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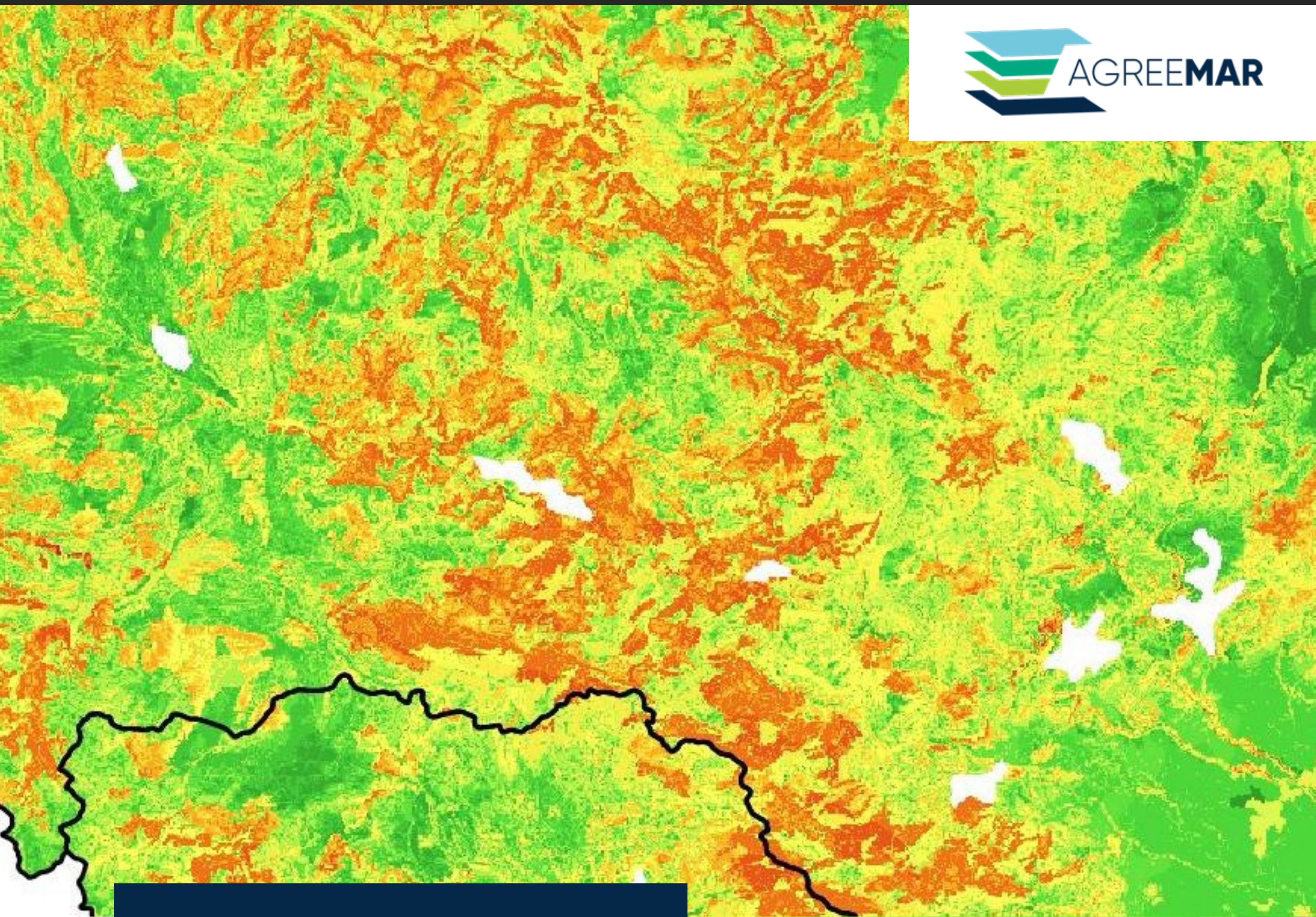

Project deliverables

Deliverable #D2.3

MAR feasibility maps validated for each demo region

Funded by

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AGREEMAR

Adaptive agreements on benefits sharing for managed aquifer recharge in the Mediterranean region

Deliverable #D2.3

MAR feasibility maps validated for each demo region

Author(s)

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Executive summary

Deliverable 2.3 is dedicated to the development of feasibility maps for each demo region based on the adaptive methodology described in Deliverable 2.2 which integrates two workflows centered on expert-based input and active stakeholder participation. This report focuses on providing a step-by-step description of the methodology used for creating the MAR feasibility maps, including problem definition, constraint mapping, criteria selection, standardization of criteria values, weights assignment, feasibility mapping and validation.

Work package	Work package 2. MAR feasibility mapping
Deliverable number & title	D2.3. MAR feasibility maps validated for each demo regions
Partner responsible	National Agronomic Institute of Tunisia (INAT)
Deliverable author(s)	Anis Chekirbane (INAT), Khaoula Khemiri (INAT), Constantinos F. Panagiotou (ERATOSTHENES CoE), Tiago N. Martins (LNEC), Teresa E. Leitão (LNEC), Sarah Eisenreich (TUD), Catalin Stefan (TUD)
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V0.1	24.07.2023	Constantinos F. Panagiotou (ECoE)	First version
V0.2	07.08.2023	Constantinos F. Panagiotou (ECoE)	Updated with contributions from partners
V0.3	18.08.2023	Anis Chekirbane (INAT)	Several rounds of revisions and recommendations
V0.4	28.08.2023	Anis Chekirbane (INAT)	Several rounds of revisions and recommendations
V1.0	31.08.2023	Catalin Stefan (TUD)	Revisions, additional sections and copyediting

Abstract

The present report aims to present and analyze the obtained managed aquifer recharge (MAR) feasibility maps of the demo sites of AGREEMAR project. MAR objectives/typology and criteria of each demo region were identified through interaction with stakeholders and results of online questionnaires. The weighting process of the selected criteria was performed with respect to deliverable D2.2 (https://agreemar.inowas.com/deliverables/) which states a new stakeholder-adapted weighting system including two methodological workflows that integrate the expert-based input with contributions resulted from interaction with stakeholders. Three thematic maps of suitability including: (i) intrinsic site suitability; (ii) availability of conventional and non-conventional water sources for MAR and (iii) demand for groundwater-dependent services were established for each demo site in Tunisia, Portugal, Spain and Cyprus based on GIS-MCDA approach. Temporal variability of these maps was taken in consideration and the maps were obtained at least for two seasons (wet and dry). The MAR feasibility maps are the result of combining these three weighted thematics. The weight coefficients of these maps are also determined through a participative process after interaction with stakeholders during the validation workshops. In addition to their role in identifying the areas where MAR is mostly feasible, the obtained maps are efficient tools of negotiation with decision makers to support them advance successful MAR projects in the most feasible areas within a region.

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MAR site feasibility mapping

1. Introduction

The present report is compiled within the work package 2 of the AGREEMAR project and focuses on the application and validation of the general methodology described in the project deliverable D2.2 “Participative methodology for criteria selection and weighting in MAR site feasibility mapping” (Martins et al., 2022). The scope of the work is to assess the geospatial feasibility of four demo regions from Tunisia, Portugal, Spain and Cyprus for the implementation of managed aquifer recharge (MAR) projects. The maps are generated by integrating a set of feasibility criteria for areas of different scales, sizes, environmental and socioeconomic conditions.

As described in very detail in project deliverable D2.2, MAR feasibility maps are the result of integrating three thematics: (i) intrinsic site suitability; (ii) availability of conventional and non-conventional water sources for MAR and (iii) demand for groundwater-dependent services. In addition to these physical parameters, a set of non-physical ones are be taken into consideration especially during the weighting process of the selected MAR criteria. The weighting procedure is based on two “streamflows”. The first streamflow evaluates the relative importance between the physical parameters that contain information regarding the three thematics in terms of the non-physical ones based on the opinion of MAR experts, whereas the second streamflow focuses on weighting the physical parameters based on stakeholders’ opinion.

MAR feasibility maps were developed via the integration of GIS tools and multi-criteria decision analysis (MCDA) at a regional and watershed scale. These maps are expected to be used by the water policy makers and water authorities for licensing the implementation of sustainable water management strategies (such as MAR), not only in the selected demo regions, but also across the entire Mediterranean region. The general approach includes seven main steps which reflect also the structure of this report (Figure 1).

Figure 1. General concept of MAR site suitability mapping highlighting the steps covered by this report

2. Problem definition

2.1 The concept of “MAR typology”

MAR represents a wide and growing range of measures to support active management of groundwater resources at the local and basin level, to make more efficient use of water resources, assist conjunctive management of surface and groundwater resources, to buffer against increasing intensity of climate extremes, particularly drought, and to protect and improve water quality in aquifers (Dillon et al., 2019). MAR is an innovative practice spread globally (Stefan and Ansems, 2018) that includes a set of techniques to increase the availability of good quality groundwater or for the qualitative and quantitative rehabilitation of groundwater resources. The performance of a MAR scheme can be roughly described by two factors: (a) the capacity of the water to percolate through the soil, and (b) the capacity of the aquifer to receive and store this water. In full-scale applications, the feasibility can be defined by the existence and good functioning of a larger number of components: (1) a reliable water source, (2) a pre-treatment system or a control measure to ensure a satisfactory quality of the infiltration water, (3) a recharge system that is able to transfer large volumes of water into subsurface, (4) a suitable aquifer to temporarily store the water, (5) a recovery system in form of a pumping well or connected stream that can be used to bring the infiltrated water back to surface (in cases when the water is needed for further use), (6) another treatment or control mechanism that secures a good (often ‘fit-for-purpose’) water quality, and (7) a receiver or a final user of the recovered water (see Figure 2).

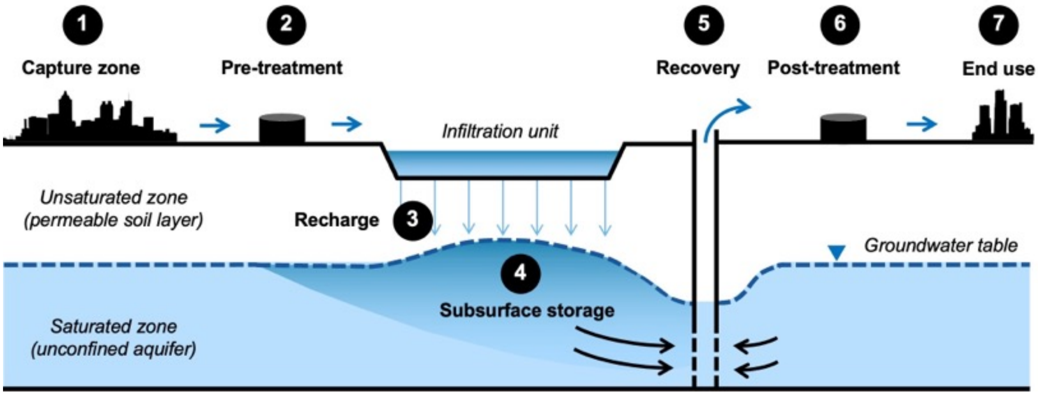


Figure 2. Simplified representation of the main components of a MAR scheme (adapted from Dillon et al., 2019)

As each of the seven individual steps can describe a wide range of solutions, there is an almost unlimited number of combinations possible for the design and operation of a MAR scheme. Examples include the filtration of surface water through the riverbank for water quality improvement, infiltration of tertiary-treated wastewater into the subsurface through ponds or trenches for seasonal storage and further use in agriculture, discharging desalinated water by means of infiltration wells to compensate the diurnal variability in drinking water demand, creating hydraulic barriers in form of infiltration well galleries to mitigate the impact of seawater intrusion, etc. – all these are examples of possible configurations of a MAR scheme.

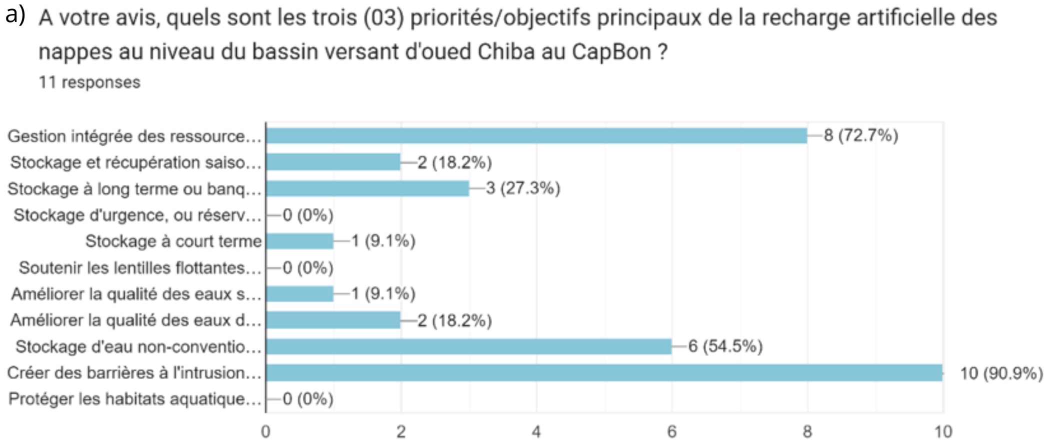
For the purpose of this report and throughout the AGREEMAR project, we will refer to this relationship between the MAR objectives, water source, recharge technique etc. as a "MAR typology" so the maps are created not to assess the MAR feasibility in general but for very specific MAR typologies at the four demo regions considered.

2.2 Methodology for co-creation of country-specific MAR typologies

The methodology is based on the general understanding that the assessment of a region's feasibility for MAR is strongly influenced by the components of the MAR typology, i.e., by the objective and scope of the MAR project, the available water source, the suitability of the aquifer to store the water etc. In order to understand the water-related challenges and the needs of each demo region for improved water management, a series of needs assessment campaigns were initiated at each demo region right after the start of the project. These campaigns enabled the consortium to identify the key stakeholders at national, regional and local level and provided a very good understanding of their needs and responsibilities (for a detailed report see also the AGREEMAR deliverables D1.1a "Preliminary analysis of project relevant stakeholders" and D1.1 "Stakeholders engagement strategy and plan": https://agreemar.inowas.com/deliverables/). This knowledge was then used in the work package 2 for the development and validation of the methodology used for geospatial feasibility mapping of region-specific MAR typologies. A series of interactions with stakeholders using surveys and direct interview enabled the compilation of two specific MAR typologies for each demo region.

2.2.1 Tunisia

The MAR typologies for Chiba basin were determined based on a participative approach after consulting the key stakeholders from general, regional, and local scales. The online questionnaire used revealed that in addition to the general goal of integrated water resources management (IWRM), the main two MAR objectives for the Tunisian demo region are (i) improvement of groundwater quality and (ii) long term storage of groundwater (Figure 3a). Stakeholders were also able to define the most suitable MAR scheme: infiltration ponds and basins; soil aquifer treatment (SAT) using treated wastewater and dam water release (Figure 3b).



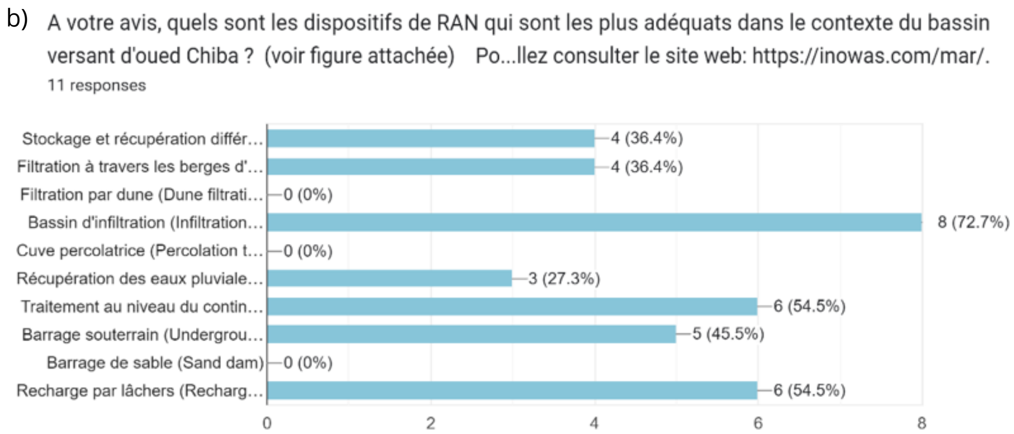


Figure 3. Online questionnaire (in French) used to rank the MAR objectives (a) and the recharge techniques (b) to be used in future MAR projects in Chiba basin based on stakeholders' perceptions and needs

2.2.2 Portugal

To ease the selection of a MAR objective in a broad-enough manner to integrate solutions to the most relevant problems in the demo region, the initial list of 32 MAR objectives presented in AGREEMAR deliverable 2.1 (Panagiotou et al., 2022) (Table 1) was summarized into six MAR objective clusters. This was conducted by grouping into clusters the MAR objectives that conduct to a similar result (e.g., MAR objective #2 "Seasonal storage and recovery of water" and MAR objective #3 "Long-term storage or water banking" were included in MAR objective cluster #1 "Increase of piezometric levels, groundwater and energy storage") – Table 2.

Table 1. Recharge objectives of MAR projects under different development stages around the world (Panagiotou et al., 2022)

No	Recharge objective	No	Recharge objective
1	Integrated water management	17	Thermal energy storage
2	Seasonal storage and recovery of water	18	Stabilize aggressive water
3	Long-term storage, or water banking	19	Disinfection by-product reduction
4	Emergency storage, or strategic water reserve	20	Hydraulic control of contaminated water
5	Short-term storage	21	Nutrient reduction in agricultural runoff
6	Enhance well field production	22	Improve quality of surface water by soil-aquifer treatment
7	Restore ground water levels, replace overdraft	23	Reclaimed water storage for reuse
8	Raise water levels, reduce pumping costs	24	Create barriers to salt water intrusion to stop, reverse, or prevent intrusion
9	Substitute for or supplement surface or pipeline distribution systems	25	Compensate for surface salinity barrier leakage losses
10	Maintain distribution system pressure and flow	26	Reduce environmental effects of stream flow diversions

No	Recharge objective	No	Recharge objective
11	Increase system reliability for pressure and flow	27	Protection and restoration of streamflow
12	Maintain floating freshwater lenses	28	Fish hatchery water temperature control
13	Defer construction or expansion of water facilities	29	Water recreation
14	Stop or reduce rate of land surface subsidence	30	Flood control
15	Improve ground water quality to agricultural standards	31	Fish and wildlife enhancement
16	Improve ground water quality to municipal standards	32	Protect aquatic and riparian habitat

Table 2. List of MAR objective clusters

No	Recharge objective cluster
1	Increase of piezometric levels, groundwater and energy storage
2	Improve groundwater quality
3	Prevent contamination and geotechnical problems
4	Enhance Groundwater Dependent Ecosystems (GDE), natural and recreational areas
5	Contribute to control floods
6	Water infrastructure maintenance or improvement

Note: *the different colours show the correlation between MAR objectives in Table 1 and Table 2.*

In the deployed stakeholder/specialist questionnaires, the participants were asked to select five of the initial 32 MAR objectives according to what they considered to be the most important MAR achievements in the demo region and their respective area of intervention. 62% of all the selected MAR objectives are included within the MAR objective cluster #1, which refers to the "Increase piezometric levels, groundwater and energy storage", followed by 16% related with MAR objective cluster #2 ("Improve groundwater quality"). This was the basis for establishing the priority for MAR implementation in the Portuguese demo region (Figure 4).

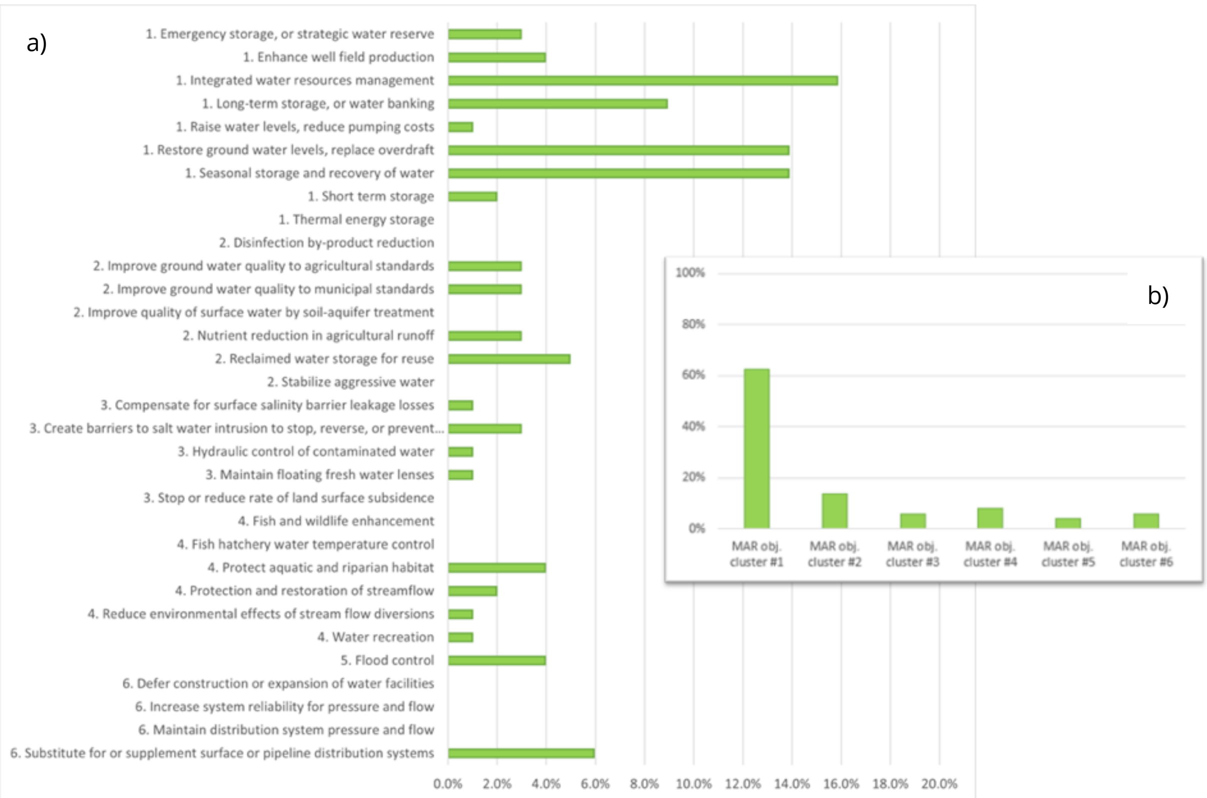


Figure 4. Percentage of the total answers provided in the stakeholder questionnaire by (a) MAR objective and (b) MAR objective cluster

2.2.3 Spain

During the workshop and consultations conducted within the Júcar Water District in Spain to assess the needs of stakeholders, the participants engaged in thoughtful discussions concerning the core objectives of MAR. These objectives were carefully determined based on their significance in guiding the successful implementation of MAR within the region. As a result, the central focus of MAR revolves around the reduction of aquifer overexploitation. This endeavor encompasses the restoration of groundwater levels, the replacement of overdraft conditions, and the mitigation of saltwater intrusion. To bring these intentions to fruition, it was envisaged to use infiltration basins and dams, along with appropriate use of conventional water sources.

2.2.4 Cyprus

Due to the overexploitation of groundwater resources, seawater intrusion in aquifers alongside the Cypriot coastline poses a severe problem. According to previous studies (Demetriou and Georgiou, 2004), all of the four most important aquifers for source water in Cyprus are facing seawater intrusion due to over-pumping and the fall of the groundwater level below critical levels. Regarding the water consumption in Cyprus, the high demand of water resources for agricultural needs correspond to a percentage of about 59 % of the total annual water consumption in Cyprus (LDK Consultants Engineers & Planners S.A. and ECOS Consulting S.A, 2016).

In addition to the above-mentioned literature works, frequent discussions were taking place between members of the local project partner and key water stakeholders in a local, regional, and a national level, aiming to jointly formulate the MAR typologies for the Cypriot demo region. During these discussions, it was emphasized that the MAR through infiltration ponds is the only acceptable practice for implementation in Cyprus when tertiary-treated wastewater is used as a water source. This choice is justified by the fact that infiltration of wastewater via ponds has the advantage of being subjected to additional purification through its percolation in the vadose zone until it reaches the aquifer. These considerations helped the Cypriot project partner and the key stakeholders, particularly Water Development Department and Geological Survey, to jointly identify two MAR typologies that reflect the needs of the demo region and are expected to contribute to the future planning of MAR implementation in Cyprus.

2.3 MAR typologies created with stakeholders' participation

Table 3 provides a general overview of the selected MAR typologies for each case site, consisting of the specific objectives, water source for MAR and recharge technique.

Table 3. MAR typology for each case site

ID	Overall goal	Specific objectives	Water source	Recharge technique	Other considerations	Demo regions
				Tunisia		
T1	Long term storage of groundwater	Increase piezometric levels and groundwater storage	Conventional & non-conventional water resources	Infiltration ponds and SAT (costal region) and dam water release near the dam	Water availability and demand were estimated for both dry and wet seasons	Chiba watershed (Tunisia)
T2	Improve groundwater quality	Create a barrier to seawater intrusion	Treated wastewater	Infiltration ponds (costal region) and injection wells near the dam	Water availability and demand were estimated for both dry and wet seasons	Chiba watershed (Tunisia)
				Portugal		
P1	Increase piezometric levels, and groundwater storage	Augment the groundwater reserves	Non-conventional water sources (stormwater, surface runoff, treated wastewater)	Surface ponds, infiltration basins, ditches, wetlands, riverbeds	n.a.	Alentejo and Algarve regions (Sado, Mira and Guadiana hydrographic regions), Portugal

ID	Overall goal	Specific objectives	Water source	Recharge technique	Other considerations	Demo regions
P2	Improve groundwater quality	Augment the groundwater volume providing dilution. Improve water quality using nature-based solutions for tertiary treatment	Non-conventional water sources (stormwater, surface runoff, treated wastewater)	Surface ponds, infiltration basins (with SAT-MAR systems), ditches, wetlands, riverbeds	n.a.	Alentejo and Algarve regions (Sado, Mira and Guadiana hydrographic regions), Portugal
			Spain			
S1	Reduce overexploitation of aquifers	Restore ground water levels, replace overdraft and mitigate saltwater intrusion	Conventional water sources	Infiltration ponds	n.a.	Mijares watershed, Spain
S2	Reduce overexploitation of aquifers	Restore ground water levels, replace overdraft and mitigate saltwater	Conventional water sources	Infiltration dam	n.a.	Palancia watershed, Spain
			Cyprus			
C1	Increase water availability for agriculture	Reclaimed water storage for reuse in agriculture	Tertiary-treated wastewater	Spreading methods (infiltration ponds)	Intrinsic suitability and water demand were estimated for two seasons (January-June, July-December).	Republic of Cyprus
C2	Prevent contamination and geotechnical problems	Create barriers to saltwater intrusion to stop, reverse, or prevent intrusion	Tertiary-treated wastewater	Spreading methods (infiltration ponds)	Intrinsic suitability and water demand were estimated for one season (July- December).	Republic of Cyprus

3. Constraint mapping

As a first step before the construction of the maps, the areas with constraints (i.e., areas where MAR is not allowed by law or areas where MAR is not physically possible, such as lakes, etc.) were defined for each demo region (Table 4). Those areas were excluded from the analysis during the mapping step, simply using Boolean logic: unsuitable areas are removed, and the rest is considered for analysis. Yet, there is a difference between areas with constraints and areas of low feasibility, the latter being very low suitable areas where MAR could be still feasible, but with technical and socioeconomic difficulties.

Table 4. Constraints adopted for each demo region

Constraint type	Tunisia	Portugal	Spain	Cyprus
Geopolitical				•
Land use	•	•		•
Major roads				•
Drinking water protection zones		•		•
Groundwater bodies				•
Confined aquifers				•
Contamination sources		•		

For the Tunisian demo region (Chiba watershed), only land use constraints were considered, especially dense urban areas, forests, and protected zones.

For the Portuguese demo region three main constraints were considered: (1) land use, specifically dense urban areas and other type of artificial surfaces such as mines, airfields, roads and commercial structures, (2) immediate and intermediate perimeters where severe restrictions are defined for several activities and (3) the vicinity of contamination sources (e.g., landfills) and the coastline in a buffer of 100 m.

For the Spanish demo regions, no constraints were considered for the mapping but later, for the selection of the MAR site, some constraints will be considered depending on the specific locations. For example, if the most feasible zone will be located in residential or protected areas, it will be excluded.

For Cyprus, six constraint factors are selected. The first constraint is geopolitical, stemming from the illegal invasion and military occupation of the northern part of the Republic of Cyprus by Turkey in 1974. As a result, the northern part is not under effective control of the Cypriot Government. The second constraint excludes areas where unconfined aquifers are not present, due to the adaptation of infiltration ponds as the only MAR method. Additional constraint factors include the distance to water bodies (hill dams and reservoirs), distance to residential areas, distance to roads and land use. In particular, a buffer of 200 m around residential areas is applied to avoid possible harm caused by mosquitoes or smell. A distance of 500 m from stagnant water bodies such as lakes is applied to protect the surface water from potential contamination with reclaimed water. Furthermore, a buffer of 50 m around roads is proposed as a constraint (Gdoura et al., 2015; Shawaqfah et al., 2021).

4. Criteria selection

NOTE: *The work presented in this and the following chapters follows the methodology developed by the AGREE-MAR project for the selection and weighting of criteria in MAR site feasibility studies. A detailed description of this methodology with adequate examples is presented in AGREEMAR Deliverable D2.2 (Martins et al., 2022).*

The AGREEMAR project proposes an extended methodology for the selection of MAR feasibility criteria and ranking their relevance in the context of integrated management of water resources. The method is widely based on the integration of expert-based multi-criteria decision analysis with a multi-stakeholder participative process. The novelty of the method consists in the integration of expert-based inputs ("Streamflow 1") with contributions resulted from interaction with stakeholders ("Streamflow 2").

Streamflow 1 is developed by the AGREEMAR team and external experts for all categories of criteria deemed relevant for the MAR typologies considered, and involves assembling the relevance of each category of criteria to the three IWRM pillars using a ternary diagram (see following section). For more details about this approach see also the sections 3.2.1 to 3.2.2 in AGREEMAR Deliverable D2.2. In order to integrate in the analysis also the non-physical criteria (which are understood as those feasibility criteria that cannot be georeferenced but are important for the site feasibility analysis), a second step is considered consisting in a Boolean rating of the interactions physical vs. non-physical criteria (for more details see section 3.2.3 of AGREEMAR Deliverable D2.2). The outcome of the two steps consists of an objective-oriented ranking of the relevance of different criteria used in the MAR site feasibility mapping. The preselection of criteria to be analysed in Streamflow 1 is based on a dedicated questionnaire and interviews with key stakeholders and international MAR experts, also taking into account the conditions depicted in chapter 4.1 of this report.

Streamflow 2 aims at the selection and ranking of case-specific set of criteria by key stakeholders from the demo regions of the project. The methodology is described in chapter 3.3 of AGREEMAR Deliverable D2.2.

4.1 Conditions for criteria selection

The physical criteria are the basic elements in the decision analysis, since they can be quantified and compared in terms of their relevance to the MAR typologies. The selection of a set of criteria that reflects the needs of a demo region is an extremely important and non-trivial process, which requires a very good understanding of various underlying processes and factors associated with MAR implementation. In accordance with the participatory approach of AGREEMAR, a set of physical criteria were selected after consulting the key stakeholders of every demo region.

In Tunisia, the most relevant physical criteria were selected in a way that fulfil the complete coverage of the watershed. The choice was also influenced by the availability of the existing spatial data. A special attention was paid to the temporal aspect of the data such the annual rainfall distribution or crop water demand. Some data such as hydrological parameters, land use / land cover (LULC), etc. were considered for both dry season and wet season.

In Portugal, the reasoning behind the set of selected physical criteria is based on the geographical information made available during the assembling of the maps, considering the relevant physical criteria previously selected. Some information was derived/computed from other original maps (e.g., distance to source score weighted by source characteristics, e.g., available volume and/or chemical status). The initial set of data did not allow to integrate seasonal variability of parameters such as groundwater levels or other meteorological and hydrological information for the whole region. So, to include some kind of temporal variability an evaluation of the variation of some meteorological and hydrological criteria was conducted based on future climatic scenarios (e.g., natural groundwater recharge rate expected increase/decrease under the scenario of Representative Concentration Pathway (RCP) 4.5 for the period of 2020 – 2060).

In the Spanish context, the selection of relevant physical criteria was based on their direct relevance to the demo regions, combined with data availability. This process relied heavily on the geographical information available. In particular, some criteria were derived or calculated from original maps, while the simulation of a hydrological model involved a number of other criteria. Overall, only few criteria were selected compared to the other demo regions because of lack of data availability in this framework.

In Cyprus, a number of criteria for each thematic was pre-selected from an extended database (see AGREEMAR deliverables 2.1 and 2.2). These criteria were further modified, and eventually validated, by key stakeholders of the water sector during bi-lateral meetings that took place within the time frame of the AGREEMAR project. Some adaptations, either exclusions of some criteria or simplification of their evaluation process, were conducted according to the data availability. Different sources of data were considered, such as geoportals of governmental services, in-situ data, satellite data, stored in different formats (e.g., shapefiles, raster files, text files).

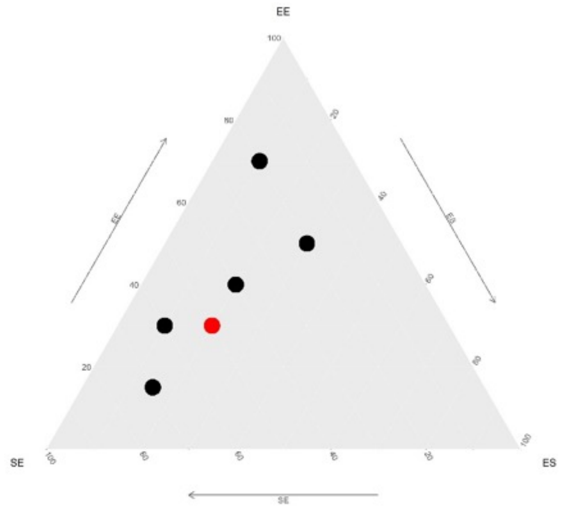
4.2 Expert-based criteria selection (“Streamflow 1”)

4.2.1 Relevance of non-physical categories based on IWRM principles

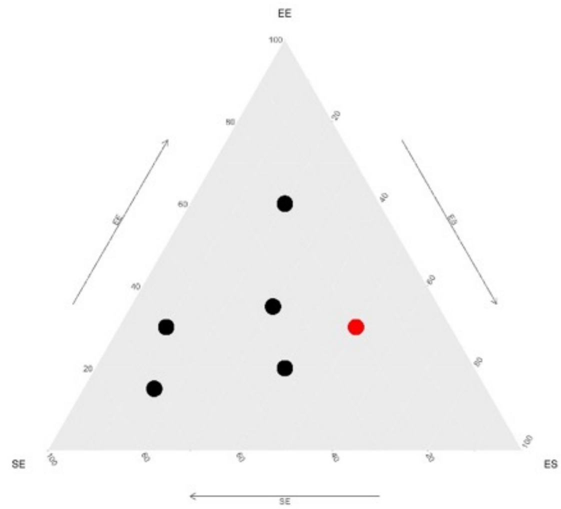
MAR is well-embedded in the general concept of integrated water resources management (IWRM). The Technical Committee of the Global Water Partnership (GWP) defined IWRM as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems". IWRM is based on three principles: (i) social equity (SE); (ii) economic efficiency (EE); (iii) ecological sustainability (ES). Depending on the MAR typology (objective and scheme), the focus might shift towards one or another pillar.

Applied for the considered demo regions, a percentage is assigned to each pillar, reflecting its importance for that specific objective. The sum of the percentages must be 100 %, so it is necessary to ponder the compromise between SE-EE-ES pillars. The non-physical (NP) categories are then selected according to their proximity to the point representing the MAR typology (Tunisia – T, Portugal – P, Spain – S, Cyprus – C; for a description of each typology see Table 3). The Euclidean distance is then calculated from the MAR typology point for each of the NP criteria. Based on this analysis, a set of weights was calculated for all MAR typologies considered. The calculation methodology is explained in detail in Martins et al., 2022 (AGREEMAR Deliverable D2.2).

Figure 5 includes the MAR typology and criteria projected in the ternary diagram of IWRM at the different demo regions of the project.

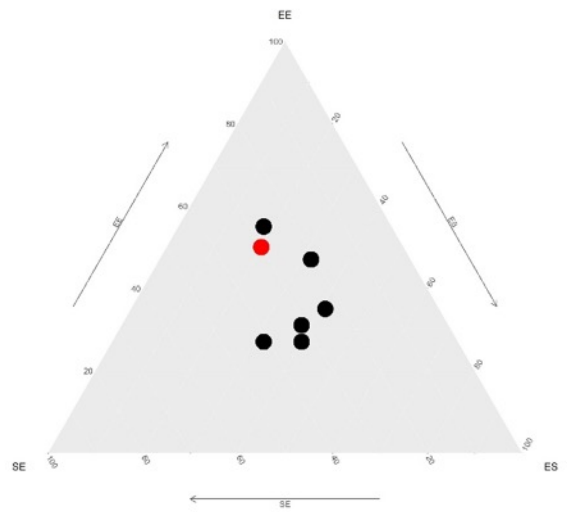


T1

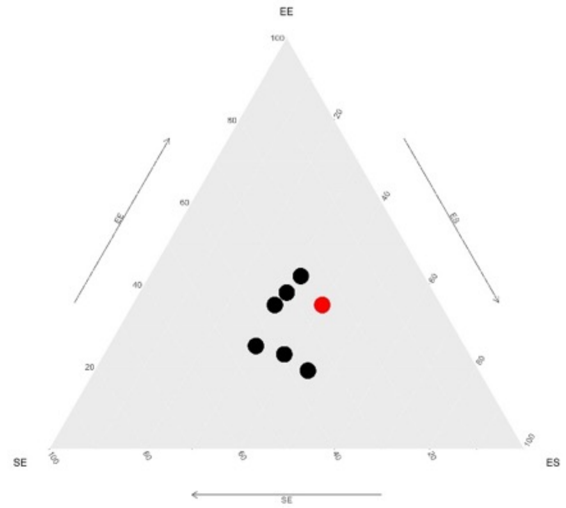


T2

Tunisia

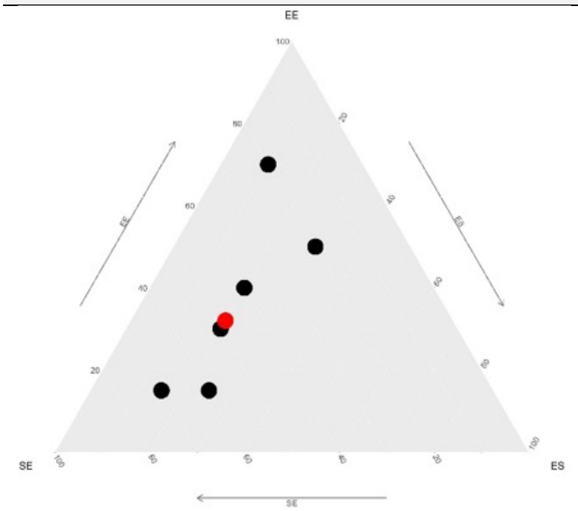


P1

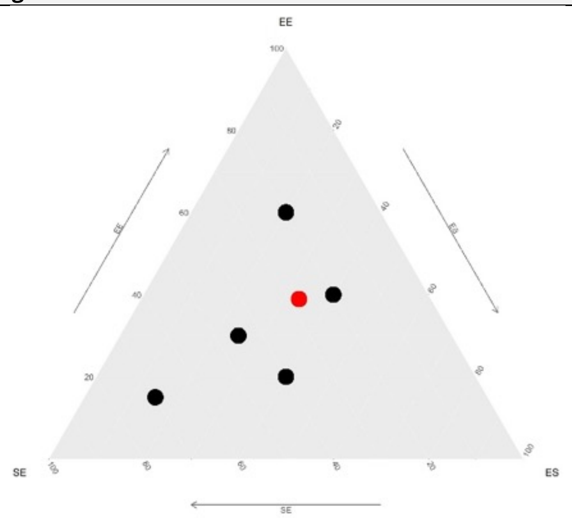


P2

Portugal

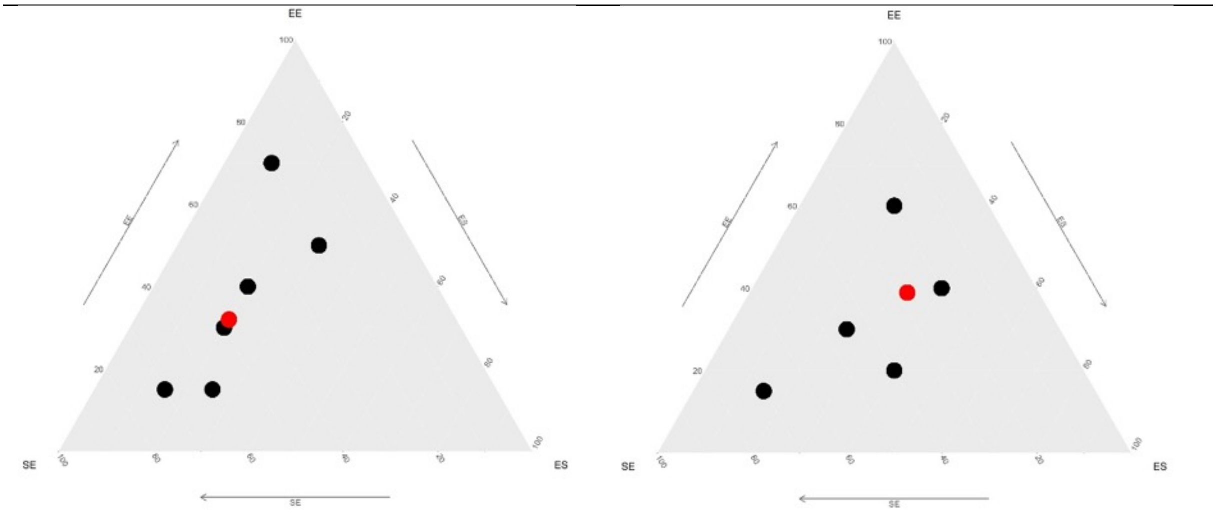


S1



S2

Spain



C1	C2
Cyprus	

Figure 5. Ternary diagrams of all demo regions in terms of selected MAR typologies. Red dots denote the IWRM coordinates of the MAR typology, whereas black dots denote the IWRM coordinates of the non-physical criteria

4.2.2 Boolean rating of interactions between physical and non-physical categories of criteria

The selected non-physical categories for each MAR typology were used to rate the physical categories based on a Boolean classification. The classification is prepared by the AGREEMAR team and validated by MAR experts and is based on understanding the possible interactions between Physical (P) and Non-physical (NP) categories. A simple NP x P matrix was developed for the sets of MAR objectives based on the inputs of the consortium members and MAR experts. An example of the established matrix for the first set of MAR objectives and intrinsic site suitability criteria is presented in Table 5. A preliminary version of this Boolean matrix was presented in AGREEMAR Deliverable 2.2. (Martins et al., 2022) but, as a result of internal discussion, the matrix was simplified by reducing the original number of non-physical categories.

The Boolean matrices for all MAR typologies and thematic maps are presented in Annex A1.

Filling up the Boolean matrix:

The selected non-physical categories for each MAR objective are used to rate the physical categories based on a Boolean classification. The classification is prepared by the AGREEMAR team and validated by MAR experts and is based on understanding the possible interactions between Non-Physical (NP) and physical (P) categories. To ease the understanding on how the Boolean classification is conducted, a simple question can be answered, for example: "Given this specific MAR objective, do the Water rights impact the Aquifer characteristics?" - Yes (1) - No (0) (for each column provide the impacts for each line)

Table 5. Template of a Boolean matrix of intrinsic categories based on non-physical categories. Values of 0 and 1 can be added and each cell can be colored in green and red to indicate the presence and absence of relevance between the categories respectively

	Topic	Governance / Environmental constraints		Social/Economic constraints			
Topic	**Category**	**Legal constrains**	**Transborder issues - agreements**	**Culture, religion, education**	**Health-related issues**	**Costs**	**Accessibility and communications**
Aquifer/vadose zone	Aquifer characteristics						

	Topic	Governance / Environmental constraints		Social/Economic constraints			
Topic	**Category**	**Legal constrains**	**Transborder issues - agreements**	**Culture, religion, education**	**Health-related issues**	**Costs**	**Accessibility and communications**
	Groundwater flow characteristics						
	Aquifer structure and physical boundaries						
	Aquifer structure and physical boundaries						
	Groundwater table						
	Geochemistry						
	Geomorphology						
	Hydrography						
	Land use / land cover						
Climatic context	Hydrometeorology						
Source water	Source water quality						
	Source water availability						
Provisioning needs	Domestic supply						
	Agricultural supply						
	Industrial supply						
	Geothermal energy						
Regulatory needs	Buffering water quality						
	Buffering water quantity						
Supporting needs	Groundwater dependent ecosystems						
	Land surface stability						
Cultural needs	Hot springs						
	Leisure and recreation						

4.3 Stakeholder-based criteria selection (“Streamflow 2”)

Streamflow 2 focuses on selecting the site-specific criteria and calculating their weight coefficients through a co-participative, stakeholder-centered approach. In most cases, the preselection of physical criteria was done through direct interaction with key stakeholders and by using a dedicated questionnaire targeted at stakeholders that are relevant for the demo regions. Table 6 summarizes the selected criteria used to generate the three MAR suitability maps.

Table 6. Selection of intrinsic criteria for all demo regions and typologies (see also (Table 3)

			Tunisia		Portugal		Spain		Cyprus	
Topic	**Category**	**Criterion**	**T1**	**T2**	**P1**	**P2**	**S1**	**S2**	**C1**	**C2**
		Intrinsic site suitability								
Aquifer	Aquifer characteristics	Aquifer storage/capacity			•	•				
Aquifer	Aquifer characteristics	Specific yield			•	•			•	•
Aquifer	Aquifer characteristics	Aquifer geochemistry	•	•	•	•			•	•
Aquifer	Groundwater flow characteristics	Hydraulic conductivity			•	•			•	•
Aquifer	Aquifer structure and physical boundaries	Aquifer geometry			•	•				
Aquifer	Groundwater flow characteristics	Hydrogeology / Lithology	•	•	•	•	•	•	•	•
Vadose zone	Groundwater table	Thickness of vadose zone	•	•	•	•			•	•
Vadose zone	Groundwater table	Infiltration capacity of the vadose zone			•	•				
Surface	Geomorphology	Land slope	•	•	•	•	•	•	•	•
Surface	Hydrography	Drainage density	•	•						
Surface	Land use / land cover	Soil occupation	•	•	•	•	•	•	•	•
Surface	Soil	Top-soil texture	•	•	•	•				
Surface	Soil	Lineament density	•	•						
		Water availability								
Climatic context	Hydrometeorology	Precipitation	•	•	•	•				
Climatic context	Hydrometeorology	Evapotranspiration	•	•	•	•			•	•
Climatic context	Hydrometeorology	Direct run-off	•	•	•	•	•	•		
Climatic context	Source water quality	Proximity to contamination sources			•	•				
Source water	Source water quality	Quality compliance			•	•	•	•	•	•
Source water	Source water availability	Non-conventional water availability					•	•	•	•
Source water	Source water availability	Proximity to origin of water sources (non-conventional)	•	•	•	•			•	•
Source water	Source water availability	Proximity to origin of water sources (dam)	•	•	•	•				
Source water	Source water availability	Proximity to origin of water sources (rivers and streams)			•	•				
Source water	Source water availability	Water supply connection density	•	•						
		Water demand								
Provisioning needs	Domestic supply	Consumption per unit area for domestic supply			•	•				
Provisioning needs	Agricultural supply	Crop pattern			•	•				
Provisioning needs	Agricultural supply	Annual growth /decline rate of agricultural supply			•	•				
Provisioning needs	Agricultural supply	Crop irrigation water needs							•	
Provisioning needs	Agricultural supply	Consumption per unit area for agriculture	•	•	•	•				
Provisioning needs	Industrial supply	Consumption per unit area for industrial supply			•	•				

Topic	Category	Criterion	Tunisia T1	Tunisia T2	Portugal P1	Portugal P2	Spain S1	Spain S2	Cyprus C1	Cyprus C2
Regulatory needs	Buffering water quality	Rate of aquifer salinization								•
Regulatory needs	Buffering water quality	Chemical status			•	•				
Regulatory needs	Buffering water quantity	Natural groundwater recharge rate			•	•				
Regulatory needs	Buffering water quantity	Natural groundwater recharge rate expected decrease/increase			•	•				
Regulatory needs	Buffering water quantity	Decrease in groundwater levels			•	•				•
Supporting needs	Groundwater depending on ecosystems	Groundwater dependent ecosystems	•	•	•	•				
-	-	Water demand					•	•		

5. Criteria standardization

The standardization step involves arranging the attribute values of all thematic criteria in the same, uniform scale (usually in the range from 0 to 1). The value scaling can be done on continuous data using a linear function (when the values are within a certain range, i.e., terrain slope, rainfall, etc.) or on discrete data using a stepwise discretization (when the values are grouped in thematic classes, i.e., soil texture classes, geological formations etc.). The complete standardization table for all demo regions is available in Annex 2.

5.1 Physical criteria standardization for Tunisian demo region

The same scale is needed to be assigned for all selected criteria in Tunisia in order to explain the relative level of suitability. Transformation of criteria in Tunisia into comparable scale was done also through standardization, for which two reliable methods were: stepwise and linear functions. The former described by Rahman et al. 2012 was applied to standardize the selected criteria of the Chiba watershed. The source of information, data type and rationale behind standardization is explained in Table 7.

Table 7. Details of the approach adopted at the Tunisian demo region to classify the physical criteria in terms of their suitability for MAR

Criteria	Data type	Description	Standardization approach
Intrinsic suitability			
Aquifer geochemistry	Discrete	Computed based on published salinity values of groundwater	Assigned values 0.1 to 1 for each of the parameters and computed the average resulting in a single "Aquifer geochemistry" representative map
Aquifer lithology	Discrete	Lithological description clustered into main lithological groups (e.g., sedimentary, fractured, etc.)	Assigned values 0.2 to 1
Thickness of the vadose zone	Discrete	Soil thickness grouped into interval classes (e.g., < 20 m)	Assigned values 0.2 to 1
Land slope	Discrete	Slope computed from surface topography (USGS-SRTM30m); reclassification assumed that above 20% slope feasibility remains as 0.2	Assigned values 0.2 to 1
Land surface area	Discrete	Agricultural database of Nabeul governorate was used to generate the LULC	Assigned values 0.2 to 1
Drainage density	Discrete	Computed from surface topography (USGS-SRTM30m); reclassification assumed that less than 0.1 km/km^2 feasibility remains as 0.2	Assigned values 0.2 to 1

Criteria	Data type	Description	Standardization approach
Lineament density	Discrete	Computed from surface topography (USGS-SRTM30m) and Landsat 8 image reclassification assumed that less than 0.5 km/km^2 feasibility remains as 0.2	Assigned values 0.2 to 1
Water availability			
Precipitation	Discrete	Spatial distribution of average precipitation (mm/yr) computed from INM data [1980 – 2022]	Scaled between minimum (0.2) and maximum (1)
Direct run-off	Discrete	Spatial distribution of average direct run-off (mm/yr) computed with SWAT model	Scaled between minimum (0.2) and maximum (1)
Evapotranspiration	Discrete	Spatial distribution of average actual evapotranspiration (mm/yr) computed with SWAT model	Scaled between minimum (0.2) and maximum (1)
Distance to source (conventional and non-conventional)	Discrete	Based on the classification conducted by Aloui et al. (2022)	Scaled between minimum (0.2) and maximum (1)
Water supply connection density	Discrete	Based on the classification conducted by Aloui et al. (2022)	Scaled between minimum (0.2) and maximum (1)
Water demand			
Consumption per unit area for agriculture supply	Discrete	Computed based on comparison between crop water need and available irrigation amounts. The estimation of crop water demand relied on the NDVI and the FAO (1986) methodology	Scaled between minimum (0.2) and maximum (1)
Groundwater dependent ecosystems (supporting needs)	Discrete	Based on the diagnostic report of conservation sites for coastal wetlands and coastal ecosystems in Cap Bon, conducted by Baccar et al. (2001)	Assigned values 0.2 to 1

5.2 Physical criteria standardization for Portuguese demo region

In the standardization process, the lowest suitability value given is 0.1, except for exclusion areas such as dense urban areas for which 0 value was given. This low value of 0.1 underlines the idea that feasibility is low – as in no MAR objective will be successfully achieved – but there is no clear restriction to MAR implementation. For most continuous criteria a linear function was used to reclassify the minimum and maximum values of that variable to an interval between 0.1 and 1. One such example is the precipitation which varies from 400 mm/year to 1200 mm/year and for which the minimum standardized value is 0.1 and the maximum is 1. For other criteria where feasibility assumptions do not allow for a single linear function, the continuous values were divided by intervals for which a sub-function was computed. For discrete type criteria, such as aquifer lithology the feasibility was assessed case by case under the 0.1 - 1 scale. All standardized maps in vector format were converted into 100 m resolution raster files. The source of information, data type and rationale behind standardization is explained in Table 8.

Table 8. Details of the approach adopted at the Portuguese demo region to classify the physical criteria in terms of their suitability for MAR

Criteria	Data type	Description	Standardization approach
Intrinsic suitability			
Aquifer storage capacity	Continuous	Computed difference between topographic surface (USGS-STRM) and the GW levels (SNIRH)	Scaled between minimum (0.1) and maximum (1)
Specific yield / storativity of the aquifer	Discrete	Aquifer productivity classification (APA) with minimally to highly productive	Assigned values 0.5 to 1
Aquifer geochemistry	Continuous	The spatial distribution of Chloride (mg/L), Electric conductivity (µS/cm) and Nitrates (mg/L) parameters.	Assigned values 0.1 to 1 for each of the parameters and computed the average resulting in a single "Aquifer geochemistry" representative map

Criteria	Data type	Description	Standardization approach
Hydraulic conductivity	Discrete	Original information classified aquifers by average hydraulic conductivity intervals in Aller, et al. (1981), presented in Lobo Ferreira & Oliveira (1993)	Assigned values 0.5 to 1
Aquifer geometry	Discrete	Based on the aquifer dynamics and structure made by APA (e.g., Multilayer, phreatic to confined, high thickness)	Assigned values 0.1 to 1
Aquifer lithology	Discrete	Lithological description clustered into main lithological groups (e.g., sedimentary, volcanic, etc.)	Assigned values 0.4 to 1
Thickness of the vadose zone	Discrete	Soil thickness grouped into interval classes (e.g., < 10 cm) produced by EPIC web-GIS (LEAF-ISA)	Assigned values 0.1 to 1
Infiltration capacity of the vadose zone	Discrete	Soil permeability classes produced by EPIC web-GIS (LEAF-ISA)	Assigned values 0.2 to 1
Land slope	Continuous	Slope computed from surface topography (USGS-SRTM30m); reclassification assumed that above 20% slope feasibility remains as 0.1	Scaled between minimum (0.1) and maximum (1)
Soil occupation	Discrete	CORINE Land Cover 2018 map	Assigned values 0 to 0.9
Top-soil texture	Discrete	Soil texture classes produced by EPIC web-GIS (LEAF-ISA)	Assigned values 0.1 to 1
Water availability			
Precipitation	Continuous	Spatial distribution of average precipitation (mm/yr) computed from SNIRH data [1941 – 2019] (Martins et al., 2023 – under review)	Scaled between minimum (0.1) and maximum (1)
Direct run-off	Continuous	Spatial distribution of average direct run-off(mm/yr) computed with BALSEQ model [1941 – 2019] (Martins et al., 2023 – under review)	Scaled between minimum (0.1) and maximum (1)
Evapotranspiration	Continuous	Spatial distribution of average actual evapotranspiration (mm/yr) computed with BALSEQ model [1941 – 2019] (Martins et al., 2023 – under review)	Scaled between minimum (0.1) and maximum (1)
Distance to source (non-conventional) score weighted by quality status, volume and distance buffers	Discrete	Based on the classification conducted by APA under the river basin management plans	Scaled between minimum (0.1) and maximum (1)
Distance to source (dams) score weighted by quality status, reservoir volume and distance buffers	Discrete	Based on the classification conducted by APA under the river basin management plans	Scaled between minimum (0.1) and maximum (1)
Distance to source (rivers/streams) score weighted by quality status and distance buffers	Discrete	Based on the classification conducted by APA under the river basin management plans	Scaled between minimum (0.1) and maximum (1)
Proximity to contamination sources (including the sea) score	Discrete	Based on the coastline, landfills and solid waste treatment areas position	Assigned values 0 (within a 100 m buffer from the contamination source) to 1
Water demand			
Consumption per unit area for domestic supply	Continuous	Computed based on abstracted volumes for urban water supply sector (hm^3/yr)	Scaled between minimum (0.1) and maximum (1)
Consumption per unit area for agriculture supply	Continuous	Computed based on abstracted volumes for agriculture sector (hm^3/yr)	Scaled between minimum (0.1) and maximum (1)
Crop pattern	Discrete	CORINE land cover 2018 type of agricultural areas; reclassification base on water needed for irrigation	Assigned values 0.1 to 1
Annual growth/decline rate of agricultural supply	Discrete	Based on previsions for agriculture sector (APA)	Scaled between minimum (0.1) and maximum (1)
Consumption per unit area for industrial supply	Continuous	Computed based on abstracted volumes for industrial supply sector (hm^3/yr)	Scaled between minimum (0.1) and maximum (1)

Criteria	Data type	Description	Standardization approach
Chemical status (of buffering water – regulatory needs)	Discrete	Based on the characterization of the GW chemical status conducted by APA for the river basin management plans	Assigned values 0.5 to 1
Decrease of groundwater levels (e.g., annual mean values, seasonal) (of buffering water – regulatory needs)	Discrete	Based on the characterization of the GW quantity status conducted by APA for the river basin management plans	Assigned values 0.5 to 1
Natural groundwater recharge rate (of buffering water – regulatory needs)	Continuous	Spatial distribution of average infiltration (mm/yr) computed with BALSEQ model [1941 – 2019] (Martins et al., 2023 – under review)	Scaled between minimum (0.1) and maximum (1)
Natural groundwater recharge rate expected increase/decrease (of buffering water – regulatory needs)	Continuous	Ratio of the spatial distribution b/w infiltration [RCP4.5 2020 – 2060]/ [1941 – 2019] (%) (Martins et al., 2023 – under review)	Scaled between minimum (0.1) and maximum (1)
Groundwater dependent ecosystems (supporting needs)	Discrete	Based on APA evaluation of the occurrence of GWDE by GW bodies area	Assigned values 0.5 to 1

5.3 Physical criteria standardization for Spanish demo region

The standardization process involved transforming the original datasets, such as lithology, slope, land use / land cover (LULC), natural runoff, water quality, non-conventional water (WWTP effluent), and water demand, into a common scale between 0 and 1 (Table 9). To determine the suitability of different areas for MAR, lithology, slope, and LULC were categorized into specific classes and assigned corresponding values ranging from 0.2 to 1, with 1 indicating the most suitable conditions for MAR. Water quality was assessed using a binary classification approach. If the water quality met specified standards, a value of 1 was assigned, indicating suitability for MAR. Conversely, if it did not meet the required norms, a value of 0 was assigned, signifying that MAR would not be feasible in those areas. For natural runoff, WWTP, and water demand, a linear standardization method was employed to scale the values between the minimum and maximum presented. This allowed for the evaluation of their relative suitability for MAR implementation.

Table 9. Details of the approach adopted at the Spanish demo region to classify the physical criteria in terms of their suitability for MAR

Criteria	Data type	Description	Standardization approach
		Intrinsic suitability	
Aquifer lithology	Discrete	Lithological description clustered into main lithological groups (e.g., sedimentary, fractured, etc.)	Assigned values 0.2 to 1
Land slope	Discrete	Slope computed from surface topography (USGS-SRTM30m); reclassification assumed that above 20% slope feasibility remains as 0.2	Assigned values 0.2 to 1
Land use / land cover	Discrete	CORINE Land Cover 2018 map	Assigned values 0.2 to 1
		Water availability	
Natural runoff	Continuous	Spatial distribution of average direct run-off (hm^3/month)	Scaled between minimum (0.2) and maximum (1)
Water quality	Binary	Spatial distribution of average water quality (percentage of non-fulfilment of water quality criteria)	Binary classification
Volume of tertiary-treated wastewater effluent	Continuous	Spatial distribution of tertiary-treated wastewater effluent volume	Scaled between minimum (0.2) and maximum (1)
		Water demand	
Water demand	Continuous	Spatial distribution of average water demand (hm^3/month)	Scaled between minimum (0.2) and maximum (1)

5.4 Physical criteria standardization for Cypriot demo region

Similar to the other case sites, the selected criteria consisted of both numerical and categorical parameters. After consulting with the stakeholders, the range of values for each criterion was partitioned into discrete intervals. Each interval was assigned a score ranging from 0.1 to 1.0 with respect to its suitability for MAR implementation. Scores close (or equal) to 0.1 denote very low MAR suitability (but not a constraint), whereas values close (or equal) to 1 denote very high suitability for MAR implementation. Table 10 provides the type of data used and the range of the standardized suitability scores for the Cypriot demo region.

Table 10. Details of the approach adopted at the Cypriot demo region to classify the physical criteria in terms of their suitability for MAR

Criteria	Data type	Description	Standardization approach
		Intrinsic suitability	
Land Slope	Continuous	Differentiate the Digital Elevation Model (25 m resolution)	Scaled between minimum (0.33) and maximum (1)
Hydraulic conductivity	Continuous	Average values for 66 aquifers, as described in WDD report with title "Assessment of Groundwater Resources of Cyprus" (Georgiou, 2002)	Scaled between minimum (0.33) and maximum (1)
Specific yield	Continuous	Average values for 66 aquifers, as described in WDD report with title "Assessment of Groundwater Resources of Cyprus (Georgiou, 2002).	Scaled between minimum (0.33) and maximum (1)
Thickness of the vadose zone	Continuous	Monthly-averaged groundwater levels at 42 locations, as provided by Geological Survey.	Scaled between minimum (0.33) and maximum (1)
Aquifer geochemistry	Discrete	Concentration values for several chemical parameters collected from the WDD Report with title "Chemical status Assessment Report of Groundwater in Cyprus for 2019-2020" (Adamou, 2022)	Scaled between minimum (0.33) and maximum (1)
Land use- land cover	Discrete	Corine Land Cover (CLC), 2018	Scaled between minimum (0.33) and maximum (1)
Hydrogeology	Discrete	Hydrogeology map provided by the Geology Survey for all groundwater bodies, along with expert-classification in terms of infiltration, storage and extraction capacity.	Scaled between minimum (0.33) and maximum (1)
		Water availability	
Quantity of reclaimed water available for MAR	Continuous	Monthly volume amounts of wastewater produced at the exit of Wastewater Treatment Plant stations for period 2018-2022, along with its allocation for different uses.	Scaled between minimum (0.33) and maximum (1)
Quality compliance of reclaimed water available for MAR	Discrete	Data provided by WDD regarding the physico-chemical parameters at the exit of WWTPs. Evaluation based on Directive 91/271/EC. In particular, the dataset included concentrations for BOD, COD, TSS, N-total, P-total. Measurements for additional parameters are provided, such as pH, EC and Chlorine.	Scaled between minimum (0.33) and maximum (1)
Evapotranspiration	Continuous	Spatial distribution of annual values of actual evapotranspiration rates (mm/yr), provided by MODIS satellite data for period 2018-2022.	Scaled between minimum (0.33) and maximum (1)
Distance to non-conventional water source (wastewater)	Continuous	Distance from WWTPs and the associated pipeline networks. Shawaqfah et al. (2021) suggested a maximum distance of 8 km around WWTPs as an economic criterion.	Scaled between minimum (0.33) and maximum (1)
		Water demand	
Crop irrigation water needs	Continuous	Use of farmers' declaration for crop types, collected from Cypriot Agricultural Payments Organization, and crop irrigation water needs collected from Cypriot Agriculture Research Institute (m^3/da)	Scaled between minimum (0.2) and maximum (1)

Criteria	Data type	Description	Standardization approach
Aquifer Salinization	Discrete	The salinization status of the aquifer is evaluated based on EC values for 2019-2020, collected from the WDD Report with title "Chemical status Assessment Report of Groundwater in Cyprus for 2019-2020" (Adamou, 2022)	Scaled between minimum (0.33) and maximum (1)
Groundwater level	Continuous	Monthly-averaged groundwater levels at 42 locations are provided by Geological Survey.	Scaled between minimum (0.33) and maximum (1)

6. Weighting coefficients assignment

6.1 Criteria weights for intrinsic site suitability mapping

The final weights of the physical criteria were calculated by weight-averaging the computed values both streamflows: the scores from the Boolean matrix multiplied by the standardized distance weight in the ternary diagrams in Streamflow 1 - Table 11, averaged with the weights provided by the stakeholders for each physical criterion in Streamflow 2 - Table 12. To note that the weights in Streamflow 1 were calculated at category level while in Streamflow 2 they are at criteria level. To unify the two scales, the values obtained in one category in Streamflow 1 were assigned to all associated criteria (for simplicity, the calculation in Streamflow 1 was based on the hypothesis that all criteria within one category have the same relevance). For a complete classification of criteria see the AGREEMAR Deliverable D2.1 (Panagiotou et al., 2022).

Table 11. Weighting coefficients for intrinsic categories via Streamflow 1

	Tunisia		Portugal		Spain		Cyprus	
Category	**T1**	**T2**	**P1**	**P2**	**S1**	**S2**	**C1**	**C2**
Aquifer characteristics	0.37	0.27	-	-	-	-	-	-
Groundwater flow characteristics	-	-	0.10	0.16	-	-	0.223	0.149
Aquifer structure and physical boundaries	0.03	0.07	0.04	0.05	-	-	0.007	0.035
Groundwater table	0.27	0.27	0.14	0.12	-	-	0.234	0.232
Geochemistry	-	-	0.14	0.12	0.444	0.218	0.234	0.232
Geomorphology	0.07	0.13	0.12	0.09	0.278	0.391	0.022	0.116
Hydrography	0.27	0.27	0.22	0.25	0.278	0.391	0.234	0.232
Land use/ land cover	-	-	0.19	0.17	-	-	-	-
Soil	-	-	0.05	0.04	-	-	-	-

Table 12. Weighting coefficients for intrinsic criteria calculated during Streamflow 2 process

	Tunisia		Portugal		Spain		Cyprus	
Criterion	**T1**	**T2**	**P1**	**P2**	**S1**	**S2**	**C1**	**C2**
Aquifer storage/capacity	-	-	0.104	0.104	-	-	-	-
Specific yield	-	-	0.102	0.102	-	-	0.150	0.050
Aquifer geochemistry	0.13	0.13	0.087	0.087	-	-	0.150	0.160
Hydraulic conductivity	-	-	0.092	0.092	-	-	0.160	0.170
Aquifer geometry	-	-	0.092	0.092	-	-	-	-
Hydrogeology / Lithology	0.13	0.13	0.093	0.093	0.378	0.378	0.100	0.140
Thickness of vadose zone	0.13	0.13	0.086	0.086	-	-	0.160	0.170
Fluctuations of groundwater table	-	-	-	-	-	-	-	-
infiltration capacity of the vadose zone	-	-	0.096	0.096	-	-	-	-
Land slope	0.11	0.11	0.084	0.084	0.310	0.310	0.130	0.140
Drainage density	0.11	0.11	-	-	-	-		
Soil occupation	0.11	0.11	0.084	0.084	0.310	0.310	0.160	0.170
Top-soil texture	0.13	0.13	0.080	0.080	-	-	-	-
Lineament density	0.13	0.13	-	-	-	-	-	-

6.2 Criteria weights for water availability mapping

Weighting coefficients of criteria related to water availability were computed using Streamflow 1 (Table 13) and Streamflow 2 (Table 14) processes using the same procedure as for the intrinsic site suitability analysis.

Table 13. Weighting coefficients for water availability categories via Streamflow 1

Category	Tunisia		Portugal		Spain		Cyprus	
	T1	T2	P1	P2	S1	S2	C1	C2
Hydrometeorology	0.13	0.25	0.18	0.14	-	-	0.027	0.126
Source water quality	-	-	0.41	0.43	0.924	0.806	0.486	0.437
Source water availability	0.88	0.75	0.41	0.43	0.075	0.193	0.486	0.437

Table 14. Weighting coefficients of criteria related to water availability calculated during Streamflow 2 process

Criterion	Tunisia		Portugal		Spain		Cyprus	
	T1	T2	P1	P2	S1	S2	C1	C2
Precipitation	0.17	0.17	0.160	0.160	-	-	-	-
Evapotranspiration	0.15	0.15	0.124	0.124	-	-	0.117	0.166
Direct run-off	0.17	0.17	0.145	0.145	0.347	0.347	-	-
Proximity to contamination sources	-	-	0.141	0.141	-	-	-	-
Quality compliance	-	-	-	-	0.305	0.305	0.294	0.277
Non-conventional water availability	-	-	-	-	0.347	0.347	0.294	0.277
Proximity to non-conventional water sources	0.19	0.19	0.142	0.142	-	-	0.294	0.277
Proximity to dams	0.19	0.19	0.144	0.144	-	-	-	-
Proximity to rivers and streams	-	-	0.144	0.144	-	-	-	-
Water supply connection density	0.15	0.15	-	-	-	-	-	-

6.3 Criteria weights for water demand mapping

Weighting coefficients of criteria related to water demand were determined using streamflow 1 and 2 (Table 15 and Table 16).

Table 15. Weighting coefficients for water demand categories via Streamflow 1

Category	Tunisia		Portugal		Spain		Cyprus	
	T1	T2	P1	P2	S1	S2	C1	C2
Domestic supply	-	-	0.11	0.10	0.116	0.135	0.075	0.109
Agricultural supply	0.70	0.86	0.07	0.06	0.116	0.135	0.075	0.109
Industrial supply	-	-	0.07	0.06	0.116	0.135	0.020	0.057
Geothermal energy	-	-	-	-	-	-	0.102	0.031
Buffering water quality	-	-	0.21	0.24	0.335	0.223	0.211	0.183
Buffering water quantity	-	-	0.21	0.24	0.116	0.135	0.211	0.183
Groundwater dependent ecosystems	0.30	0.14	0.17	0.19	0.116	0.135	0.154	0.133
Land surface stability	-	-	0.06	0.02	-	-	0.126	0.105
Hot springs	-	-	-	-	-	-	0.004	0.016
Leisure and recreation	-	-	0.10	0.09	0.083	0.097	0.024	0.074

Table 16. Weighting coefficients of criteria related to water demand calculated during Streamflows 2 process

Criterion	Tunisia		Portugal		Spain		Cyprus	
	T1	T2	P1	P2	S1	S2	C1	C2
Crop pattern	-	-	0.100	0.100	-	-	-	-
Annual growth/decline rate of agricultural supply	0.70	0.86	0.103	0.103	-	-	-	-
Deficit of crop water needs	-	-	-	-	-	-	1.00	-
Consumption per unit area for domestic supply	-	-	0.109	0.109	-	-	-	-
Consumption per unit area for agricultural supply	-	-	0.103	0.103	-	-	-	-
Consumption per unit area for industrial supply	-	-	0.092	0.092	-	-	-	-
Rate of aquifer salinization	-	-	-	-	-	-	-	0.50
Chemical status	-	-	0.094	0.094	-	-	-	-

Criterion	Tunisia		Portugal		Spain		Cyprus	
	T1	T2	P1	P2	S1	S2	C1	C2
Natural groundwater recharge rate	-	-	0.108	0.108	-	-	-	-
Natural groundwater recharge expected decrease	-	-	0.108	0.108	-	-	-	-
Decrease in groundwater levels	-	-	0.105	0.105	-	-	-	0.50
Groundwater dependent ecosystems	0.30	0.14	0.078	0.078	-	-	-	-
Water demand	-	-	-	-	1.00	1.00	-	-

6.4 Final weighting coefficients

The final weights of the physical criteria were calculated by weight-averaging the already computed weights obtained from Streamflow 1 with the weights provided by the stakeholders for each physical criterion in Streamflow 2 (Table 17).

The values in each physical category are summed to provide the weighted value that represents the overall effect/weight/impact of a non-georeferenced parameter in a map. This weight is multiplied by the standardized set of selected physical criteria. This process will provide different results for each MAR typology.

Table 17. Weighting coefficients of physical criteria of all thematic layers resulting from Streamflows 1 and 2

Criterion	Tunisia		Portugal		Spain		Cyprus	
	T1	T2	P1	P2	S1	S2	C1	C2
Intrinsic site suitability								
Aquifer storage/capacity	-	-	0.060	0.063	-	-	-	-
Specific yield	-	-	0.059	0.062	-	-	0.09	0.03
Aquifer geochemistry	0.18	0.15	0.051	0.053	-	-	0.09	0.09
Hydraulic conductivity			0.054	0.056	-	-	0.25	0.18
Aquifer geometry			0.076	0.086	-	-		
Hydrogeology / Lithology	0.09	0.09	0.077	0.087	0.10	0.10	0.07	0.09
Thickness of vadose zone	0.16	0.15	0.134	0.123	-	-	0.26	0.23
infiltration capacity of the vadose zone	-	-	0.140	0.130	-	-	-	-
Land slope	0.09	0.10	0.121	0.106	0.45	0.45	0.11	0.15
Drainage density	0.14	0.13	-	-	-	-	-	-
Soil occupation	0.11	0.13	0.158	0.155	0.45	0.45	0.13	0.19
Top-soil texture	0.12	0.13	0.070	0.079	-	-	-	-
Lineament density	0.12	0.13	-	-	-	-	-	-
Water availability								
Precipitation	0.14	0.16	0.109	0.093	-	-	-	-
Evapotranspiration	0.12	0.15	0.098	0.082	-	-	0.06	0.12
Direct run-off	0.13	0.16	0.104	0.088	0.13	0.13	-	-
Proximity to contamination sources	-	-	0.171	0.183	-	-	-	-
Quality compliance	-	-	-	-	0.69	0.62	0.31	0.29
Non-conventional water availability	-	-	-	-	0.18	0.25	0.31	0.29
Proximity to non-conventional water sources	0.31	0.28	0.172	0.184	-	-	0.31	0.29
Proximity to dams	0.31	0.28	0.173	0.185	-	-	-	-
Proximity to rivers and streams	-	-	0.173	0.185	-	-	-	-
Water supply connection density	0.29	0.25	-	-	-	-	-	-
Water demand								
Non-satisfied domestic demand	-	-	0.089	0.083	-	-	-	-
Annual growth rate of domestic water supply	-	-	-	-	-	-	-	-
Agricultural supply	0.71	0.84	-	-	-	-	-	-
Crop pattern	-	-	0.072	0.064	-	-	-	-
Annual growth/decline rate of agricultural supply	-	-	0.073	0.065	-	-	-	-
Deficit of crop water needs	-	-	-	-	-	-	1.00	-
Consumption per unit area	-	-	0.073	0.065	-	-	-	-
Consumption per unit area for industrial supply	-	-	0.069	0.061	-	-	-	-
Rate of aquifer salinization	-	-	-	-	-	-	-	0.50
Chemical status	-	-	0.125	0.134	-	-	-	-

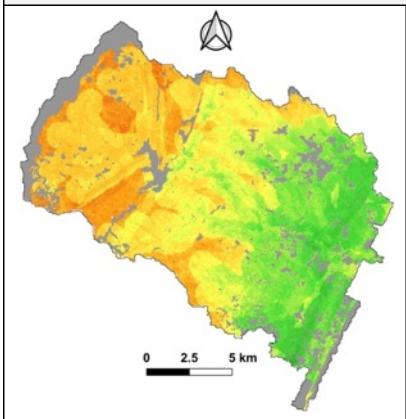
Criterion	Tunisia		Portugal		Spain		Cyprus	
	T1	T2	P1	P2	S1	S2	C1	C2
Natural groundwater recharge rate	-	-	0.132	0.139	-	-	-	-
Natural groundwater recharge expected decrease	-	-	0.132	0.139	-	-	-	-
Decrease in groundwater levels	-	-	0.130	0.139	-	-	-	0.50
Groundwater dependent ecosystems	0.29	0.16	0.105	0.110	-	-	-	-
Water demand for agricultural sector	-	-	-	-	1.00	1.00	-	-

7. Compilation of MAR suitability maps

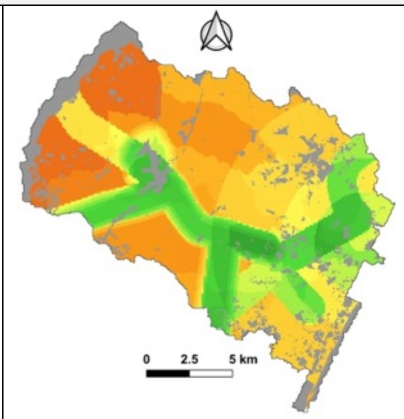
7.1 Results of MAR suitability mapping

Reliable, high-resolution maps of the different criteria are combined through robust decision-making processes to map the suitability of selected MAR typologies in all demo regions. Remote sensing as well as digitization of analogue data were used to acquire recent and accurate data sets and the results are presented in Figure 6 for each MAR typology and thematic level. The description of each MAR typology is given in Table 3.

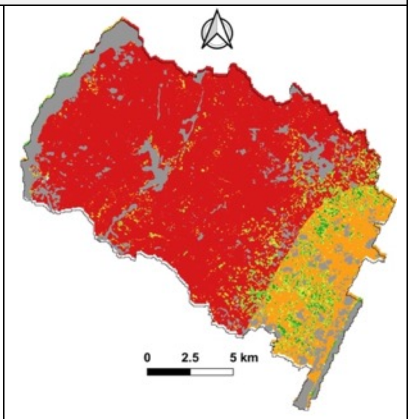
Tunisia



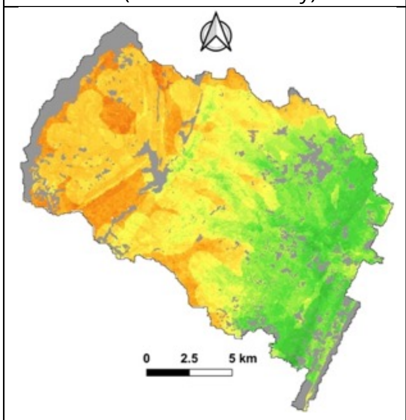
T1 (Intrinsic suitability)



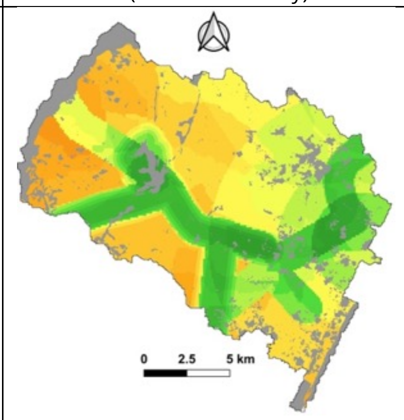
T1 (water availability)



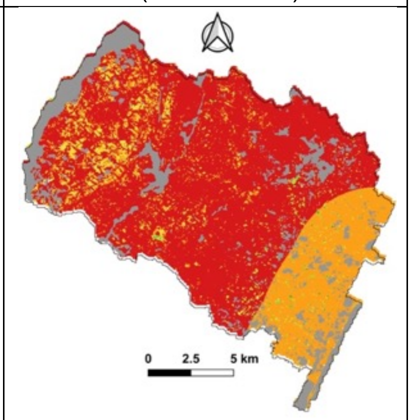
T1 (water demand)



T2 (Intrinsic suitability)

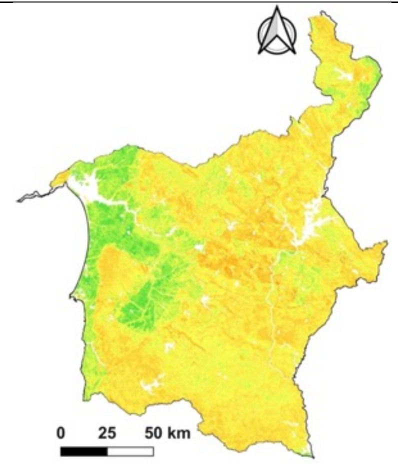


T2 (water availability)

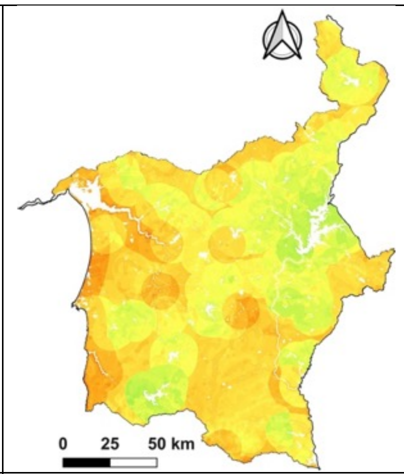


T2 (water demand)

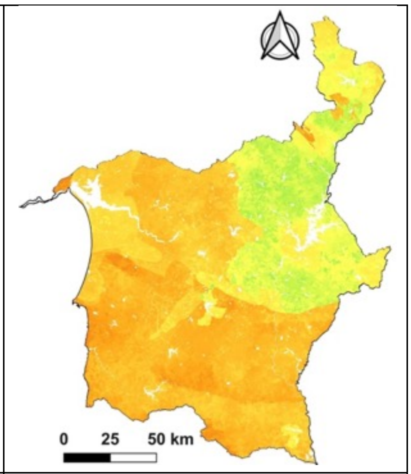
Portugal



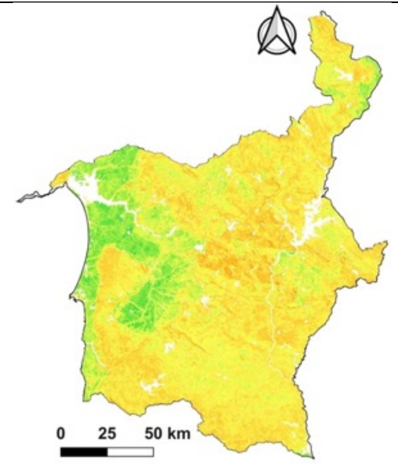
P1 (Intrinsic suitability)



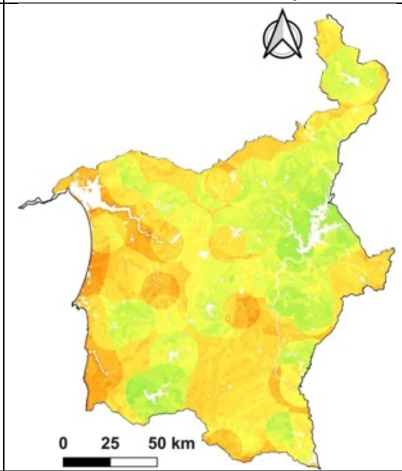
P1 (water availability)



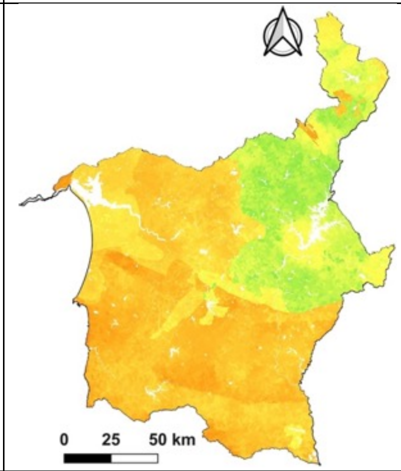
P1 (water demand)



P2 (Intrinsic suitability)

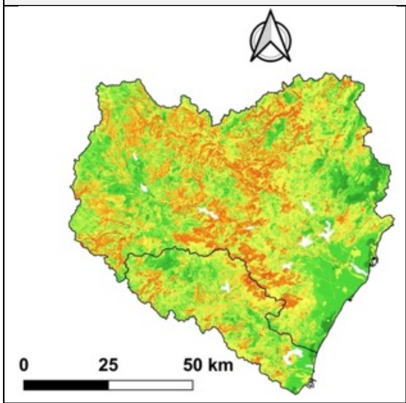


P2 (water availability)

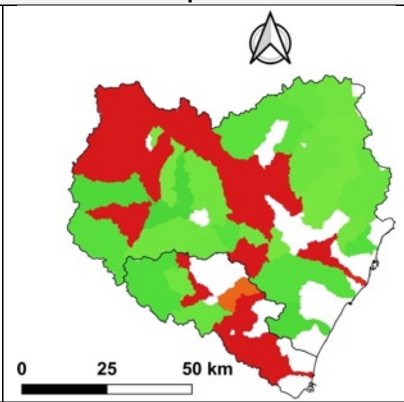


P2 (water demand)

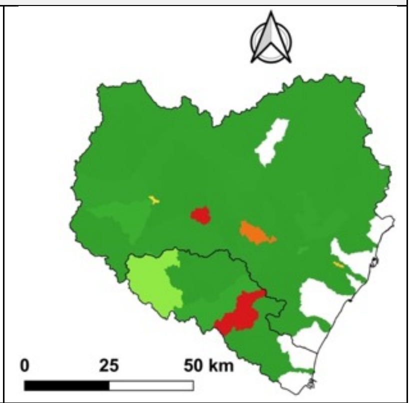
Spain



S1 (Intrinsic suitability)



S1 (water availability)



S1 (water demand)

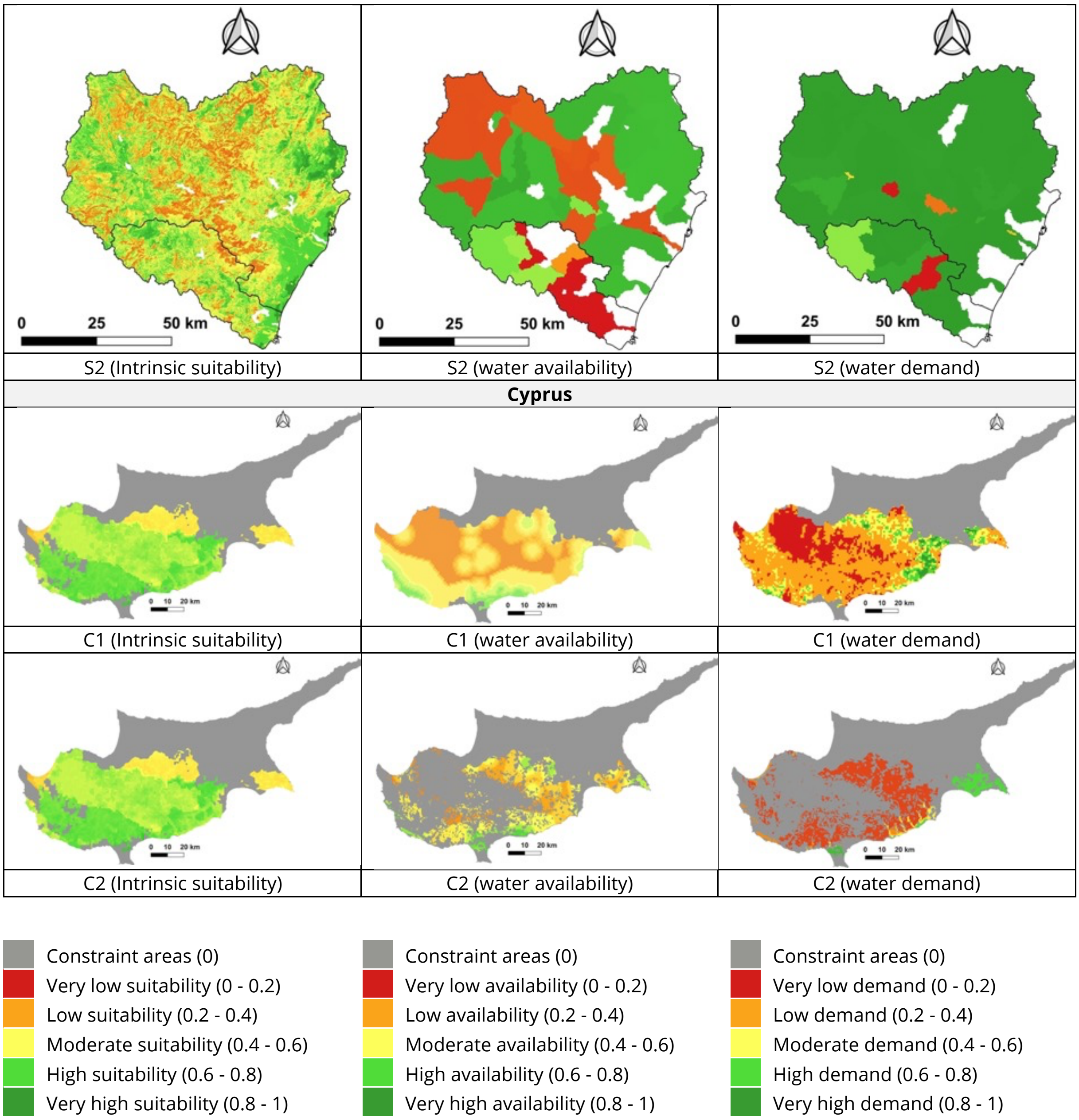


Figure 6. Suitability maps of the three physical thematic layers for each MAR typology

7.2 Stakeholder-based validation of MAR suitability maps

7.2.1 Maps validation by key stakeholders in Tunisia

For the Tunisian demo region, suitability mapping for each thematic layer was carried out in a way to highlight the strong climate seasonality in the Tunisian demo region (dry and wet seasons). On 13 July 2023, a validation workshop at the premises of the Department of Rural Engineering Water and Forests, Agronomic National Institute of Tunisia (INAT) provided the opportunity to interact with the stakeholders from national, regional, and local levels who generally agreed about the methodology and the obtained suitability maps.

7.2.2 Maps validation by key stakeholders in Portugal

The meeting with the main stakeholder (APA Alentejo) was conducted on 27 July 2023. The stakeholder validated the implemented methodology and accepted the weights used for the preparation of the maps. The presented results for each thematic were generally accepted by the stakeholder who envisages this information as another layer to help decision-making. Some modifications were suggested, particularly for the definitions of classes for the continuous scale of 0 to 1 of the Feasibility Index (e.g., 0 – 0.2 for Very low feasibility, etc.). The discussion that followed allowed for the verification and validation of some of the pre-established expectations for the thematic maps. One example is that the more suitable areas are strongly related with geologically suitable areas such as Bacia do Tejo-Sado and Orla Ocidental hydrogeological units (thick sedimentary structures). The computed thematic weights weren't also a surprise, reinforcing the premise that for MAR the intrinsic suitability plays the most relevant role in the detection of adequate implementation areas.

7.2.3 Maps validation by key stakeholders in Spain

The suitability maps for the Spanish demo region were generated to emphasize MAR typologies, which include restoring groundwater levels, replacing overdraft, and creating barriers to prevent saltwater intrusion. These maps were presented during the training course on "Conjunctive Management of Surface and Groundwater in the Mediterranean," held by the Júcar River Basin Agency on 17-19 May 2023. The presentation covered the suitability maps and other project advancements. Nevertheless, the validation workshop involving stakeholders is still pending at the time when this report was submitted.

7.2.4 Maps validation by key stakeholders in Cyprus

The outcomes of the multi-criteria decision analysis, along with the assumptions/limitations applied to derive the feasibility maps, were discussed with the key stakeholders, particularly members of the Geological Survey and Water Development Department, on 30 August 2023. A step-by-step description of the proposed methodology, the classification of the physical criteria for each thematic layers and associated where discussed in order to validate them. Subsequently, the resulting suitability maps were presented, which were generally accepted by the stakeholders. There different scenarios were also considered, particularly:

- Scenario 1: The qualitative status of all assessed urban WWTPs (Limassol, Paphos, Larnaca, Anthoupoli, Vathia Gonia SAL, Ayia Napa & Paralimni) changed to good status (class = 1.00). For the given MAR typology, this could be achieved, for example, by additional treatment of the wastewater effluent before it enters the infiltration basin.
- Scenario 2: A projection of wastewater quantities for the year 2050 is used for the criterion 'available wastewater volumes for MAR'. The projection is based on information provided by the Limassol Water Development Department, which assumes a 5% annual increase in discharges from the WWTP, which is applied to the available effluent volumes for MAR of all WWTPs in the demo region for this scenario.
- Scenario 3: Combination of Scenarios 1 and 2.

In addition, the Cypriot team present a number of modifications/improvements which are expected to be applied to the feasibility mapping, which were further elaborated and eventually validated by the stakeholders. It was agreed to meet again during the forthcoming months to present the updated maps in a wider audience that will involve members from additional sectors of the Water Development Department.

7.3. Final weighting coefficients for each thematic layer

The MAR Feasibility Index is the weighted sum of the suitability index of every thematic (intrinsic site suitability, water availability and water demand). Therefore, determination of weight coefficients of these thematics is a crucial step of MAR feasibility mapping. In accordance with the participatory approach of AGREEMAR project, the present step should be performed through the involvement of stakeholders of every demo region.

7.3.1 Country-specific approach for stakeholders' involvement

In Tunisia, the validation workshop held on 13 July 2023 at INAT was an occasion to determine the weight coefficients of the three thematics. In fact, attendees from INAT team together with representatives of key stakeholders performed an exercise of pairwise comparison matrix which was useful to compute the final weights of each thematic (Figure 7).

	Intrinsic site suitability	Water availability	Water demand	Weigh	STD±
Intrinsic site suitability	1	1/2	1/2	19.58%	4.5%
Water availability	2	1	2	49.34%	11.3%
Water demand	2	1/2	1	31.08%	7.1%

Consistency Ratio = 5.6 %

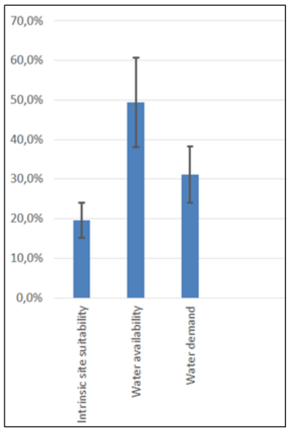


Figure 7. Weights calculated using the pairwise comparison matrix during the validation workshop at INAT, Tunisia

In Portugal, through the stakeholder/specialist questionnaires, the participants were asked to select the most important thematic to be considered in the computation of a feasibility index. The thematic weight as extracted from the percentage of total answers that were given to each thematic (Figure 8).

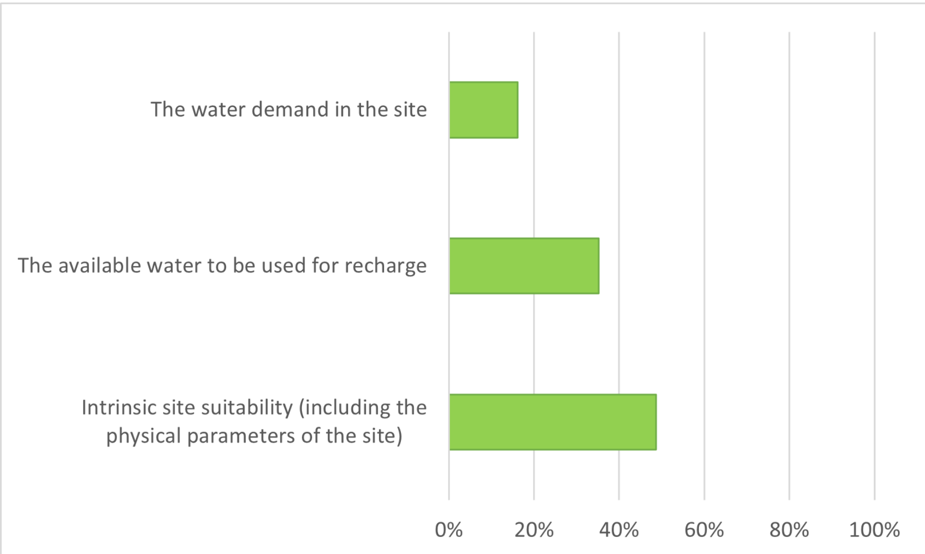


Figure 8. Percentage of total answers from the stakeholder's questionnaire by thematic for Portugal

In Spain, the allocation of weighting coefficients to the thematic layers followed a uniform distribution, meaning equal importance for each layer, assigned a value of 0.33. In the end, the maps were produced and will be presented to stakeholders for consultation. Based on this collaborative process, the weighting coefficients could be refined on the basis of collective reflection.

In Cyprus, the weighting coefficients of the thematic layers were determined by the Cypriot project partners and accepted by the stakeholders. Due to the disparity of the number of criteria at each thematic layer, the intrinsic suitability layer was assigned the highest weight (0.5), followed by water availability (0.3) and the water demand (0.2). Each participant was requested to suggest a suitable combination of weighting coefficient in terms of the MAR typologies. Their responses suggested that, instead of using the averaged values for each coefficient based on the survey, it is preferable to conduct a sensitivity analysis in terms of the suitability weighting coefficients and assign a scenario at each pair of these coefficients. Similar to the Tunisian case, these scenarios can be associated with the pillars of the Integrated Water Resources Management. For example, adaptation of high weighting scores on the intrinsic component indicates a bias towards the environmental aspects. Future work involves the incorporation of the feedback provided by the stakeholders to further improve the produced maps, which, according to the stakeholders, are expected to be used in future revising/improvements of water management policies. It was also pointed out that the intrinsic suitability map can be used to assist the authorities to identify suitable areas for intentional recharge of natural water sources (rivers), which can be very useful for the rural communities located at mountainous territories.

7.3.2 Final weighting coefficients

Table 18 presents a wrap-up of the weighting coefficients for thematic layers of the project demo sites. While in Tunisia water availability is dominantly controlling the MAR feasibility, intrinsic site suitability is the most important thematic to be considered in the Portuguese and Cypriot demo regions.

Table 18. Weighting coefficients for thematic layers

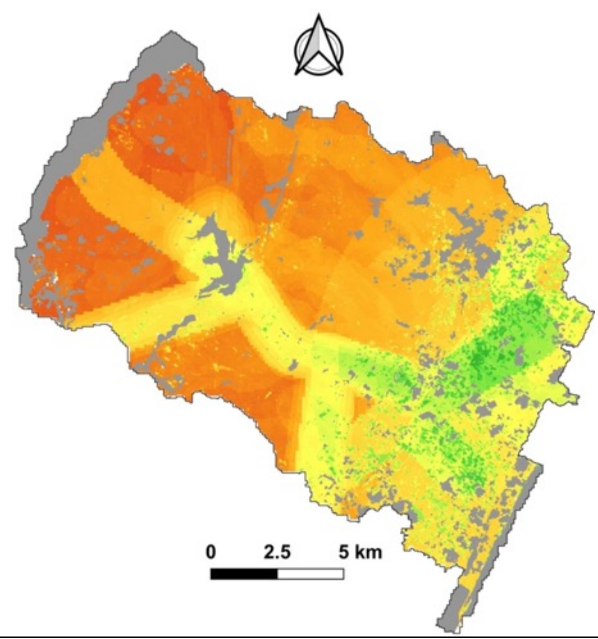
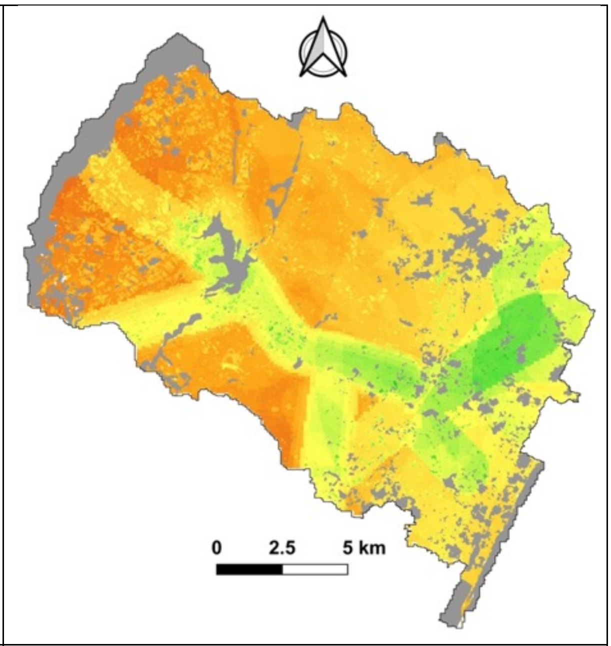
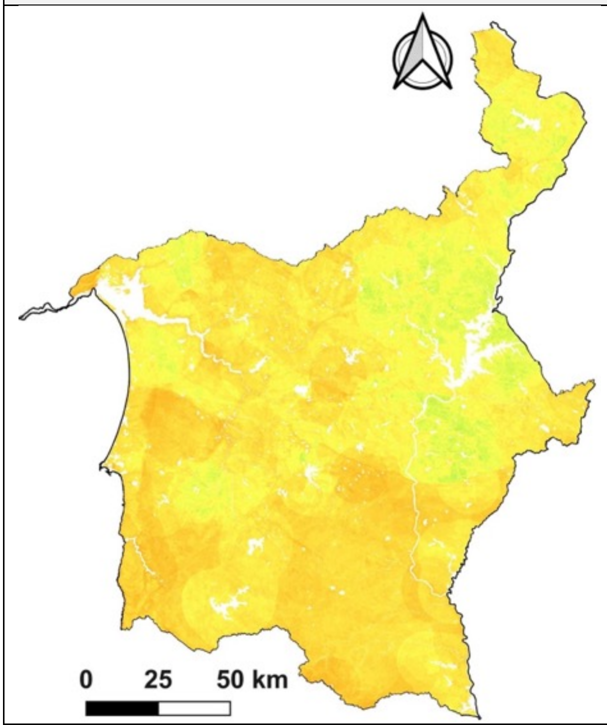
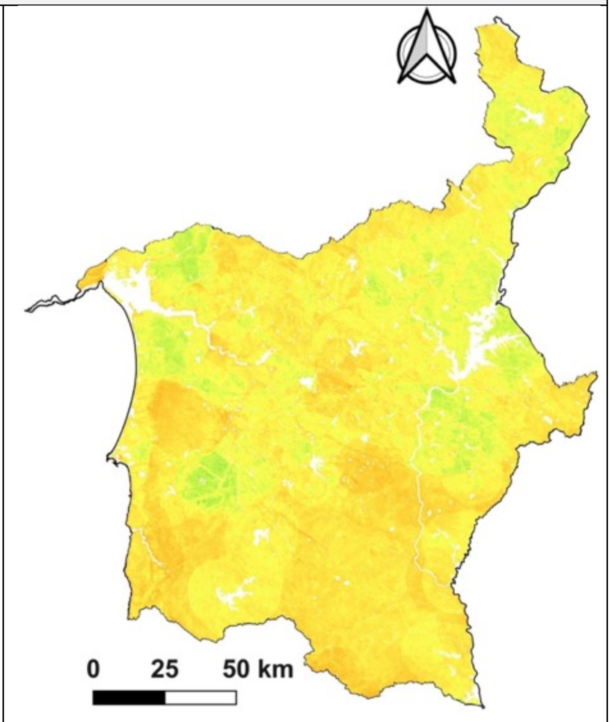
	Tunisia		Portugal		Spain		Cyprus	
Thematic map	**T1**	**T2**	**P1**	**P2**	**S1**	**S2**	**C1**	**C2**
Intrinsic site suitability	0.19		0.49		0.33		0.5	
Water availability	0.49		0.35		0.33		0.3	
Water demand	0.32		0.16		0.33		0.2	

Please note that Table 18 represents a basis for further discussions, allowing the development of future scenarios in each the thematic layers could receive different weighting coefficients. An objective-oriented sensitivity analysis taking into account possible variability in climate and anthropogenic factors shall provide further insights in the potential feasibility of MAR at each demo region. For the purpose of this report, the values presented in Table 18 were used for the compilation of the final feasibility maps for each MAR typology and demo region (see Figure 9).

8. Feasibility mapping for each MAR typology

8.1 Results of feasibility mapping for each MAR typology

MAR feasibility maps are established through the combination of the three thematics of intrinsic site suitability, water availability, and water demand (Figure 9). Weight coefficients are decided in collaboration with the key stakeholders of each demo site. These maps are updatable and following an ongoing process within time frame of AGREEMAR project. In addition to their ability to identify the zones where MAR is feasible, these maps could serve as a negotiation tool with decision makers - together with groundwater and governance models – to convince/help them implement successful MAR projects.

	
T1	T2
Tunisia	
	
P1	P2
Portugal	

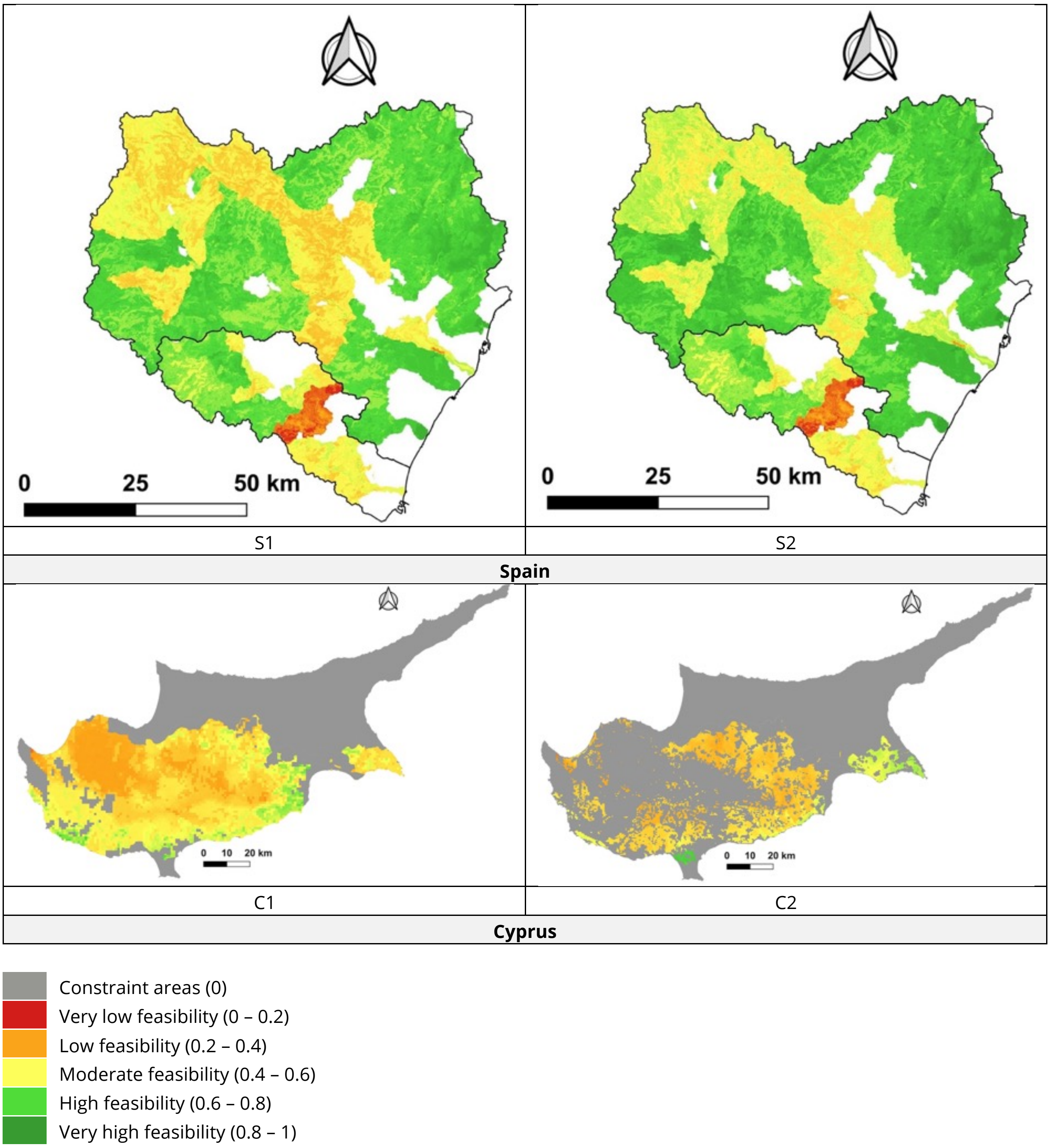


Figure 9. MAR feasibility maps of the demo regions in Tunisia, Portugal, Spain and Cyprus

8.2 Discussion on the MAR feasibility maps at each demo region

8.2.1 Mapping the feasibility of MAR in Chiba watershed, Tunisia

The feasibility map was developed following weighted assessments by stakeholders at the work package 2 results validation workshop, held at INAT on 13 July 2023. Through the use of pairwise matrices, stakeholders chose the scenario prioritizing water availability, as it best corresponds to their preferences and priorities for MAR in Chiba watershed. The obtained weights are as follow: Intrinsic site suitability: 19.6%; Water availability: 49.3%; Water demand 31.1%. The resulting maps are similar for both dry and wet season. Zones where MAR is feasible and highly feasible are basically located near the coastal region where intrinsic site characteristics are mostly suitable, conventional and non-conventional water resources for recharge water are available and agricultural and ecosystem demand are high. The high feasibility areas close to the water supply network reflects the importance of the water availability thematic (weight coefficient ≈ 50%). Low feasibility zones are located in the upstream part of the watershed where the intrinsic characteristics are unsuitable (e.g., slope is exceeding 20°) and recharge water is rare. Considering the MAR objectives/typology of Chiba watershed, the most relevant MAR scheme could be infiltration basins and SAT near the coastal region to mitigate seawater intrusion using treated wastewater from Korba WWTP. However, in the dam region, water release and check dams can be efficiently used to long term storage of groundwater. The existing dug wells in the public irrigated perimeters could constitute a MAR scheme based on injection wells concept. A special document summarizing the MAR feasibility mapping method and containing the obtained maps will be written in French and Arabic and will be shared with the key stakeholders. The results of work package 2 will be an important step towards signing the adaptive agreements to share the benefits of MAR in Chiba basin and convincing decision makers to implement consequent MAR projects.

8.2.2 MAR feasibility map of Algarve and Alentejo regions in Portugal

A final meeting is to be conducted in October, to present the results to all the APA Alentejo team and discuss on how to implement the maps in the day-to-day decision-making process. At this stage, and after the validation meeting, this stakeholder is aware of the limitations of the final maps, mainly related with the observation that at this regional scale the generated maps do not allow for a clear selection of a specific MAR scheme. On the other hand, the map outcomes do not exclude any of the methodologies, and primarily identify the areas for which MAR may prove as a promising complementary water management method. The stakeholder is aware these maps do not replace carrying out a detailed environmental impact study on a local scale for MAR to be authorized. In a broader scale, the detection of feasible MAR areas may provide a basis for possible improvement of water resources management policies and ease MAR implementation.

It is also relevant to point out for the Portuguese demo region that although a single final feasibility map was produced and seasonality was not integrated through any criteria (e.g., wet season/dry season), there was an identification of the areas which are prone to water scarcity by comparing reference scenarios with future expected scenarios with underlying decrease of precipitation and increase of evapotranspiration related to increased average temperatures. This provides to the computed feasibility index some temporal properties by allowing to characterize water availability and demand in terms of probable expected increase/decrease (see, for example, annual growth/decline rate of agricultural supply criteria).

In the near future it is expected that the methodology may be implemented in all of the Algarve administrative region (as only the Guadiana river watershed that covers the eastern part of the Algarve is included at this stage), once the necessary data is made publicly available. The stakeholder is aware that these maps are not definitive and they can be updated and expanded.

8.2.3 Feasibility map for MAR in the demo regions in Spain

As the meeting with stakeholders to determine the appropriate weights for each suitability map is pending, for the creation of feasibility maps in the Spanish demo region, equal weights have been temporarily assigned to the three suitability maps. Once the stakeholder meeting takes place and the consensus on the weight distribution is reached, the feasibility maps will be updated accordingly to reflect the most accurate and informed representation of the MAR potential in the region.

The feasibility maps were established using equal weighted scores, assigning 33% weight to each thematic layer. These resulting maps exhibit similarity for both MAR objectives: objective 1 involves groundwater level restoration and overdraft replacement, while objective 2 focuses on creating barriers to prevent saltwater intrusion. However, it's worth noting that the map corresponding to objective 1 showcases more regions of low feasibility compared to the map for objective 2. In particular, the Belcaire pond area, being an operational MAR infrastructure, stands out with the most favorable feasibility scores. Conversely, the Algar reservoir region exhibits moderate to low MAR feasibility. These feasibility maps hold significant value in assessing the effectiveness of existing MAR infrastructure within the demo region, while also facilitating the identification of potential new MAR sites in the region. Both the central portion of the Mijares river basin and the eastern segment of the Palancia river basin indicate low to moderate feasibility, primarily due to low water availability and unsuitable intrinsic criteria for MAR. These insights suggest that aquifers in these regions might not present the optimal sites to benefit from MAR, highlighting the necessity for guidance on strategies for aquifer exploitation.

The outcomes of work package 2 will significantly contribute to enhancing comprehension and fostering informed discussions regarding MAR implementation within the studied region. These findings pave the way for initiating work on adaptive agreements to equitably distribute benefits and persuading decision makers to undertake subsequent MAR projects.

8.2.4 Feasibility map for MAR in the Republic of Cyprus

For both MAR typologies considered for the Cypriot case site, the highest feasibility scores are observed around the areas where MAR systems are already operating, particularly Akrotiri (Limassol) and Ezousa (Paphos). High suitability in terms of water availability is observed at both locations partly due to the fact that their urban WWTPs release the largest volumes of treated effluent in the entire demo region, accompanied with an existing pipeline network that facilitates the accessibility of the source water to the surrounding areas.

Both the north-western and eastern parts of the demo region exhibit moderate to low or very low feasibility for MAR implementation, mainly attributed to low intrinsic suitability scores. In particular, decisive for this outcome seems to be the low intrinsic suitability of the underlying aquifers which are located in Kiokkinochoria, Androlikoi Limestone and Khrysokou due to their poor geochemical status and permeability due to low values of hydraulic conductivity. The aquifers located in the north-western part exhibit very low groundwater depths. In addition, the central part of the island is characterized by very low feasibility, mainly due to the presence of high terrain slopes, presence of forested areas (LULC criterion) and low suitability of the vadose zone. More discussions and refinements are expected to be performed during the forthcoming meetings that will take place with the stakeholders before the end of this year.

8.3 General comparison between countries and typologies

- The project aimed to develop and test a common MAR feasibility methodology at different regions and scales in the Mediterranean region. Concerning scales, which differ, Cyprus and Portugal conducted feasibility mapping at regional scale, which included multiple hydrographic regions, while Tunisia and Spain assembled the maps at watershed scale.
- Differences aside, a particular effort was conducted in the standardization and classification methods. This ultimately resulted in a common classification scale set of maps which are strongly comparable between themselves. This resulted, as expected, in situations where it is possible to observe the effects of intrinsic site suitability in the final maps – low suitability areas result essentially in low feasibility.
- From the interaction with the stakeholders some interesting contrasts were detected. While in Cyprus and Portugal the highest thematic weight is given for the intrinsic site suitability, in Tunisia the most relevant thematic is found to be water availability. This reflects the main water-related problems in each region and encompasses the different stakeholders' concerns across the geographic zones covered.
- On the other hand, the main problems to be addressed by making use of MAR typologies are essentially connected with two problems: to mitigate overexploitation and increase storage while improving or protecting groundwater quality. This essentially reflects the importance of groundwater resource as strategic reserve that may be one of the main sources under water stress situations which are expected to become recurrent in the Mediterranean area in the very near future.

9. Summary and conclusions

The MAR feasibility maps presented in this report are the main deliverables of the work package 2. They serve as support for decision-making in the project demo regions regarding the potential implementation of new MAR projects or expansion of existing groundwater recharge schemes. The feasibility maps represent also the basis for the next important task in the project, which is the assessment of MAR impact on local groundwater systems using numerical flow models developed for areas deemed as feasible for MAR implementation. The robustness and applicability of the methodology developed by AGREEMAR for regions under different environmental, social and economic conditions across multiple geographic scales has been demonstrated by this study with some of the most relevant lessons learned being presented in the next sections.

9.1 Mapping the feasibility of different MAR typologies

This deliverable provides a step-by-step description on the implementation of a stakeholder-adapted methodology for assessing the site feasibility for MAR implementation at four demo regions located in Tunisia, Portugal, Spain and Cyprus. To demonstrate the general applicability of the proposed approach, the selected regions differ in terms of scale, water source, recharge technique and MAR objective, leading to a total number of eight MAR typologies (two from each country). Moreover, the effect of climate seasonality was also considered, with strong implications in the assessment of cross-sectorial water demand and the availability of water for infiltration. For the multi-criteria decision analysis, a different number of feasibility criteria were used, reflecting the regional needs, scope and data availability: Spain – 7 criteria, Cyprus – 12, Tunisia – 16, and Portugal – 29. Nevertheless, the main steps of the mapping process were identical for all eights typologies, providing for good consistency of the results. The final feasibility maps indicate slight differences in the percentage of different feasibility classes, validating the assumption that the feasibility of an area for MAR implementation depends on the technical and non-technical characteristics of the MAR scheme, supporting the hypothesis that MAR typologies are crucial for the applicability of MAR feasibility mapping.

9.2 Continuous stakeholders' engagement

Each step of the implementation process enabled the engagement of key stakeholders to ensure that the scientific outcomes will reflect their actual needs. A comprehensive needs assessment campaign has been conducted at all four demo regions right after the start of the project, enabling the identification of key stakeholders at national, regional and local level and a very good understanding of their needs and responsibilities in the water management sector (see also the AGREEMAR Deliverable "D1.1a Preliminary analysis of project relevant stakeholders" and Deliverable "D1.1 Stakeholders engagement strategy and plan": https://agreemar.inowas.com/deliverables/). Within work package 2, continuous interaction between the project team and governmental authorities was achieved by organizing joint activities, such as bilateral meetings, daily workshops, and personal communications (see short reports of these activities on the News section of the project website: https://agreemar.inowas.com/news/). As a result, the stakeholders were informed, consulted, and involved in the development of the feasibility maps, while a close collaboration was achieved with at least one key stakeholder from each demo region. The involvement started with the joint definition of MAR objectives, identification of potential water sources and recharge techniques, and continued with the refinement of the MAR typologies according to stakeholders' needs and interests, data collection and analysis, and consultations for the compilation of the feasibility maps and validation and acceptance of the overall outcomes.

9.3 Strengths and potential limitations

During the time frame of this deliverable, a number of strengths and weaknesses of the proposed methodology have been identified, particularly:

9.3.1 Strengths

- Stakeholders' participation in each stage of the implementation process ensured the validity of the suitability maps.
- The general applicability of the method has been demonstrated in four different regions that differ in terms of scales, water source and MAR objective, within different eco-regions, hydrogeological contexts, and socioeconomic conditions.
- The MAR feasibility maps are important project deliverables that are easy to understand and ready-to-use tools supporting the decision-making processes in different countries of the Mediterranean basin and beyond.

- The methodology used is coherent and consistent with both the scientific state-of-the-art and the societal needs, successfully integrating expert-based knowledge with contributions from key stakeholders across different scales.
- The general acceptance of the resulting maps is expected to facilitate the discussions between the AGREEMAR team and the local stakeholders for achieving their inclusion in water management policies. The feasibility maps can be used to identify small-scale regions suitable for intentional recharge, which can be further analyzed with the development of numerical transient models of groundwater transport.
- It is possible to conclude that the presented methodology can be used in different regions of the Mediterranean basin. This opens the possibility of expanding the scale of the implementation, from watershed to hydrographic region, considering as side-effect the potentially coarser outcomes due to changes in resolutions and data availability.

9.3.2 Limitations

- Selecting a proper combination of criteria is not a trivial task. Small number of criteria can lead to the generation of maps that lack important information relevant to the MAR objective, whereas very high number of criteria can mitigate the impact of the important information due to the "dilution effect" resulted from the potentially low weighting coefficients.
- Data availability differs between regions, whereas different regulations are adopted by the non-European partner (Tunisia) compared to the European partners (e.g., the information concerning water quantity and quality). Some expected challenges were encountered while collecting and data, particularly in the larger study regions which resulted in some cases in compatibilization problems or total lack of data. Some data simplifications were introduced and, in some cases, after internal discussion some criteria were dropped.
- Sensitivity analysis is required to assess the impact of each criterion on the resulting maps, and in order to quantify the uncertainty of the outcomes.
- Some regions considered are rather large and the scale of the maps allow only for regional analysis. The local impact of MAR cannot be represented properly only in combination of more detailed, local studies (geophysical investigations, field tests, numerical modelling etc.).
- Although the results are considered acceptable and validated, the robustness of the generated maps can be tested through a sensitivity analysis – meaning that by changing the criteria and thematic weights new maps should provide very similar results. This was not within the scope of this deliverable but some future work should be conducted on this subject.

9.4 Conclusions

The results presented in this report are obtained using a comprehensive methodology that integrates expert-based knowledge and stakeholders' participation. The final feasibility maps were validated by the representative stakeholders and will be used in the project for the identification of areas where numerical groundwater flow models will be constructed. However, the methodology allows for a more detailed analysis at different scales by adapting the Boolean tables, changing the coordinates of the SE-EE-ES triangles or the specific thematic weights. Thus, they represent a very powerful yet easy-to-use tool for assessing the site feasibility for MAR under variable conditions such as climatic changes, demographic dynamics, land use seasonality and many others.

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Annexes

A1. Boolean matrices for all MAR typologies

Tunisia

Thematic	Category	Criteria	Legal constraints	Trans-border issues/agreements	Culture, religion, education	Health	Costs	Accessibility and communications
Intrinsic site suitability	Aquifer characteristics	Aquifer geochemistry	1	1	0	1	1	0
	Aquifer structure and physical boundaries	Aquifer lithology	0	0	0	0	1	0
	Groundwater table	Thickness of vadose zone	1	1	0	0	1	1
	Geomorphology	Land slope	0	0	0	0	1	1
	Hydrography	Drainage density (abundance of rivers and streams)	1	1	0	0	1	1
	Land use / Land cover	Land surface area	1	0	0	0	1	1
	Soil	Top-soil texture	1	0	0	0	1	1
		Lineament density	1	0	0	0	1	1
Water availability	Hydrometeorology	Precipitation	0	0	0	0	1	1
		Evapotranspiration	0	0	0	0	1	1
		Direct run-off	0	0	0	0	1	1
	Source water quality	Proximity to origin of water sources (incl. conventional and non-conventional)	1	1	1	1	1	1
		Water supply connection density	1	1	1	1	1	1
Water demand	Provisioning needs	Agricultural supply	1	1	1	1	1	1
		Groundwater dependent ecosystems	0	1	1	0	0	0

Portugal

Thematic	Topic	Category	Legal constrains	Transborder issues/agreements	Culture/religion/education	Health	Costs	Accessibility and communications
Intrinsic suitability	Aquifer vadose zone	Aquifer characteristics	0	0	0	0	0	0
	Aquifer vadose zone	Groundwater flow characteristics	1	1	0	0	0	0
	Aquifer vadose zone	Aquifer structure and physical boundaries	0	0	0	0	1	0
	Aquifer vadose zone	Groundwater table	1	0	0	0	1	1
	Aquifer vadose zone	Geochemistry	1	0	0	0	1	1
	Surface	Geomorphology	0	0	0	0	1	1
	Surface	Hydrography	1	1	0	0	1	1
	Surface	Land use/land cover	1	0	0	1	1	1
	Surface	Soil	0	0	0	0	1	0
Water availability	Climatic context	Hydrometeorology	0	0	0	0	1	1
	Source water	Source water quality	1	1	0	1	1	1
	Source water	Source water availability	1	1	0	1	1	1
Water demand	Provisioning needs	Domestic supply	1	0	0	1	0	1
	Provisioning needs	Agricultural supply	1	0	0	0	0	1
	Provisioning needs	Industrial supply	1	0	0	0	0	1
	Provisioning needs	Geothermal energy	0	0	0	0	0	0
	Regulatory needs	Buffering water quality	1	0	1	1	1	1
	Regulatory needs	Buffering water quantity	1	0	1	1	1	1
	Supporting needs	Groundwater dependent ecosystems	1	0	1	0	1	1
	Supporting needs	Land surface stability	0	0	0	0	0	1
	Cultural needs	Hot springs	0	0	0	0	0	0
	Cultural needs	Leisure and recreation	1	0	0	0	1	1

Spain

Thematic	Category	Legal constraints	Transborder issues/agreements	Culture/religion/education	Health	Costs	Accessibility and communications
Intrinsic suitability	Aquifer characteristics	0	0	0	0	0	0
	Groundwater flow characteristics	0	0	0	0	0	0
	Aquifer structure and physical boundaries	0	0	0	0	0	0
	Groundwater table	0	0	0	0	0	0
	Geochemistry	1	0	0	0	0	0
	Geomorphology	0	0	0	0	0	1
	Hydrography	0	0	0	0	0	1
	Land use Land cover	1	0	0	0	1	1
Water availability	Hydrometeorology	0	0	0	0	0	0
	Source water quality	1	0	1	1	0	1
	Source water availability	1	0	0	0	1	1
Water demand	Domestic supply	1	0	0	0	1	1
	Agricultural supply	1	0	0	0	1	1
	Industrial supply	1	0	0	0	1	1
	Geothermal energy	0	0	0	0	0	0
	Buffering water quality	1	0	1	0	1	1
	Buffering water quantity	1	0	0	0	1	1
	Groundwater dependent ecosystems	1	0	0	0	1	1
	Land surface stability	0	0	0	0	0	0

A2. Values for criteria standardization for all demo regions

	Tunisia		Portugal		Spain		Cyprus	
Criterion	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**
Aquifer storage/ capacity	-	-	**Unsaturated zone thickness (m)**		-	-	-	-
			0 – 1	0.1				
			1 – 5	0.1 – 0.5				
			5 – 20	0.5 – 1				
			20 – 30	1.0				
			30 – 50	1 – 0.3				
			50 – 200	0.3 – 0.1				
			200 – Max.	0.1				
Specific yield	-	-	**Aquifer productivity (-)**		-	-	**Assessment of aquifer productivity including 66 aquifers (%)**	
			highly productive	1.00			0.002 – 6	0.33
			moderately prod.	0.75			6 – 12	0.66
			minimally productive	0.50			12 – 18	1.00
Aquifer geochemistry	**Groundwater salinity (g/L)**		**Cl (mg/l)**		-	-	**Groundwater status (-)**	
	6 – Max	< 0.2	0 – 250	0.1 – 1.0			Bad	0.33
	4.5 – 6	0.2 – 0.4	> 250	1.0			Good	1.00
	3 – 4.5	0.4 – 0.6	**EC (µS/cm)**					
	1.5 – 3	0.6 – 0.8	0 – 2500	0.1 – 1.0				
	Min. – 1.5	0.8 – 1.0	> 2500	1.0				
			NO_3 (mg/l)					
			0 – 50	0.1 – 1				
			> 50	1.0				
Hydraulic conductivity	-	-	**Hydraulic conductivity (m/d)**		-	-	**Hydraulic conductivity (m/d)**	
			< 4.1				2.5 – 4.5	0.33
			4.1 – 12.2	0.5			45.0 – 87.5	0.66
			> 12.2	0.8			87.5 – 130	1.00
				1.0				

	Tunisia		Portugal		Spain		Cyprus	
Criterion	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**
Aquifer geometry	-	-	**Geometry classification**		-	-	-	-
			C1	0.1				
			C2	0.2				
			C3 to C5	0.3				
			C6 to C11	0.4				
			C12	0.5				
			C13 to C14	0.6				
			C15 to C17	0.7				
			C18	0.8				
			C19	1.0				
Hydrogeology /	**Aquifer materials**		**Main lithological groups**		**Aquifer materials**		**Aquifers' classification**	
Lithology	Unfractured / clayey	< 0.2	I, V	0.4	Unfractured / clayey	0.00	Expert classification (GSD) of	0.33
	Sedimentary in clay matrix	0.2 – 0.4	V/M	0.5	Sedimentary in clay matrix	0.25	22 groundwater bodies	0.66
	Permeable sedimentary	0.4 – 0.6	K/M, K/V/S, V/S	0.6	Permeable sedimentary	0.50		1.00
	Fractured / weathered	0.6 – 0.8	K, M, S/V	0.7	Fractured / weathered	0.75		
	Sand and gravel	0.8 – 1.0	K/S, M/K, S/M	0.8	Sand and gravel	1.00		
			M/S, S/K	0.9				
			S	1.0				
Thickness of vadose	**Thickness (m)**		**Thickness (m)**		-	-	**Thickness (m)**	
zone	50 – Max.	< 0.2	< 30 m	1.00			< 5 or > 50	0.33
	40 – 50	0.2 – 0.4	30 m – 50 m	0.75			5 – 7 or 25 – 50	0.66
	30 – 40	0.4 – 0.6	50 m – 100 m	0.50			7 – 25	1.00
	20 – 30	0.6 – 0.8	> 100 m	0.25				
	Min. – 20	0.8 – 1.0						
Infiltration capacity	-	-	**Permeability (-)**		-	-	-	-
of the vadose zone			Low	0.2				
			Low to moderate	0.4				
			Moderate	0.6				
			Moderate to high	0.8				
			High	1.0				
Land slope	**Land slope (°)**		**Land slope (%)**		**Land slope (°)**		**Land slope (%)**	
	20 – Max.	< 0.2	0 – 20	1.0 – 0.1	> 30	0.00	8 – 12	0.33
	10 – 20	0.2 – 0.4	20 – Max.	0.1	10 – 30	0.25	4 – 8	0.66
	5 – 10	0.4 – 0.6			5 – 10	0.50	0 – 4	1.00
	2 – 5	0.6 – 0.8			2 – 5	0.75		
	Min. – 2	0.8 – 1.0			0 – 2	1.00		

Criterion	Tunisia		Portugal		Spain		Cyprus	
	Intervals	**Score**	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**
Drainage density	**Density (km/km^2)**		-	-	-	-	-	-
	Min. – 0.1	< 0.2						
	0.1 – 0.17	0.2 – 0.4						
	0.17 – 0.24	0.4 – 0.6						
	0.24 – 0.32	0.6 – 0.8						
	0.32 – Max.	0.8 – 1.0						
Soil occupation	**Land use / land cover (-)**		**Land use / land cover (-)**		**Land use / land cover (-)**		**Land use / land cover (-)**	
	Artificial area / wetland / water body / bare rock	< 0.2	Class 1	0.0	Artificial area / wetland / water body / bare rock	0.00	Forest, mineral areas	0.33
			Class 2	0.3			Agricultural land	0.66
	Forest	0.2 – 0.4	Class 3	0.4	Forest	0.25	Grassland, woodland-shrub, burnt areas	1.00
	Permanent crop / heterogenous agricultural area	0.4 – 0.6	Class 4	0.5	Permanent crop / heterogenous agricultural area	0.50		
			Class 5	0.6				
	Arable land / pasture		Class 6	0.7	Arable land / pasture			
	Scrub and herbaceous /	0.6 – 0.8	Class 7	0.9	Scrub and herbaceous /	0.75		
	Sparse vegetation	0.8 – 1.0			Sparse vegetation	1.00		
Top-soil texture	**Soil texture**		**Soil texture**		-	-	-	-
	Clay	< 0.2	Coarse	1.00				
	Silty clay	0.2 – 0.4	Medium	0.75				
	Clayey silt	0.4 – 0.6	Fine	0.25				
	Sand – silt	0.6 – 0.8	No soil	0.10				
	Sandy to coarse	0.8 – 1.0						
Lineament density	**Density (km/km^2)**		-	-	-	-	-	-
	Min – 0.5	< 0.2						
	0.5 – 1	0.2 – 0.4						
	1 – 1.5	0.4 – 0.6						
	1.5 – 2	0.6 – 0.8						
	2 – Max.	0.8 – 1.0						
Precipitation	**Precipitation (mm/year)**	< 0.2	**Precipitation (mm/year)**		-	-	-	-
	Min. – 300	0.2 – 0.4	Min. – Max. (mm/yr)	0.1 – 1.0				
	300 – 400	0.4 – 0.6						
	400 – 500	0.6 – 0.8						
	500 – 600	0.8 – 1.0						
	600 – Max. (mm/yr)							

Criterion	Tunisia Intervals	Score	Portugal Intervals	Score	Spain Intervals	Score	Cyprus Intervals	Score
Evapotranspiration	**EVT (mm/year)**		**EVT (mm/year)**		-	-	**EVT (mm/year)**	
	900 – Max.	< 0.2	Min. – Max.	0.1 – 1.0			535 – 765	0.33
	700 – 900	0.2 – 0.4					306 – 535	0.66
	500 – 700	0.4 – 0.6					77 – 306	1.00
	300 – 500	0.6 – 0.8						
	Min. – 300	0.8 – 1.0						
Direct run-off	**Run-off (m^3/year)**		**Run-off (hm^3/year)**		**Run-off (hm^3/year)**		-	-
	Min. – 0.005	< 0.2	Min. – Max.	0.1 – 1	Min. – Max.	0.2 – 1		
	0.005 – 0.01	0.2 – 0.4						
	0.01 – 0.04	0.4 – 0.6						
	0.04 – 0.12	0.6 – 0.8						
	0.12 – Max.	0.8 – 1.0						
Proximity to contamination sources	-	-	**Distance (m)**		-	-	-	-
			< 100	0.00				
			> 100, < 1000	0.25				
			> 1000, < 10 000	0.50				
			> 10 000	1.00				
Quality compliance	-	-	-	-	Poor	0	**Directive 91/271/EC**	
					Good	1		
							Do not satisfy standards of Directive 91/271/EC	0.33
							Satisfy standards of Directive, but not other measured parameters	0.66
							Threshold values are not exceeded for none of the measured parameters	1.0
Non-conventional water availability	-	-	-	-	**Water volume (m^3/year)**		**Water volume (m^3/year)**	
					Min. – Max.	0.2 – 1	10^4-10^5	0.33
							10^5-10^6	0.66
							10^6-10^7	1.00

Criterion	Tunisia		Portugal		Spain		Cyprus	
	Intervals	**Score**	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**
Proximity to origin of water sources (non-conventional)	**Distance (m)** 1000 – Max. 1000 – 800 800 – 600 600 – 400 Min. – 400	 < 0.2 0.2 – 0.4 0.4 – 0.6 0.6 – 0.8 0.8 – 1.0	**(Distance score weighted by source characteristics)** Min. – Max.	 0.1 – 1	-	-	**Distance from WWTP and pipeline network (m)** >5000 [m] from pipeline or >8000 [m] from WWTP <5000 [m] from pipeline or <8000 [m] from WWTP < 1000 [m] from pipeline or <5000 [m] from WWTP	 0.33 0.66 1.00
Proximity to origin of water sources (dam)	**Distance (m)** 1000 – Max. 1000 – 800 800 – 600 600 – 400 Min. – 400	 < 0.2 0.2 – 0.4 0.4 – 0.6 0.6 – 0.8 0.8 – 1.0	**(Distance score weighted by source characteristics)** Min. – Max.	 0.1 – 1	-	-	-	-
Proximity to origin of water sources (rivers and streams)	-	-	**(Distance score weighted by source characteristics)** Min. – Max.	 0.1 – 1	-	-	-	-
Water supply connection density	**Density (km/km^2)** Min. – 0.15 0.15 – 0.2 0.2 – 0.25 0.25 – 0.3 0.3 – Max.	 < 0.2 0.2 – 0.4 0.4 – 0.6 0.6 – 0.8 0.8 – 1.0	-	-	-	-	-	-
Consumption per unit area for domestic supply	-	-	**Water volume (hm^3/yr)** 0 – 10^2	 0.1 – 1	-	-	-	-

	Tunisia		Portugal		Spain		Cyprus	
Criterion	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**
Crop pattern	-	-	**Types of crops**		-	-	-	-
			Class 1	0.10				
			Class 2	0.20				
			Class 3	0.30				
			Class 4	0.40				
			Class 5	0.50				
			Class 6	0.60				
			Class 7	0.70				
			Class 8	0.80				
			Class 9	1.00				
Annual growth / decline rate of agricultural supply	-	-	**Expected increase/ decrease (%)**		-	-	-	-
			0 – 100	0.1 – 1.0				
Crop irrigation water needs	-	-	-	-	-	-	**Crop irrigation water needs (10^3 m^3)**	
							0	0.2
							0-33	0.4
							33-66	0.6
							66-100	0.8
							>100	1.0
Consumption per unit area for agriculture	**Irrigation water supply (mm)**		**Abstracted volumes (hm^3/yr)**		-	-	-	-
			0 – 10^2	0.1 – 1.0				
	Min. – 5	< 0.2						
	5 – 10	0.2 – 0.4						
	10 – 20	0.4 – 0.6						
	20 – 30	0.6 – 0.8						
	30 – Max.	0.8 – 1.0						
Consumption per unit area for industrial supply	-	-	**Abstracted volumes (hm^3/yr)**	0.1 – 1.0	-	-	-	-
			0 – 10^2					
Rate of aquifer salinization	-	-	-	-	-	-	Bad (-)	0.33
							Good (-)	1.00
Chemical status	-	-	Good	0.5	-	-	-	-
			Mediocre	1				
Natural groundwater recharge rate	-	-	Min. – Max.		-	-	-	-
			(mm/year)	0.1 – 1.0				

	Tunisia		Portugal		Spain		Cyprus	
Criterion	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**	**Intervals**	**Score**
Decrease in groundwater levels	-	-	**Groundwater quantity status** Good Mediocre	 0.5 1	-		**Decrease in groundwater levels**	 0.2 – 0.8
Natural groundwater recharge rate expected decrease/increase	-	-	**Expected increase/ decrease (%)** -100% – 100%	 0.1 - 1	-	-	-	-
Groundwater dependent ecosystems	**Distance to wetlands (m)** 1000 – Max. 800 – 1000 800 – 600 600 – 400 Min. – 400	 < 0.2 0.2 – 0.4 0.4 – 0.6 0.6 – 0.8 0.8 – 1.0	**Possibility of occurrence (-)** Yes No	 1.0 0.5	-	-	-	-
Water demand	-	-	-	-	**Water demand (hm^3/year)** Max. – Min.	 0.2 – 1	-	-