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Deliverable #D2.2

Participative methodology for criteria selection and weighting in MAR site feasibility mapping

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AGREEMAR

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

Deliverable #D2.2

Participative methodology for criteria selection and weighting in MAR site feasibility mapping

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Executive summary

Deliverable D2.2 is dedicated to the development of a new methodological approach for mapping the geospatial feasibility of managed aquifer recharge applications. The report focuses on the selection and weighting of feasibility criteria and their integration into a GIS-based multi-criteria decision analysis. The method integrates two workflows centred on expert-based input and active stakeholder participation.

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v0.2	23.11.2022	Anis Chkirbene (INAT)	Contributions to weightning methods
V0.3	24.11.2022	Tiago N. Martins (LNEC)	Structure update and first draft version
v0.4	29.11.2022	Manuel M. Oliveira (LNEC)	Several rounds of revisions and recommendations
v1.0	30.11.2022	Catalin Stefan (TUD)	Chapters 1, 2, 4 and revisions, final version

Abstract

The present report introduces a new methodological approach for mapping the geospatial feasibility of managed aquifer recharge (MAR) applications. The method addresses several limitations of current mapping practices and aims to contribute to reducing the bias associated with them. The concept is based on a multi-criteria decision analysis composed of several steps: problem definition, constraint mapping, criteria selection, standardization of criteria values, weights assignment, feasibility mapping and process validation. The novelty is represented by positioning MAR in the framework of integrated water resources management (IWRM), by pondering several thematic clusters (physical and non-physical feasibility criteria), increasing the importance of problem definition and, most importantly, integrating a participative process with active stakeholders' participation.

The new stakeholder-adapted weighting system includes two methodological workflows that integrate the expert-based input with contributions resulted from interaction with stakeholders. The first branch establishes the connection between physical and non-physical criteria and is based on the expertise of AGREEMAR consortium and external experts. In the second branch, the information provided by stakeholders and their perception for MAR is collected and converted into criteria weights. Merging the two branches leads to a final set of weighted criteria that can be used to map the potential feasibility for MAR of a particular geographic region. The method is presented from a theoretical perspective and it will be applied for the compilation of specific MAR site feasibility maps at four demo regions in Cyprus, Portugal, Spain and Tunisia.

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Participative methodology for criteria selection and weighting in MAR site feasibility mapping

1. Introduction

AGREEMAR is a research project funded by national funding agencies from five countries under the Partnership for Research and Innovation in the Mediterranean Area (PRIMA). The PRIMA Programme is supported under Horizon 2020 by the European Union's Framework for Research and Innovation. The project proposes an improved and integrated management of water resources centered on optimizing the storage of water in the subsurface with the aim of increasing water security in the Mediterranean region.

One of the main goals of the AGREEMAR project is to develop a methodology for the selection of feasible locations for development of managed aquifer recharge (MAR) schemes based on the integration of three pillars: a) demand for groundwater-dependent services, b) availability of conventional and non-conventional water sources for MAR, and c) intrinsic hydrogeological characteristics. Besides these physical considerations, the ranking of potentially feasible regions for MAR implementation is very much affected by a series of economic, social, environmental and legal constrains. Since these non-physical considerations cannot be easily georeferenced, a methodology is needed for their integration. MAR represents a bundle of interventions in the hydrological cycle aiming at storing water in the subsurface for multiple benefits and the challenges encountered in developing such integrative approach consist in: i) the compilation of a comprehensive list of feasibility criteria covering biophysical, technological, social, economic, environmental, hydrological, institutional and financial parameters, and ii) assessing the relevance and potential contribution of different criteria to the overall performance of the MAR scheme.

2. Selection of suitable areas for MAR

2.1 GIS-based multi-criteria decision analysis

Many efforts have been dedicated lately to the selection of suitable sites for MAR implementation using geospatial analysis (Sallwey et al., 2019). The mapping approach involves the use of Geographical Information Systems (GIS) coupled to multi-criteria decision analysis (GIS–MCDA) for ranking areas that are potentially suitable for the construction of MAR schemes. MCDA is used to manipulate available GIS data and to transform a set of preferences in decision rules for ranking a pre-defined set of thematic layers. The method involves usually several steps (Figure 1, adapted from Rahman et al., 2012 and Bonilla Valverde, 2016):

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

Problem definition

The problem definition is the main driver for the GIS-MCDA analysis as it influences which criteria will be selected and potentially also the weights assigned to them. Any GIS-MCDA for MAR site selection shall consider the main objectives of the MAR project and include, if possible, a good characterisation of the social, economic and environmental context.

Constraint mapping

The areas that are absolutely not feasible for MAR (such as ecological protected zones etc.) can be excluded from the analysis during the constraint mapping step. This can be done using simple Boolean logic: unsuitable areas are removed and the rest is considered for the analysis.

Criteria selection

The criterion is the basic element in the analysis that can be measured and analysed. The selection of criteria for the GIS-MCDA is extremely important and has to be done based on a very good understanding of underlying processes and factors affecting the MAR implementation. The set of criteria must be:

- complete (cover all decisional aspects related to MAR implementation)
- operational (selected criteria must be meaningful and understandable)
- decomposable (the decision based on criteria analysis can be disaggregated into parts)
- non-redundant (duplicate criteria and components must be avoided)
- minimal (the set of criteria shall be kept as small as possible).

Standardization

The standardization step involves arranging the attribute values of all thematic criteria on 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 step-wise discretisation (when the values are grouped in thematic classes, i.e., soil texture classes, geological formations etc.).

Weights assignment

The criteria selected for the analysis have a differentiated impact on the MAR scheme. To acknowledge this, the more relevant criteria are assigned higher weights (or scores) and the less important ones are ranked lower. This step is crucial as small variations in the weights allocation might lead to significantly different results. The most common methods are:

- *rating method* – individual scores are directly assigned based on the author's knowledge or by comparison with other similar studies)
- *ranking method* – criteria are ranked according to their importance with the most important criterion given the highest rank)
- *multi-influence method* – the weights are assigned by plotting the criteria and assessing the influence that they have on each other by giving a differentiated score for major and minor effects)
- *pairwise comparison matrix* – using a semantic 9-point scale for attributing priority values of 1, 3, 5, 7, and 9 that correspond to equally important, moderately important, strongly important, very strongly important and extremely important criterion when compared with one another.

The web-based groundwater modelling platform www.inowas.com includes a dedicated tool for the compilation of MAR site suitability maps where the methods for weights assignment are described in detail (for more info see https://inowas.com/tools/t05-gis-mcda/).

Suitability mapping

This step represents the compilation of the maps based on pre-defined criteria rules. These rules define how the criteria values and weights are integrated. The most common rules are the *weighted linear combination* (WLC) and the *analytic hierarchical process* (AHP). The result of this step takes into consideration the different weights allocated to the criteria attributes and provides a range of suitability classes (very suitable, moderately suitable, less suitable etc.). A simplification of this process is the *Boolean* method, where the results are absolute (an area is either suitable or not suitable).

Note: Most GIS-MCDA studies for MAR site selection use the term "suitability" to define areas that are potentially relevant for MAR. In the AGREEMAR project, we consider the term *suitability* only for one thematic criteria cluster (mostly the intrinsic site characteristics – see Figure 3 and AGREEMAR Deliverable 2.2). When the GIS mapping includes also the other thematic layers (water availability, water demand, non-physical criteria), then the term "feasibility" is used. Hence, the term "**feasibility mapping**" will be used hereafter in this report and in most of AGREEMAR publications.

Maps validation

The validation of the maps is necessary due to the highly biased methodological approach. The validation is often done by conducting a sensitivity analysis, usually creating the maps with small variations either in the number of criteria selected or in the assigned weights. The sensitivity analysis will allow a better understanding of the role of criteria analysed and can suggest the exclusion of less relevant criteria or inclusion of additional components.

2.2 Limitations

This report focuses mostly on criteria selection, weights assignment, feasibility mapping and maps validation as these are arguably considered the most biased steps in the GIS-MCDA methodology for MAR site selection.

2.2.1 Criteria selection

The analysis of over 60 GIS-MCDA studies for MAR site selection (Sallwey et al., 2019) revealed that the selection of criteria is overwhelmingly based on literature review (similar studies) and author's judgement. While this is common practice in scientific research, the selection does not consider the particular environmental, social and economic context of the original study. Another factor influencing the selection is data availability, the authors being understandingly attracted to favour data that is widely available and easily accessible. A combination of these factors leads to the fact that, for example, the terrain slope is the criterion used in almost 90% of the GIS-MCDA studies for MAR (Sallwey et al., 2019). Moreover, a confusion might appear when a certain area is deemed as "suitable" for MAR despite the fact that only the groundwater recharge potential is assessed and no information is provided about water availability for infiltration. In this case, it is always important to mention the limitations of the study and whenever possible, to expand the range of criteria considered (see also the note above regarding "feasibility vs. suitability").

2.2.2 Weights assignment

Since criteria don't have the same degree of influence on the MAR applicability, their relevance shall be weighted accordingly during the integration in the feasibility maps. This process is also very much biased by the expertise of the author and is often limited to a superficial understanding of the physical processes at a MAR site. The weights of the criteria are frequently chosen based by reviewing similar studies and based on own judgement but not always considering the problem definition (the objective of the MAR project, the type of infiltration technique etc.). Moreover, consultations with stakeholders for criteria weighting is extremely seldom, the maps failing thus to reflect the variety of interests of societal sectors. Therefore, MAR feasibility maps are still lacking pertinence in term of convincing stakeholders and decision makers to implement MAR projects.

2.3 Research hypotheses

To address the limitations listed above and reduce the associated bias, 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 approach is tailored on the belief that the site feasibility assessment shall be guided by the following principles:

a) The MAR project shall generally adhere to the three pillars of the integrated water resources management (IWRM): economic efficiency, environmental sustainability and social equity

b) The geospatial analysis must simultaneously consider the capacity of an aquifer to get recharged, the availability of water for subsurface storage, and the demand for MAR of a certain societal sector

c) The pre-selection of biophysical feasibility criteria depends strongly on the overall objective of the MAR project

d) The non-physical constrains (economic, social, legal, etc.) have a direct influence on the feasibility of the site for MAR implementation and need to be integrated in the geospatial analysis

e) The selection and ranking of criteria must be conducted in a participative stakeholder process, having in mind a specific MAR objective

Based on the principles enlisted above, the AGREEMAR project developed a stakeholder-adapted weighting system for MAR feasibility mapping considering the important role of MAR in IWRM and water resource planning. An initial set of feasibility criteria was already compiled and presented in the deliverable D2.1 (download the deliverable and the initial set of feasibility criteria: https://agreemar.inowas.com/deliverables/).

3. Stakeholder-adapted weighting system for MAR feasibility mapping

3.1 General approach

Starting from the principles enlisted above and adressing the limitations of current practives, the new methodology integrates expert-based inputs with contributions resulted from interaction with stakeholders (Figure 2). The procedure is divided into two main branches, hereafter designated as streamflows. Streamflow 1 will establish the non-physical criteria selection method and definition of weighting coefficients based on the expertise of AGREEMAR consortium and external MAR experts. Streamflow 2 will aggregate the information provided by the stakeholders concerning weights attributed to each criteria based on the outcomes of interaction activities (questionnaire and workshops). A final set of representative weights should result from merging the two streamflows, encompassing both expert (AGREEMAR team) and stakeholder inputs. These will be used in the Feasibility Index concept maps which will ultimately be discussed with the project stakeholders.

To facilitate a better understanding of the concept and the terminologies used hereafter, Table 1 summarizes the main differences between the two streamflows:

Table 1. Main differences between the two methodological streamflows

	Streamflow 1	**Streamflow 2**
Scope	General (baseline for any MAR feasibility mapping study)	Specific (applied to a particular region)
Contributions	Expert-based process with input provided by AGREEMAR team and external MAR experts	Co-participative process based on interaction with stakeholders from project demo regions
Detail level	Category level (assuming that all criteria within one category have the same relevance)	Criterion level (assuming that each specific criterion has a different relevance)
Criteria coverage	All physical and non-physical criteria included in the database, regardless of their format, scale, availability	Only selected physical criteria that are relevant to the region and readily available in geospatial format
Weighting methodology	Comparing physical with non-physical categories and assigning weights based on MAR objectives and IWRM principles	Comparing physical criteria with themselves based on their contributions to MAR feasibility
MAR objectives	Applied to all 32 MAR objectives	Applied only to one regional objective

The combination of scientific expertise (Streamflow 1) and stakeholder interractions (Streamflow 2) in the process of selection and weightning of feasibility criteria is expected to reduce the bias associated with the compilation of MAR feasibility maps, strenghten the methodological approach, rise awareness and attract the interest of stakeholders, and contribute to increasing the general acceptability of MAR in the society. While the Streamflow 1 provides a baseline methodology for the compilation of any MAR feasibility maps, Streamflow 2 works with a limited set of criteria that are specific to the case study chraracteristics (aim of the project, expected benefits, spatial and temporal scale, data availability, stakeholders interests etc.).

The procedure will rely on the extensive list of criteria incorporated and structured in the Criteria Matrix developed and documented in AGREEMAR deliverable D2.1. (Panagiotou et al., 2022, Figure 3). The structure is divided into four levels, from the Thematic level (which include the four main feasibility components), to the most detailed level, the Criteria. Non-physical criteria are defined by those characteristics that are not easily mappable and available, such as socio-economic information (governance, social, economic data, etc.). The procedure described in this report aims to cover all principles listed in section 2.3, including the connection of non-geographical data with physical processes by weighting the magnitude of importance and reciprocal impact between physical and non-physical components.

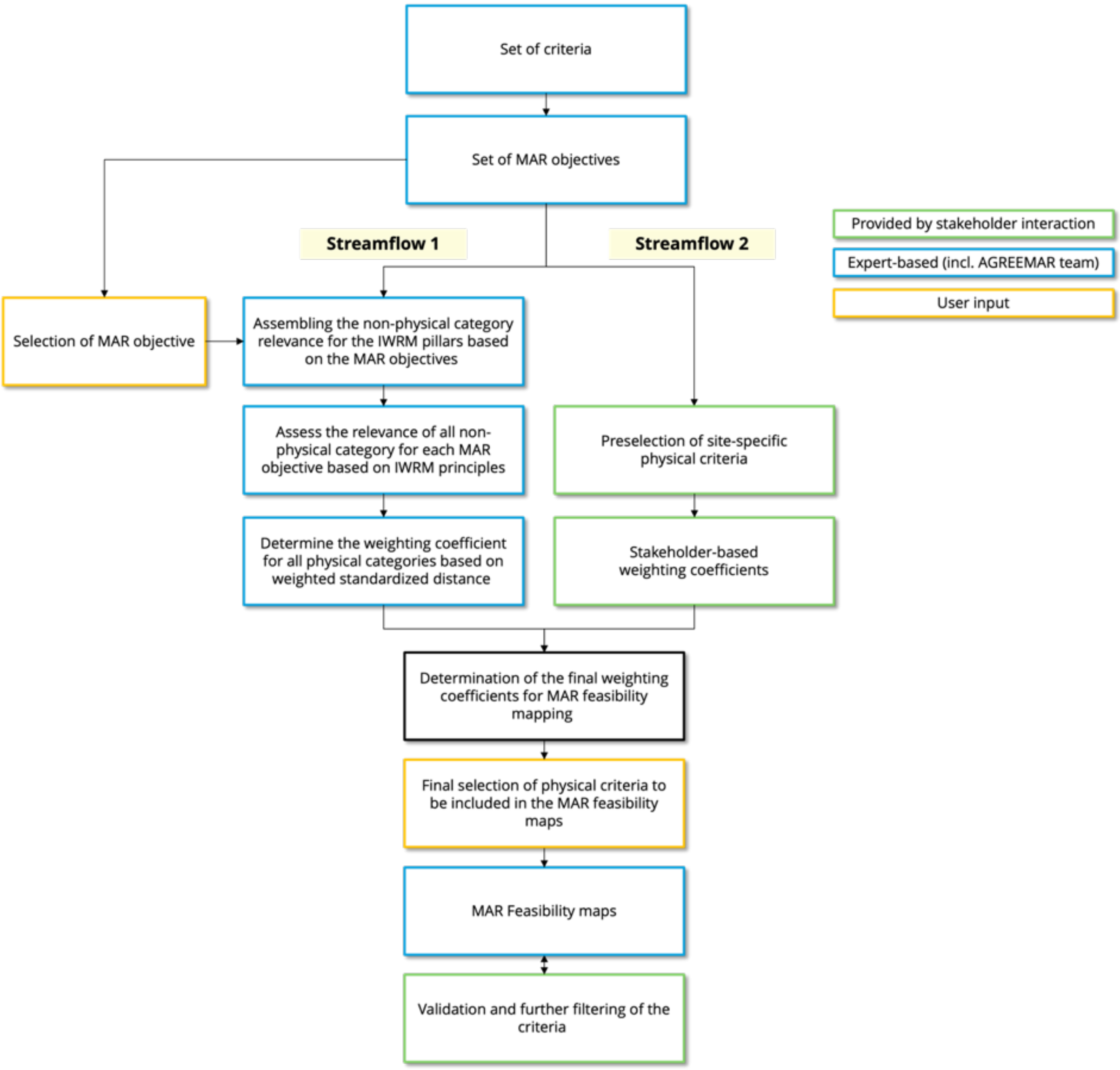


Figure 2. Overview of the proposed methodology for weighting criteria and generate feasibility maps

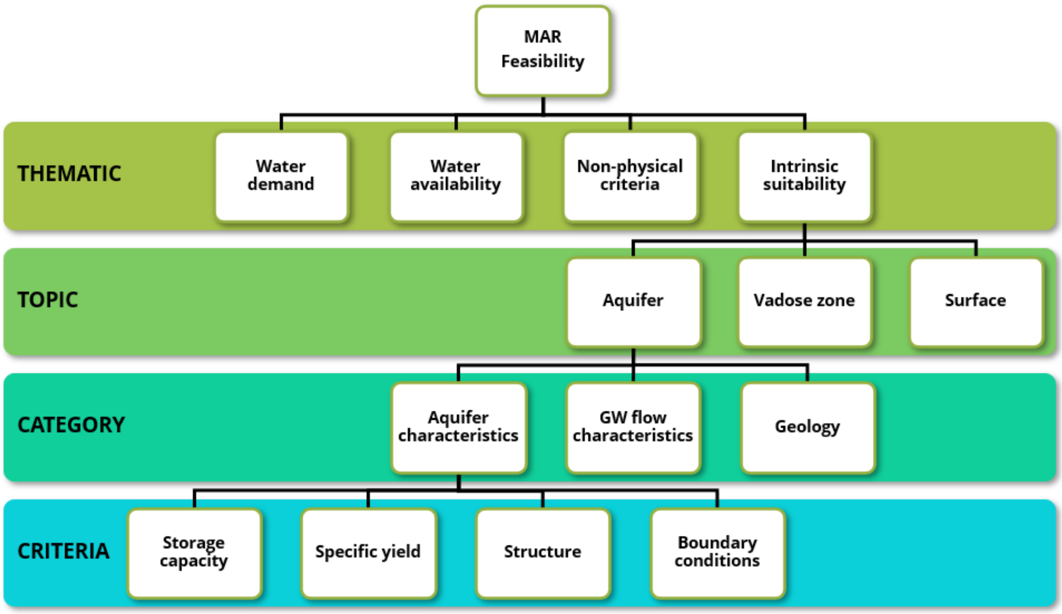


Figure 3. Overview on criteria matrix structure focusing on an example (Intrinsic Suitability > Aquifer > Aquifer Characteristics > Storage capacity)

In the following sections, the entire workflow highlighted in Figure 2 will be described in detail and a complete step-by-step theoretical example will be provided. It is important to note that once this is applied in the case-study areas some modifications may be implemented.

BOX

The theoretical implementation of the procedure is presented in the following sections in these boxes. At this stage no real data was used, only theoretical values. The complete calculations with practical examples from the demo regions will be available on the project website https://www.agreemar.inowas.com.

3.2 Streamflow 1: Expert-based criteria selection process and weighting coefficients

3.2.1 Step 1: Assembling the non-physical criteria relevance based on the MAR objectives and following the IWRM principles

Relevance of MAR objectives

The methodology is based on the assumption that the selection of feasibility criteria is highly dependent on the MAR objective. As an example, implementing MAR to restore depleted groundwater levels or for combating marine water intrusion will have different economic, social and environmental effects in the integrated water resources management (IWRM), if compared with implementing MAR for flood control or for fish and wildlife ecosystems enhancement. A comprehensive list of 32 MAR objectives was compiled and published in the deliverable D2.1. The list covers all major MAR applications on enhancing the aquifer storage, improving water quality and sustaining ecological functions. Defining a specific objective will be the first step for selecting which non-physical criteria will be included in the feasibility computation.

Note:

For simplicity reasons, the methodology presented in this report will consider the category level, assuming that, at this stage, all criteria within one category will implicitly have the same behavior and relevance. For the application of methodology at case study level, the workflow will consider each separate criterion.

Relevance of IWRM guiding principles

From a wider perspective, 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:

- **Social equity** (*"how will my decision/ action affect access for other users to water or the benefits from its use?"*). MAR shall ensure the provision of equal access for all users to an adequate quantity and quality of water. Planning of a MAR system shall take into consideration the rights of all users to water resources and that no conflicts are generated by the new MAR water allocation plans. This refers not only to direct provisional ecosystem services, like drinking water supply, but also to other regulating, supporting and cultural services.
- **Economic efficiency** (*"will my decision/ action result in the 'most efficient use of the available financial & water resources?"*). Implementation of MAR shall strive to provide multiple benefits to the greatest number of users, by using the available financial and water resources. Generally, the most economically feasible option shall be selected by including current and future social and environmental costs and benefits.
- **Ecological sustainability** (*"how will my decision/ action affect the functioning of natural systems?"*). MAR can be used to sustain and provide additional benefits to groundwater dependent ecosystems and acknowledge them as end-users. This means that MAR developments shall take into consideration the maximization of ecological benefits and avoid any negative impact on the ecosystem possibly generated from its implementation.

Integration of MAR objectives and IWRM principles

Since MAR is not able to fully satisfy simultaneously the needs of every sector (population supply, agriculture, industry, etc.), it is necessary to ground the selection of non-physical criteria for each objective on the idea of a trade-off among the three IWRM pillars – Social Equity (SE), Economic Efficiency (EE), and Ecological Sustainability (ES). In general, all three pillars shall be considered guiding principles of equal relevance but we acknowledge that, depending on the specific MAR objectives, the focus might shift towards one or other pillar. For the present methodology, 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. They can be represented in a percent triangle (Figure 4).

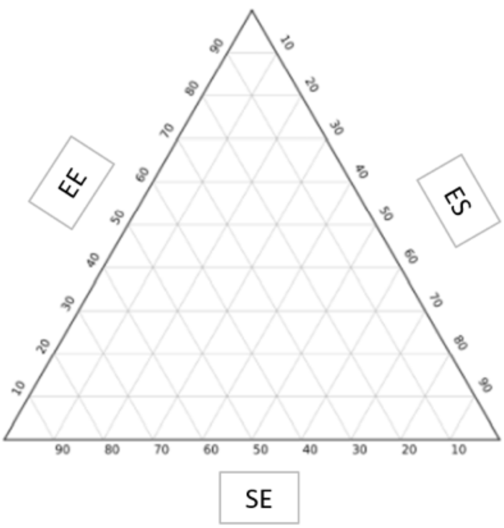


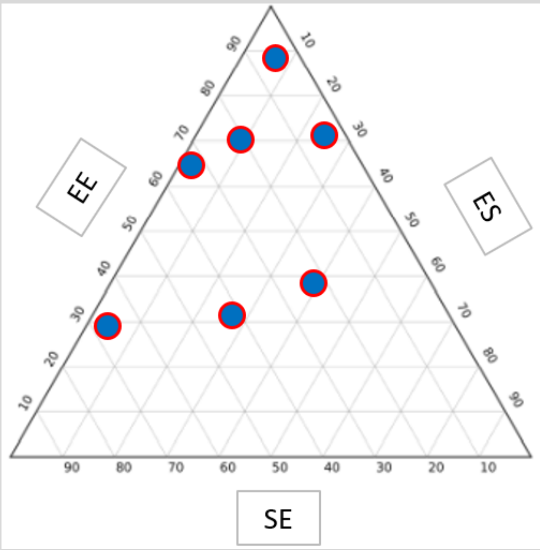
Figure 4. Representation of the three IWRM guiding principles

The AGREEMAR team will pre-establish, for each of the 32 inventoried MAR objectives, the most adequate position of each non-physical (NP) category within the percentage triangle. Each expert partner of the consortium will provide the percentages of the IWRM pillars for each non-physical category based on their perception of importance for EE, ES and SE, from which an average value will be computed and each NP category will be plotted in the triangle. A percentage triangle with the position of all NP categories will be developed for each MAR objective. In total, 32 such triangles are thus generated, one for each MAR objective (see Box 1). For simplicity reasons, the 32 objectives can be clustered in six main categories and therefore the number of triangles can be reduced from 32 to 6: 1) Increase groundwater levels and storage, 2) Improve surface water and groundwater quality, 3) Prevent land surface subsidence, 4) Prevent saltwater intrusion, 5) Enhance groundwater-dependent ecosystem, 6) Contribute to control floods. The output will be validated by repeating the exercise with members of scientific community.

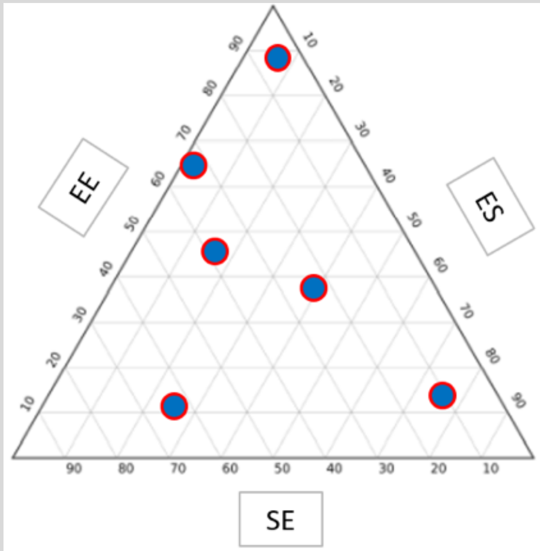
BOX 1

Pre-established IWRM pillars triangle for MAR objective A and MAR objective B
(theoretical example)

Objective A



Objective B



EE: Economic efficiency
ES: Ecological sustainability
SE: Social equity

Non-physical category (NP) - pre-established position

3.2.2 Step 2: Assess the relevance of all non-physical categories for each MAR objective based on IWRM principles

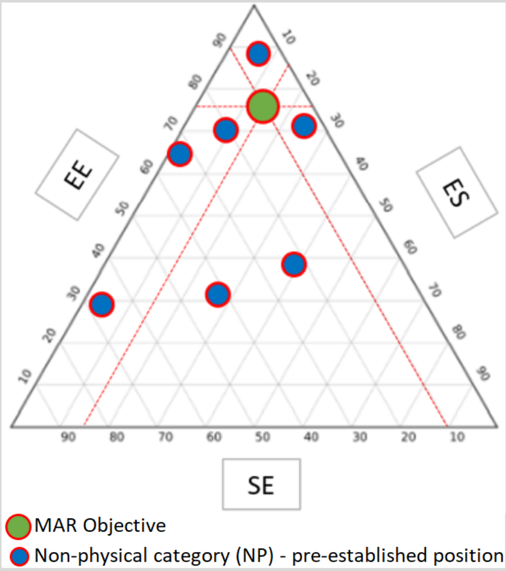
To select and assess the relevance of the non-physical categories that are closely related with the specific MAR objective, the User[1] will be asked first to select one of the 32 triangles with the objective that is closest to their own objectives. Then, the User will provide the coordinates (percentages) of their own specific objective in the IWRM pillars triangle (Box 2).

[1] In the context of this report, a "User" is the author of a MAR site feasibility map for which the present methodology is proposed.

BOX 2

Example of the User coordinates (percentages) for MAR objective A

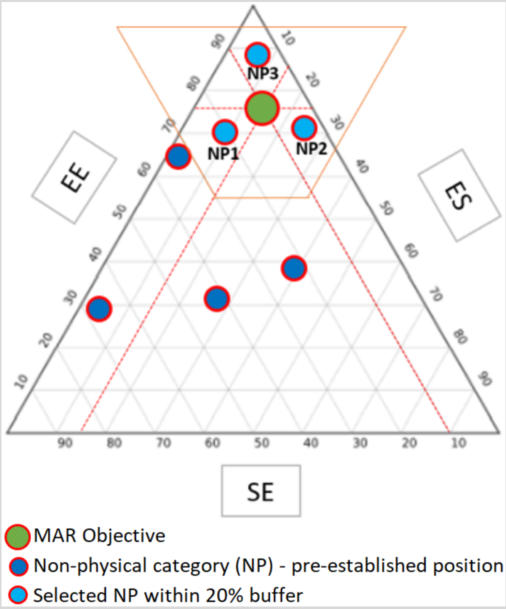
	EE	ES	SE
User input	75	15	10



The non-physical categories are then selected according to their proximity to the point of the MAR objective. For that purpose, a buffer of 20% (exact value can be adjusted) is drawn around the coordinate of the MAR objective point defined by the User input (Box 3). The Euclidean distance is then calculated from the MAR objective point for each of the NP within the 20% buffer polygon from which a proximity score will be computed (Box 4 and 5).

BOX 3

Selection of all the NP categories within a +/-20% buffer
(and respective pre-established coordinates)

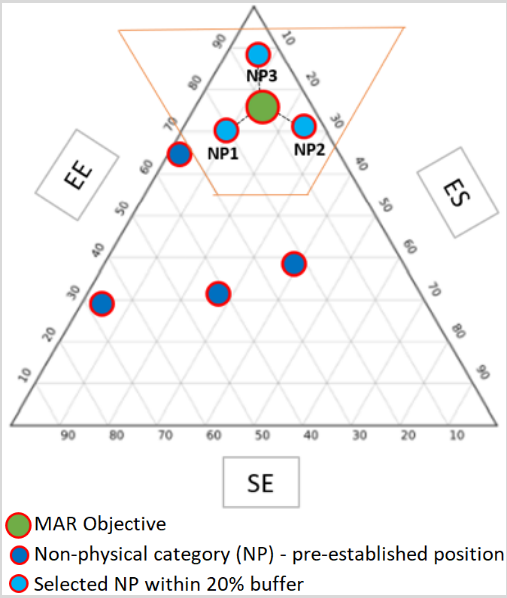


	EE	ES	SE
NP1	70	10	20
NP2	71	27	2
NP3	88	8	4

NP - Non-physical category

BOX 4

Computation of the distance between MAR objective and selected NP categories



	EE	ES	SE	D	D_{max}	D_{ad}
NP1	70	10	20	12.247	141.421	0.087
NP2	71	27	2	14.967		0.106
NP3	88	8	4	15.937		0.113

D: Euclidean distance

$\boldsymbol{D} = \sqrt{(\boldsymbol{EE}_{\boldsymbol{MAR_{obj}}} - \boldsymbol{EE}_{\boldsymbol{NP}})^2 + (\boldsymbol{ES}_{\boldsymbol{MAR_{obj}}} - \boldsymbol{ES}_{\boldsymbol{NP}})^2 + (\boldsymbol{SE}_{\boldsymbol{MAR_{obj}}} - \boldsymbol{SE}_{\boldsymbol{NP}})^2}$ where $\boldsymbol{EE}_{\boldsymbol{MAR_{obj}}}$ is the EE coordinate of the MAR objective point and $\boldsymbol{EE}_{\boldsymbol{NP}}$ is the EE coordinate for the Non-physical category point

D_{max} - maximum distance possible

D_{ad} – non-dimensional/standardized distance (0 to 1 scale)

BOX 5

Computation of a standardized weight based on distance
(the near the NP criteria the higher the weight)

	w_D
NP1	0.339
NP2	0.332
NP3	0.329

w_D - weighted standardized distance (0 to 1 scale, computed from [1 – D_{ad}] / Σ [1 – D_{ad}])

3.2.3 Step 3: Boolean rating of all physical categories based on the selected non-physical categories

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 interractions between Physical (P) and Non-physical (NP) categories. To ease the undestanding on how the Boolean classification is conducted, a simple question can be answered, for example: "Given this *specific MAR objective*, do the *Aquifer characteristics* impact the *Water rights*?" - Yes (1) - No (0).

A simple NP x P matrix is then developed for each of the 32 MAR objectives based on the inputs of the consortium members and MAR experts (Box 6). This matrix should be standardized so that the total of all physical categories is 1 (the value at each cell is obtained dividing its value by the total of the column). The template for this matrix is presented in Figure 5:

BOX 6

Select the pre-filled Non-physical (NP) vs Physical (P) criteria matrix based on MAR objective (NP x P matrix)

Category	NP1	NP2	NP3
P1	1	0	1
P2	0	1	1
P3	1	1	0

→

Category	NP1	NP2	NP3
P1	0.5	0	0.5
P2	0	0.5	0.5
P3	0.5	0.5	0

Standardization of the matrix

Thematic			Non-physical (qualitative)																
	Topic		Governance constraints				Social constraints				Environmental constraints			Economic constraints			Infrastructural constraints		
		Category	Legal constraints	Water rights	Trans-border issues	Political stability	Awareness of MAR	Vulnerability to groundwater supply	Health	Social capital	On optical aesthetics during the construction stage	On emissions	Cultural heritage	Investement costs	Operating costs	Levelized costs	Accessibility	Communications	Safety of the workers and the users
Intrinsic suitability	Aquifer	Aquifer characteristics																	
		Groundwater flow characteristics																	
		Aquifer structure and physical boundaries																	
	Vadose zone	Groundwater table																	
		Geochemistry																	
	Surface	Geomorphology																	
		Hydrography																	
		Land use / Land cover																	
		Soil																	
		Karst features																	
Water availability	Climatic context	Hydrometeorology																	
	Source water	Source water quality																	
		Source water availability																	
Water demand	Provisioning needs	Domestic supply																	
		Agricultural supply (AS)																	
		Industrial supply																	
		Geothermal energy																	
	Regulatory needs	Buffering water quality																	
		Buffering water quantity																	
	Supporting needs	Groundwater dependent ecosystems																	
		Land surface stability																	
	Cultural needs	Hot springs																	
		Leasure and recreation																	

Impacts?

1	Yes
0	No

Figure 5. Template of the Boolean weighting of physical categories based on their relevance to the selected non-physical criteria

3.2.4 Step 4: Determine the weighting coefficient for all physical categories based on weighted standardized distance

The weights for the physical categories are obtained by multiplying the standardized Boolean values achieved by comparing non-physical (NP) to physical (P) categories (see Step 3) by the proximity scores (weighted standardized distance) (see Step 2). The results will look similar as in Box 7 below:

BOX 7

Multiply the Boolean value matrix by the standardized distance weight

and compute the weight for each P category

Category	NP1	NP2	NP3
P1	0.5	0	0.5
P2	0	0.5	0.5
P3	0.5	0.5	0

Step 3

x

	w_D
NP1	0.339
NP2	0.332
NP3	0.329

Step 2

=

	wP
wP1	0.334
wP2	0.331
wP3	0.335

Step 4

3.3 Streamflow 2: Stakeholder-based weighting coefficients

While Streamflow 1 establishes an expert-based methodology for semi-automatic calculation of weighting coefficients for physical categories, Streamflow 2 aims to obtain the same coefficients for site-specific physical criteria through a co-participative, stakeholder-centered approach (see the entire workflow in Figure 2).

3.3.1 Step 1: Pre-selection of physical criteria

The preselection of physical criteria can be done using a dedicated questionnaire targeted at stakeholders that relevant for the region where the MAR feasibility maps are generated. A comprehensive list of criteria is available for download on the AGREEMAR website (https://agreemar.inowas.com/feasibility-criteria/) with the methodology being described in deliverable D2.1. The questionnaire can be promoted online to larger stakeholder groups or to key stakeholders via bilateral meetings and workshops. In the AGREEMAR project, a detailed analysis and mapping of relevant stakeholder was conducted at all demo regions and the results are published in deliverable D1.1a. For simplification purposes, the total number of criteria presented in the questionnaire can be reduced, based on the identified objective and existing non-physical constrains.

3.3.2 Step 2: Weighting of the selected criteria based on stakeholders' inputs

One of the processes that can be adopted for weighting the categories based on stakeholder inputs is the *pairwise comparison matrix* method. Participants will be asked to compare the importance of the criteria in terms of relevance to MAR: which criterion of each pair is more important, A or B, and how much more on a scale from 1 to 9 as given by the example in Figure 6. Scores might be adjusted to improve consistency (CR < 10%). The intensity of importance is explained in Table 2.

Table 2. Assignment of intensity of importance

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to MAR feasibility
3	Moderate importance	Experience and judgement slightly favor one criterion over another
5	Strong importance	Experience and judgement strongly favor one criterion over another
7	Very strong importance	One criterion is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one criterion over another is of the highest possible order of affirmation

(2, 4, 6 and 8 can be used to express intermediate values)

		Criteria		more important ?	Scale
i	j	A	B	A or B	(1-9)
1	2	Criterion 1	Criterion 2	A	3
1	3		Criterion 3	B	3
1	4		Criterion 4	B	2
1	5		Criterion 5	A	4
1	6		Criterion 6	A	5
1	7		Criterion 7	B	5
1	8				
2	3	Criterion 2	Criterion 3	B	3
2	4		Criterion 4	B	2
2	5		Criterion 5	A	2
2	6		Criterion 6	A	2
2	7		Criterion 7	B	5
2	8				
3	4	Criterion 3	Criterion 4	A	2
3	5		Criterion 5	A	3
3	6		Criterion 6	A	3
3	7		Criterion 7	B	3
3	8				
4	5	Criterion 4	Criterion 5	A	3
4	6		Criterion 6	A	3
4	7		Criterion 7	B	3
4	8				
5	6	Criterion 5	Criterion 6	A	1
5	7		Criterion 7	B	5
5	8				
6	7	Criterion 6	Criterion 7	B	5
6	8				
7	8				

Figure 6. General methodology for scoring step

After obtaining these comparison values, a matrix is created that shows the comparison values of all the criteria towards each other. The comparison matrix is reciprocal which means that if criterion 1 receives a score of 3 compared to criterion 2, criterion 2 in return receives the reciprocal value 1/3 compared to criterion 1 (Table 3).

Table 3. Example of comparison matrix with three criteria

	Criterion 1	Criterion 2	Criterion 3
Criterion 1	1	3	6
Criterion 2	1/3	1	3
Criterion 3	1/6	1/2	1

From the comparison matrix, the criterion weights are computed following three steps: (1) sum the values of each column of Table 3; (2) divide each element of the matrix by its column total (the result is called normalized pairwise comparison matrix) and (3) compute the average of the elements of each row of the normalized matrix. These averages are an estimate of the relative weights of each criterion (Table 4).

Table 4. Normalized comparison matrix and calculated weights

	Criterion 1	Criterion 2	Criterion 3	Weight
Criterion 1	0.67	0.67	0.60	0.64
Criterion 2	0.22	0.22	0.30	0.25
Criterion 3	0.11	0.11	0.10	0.11

After computing the weights, the consistency of the comparisons is assessed. To do so, the weighted sum vector needs to be determined by multiplying the weight of the first criterion times the first column of the original comparison matrix (Table 3). The other columns are handled accordingly and the sums of the rows are calculated. This weighted sum vector is then divided by the criterion weights; the result being the consistency vector (Table 5).

Table 5. *Determination of the consistency vector*

	Weighted sum vector	Consistency vector
Criterion 1	(0.64 × 1) + (0.25 × 3) + (0.11 × 6) = 2.05	2.05 / 0.64 = 3.2
Criterion 2	(0.64 × 1/3) + (0.25 × 1) + (0.11 × 3) = 0.79	0.79 / 0.25 = 3.16
Criterion 3	(0.64 × 1/6) + (0.25 × 1/2) + (0.11 × 1) = 0.45	0.45 / 0.11 = 4.09

Consistency Ratio *CR* can be calculated using the equation:

$$CR = \frac{\lambda - n}{RI\ (n-1)}$$

where *n* is the number of criteria, λ is the average of the consistency vector and RI is a random index which depends on the number of criteria used (Table 6). If CR ≥ 10% the pairwise comparison should be reconsidered as the comparisons are inconsistent.

Table 6. *Random index to be used in the computation of the consistency (Saaty, 1980)*

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.56	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

The outcome from this rating/scoring process should provide an average weight. This average can be computed from data grouped, for example, by the stakeholder's profile or site-specific characteristics, instead of an overall average of all the ratings obtained. This will require an exploratory statistical analysis of the questionnaire results, for which the questionnaire structure is already prepared if needed.

The pairwise comparison method can be presented as online questionnaire or integrated in a dedicated workshop where participants are asked to select the relevant criteria from the AGREEMAR database and assign values to the comparison matrix. The results can be obtained by averaging the individual opinions and jointly discussing the results. To simplify the process, web-based tools are also available such as the free platform developed by the research group INOWAS at TUD (Figure 7).

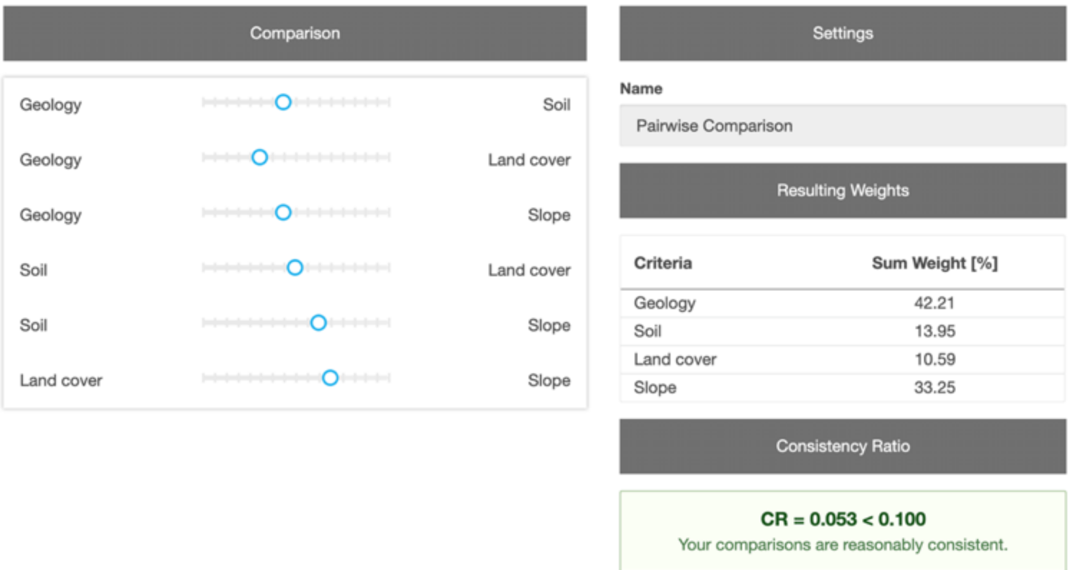


Figure 7. *Example of criteria weighting using the pairwise matrix method implemented as web-based tool on the INOWAS platform (https://www.inowas.com/tools/t05-gis-mcda)*

The ratings provided by the pairwise comparison matrix with input from stakeholders can be integrated, after standardization on the same scale (in the previous examples a scale of 0-1 was implemented) within the scores of the NP x P matrix (see next section).

3.4 Feasibility mapping

3.4.1 Determination of the final weighting coefficients for MAR feasibility mapping

The final weights of the physical criteria can be calculated by weight-averaging the already computed weights in section 2.2 (NP x P matrix Boolean scores multiplied by the standardized distance weight) with the weights provided by the stakeholders for each physical criterion. The final weight for each physical criterion will be provided by summing up the NP x P scores (Box 8).

Note: Streamflow 1 calculated the weights at category level while Streamflow 2 at criteria level. To unify the two scales, the values obtained for one category in Streamflow 1 can be simply assigned to all associated criteria (for simplicity, the calculation in Streamflow 1 was based on the hypothesis that in all criteria within one category have the same relevance).

BOX 8

Average the scores of the expert-based weights with the stakeholders' weights for each P

0.5 x (

	Expert-based Weights
wP1	0.334
wP2	0.331
wP3	0.335

Streamflow 1

+

	Stakeholders' Weights
wP1	0.640
wP2	0.250
wP3	0.110

Streamflow 2

) =

	Average wP
wP1	0.487
wP2	0.290
wP3	0.223

Final weights

**Note that each expert-based weight corresponds to a category while the stakeholders' weights correspond to a criterion. The matrix of the expert-based categories' weights is transformed into a criterions' weight assuming that all criterion belonging to a category have the same weight. The average is made at criterion level*

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

3.4.2 Characterization of the physical criteria to be included in the MAR feasibility mapping

The selected physical criteria will be charaterized and standardized using the methodology explained in Box 9 where a theoretical situation in which three physical criteria are considered and standardized acccordingly to the values of each criterion is shown. This standardization is applied to an area under study.

BOX 9

Standardization rules for a set of three physical criteria and assignment of these values to produce a combined map with the standardized characteristics of the physical criteria

Standardization rules of three physical criteria

	Min.	Max.
E.g. P1	No demand	High demand
E.g. P2	Low permeability	High permeability
E.g. P3	High distance to source	Low distance to source

0	**0.25**	**0.5**	**0.75**	**1**

Combined map of the standardized characteristics

ID_polygon	sP1	sP2	sP3
1	0.90	0.45	0.96
2	0.48	0.66	0.60
:	:	:	:
n	0.96	0.71	0.40

Note: ID_polygon refers to the identification of an individual polygon in the map where all the physical standardized characteristics have the same value (sPi denotes each standardized physical criteria).

3.4.3 Feasibility index computation

With the final standardized characteristics (Box 9) and the standardized weights matrix of physical parameters (Box 8), the last step is to compute the feasibility index. This is obtained by multiplying both matrixes, as shown in Box 10.

BOX 10

Multiply the Boolean value matrix by the standardized distance weight and compute the NP weight for each P category

ID_polygon	sP1	sP2	sP3
1	0.90	0.45	0.96
2	0.48	0.66	0.60
:	:	:	:
n	0.96	0.71	0.40

(Box 9)

x

	Average wP
wP1	0.487
wP2	0.290
wP3	0.223

(Box 8)

=

ID_polygon	FI	
1	0.783	More feasible
2	0.559	Less feasible
:	:	
n	0.763	

Feasibility index (FI)

3.5 Validation and further filtering of the criteria

Although the methodology presented aims to reduce the bias associated with criteria selection and weighting, a complete automatization of the process is impossible due to limitations in data availability, spatial and temporal scale of the project, inconstant definition of objectives, etc. The authors of the maps have to balance the scientific, process-based aspects with practical, site-specific considerations. To enable flexible decisions, the methodology presented is transparent, allowing the User to make adjustments at any stage of the project. This can start with the localization of non-physical categories on the IWRM triangles for each MAR objective (Box 1) up to the integration of the results from the two streamflows (Box 8). For advanced applications, it is of course possible for the User to reconstruct the entire scheme and provide their own version of the NP x P matrix with Boolean values or simply adjust the pre-set values, adding their own perception of physical and non-physical impacts.

Since the criteria database is a living document that will be updated on a monthly basis based on the feedback from online questionnaire and stakeholders' input, the present document can only provide a step-by-step description of the general methodology. The potential Users are welcome to visit our project website at https://www.agreemar.inowas.com and stay updated with the latest version of the database and also follow the further development of the criteria weighting methodology. Especially in Streamflow 2, the approach will be validated by selecting site-specific criteria and compiling specific feasibility maps at four regions in Cyprus, Portugal, Spain and Tunisia.

4. Summary and conclusions

The present report describes a new methodology for delineation of areas that are potentially feasible for the implementation of managed aquifer recharge (MAR). The method brings a series of contributions to the existing practices and aims at reducing the bias associated with the selection of feasibility criteria and weights assignment. The approach is based on several key considerations: the positioning of MAR in the integrated water resources management (IWRM) context, the pondering of four thematic criteria clusters (non-physical criteria, water availability and water demand, in addition to intrinsic site characteristics), increasing the importance of problem definition in the mapping process and, most importantly, the design of a participative process with active stakeholders participation in the entire methodological workflow.

The approach includes two methodological "streamflows" that integrate the expert-based input with contributions resulted from interaction with stakeholders. The first branch establishes the connection between physical and non-physical criteria and is based on the expertise of AGREEMAR consortium and external experts. In the second branch, the information provided by stakeholders and their perception for MAR is collected and converted into criteria weights. Merging the two branches leads to a final set of weighted criteria that can be used to map the potential feasibility for MAR of a particular geographic region.

While the new method is expected to contribute to the consolidation of MAR feasibility mapping, its applicability could be limited by a series of factors, such as (the list gives only some examples):

- The criteria database is not comprehensive and more relevant aspects would need to be included. Nevertheless, the database is a living document expected to be continuously improved during the lifecycle of the project.
- The method is presented from a rather theoretical perspective and could undergo future adaptations upon its application at the project demo regions, when real criteria values will be used.
- The 32 MAR objectives identified cover a very wide range of situations but this might create substantial load on the workflow, especially since some objectives are quite specific. Future clustering of the objectives might reduce the workload and simplify the methodology.
- The approach was developed by the AGREEMAR consortium and future validation is needed in order to identify missing aspects, eliminate redundancy, streamline the workflow etc. This shall be addressed by organizing a series of dedicated workshops and attracting the participation of the MAR community (among others through the working group on MAR feasibility mapping of the Commission on Managing Aquifer Recharge of the International Association of Hydrogeologists).

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