will be needed in addition to, or as an alternative to MAR. Hugman & Doherty (2022) have shown that extraction rates would need to be reduced at least to 30% of current rates in Vale do Lobo, possibly even less. Required reduction in extraction would be less in conjunction with MAR.

Predicted climate change impacts on rainfall indicate that for the RCP4.5 scenario, rainfall is expected to decrease by 10% in the south of Portugal, with an associated reduction in wet days of 10-20%, which will lead to associated reductions in recharge (Soares et al. 2017). River flows in the Mediterranean region are likely to be even more intermittent in the future due to climate change, with an increasing number of zero flow events (Schneider et al. 2013), reducing the availability of water for MAR from this source. Meanwhile, socio-economic and agricultural development in the region will result in increased water demand for irrigation (Stigter et al. 1998; Hugman et al. 2017). These compounding factors will result in higher demand at a time when less water is available. Without action, the aquifer will face even more severe pressures in the future.

We have demonstrated an approach and associated model to support decision-making with the data currently available. This modelling has limitations, but we are still able to state with a relative degree of confidence that investing in MAR on its own is not going to solve the problem. In conjunction with Hugman & Doherty (2022), we have demonstrated that substantial further actions are needed to protect groundwater quality in the Vale do Lobo sector.

4.1.3 Water resource options and financial aspects

MAR therefore needs to be considered together with alternative water resource options for the Campina de Faro aquifer. Potential options are summarised in **Table 1** based on the Regional Water Efficiency Plan (APA 2020), and the MAR investigations described within MARSoluT's D4.2. Options are limited due to the high demand and lack of water sources. Ultimately, direct re-use of treated wastewater for irrigation appears to be a more appropriate use of this water source than for MAR at this stage, given the regulatory framework to support direct reuse. Therefore, the only sources of water for MAR are ephemeral rivers or rainwater harvesting from greenhouse runoff.

In the Campina de Faro, APA estimates that an additional 5.7 Mm^3/year to be needed just to meet current demand, but to protect the aquifer in the long term, and under future climate change, significantly greater volumes will be needed as our modelling has shown. This can be compared to 3.4 Mm^3/year available for MAR in this area from the Rio Seco, Ribeira da São Lourenço and greenhouse runoff. However, by implementing treated wastewater reuse from Quinta do Lago, Vale do Lobo, Faro Noroeste and Faro-Olhão ETARs with consequent reductions in groundwater abstraction, the deficit could potentially be met.

Estimated unit costs (€/m^3/year) are also provided in **Table 1**, from the Water Efficiency Plan, and from similar MAR schemes developed in Spain. Levelized costs are not available for all, therefore the cost comparison is based on capital costs for the average water resource benefit, presented in €/m^3/year. The most suitable scheme to base the estimated MAR costs on is that of Los Arenales, which recharges on average 2.4 Mm^3/year for a capital cost of 5.27 M€, i.e., a cost of 2.19 €/m^3/year (Fernández Escalante & San Sebastián Sauto, 2021). No costs were available for the greenhouse runoff recharge.

Costs for other measures being considered for the Campina de Faro area were available from the regional water efficiency plan (APA 2020). It can be seen that MAR could be a more cost-effective option than treated wastewater reuse and has significantly lower costs than the demand reduction measures at the golf courses. This is partially because all the 'quick-wins' and easier efficiency measures have already been introduced, therefore making further reductions is more difficult and expensive. Desalination is also being considered as a regional measure, but costs for desalination are not yet known. Capital costs are likely to be significantly higher, with significantly higher operational costs and energy requirements.

***Table 1.** Summary of Supply and Demand Options for Campina de Faro (from MARSoluT's Deliverable D4.2).*

Name	**Type**	**Horizon**	**Water Resource Benefit (Mm^3/year)**	**Unit Cost (€/m^3/year)**	**Details**
MAR at Ribeira da São Lourenço	Supply	Short	0.5	2.19	Limited water availability in Ribeira da São Lourenço, many years with zero flow, and low resilience of this option to climate change.
MAR at Rio Seco	Supply	Short	1.5	2.19	Water availability also limited in Rio Seco. Costs could potentially be reduced by re-using existing infrastructure (noras).
MAR greenhouse roof runoff	Supply	Medium	1.4	-	Assumes that runoff from 50% of all greenhouse roof runoff in M19, M10 and M11 can be captured and recharged.
Direct reuse - Quinta do Lago ETAR*	Supply	Short	0.76	2.46	Volumes available do not include proportion already re-used for golf course irrigation.
Direct reuse Vale do Lobo ETAR*	Supply	Short	0.16	2.46	Only small volumes available.
Direct reuse Faro Noroeste ETAR*	Supply	Short	1.50	2.46	Relatively small volume available, but located close to the Vale do Lobo sector.
Direct reuse Faro-Olhão ETAR*	Supply	Medium	5.82	2.46	Higher volumes available, but further away from Vale do Lobo sector where water is needed.
Demand reduction measures at Golf Courses	Demand	Medium	0.39**	4.28	Efficiency savings by reducing irrigated areas, changing type of grass and plants, and by reducing water demand in tourism sector.

*Reuse of treated wastewater in golf courses is estimated in the water efficiency plan to cost 13.81 M€ for a total of 5.62 Mm^3/year, which includes golf courses in the Vale do Lobo sector and others. **Water resource benefit proportioned based on number of golf courses / tourist areas within Campina de Faro compared to totals in Water Efficiency Plan.

4.2 The Los Arenales MAR sites (Spain)

4.2.1 Introduction

It is important to notice that a great part of this chapter´s contributions proceed from MARSoluT's Early Stage Researcher (ESR) José David Henao Casas and his tutors during the project's development.

Los Arenales MAR site is located in the region of Castile and Leon, central Spain (**Figure 9**), in the southern reaches of Douro River basin. It comprises three large-scale MAR systems: Santiuste, El Carracillo and Pedrajas-Alcazarén. Combined, these systems have 21 infiltration basins, approximately 50 km of infiltration basins, and six artificial wetlands to improve the quality of the recharged water before infiltration.

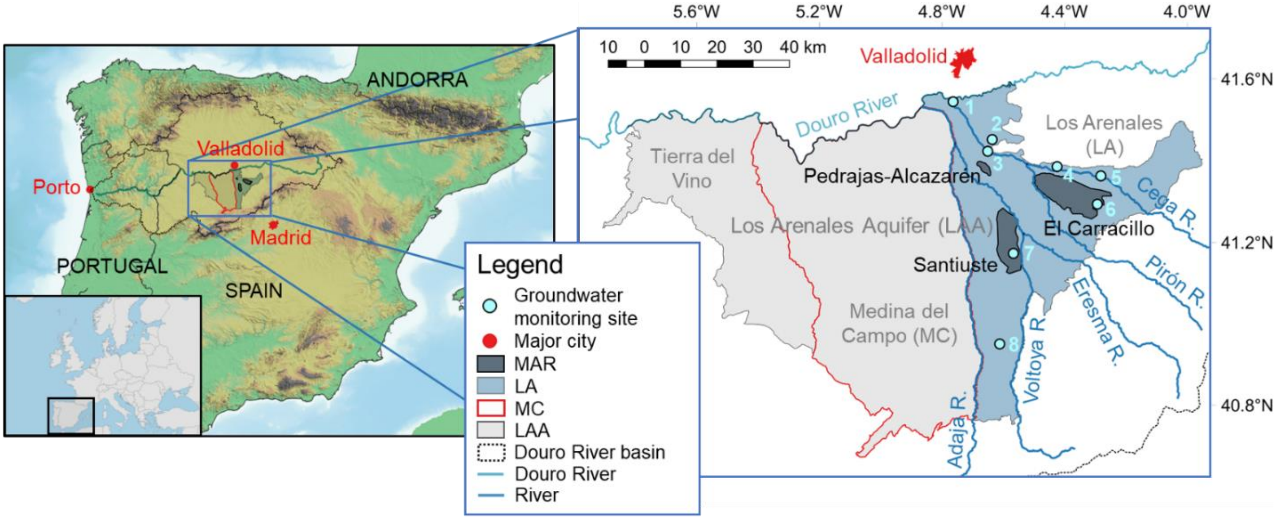


Figure 9. Location of Los Arenales MAR sites. LA: Los Arenales groundwater body; MC: Medina del Campo groundwater body; LAA: Los Arenales Aquifer. From Henao Casas et al. (2022d).

The Los Arenales MAR system aims to reverse groundwater storage decline and provide means for irrigation. In the second half of the 20th century, favourable financial and governmental conditions for agricultural entrepreneurs led to an unplanned and uncontrolled increase in irrigated agricultural land that resulted in groundwater abstractions beyond sustainable yields. Groundwater level decline rates of about 1 m/year were observed in several parts of the aquifer (**Figure 10**). To counteract this situation, the national government provided funds for constructing El Carracillo and Santiuste MAR sites (**Figure 11**). The works started in 1999 and were finalised in 2002. The first recharge cycle took place in the hydrological year 2002/2003. The Pedrajas-Alcazarén MAR site was built in 2012 because of the positive results observed in the pioneering MAR sites of Santiuste and El Carracillo and favourable technical conditions.

The study site is part of the Los Arenales Aquifer (LAA), which entails two aquifer systems. One of the systems comprises shallow and unconfined aquifers in quaternary fine sand dunes and alluvial deposits with thicknesses ranging between 5 m and 45 m (and commonly around 20 m). The second system is more profound and includes Paleogene-Neogene "sand and gravels from alluvial origin arranged in lenticular and elongated structures that are embedded in a predominantly silty and clayey matrix with varying degrees of permeability" (Henao Casas et al. 2022a) (**Figure 12**). Groundwater flow vectors converge to the Douro River (**Figure 9**) and have a predominant north-northeast direction. The shallow system is fed by rainfall, and, to a minor extent, irrigation returns. The deep system is replenished by natural seeping from the shallow system.

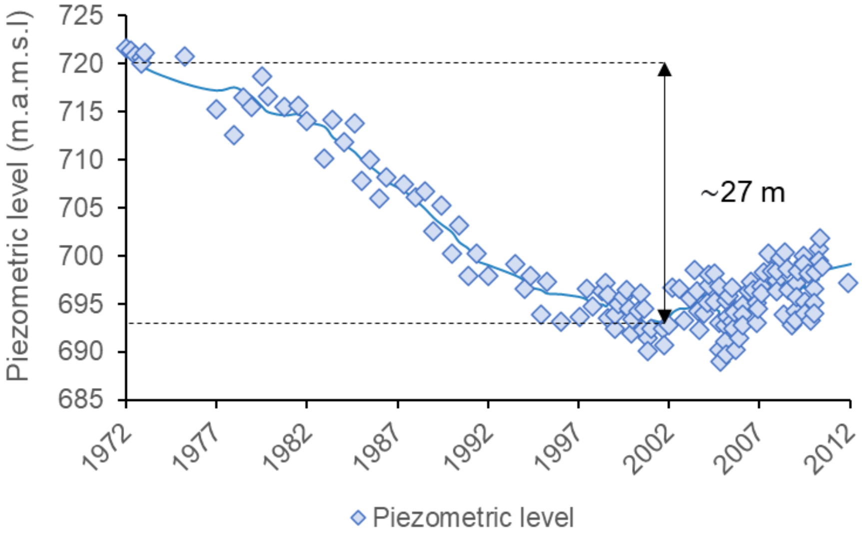


Figure 10. *Groundwater level decline since the 1970s and subsequent recovery thanks to MAR. The piezometric level observations correspond to Mojados groundwater monitoring site (site number 3 in Figure 9). From Henao Casas et al. (2022d).*

Figure 11. *Some of the infrastructure of the Los Arenales MAR systems: a) Santiuste infiltration basin during a recharge cycle; b) relatively small infiltration basin in the area of El Carracillo; c) infiltration channel connected to the Santiuste infiltration basin; d) La Laguna del Señor infiltration basin during a recharge cycle (El Carracillo area); e) La Laguna del Señor infiltration basin during a dry cycle; f) large infiltration basin in El Carracillo area. The pictures were taken between 2020 and 2022.*

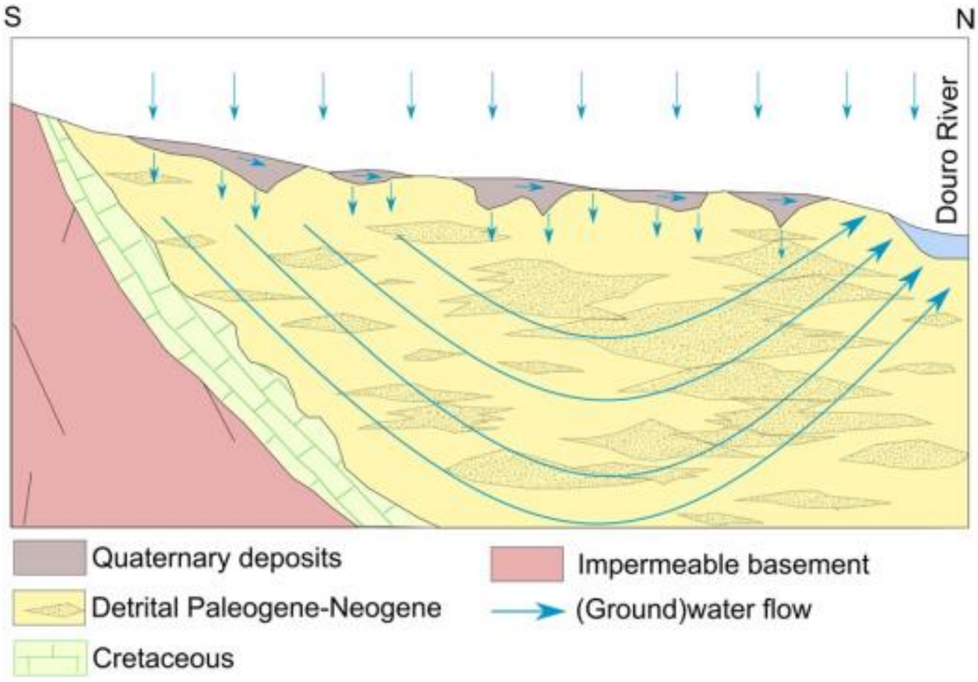


Figure 12. South-North hydrogeological section of the Los Arenales aquifer depicting the upper unconfined aquifer system (quaternary deposits) and the deep system. From Henao Casas et al. (2022a).

The study site features a Mediterranean continental climate with cold, wet winters and dry summers. Annual precipitation and evapotranspiration between 2002 and 2021 were 441 mm and 1,103 mm, respectively (**Figure 13**). The mean maximum temperature is about 19 °C, making it one of Spain's coldest regions. The rainy season extends between October and June, and maximum monthly precipitation is observed in October and May (**Figure 13)**. Interannual variability is relatively high (González-Hidalgo et al. 2010; Llorente et al. 2018).

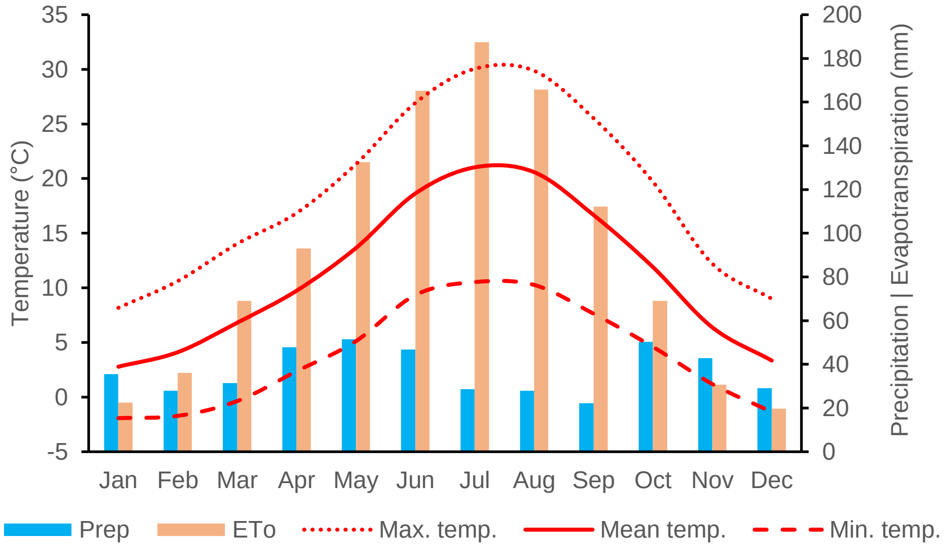


Figure 13. Climatological conditions in the site based on data from Nava de La Asunción (SG02) climatological station of the InfoRiego network.

4.2.2 Yearly recharge volumes and periods

The total MAR volume that the Los Arenales MAR systems have contributed to LAA between the hydrological years 2002/2003 and 2019/2020 was 93.5 Mm^3. The following subsections detail each system's characteristics and recharge over time.

4.2.2.1 El Carracillo

The characteristics of the Carracillo MAR system are the following:

- Length of infiltration channels: 17 km
- Infiltration ponds: 16
- Distribution points: 14
- Artificial wetlands: 3
- Additional elements: 1 river bank filtration (RBF) system

A scheme showing how the different elements combine can be found in Fernández Escalante et al. (2016) and Fernández Escalante & López-Gunn (2021). The characteristics of the water allowances for MAR are the following:

- River water source: Cega River
- Water allowance period:
  - 1 December - 30 April between 2009/2010 and 2012/2013
  - 1 January - 30 April the rest of the hydrological years
- Maximum allowed recharge duration:
  - 150 days/year between 2009/2010 and 2012/2013 (unless leap years)
  - 120 days/year for the rest of the hydrological years (unless leap years)
- Maximum allowed deviation rate: 1.37 m3/s.
- Maximum allowed deviation volume: 14 Mm3/year.

The regional water authority, the Douro River Basin Agency (CHD), changed the allowance period between the hydrological years 2009/2010 and 2012/2013. This decision was reverted due to conflicts with downstream water users, notably hydropower generators. **Table 2** shows the El Carracillo MAR system's recharge volumes and diversion days over time and the percentage of the maximum allowed volume and diversion duration they represent.

In the El Carracillo site, diverted volumes from the Cega River are, on average, 2.1 Mm^3 per hydrological year. Nonetheless, these volumes are variable and can go as high as 7.2 Mm^3 (2012/2013) and as low as 0.3 Mm^3 (2014/2015). There were even some years when MAR couldn't be conducted due to low Cega River flows (2004/2005 and 2007/2008). This variability is also reflected in the total days of recharge, which are, on average, 91.3, but range between 29 and 149.

The percentage of the maximum allowed volume of water that can be diverted and the maximum days for this diversion show that the system's capacity is never fully harnessed. On average, only 10% of the maximum allowed volume is diverted. 50% has been surpassed in a single occasion (2012/2013).

Concerning the maximum number of days allowed for extracting water from the Cega River, they tend to have a higher average of 56%, indicating that diversion takes place through a good extent of the allowed days, but volumes are considerably below optimal.

Table 2. *Diverted water volume and water diversion days from the Cega River to conduct MAR in the El Carracillo MAR system. The percentage of diverted volumes to the total maximum allowed volumes and diversion days to the maximum allowed duration are also presented.*

Hydrological year	Diverted volume (Mm^3)	% of maximum allowed volume	Diversion duration (days)	% of the maximum allowed duration
2002/03	0.5	3.5%	149	124%
2003/04	5.5	38.7%	149	124%
2004/05	0.0	0.0%	0	0%
2005/06	1.9	13.0%	149	124%
2006/07	2.1	14.8%	149	124%
2007/08	0.0	0.0%	0	0%
2008/09	1.6	11.3%	149	124%
2009/10	5.6	39.5%	89	59%
2010/11	3.0	21.0%	90	60%
2011/12	1.9	13.5%	60	40%
2012/13	7.2	50.6%	119	79%
2013/14	1.6	11.5%	89	74%
2014/15	0.3	1.8%	27	23%
2015/16	1.6	11.0%	59	49%
2016/17	0.1	0.9%	-	0%
2017/18	4.7	33.0%	-	0%
2018/19	0.1	0.4%	-	0%
2019/20	0.2	1.6%	-	0%
Average	2.1	10%	91.3	56%
Total	37.8		1278	

*The irrigation community have not provided figures for the last years yet.

4.2.2.2 Santiuste basin

The characteristics of the Santiuste MAR system are the following:

- Length of infiltration channels: 27 km
- Infiltration ponds: 5
- Artificial wetlands: 3
- Additional elements: 1 RBF system and 3 rehabilitated recharge wells

A scheme showing how the different elements combine can be found in Fernández Escalante et al. (2016) and Fernández Escalante & López-Gunn (2021). The water allowance characteristics are the following:

- River water source: Voltoya River

- Water allowance period: 1 November - 31 April
- Maximum allowed recharge duration: 182 days/year (unless leap years)
- Maximum allowed deviation rate: 1 m3/s.
- Maximum allowed deviation volume: 8.5 Mm3/year.

Table 3 shows the El Carracillo MAR system's recharge volumes and diversion days over time and the percentage of the maximum allowed volume and diversion duration they represent.

Table 3. *Diverted water volume and water diversion days from the Voltoya River to conduct MAR in the Santiuste MAR system. The percentage of diverted volumes to the total maximum allowed volumes and diversion days to the maximum allowed duration are also presented.*

Hydrological year	Santiuste diverted volume (Mm^3)	% of maximum allowed volume	Diversion duration (days)	% of the maximum allowed duration
2002/03	3.5	41.2%	145	79.7%
2003/04	2.25	26.5%	175	96.2%
2004/05	1.26	14.8%	212	116.5%
2005/06	5.11	60.1%	137	75.3%
2006/07	12.68	149.2%	212	116.5%
2007/08	0.52	6.1%	7	3.8%
2008/09	4.35	51.2%	181	99.5%
2009/10	0.91	10.7%	43	23.6%
2010/11	2.9	34.1%	68	37.4%
2011/12	0	0.0%	0	0.0%
2012/13	3.48	40.9%	76	41.8%
2013/14	2.03	23.9%	57	31.3%
2014/15	3.58	42.1%	76	41.8%
2015/16	3.43	40.4%	61	33.5%
2016/17	2.44	28.7%		
2017/18	4.12	48.5%		
2018/19	0	0.0%		
2019/20	3.14	36.9%		
Average	3.09	36%	103.57	57%
Total	55.7		1450	

*The irrigation community have not provided figures for the last years yet.

In the Santiuste site, diverted volumes from the Voltoya River are, on average, 3.09 Mm^3 per hydrological year. Nonetheless, these volumes are variable and can go as high as 12.68 Mm^3 (2006/2007) and as low as 0.52 Mm^3 (2007/2008). There were even some years when MAR couldn't be conducted due to low Voltoya River flows (2011/2012 and 2018/2019). This variability is also reflected in the total days of recharge, which are, on average, 103.57, but range between 7 and 212.

Similar to El Carracillo MAR site, the percentage of the maximum allowed volume of water that can be diverted and the maximum days for this diversion show that the system's capacity not consistently harnessed. Nonetheless, in Santiuste, the diversion days in terms of the maximum allowed concession is near or above 100% in some hydrological years (e.g., 2003/2004, 2004/2005, 2008/2009) and in terms of maximum allowed volume (36% on average) is superior to El Carracillo site (10% on average).

4.2.2.3 Pedrajas-Alcazarén

The characteristics of the Pedrajas-Alcazarén MAR system are the following:

- Length of infiltration channels: 5.5 km
- Infiltration ponds: 1 (spreading field)
- Artificial wetlands: 2
- Additional elements: 1 RBF system

A scheme showing how the different elements combine can be found in Fernández Escalante et al. (2016) and Fernández Escalante & López-Gunn, (2021). The water allowance characteristics are the following:

- River water source:
  - Pirón River (diversion temporarily banned).
  - Treated wastewater effluent from the Pedrajas wastewater treatment plant.
  - Urban runoff from the Pedrajas municipality.
- Water allowance period:
  - Year-round treated wastewater, depending on availability.
  - Year-round Pedrajas runoff, depending upon availability and water quality.

The diversion initially envisaged from the Pirón River has been temporarily banned until administrative conflicts are sorted out. **Table 4** shows the volumes recharged at the Pedrajas-Alcazarén MAR site.

***Table 4**. Treated wastewater volumes from the Pedrajas de San Esteban wastewater treatment plant (WWTP) that were recharged in the Pedrajas-Alcazarén MAR site.*

Hydrological year	**WWTP effluent (Mm^3)**
2011/12	0.002
2012/13	0.100
2013/14	0.048
2014/15	0.048
2015/16	0.071
2016/17	0.102
2017/18	0.095
2018/19	0.001
2019/20	0.002
Average	0.052
Total	0.5

*The irrigation community have not provided figures for the last years yet.

Due to the nature of the source water, in the Pedrajas-Alcazarén system there is no maximum allowed volume per hydrological year. Water can be utilised for MAR as it becomes available. The total volumes of water for MAR are considerably lower compared to the other systems. On average, the Pedrajas Alcazarén site has infiltrated around 0.052 Mm^3 per year. Nonetheless, the system has infiltrated water every year since the beginning of operation, showing one of the advantages of using treated wastewater. This is a very important point, thinking of the very high fluctuations of river water.

4.2.3 Impacts on groundwater levels

4.2.3.1 Long-term assessment of the impact of the MAR sites on groundwater storage

Henao Casas et al. (2022b) evaluated the behaviour of groundwater levels in the Los Arenales aquifer and the impact of MAR on them. They utilised several statistical tools. They contrasted the behaviour between the Los Arenales groundwater body (LA) and the Medina del Campo groundwater body (MC), which are part of the same aquifer and share socioeconomic characteristics but differ because only the former has implemented MAR.

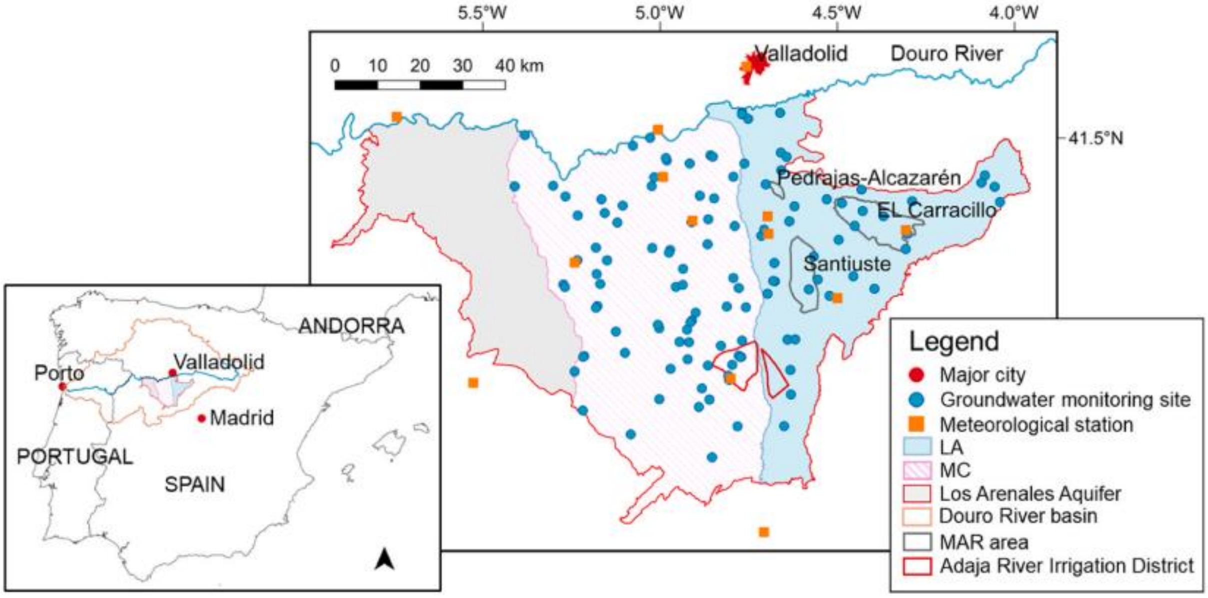


Figure 14. Location of the groundwater monitoring sites and the precipitation stations. From Henao Casas et al. (2022b).

The evaluation started with an analysis of the average annual groundwater levels in LA and MC, which were constructed using groundwater monitoring sites of the CHD and contrasted with precipitation data from meteorological stations of the Spanish Meteorological Agency (AEMET) and InfoRiego networks (**Figure 14**). Between 1985 and 2002, there was a decline in the average annual groundwater level in both groundwater bodies, attesting to the dramatic situation described in the introduction of this document (**Figure 15**). The Theil-Sen slope during this period was about - 1.1 m/year in LA and - 0.8 m/year MC. Subsequently, groundwater storage in the groundwater bodies entailed has diverged. In LA, there is a recovery trend with an average rate of 0.35 m/year; in MC, there seems to be a minor groundwater level increase (2004-2014), followed by an abrupt decrease. The increasing trend in LA coincides temporarily with the implementation of MAR systems around 2003.

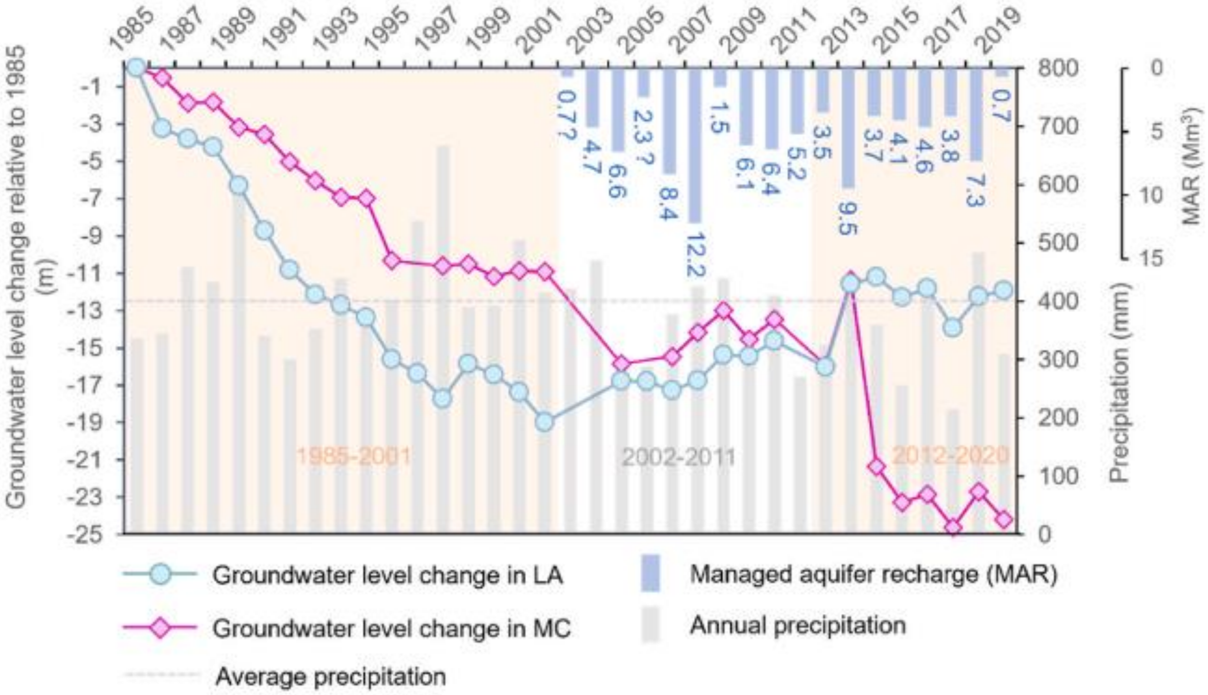


Figure 15. *Average annual groundwater level in the Los Arenales (LA) and Medina del Campo (MC) groundwater bodies, regional annual precipitation and annual managed aquifer recharge (MAR) volumes in LA. From Henao Casas et al. (2022b).*

Trend analyses were conducted through the Man-Kendall (MK) test, which assesses the statistical significance of linear trends, and the Theil-Sen estimator, which calculates trend slopes. These trend analyses were performed in three different periods delimited as a function of the groundwater level sampling frequency and milestones related to MAR: (i) 1986-2001, comprising the period of heightened groundwater abstractions and perceived widespread groundwater level decline; (ii) 2002-2011, which comprises the first MAR cycle in LA (i.e., the hydrological year 2002/2003); and (iii) 2012-2020, marked by the inauguration of the Pedrajas-Alcazarén MAR site.

In the first period, groundwater level trends in nearly all monitoring sites exhibit significant decreasing trends, reflecting unregulated groundwater abstractions beyond the sustainability thresholds (**Figure 16** a,b). The subsequent analysis period is characterised by some stability in LA and MC, where increasing and decreasing trends can be found in nearly equal proportions (**Figure 16** c,d). The last period shows that increasing groundwater levels predominate in LA (75% of statistically significant trends) (**Figure 16** f,g). The opposite occurs in MC, where decreasing trends are roughly three-quarters of all significant trends (**Figure 16** f,g).

The groundwater level analyses included the assessments of trends at the regional level, which aimed to elucidate whether something can be concluded on the regional scale based on local groundwater level trend tests. Two approaches were employed, namely, the empirical method by Douglas et al. (2000) and the regional Kendall test (Helsel & Frans 2006), which are suitable when the correlation among groundwater observation sites is consequential and absent, respectively. These analyses showed exclusively significant results through the regional Kendall test. These results agreed well with the trend analysis, finding a regional increasing trend in LA and a regional decreasing trend in MC for the last analysis period (2012-2020).

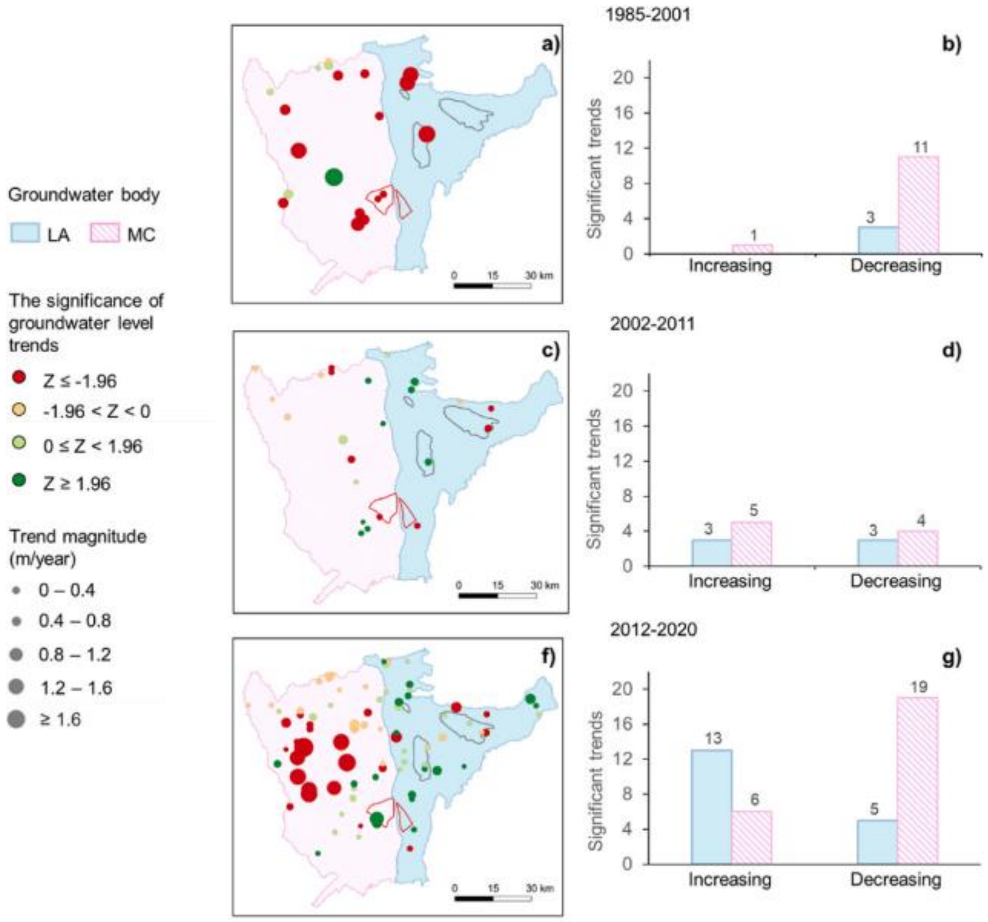


__Figure 16.__ Groundwater level trends in the Los Arenales (LA) and Medina del Campo (MC) groundwater bodies geographically distributed (a, c, and f) and as the number of statistically significant trends (b, c, d). Trends are divided into the three analysis periods: (1) 1985-2001 (a and b); (2) 2002-2011 (c and d); and 2012-2020 (f and g). The size of the circles in Figures a, c, and f represent the magnitude of the trend. From Henao Casas et al. (2022b).

Groundwater level trend analyses show a temporal and partly spatial correlation between groundwater storage recovery and MAR. However, given the evidence above, other water management measures related to enhancing water use efficiency or more sustainable agricultural practices cannot be conclusively ruled as responsible for improving groundwater availability in LA. Thus, the authors decided to evaluate land use, agricultural water use, and measures to increase irrigation efficiency in the study site. Land use was assessed using two information sources: CORINE land cover (CLC) between 1990 and 2006 and The Spanish Land Occupancy System (SIOSE) between 2005 and 2014. These systems employ different methodologies to categorise land use. The adoption of three irrigation technologies (gravity, aspersion, and localised irrigation) in the Spanish provinces comprising LA and MC (Ávila, Segovia and Valladolid) was evaluated based on information from the Crop Area and Yield Survey (ESYRCE) by the Ministry of Agriculture, Fishery and Food. Agricultural water use was explored by computing the product between the area of different crop types and the average water use (reported by InfoRiego) between the years 2009 and 2020.

Concerning land use, Henao Casas et al. (2022b) found that the total agricultural area remained unchanged between 1990 and 2020 (**Figure 17** a,b). They also found that in LA and MC, there was a considerable increase in irrigated land between 1990 and 2000, which was exceptionally high in the latter (**Figure 17** a). After 2005, irrigated land expanded notably in LA (**Figure 17** b). In Castile and Leon, the region where Los Arenales Aquifer is located, there was a significant uptake of efficient irrigation technologies such as dripping and aspersion systems in contrast to gravity irrigation. Such an uptake was, however, very limited in the provinces comprising LA and MC, and aspersion irrigation remained nearly constant and the primary method throughout the period analysed (2001-2017).

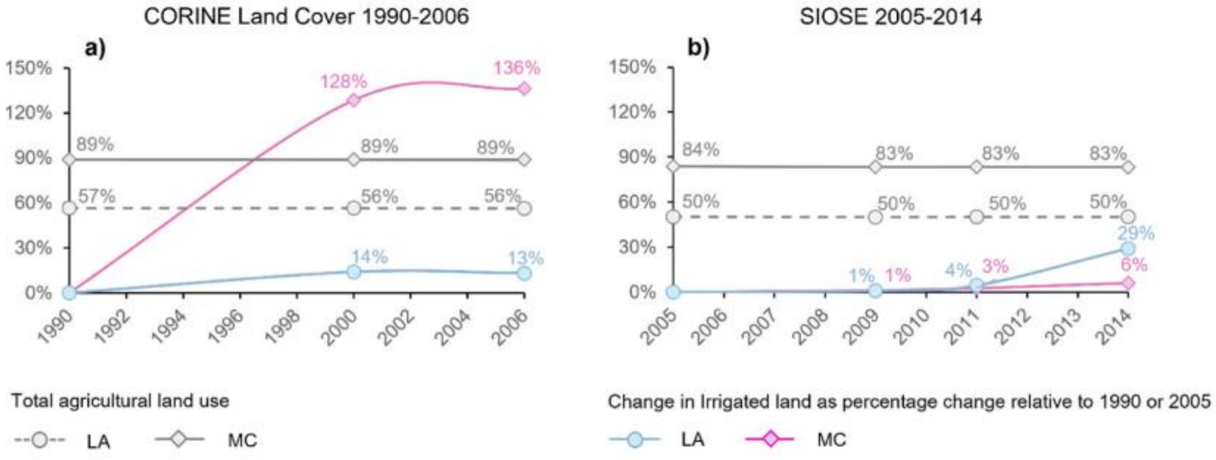


__Figure 17.__ Total agricultural land use and change in irrigated land area in the Los Arenales (LA) and Medina del Campo (MC) groundwater bodies. From Henao Casas et al. (2022b).

Analysis of major crop groups shows that cereals predominate in LA and MC. In LA, the second largest group of crops in terms of irrigated area are vegetables, followed by fodder crops and tubers. In MC, industrial crops such as sugar beet are the second most common crops. Crop groups in both groundwater bodies show inter-annual changes. However, the total agricultural water demand for irrigation remained nearly constant between 2009 and 2020 (**Figure 18**).

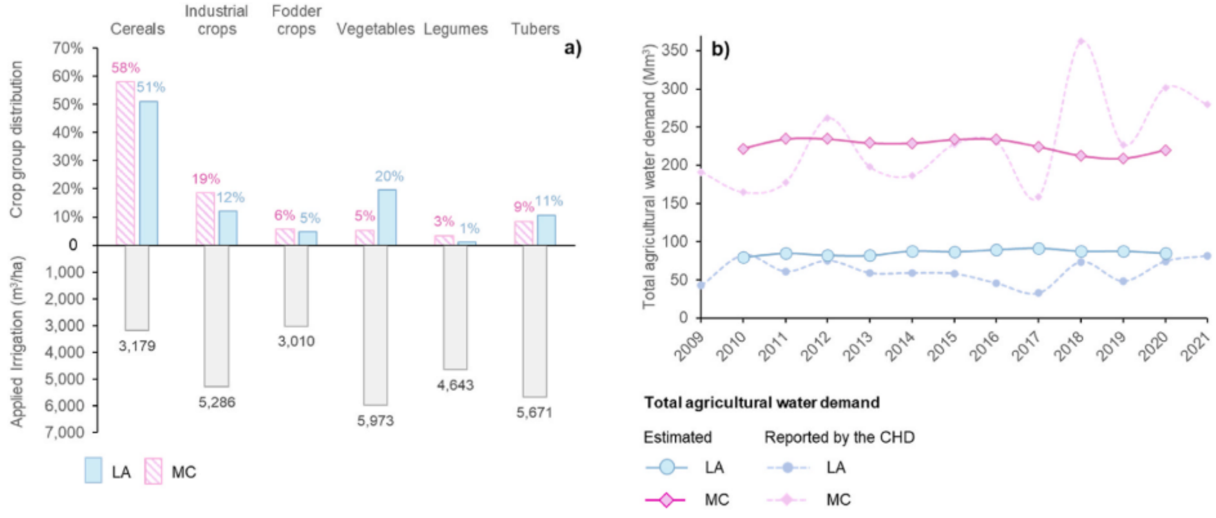
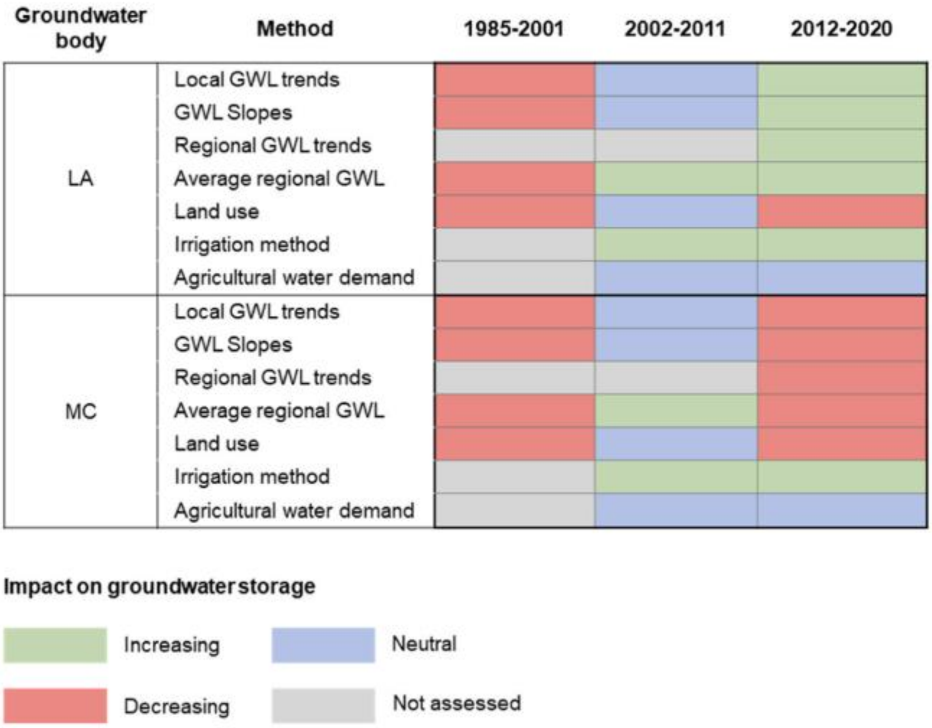


__Figure 18.__ Analysis related to water use for irrigation in the study area: (a) Crop group distribution and their corresponding applied irrigation volumes in Los Arenales (LA) and Medina del Campo (MC) groundwater bodies; (b) total irrigation agricultural water demand in LA and MC between 2009 and 2020. From Henao Casas et al. (2022b).

A summary of the evidence related to the different statistical approaches applied, shown in **Figure 19**, reveals that MAR is likely the water management measure capable of explaining the recovery groundwater trends in LA.



Groundwater body	Method	1985-2001	2002-2011	2012-2020
LA	Local GWL trends	🟥	🟦	🟩
	GWL Slopes	🟥	🟦	🟩
	Regional GWL trends	⬜	⬜	🟩
	Average regional GWL	🟥	🟩	🟩
	Land use	🟥	🟦	🟥
	Irrigation method	⬜	🟩	🟩
	Agricultural water demand	⬜	🟦	🟦
MC	Local GWL trends	🟥	🟦	🟥
	GWL Slopes	🟥	🟦	🟥
	Regional GWL trends	⬜	⬜	🟥
	Average regional GWL	🟥	🟩	🟥
	Land use	🟥	🟦	🟥
	Irrigation method	⬜	🟩	🟩
	Agricultural water demand	⬜	🟦	🟦

Impact on groundwater storage

🟩 Increasing
🟦 Neutral
🟥 Decreasing
⬜ Not assessed

Figure 19. *Summary of the methods utilised to assess groundwater levels in the study region and possible drivers for the observed trends. From Henao Casas et al. (2022b).*

4.2.3.2 Assessment of the effect of MAR on groundwater levels to combat drought

Henao Casas et al. (2022a) explored potential improvements in drought resilience in LA due to MAR. This study also entailed a comparative approach between LA and MC (**Figure 20**), where the most significant difference in water management is the MAR systems in the former groundwater body. To achieve the research objective, several drought indexes were computed and analysed from groundwater levels at selected monitoring sites (**Figure 20**) with continuous data between 2001 and 2020. Also, trend tests were calculated using the MK test.

A preliminary analysis of groundwater level behaviour in the study site was carried out. This analysis revealed that most groundwater levels had visible linear trends, either decreasing or increasing, and that average annual piezometric levels are correlated to annual precipitation (**Figure 21**).

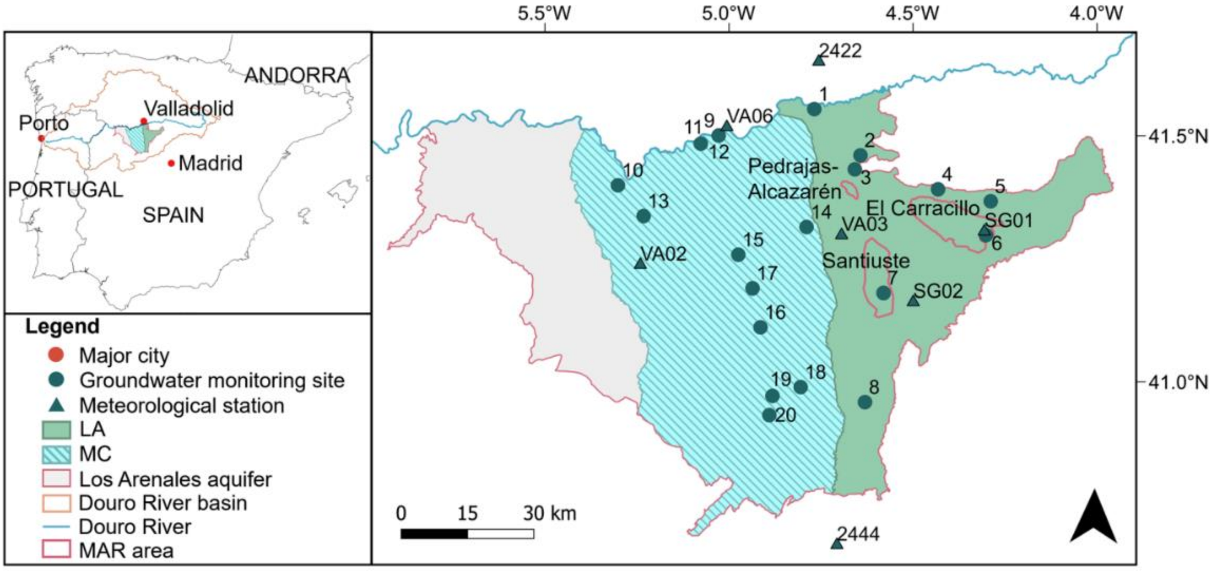


Figure 20. Location of Los Arenales (LA) and Medina del Campo (MC) groundwater body, the groundwater monitoring sites used in the study and Los Arenales managed aquifer recharge (MAR) systems. From Henao Casas et al. (2022a).

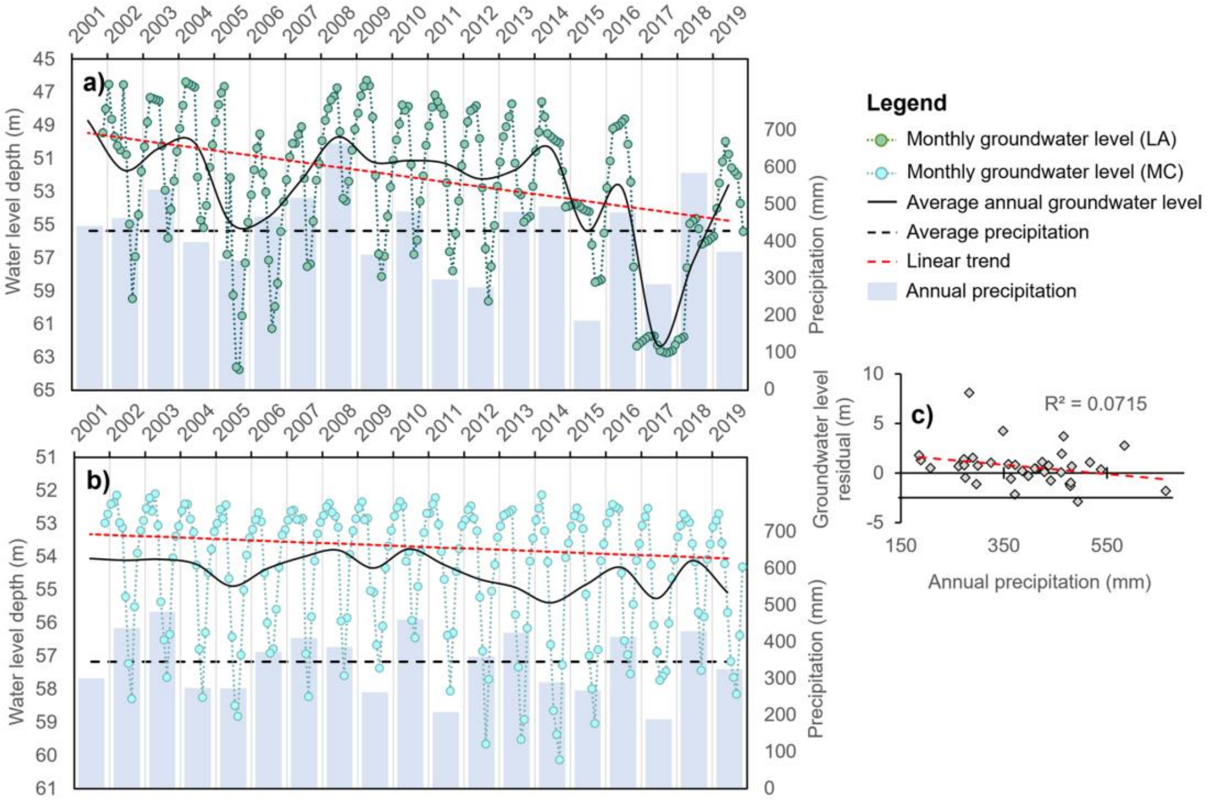


Figure 21. Behaviour of groundwater levels at selected monitoring sites in LA (a) and MC (b) and linear relationship between annual precipitation and the groundwater level residual resulting by substracting linear trends from groundwater level time series. From Henao Casas et al. (2022a).

The Standardised Precipitation Index (SPI) indicates whether precipitation is above or below the long-term average. It relies on lengthy precipitation time series and is determined for different rainfall accumulation periods, such as monthly, biannual, annual, or multi-annual. The Standardised Groundwater Level Index (SGI) is the analogous index of the SPI for groundwater levels. It shows the period in which piezometric levels are above or below the long-term average. The SGI is non-parametric and is computed for the average groundwater level of different durations, including monthly, biannual, and annual. When calculating the SGI for groundwater level time series of the study site, linear trends can result in a single continuous "drought" followed by "wet periods" or vice versa, which is not intuitively correct (**Figure 22** a,b). To avoid such an artefact, linear trends were removed (**Figure 22** c,d), resulting in a higher cross-correlation between the SGI and the average SPI for the region (with an accumulation period of 24 months, station VA03, **Figure 20**) (**Figure 22** e,f).

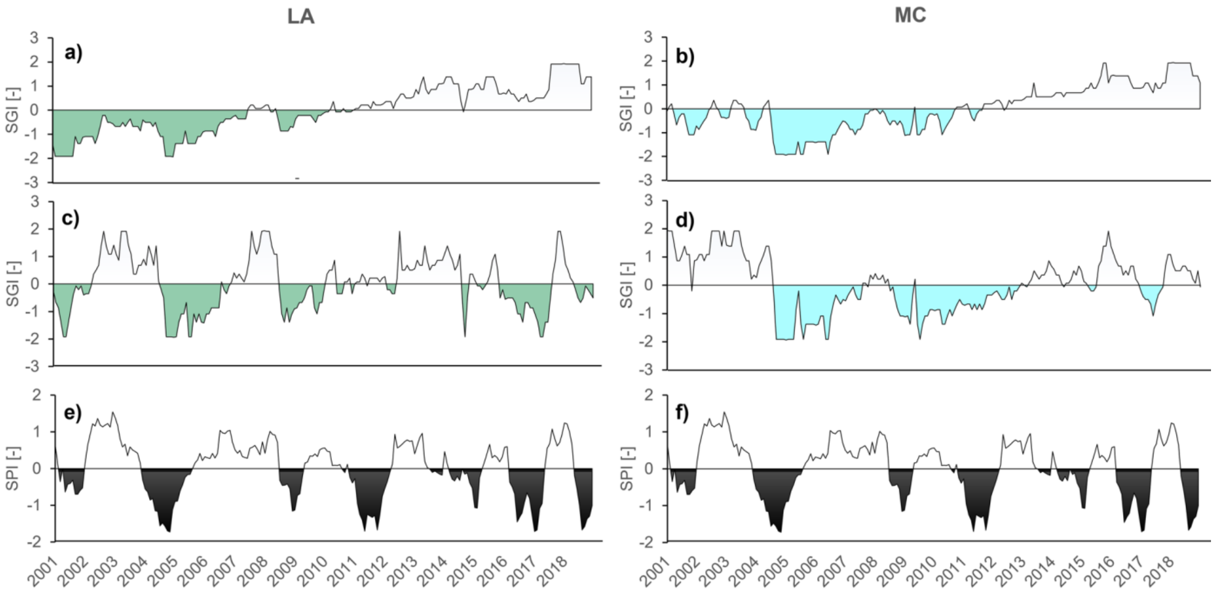


Figure 22. *Analysis of the effect of detrending groundwater level time series on standardised groundwater level indexes (SGIs) in the Los Arenales (LA) and Medina del Campo (MC) groundwater bodies. (a) and (b) show the SGI without detrending, while (c) and (d) show the same index computed on detrended groundwater level time series. (e) and (f) show the average standardised precipitation index in the area as a reference for below-average precipitation. From Henao Casas et al. (2022a).*

The MK test showed statistically significant linear trends in all monitoring sites investigated. These trends were equally distributed between increasing and declining trends in both groundwater bodies. However, in LA, increasing trends tend to have higher slopes than decreasing trends (**Figure 23**). The contrary was found in MC, where declining trends had stronger slopes (**Figure 23**).

The average annual groundwater level in LA recovers since 2001. In MC, the trend is contrary; groundwater levels decreased between 2001 and 2019 (**Figure 24**). Using the average SPI for the region as a reference (**Figure 24**), groundwater levels in LA seem to be less constrained by below-average precipitation than they do in MC (**Figure 24**).

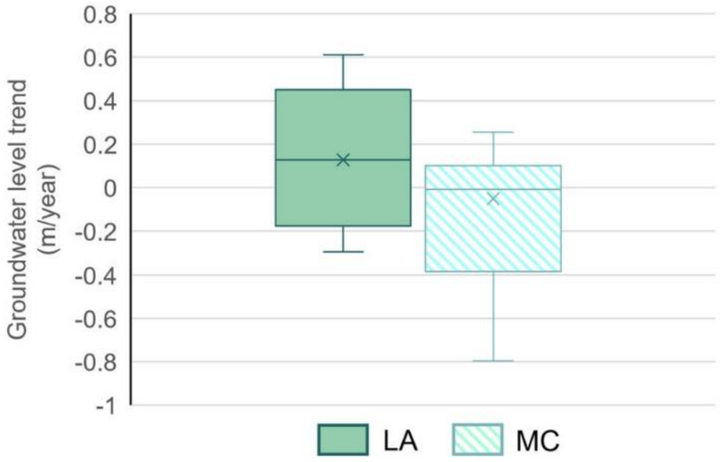


Figure 23. *Box and whisker plots of linear trend slopes in the Los Arenales (LA) and Medina del Campo (MC) groundwater bodies. From Henao Casas et al. (2022a).*

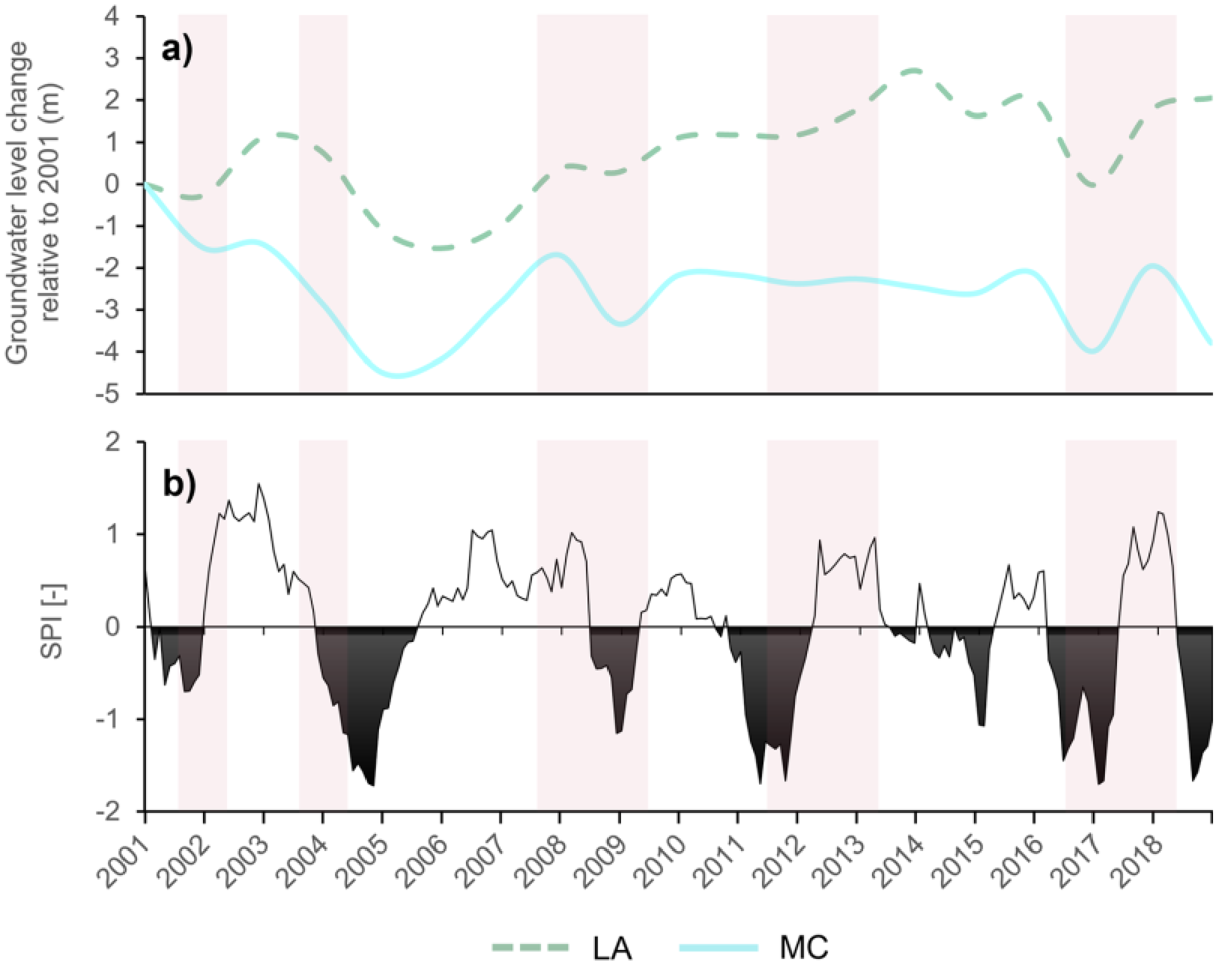


Figure 24. *(a) Evolution of average annual groundwater levels in the Los Arenales (LA) and Medina del Campo (MC) groundwater bodies based on piezometric levels recorded at groundwater monitoring stations in **Figure 20**. (b) average standardised precipitation index (SPI) with an accumulation period of 24 months for the study site based on data from station VA03 (**Figure 20**). From Henao Casas et al. (2022a).*

Drought is considered to occur in periods of negative SGI (SGI < 0) where there is at least one occurrence of SGI below minus one (SGI < -1), following the approach by Bloomfield & Marchant (2013) and Brauns et al. (2020). The following drought parameters were explored using the SGI computed from detrended groundwater level time series: "drought frequency, representing the number of droughts over a period (in this case, 2001-2020); the mean drought duration, which accounts for the average duration of drought; the mean magnitude, which is the mean accumulation of negative SGI values during a drought; the maximum drought duration, which corresponds to the longest drought interval; and the total drought magnitude, which is the accumulation of negative SGI indexes over a given interval of time (2001-2020)" (Henao Casas et al. 2022a).

The parameters show that LA suffers less frequent droughts than MC (**Figure 25** a). However, dry spells have a higher mean magnitude and duration in the former body (**Figure 25** a). Furthermore, the total drought duration and maximum drought magnitude in LA between 2001 and 2020 were larger than in MC (**Figure 25** c,d). These results suggest that, when the effect of MAR is subtracted from groundwater level time series, LA is more sensitive to drought, which translates as less frequent below-average water level events that result, however, in more detriment to subsurface water resources.

The bottom line is that LA suffers more severe drought events when the effect of MAR is subtracted (i.e., as part of the linear trends of groundwater level time series) and shows a groundwater storage recovery trend when the influence of the technology is preserved. Consequently, MAR is helping to adapt to drought in the Los Arenales groundwater body, helping to maintain and even increase groundwater level despite a lower overall availability of water resources.

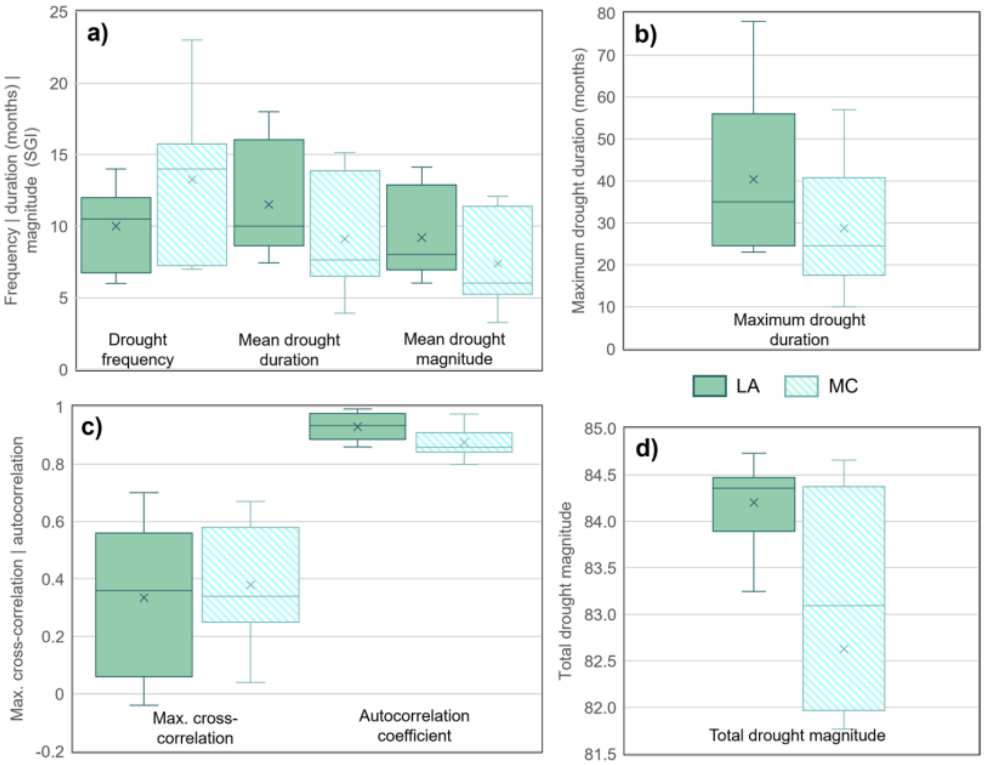


Figure 25. *Drought parameters estimated from detrended SGI series: (a) drought frequency, mean drought duration, and mean drought magnitude; (b) maximum drought duration; (c) Maximum cross-correlation and autocorrelation; and (d) total drought magnitude. LA: Los Arenales groundwater body; MC: Medina del Campo groundwater body. From Henao Casas et al. (2022a).*

4.2.4 Infiltration rates and clogging

Clogging of the infiltration basins was monitored through two different approaches: (i) by measuring infiltration rates with double ring infiltrometers more than once at different times over the exact location during the MARSoluT project and (ii) by determining the change in the proportion of the main grain sizes (sand, silt, and clay) over time for specific sites. Clogging was surveyed at two locations in the Santiuste (ST) and La Laguna del Señor (LS) infiltration basins: the vicinity of tree trunks and some metres away from tall vegetation. Some results were also utilised in a parallel study concerning infiltration rates in vegetated areas (**Figure 26**). A total of eight fieldwork campaigns were carried out between November 2020 and September 2022.

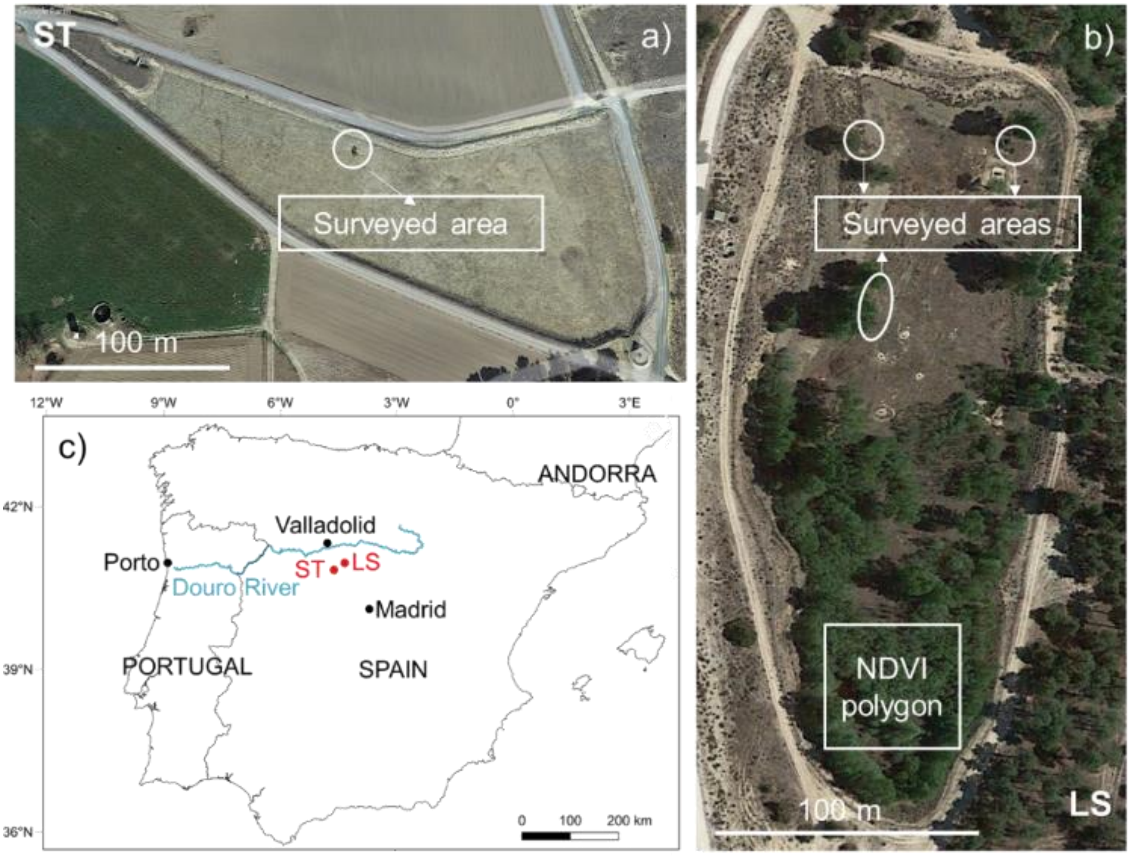


Figure 26. Location of the surveyed areas to assess infiltration rate performance: (a) Santiuste infiltration (ST); (b) La Laguna del Señor infiltration basin (LS); and (c) geographical location of the infiltration basins. Coordinates are in the WGS 84 coordinate reference system (EPGS: 4326).

Steady-state infiltration rates (SSIR) measured with double-ring infiltrometers changed throughout the project. To assess these variations, we computed percentage changes relative to the first measurement at a given site and plotted them in whiskers and boxplots. Steady-state infiltration rates tended to increase in both infiltration basins (LS and ST) (**Figure 27**). These patterns could be explained by the continuous maintenance of the infiltration basins by the irrigation communities, namely, the El Carracillo and Santiuste irrigation communities. Furthermore, the MAR system spillways preclude fine-sediment mobilisation, and the source water is of good quality.

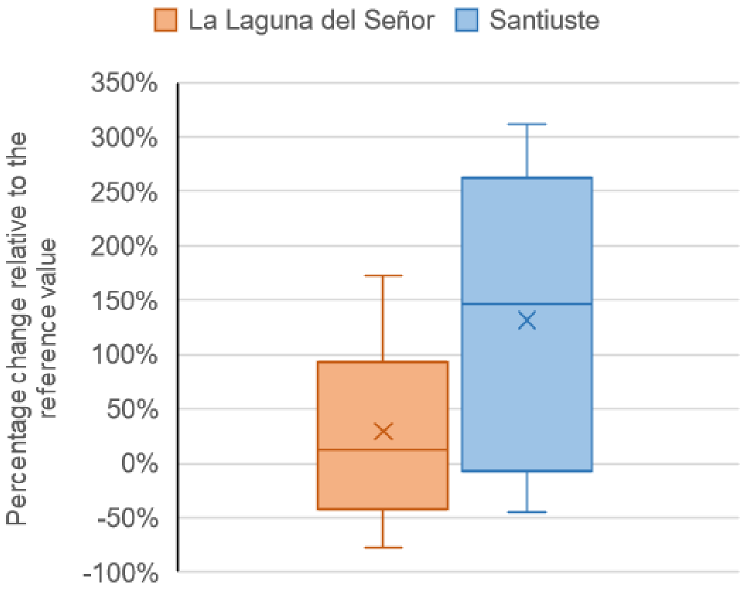


Figure 27. *Percentage changes in steady state infiltration (SSIR) rate relative to the reference SSIR, which in all cases corresponds to the first SSIR measured at a given site.*

The analysis of fine sediment proportion tells a similar story for the Santiuste site. Clay and silt have decreased over time, likely due to continuous maintenance by the Santiuste irrigation community (**Figure 28**). In La Laguna del Señor, there seems to be an increase in the proportion of silt (**Figure 28**). However, such an increase has no significant effect on infiltration rates (**Figure 27**).

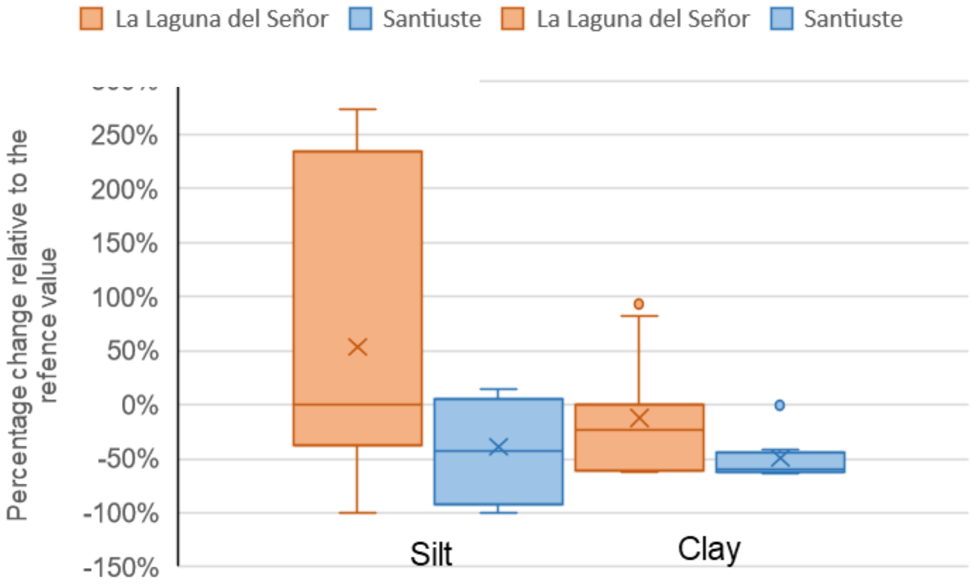


Figure 28. *Percentage changes of silt and clay relative to the reference values, which in all cases corresponds to the firs grain size distribution measured at a given site.*

Tables 13 and **14** of the annexes provide more detailed information on the sites where SSIR and grain size distribution were evaluated to assess clogging.

4.2.5 Site upgrade

The Los Arenales MAR systems were upgraded with on-site interventions to monitor various parameters of large infiltration basins. A conceptual upgrade was also developed consisting of a standard for data integration that is expected to be applied to the system's data management in the coming years.

4.2.5.1 On-site interventions

Some works were conducted in Los Arenales MAR sites to improve monitoring and site characterisation. The works were primarily concerned with constructing piezometers and maintenance in the Santiuste infiltration basin, La Laguna del Señor infiltration basin, and stations controlling unsaturated conditions in the vicinity (ZNS1, ZNS2, and ZNS3).

A total of six piezometers were built. Two of them were located within the La Laguna del Señor infiltration basin (LSR and LSC, **Table 5**), in El Carracillo, two more within the Santiuste infiltration basin (STR and STC, **Table 5**), and a fifth at the nearby ZNS 1 station (ZNS1R, **Table 5**). A sixth piezometer was excavated a few metres away from ZNS3 (ZNS3R, **Table 5**). These vertical structures aim to monitor groundwater levels and allow for performing slug tests to determine water infiltration rates below the ground surface. The piezometer located at ZNS 1 (i.e., ZNS1R) was also equipped with a permanent level logger to monitor groundwater levels and the wetting bulb close to the Santiuste infiltration basin (**Table 6**). Moreover, the piezometer was placed as part of an arrangement that allows calculating horizontal hydraulic conductivities as the travel time of the wetting front between ZNS1R and ZNS1. Unfortunately, the cables connecting the level logger to a data logger in ZNS1 were damaged in the middle of the project and require fixing (**Figure 29**).

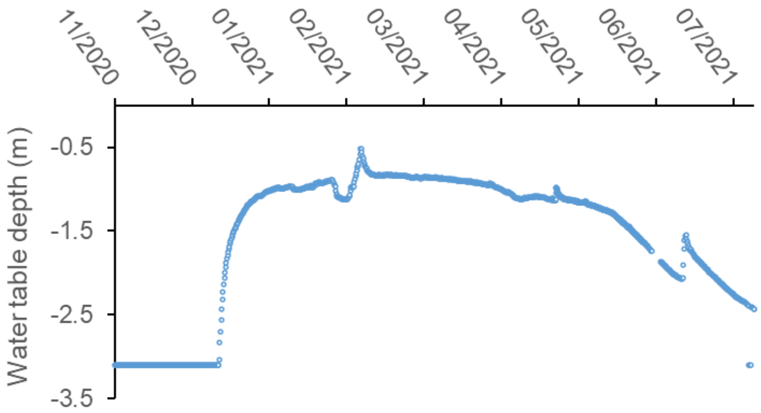


Figure 29. *Groundwater table depth measured in the piezometer close to ZNS 1 (unsaturated zone station) showing the increase in groundwater levels due to MAR. Hydrological year 2020/2021.*

Two types of piezometers were built. In the first one, a piezometer screen allowed water circulation in both directions (LSR, STR, ZNS1R, and ZNS3R). The screen was made by slotting the lower end of the PVC tube and covering the intervened region with a fabric that prevents particle mobilisation (**Figure 30** a,b). The second design did not involve any screen (LSC and STC). A pair of slotted and not-slotted piezometers were built inside each infiltration basin (LSC and LSR in La Laguna del Señor and STC and STR in Santiuste) that facilitates comparing approaches to determine infiltration rates. Maintenance of infiltration sites was also carried out. The small basin adjacent to the ZNS3 was cleared (**Figure 30** c). The deep soil moisture sensors in ZNS1 and ZNS2 were replaced with new sensors since the previous devices provided flawed data (**Table 6**).

Table 5. *Information of the piezometers constructed during the second half of 2020. Coordinates in UTM format zone 30 with WGS 84 ellipsoid. ZNS: Unsaturated Zone Station.*

Code	X	Y	Diameter (cm)	Is the well slotted?	Depth (m)	Location
LSC	392040	4571766	5.1	No	2.68	Laguna del Señor infiltration basin
LSR	392031	4571748	5.1	Yes	2.5	Laguna del Señor infiltration basin
STR	359916	4557408	5.1	Yes	2.9	Santiuste infiltration basin
STC	359897	4557421	5.1	No	2.93	Santiuste infiltration basin
ZNS1R	369694	4557512	5.1	Yes	-	Close to ZNS 1
ZNS3R	391876	4571293	5.1	Yes	2.93	Close to ZNS 3

Figure 30. *Fieldwork conducted in the study site to construct the monitoring piezometers and maintain infiltration infrastructure: a) slotted pipe with filtering fabric installed in one of the infiltration basins; b) Installation of the slotted pipe in La Laguna del Señor infiltration basin; and c) Maintenance of a small infiltration pond next to station the ZNS-3.*

Table 6. *Devices installed in the study area during the second half of 2020.*

Device	Measured parameters	Location
PICO64	Humidity, temperature and electrical conductivity	ZNS 1 at 2.15 m depth
PICO64	Humidity, temperature and electrical conductivity	ZNS 2 at 2.15 depth
Hydros 21	Water level, temperature, and electrical conductivity	Piezometer at ZNS1

Three methods to interpret the result of the slug tests were tested: (i) Bouwer & Rice, (ii) Hvorslev, and (iii) Cooper-Bredehoeft-Papadopoulos. The first two methods were employed to estimate infiltration rates below the ground surface at nearly 3 m depth. The third method (i.e., Cooper-Bredehoeft-Papadopulus) estimates transmissivity. To this end, the software SlugIn 1.0 was used (Padilla Benítez et al. 2002). The only method that provided reasonable values of infiltration rates was Bouwer & Rice. Hvorslev resulted in many cases in negative infiltration rates. Furthermore, infiltration rates were very high after piezometer construction and declined, except for STC. The overall declining behaviour is likely a consequence of soil compaction. Piezometer clogging cannot be conclusively ruled out. An interesting pattern observed in the infiltration rates using Bouwer and Rice is an increase in infiltration rates before and during November (**Figure 31**). Slug tests from ZNS1R are not included since the connection between the data logger and the level logger stopped working and couldn't be re-established.

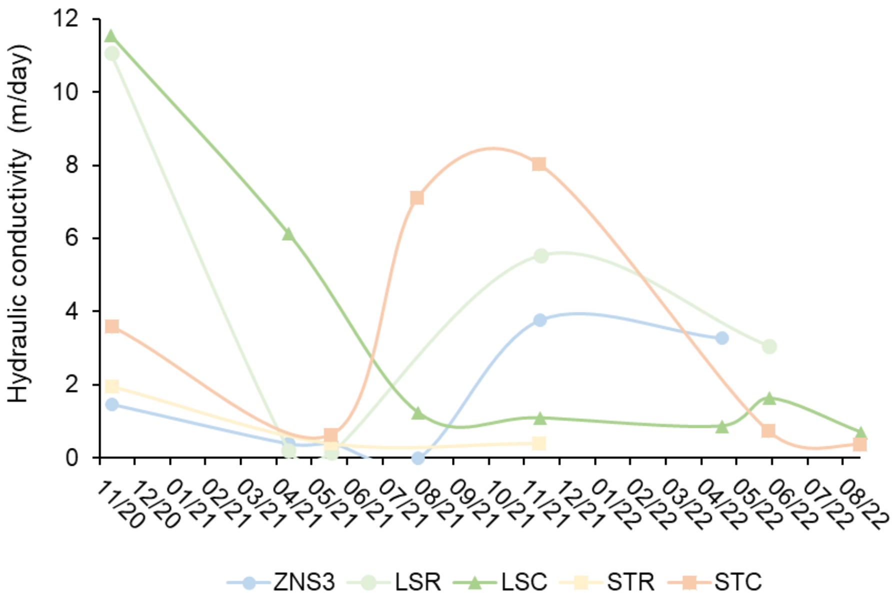


Figure 31. *Evolution over time of infiltration rates computed through the Bouwer & Rice method for piezometers built in Los Arenales Mar site during the MARSoluT project.*

4.2.5.2 Conceptual solutions to improve monitoring

Four solutions to increase interoperability around MAR systems have been developed in TRAGSA. These solutions are being tested in the Los Arenales MAR sites and will likely be implemented in this scheme soon. A short article on this topic has been published by Henao Casas et al. (2022c).

The state of the art in MAR monitoring systems was evaluated to identify the most urgent needs in this realm of research. This evaluation was conducted through a survey among MARSoluT consortium partners who were studying or operating schemes involving MAR. The survey consisted of the following questions/requests:

1. A list of the sensors that the partner institution currently uses for its MAR-related projects.
2. Information on how the sensor data is collected and if a software tool is used to integrate the measurements from different devices.
3. Files with the data recorded in data loggers.
4. A brief description of the MAR project involved.

All ten MARSoluT beneficiary institutions responded to the survey, which revealed the following four aspects that could be improved towards better interoperability: i) there is a lack of consensus on MAR terminology (what is considered an important topic by most of the consortium); ii) monitoring data is registered by data loggers that retrieve data in different formats and often require the use of manufacturer's software; iii) there are not standardised software tools to deal with the information generated at a site; and iv) there are not conceptual solutions to interconnect the information from various MAR systems. Four conceptual solutions have been developed as a response to these gaps (**Figure 32**): (i) a common language for MAR, i.e., an ontology; (ii) a standard to store data logger information; (iii) a standard for developing Supervisory Control and Data Acquisition (SCADA)-type tools; and (iv) a standard for integrating the operation and monitoring of different MAR systems.

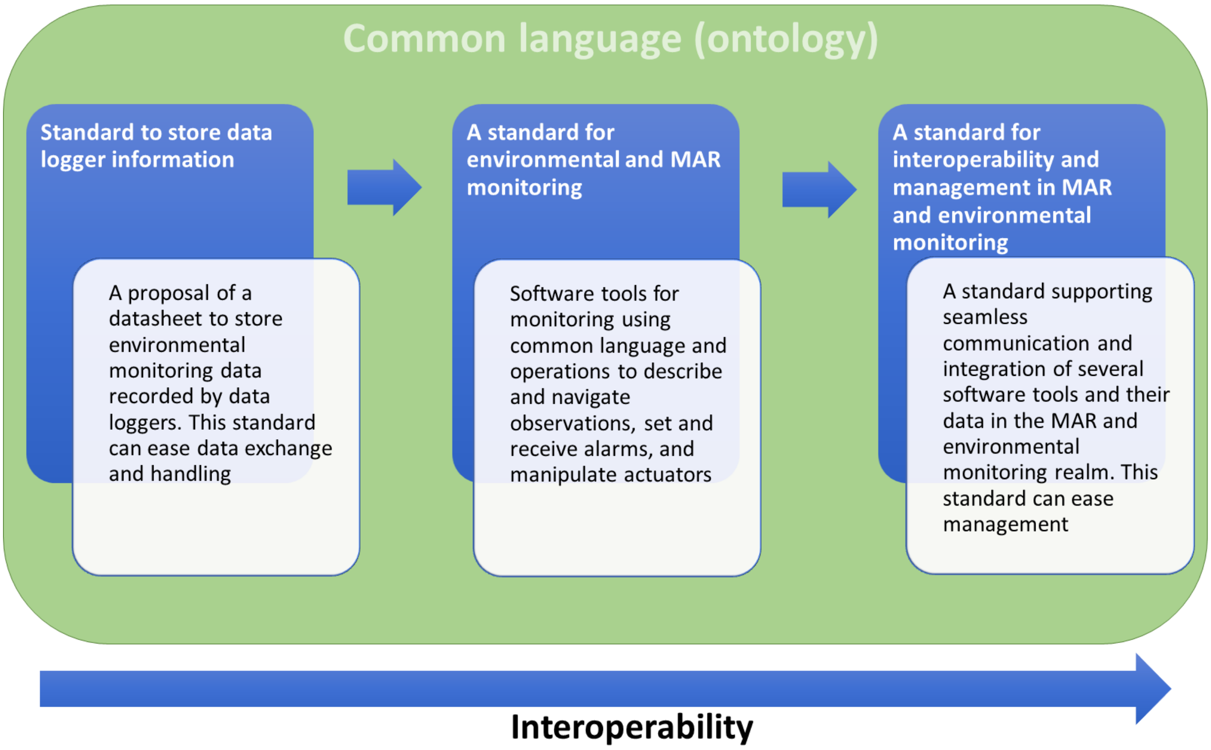


Figure 32. *Proposed steps to improve interoperability in managed aquifer recharge (MAR) system: i) a MAR ontology, ii) a standard to store data logger information; iii) a standard for MAR and environmental monitoring; iv) a standard for interoperability and management of various MAR schemes.*

In addition to identifying needs concerning monitoring, interesting information was derived from the responses received. For example, it was found that the most used type of sensor are level loggers, followed by temperature sensors (**Figure 33**) and that the most measured properties monitored are temperature, electrical conductivity, water level, capillary pressure and volumetric water content. Furthermore, most of the measured properties are part of the hydrosphere (76% of the sensors) and the pedosphere (19), while the parameters measured in the atmosphere (5%) and the lithosphere (0%) have less relevance. The origin of the sensors was also determined, with up to 28 different manufacturers, and that only one of the ten MARSoluT's beneficiary institutions has implemented a SCADA to integrate monitoring data.

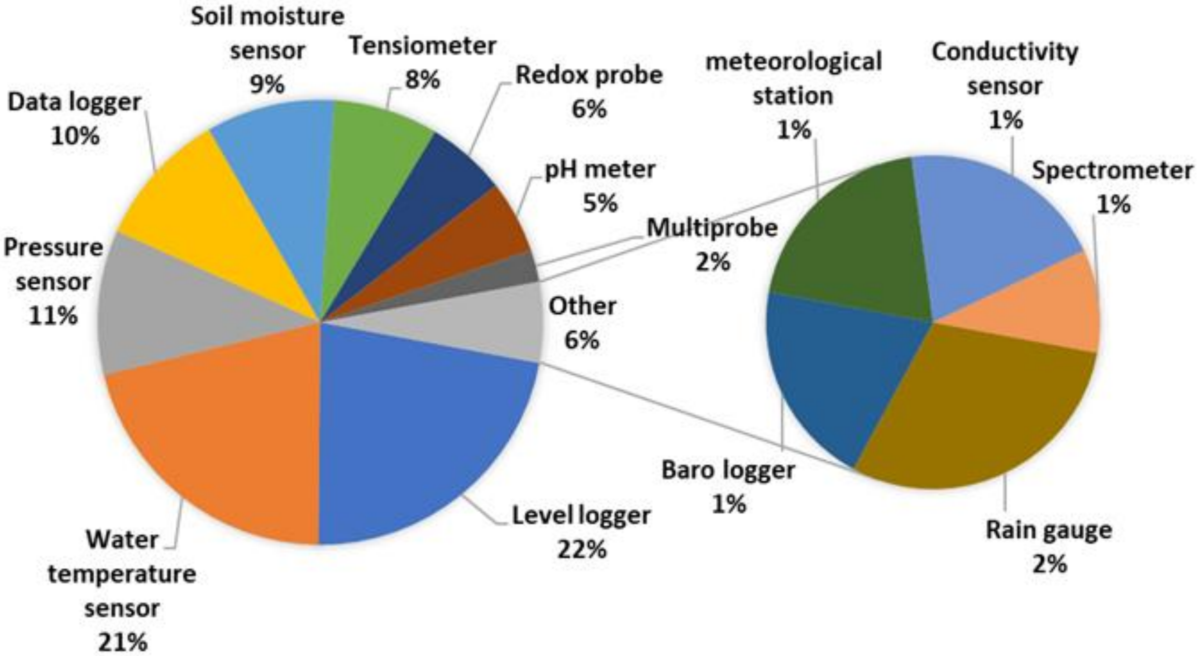


Figure 33. Proportion of the sensors utilised within the MARSoluT consortium.

The first element is an ontology for MAR, which defines the terms referring to the different techniques that involve this technology (**Figure 34**). This ontology shows the interrelationship among terms and includes their definition, contextualisation, and a list of synonyms in the literature. The contextualisation aims to clarify the criteria used to group some MAR types within a given denomination and give context to the term definition. This contribution provides a common language in which other proposals to improve interoperability can be framed (**Figure 33**). Furthermore, it eases communication on MAR.

The following solution (**Figure 35**) is a format to store output data from different data loggers. It is based on studying data logger output files from the consortium sensors. It provides a standardised structure to present information and metadata about the observed properties, the sensor, and the organisation responsible for the sensor, among others. This proposal can facilitate the exchange of "raw" information clearly and easily. Furthermore, it is a starting point towards a consensual and robust standard that can be reached by involving manufacturers and practitioners.

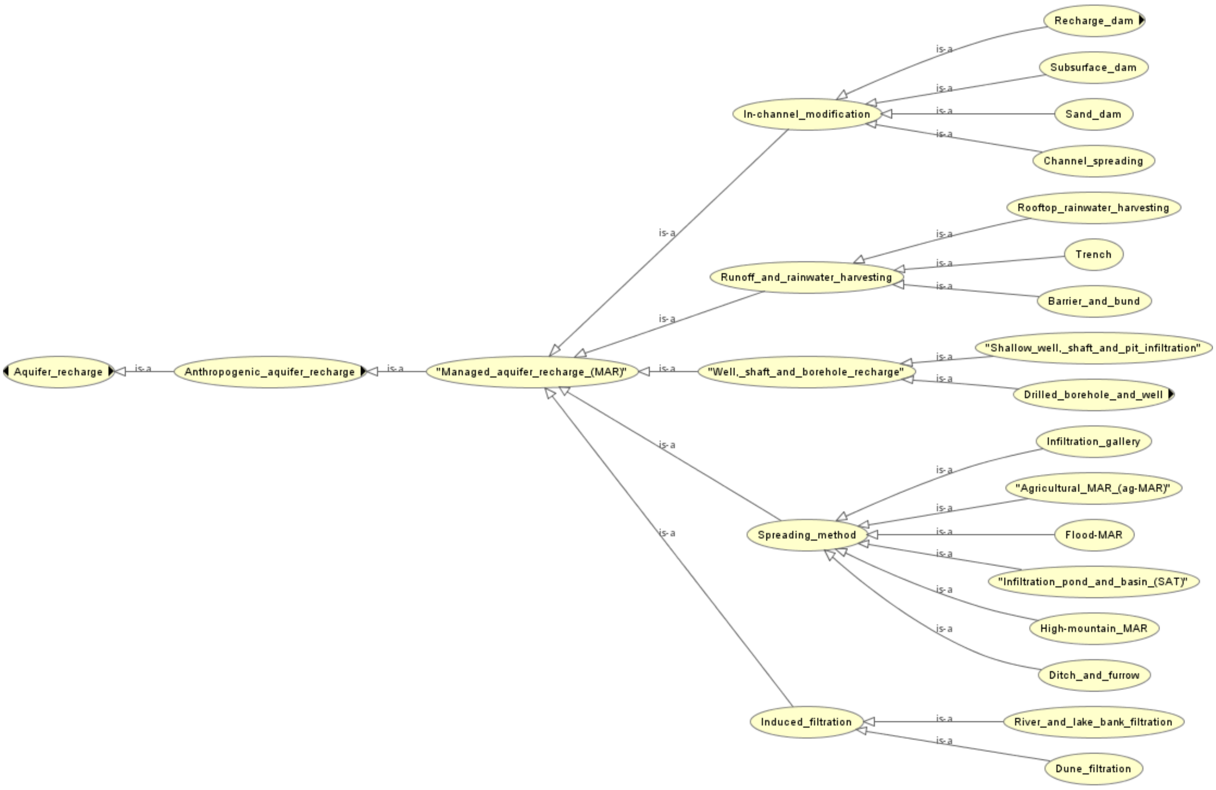


Figure 34. *Main branch of the ontology showing MAR technique terms.*

SERIES METADATA					
Start date and time: [RecordStart]					
End date and time: [RecordEnd]					
Total observations: [TotalObservations]					
Sampling Interval: [SamplingInterval]					
Date and time	Identifier	[ObservedProperty]$_{i}$, [ObservedPropertyUnits]$_{i}$	[ObservedProperty]$_{i+1}$, [ObservedPropertyUnits]$_{i+1}$	…	[ObservedProperty]$_{n}$, [ObservedPropertyUnits]$_{n}$
[PhenomenonTime]$_{j}$	[ObservationID]$_{j}$	[Observations]$_{i, j}$	[Observations]$_{i+1, j}$	…	[Observations]$_{n, j}$
…	…	…	…	…	
[PhenomenonTime]$_{N}$	[ObservationID]$_{N}$	[Observations]$_{i, N}$	[Observations]$_{i+1, N}$	…	[Observations]$_{n, N}$

Figure 35. *Section of the standard format to store data logger observations and metadata.*

The third solution is a standard for developing SCADA-like tools, which is mainly based on the MEGA standard created by Tragsa and Open Geospatial Consortium (OCG) standards for Sensor Observation Services (SOS) and Sensor Alert Services (SAS). The developed standard has a set of SOS processes that allow obtaining information about the software tool used (GetCapabilities), the sensors that are registered (DescribeEntity), and the data they have generated (GetObservation). The standard also has processes that allow the software tool to be fed with data, such as registering sensors (RegisterEntity) and inserting the data produced (InsertObservation). Regarding SAS processes, the system allows the publication of sensors (Advertise) and the subscription to specific sensors to receive alerts (Subscribe). The standard also considers the renewal of sensors before they expire (RenewAdvertisement), and subscriptions to the respective alerts (RenewSubscription), as well as their cancellation

(CancelSubscription and CancelAdvertisement). **Table 7** summarises the main processes included in the standard and the type of service they are part of.

***Table 7**. List of the processes included in the draft standard for MAR and environmental monitoring.*

Process	Service
GetCapabilities	SOS & SAS
DescribeEntity	SOS & SAS
GetObservation	SOS
RegisterEntity	SOS
InsertObservation	SOS
GetResult	SOS
DescribeAlert	SAS
Subscribe	SAS
RenewSubscription	SAS
CancelSubscription	SAS
Advertise	SAS
RenewAdvertisement	SAS
CancelAdvertisement	SAS

MAR systems could be integrated into information management systems, e.g., by water authorities or companies, allowing different schemes to be automatically compared by means of benchmarking methodologies. To this end, a standard has been generated that adopts the architecture and some of the elements developed in the UNE 318002-3:2021 standard led by the Ministry of Agriculture, Fisheries and Food (MAPA) and TRAGSA for interoperability in irrigation systems. This standard incorporates the same processes as the standard for developing SCADA-type tools. MAR systems that do not use the latter standard, but are controlled by tools based on OGC standards, could be easily incorporated into the interoperable system due to the equivalence between the processes of the standard and those proposed here. The integration among MAR systems and information management systems is intended to be achieved through a coordination broker (**Figure 36**).

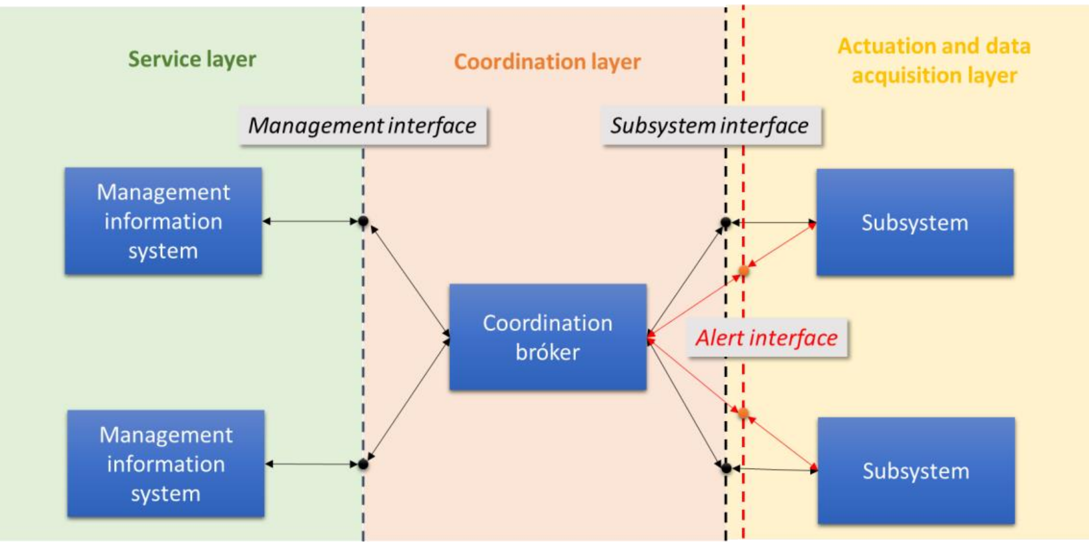


***Figure 36.** Proposed architecture to generate interoperable systems in MAR and the environment. Based on the UNE 318002-3:2021 standard.*

4.2.6 Financial aspects

Henao Casas et al. (2022d) evaluated the potential extra cost, CO_2 emissions and energy consumption if MAR was never implemented in the Los Arenales groundwater body. The following is the description of the methodology employed and the results described by Henao Casas et al. (2022d) (please notice that the external references have been omitted, and any interested reader should consult the original paper).

"We estimate the hypothetical extra cost and CO_2 emissions caused by groundwater pumping in the LAGB (Los Arenales groundwater body) if MAR was not implemented. We decrease the groundwater levels in each of the wells in the 2021 groundwater abstraction database by 27.4 m, assuming that the decrease observed between 1985 and 2001 (i.e., 1.37 m year^{-1}) continued in the period 2002-2021. Subsequently, we estimate the abstraction cost and energy consumption using an average groundwater pumping efficiency for crop irrigation in Spain (56%). To estimate CO_2 emissions, we employ equivalent CO_2 emission factors. The computed emissions are increased by 45%, corresponding to the percentage of illegal abstractions in the LAGB concerning legal groundwater rights.

We considered two scenarios to estimate energy cost and CO_2 emissions. In one of them, 100% of the energy is produced by different energy sources (i.e., energy mix) and delivered by the Spanish electrical grid. In the other scenario, 100% of the energy is generated through diesel. We obtained the average cost of pumping groundwater through the energy mix (EUR 0.00081 m^{-3} m^{-1}) and diesel (EUR 0.00168 m^{-3} m^{-1}) in Castile and Leon, from the Castile and Leon Institute of Agricultural Technology (ITACYL). We selected CO_2 emission factors for diesel and the energy mix of 0.27 and 0.25, respectively."

If MAR was not implemented, groundwater pumping would result in about 22% higher energy consumption (52.2 GW·h without MAR vs. 41.8 GW·h with MAR) (**Figure 37** a), farmers would have to spend 16% more economic resources to pump the same water volume either through diesel or the energy mix (**Figure 37** b), and CO_2 emissions would be 22% higher regardless of the energy source (**Figure 37** c). Approximately 70% of the energy consumed in the Spanish irrigation sector comes from the electrical grid. Thus, the total pumping energy cost and CO_2 emissions values are closer to the energy mix scenario.

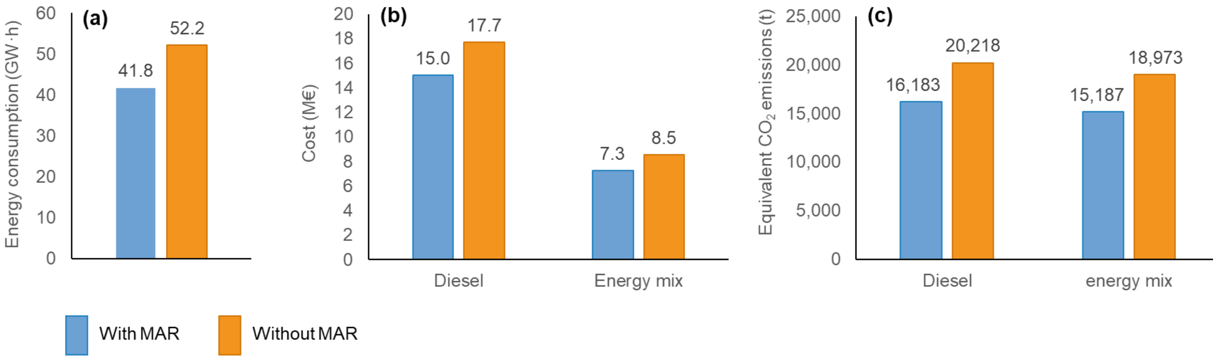


Figure 37. "Groundwater pumping energy consumption, cost, and equivalent CO_2 emissions in the Los Arenales groundwater body (LAGB) in 2021 for the actual scenario, i.e., with managed aquifer recharge (MAR), and a hypothetical situation without MAR: (a) pumping energy consumption, (b) cost of pumping, and (c) equivalent CO_2 emissions generated by groundwater pumping." From Henao Casas et al. (2022d).

Previous studies by Fernández Escalante et al. (2016) pointed out that gravity conveys water to the MAR systems, resulting in additional energy savings by avoiding surface water pumping. The same study also found that an increase of 2.3 m in groundwater levels in El Carracillo saved 12-36% in groundwater pumping energy, cut CO_2 emissions by about 11 tonnes, and reduced farmers' energy bills by EUR 3,000 per year.

4.2.7 Other aspects

Irrigation communities are serious to the proper functioning and success of the Los Arenales MAR sites. Henao Casas et al. (2022d) have summarised the role of these user organisations in a publication that is part of the MARSoluT ITN as follows:

"One of the major challenges Spain faces concerning groundwater management is the control of illegal abstractions. Since the Spanish Water Act of 1985 (Law 29/1985), water has been considered a public good in Spain. The transition from private ownership to the water allowance model has overflowed the ability of water management authorities to grant water rights and monitor their compliance, resulting in weak territorial control and an ambience that favours unauthorised groundwater extraction. We discuss the benefits of ICs (irrigation communities) on groundwater governance and security in the LAGB (Los Arenales groundwater body) and their vital role in decreasing unregulated groundwater consumption. The improvements in water governance discussed are based on workshops conducted with decision agents during the DINA-MAR and MARSOL projects (Fernández Escalante & López-Gunn, 2021). For the sake of contrast, we also draw elements from workshops conducted in MCGB (Medina del Campo groundwater body), where an IC has been recently stablished.

Following the Spanish Water Act of 1985 (updated in 2001 through the Royal Decree 1/2001 of 20 July), users' organisations must be formed to establish direct communication and cooperation between regional water authorities and water users under three scenarios: (i) when users benefit from the same water intake or concession (art 81.1); (ii) when an aquifer has been declared over-exploited, or a groundwater body might fail to meet the objectives of the Water Framework Directive; and (iii) for the authorisation of any large-scale river water diversion for artificial recharge.

Users' organisations are called irrigation communities (ICs) when irrigation is the end use of water allowances and groundwater user communities when nearly 100% of the water granted is extracted from the subsurface. In the LAGB, users' organisations correspond to both groundwater user communities and irrigation communities. For reasons of tradition, farmers have chosen to set up "irrigation communities" in the study site. Three ICs have been established in the LAGB: the El Carracillo Irrigation Community, the Cubeta de Santiuste Irrigation Community (formally the Cubeta de Santiuste de San Juan Bautista, Villagonzalo de Coca, Ciruelos de Coca, and Villeguillo irrigation community), and the Alcazarén Association of Commoners, which gather 713, 440, and 190 farmers, respectively (Fernández Escalante & López-Gunn, 2021).

Every year, the CHD assesses the water volume conveyed from the river source to the MAR systems and accordingly grants water rights to the ICs. The ICs set rules to distribute these water rights and report to the water authority on water use. This process occurs predominantly via meetings between the CHD and representatives of the IC and between these representatives and the IC members. Concerning finances, the MAR systems in the LAGB were funded by the national government. However, the ICs benefiting from MAR have the legal obligation to operate and maintain the infrastructure for 35 years. IC members pay annual fees to meet these legal obligations and administrative costs. This groundwater allocation scheme constitutes a co-managed institutional arrangement where the state and users share responsibilities. For the particular case of the LAGB, which involves MAR, this scheme has also been called Co-Managed Aquifer Recharge (Co-MAR) (Fernández Escalante & López-Gunn, 2021).

The ICs improve groundwater governance and water security due to the transparency in the water allocation process, the active information exchange among decision agents, and the shift in farmers' mind-set from individual to collective action. Moreover, legally binding ICs to the conservation and performance of MAR infrastructure is crucial for successfully co-managing water resources. We illustrate these dynamics through a simple process diagram based on stakeholder workshops conducted in Los Arenales and Medina del Campo groundwater bodies during the DINA-MAR, MARSOL, and NAIAD projects (**Figure 38** a and c). We also show the situation when ICs are not conformed (**Figure 38** b and d), following the agent-based/system dynamic model built to assess the implementation of nature-based solutions in MCGB.

ICs create a platform for assessing and distributing water rights, increasing transparency in the process, and building an environment of trust (**Figure 38** a). They also ease the bidirectional exchange of information between the water authority and farmers for better decision-making based on factual data. Under such circumstances, farmers are more likely to abide by the water rights assigned, cooperate, and perceive that the CHD has a more robust territorial control, which deters illegal groundwater abstractions (**Figure 38** a). On the contrary, without ICs, water users see the traditional top-down approach to granting water rights as unfair and not entirely transparent, resulting in a lack of trust in the water authority and the notion that its territorial control is weak (**Figure 38** b). This ambience promotes individual behaviour, less acceptance of water rights, and ultimately, groundwater overdraft (**Figure 38** b)”.

ICs play the additional role of enabling interaction among farmers and increasing their social capital (**Figure 38 c**). Since farmers in the area tend to adopt the predominant cropping behaviour they observe in their communities, they can find innovation and technical support in the ICs to cope with adverse conditions, such as low water availability or unfavourable market prices (**Figure 38 c**). In contrast, farmers with low social capital act as isolated agents and have less chance to discover strategies to grapple with market and environmental difficulties. The lack of innovation sometimes equals maintaining cropping patterns that are not sustainable, which can have an adverse impact on groundwater resources and the environment (**Figure 38 d**).

ICs are an instrument to solve conflicts among farmers and exchange points of view with actors that advocate for a different and sometimes opposite use of water resources, such as environmental protection organisations and downstream water users (e.g., fishermen and hydropower producers). ICs also give voice to members of society not directly involved in water use, which can deliver valuable contributions. These agents, collectively designated by Fernández Escalante & López-Gunn, 2021, as "*stakehomers*", include the local population, NGOs, researchers, and academia. ICs can also collectively negotiate optimal energy supply contracts, decreasing the cost of irrigation. They can ease the penetration of new farming and irrigation technologies that increase yield and water use efficiency and control (e.g., correct sizing of pumps, guidance on the installation of well flow meters, and the optimisation of irrigation systems). Some ICs are helping to improve groundwater quality by adopting internal rules and supervision mechanisms to reduce agro-chemical inputs in their plots.

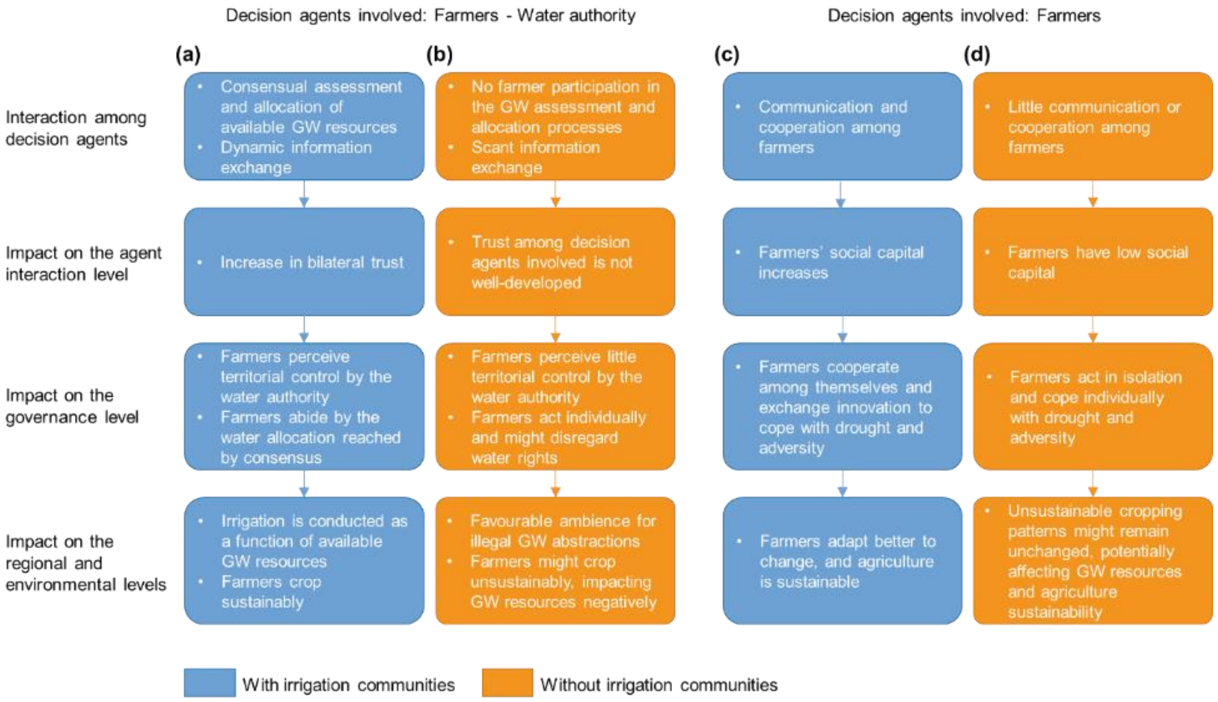


Figure 38. *Interaction between farmers and the water authority and the ensuing impacts at various levels when irrigation communities (ICs) are implemented (a) and when they are lacking (b). Interaction among farmers and the subsequent effects at different levels with access to ICs (c) and without this access (d). GW: groundwater. From Henao Casas et al. (2022d).*

However, members of the ICs are occasionally unsatisfied with their representatives in the governance scheme. In most cases, this situation has been solved by designating a delegate with a technical background (e.g., an independent agricultural engineer) and no conflict of interest that stands for the collective benefit. Furthermore, some farmers consider the distribution of water rights unfair because everyone pays similar fees but does not receive proportional water allowances. This issue compounds when groundwater users not involved in the ICs benefit from increasing groundwater levels and storage due to MAR. Problems pertaining to the distribution of water and fair IC fees might be circumvented by considering further technical aspects during the water allocation process. Concerning CC, ICs have also contributed to building adaptive capacity because they constitute an interlocution instrument that can be used to disseminate CC information and implement adaptation and mitigation strategies at the farmer level, such as, for instance, programs for carbon sequestration in soils through agricultural conservation practices.

4.3 Suvereto MAR site (Italy)

4.3.1 Introduction

It is worth to mention that most of this chapter's contributions proceed from MARSoluT's Early Stage Researcher (ESR) Esteban Caligaris and his tutor during the project's development.

The study site is located in the municipality of Suvereto (Tuscany, Italy) in the alluvial plain of the Cornia River (**Figure 39**). The Cornia plain hosts a Holocene coastal aquifer constituted by alluvial and swamplagoon deposits. The deposits, largely influenced by the Cornia River dynamics, include gravel, sand, silt, and clay in different proportions and distributions. The stratigraphy of the aquifer under investigation is well presented by Barazzuoli et al. (1999). New drillings performed in the context of the MARSoluT project confirmed the previous hypotheses and work (Caligaris et al. 2022). A large proportion of the aquifer is composed of a gravel lithology in a silty-sandy matrix, possessing a prevalent permeability by interstitial porosity. This layer outcrops the surface or is covered by a layer of silt as a result of fluvial overflows. The aquifer is unconfined in the area of the infiltration basin. Large surface water/groundwater exchanges occur between the river Cornia and the aquifer.

The lower Cornia valley aquifer system provides the only source of water for drinking, irrigation, and industrial purposes and it also contributes to the water needs of the nearby Elba Island. Since 60 years, intensive exploitation of groundwater resulted in consistent head lowering and water balance deficit, causing subsidence, reduction of groundwater dependent ecosystems, and salinization of freshwater resources. Rebalancing the water budget of the hydrologic system was the main objective of the LIFE REWAT project (sustainable WATer management in the lower Cornia valley through demand REduction, aquifer Recharge and river REstoration; https://www.liferewat.eu/). Here, five demonstration measures (river restoration; Managed Aquifer Recharge; reuse of treated wastewater for irrigation; high irrigation efficiency scheme; and leakage management in water distribution systems) were set in place for promoting water resource management, along with capacity building and participatory actions.

Figure 39. *Study area location and measured points. Taken from Caligaris et al. (2022).*

Caligaris et al. (2022) presents the stratigraphies at points REW_10 (in the centre of the infiltration basin), REW_12 and REW_6 (north of the infiltration basin) (**Figure 39**). A relatively thin layer of agricultural soil covers an alternate layer of gravel with different size distributions in a silty matrix in the vicinity of the infiltration basin up to about 15 m from the soil surface. Some thin gravel lenses in a clayey matrix can also be found at different depths. As such, the experimental area shows up to a depth of about 15 m from the soil surface, the presence of a gravel-dominated environment in a matrix variable from silt to sand.

The Cornia River is the main hydrologic feature in the area. The high hydraulic conductivity of the riverbed provides high hydraulic connectivity between the surface water and the aquifer. This enhances surface and groundwater exchanges in the areas near the river. Hence, the groundwater heads are controlled by the river's water level and, locally, by pumping wells. Because of this, values of electrical conductivity in the aquifer slightly differ from those of surface water. As such, the parameter electrical conductivity cannot be easily used to trace the recharged water. The main groundwater natural flow is directed towards the West, resulting from river recharge and inflows from adjoining hilly areas, with an average hydraulic gradient of 0.2% (Caligaris et al. 2022) (**Figures 40** and **41**). From the regional hydrology point of view, the area is a recharge area.

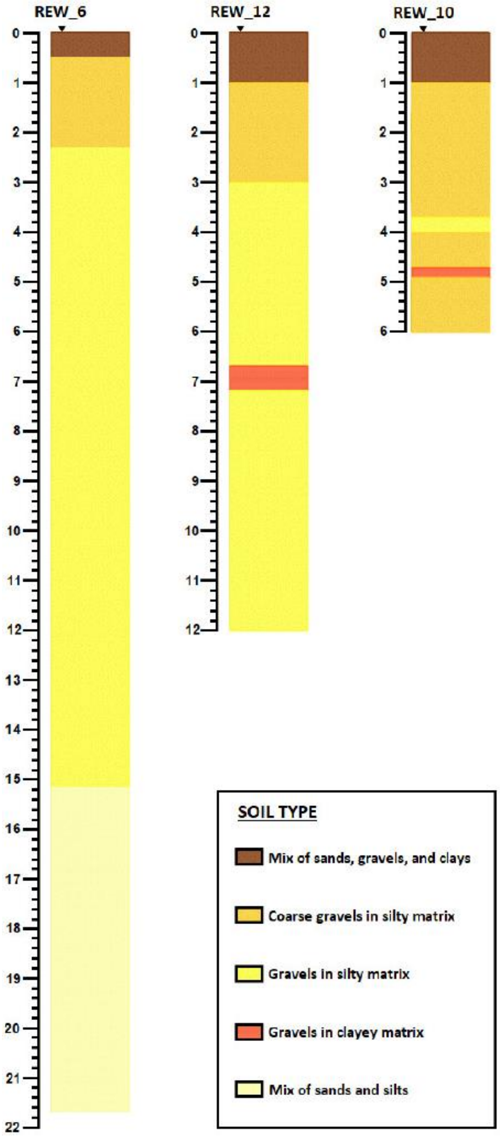


Figure 40. *Stratigraphy of three piezometers near the infiltration basin. Information obtained from the analysis of the soil cores during the construction of these piezometers. Taken from Caligaris et al. (2022).*

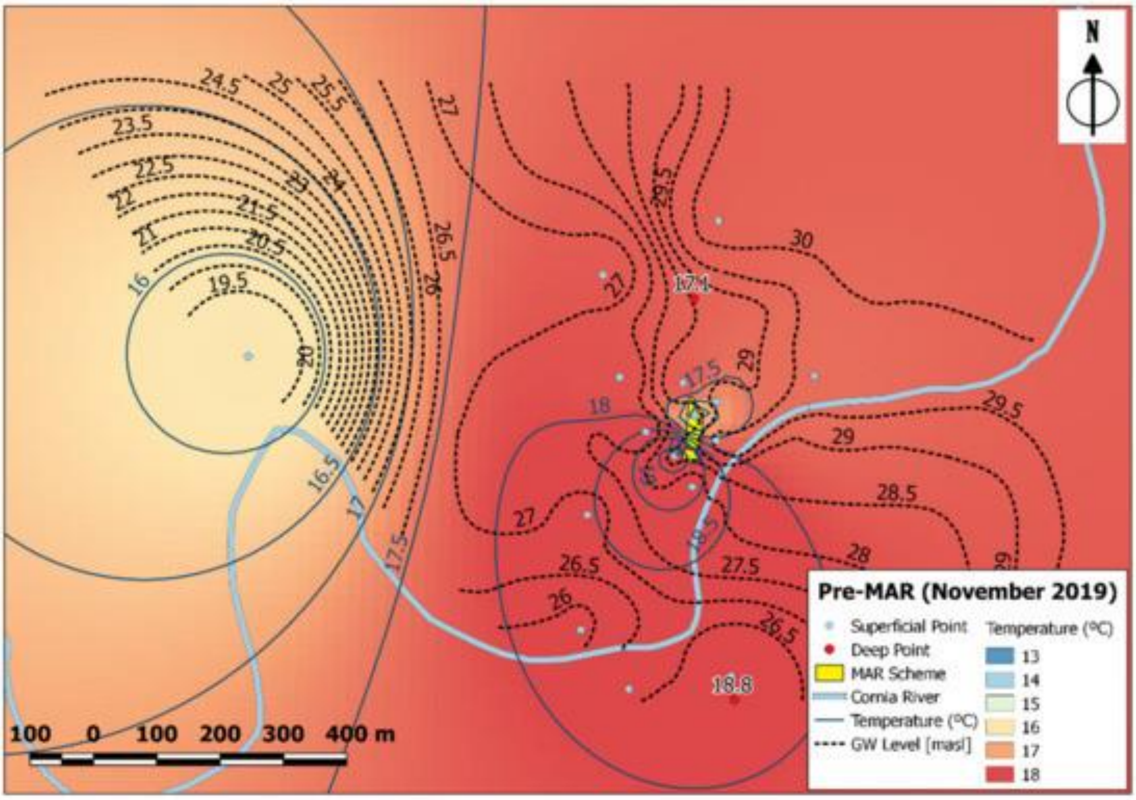


Figure 41. Groundwater temperature distribution in the aquifer before MAR operations started. Data taken from 25 to 27 November 2019. Taken from Caligaris et al. (2022).

The LIFE REWAT Managed Aquifer Recharge scheme is a two-stage infiltration basin using harvested rainwater from the Cornia River during high-flow periods. The design tested for the first time the Italian regulation on artificial recharge of aquifers (DM 100/2016). The scheme consists of diversion infrastructure and two basins: a settling pond and the infiltration basin (Caligaris et al. 2022) (**Figure 42**). Surface water is firstly diverted from the Cornia River into the decantation pond, where the suspended solids are deposited. The river, having intermittent flow, provides the recharge water during high flow periods, including floods, and when discharge is above the minimum ecological flow. Afterwards, the water enters the infiltration pond. The infiltration pond was constructed in a topographic low, where the soil (sandy/silty gravels) provides a full hydraulic connection with the phreatic aquifer.

The facility consists of the following elements: i) intake work on the River Cornia; ii) the inlet structure control system, managed by quality (mass spectrometer defining surface water spectral signature) and level probes, and allowing pumping into the facility at predefined head and chemical quality thresholds; iii) a sedimentation basin; iv) the infiltration area (less than 1 ha large); v) the operational monitoring system, based on a network of piezometers where both continuous data (head, T, EC, DO) are gathered and discrete measurements/sampling performed.

The MAR scheme is operated using a hi-tech high-frequency, automated and remotely controlled system, and quasi-real-time water quantity and quality monitoring are run. This system is supported by the data gathered from different sensors installed in the area, recording different parameters into a database with a frequency of fifteen minutes.

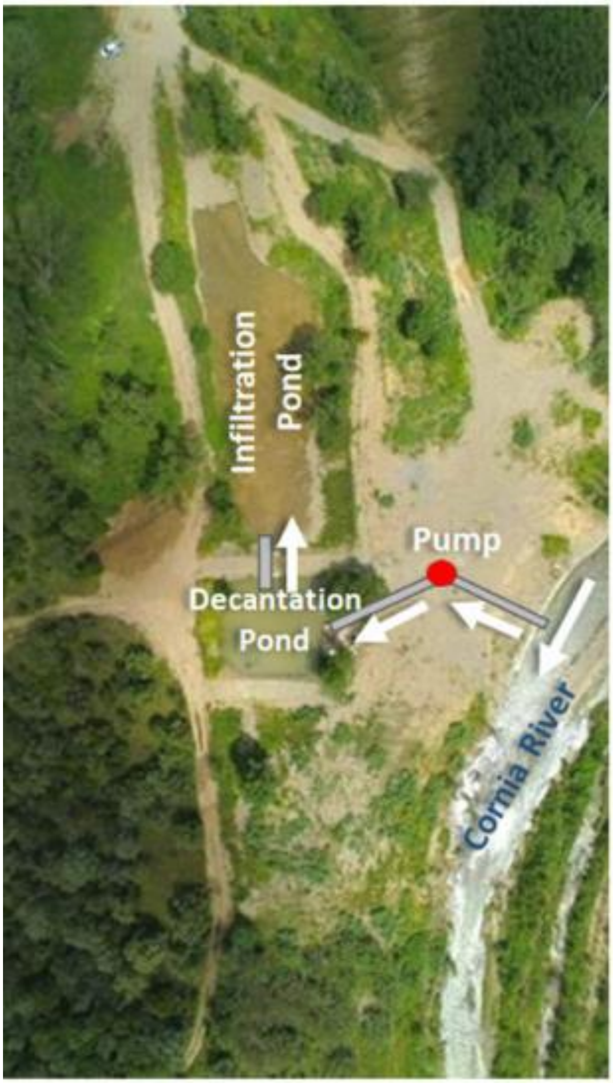


__Figure 42.__ LIFE REWAT Managed Aquifer Recharge scheme. Taken from Caligaris et al. (2022).

4.3.2 Yearly recharge volumes

The MAR scheme has been operating for three full years, from roughly December to mid-June. In these three years, the yearly recharge volume is estimated to be 500,000 m^3/year. The last recharge season (2021/22) was affected by a relevant drought – the estimated recharge volume was of about 180,000 m^3/year.

4.3.3 Groundwater level behaviour

Within a radius of about 250 m from the MAR scheme, the groundwater level rises by about 1 m when recharge is in steady-state conditions.

4.3.4 Water quality evolution

The MAR scheme is seated in an area whose main hydrochemical characteristics are related to the presence of Calcium and Carbonate as main ions. The site is also geogenically rich in Boron and Arsenic (Pennisi et al. 2009). Recharge with surface water poor in Arsenic and Boron improved groundwater quality in the recharge area, lowering monitored Arsenic and Boron concentrations.

4.3.5 Infiltration rates and clogging

Even though a clogging crust is detected at the bottom of the basin at the end of each recharge season, the MAR site maintained high stable infiltration rates over the past four years of operations.

Given the low suspended solids in the recharge water, the low content of clays, and the presence of gravels and vegetation at the banks, the Suvereto MAR infiltration basin has proved to be an excellent example of MAR design.

4.3.6 Site upgrade

At the end of 2022, the Consorzio di Bonifica 5 Toscana Costa received funds to enlarge the MAR scheme. Waterworks started in December 2022 and will be completed in February 2023 (**Figure 43**). The new configuration will allow a maximum yearly recharge volume of more than 2 Mm^3.

Figure 43. *New area for recharge at the LIFE REWAT MAR scheme.*

4.3.7 Financial aspects

A preliminary project and an executive report were prepared and discussed with the relevant authorities, following one-year long monthly monitoring of surface- and groundwater. The project was supported by a groundwater flow modelling-based approach using the FREEWAT platform (http://www.freewat.eu/). Minimal site development and modification was required, resulting in a no-impact water-work, while providing ecosystem benefits by reconnecting and inundating former abandoned riverbeds. Roughly, the construction costs (including waterworks and the monitoring system) account for 300,000 €. Maintenance and operation costs are in the order of 10-20,000 €/year.

4.4 The Pwales Valley MAR site (Malta)

4.4.1 Introduction

It is worth to mention that most of this chapter's contributions proceed from MARSoluT's Early Stage Researcher (ESR) Francesco Demichele and his tutor during the project´s development.

Malta, situated in the central Mediterranean, has a typical Mediterranean climate with an average rainfall of circa 530 mm, of which 85% occurs from October to March. Mean monthly temperatures range from 12 to 26 °C, and the islands can be very windy and sunny.

The Pwales Valley MAR site is located along the northern part of Malta close to Xemxija and St. Paul's Bay, with an underlying aquifer covering an area of 2.8 km^2. As one of the most fertile valleys in the Northern Malta region, Pwales is characterised by intensive agricultural activity, mainly maintained through utilising the site's groundwater body. Due to its high demand, the site's groundwater body faces quantity and quality issues; seawater intrusion is an important issue due to the high abstraction rates through agricultural wells dispersed in the valley. Another issue is the small area overlying this groundwater body which is also related to the intense fertiliser use. In addition to this socio-economic aspect, a Natura 2000 coastal saltmarsh is located on the eastern side, serving as an important stop-over for migratory avifauna.

This MAR type, which shall be applying direct recharge, aims to improve the groundwater body's qualitative and quantitative status. Highly polished reclaimed water (known as *New Water*) from a sewage treatment plant in the Northern region will be utilised to inject the aquifer through multiple newly drilled wells. Private wells shall be used for abstraction purposes. Newly drilled wells shall also serve as groundwater monitoring stations for pre and post implementation of MAR infrastructural works, ensuring monitoring of the MAR scheme effects on both the qualitative and quantitative status.

Figure 44 below (Lotti et al. 2021) describes the Pwales aquifer as located between the Wardija and the Bajda Ridge, with its base rising slightly above sea level on its west side with a limited area perched above sea level. On the eastern coast, the Blue Clay formation dips below sea level with seawater intrusion. The groundwater body is located within the Upper Coralline Limestone, sitting over the Blue Clay layer at an altitude of 21m asl on the western side (Ghajn Tuffieha side) and dipping below sea level to a depth of circa -30m asl on the eastern side of the valley (Xemxija side). The Ballut springs and springs of Wardija and Ghajn Stas, among others, discharge freshwater into the valley.

4.4.2 Yearly recharge volumes

The Pwales Valley MAR Site is still at the baseline study stage, where both the quantitative and qualitative aspects of the groundwater body are being determined prior to planning the implementation of the MAR scheme itself. Sites for groundwater body injection are still being discussed, along with the sources of water.

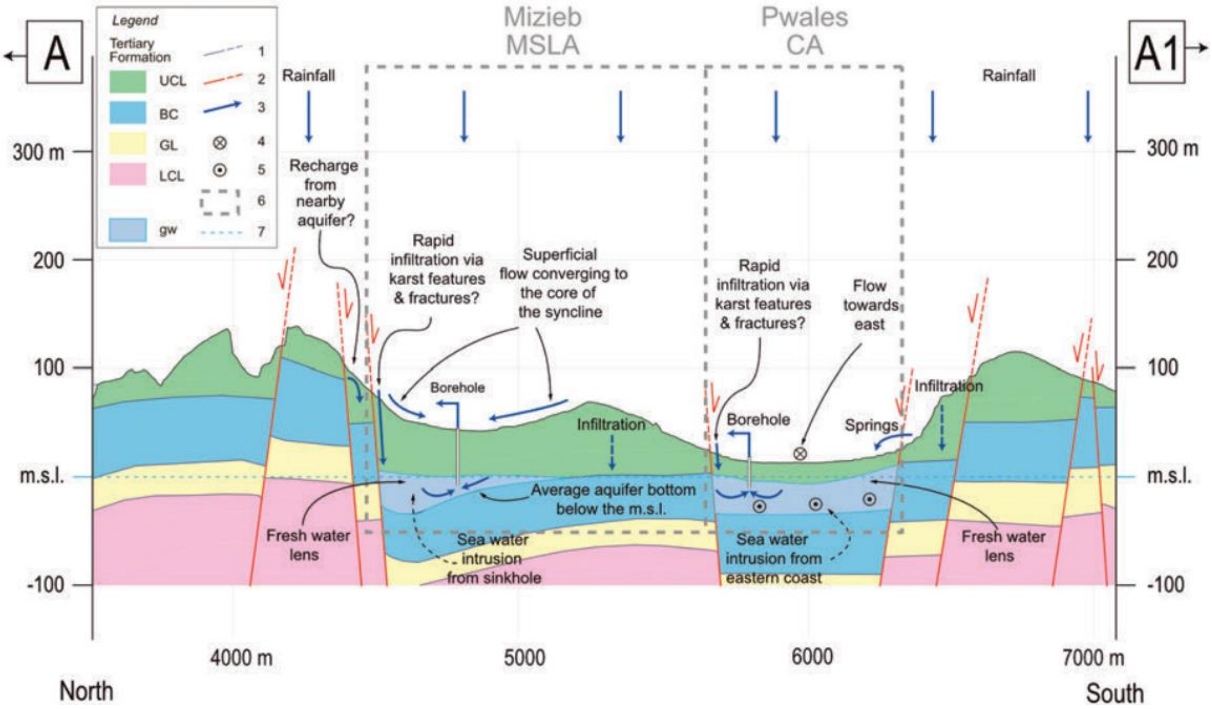


Figure 44. *Mizieb and Pwales aquifers' hydrogeological conceptual scheme cross-section. Taken from Lotti et al. (2021).*

4.4.3 Groundwater level behaviour

The MAR scheme applied in Pwales valley, which will inject high-quality recharge water into its groundwater body, is expected to result in a rise in piezometric levels in the recharge area of the groundwater body, creating a positive hydraulic gradient towards the coast on the eastern margins thereby enabling the progressive "flushing out" of contaminated groundwater towards the coast. The increased recharge shall, therefore, not only contribute to improving the quantitative status of the groundwater body (by increasing inflow) but will also support the progressive improvement in its qualitative status by enhancing the outward flow of contaminated groundwater.

4.4.4 Water quality evolution

Given that the Pwales groundwater body is characterised by high concentrations of nitrate and chlorides due to intense agricultural activity, the aquifer system is classified as being in poor qualitative status. The MAR scheme applied in Pwales Valley aims at flushing out pollutants, thereby contributing to the achievement of the less stringent objectives established under Malta's 2nd River Basin Management Plan for this groundwater body – potentially also resulting in the progressive achievement of good qualitative status.

In order to determine the baseline conditions prevailing in the Pwales groundwater body, seven private wells were identified to form part of a monitoring network within the body of groundwater. The spatial location of these monitoring points is shown in **Figure 45** below. **Table 8** shows the average annual content (2022) for key qualitative indicators, namely chloride and nitrate concentration and electrical conductivity.

Figure 45. *Location of private wells part of the monitoring network to establish the baseline conditions in the Pwales groundwater body.*

Table 8. *Average Chlorides, Nitrates and Conductivity values for the Pwales Baseline Monitoring Network.*

Source No.	Chlorides Avg (mg/L)	Nitrates Avg (mg/L)	Conductivity Avg (µS/cm)
PW1	5170.0	160.5	3949.6
PW2	1915.0	489.0	5911.8
PW3	2905.7	348.2	9909.2
PW4	1459.7	398.7	6004.8
PW5	1455.0	118.5	4930.6
PW6	1230.0	244.3	4108.2
PW7	940.0	245.0	4018.6

4.4.5 Infiltration rates and clogging

This MAR scheme is still at the design stage, and investigations are currently being undertaken to determine optimal infiltration rates based on the hydrogeological properties of the aquifer formation (Upper Coralline Limestone) in the region. These investigations were supported by the National Research Council of Italy, Water Research Institute (CNR-IRSA).

4.2.6 Financial aspects

The Water and Energy Agency of Malta undertook an economic assessment of MAR with the scope of identifying the unmonetised benefits related to the application of MAR. Economic sustainability needs to be ensured for MAR to be viable in the long term.

Interviews with main stakeholders were held where the value of crop yield for cultivation with saline groundwater was compared to the value of crop yield for cultivation with good quality groundwater (both scenarios were for each tumuli, per season). In this manner, such evaluation enabled the assessments of the added value of agricultural production, which can be achieved by restoring the groundwater body to good status. The Cost-Benefit Assessment for undertaking MAR in Pwales Valley has shown that it can provide a positive net economic impact on the Maltese society.

4.5 The Argolis Field (Greece)

4.5.1 Introduction

It is important to mention that most of this chapter's contributions proceed from MARSoluT's Early Stage Researcher (ESR) Angeliki Vlassopoulou and her tutor during the project´s development.

The MAR site of Argolis is located in the 3rd Water District of Greece (EL03), as shown in **Figure 46**. The Gulf of Argolis is mostly a mountainous zone, with steep high mountains delimiting the region's plains. The altitudes of mountainous areas range from 500 m up to around 2,000 m on the highest peaks. The plain of Argolis stretches from the Argolis Gulf to Mycenae.

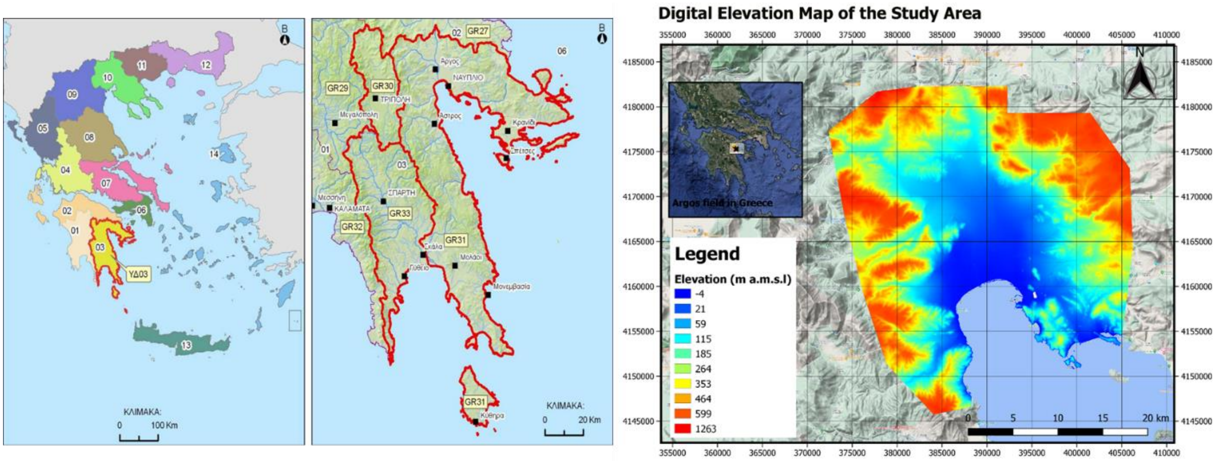


Figure 46. *Water District of Eastern Peloponnese – EL03 (left), and digital elevation maps of the area of study where the MAR site is located (right).*

The region's climate is Mediterranean, with a typical continental European influence. The Mediterranean type refers to the climate of the broader area of the Mediterranean basin. It represents a transitional state between the temperate zone in the north and the tropical zone in the south. The main characteristics of this climate are dry and hot summers and the mild, wet winters.

The intense abstraction of groundwater resources in the coastal aquifer system of Argolis has been investigated since the late 1950s. Increasing water demands due to the agricultural development (mainly citrus trees) during the last years, in combination with tourism growth, has led to the overexploitation of groundwater resources in the coastal aquifer system of Argolis (Panagopoulos 2000).

The location of the MAR sites injecting water into the aquifer system is shown in **Figure 47**. The study area includes an infrastructure system of hydraulic works composed of a) the only source of water supply for artificial recharge, which is the Kefalari spring, b) a conveyance system of mainly open canals for the transfer of water from the primary intake structure to the agricultural area, and c) the MAR facilities, which either inject water in the subsurface through deep wells or via infiltration ponds and/or river bank filtration (**Figures 48** and **49**).

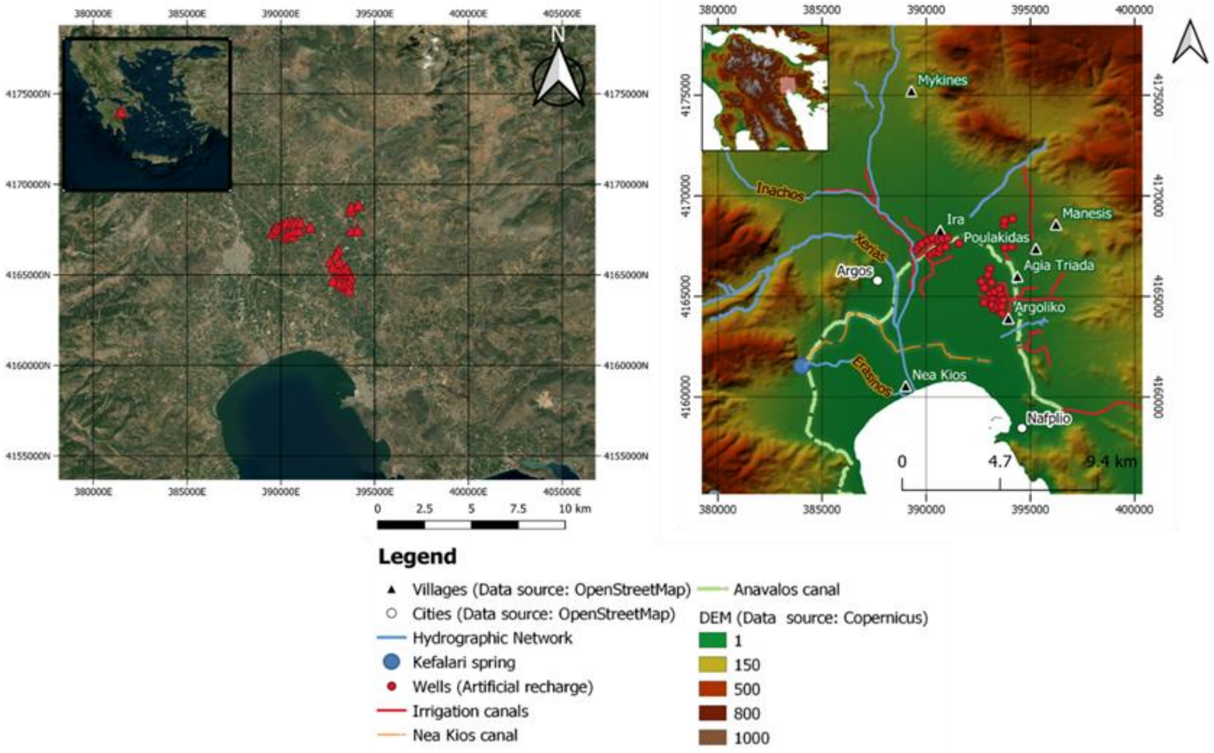


Figure 47. *Location of 38 wells used for artificial recharge (right and left) and the Anavalos and Nea Kios canals used for water conveyance from the Kefalari spring and the Anavalos dam (right). From Chrysanthopoulos (2018).*

Water is conveyed to the wells injecting water for MAR via the Nea Kios Canal, while the Anavalos canal relies on gravity or pumping to convey water. The water for MAR is exclusively surpluses from the Kefalari spring, which feature high quality. In 2017, a year in which MAR was conducted, the electrical conductivity of the Kefalari spring was of the order of 447 µS/cm measured at 25°C and a maximum chloride ion content of less than 17 mg/l. Of the approximately 2,256,000 m^3 of water taken from the Kefalari spring, it is estimated that:

- 1,131,200 m^3 were channelled directly into the area's aquifers through the disposal of water in wells and boreholes.
- 43,300 m^3 were recharged indirectly in the riverbed of Amarianos stream.

- 746,500 m^3 were allocated to cover the irrigation needs in the Irian plain.
- 335,000 m^3, which constitute the remaining water, is predominantly infiltrated into the aquifer as leakages from the Anavalos canal (of the order of 280m^3/hour). A small percentage of this volume overflows the canal (either for cleaning or due to overloading) at the connection with the Ramadanis stream.

Figures 48 and **49** show some of the infrastructures for water extraction, conveyance, irrigation, and water infiltration/injection.

a) Irrigation canal b) Artificial recharge well c) Infiltration basin

d)Anavalos dam e) Pumping well f) Anavalos canal

Figure 48. *The infrastructure system of water resources management (MAR and irrigation) in the Argolis field. Water is transported from the Anavalos dam through the Anavalos canal.*

Figure 49. *The infrastructure system of water management in the South part of the study area consisting of A) the Anavalos dam, where fresh water is collected and transported to the north through B) the Anavalos canal, mainly used for irrigation purposes. C) Is a buffer lake in Lerni, which is used as part of the transportation system of fresh water from Lerni Lake to the Argolis field through D) the canal network. On the right map E). The water pipes system is shown in red, and F) the irrigation pipes system (Anavalos and Nea Kios canals) is shown in yellow, respectively.*

Concerning hydrogeology, groundwater movement is controlled by both the geological formations' tectonic structures and hydrolithological features. The formations in the West of the Argolis field differ in hydrogeological characteristics from those in the East. The Pindos Limestones laterally supply the alluvium deposits of the Argolis field on the western margins. The geological formations on the east side are unlikely to contribute significantly to groundwater recharge. The geological map of the study area is given in **Figure 50**.

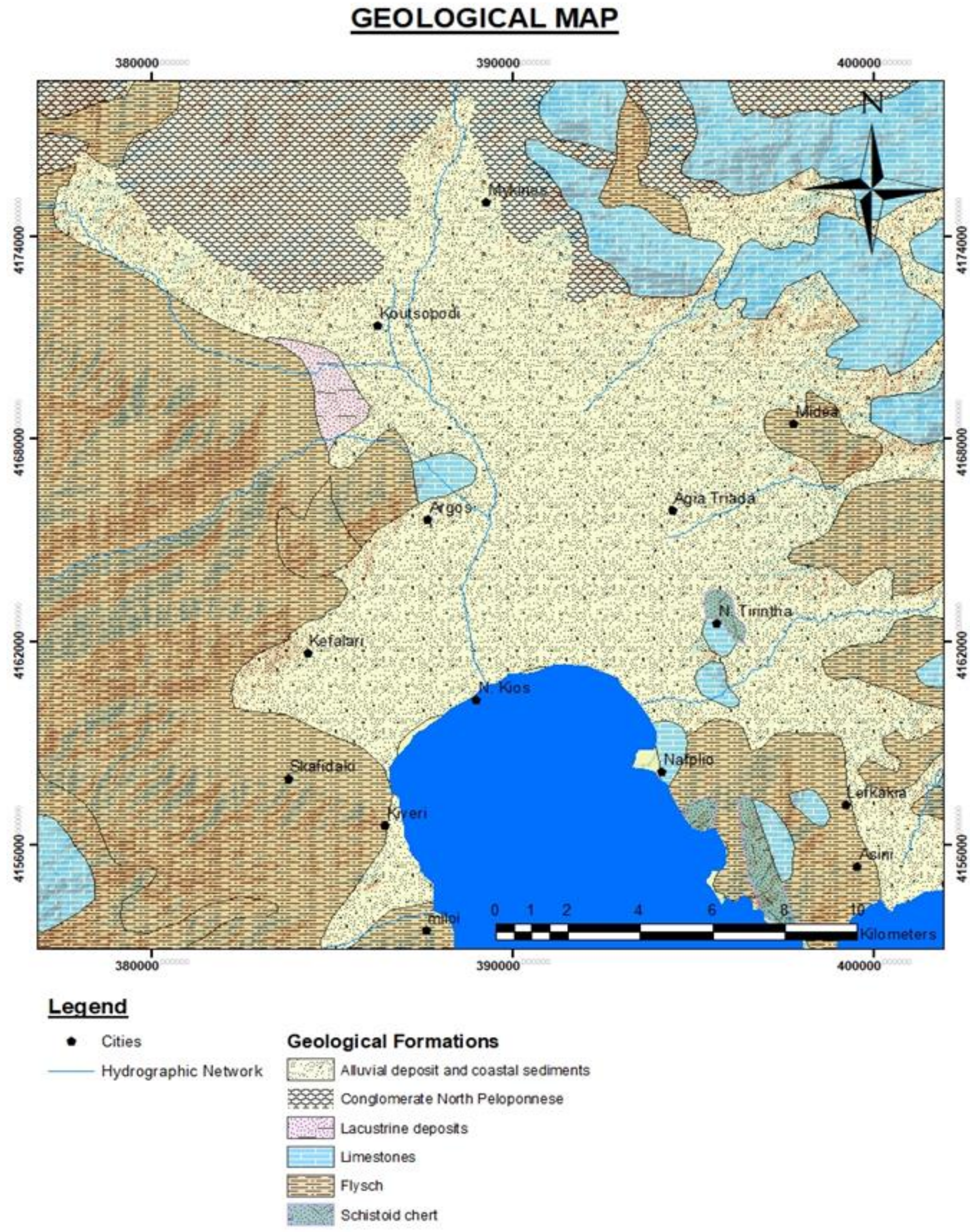


Figure 50. *Geological Map of the Argolis field. The main geological features are 1) the unconfined alluvial aquifer body, consisting of multiple permeable layers separated by clay of variable thicknesses, 2) the semi-confined conditions close to the coast, 3) Karstic surrounding aquifers 4) Significant spring systems such as this of Kefalari at the west margin. From Makaratzi (2020).*

Groundwater recharge usually comes from (Giannoulopoulos, 2000):

a) Runoff

b) Lateral flow from the limestone formations at the western fringes of the Argolis field

c) Managed aquifer recharge

d) Infiltration from the Inachos River and other streams in the area

e) Irrigation returns

f) Losses from the water supply and irrigation networks.

On the other hand, groundwater Outflows comprise:

(a) Groundwater supply and irrigation abstractions

(b) Springs, the sea, rivers (gaining streams)

(c) Neighbouring aquifer formations depending on their hydrodynamic and boundary conditions.

The main components of the water balance for this particular case study are precipitation, evapotranspiration, surface runoff, lateral recharge (in this case from karstic aquifers), diffuse recharge, focused recharge through ephemeral streams, and groundwater extractions for various uses such as irrigation, water supply, industry, etc.

The above components are regulated by several factors such as climatic, geology, soils, morphological characteristics of the area, land cover and use, anthropogenic factors, etc. In **Figure 51** (left), the precipitation in the Argos district is displayed for every month of the most recent years. Most rainfall occurs between September and March and shows high interannual variability. MAR had been applied in the Argolis field in February and March 2017.

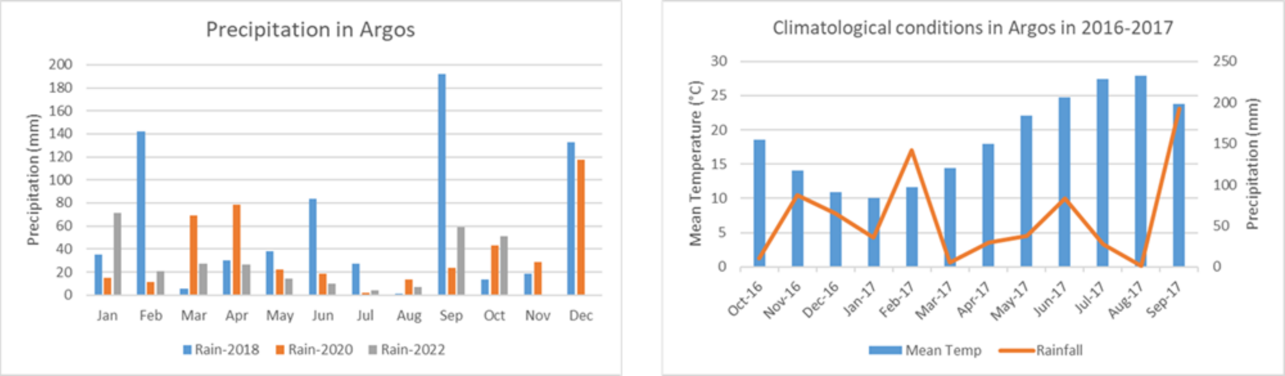


Figure 51. *Precipitation (mm) data for the years 2018-2020-2022 and October 2016 – September 2017, when MAR was applied in the Argolis field (February and March 2017). Data were taken from meteo.gr.*

Figure 52 shows the land use distribution in the area. The total annual water needs for all activities and uses in Argolis amount to ~268.4 Mm^3. Irrigation consumes ~90.8% (243.7 Mm^3) of the total needs, industry ~2.3% (6.3 Mm^3), water supply ~6.5% (17.5 Mm^3), and animal husbandry ~0.4% (1.0 Mm^3).

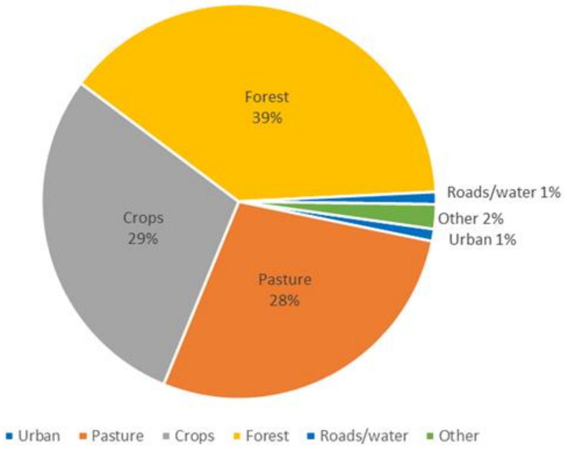


Figure 52. *Distribution of land uses in the Argolis Gulf (EL0331). From Joint Venture of Peloponnese Waterbodies (2018).*

The population numbers for every municipality of the Argolis region are presented in **Table 9**, together with an estimation of the population in 2021. It had been predicted that the population increase in the area would be insignificant from 2015 to 2021. This demographic pattern is due to the exodus of the young population to the urban areas, which has been verified through oral accounts by various farmers in the study region.

Table 9. *Population structure of the current population of the Municipal Units of the Argolis Gulf (EL0331). Source: 1st Revision of the River Basin Management Plan of the Eastern Peloponnese (EL03), 2017.*

Regional unity	Municipality	Municipality unity	Real population 2001 (people)	Real population 2011 (people)	Polulation change % 2001-2011	Estimation of real population 2015 (people)	Estimation of real population 2021 (people)
Argolis	Argos-Mycenae	Argos	28.793	26.554	-7.776	26.700	26.850
Argolis	Argos-Mycenae	Achladocampos	654	499	-23.700	500	500
Argolis	Argos-Mycenae	Koutsopodi	3.575	3.324	-7.021	3.350	3.350
Argolis	Argos-Mycenae	Lerna	3.042	2.313	-23.964	2.350	2.350
Argolis	Argos-Mycenae	Lyrkeia	2.398	1.748	-27.106	1.750	1.750
Argolis	Argos-Mycenae	Mycenae	4.349	3.384	-22.189	3.400	3.400
Argolis	Argos-Mycenae	Nea Kios	3.646	2.82	-22.655	2.850	2.850
Argolis	Argos-Mycenae	Asclepius	4.804	4.286	-10.783	4.300	4.300
Argolis	Argos-Mycenae	Epidaurus	4.471	4.018	-10.132	4.050	4.100
Argolis	Argos-Mycenae	Ermioni	4.554	4.102	-9.925	4.150	4.150
Argolis	Argos-Mycenae	Kranidi	10.347	9.628	-6.949	9.700	9.750
Argolis	Argos-Mycenae	Asini	6.117	5.948	-2.763	6.000	6.100
Argolis	Argos-Mycenae	Medea	6.724	5.6	-16.716	5.600	5.600
Argolis	Argos-Mycenae	Nafplion	16.885	19.462	15.262	20.800	23.200
Argolis	Argos-Mycenae	Nea Tirintha	3.680	3.483	-5.353	3.550	3.600

For decades, the main economic activity in Argolis has been agriculture. This region is considered one of the most irrigated areas in Greece. Consequently, groundwater contamination due to seawater intrusion and nitrate pollution has occurred. Since the 1990s, MAR has been applied by the local authorities to improve water quality, increase groundwater storage and reverse or stop seawater intrusion. The MAR methods employed range from surface basins to shallow wells and deep boreholes.

Systematic application of MAR in Argolis was carried out from 1990 to 1996 as part of a research project program and then from the South-East Argolida District- Department of Management of the Land Improvement Agencies until December 2010, when it was repealed by Law 3852/2010. Since then, MAR has been carried out by the Region of Peloponnese, the successor body of the South-East Argolida District. Summary data on the application of MAR in the period 1990-2017 are provided in **Table 10** and **Figure 53**.

The Anavalos canal started operating in 1994, and since then, the cost of MAR has decreased due to a reduction in energy consumption for pumping. Artificial recharge was not executed in the years 1999, 2000, 2005, 2006 and 2015 due to technical problems or lack of approval-licensing, as well as the years 2007 and 2016 due to non-activation of the Kefalari spring.

Table 10. *Amount of water used for MAR during the years 1990-2017 and the corresponding costs. Modified from Giannoulas (2017).*

Year	Water quantity (m^3) via the Nea Kios canal	Water quantity (m^3) via the Anavalos canal	Total water quantity (m^3) for recharge	Cost of MAR (€)
1990	3,094,000	0	3,094,000	73,847.60
1991	6,929,580	0	6,929,580	70,761.09
1992	5,685,370	0	5,685,370	112,451.47
1993	3,891,590	0	3,891,590	128,508.36
1994	4,500,000	9,500,000	14,000,000	80,537.53
1995	1,364,200	12,228,000	13,592,200	36,124.89
1996	0	7,224,000	7,224,000	13,923.00
1997	0	4,000,000	4,000,000	22,521.67
1998	598,920	4,320,000	4,918,920	34,836.68
1999	0	0	0	0
2000	0	0	0	0
2001	423,000	2,195,000	2,618,000	16,815.03
2002	1,406,470	5,136,385	6,542,855	58,845.00
2003	0	2,800,000	2,800,000	17,556.00
2004	255,000	3,103,000	3,358,000	27,150.00
2005	0	0	0	0
2006	0	0	0	0
2007	0	0	0	0
2008	144,320	0	144,320	3,057.00
2009	0	6,877,596	6,877,596	40,000.00
2010	0	4,587,466	4,587,466	43,123.59
2011	0	1,353,200	1,353,200	22,747.00
2012	0	3,836,000	3,836,000	41,515.00
2013	0	4,000,000	4,000,000	54,726.73
2014	0	4,455,453	4,455,453	55,067.00
2017	0	1,509,500	1,509,500	28,864.00
TOTAL	28,292,450	77,125,600	105,418,050	982,978.64

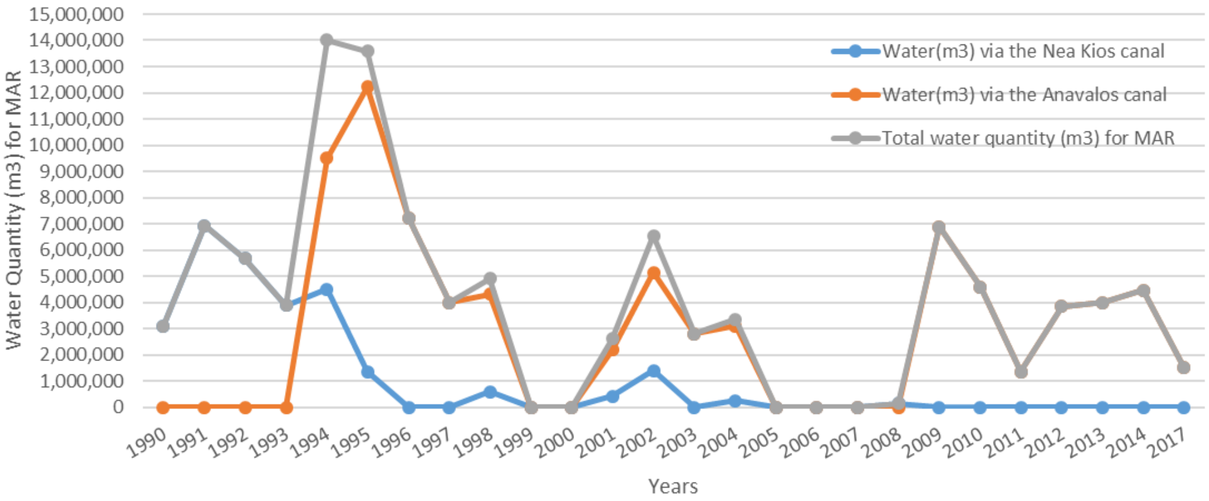


Figure 53. *Graphical representation of the amount of water in Mm^3 that was used for artificial recharge in Argolis between 1990 and 2017.*

The average hourly water volume injection in the Argolis field was 10-60m^3/hour. The significant range is due to the heterogeneity of the prevailing hydrogeological conditions and the large area where MAR is applied.

4.5.2 Impact on groundwater levels

To monitor the present condition of the groundwater aquifer, water level measurements were taken from 35-50 wells visited between 2021 and 2022. The location of the wells is shown in **Figure 54**. It was not always possible to retrieve a water level measurement from the same well each time.

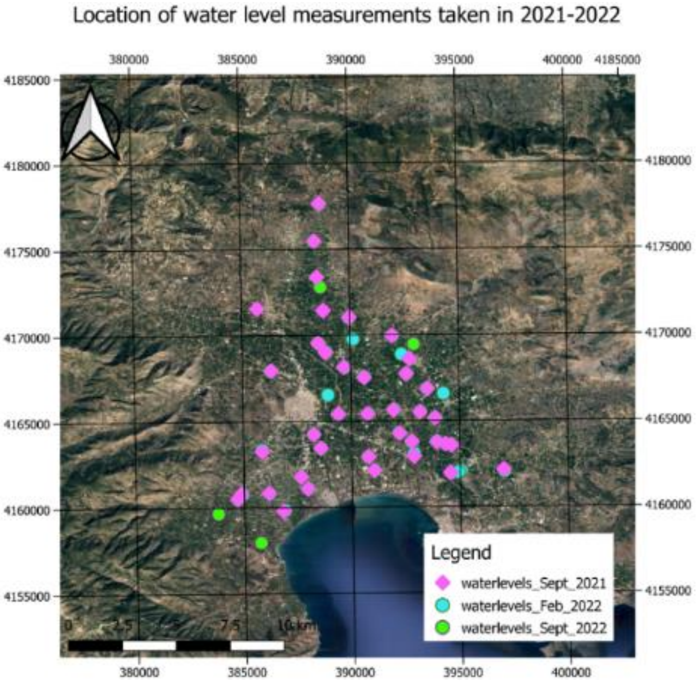


Figure 54. *Location of the monitoring stations/wells where water level measurements were conducted in 2021-2022.*

A comparison of water levels (without subtracting the topographic elevation) is presented in **Figure 55** for the dry (Sep 2021 & Sep 2022) and wet (Feb 2022) seasons. As expected, groundwater levels are higher during wet periods, not only because of more precipitation but also because of less groundwater extraction volumes for irrigation. For the same time periods the interpolated water table/piezometric surface depth is shown in **Figure 56**.

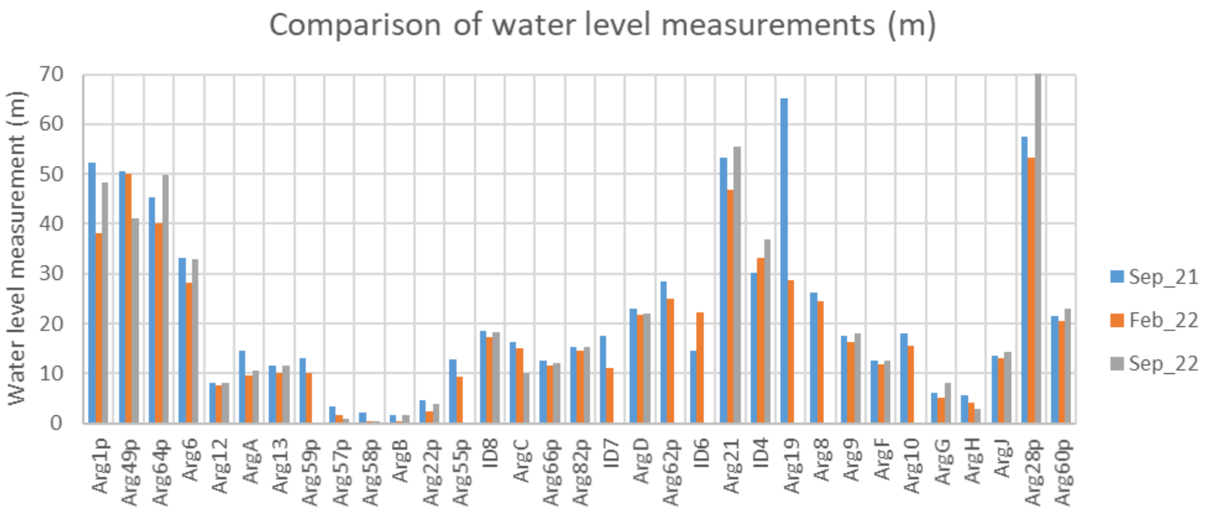


Figure 55. *Comparison of water levels measured at each well head of various monitoring stations/wells. Depth is measured as distance to the water table/piezometric surface.*

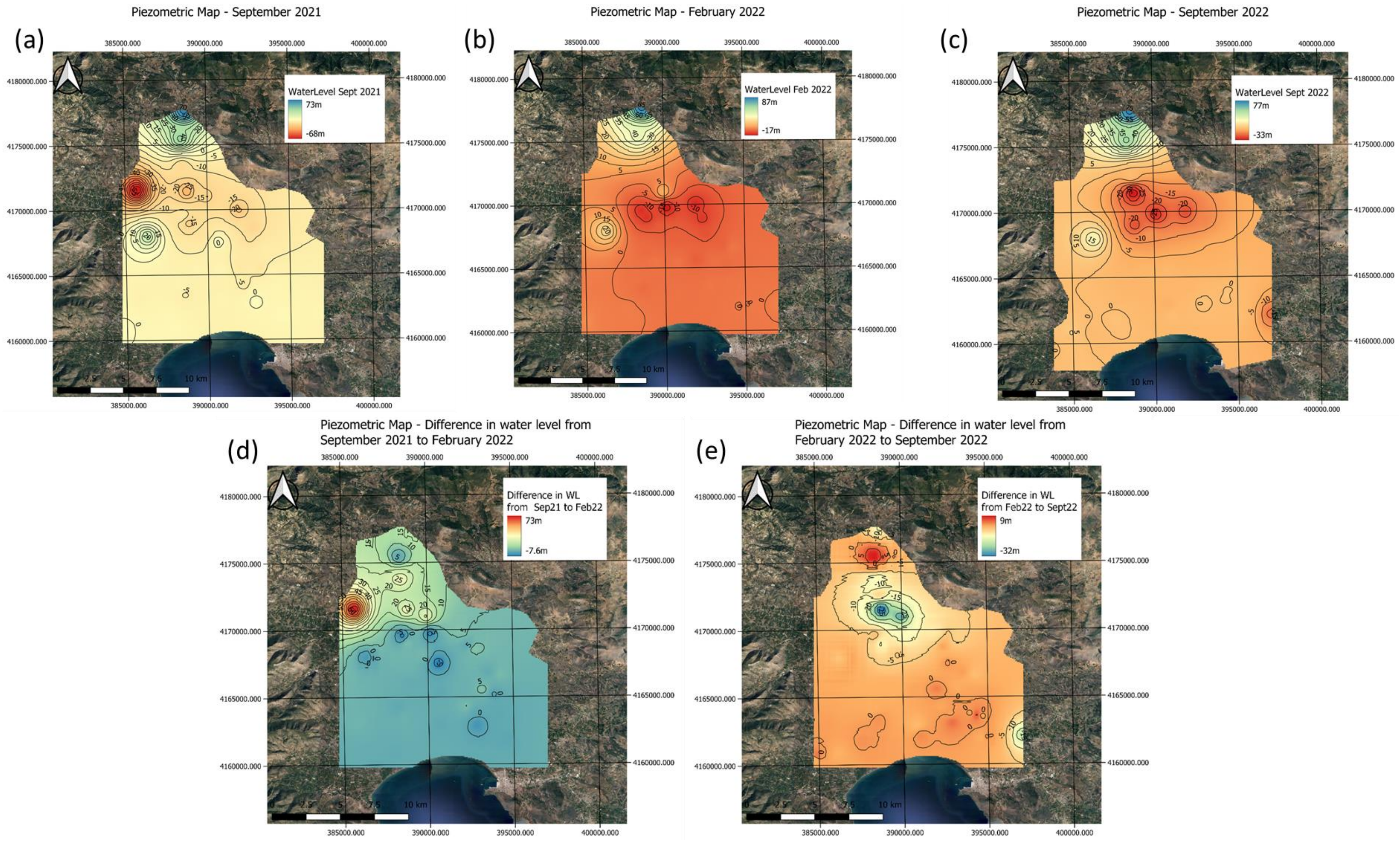


Figure 56. *Interpolated water table/piezometric surface depth in the study area in a) September 2021, b) February 2022, and c) September 2022. The difference between these maps is given in d) and e). Positive values indicate water level rise.*

4.5.3 Impacts on water quality

During 2021 and 2022, water samples were collected in the Argolis field as part of the MARSoluT project. Groundwater samples (**Figure 57**) were taken during pumping time for irrigation or upon request by local farmers. The hydrochemical analysis of groundwater samples took place in NTUA's laboratory. Measured chemical parameters were predominantly major ions, namely, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, and NO_3^{-}). Electrical conductivity (EC), temperature, and pH were determined on-site. **Figure 58** is a Piper-Hill-Langelier hydrogram to visualise the concentration of the major cations and anions in September 2021.

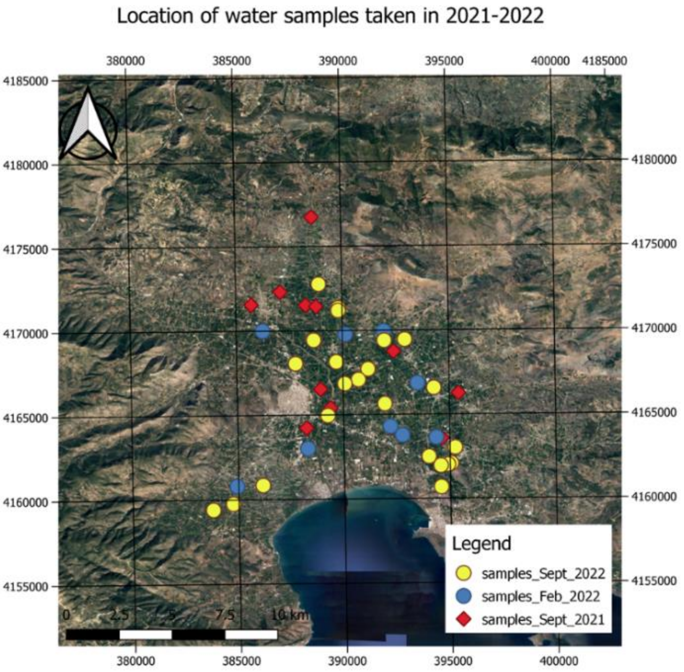


Figure 57. *The location where the water samples have been collected.*

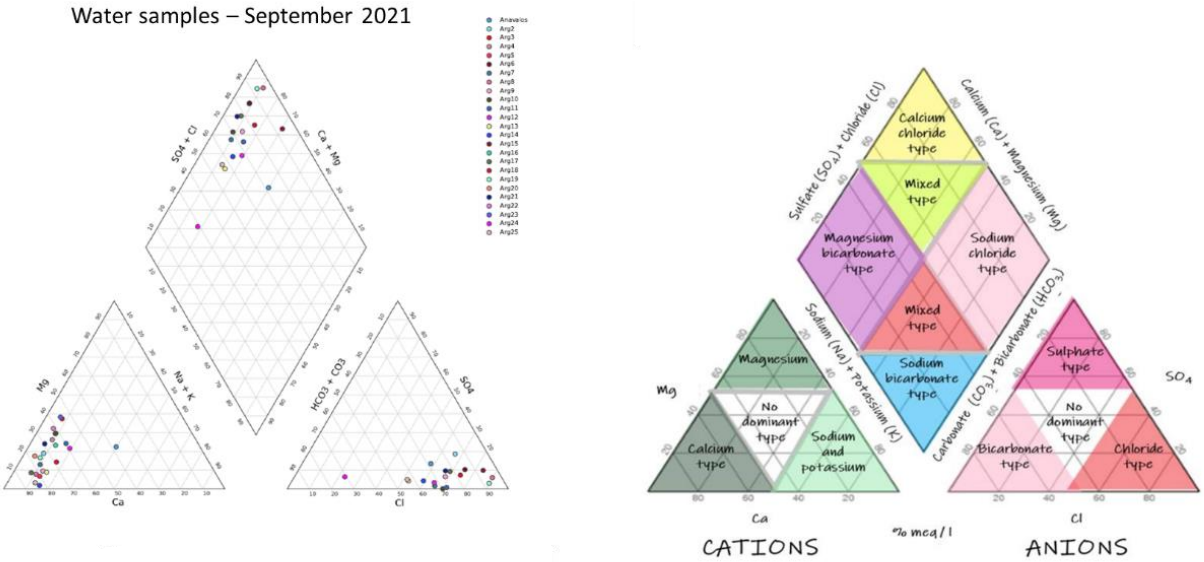


Figure 58. *Piper diagram for the water samples collected and analysed in September 2021. It is concluded that mainly the samples are a mixed type of calcium and chloride type. (The diagram was created in Python.)*

The distribution and evolution of the nitrate and chloride concentration in three sampling periods are presented in **Figure 59** and **60**, respectively. MAR was not applied during this time.

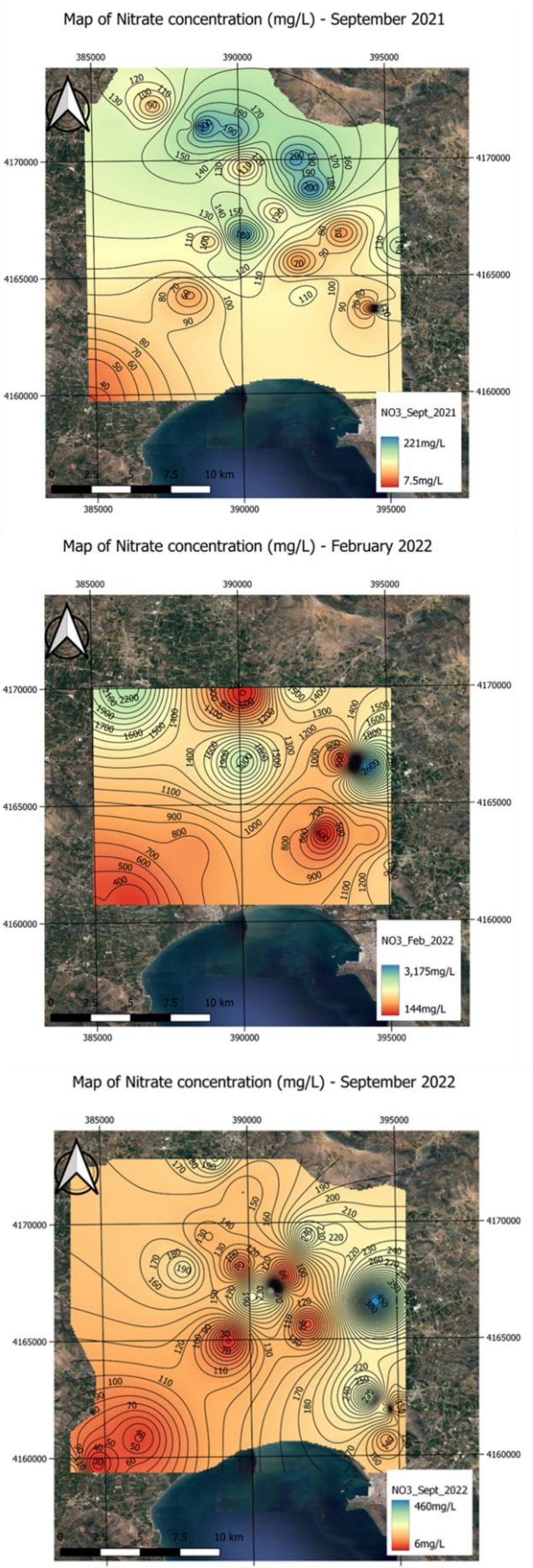


Figure 59. Nitrate concentration for three different time periods during 2021-2022.

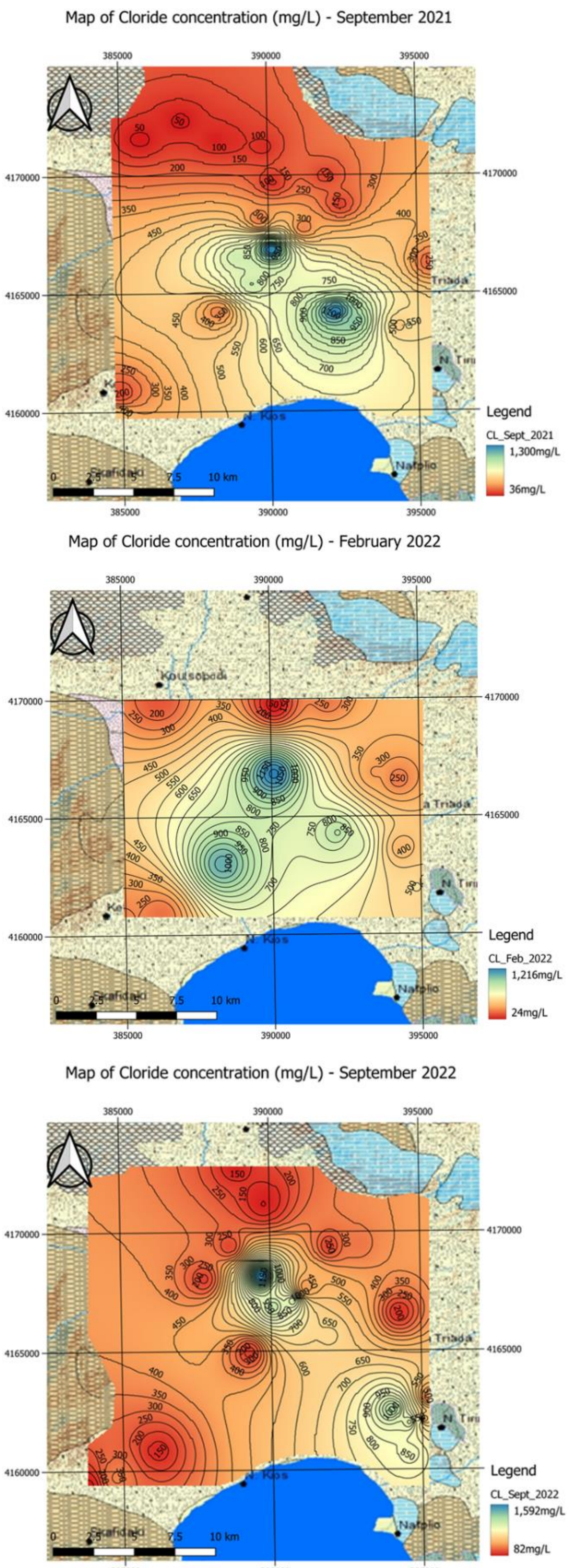


Figure 60. Chloride concentration distribution for three different time periods during 2021-2022.

4.5.4 Financial aspects

The Anavalos canal started operating in 1994, and since then, the cost of MAR has decreased due to a reduction in energy consumption for pumping. Artificial recharge was not executed in the years 1999, 2000, 2005, 2006 and 2015 due to technical problems or lack of approval-licensing, as well as the years 2007 and 2016 due to non-activation of the Kefalari spring. **Table 10** presents the annual MAR operation cost between 1990 and 2017. According to the Local Authorities, expanding the current MAR infrastructure and capacity would considerably increase costs as new irrigation networks must be completed. Also, implementing MAR in areas above the topographic level of the Kefalari spring (such as Koutsopodi, located in northern Argolis plain) would imply high pumping costs.

4.6 The Menashe Streams MAR site (Israel)

4.6.1 Introduction

It is worth to mention that most of this chapter's contributions proceed from MARSoluT's Early Stage Researcher (ESR) German Rudnik and his tutor during the project´s development.

The Menashe Streams MAR site is located on the northern part of the unconfined sandy Israeli (Mediterranean) coastal aquifer. It was constructed in the 1960s as part of an effort to maintain water security in a semi-arid Mediterranean climate. Winter ephemeral streams from the 110 km² Menashe Hills catchment, where runoff is high and infiltration is low, are diverted via a 16 km long channel into a settling pond. Subsequently, depending on water level and turbidity, flow is channelled into three infiltration ponds (referred to as ponds #1, #2 and #3, **Figure 61**) via a system of hydraulic control structures. The site is situated on a sandy dune landscape at a mean elevation of 30 m above sea level and is dominated by a Mediterranean climate, with average temperatures of 20.2 ºC and a mean precipitation of 556 mm/year.

The aquifer, stretching over an area of 2,000 km² along the coast, has a thickness varying between 200 m on the coastline (western boundary) and several meters at the eastern edge. It comprises Pleistocene calcareous sandstone and sand interleaved with continuous marine and continental silt and clay lenses. These sequences overly a highly impermeable clay aquiclude of the Saqiye Group. The regional mean groundwater level in summer fluctuates between 0 and 8 m above sea level due to intense winter recharge of runoff water (historic annual mean of 10 Mm^3) and abstractions driven by dozens of designated wells during summer (**Figure 61**).

Since 2015, an annual mean of ~2.1 Mm^3 reverse osmosis desalinated seawater (DSW) from the Hadera desalination plant (total annual production ~130 Mm^3/year) constitutes an additional source of water for the MAR site. This source is usually employed when maintenance is conducted at the National Water Carrier, which stretches over a few days to weeks per year. Therefore, every year a volume of DSW is bypassed to pond #3, which is geographically close to the DSW pipeline (**Figure 61**), turning the Menashe MAR site into a de-facto double-source MAR site.

An annual mean of 15.3 Mm^3 of drinking quality water is produced from the ~50 public and private production wells scattered in the region. More details on the Menashe MAR site are provided by Kurtzman & Guttman (2021).

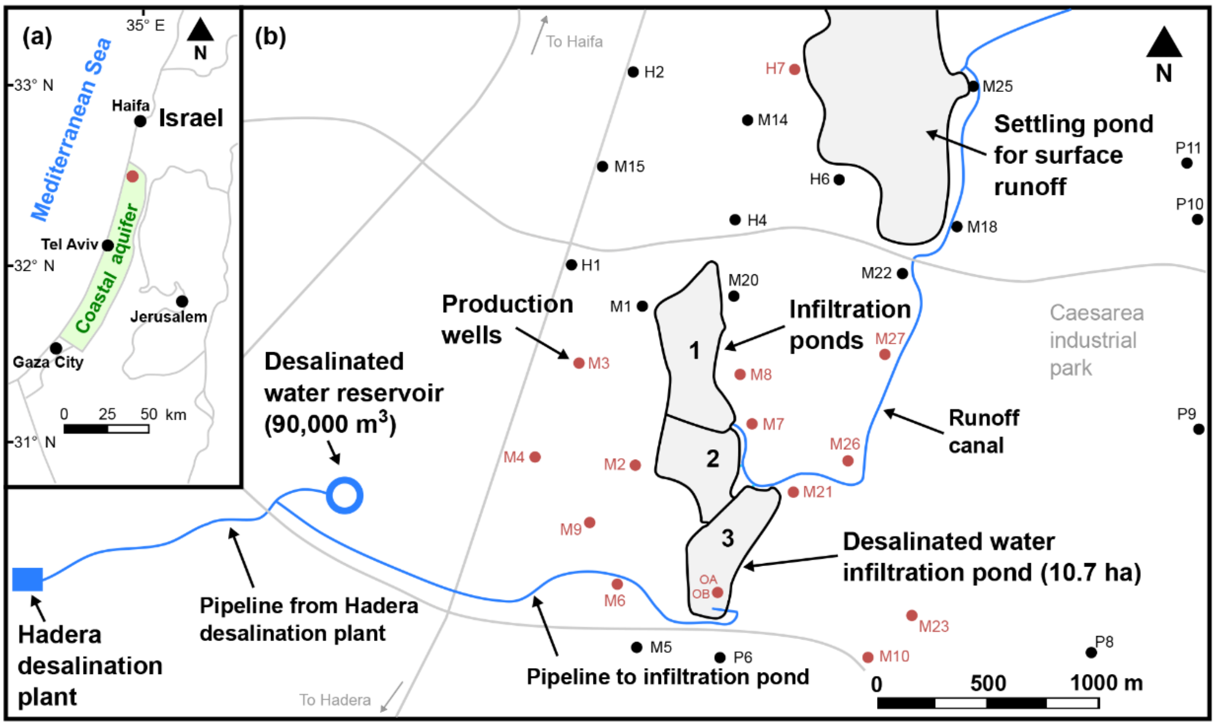


Figure 61. Map of the study region: (a) Location of the Israeli Coastal Aquifer (green) and study domain (red point). (b) The Menashe Streams MAR site. Rainfall runoff from an upstream north-eastern catchment is diverted into the settling and infiltration ponds, and surplus desalinated seawater is diverted to pond #3 from the Hadera Desalination Plant. From Ganot et al. (2018a).

4.6.2 Yearly recharge volumes

Historic annual runoff volumes are highly dependent on hydroclimatic variability and result in between 0 and more than 30 Mm^3/year of recharge (**Figure 62** a). Annual MAR volumes since the addition of a DSW during 2015-2022 are shown in **Figure 62** (b). Mixing ratio values (%DSW in a sample) from several production wells are presented in **Figure 62** (b), indicating the strong effect of the additional source on the entire operation. Wells M2, M6 and M9 are located within 1 km down-gradient of pond #3, which is the sole receptor of the DSW, while M26 is located up gradient (**Figure 61**). Well M2 (yellow line in **Figure 62** (b) is further away from pond #3 and is closer to the runoff-recharge ponds (#1 and #2), which explains the decrease in the mixing ratio starting from 2018 when rainy years resulted in a larger contribution of runoff to recharge (light blue bars in **Figure 62** b).

Mixing ratios are calculated using the stable water isotope deuterium. DSW sustains high values corresponding to the Eastern Mediterranean Sea (~+10‰) during the reverse osmosis desalination process. In contrast, native groundwater has a low value (~-20‰). These differences allow following the DSW spreading in the aquifer (Ganot et al. 2018b; Rudnik et al. 2022) (**Table 11**).

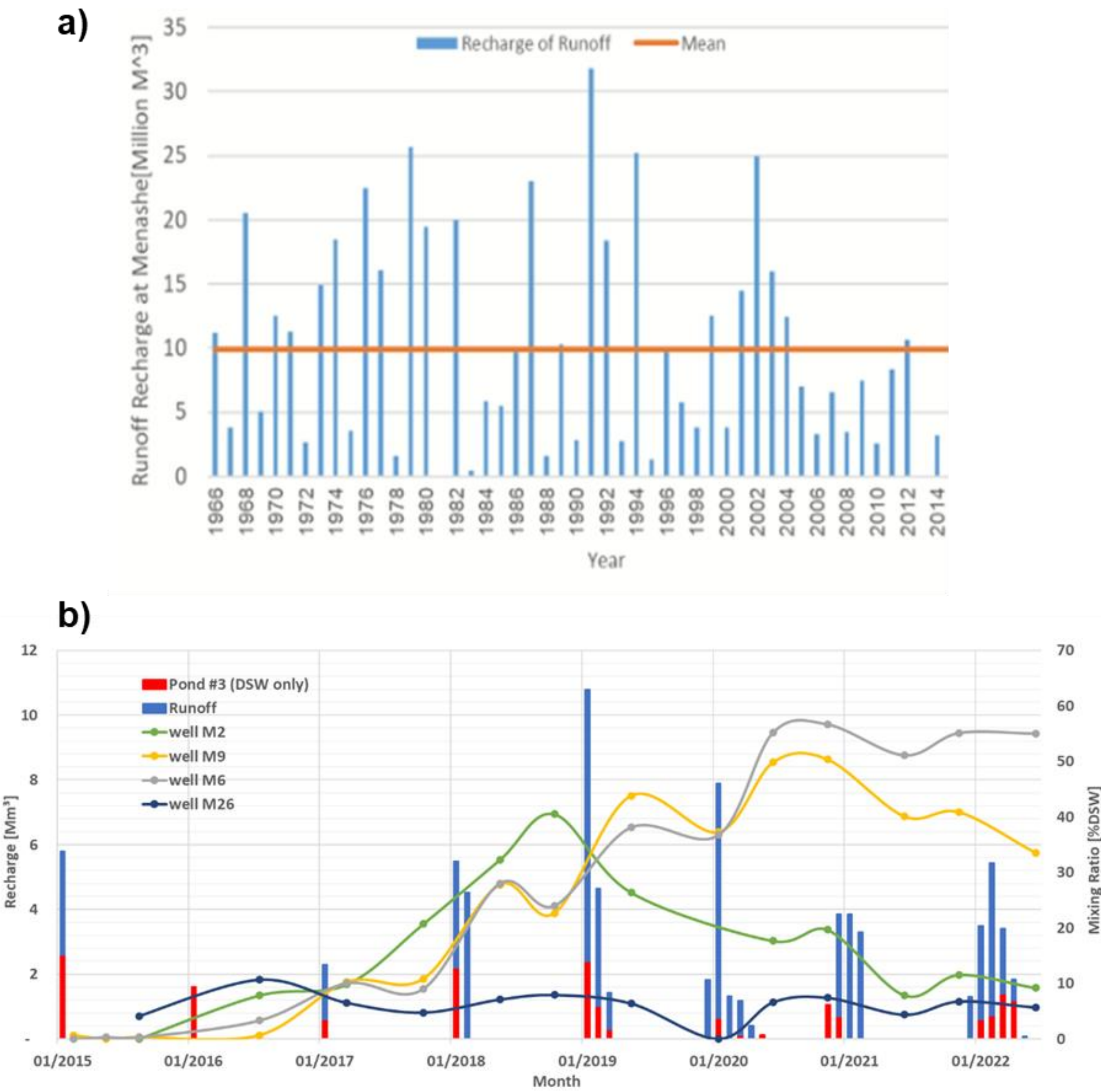


***Figure 62**. (a) Historical data of runoff recharge at Menashe Streams MAR site; (b) Runoff (blue bars) and DSW (red) monthly recharge volumes since the addition of the DSW as a recharge source and mixing rations at selected production wells (see Fig. 1 for wells location).*

4.6.3 Impacts on groundwater levels

Figure 63 shows the hydraulic head and electrical conductivity (EC) data from a logger (CTD Diver, Eijkelkamp) located in an observation well (well OA inside pond #3) between 2015 and 2022 during the MARSOL and MARSoluT projects. The observation well, installed in the framework of MARSOL, is 30 m deep and perforated at the lower 10 m. This setup allows monitoring the upper part of the aquifer (Ganot et al. 2017).

The water table fluctuates strongly between 1.8 and 24 m. The recharge of DSW produces sharp decreases in EC due to the low ionic content (~0.2 mS/cm). Water level fluctuations are much milder in locations nearby the ponds but not inside them (e.g., -0.5 m to +10 m above sea level at monitoring well T1 during the years 2015-2020 (Rudnik et al. 2022).

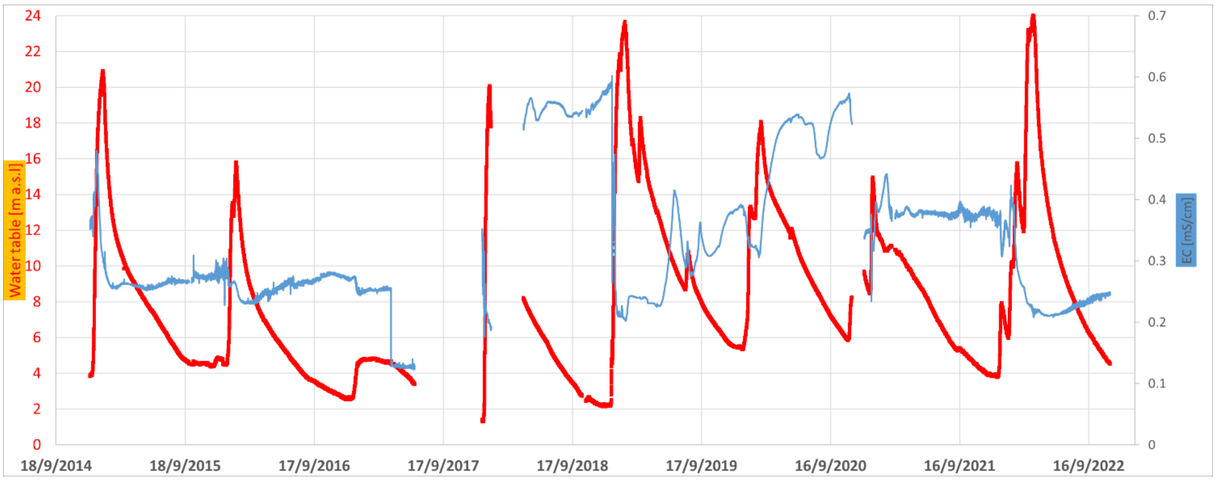


Figure 63. *Head (red) and electrical conductivity (blue) time series recorded in the monitoring well OA located at the DSW recharge pond.*

4.6.4 Impacts on water quality

The water produced at the MAR site is of drinking quality and traditionally does not require further treatment beyond chlorination before it is pumped for domestic, or irrigation uses. Since the introduction of DSW as an additional water source in 2015, changes in water quality have been evident due to the mixing of the native groundwater with the low-mineral DSW. **Table 11** (from Ganot et al., 2018a) shows (a) water quality from production wells before the DSW recharge campaign in 2014, and (b) during the first three years of DSW recharge at monitoring well OA (water-table below pond # 3, **Figure 61**), and (c) the quality of DSW after post-treatment with limestone before discharge into pond #3. The increase of magnesium concentration [Mg^{2+}] from almost zero in DSW to 3.1 mg/L in shallow groundwater is attributed mainly to cation exchange processes in the variably saturated zone below pond #3. This enrichment in magnesium is, however, much lower than the magnesium concentration in the native groundwater (~13 mg/L) and below the World Health Organisation (WHO) threshold recommended for drinking water (10 mg/L).

Major ions and stable water isotopes from water samples of 10 production and observation wells were analysed twice a year before and during MARSoluT. Chloride, magnesium and calcium show a decreasing trend (**Figure 64**) attributed to the mixing between mineral-rich native groundwater and DSW. However, additional mineralisation of the recharged DSW is observed in the aquifer during transit from pond #3 to the pumping wells. The orange lines in **Figure 64** (a-c) indicate the concentration of ions in well M9 in a hypothetical case of conservative mixing, where no further enrichment (or depletion) of the recharged DSW occurs. These values are calculated using the mixing ratios obtained from stable water isotopes (**Figure 62** b) and take in account ion concentration in the DSW as observed in the shallow groundwater, after initial enrichment at the unsaturated zone (**Table 11**). The hypothetical magnesium concentrations are lower than the observed values, meaning the conservative-mixing hypothesis is invalid. The DSW is enriched with magnesium due to the interaction with the local porous matrix in the deeper aquifer. The enrichment in the aquifer can be estimated through equation 1 as follows:

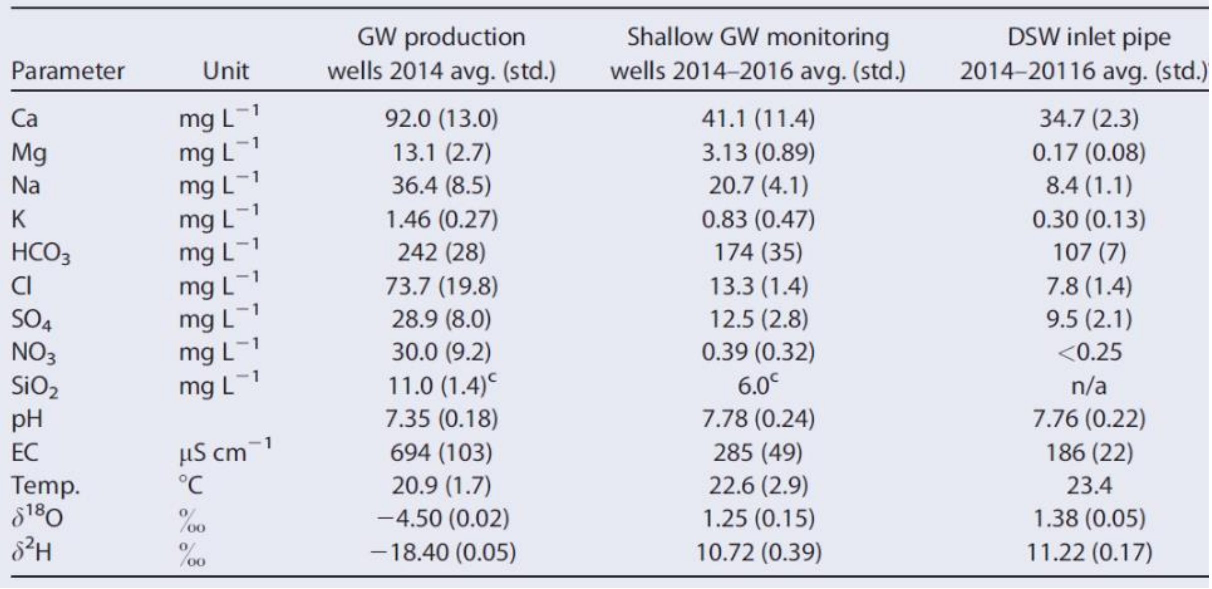
(1) $$[X]_{aquifer\ enrichment} = \frac{100*[X]_{well_i(t)} - [X]_{native\_GW\_i}*(100-\%DSWt_{i,})}{\%DSWt_{i,}} - [X]_{pond\ 3\ UZ\ enrichment}$$

where $[x]$ is the concentration of a given ion, i is the well, t is the sampling date, and %DSW is the mixing ratio.

The magnesium concentration at well M9 was 9.5 mg/l in November 2021, when the mixing ratio according to stable water isotopes was 41%. The native groundwater at this well had a magnesium concentration of 10.6 mg/l before the recharge with DSW (year 2015). The total enrichment of the recharged DSW is 7.4 mg/l, out of which 3.1 mg/l are attributed to the reactions in the variably saturated zone below pond #3 and 4.3 mg/l to reactions in the deeper aquifer. In the hypothetical case that no interaction took place in the deeper aquifer, DSW with an initial concentration of 3.1 mg/l would mix with the native groundwater in a ratio of 41% to 59%, respectively, resulting in 7.5 mg/l (0.41*3.1+0.59*10.6), which is represented in **Figure 64** with the orange line.

Ongoing work aims to quantify the mineralisation of the recharged DSW as it flows from pond #3 to the pumping wells, using numerical simulations of reactive transport.

Table 11. *Water quality at Menashe Streams MAR site and the recharged DSW. From Ganot et al., 2018a.*



Parameter	Unit	GW production wells 2014 avg. (std.)	Shallow GW monitoring wells 2014–2016 avg. (std.)	DSW inlet pipe 2014–20116 avg. (std.)
Ca	mg L^{-1}	92.0 (13.0)	41.1 (11.4)	34.7 (2.3)
Mg	mg L^{-1}	13.1 (2.7)	3.13 (0.89)	0.17 (0.08)
Na	mg L^{-1}	36.4 (8.5)	20.7 (4.1)	8.4 (1.1)
K	mg L^{-1}	1.46 (0.27)	0.83 (0.47)	0.30 (0.13)
HCO_3	mg L^{-1}	242 (28)	174 (35)	107 (7)
Cl	mg L^{-1}	73.7 (19.8)	13.3 (1.4)	7.8 (1.4)
SO_4	mg L^{-1}	28.9 (8.0)	12.5 (2.8)	9.5 (2.1)
NO_3	mg L^{-1}	30.0 (9.2)	0.39 (0.32)	<0.25
SiO_2	mg L^{-1}	11.0 (1.4)^c	6.0^c	n/a
pH		7.35 (0.18)	7.78 (0.24)	7.76 (0.22)
EC	µS cm^{-1}	694 (103)	285 (49)	186 (22)
Temp.	°C	20.9 (1.7)	22.6 (2.9)	23.4
$\delta^{18}O$	‰	−4.50 (0.02)	1.25 (0.15)	1.38 (0.05)
$\delta^{2}H$	‰	−18.40 (0.05)	10.72 (0.39)	11.22 (0.17)

4.6.5 Infiltration rates and clogging

Ganot et al. (2016) thoroughly investigated issues of infiltration rates in the Menashe Streams MAR site during MARSOL project. Initial infiltration rates were around 10 m/day and went down to 3 m/day after 1 day, 0.7 m/day after a week, and 0.4 m/day after four weeks of ponding. The authors concluded that the effective saturated hydraulic conductivity of the sediment layers between the surface and the water table is a good estimate of the infiltration rate after a few days of flooding, and clogging is in significant.

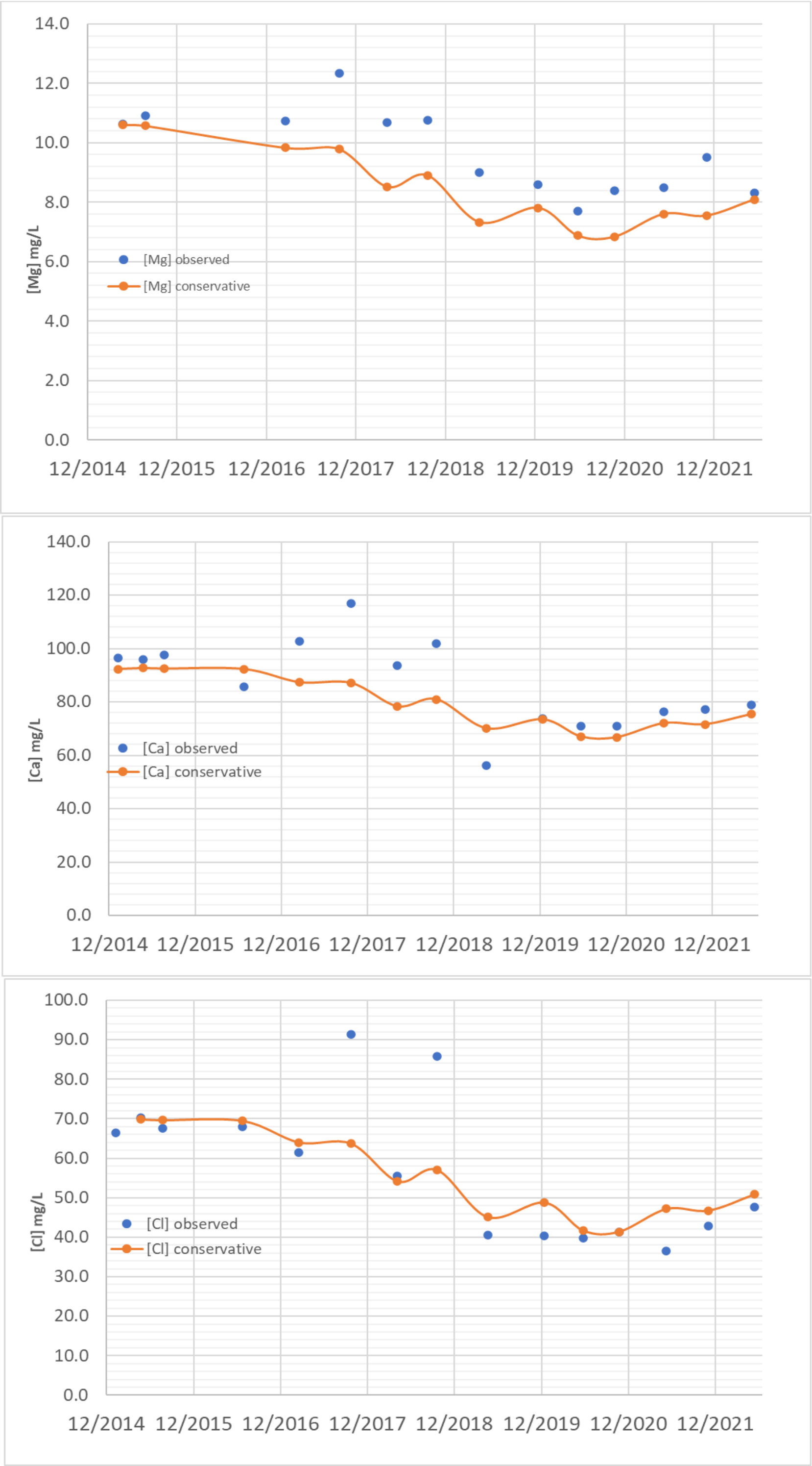


Figure 64. *Values of [Mg], [Ca] and [Cl] (top to bottom) at well M9: observed (blue dots) and calculated with the hypothesis of conservative mixing (orange).*

4.6.7 Financial aspects

Three main financial aspects of MAR using DSW as one of the sources:

1. Recharged DSW is remineralised with calcium and magnesium during percolation beneath the infiltration pond and transit in the aquifer. Currently, 30 tonnes of limestone are delivered from quarries daily and applied for post-treatment in the Hadera Desalination Plant. According to Ganot et al. (2018a), introducing soft DSW can partially replace the limestone post-treatment process and reduce production and environmental costs.
2. Lack of magnesium in drinking water in Israel since the beginning of the "desalination era" is a public health concern. The remineralisation of the DSW through MAR can play an important role in reducing diseases related to insufficient magnesium levels.
3. Annual surplus of produced DSW is an ongoing reality caused by operational circumstances. The recharge of DSW is used to increase water levels in the aquifer.

5. Recharge of Aquifers Through Dams and Dykes in Spain

5.1 Introduction

According to the DINAMAR project (2010), the total volume of water infiltrated in Spain through MAR (considering about 32 projects) and a preliminary inventory of about 800 dykes was about 380 Mm^3/year. The Spanish water authorities have estimated this volume (i.e., from dykes, dams, and MAR) could increase the previous figure up to 500 Mm^3/year during the 2020 CONAMA conference. In Wikipedia, “*recarga artificial*” definition, uploaded in Spanish by the second author in 2007, it is mentioned that most of the large-scale MAR implementations were built on an experimental basis in Spain, with few large-scale operational schemes located in Castile and Leon and in Catalonia. According to the same source, the amount of water artificially recharged to aquifers through MAR varies from 50 Mm^3/year (IGME 2000) to 350 Mm^3/year (LBAE, MIMAM, 2000) and 380 Mm^3/year (DINA-MAR, 2010). The figures exceeding 60 Mm^3/year also consider infiltration from dykes and dams in urban and forested areas, which help to mitigate floods and recharge groundwater. The infiltration through the bottom of large dams (there are more than 1,400 in Spain) and dykes, which can be significant, is not included in these estimations and could result in artificial recharge, whether intentional or not, in the order of about 800 Mm^3/year.

The difference in these figures is attributed to differences is the number of transversal structures in water courses, such as dykes and dams, constructed predominantly in the heading of river basins. Most of them are intended for flood lamination, damming, and surface water retention. Their water storage and unintentional aquifer recharge are more significant than the volume of intentional recharge by MAR systems.

This section focuses on an estimation of recharge from transversal structures. This analysis does not imply that recharge from transversal structures is considered an intentional means to increase groundwater storage and, therefore, can be regarded as MAR. Such additional recharge constitutes rather a secondary effect.

5.1.1 Background

In 2019, the Spanish Ministry for the Ecological Transition and the Demographic Challenge (MITERD) requested Tragsatec, a public company, to conduct and digitalize the first inventory of dykes and transversal structures in watercourses in the entire Spanish territory.

Rivers obstacles, either longitudinal or transversal, are framed within hydrological and forestry restoration efforts. They contribute to reducing torrential phenomena by preventing flooding of the marginal lands of watercourses and defining a section with sufficient drainage capacity to evacuate flood flows. The main difficulties of this type of work arise from the analysis and forecasting of phenomena related to sediment transport, its influence on the stability of the modified channel, both in terms of the extent of this influence and its evolution over time, and finally, the "anthropic" seepage increase.

Most of the transversal structures in Spain were constructed by former institutions for forest protection and agricultural development (ICONA and IRYDA, respectively) in the 50s and 60s, leaving aside the big dams. Most of the documents concerning the construction projects of these dykes were dispersed across numerous libraries. The inventory, which initially was expected to count on about 8,000 dykes and small dams, had been underestimated. Including minor structures, and after three years of intense work, the final count exceeds 26,000 units (**Figure 65**), most of them infiltrating a certain amount of water into the aquifers intentionally or not. It is precisely this figure that MARSoluT partners seek to estimate as a contribution to water authorities, helping to approximate the volume of surface water converted into groundwater thanks to transversal structures constructed along watercourses. The resulting inventories and the related thematic coverages are publicly available online (**Table 12**). These inventories are the starting point to estimate the total volume of water infiltrated into the aquifers from transversal structures, which is the main goal of this chapter.

***Table 12**. Links to the websites that present the results of the inventory of dykes, dams, and water obstacles in water courses. All websites were accessed on 28/02/2023.*

Theme	**Website**
Dykes and dams	https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/agua/inventario-presas-embalses.aspx
Transversal obstacles	https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/agua/Inventario-Obstaculos-Transversales.aspx
Viewer with diverse thematic coverages	https://sig.mapama.gob.es/geoportal/index.html?services=60005&herramienta=ServiceTree&dir=Agua|Inventario%20de%20Presas%20y%20Embalses

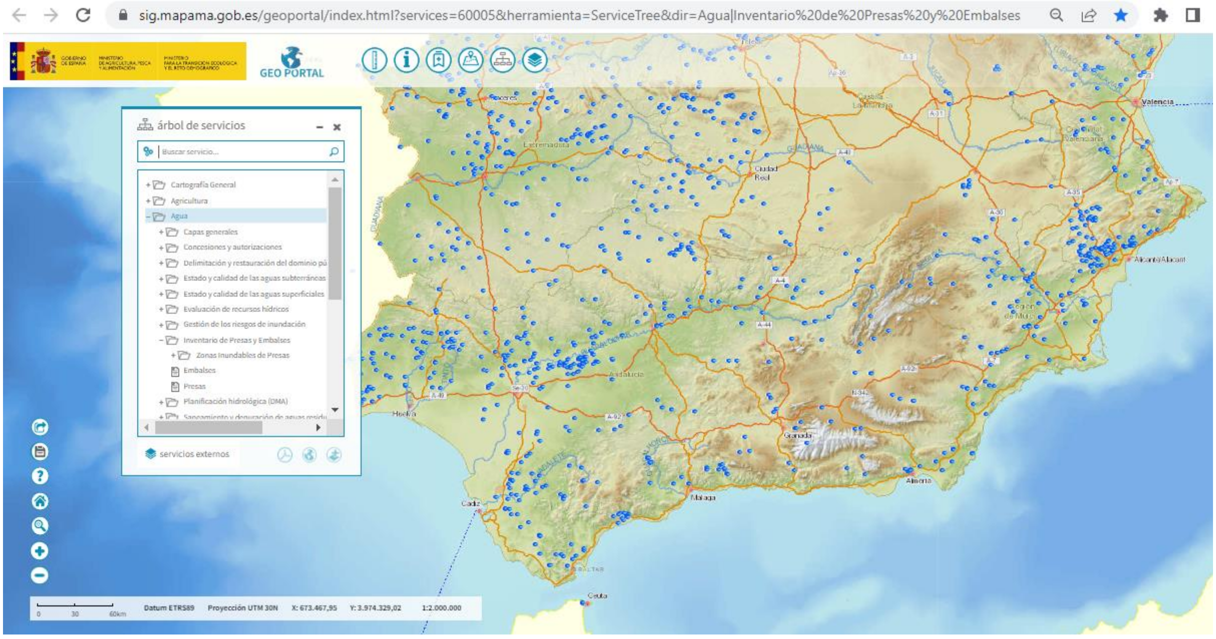

sig.mapama.gob.es/geoportal/index.html?services=60005&herramienta=ServiceTree&dir=Agua|Inventario%20de%20Presas%20y%20Embalses

***Figure 65.** MITERD Geoportal screenshot.*

5.2 Objective

The objective of this section is to provide a first approximation to the recharge induced by transversal structures (dykes and dams) in Spain.

5.3 Methodology

The calculation of the recharge caused by transversal structures is based on geospatial analysis and uses predominantly information from the new inventory of transversal structures in Spain, and other layers that contain relevant information, such as the map of lithologies. This preliminary calculation uses a simple approach (**Equation 1**):

$$\sum_{i=1}^{n} A_{wi}\, K_{vi}\, C.f_i$$

Equation 1

where A_{wi} is the wetted area, K_{vi} is the vertical hydraulic conductivity, and $C.f_i$ is a correction factor of the i*th* transversal structure.

The general steps followed are:

- Calculating of the wetted area A_w of dykes and dams based on information from the inventory of transversal structures.
- Obtaining the average vertical permeability, K_v, below transversal structures based on the lithological permeability.
- Using a conversion factor that translates potential seepage volumes into realistic recharge based on clogging, sand deposits, air entrapment, and other factors.
- Integrating this information into **Equation 1** to compute the intended figure.

5.3.1 Calculation of Aw

The source of information to estimate this parameter is the inventory of transversal structures in Spain. This information is part of a geodatabase with information (some not public) with the description of the structures including construction information, height, length, etc. In this database transversal structures are represented as points. The geodatabase includes a layer of the National Flood Zone Mapping System (SNCZI), with additional cross-cutting obstacles, such as minor vertical jumps, piped crossings, and crossings over faces. The total number of transversal structures inventoried is 27,780 (**Figure 66**).

Each transversal structure has a set of attributes including:

- Type of structure: describes the type of structure.
- Use: the use of the obstacle is provided. Obstacles that are generating backwaters (impress categories) were given special attention.
- Year of construction: It provides the year of construction. This information can be used to estimate clogging.
- Total height and height of the fall: Provides the dimensions of the obstacle. An obstacle with a height of more than 10 m is considered a large dam, and values of more than 3 m are likely to cause large backwaters. The total height includes the height of the pool, which also serves as a reference.

- Additional information on spatial distribution, including crest length, backwater length, backwater width, backwater depth, mean channel width before backwater, and mean channel draught before the backwater created by the obstruction. These fields could allow approximating the size of the backwater and the wet perimeter. However, the data is not complete.

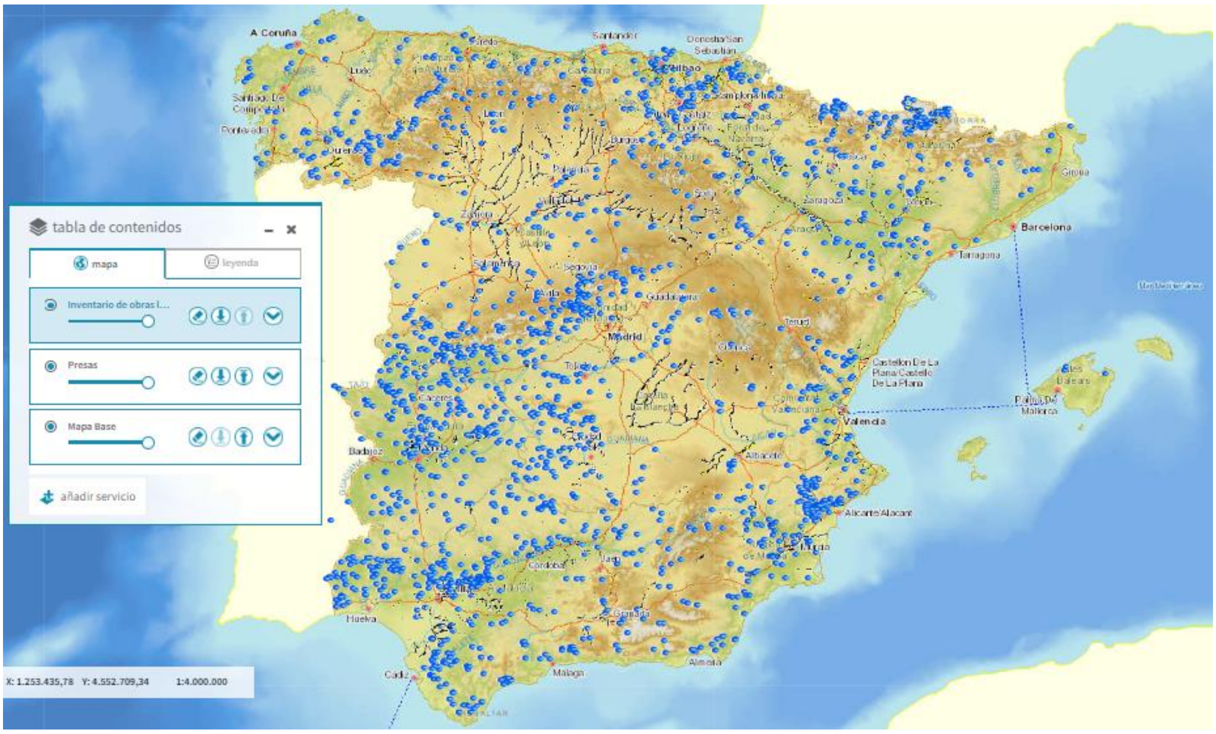


Figure 66. *Dykes and dams in Spanish river courses (Source MITERD Geo Portal).*

Two types of structure from the geodatabase have been merged to calculate the wet area whereby infiltration into the underlying aquifer occurs: "ObsTrans" and "TransTecnicos". The length of these structures and the length of the wetted perimeter were extracted. When both attributes are available, the wet area was estimated as the average between length and width. If one or both attributes are missing, mean values obtained from the rest have been utilised (6,914.88 m²).

5.3.2 Estimation of Kv for different lithologies and the transversal structures

This calculation was based on assigning a characteristic lithology and vertical permeability to each transversal structure. The predominant lithology in which the transversal structures have been built was estimated crossing a buffer zone (**Figure 67**) with the shape file of lithological units of Spain. The buffer zone was defined using the length of the wet perimeter. In case this value was missing, the average was employed.

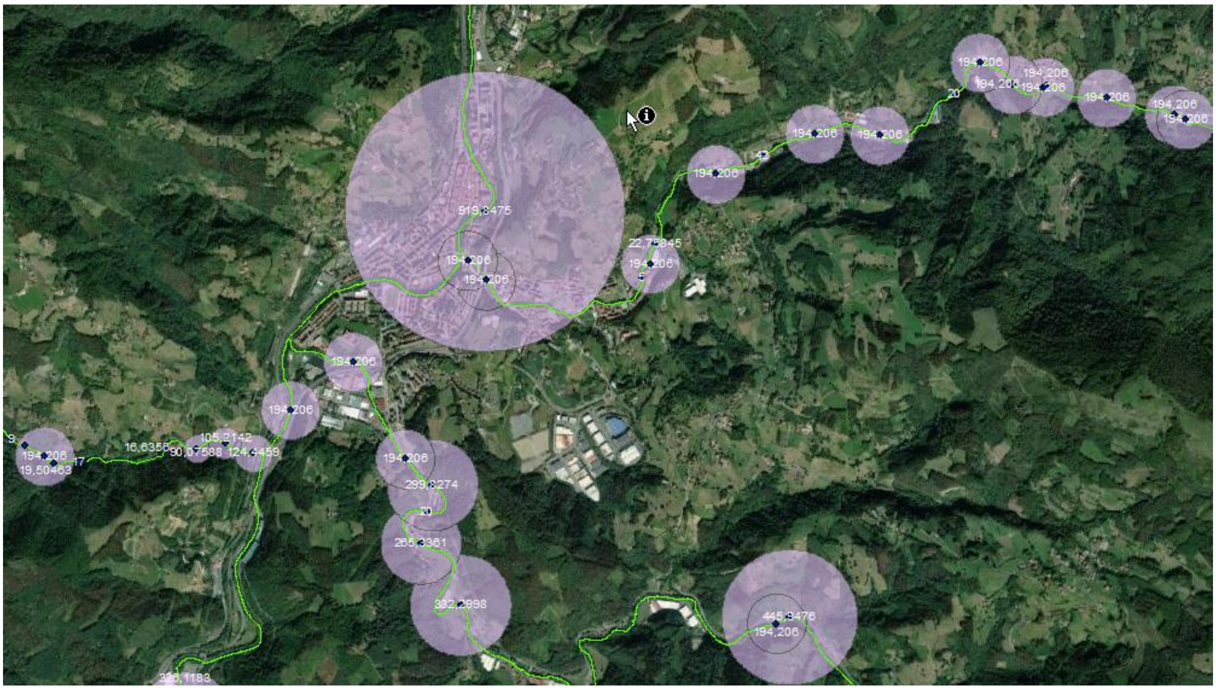


__Figure 67.__ Example of influence area for some transversal structure. The buffers have permitted assigning a permeability value for the each transversal structure expressed in the map for big areas covered in water.

Characteristic lithological units were translated into K_v values using the permeability map of Spain (**Figure 68**) 1:200,000, which is based on the continuous lithostratigraphic Map of Spain at a scale of 1:200,000.

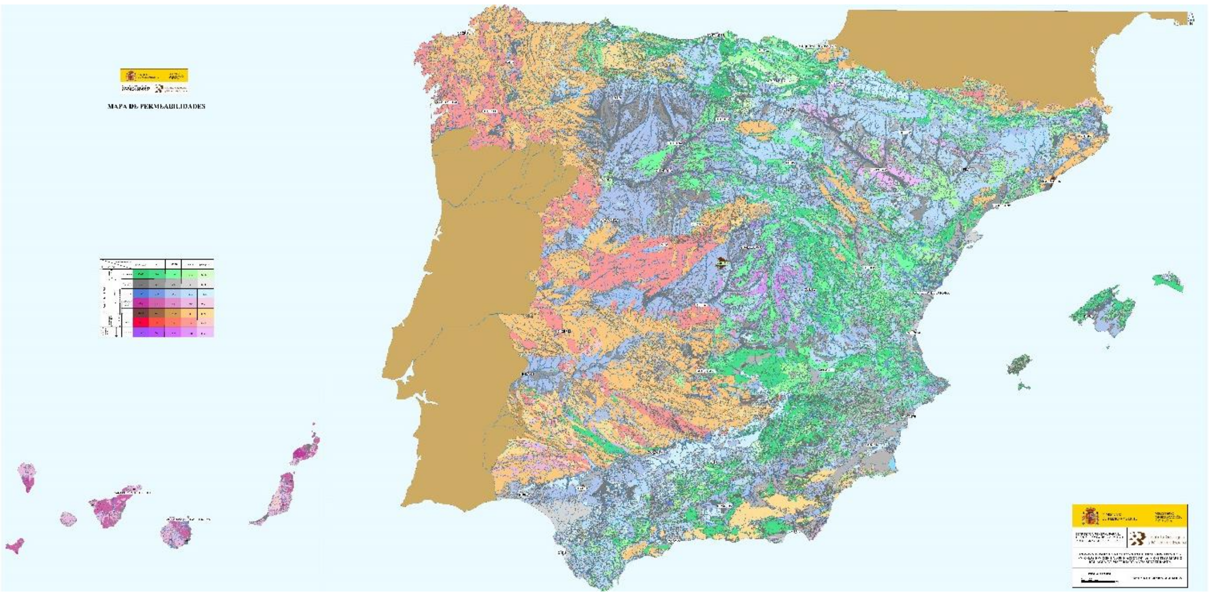
The permeability map of Spain shows qualitatively the degree of permeability of the mapped litho-stratigraphic units grouped by similar permeability values. It establishes five permeability categories: very high, high, medium, low, and very low. In addition, the maps consider seven large groups of lithologies (carbonate, detrital, quaternary detrital, volcanic, meta-granular, igneous, and evaporitic) (**Figure 68**).

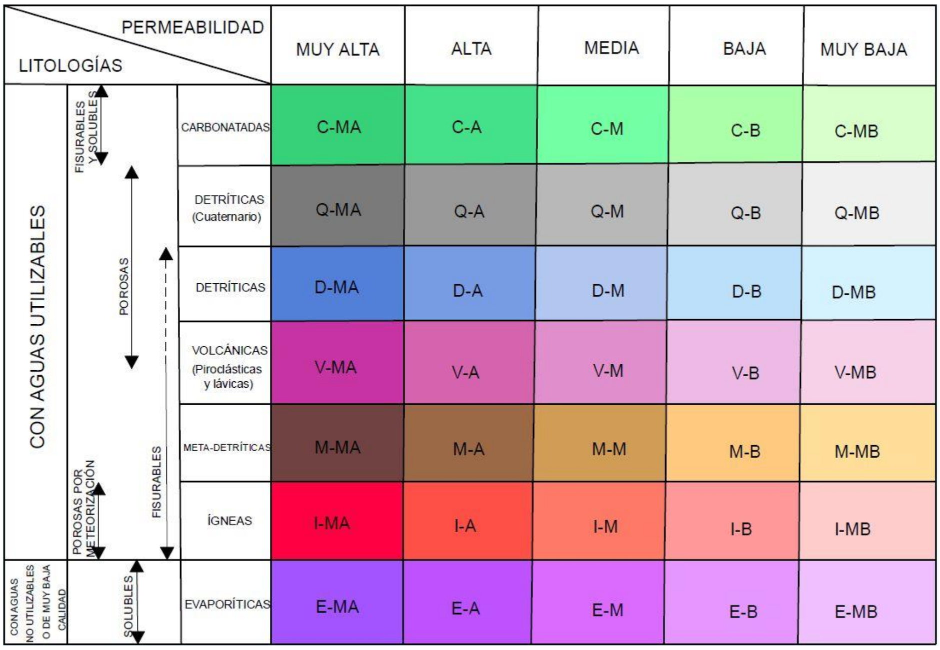
Each of the permeability categories were assigned a value based on various sources (Terzaghi and Peck, and USDA 1994´s classification) resulting in the following mean values of K_v:

- Very low: 0.02 m/day
- Low: 0.07 m/day
- Medium: 1.02 m/day
- High: 4.5 m/day
- Very high: 6 m/day

5.3.3 Correction factor (C.f)

The appraisal for a mean infiltration rate for each case has been calculated by applying a conversion factor (C.f) of 0.75 (Fernández Escalante et al., 2016 and 2022). This conversion factor considers aspects such as clogging and is based on fieldwork in real selected sites located on different lithologies. An additional and more conservative correction factor of 0.5 was also utilised.





LITOLOGÍAS			PERMEABILIDAD MUY ALTA	ALTA	MEDIA	BAJA	MUY BAJA
CON AGUAS UTILIZABLES	FISURABLES Y SOLUBLES	CARBONATADAS	C-MA	C-A	C-M	C-B	C-MB
	POROSAS	DETRÍTICAS (Cuaternario)	Q-MA	Q-A	Q-M	Q-B	Q-MB
	POROSAS FISURABLES	DETRÍTICAS	D-MA	D-A	D-M	D-B	D-MB
	POROSAS FISURABLES	VOLCÁNICAS (Piroclásticas y lávicas)	V-MA	V-A	V-M	V-B	V-MB
	FISURABLES	META-DETRÍTICAS	M-MA	M-A	M-M	M-B	M-MB
	POROSAS POR METEORIZACIÓN FISURABLES	ÍGNEAS	I-MA	I-A	I-M	I-B	I-MB
CON AGUAS NO UTILIZABLES O DE MUY BAJA CALIDAD	SOLUBLES	EVAPORÍTICAS	E-MA	E-A	E-M	E-B	E-MB

Figure 68. *Permeability map for Spain and legend expressing lithology and corresponding permeability. Taken from:* https://catalogo.igme.es/geonetwork/srv/spa/catalog.search#/metadata/ESPIGMEPERMEABILIDADES200CONTINUODIGITAL20100805637842

5.4 Result and discussion

The final estimated figure with a *C.f* of 0.75 is 1,218.79 Mm^3/year. If the correction factor for the permeability is 0.5 instead of 0.7, the final volume is 812.52 Mm^3/year.

The calculated volume exceeds considerably previous estimations by the Water General Directorate of the Spanish Ministry (500 Mm^3/year, during an oral presentation, unpublished data) and DINAMAR

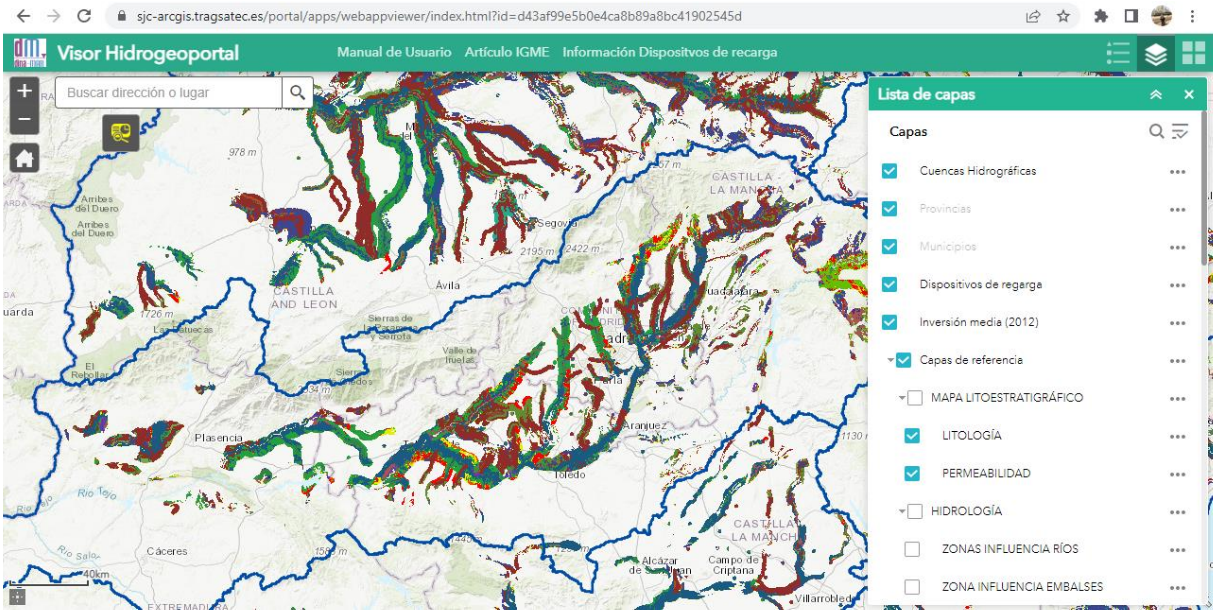
(380 Mm^3/year), which considered the combined recharge through MAR and a limited inventory of dykes. This calculation is at a very preliminary stage and starts a new line of research.

This inventory has not been developed in other countries where MARSoluT partner institutions are located because, to the authors' best knowledge, an inventory of transversal structures is not available.

5.6 Factors to consider in future estimations

Future refinements of this figure will consider the following information:

- Meteorological variability, which will change the wetted perimeters of the transversal structures.
- Detailed correction factors for each lithology.
- The year of construction of the structures, which is available in the geodatabase and can be used in the correction factors to better represent clogging.
- The water table, which can constraint recharge.
- Utilise some of the cartographic information from previous works by TRAGSA, in particular, the "hydro-geoportal"[2] (**Figure 69**) which allows determining the zones more appropriate for MAR in peninsular Spain and has detailed information on permeability.
- Using the slopes around the structures to constrain more precisely the wetted area.



☑ Cuencas Hidrográficas
☑ Provincias
☑ Municipios
☑ Dispositivos de regarga
☑ Inversión media (2012)
☑ Capas de referencia
  ☐ MAPA LITOESTRATIGRÁFICO
    ☑ LITOLOGÍA
    ☑ PERMEABILIDAD
  ☐ HIDROLOGÍA
    ☐ ZONAS INFLUENCIA RÍOS
    ☐ ZONA INFLUENCIA EMBALSES

Figure 69. *DINAMAR, TRAGSA Hydrogeoportal. Screenshot.*

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[2] https://sjc-arcgis.tragsatec.es/portal/apps/webappviewer/index.html?id=d43af99e5b0e4ca8b89a8bc41902545d.

6. MARSoluT's Technical Solutions

6.1 MARSOL Sustainable Managed Aquifer Recharge Technical Solutions (SMARTS) - background

Holding the line of action initiated during the FP7 project MARSOL, Deliverables D13.1 and D13.3, in which 73 Sustainable Managed Aquifer Recharge Technical Solutions (SMARTS) were proposed and classified according to five major groups and 14 subgroups (see chapter 3-1).

Major groups:

1. Applied to water from its source (quantity).
2. Applied to water from its source (quality).
3. Applied to the receiving medium (in both soil and aquifer).
4. Applied to management parameters plus cleaning and maintenance operations.
5. Applied to the combination of all of them (integrated system).

Subgroups (including the SMARTS number as presented in the MARSOL deliverable 13.1)

1.1. Water quantity aspects (T.S. 1 to 5).

2.1. Pre-treatment-treatment (T.S. 6 to 12).

2.2. Surface facilities (T.S. 13 to 16).

2.3. Deep injection (T.S. 17 to 19).

2.4. Receiving medium (T.S. 20 to 24).

2.5. Others (T.S. 25).

3.1. Previous studies (T.S. 26 to 27).

3.2. Surface facilities (T.S. 28 to 35).

3.3. Injection facilities and piezometers (T.S. 36 to 41).

3.4. Operative aspects (T.S. 42 to 46).

4.1. Operation (T.S. 47 to 53).

4.2. Maintenance (T.S. 54 to 56).

4.3. Decision support systems (T.S. 57 to 63).

4.4. Management (T.S. 64 to 70).

4.5. Reuse (T.S. 71 to 73).

Please, notice that two of them have been removed due to redundancies, with a final total amount of 71 previous SMARTS; and 22 more have been aggregated from the different MARSoluT sites.

6.2 Proposal of new SMARTS from MARSoluT

The following are the TSs resulting from MARSoluT's MAR site performance analysis. The numbering continues the previously referenced work (MARSOL, Deliverable D13.3, groups-hyphen-technical solution number).

6.2.1 Set 1. SMARTS applied to water from its source (quantity)

1-72. Considering all possible sources of water when assessing MAR effects

MAR is one of the multiple measures to increase groundwater storage in aquifers. Increasing irrigation efficiency that decreases groundwater abstractions, changing cropping strategies, or irrigation returns are some anthropogenic modifications to the hydrological cycle that can directly affect water resource availability. Consequently, considering these and other measures is crucial when assessing some MAR risks or environmental impact assessment.

In the Los Arenales MAR sites, the appraisal of the impact of MAR on groundwater resources beards into consideration the effect of all measures above, resulting in a more robust analysis.

The problem-solution method by Fernández Escalante et al. (2021) can help in improving any risk or impact MAR-related study. The document is available at the following link:

http://www.conama11.vsf.es/conama10/download/files/conama2020/CT%202020/5218.pdf

1-73. Establishing a baseline of the aquifer's natural conditions

It is highly relevant to establishing the conditions of an aquifer before conducting MAR, providing a baseline to analyse the effects of the artificial recharge on groundwater quality and quantity. This characterisation is also crucial to assess MAR performance since reference conditions will determine whether the expected increase in groundwater storage or improvement in water quality is attained.

The Pwalles Valley MAR Site is subject to laborious monitoring and characterisation efforts to establish baseline conditions in the target aquifer. These baseline conditions will enable assessing whether the MAR site generates the expected additional groundwater storage and does not pose a risk to the environment or human health.

1-74. Using non-conventional sources of water for MAR to relieve pressure on surface water

The use of non-conventional sources of water for MAR, e.g., from springs, can reduce pressure on surface water bodies and increase groundwater storage to a significant extent. Furthermore, on some occasions, MAR systems could harness resources that would otherwise be lost to the sea.

In the Argolis field, the Kefalari coastal spring (**Figure 70**) provides water for MAR and irrigation, helping to boost local agriculture and reduce groundwater abstractions. Water from this spring was customarily discharged to the sea. A similar situation occurs in the Menashe Streams MAR site, where minor volumes of desalinated water that can't be supplied are redirected to the coastal aquifer through infiltration basins.

Figure 70. *The Kefalari coastal spring (Greece) provides water for MAR and irrigation, helping to boost local agriculture and reduce groundwater abstractions.*
Source: https://www.kavala-portal.gr/kefalari-drama-ollandia/

6.2.2 Set 2. SMARTS applied to water from its source (quality)

2-75. Reusing wastewater

Wastewater reuse is, in many cases, a reliable 24/7 water source for MAR. The almost permanent character of this recourse will make it vital in the Mediterranean region as surface water bodies will probably shrink under climate change and drought.

UAlg has recommended direct wastewater reuse without MAR to close the gap between available water resources and demand. Currently, the Portuguese regulation is unfavourable to MAR schemes using wastewater as the water source. TRAGSA (Henao Casas et al. 2022d) determined that urban agglomerations in LA could produce enough wastewater to completely replace surface water diversions for the Los Arenales MAR sites. In Malta, water authorities are considering using New Water from wastewater treatment plants as source water for MAR.

This TS was also considered in MARSOL's TS list, with examples such as wastewater reuse in Santiuste (**Figure 71**). It was included again as it has been further developed and characterised during MARSoluT.

Figure 71. *Purified water from the Santiuste village´s waste water treatment plant (by lagooning) is poured into the MAR channel. Los Arenales Aquifer, Spain.*

2-76. Considering aquifers as a means to improve water quality can be beneficial

Aquifers' saturated and unsaturated zones are not inert and can react with recharged water to improve water quality. This reaction can result in water mineralisation or pollutant attenuation, which is the mechanism leveraged by soil aquifer treatment (SAT). Some of the processes involved include biodegradation, sorption, and cation exchange.

In Menashe Streams MAR site, surplus desalinated water from an adjacent plant is recharged via infiltration ponds. This water arrives at the MAR site after limestone post-treatment, which improves water quality in terms of calcium content. However, magnesium content remains close to zero, a public health concern since the beginning of the “desalination era” in Israel. Infiltrating this water in the Menashe Streams MAR site increases magnesium concentration through cation exchange and, therefore, reduces the need for industrial mineralisation processes.

6.2.3 Set 3. SMARTS applied to the receiving medium (in both soil and aquifer)

3-77. Using certain plant species helps to enhance surface infiltration facilities

Macropores created by plant roots can enhance infiltration rates and penetrate clogging layers. These capabilities could be advantageous to improve recharge rates in MAR surface facilities and deal with clogging.

In the Menashe Streams MAR site, plants are present in one of the infiltration ponds (**Figure 72**). TRAGSA has explored this line of research in the Los Arenales MAR sites (**Figure 73**), studying poplars and other plant species since MARSOL. In all cases, plants seem to increase infiltration rates by as much as 30% with minimal water losses due to evapotranspiration. The next steps in this research line are constructing actual sites with plants, such as infiltration basins with poplars at the bottom planted at distances to be determined though basic cone of influence calculation and modelling.

Figure 72. *Pond at the Menashe Streams MAR site during infiltration.*

***Figure 73**. Infiltration tests inside a MAR infiltration ponds (EL Carracillo and Santiuste) to study the effect of vegetation on seepage rates.*

3-78. Applying thermography for clogging characterization and SAT-MAR

An infrared thermographic camera has been used at the Los Arenales site for multiple purposes. Two of them are detecting clogging preferential areas (previous SMARTS) and studying possible relations between thermography, infiltration rates, mixture processes, cold islands along the MAR channels, etc. (**Figure 74**).

***Figure 74.** Examples of using infrared images to study clogging distribution in the borders of the infiltration ponds (a, previous TS), and a mixture of the channel water and the lagooning wastewater treatment plant effluent (b, new TS) at the Los Arenales MAR Sites.*

6.2.4 Set 4. SMARTS applied to management parameters plus cleaning and maintenance operations

4-79. Setting a common terminology is crucial for regulating and operating MAR systems

A common language in the realm of MAR would ease communication. This aspect is essential when drafting regulations and producing scientific and engineering knowledge. Using synonyms for specific MAR methods or a word within the MAR jargon can help prepare documents by reducing word redundancy and facilitating reading. Nonetheless, in some instances, such as regulatory frameworks, laws, and guiding documents, precise words are crucial, requiring a clear vocabulary.

An ontology for MAR has been created to provide a solution. This ontology includes common terms in the realm of MAR, emphasising the methods and technologies employed to conduct it. It also shows the hierarchical relationship among these terms (**Figure 34**), and provides synonyms found across the literature (e.g., managed aquifer recharge and artificial recharge) for standardization.

4-80. Considering interoperability criteria are key for data handling and exchange

Using standards for monitoring data exchange can considerably save data handling time and ease MAR system characterisation, monitoring, and operation. The standard could be implemented preferably at the level of data loggers, which could retrieve data in a "universal format" that can be easily incorporated into data management tools. A consistent format would help to save the time required to design "data conversion boxes" that fetch information from files using various formatting schemes. This is another essential SMARTS based on the experience during MARSoluT.

Also, within the MARSoluT project, Tragsa has given a first step in this direction by creating a draft of this "universal format" (**Figure 35**). In the future, the involvement of environmental project practitioners, monitoring device manufacturers of sensors (**Figure 33**), and other relevant decision agents will be required to refine the draft and produce a robust standard. An experience of this sort with a member of the MARSoluT consortium has occurred in recent years through the production of the UNE 318002-3:2021 standard, which was led by TRAGSA and MAPA and provided a structure for interoperability in the irrigation sector.

4-81. Using SCADA systems can facilitate managing MAR facilities

Supervisory Control And Data Acquisition (SCADAs) can ease the operation of MAR systems by integrating monitoring data from various devices and controlling some processes.

TRAGSA has developed a standard to facilitate the creation of this sort of tool. It contains a series of processes for sensor observation and sensor alert services (SOS and SAS). It details the input data required to invoke each process and the corresponding output (**Figure 36**). This standard is based on OGC standards and simplifies much of the information for applicability to MAR.

4-82. Conducting an economic assessment of MAR against other solutions

An economic assessment of MAR and other solutions in dealing with water stress and increasing water availability can considerably help decision-makers to choose the most convenient solution. In the Algarve, one such analysis has helped to conclude that, in some cases, MAR is more cost-effective than other measures to reduce the groundwater overdraft gap, such as reducing demand, direct wastewater reuse, and seawater desalination (costs are not known yet but is very likely one of the highest) (**Table 1**). Nonetheless, the best solution is site dependant.

4-83. Improving governance to ensure the success of MAR implementations

Adequate water governance that guarantees the involvement of the primary decision agents is critical to successfully implementing water management measures such as MAR. The common top-down approach in which government agencies assume a command role might be limited to managing water resources. A sound alternative to circumvent such problems is to adopt a co-management approach, stake-holders share responsibilities.

In the Los Arenales MAR sites, the creation and involvement of irrigation communities have been one of the corner stones of a prosperous MAR experience. These irrigation communities are water user associations responsible for the system's maintenance. The water agency assigns irrigation rights to these communities based on MAR volumes. This shared scheme (Co-Managed Aquifer Recharge) creates a platform for bidirectional interaction that brings about benefits beyond water resources management.

4-84. Enhancing the co-managed aquifer recharge (Co-MAR) concept

This novel concept has emerged from MARSoluT (Fernández Escalante & López-Gunn 2021), particularly from the Los Arenales Living Lab. A book chapter has been published in the GWSI Series 3 and posted officially on the UNESCO Digital Library website (**Figure 75**). This volume includes cases from more than 10 countries.

Figure 75. *UNESCO book cover, including the Co-MAR chapter written by a MARSoluT member and stakeholders´ matrix. Modified from I-WSSM-UNESCO, chapter 1, pg. 38 (authors´ own).*

Its first chapter defines de Co-Managed Aquifer Recharge concept (Co-MAR). It exposes a good Spanish example where stakeholders intervene in Integrated Water Resources Management (IWRM), in close cooperation with water authorities and "*stakehomers*". Also, the term Public-Private-People Partnership (PPPP), through groundwater users associations and their relationship with authorities and among users, enhance governance for better regional water security.

In summary, Co-MAR entails a bottom-up approach in which end-users and stakeholders, organized in groundwater users' associations, play a key role in decision-making and regulation drafting.

4-85. Listening to specialists and strengthening relations between technicians/farmers/regulators

The "*stakehomers*" term mentioned in the previous TS, are those groups of scientists, external specialists, NGOs, observers, etc., directly or indirectly involved in any MAR activity. They are not part of the decision-making process, but their presence is important for technical advances and may even be key to the success of a project.

They could be included, according to the stakeholder´s matrix, within either the "coverts" or "apathetics" groups (**Figure 75**). Their contribution to the development is essential beyond any doubt.

4-86. Promoting public-private collaboration

Public-private cooperation can ease MAR implementation at various stages. For instance, private companies and landowners can give public agencies access to information and infrastructure that could be critical for MAR. Furthermore, this sort of cooperation is the core of co-management schemes, which can result in considerable improvements in water governance.

In the Pwales MAR Site, the authorities will benefit from information from private wells to further characterise the groundwater body that will be subject to MAR. In the Los Arenales MAR sites, the co-management scheme established between the regional water agency and farmers is crucial to water resources governance and the local success of MAR (see previous SMARTS and reference) (**Figure 76**).

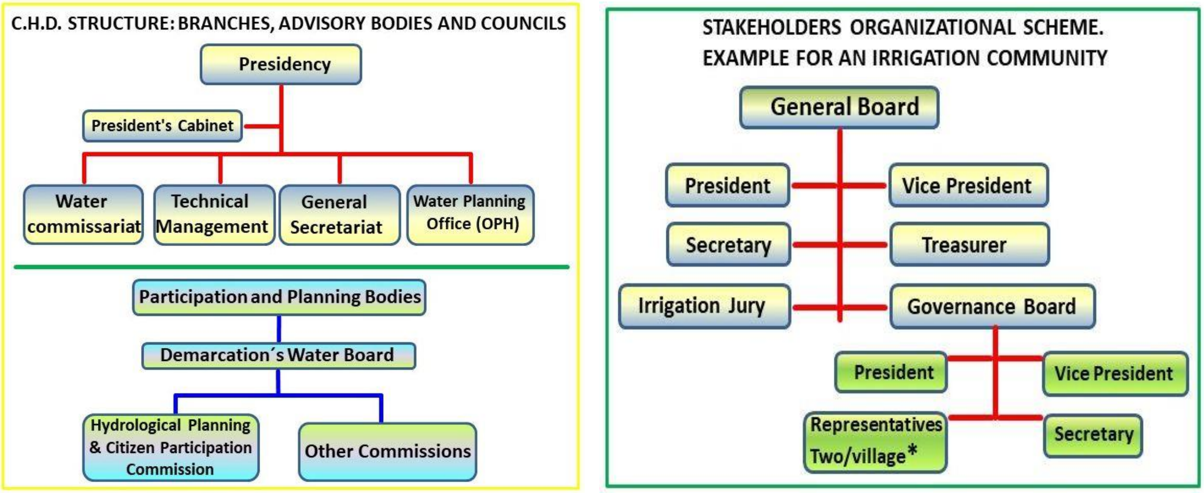

Figure 76. *Structure of the governing units into water authorities and groundwater user associations in which the Co-MAR study was conducted. Notice the presence of the stakeholders in the base of both* organisational charts.

4-87. Detecting and involving a local key promotor for MAR implementation

At any MAR site, people frequently feel the project is something "personal" and take part in the activity voluntarily, being aware of the importance of simple and even naive actions, which very often becomes key during any implementation process.

This situation is common in places with MAR activities, such as India, where a single person can follow a project, taking responsibility for a few maintenance tasks, observing construction works, and paying general attention to the MAR system during the different stages. This person, called "*Jal doots*" (**Figure 77**) is very appreciated by the community, who sees the benefits of this "self-nominated" occupation, very often with a small monetary compensation or even without any salary. Their main benefit is their social consideration, desire to take care of the environment, satisfaction, conviction, illusion, and other personal profits.

The *Managing Groundwater Use and Aquifer Recharge through Village-level Intervention* project (MARVI project) has used a citizen science approach to engage local villagers to collect, analyse, interpret and disseminate information within the community. The project has involved socio-economic and cultural understanding of groundwater challenges and monitoring water tables, rainfall, water-levels in check-dams, and field trials to identify water-saving practices.

Figure 77. *Monitoring of water table in dug wells: BJ Hari Ram Gadri. Source: marvi.org.*

This person and the activity that they perform is considered a new SMARTS.

6.2.5 Set 5. SMARTS applied to the combination of all of them (integrated system)

5-88. Assessing all possible IWRM solutions is necessary, as MAR is not always the unique/best solution

The uptake of MAR worldwide has increased in recent years as a key component of Integrated Water Resources Management (IWRM) schemes. MAR comprises a promising set of techniques to counteract the effects of multiple pressures on water resources. It can buffer the increasing variability of surface water, which might become more acute under climate change. MAR can also help to enhance water quality and shows great potential as an effective method for wastewater reuse. Nonetheless, the efficacy and potential of MAR don't mean it is always the best solution to manage water resources.

In the Argolis field, although MAR has contributed to harnessing and storing water resources that could be lost to the sea or the atmosphere, the high-cost involved in expanding the current irrigation network precludes the expansion of MAR capacity. In the Los Arenales MAR systems, a side benefit of MAR can be to decrease streamflow during floods. However, these systems are not sufficient to deal with too-much water. Consequently, reducing flooding risk requires additional strategies. In the Algarve, MAR generally costs less per cubic metre of water than other solutions. However, it is site-specific, and solutions such as direct wastewater reuse might be more profitable in some cases than MAR.

In summary, MAR is a component of IWRM systems, and its effectiveness and importance are different for each one. Still, a broad, integrated vision, analysing each component, is necessary to raise water security. The willingness to integrate is considered a SMARTS.

Figure 78 presents an IWRM sketch for the El Carracillo Shield, one of the three Los Arenales Living Lab sites.

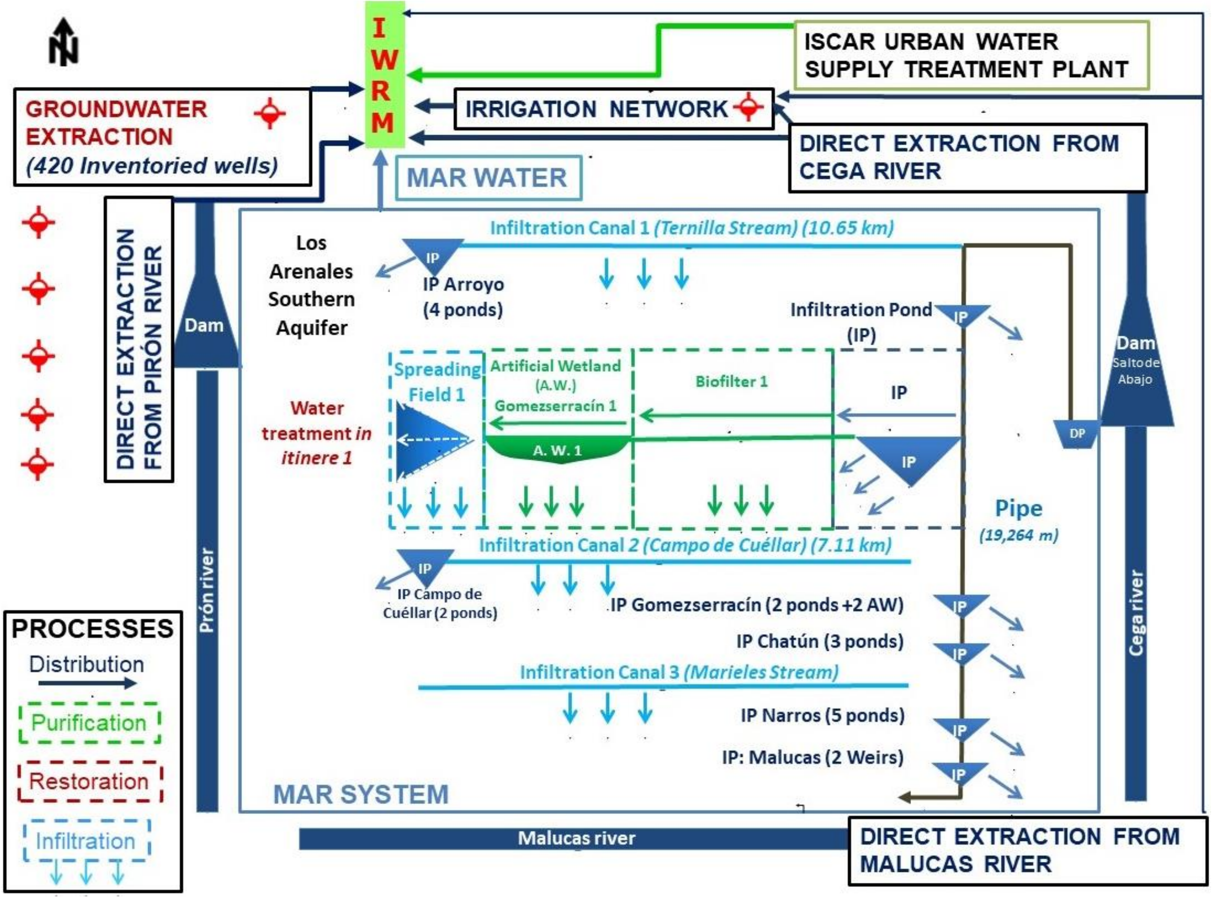

Figure 78. El Carracillo IWRM sketch, Los Arenales aquifer, Spain. Taken from Fernández Escalante & López-Gunn, UNESCO, 2021.

5-89. Conducting MAR trials before actual implementation

MAR directly entails intervening aquifers, which are, for the most part, invisible and require, in most cases, costly and detailed studies for proper characterisation. Even if an aquifer characterisation is robust, not all aspects can accurately be determined. Consequently, there is always big room for unforeseen effects or performance of MAR systems, which makes it appropriate to conduct small trials or start with a part of the original project before full-scale systems are implemented.

MAR sites, such as Suvereto and the Los Arenales, have been expanded after successfully proving the adequate performance of the MAR infrastructure and the technology utilised to improve groundwater storage without considerably affecting water quality. Suvereto is currently being enlarged, and the Pedrajas Alcazarén site of the Los Arenales MAR systems is the consequence of successful results at the Santiuste and El Carracillo sites, learning from previous mistakes, and obtaining permanent feedback in a looping process. It is a classical MAR rule to begin softly and speed up after the first experiments have resulted successfully.

5-90. Modelling MAR in the context of groundwater systems for decision-making

Modelling MAR systems in the context of a groundwater body or aquifer can help elucidate this technique's effects on groundwater quality and quantity, aiding in decision-making.

The most tangible example of this technical solution is the groundwater model developed in MODFLOW 6 by UAlg to evaluate several MAR options in the Campina de Faro Aquifer in the Algarve, Portugal (Standen et al. 2022). The numerical simulations showed that conducting MAR with the presently available resources has a limited impact and cannot increase groundwater levels to the minimum required heads. Furthermore, this simulation, in conjunction with parallel studies in the same area (Hugman & Doherty 2022), proved the complexity of saline water intrusion in the Algarve and the need for measures beyond MAR (e.g., reducing abstraction by 30%) to achieve environmental objectives. The real SMARTS is modelling for decision-making support.

5-91. Considering the effects of climate change through indicators

Analysing the expected effects of climate change can help to evaluate the suitability of MAR as a water supply solution and in decision-making.

UAlg reviewed studies on the expected consequences of climate change in the Algarve and found a reduction in precipitation (10%), wet days (10-20%), and recharge that could compromise surface water availability for MAR. A similar situation will likely unfold in the Douro River basin. Research by Tragsa (in Henao Casas et al. 2022d) has shown that large-scale MAR systems (e.g., the Los Arenales) can contribute to alleviating the compound effects of drought and water scarcity.

Furthermore, considering the expected impacts of climate change can be a useful input for MAR design. Henao Casas et al. (2022d) suggest that considering future climate scenarios could have helped to refine the design of the Los Arenales MAR sites to reduce river water flow during floods.

5-92. Ensuring post-construction maintenance and planning a control program

This SMARTS entails written guidance on operation and maintenance (O&M) activities to improve the efficiency of the MAR system and increase the life span and the general profit.

Some potential content included in the maintenance and control program is the groundwater level follow-up, detection of infiltration rate changes, control of infiltrated volumes, method to follow up the water quality evolution, Soil and Aquifer Treatment techniques (SAT) to improve the infiltration rates and water quality, etc.

Inspection and monitoring procedures must be included in this document and considered as a SMARTS by MARSoluT partners.

5-93. Application of the Monitored and intentional Recharge (MIR) concept. Hydrodynamic monitoring

The Monitored and intentional Recharge (MIR) concept was first presented during the International Symposium on Managed Aquifer Recharge (ISMAR 11) conference in April 2022. Later, an article was published in the Journal Water by TRAGSA's team (MARSoluT's member) under the title: "*Monitored and Intentional Recharge (MIR): A Model for Managed Aquifer Recharge (MAR) Guideline and Regulation Formulation*" (Fernández Escalante et al. 2022). The study concludes that the MIR concept comprises the minimum elements to consider when drafting guiding and normative MAR documents. The evaluation of aspects analysed in 22 guidelines and regulations about MAR documents showed the importance of water reuse and risk and impact assessment.

The MIR conceptual model comprises nine blocks (**Figure 79**) summarising the most important aspects. This conceptual model, which already guides MAR regulations in two countries, has excellent potential for application in different sites under diverse contexts.

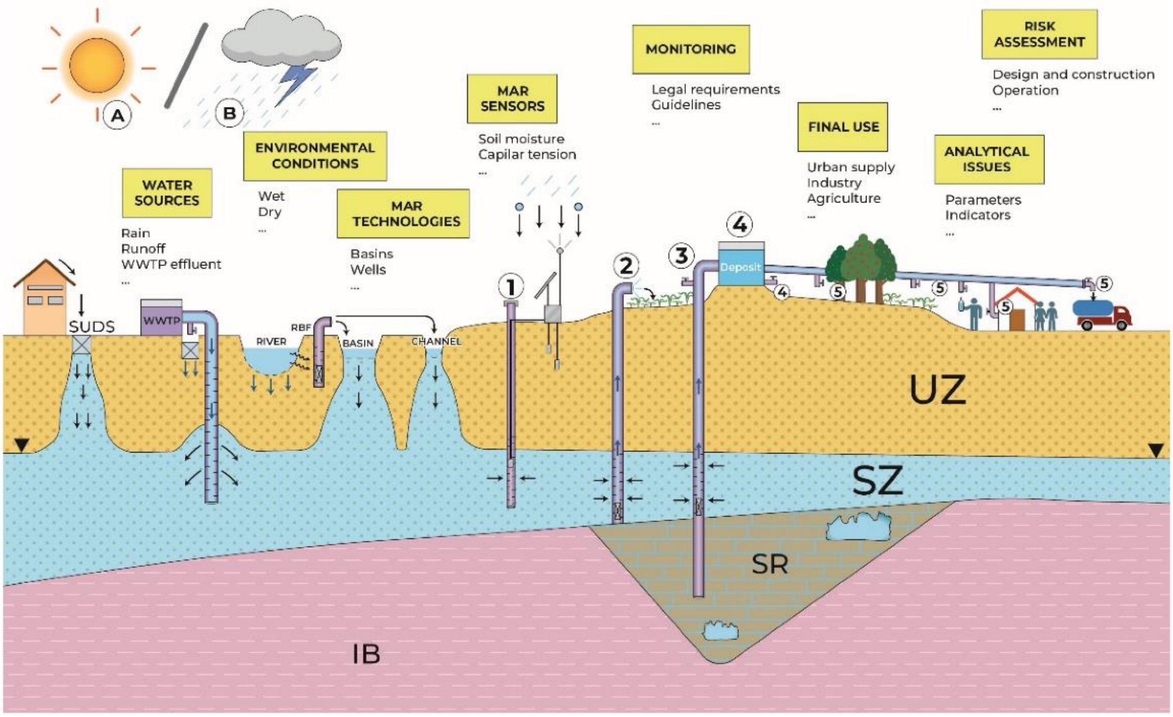

Figure 79. General scheme illustrating the main blocks comprising the monitored and intentional recharge (MIR) conceptual model. IB: impermeable bedrock; UZ: unsaturated zone; SZ: saturated zone; SR: strategic reservoir (geological formation for long term groundwater storage); WWTP: wastewater treatment plant; SUDS: sustainable urban drainage systems; RBF: riverbank filtration. A and B refer to the different climatic conditions in

MAR site areas. Number (1) refers to the UZ and SZ monitoring from a piezometer (MIR block 5, monitoring). The rest of the numbers correspond to usual sampling points, either from the extraction borehole, out of the conduction option (2) or collected inside the pipeline (3); sampling point from any storage cell where any treatment takes place at different depths (4); and hydrant from irrigation or tap for urban water supply (5). Sampling points 2 to 5 relate to the MIR blocks 6 and 7 (final use and analytical issues).

MIR has become an important SMARTS based on intensive hydrodynamic monitoring, and its review may provide missed elements during any MAR implementation under diverse environmental circumstances.

7. Summary and Conclusions of the SMARTS Chapter

Considering MARSOL's SMARTS as a starting point, some sets of SMARTS have been proposed and developed through the experience of multiple MARSoluT sites. They have been classified, enlarging the initial list from MARSOL (**Figure 80**), Deliverable D13.1, summarized in chapter 3.1. Notice that two SMARTS have been removed during this review because both were redundant, considering a total of 71.

1.1 Water quantity aspects (T.S. 1 to 5).
2.1. Pre-treatment-treatment (T.S. 6 to 12).
2.2. Surface facilities (T.S. 13 to 16).
2.3. Deep injection (T.S. 17 to 19).
2.4. Receiving medium (T.S. 20 to 24).
2.5. Others (T.S. 25).
3.1. Previous studies (T.S. 26 to 27).
3.2. Surface facilities (T.S. 28 to 35).
3.3. Injection facilities and piezometers (T.S. 36 to 41).
3.4. Operative aspects (T.S. 42 to 46).
4.1. Operation (T.S. 47 to 53).
4.2. Maintenance (T.S. 54 to 56).
4.3. Decision support systems (T.S. 57 to 63).
4.4. Management (T.S. 64 to 70).
4.5. Reuse (T.S. 71 to 73).

Figure 80. *Initial SMARTS classification and specific technical solutions provided during the MARSOL project, Deliverable D13.1.*

The new SMARTS, classified according to the previous blocks or sets, are:

1. Applied to water from its source (quantity) (72 to 74)

1-72. Considering all possible sources of water when assessing MAR effects.

1-73. Stablishing a baseline of the aquifer’s natural conditions.

1-74. Using non-conventional sources of water for MAR to relieve pressure on surface water.

2. Applied to water from its source (quality) (75 to 76)

2-75. Reusing wastewater.

2-76. Considering aquifers as a means to improve water quality can be beneficial.

3. Applied to the receiving medium (in both soil and aquifer) (77 to 78)

3-77. Using certain plant species helps to enhance surface infiltration facilities.

3-78. Applying thermography for clogging characterization and SAT-MAR.

4. Applied to management parameters plus cleaning and maintenance operations (79 to 87)

4-79. Setting a common terminology is crucial for regulating and operating MAR systems.

4-80. Considering interoperability criteria are key for data handling and exchange.

4-81. Using SCADA systems can facilitate managing MAR facilities.

4-82. Conducting an economic assessment of MAR against other solutions.

4-83. Improving governance to ensure the success of MAR implementations.

4-84. Enhancing the Co-managed aquifer recharge (Co-MAR) concept.

4-85. Listening to specialists and strengthening relations between technicians/farmers/regulators.

4-86. Promoting public-private collaboration.

4-87. Detecting and involving a local key promotor for MAR implementation.

5. Applying to the combination of all of them (integrated system) (88 to 93)

5-88. Assessing all possible IWRM solutions is necessary, as MAR is not always the unique/best solution.

5-89. Conducting MAR trials before actual implementation.

5-90. Modelling MAR in the context of groundwater systems for decision-making.

5-91. Considering the effects of climate change through indicators.

5-92. Ensuring post-construction maintenance and planning a control program.

5-93. Application of the Monitored and intentional Recharge (MIR) concept. Hydrodynamic monitoring.

The new proposed SMARTS can be classified and included in the main blocks, increasing the previous state-of-the-art on technical Solutions.

New contributions (sets one and three) have been incorporated regarding water quantity because it is the most classical and studied component of MAR science. Most of them focus on using new water sources, mainly reclaimed water, the aquifer baseline definition and MAR to relieve surface water´s impacts.

Regarding water quality (set two), aquifer reuse and self-purification capacity have been included despite previous mentions. The biggest concern is emerging-interest compounds and some preventive measures against their diffusion and techniques to break the molecules *in situ* are proposed.

In terms of the receiving medium (set three), the study of the vegetation and how it increases the infiltration capacity for different MAR systems has been an object of study conducted by MARSoluT ESR 3. This line of action concluded that root increase infiltration capacity between 28 and 42% (for the given environmental circumstances). This study can be further explored with more plant species and under other contexts, e.g. arid zones and non-Mediterranean settings.

The biggest contribution from MARSoluT falls into set four, ex-situ techniques (including management, governance, etc.), underlining the social aspects of MARSoluT. The consortium has increased the effort to involve stakeholders compared to their participation during the previous project, such as MARSOL. Some new concepts have emerged and been proposed to the scientific community, such as "stake-homers", Public-Private People Partnership (PPPP), an environment of trust, etc. Also, the bottom-up approach in decision-making and regulation drafting is a remarkable element.

The line of action on standardization and interoperability is also worth developing, which can have a practical implementation in Supervisory Control And Data Acquisition (SCADAs) systems. The new standard for irrigation proposed by the partner TRAGSA is in permanent improvement to present a future standard for MAR activities, with common terminology, and convert the format of the different sensor´s output files into an understandable language based on artificial intelligence (AI) guidance. These components will provide interoperable information adapted to the future standard for MAR.

The integrated vision and mission are also important contributions, as the connection among consortium members has been a remarkable strength during the project´s development. New SMARTS have been included in set five, paying special attention to hydro-dynamic monitoring, modelling as a tool for decision support and decision making, etc.

The consortium has demonstrated an important concern on climate change's thread, providing pragmatic responses to reduce the damage caused by global warming and related adverse impacts based on groundwater storage and extreme water-related events reduction, e.g. utilising flood-MAR and artificial wetlands.

A new concept called Monitored and Intentional Recharge (MIR) has been proposed to the water authorities of two countries by the moment (Peru and Niger). The consortium is trying to scale up this concept to the European Commission decision-makers through the Common Implementation Strategy (CIS) Group and directly asking for an interview with water decision-makers at the European level.

The proposition of SMARTS continues, as many barriers to MAR implementation are already identified and need to be solved or reduced into Knowledge and Innovation Communities (KICs) networks.

The list of barriers to future work and technical solutions to solve traditional challenges include:

- Public opinion improvement about MAR as a sustainable, safe and sound IWRM technique.
- Ecotoxicological improvement, especially concerning emergent compounds.
- Policy improvement and involvement of authorities to better know the capacities and limitations of MAR.
- Political context and willingness to face climate change adverse impacts.
- Cooperation activities and capacitation to count on skilful technicians to conduct future MAR activities.
- Experience gained from past collaborative experiences, especially hidden and unpublished failures.
- Fair resource distribution enhances the bottom-up approach for IWRM, including end-users in decision-making processes.
- Enhance the organizational culture.
- Reserve financial means to the river basin plan.
- Employ the Best Available Techniques (BATs) based on technological watching systems.
- Study other complementary alternative technologies.

- Concur in future calls in which Managed Aquifer Recharge will gain in some of the previous "unfinished subjects".

Work continues for MAR teams to improve their knowledge, skills, know-how, and motivation.

8. Conclusions and Recommendations

- The research on the MAR sites evaluated in this deliverable attains different approaches and the use of multiple tools, including groundwater numerical modelling, the analysis of hydrochemistry, the exploration of stable water isotopes, groundwater sampling and analysis, field and laboratory experiments, hydro statistics, and geospatial analysis.

- The MAR sites evaluated are performing in line with or even beyond expectations. In the Algarve, the critical situation regarding seawater intrusion and groundwater contamination warrants additional measures to ensure the good status of water bodies and meet water demands.

- The methods employed in MARSoluT's MAR sites are predominantly water-spreading methods such as infiltration basins and channels. The objective of MAR is, in most cases reversing groundwater storage decline and increasing water availability for irrigation. Not all MAR technologies are used in the research and sites of the MARSoluT.

- The MAR site performance assessment allows to identify technical solutions for MAR that can guide the conceptualisation, design, construction and operation of MAR facilities under diverse conditions.

- A total of 20 new technical solutions have been produced based on the performance assessment of active MAR sites. These technical solutions involve different aspects of managed aquifer recharge, such as operation, geochemistry, governance, and water sources.

- Sites across the Mediterranean are facing similar water stress problems. Water resources are becoming increasingly scarcer due to drought and water demand, particularly for irrigation.

- MAR is at the forefront of two diverging stresses in the Mediterranean rural context. On the one hand, groundwater resources are increasingly scarcer under unsustainable abstractions and drought. On the other hand, groundwater is key to sustaining irrigation where the rural exodus to urban centres poses the threat of declining populations. MAR can play an important role in this issue by taking advantage of untapped water resources and buffering variable precipitation and stream flows.

- Dykes and general in-river transversal structures conduct an important infiltration volume recharged into the aquifer as "unintentional" or (un)managed aquifer recharge. For the Spanish territory, a new GIS-based calculation has been presented, and the recharged volume ranges between 800 and 1,200 Mm^3/year. This figure will be studied in detail during the after-MARSoluT stage, providing a more accurate appraisal.

- Unconventional water sources will likely play a more prominent role in meeting water demands and restoring environmental assets. In particular, wastewater is emerging as a viable and reliable water supply source for multiple sectors, such as industry and agriculture. MAR can aid in wastewater reuse penetration by providing additional treatment in the unsaturated and saturated zones and directing water to aquifers that can act as water banks.

- MAR is not, in all cases, a solution to water scarcity. Factors such as costs, the limited storage capacity of aquifers in comparison to large-scale water management solutions (big dams), and an unfavourable regulatory framework can tip the balance in favour of other solutions. Nonetheless, MAR is, in many cases, an adequate technology to support systems relaying multiple measures (e.g., reducing demand and direct (treated) wastewater reuse).

- Continuing research lines across different projects can considerably help to advance the knowledge on a topic. This is particularly useful in the face of the short-lived character of many research projects, which count with funding for a limited time and, in many situations, result in the abandoning of advances and valuable ideas.

- The monitoring data used to evaluate site performance is collected majorly through on-site sensors. MAR water end-users (e.g., irrigation communities) and governmental agencies also provide critical information on site performance and research gaps.

- It is necessary to design SMARTS (Sustainable Managed Aquifer Recharge Technical Solutions), including the expertise and experiences of previous MAR projects, leaving the list open and alive for future incorporations.

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ANNEX

Tables 13 and **14** complement **Figures 26**, **27**, and **28**.

Table 13. *The sand, silt and clay proportion at different sites within the surveyed areas. LS: La Laguna del Señor; ST: Santiuste.*

	Laguna del Señor						
	Code	Date	Sand	Silt	Clay	Location	Medium
1	LS01	27/11/2020	89.7	4.0	6.4	LS	Tree
	LS08	03/06/2021	89.7	6.3	4.0	LS	Tree
	LS12	17/08/2021	95.0	2.5	2.5	LS	Tree
	LS16	30/11/2021	97.5	0	2.5	LS	Tree
	LS27	15/06/2022	90.0	5.0	5.0	LS	Tree
2	LS02	27/11/2020	90.2	6.6	3.2	LS	Basin
	LS09	03/06/2021	95.0	2.5	2.5	LS	Basin
	LS13	17/08/2021	85.3	9.8	4.9	LS	Basin
	LS18	30/11/2021	95.0	2.5	2.5	LS	Basin
3	LS17	30/11/2021	90.0	3.5	6.5	LS	Tree
	LS29	15/06/2022	75.1	13.0	11.9	LS	Tree
4	LS10	03/06/2021	80.1	13.2	6.6	LS	Tree
	LS14	17/08/2021	85.0	12.5	2.5	LS	Tree
	LS19	30/11/2021	87.5	10	2.5	LS	Tree
	LS31	02/09/2022	89.2	8.3	2.5	LS	Tree
5	LS11		96.1	1.4	2.5	LS	Basin
	LS15	17/08/2021	92.5	5.0	2.5	LS	Basin
	LS20	30/11/2021	92.5	5	2.5	LS	Basin
	LS32	02/09/2022	90.4	4.8	4.8	LS	Basin
	Santiuste						
1	ST02	27/11/2020	82.6	10.8	6.6	ST	Basin
	ST09	16/08/2021	97.5	0.0	2.5	ST	Basin
	ST14	29/11/2021	97.5	0	2.5	ST	Basin
2	ST01	27/11/2020	89.4	4.4	6.2	ST	Tree
	ST08	16/08/2021	92.5	5.0	2.5	ST	Tree
	ST13	29/11/2021	95.0	2.5	2.5	ST	Tree
3	ST04	02/06/2021	92.8	3.2	4.0	ST	Basin
	ST15	29/11/2021	95.0	3.5	1.5	ST	Basin
4	ST03	02/06/2021	95.1	2.5	2.5	ST	Tree
	ST24	14/06/2022	95.1	2.5	2.5	ST	Tree
5	ST11	16/08/2021	90.1	5.0	5.0	ST	Basin
	ST27	14/06/2022	92.6	5.0	2.5	ST	Basin
6	ST05	02/06/2021	90.6	4.7	4.7	ST	Tree
	ST13	29/11/2021	95.0	2.5	2.5	ST	Tree
7	ST07	02/06/2021	91.0	6.5	2.5	ST	Basin
	ST17	29/11/2021	97.5	1.0	1.5	ST	Basin

Table 14. *Steady-State infiltration rates (SSIR) at different sites within the surveyed areas). LS: La Laguna del Señor; ST: Santiuste.*

	Laguna del Señor					
	Code	Date	Infiltration rate	Season	Location	Medium
1	LS01	27/11/2020	26.5	4	LS	Tree
	LS08	03/06/2021	22.7	2	LS	Tree
	LS12	17/08/2021	64.7	3	LS	Tree
	LS16	30/11/2021	32.4	4	LS	Tree
	LS27	15/06/2022	27.1	2	LS	Tree
2	LS02	27/11/2020	13.2	4	LS	Basin
	LS09	03/06/2021	23.2	2	LS	Basin
	LS13	17/08/2021	36.0	3	LS	Basin
	LS18	30/11/2021	22.9	4	LS	Basin
5	LS19	30/11/2021	99.5	4	LS	Tree
	LS31	02/09/2022	22.2	3	LS	Tree
6	LS11	03/06/2021	36.3	2	LS	Basin
	LS20	30/11/2021	24.9	4	LS	Basin
	LS32	02/09/2022	9.6	3	LS	Basin
	Santiuste					
1	ST02	27/11/2020	25.3	4	ST	Basin
	ST14	29/11/2021	13.8	4	ST	Basin
2	ST01	27/11/2020	25.3	4	ST	Tree
	ST13	29/11/2021	33.3	4	ST	Tree
3	ST04	02/06/2021	3.5	2	ST	Basin
	ST15	29/11/2021	10.8	4	ST	Basin
4	ST03	02/06/2021	7.4	2	ST	Tree
	ST24	14/06/2022	18.3	2	ST	Tree
7	ST07	02/06/2021	13.2	2	ST	Basin
	ST17	29/11/2021	54.4	4	ST	Basin