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An integrated method to study and plan aquifer recharge

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ABSTRACT

This study presents a simple framework methodology for selecting the most appropriate locations for managed aquifer recharge (MAR). The proposed approach is applicable to aquifers that are located in coastal or mountainous areas and are used either for agricultural or industrial (e.g., mining) activities. A characteristic case study for the identification of the areas that are the most suitable for aquifer recharge using a GIS multi-criteria decision analysis (GIS-MCDA) method by means of MAR type spreading methods is the Geropotamos basin, Crete, Greece. Criteria combining a high relevance and high data availability, and providing unique information, were selected to assess the suitability of aquifer recharge in the basin. The criteria applied to evaluate the sites' suitability for MAR spreading methods are hydrogeology, slope, land use, rainfall, groundwater level, soil texture and distance to source water. This study uses the 'Pairwise comparison' to assign criteria weights, as part of the Analytic Hierarchy Process (AHP), and examines four different scenarios. In all four scenarios, downstream areas, and close to the river Geropotamos, coincide as the most appropriate for aquifer recharge.

Key words: AHP, aquifer recharge, GIS-MCDA, MAR, spreading method, suitability assessment

HIGHLIGHTS

- aquifer recharge.
- multi-criteria decision analysis (GIS-MCDA) method.
- to identify suitable sites for implementing an MAR (Managed Aquifer Recharge) type spreading method.
- This study uses the 'Pairwise comparison' to assign criteria weights.
- Analytic Hierarchy Process (AHP).

1. INTRODUCTION

Throughout the Mediterranean region, the semi-arid climate in conjunction with intensive agriculture is stressing scarce groundwater supplies which are over-exploited to cover irrigation water demands. Such a case is the Messara Basin in the island of Crete, Greece. This has led to increased costs associated with groundwater extraction, seawater intrusion along the coastal zone and negative environmental impacts (disappearance of wetlands). Due to over-exploitation, the groundwater of the Geropotamos basin has undergone a huge reduction. In combination with the change in climatic conditions of the area, as well as the deterioration of the water quality, this has had devastating effects on the environment and economy.

As a result, and in order to stabilize groundwater levels, the government imposed, in 2017, restrictive measures on groundwater withdrawals. These regulations prohibit, among others, the drilling of new wells, the groundwater withdrawals above certain limits and the modification of current infrastructure related to groundwater production. According to the recent River Basin Management Plan (RBMP) for the Water District of Crete, targets for the improvement of the quality and quantity of the degraded groundwater bodies in the Geropotamos Basin have been set, based on the EU Water Framework Directive (WFD). According to the regional authorities, groundwater pumping will almost certainly continue and the Water Resources Management Plan suggested considering appropriate MAR to mitigate the consequences.

MAR has been widely applied to case studies, with spatial data coverage being classified and weighted before generating suitable sites map (Saraf & Choudhury 1998); Ghayoumian *et al.* 2005; Chowdhury *et al.* 2010; Sabokbar *et al.* 2012; Tzoraki *et al.* 2018; Rahman *et al.* 2012; Zhang *et al.* 2020). Suitability studies and assessments like the ones described in this work can help in the selection of the most suitable areas for maximizing the positive impact and minimizing any potential risks associated with MAR. The purpose of this work is to determine the areas of the field case that are suitable for the aquifer recharge (suitability analysis) by analyzing surface and subsurface feasibility. This enhanced storage is achievable with various MAR methods, defined as the 'purposeful recharge of groundwater to aquifers for subsequent recovery or environmental benefits' (Dupont 2018).

An MAR application enhances the security of water supplies, improving groundwater quality, preventing saltwater intrusion, mitigating floods and maintaining groundwater-dependent ecosystems. The aquifer recharge is a key tool for tackling problems of quantitative reduction or quality degradation of groundwater systems caused by pressures in groundwater, such as over-pumping, pollution, etc. It is an environmental action that utilizes the natural underground reservoirs that are formed in the subsoil to store good quality water during the winter so that they are available for use during the summer period of increased demands.

The basic conditions for the application of MAR are Sufficient amount of surface water; Quality of the surface water and chemical compatibility with that of the groundwater; Suitable geological conditions (surfaces and subsoil with high permeability, aquifers in sequence and in hydraulic interconnection, etc.); Geomorphologically suitable areas; Ensuring negligible environmental trade-offs in terms of water availability; Construction and operating costs to be profitable (Zheng *et al.* 2021).

The suitable locations of the basin where groundwater can be recharged with maximum efficiency consider a variety of hydrogeological and geomorphological parameters under a multiple criteria decision system. A variety of MAR infiltration-based techniques was examined to select the most appropriate one for the study area such as the spreading method, infiltration basins, retention dams/river bank filtration and borehole/well infiltration methods. A detailed description of the assessed MAR techniques can be found in Dupont (2018).

Aquifer recharge aims at quantitative reinforcement and quality upgrading of groundwater systems. It is a method of integrated water resources management that can improve urban and rural water supplies, repair over-allocated or brackish aquifers, conserve ecosystems that depend on groundwater, reduce evaporation losses and increase water supply security. The effectiveness of MAR depends on a number of factors such as determining the storage capacity of aquifers, the availability of sufficient recharge water for the needs of the application and the water quality compatible and desirably better than the water quality of the recharged groundwater system.

The most suitable methodology (spreading method) for planning the aquifer recharge was selected according to the area characteristics: source of excess water available nearby, relatively flat area with permeable soils and with an unconfined aquifer. Any area with similar characteristics can be suitable for MAR spreading method application. The methodology was based on a multi-criteria matrix developed in accordance with a relative optimization (weighting) method in terms of hydrogeological and geomorphological criteria, and water availability (reservoir, river) such as slope, land cover, hydrogeology, rainfall, groundwater level (GL), soil texture and distance to source water (Dupont 2018).

These methods, which are applied in this study, have been successfully applied in many studies and are considered reliable in terms of MAR. A non-exhaustive list of applications of this specific method to solve different types of problems includes:

1. 'Comparing GIS-based multi-criteria decision-making and Boolean logic modeling approaches for delineating groundwater recharge zones' by Machiwal & Singh (2015).
2. 'A Review on Artificial Groundwater Recharge in India' by Mukherjee (2016).
3. 'Application of GIS-Based Evidential Belief Function Model to Regional Groundwater Recharge Potential Zones Mapping in Hardrock Geologic Terrain' by Mogaji *et al.* (2016).
4. 'Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of MAR through Spreading Methods' by Bonilla Valverde *et al.* (2016).
5. 'Multi-criteria analysis and GIS modeling for identifying prospective water harvesting and artificial recharge sites for sustainable water supply' by Singh *et al.* (2017).
6. 'Assessing land suitability for aquifer storage and recharge in northern Ghana using remote sensing and GIS multi-criteria decision analysis technique' by Owusu *et al.* (2017).
7. 'Suitability maps for MAR: a review of multi-criteria decision analysis studies' by Sallwey *et al.* (2018).
8. 'Assessing the accuracy of GIS-based Multi-Criteria Decision Analysis approaches for mapping groundwater potential' by Singh *et al.* (2018).

9. 'Suitability Mapping for Managed Aquifer Recharge: Development to Web-Tools' by Sallwey *et al.* (2019).
10. 'Identification of intrinsic suitable sites in Gaza Strip for the application of artificial groundwater recharge using a geographic information system multi-criteria decision analysis' by Ajjur & Mogheir (2020).
11. 'Synthesizing existing frameworks to identify the potential for Managed Aquifer Recharge in a karstic and semi-arid region using GIS Multi-Criteria Decision Analysis' by Fathi *et al.* (2020).

In this study, four scenarios were examined. In the first scenario, the criterion of distance to the water source was not taken into account. In the second scenario, the criterion of the distance to the local dam was considered. In the third scenario, the criterion of the distance to the river was added. Finally, in the fourth scenario, the distance to the dam and the river was considered.

2. MATERIALS AND METHODS

2.1. Case study

Messara valley is located in Geropotamos basin in the south-central part of Crete (Figure 1). The economy and development of the region is mainly based on the primary sector with the cultivation of intensive aquaculture and less on tourism. The climatic conditions in the area are characterized as dry, especially in the summer, which creates an increased demand for water. During the summer, the irrigation needs are covered exclusively by the groundwater of the basin aquifer, the exploitation of which began in the 1980s (Kritsotakis & Tsanis 2009).

The present study will explore the areas that are most suitable for the aquifer recharge, in the Geropotamos basin, using a GIS multi-criteria decision analysis (GIS-MCDA) method to identify suitable sites for implementing the MAR type spreading method. A collection of tools called GIS-MCDA is described as being used to plan, assess and rank alternatives. According to the objectives and preferences of the decision-makers, GIS-MCDA rates the criteria selected to support MAR site selection (Sallwey *et al.* 2018). This method has been successfully applied in many studies and is considered reliable in terms of MAR studies (Dupont 2018).

The suitability assessment is performed through the Analytic Hierarchy Process (AHP) model, which is a technique that allows an estimation of the weights. The criteria combining a high relevance and high data availability, and providing unique information, selected to assess the suitability of MAR spreading methods in Geropotamos basin are slope, land use

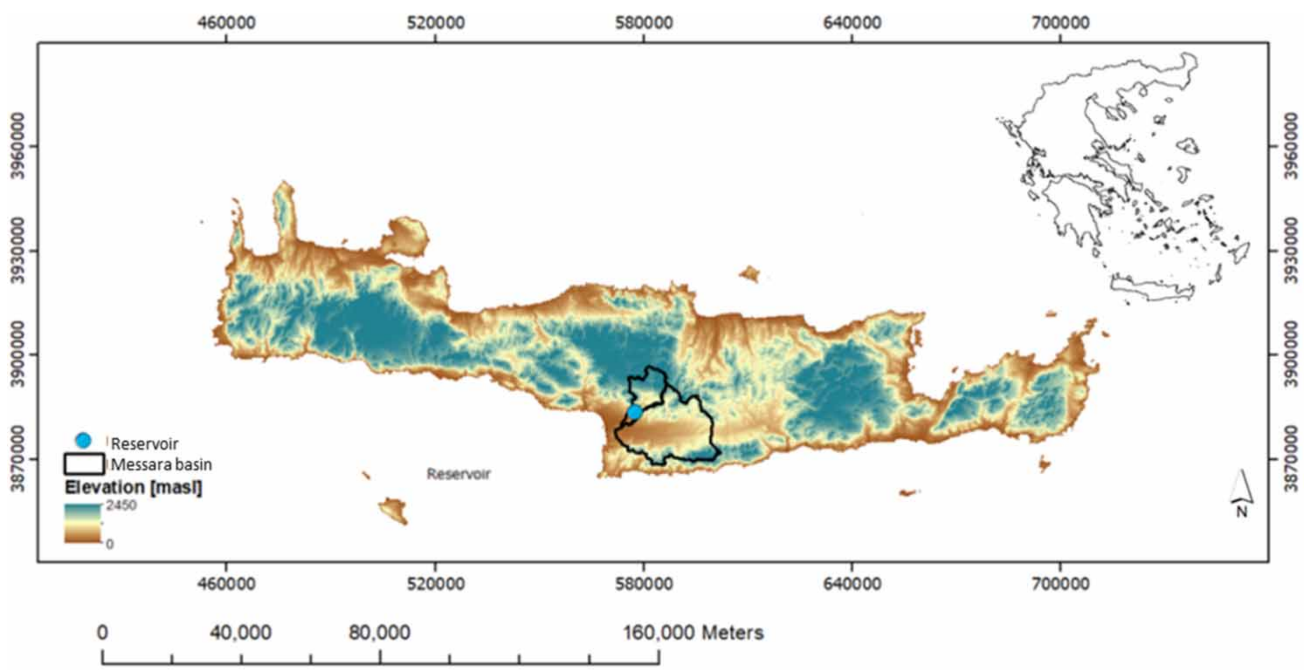

Figure 1 | Location of Geropotamos basin situated in Crete Island in Greece.

(LU), hydrogeology, rainfall, GL, soil texture and distance to source water. This study uses the 'Pairwise comparison' to assign criteria weights, developed by Saaty (1980) as part of the AHP (Vargas 2011; Dupont 2018).

As for the geological setting of the area, there is inhomogeneity, so there are several alternations of hydrogeological features even at short distances. Geological formations are mainly quaternary alluvial clays, silt, sand and gravel with a thickness of up to 100 m or more. The rainfall in the area varies with the altitude from 500 mm in the plain to 800 mm on its slopes and 1,100 mm in the Asterousia mountains. Figure 2 shows the average annual rainfall in the Messara basin for the years 1974–2020. As can be seen from the diagram, the driest hydrological year was 2016 and the wettest was 2003. The wet season lasts from November to March or April, while the dry season lasts from May to October.

The main mean of surface runoff of the plain is the river Geropotamos in the strait of Phaistos to the west. At this point, the altitude is 30 m above sea level. The river Geropotamos was constantly flowing, and at the western end of the catchment area in Phaistos, there was a wetland. However, the drop in groundwater levels resulted in the drying up of the wetland, the lack of flow in the river during the dry period of 1990, as well as during the hydrological year 1992–1993. This was the first time the riverbed had dried up, according to historical records. The average annual runoff (16.88×10^6 m^3) was calculated based on historical data from 1967 to 2019, while the highest average monthly runoff was observed during the months of January and February and the lowest during July and August.

The Valley of Western Messara includes both bigger and smaller aquifers of complex hydrogeological properties. Their level reaches its maximum in March or April and then there is a steady decline until the reserves are renewed in the winter. The aquifers were highly efficient with a high pumping capacity of about 300 m^3/h in the early 1970s. The last decade it has been reduced to about a tenth of that. The lateral groundwater outflows from the plain are low in relation to the extent of the pumping carried out in the area. An extensive pumping network has been installed since 1984 and it is estimated that on average about 40×10^6 m^3/year was pumped from the aquifers after the network installation. Such a large pumping resulted in a huge drop of 35 m of the aquifer level during the 00s. In recent years, there has been very little surface runoff but groundwater reserves have been stabilized due to the construction of a water reservoir in the area. In a general context, groundwater restores supplies from lateral upstream inflows, from the karstic springs located at the center of the basin and from the river–aquifer interactions (Kritsotakis & Tsanis 2009).

The highest hydraulic conductivity values are recorded in the Mires aquifer at the West, where the permeability ranges between 10 and 120 m/day indicating the presence of many gravel sequences in the alluvial formation. The least permeable areas are located in the Vagiona aquifer at the East, where the sparse presence of sandstone results in an average value of only

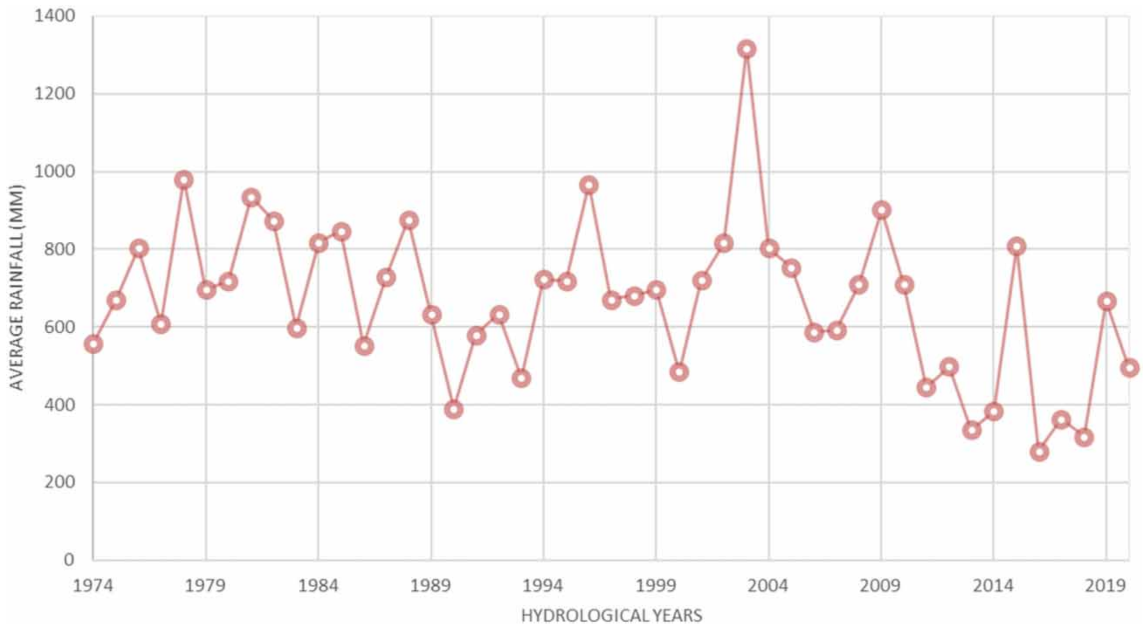

Figure 2 | Average monthly rainfall in the Messara basin (Decentralized Administration of Crete 2020).

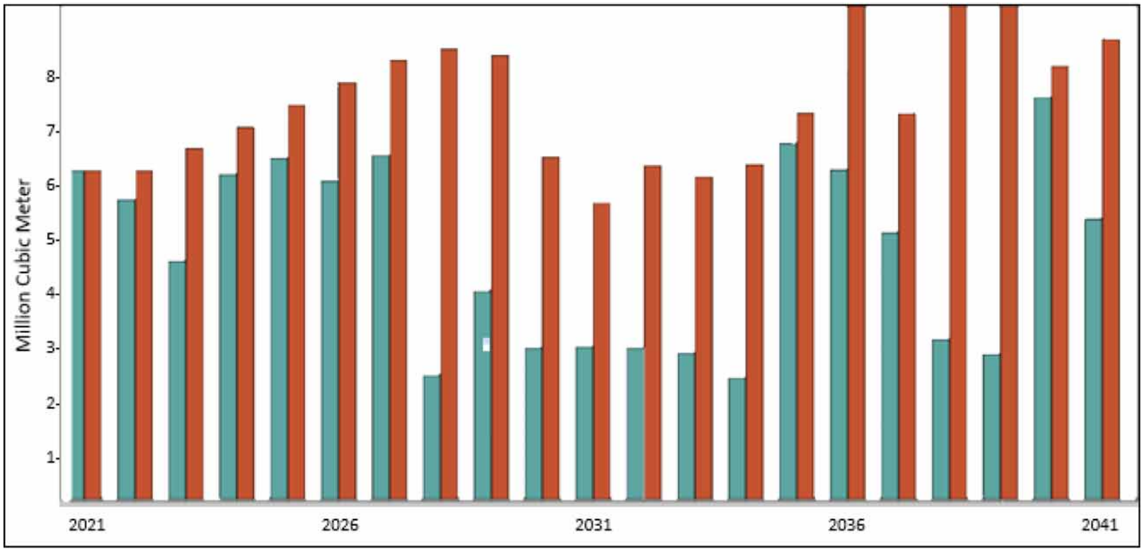

Figure 3 | Projected water allocation in the basin from groundwater (green) and the reservoir (red).

1 m/day. In general, the behavior of the aquifer shows that although inhomogeneous and locally confined, at the plain level it behaves and is characterized as an unconfined aquifer. The Mires alluvial aquifer is the most important in Messara valley. Its water capacity has been estimated at $86 \times 10^6\,m^3$ of water volume, based on the drilling data of the FAO of 1972 (Varouchakis *et al.* 2012). However, the current real storage volume of the alluvial aquifer is smaller and is estimated at $55 \times 10^6\,m^3$, due to the groundwater over-exploitation (Kritsotakis & Tsanis 2009).

A reservoir (at Feneromeni area) of 17 Mm^3 capacity has been constructed in the basin and is the major source of surface water. It became operational for the first time in 2010, but the irrigation water distribution networks were completed in 2013. Another potential source of surface water is from the wastewater treatment plant of the area that is expected in the near future to use tertiary treatment of the effluent, so the water is suitable for re-use. Conservation and storage of excess surface water for future requirements is an important factor for MAR efficient application. The Projected Irrigation demand in the basin and water allocation from groundwater (green) and the reservoir (red) using climate change scenarios, population variation, agricultural water demand and projected water availability was determined through the Water Evaluation and Planning System (WEAP) model application (Figure 3).

2.2. Suitability mapping with GIS-MCDA

The process of a GIS-MCDA involves several phases to spatially calculate and define the suitable areas to implement MAR as described in detail in Dupont (2018) and Sallwey *et al.* (2018):

1. Set the goal/define the problem (Keeney 1992).
2. Determine the criteria (Malczewski & Rinner (2015).
3. Define the criteria values (Malczewski & Rinner (2015).
4. Determine the weight of each factor. The 'Pairwise comparison method' is applied (INOWAS 2018) which is part of the Analytical Hierarchy Process (AHP), developed by Saaty (1980).
5. Aggregate the criteria. Weighted Linear Combination (WLC) is applied where the suitability score S is calculated using the following equation:

$$\boldsymbol{S} = \Sigma \boldsymbol{w_i}\, \boldsymbol{x_i} \tag{1}$$

   where **S** is the composite suitability score, $\mathbf{w_i}$ is the weight assigned to the factor criterion i, $\mathbf{x_i}$ is the index of the factor criterion at the cell considered i, Σ is the sum of weighted factor criteria.

6. Validate/verify the result using locations from a field survey.

3. RESULTS AND DISCUSSION

3.1. MAR in Geropotamos basin

The area has been facing significant problems with its groundwater as the level is showing a significant drop and part of the groundwater is facing problems with its quality. The sustainable yield of groundwater exploitation has been determined to 25 meters above sea level (m.a.s.l.) for the inland area and 10 m.a.s.l. for the coastal area (Varouchakis 2016). A good location for MAR spreading methods should normally be close to a source of excess water, have flat terrain with permeable soils and be surrounded by an unconfined aquifer. On the other hand, an MAR application on the designated sites and the continuous monitoring and sampling of the groundwater in association with the improvement of agronomic practices will improve the quality of existing groundwater.

3.1.1. Choice of criteria

Criteria combining a high relevance and high data availability, and providing unique information were selected to assess the suitability of MAR spreading methods in Geropotamos basin (INOWAS 2018):

1. Slope (influences how water from the surface infiltrates. For spreading techniques to maximize infiltration and reduce runoff, a flat landscape is necessary.)
2. LU (outlines the potential environmental issues and land availability needed to undertake a MAR project.)
3. Hydrogeology (determines the hydraulic conductivity, continuity (fractures, karst), and confinement of the aquifer as factors that affect the capacity to store water in the ground.)
4. Rainfall (Variations in rainfall have an impact on stream discharge, which affects the potential water supply for MAR. However, the water will be stored as groundwater for the dry season and preferentially taken during high discharge seasons)
5. GL (plays a significant role in the MAR spreading methods at enhancing water quality since it affects how effectively water may be filtered via the unsaturated media)
6. Soil texture (determines whether water may be infiltrated through the unsaturated zone)
7. Distance to source water (MAR implementation is only possible if a source of surface water is located nearby).

3.1.2. Standardization of factor criteria

An index is used to standardize the factor criteria ranging from 1 (minimum suitability) to 5 (maximum suitability), as presented in Table 1. It is significant to highlight that when values are assigned to criteria, they primarily reflect the developer's preferences based on their own opinion, familiarity with the research topic and the study area.

The suitability maps (Figure 4) for each criterion were created with the following principles in mind (Dupont 2018):

- Slope: A key factor in determining whether a place is suitable for spreading methods is the terrain slope. In fact, places with little runoff – which only occur on flat terrains – will obtain the best infiltration.
- LU: The LU affects surface runoff and provides details on the land's suitability for MAR site implementation. Scrub and/or herbaceous vegetation associations, sparsely vegetated areas with soils of sufficient infiltration potential and little conflict in terms of land disturbance because these terrains typically do not have a specific use, are all characteristics of terrains that are likely to offer large areas for spreading methods.
- GL: The lower the GL the greater the need for MAR. Also, the penetration of water into the underground aquifer is easier.

Table 1 | Correspondence between scale of standardization index and suitability level

Suitability class	Index
Highly suitable	5
Suitable	4
Moderately suitable	3
Low suitability	2
Unsuitable	1

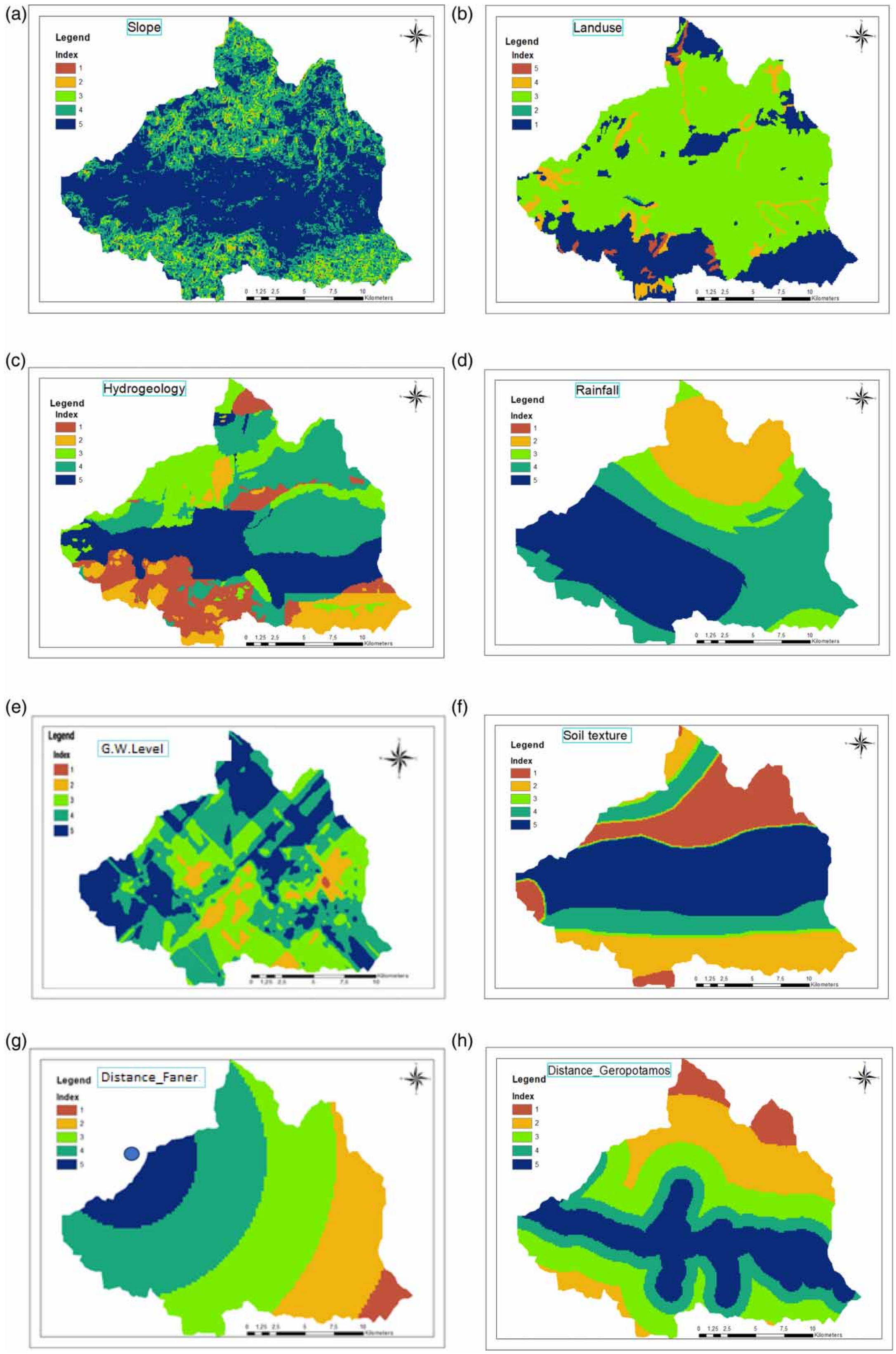

Figure 4 | Criterion map for MAR suitability in Geropotamos basin; (a) Slope; (b) Land use; (c) Hydrogeology; (d) Rainfall; (e) Groundwater Level; (f) Soil Texture; (g) Distance to Faneromeni dam; (h) Distance to Geropotamos river.

- Soil: The amount of water that may permeate through the unsaturated zone and reach the aquifer depends on the texture of the soil.
- Distance to source water: One prerequisite for setting up a MAR site for spreading methods is having an abundance of water nearby at a distance that is manageable economically. In this study, two water sources were examined, the dam of Faneromeni and the river of Geropotamos.
- Rainfall: The lower the amount of rainfall the greater the need for MAR.
- Hydrogeology: The more permeable a layer is, the more suitable it is for groundwater recharge.

3.1.3. Weight assignment

Each criterion is given a weight based on how important it is in relation to the other criteria. In this study, four scenarios were examined. In the first scenario, the criterion of distance to the water source was not taken into account. In the second and third scenarios, the criterion of the distance to the dam of Faneromeni (Figure 4 , blue circle) and to the river of Geropotamos was considered. Finally, in the fourth scenario, both distances to the dam of Faneromeni and the river of Geropotamos were added to the criteria. There are various techniques for allocating criteria weights, such as the 'Pairwise comparison' method created by Saaty (1980) as part of the AHP (Vargas 2011; Dupont 2018).

The importance of each criterion compared to every other criterion is calculated by means of a scale from 0 to 9 in a pairwise comparison matrix (>1, the criterion is considered less important than the other; 1, designates that both are considered equally important; 2–9, the criterion is considered more important than the other), (Tables 2–4). The calculated score is then transformed into relative weights (Tables 5–7).

The application of the proposed method provided that slope, hydrogeology and water source distance are the most important criteria. Even if all other conditions are very favorable, steep slopes are not appropriate for spreading methods application since most of the available water will be lost to runoff. In addition, since there needs to be an appropriate aquifer to store water, hydrogeology was regarded as being equally significant to slope for spreading methods. Consequently, hydrogeology was calculated as the second most important criterion in scenarios 2 & 3 and the third most important in scenario 4. Finally, the criteria 'Land use' and 'Rainfall' were assigned with the lowest weights.

The weights were calculated as follows:

$$\text{Weights} = \text{Total } 1/\sum \text{Total } 2_i \tag{2}$$

The final weights were calculated, normalizing the weights, dividing all the weights with the lightest weight and rounding them. This method of calculating the final weights was performed for all scenarios.

3.2. Suitability maps after criteria combination

Based on the method WLC (Equation (1)) and the results of the method 'Pairwise comparison', the following combinations of criteria are obtained for each scenario to obtain the maps of Figure 5:

Scenario 1: $6H + R + 3GL + 5Sl + 4So + LU$

Scenario 2&3: $5H + R + 3GL + 6Sl + 3So + LU + 6D$

Scenario 4:$5H + R + 3GL + 7Sl + 3So + LU + 6D.F + 6D.G$

where H is the Hydrogeology Map, R is the Rainfall Map, GL is the Groundwater Level Map, Sl is the Slope Map, So is the Soil texture Map, LU is the Land Use Map, D.F is the Distance to Faneromeni dam Map, D.G is the Distance to Geropotamos river Map.

The suitability maps for the different scenarios resulting from the GIS-MCDA (Figure 5) indicate:

- for scenario 1 (Figure 5(a)), the highest suitability for MAR spreading methods in Geropotamos basin covers the western part and some areas in the central part of the region (Agios Ioannis, Petrokefalo, Kousses, Vagionia, Choustouliana, Platanos, Mitropoli, Kappariana). This result is logical as the slope in this area is small, the hydraulic conductivity is high, the rainfall is limited and the GL is low.
- for scenario 2 (Figure 5(b)), the highest suitability for MAR spreading methods in Geropotamos basin covers the western part of the region (Agios Ioannis, Mires, Kalivia, Kappariana). As in scenario 1, in scenario 2 the result is logical for the same reasons, with the difference that in scenario 2, the appropriate areas were reduced due to the criterion of distance

Table 2 | Pairwise comparison matrix for suitability of MAR spreading methods in Geropotamos basin (scenario 1)

Scenario 1	Hydrogeology	Rainfall	Groundwater level	Slope	Soil	Land use	Total 1
Hydrogeology	1	5	2	1	3	5	17
Rainfall	0.20	1	0.5	0.2	0.50	1	3.40
Groundwater level	0.50	3	1	0.5	2	3	10
Slope	1	5	2	1	1	5	15
Soil	0.33	5	0.50	1	1	3	10.83
Land use	0.20	1	0.33	0.20	0.33	1	3.06
Total 2	3.23	20	6.33	3.90	7.83	18	59.29

Table 3 | Pairwise comparison matrix for suitability of MAR spreading methods in Geropotamos basin (scenarios 2 & 3)

Scenarios 2 & 3	Hydrogeology	Rainfall	Groundwater level	Slope	Soil	Land use	Distance	Total 1
Hydrogeology	1	5	2	1	3	5	1	18
Rainfall	0.20	1	0.50	0.20	0.50	1	0.14	3.54
Groundwater level	0.50	3	1	0.50	2	3	0.50	10.50
Slope	1	5	2	1	1	5	5	20
Soil	0.33	5	0.50	1	1	3	0.20	11.03
Land use	0.20	1	0.33	0.20	0.33	1	0.25	3.31
Distance	1	7	2	0.20	5	4	1	20.20
Total 2	4.23	27	8.33	4.10	12.83	22	8.09	86.58

Table 4 | Pairwise comparison matrix for suitability of MAR spreading methods in Geropotamos basin (scenario 4)

Scenario 4	Hydrogeology	Rainfall	Groundwater level	Slope	Soil	Land use	Distance F	Distance G	Total 1
Hydrogeology	1	5	2	1	3	5	1	1	19
Rainfall	0.20	1	0.50	0.20	0.50	1	0.14	0.14	3.68
Groundwater level	0.50	3	1	0.50	2	3	0.50	0.50	11
Slope	1	5	2	1	1	5	5	5	25
Soil	0.33	5	0.50	1	1	3	0.20	0.20	11.23
Land use	0.20	1	0.33	0.20	0.33	1	0.25	0.25	3.56
Distance F	1	7	2	0.20	5	4	1	1	21.20
Distance G	1	7	2	0.20	5	4	1	1	21.20
Total 2	5.23	34	10.33	4.30	17.83	26	9.09	9.09	115.87

Table 5 | Final weights – scenario 1

Criteria	Weights	Final weights
Hydrogeology	0.29	6
Rainfall	0.06	1
Groundwater level	0.17	3
Slope	0.25	5
Soil	0.18	4
Land use	0.05	1

Table 6 | Final weights – scenarios 2 & 3

Criteria	Weights	Final weights
Hydrogeology	0.21	5
Rainfall	0.04	1
Groundwater level	0.12	3
Slope	0.23	6
Soil	0.13	3
Land use	0.04	1
Distance	0.23	6

Table 7 | Final weights – scenario 4

Criteria	Weights	Final weights
Hydrogeology	0.16	5
Rainfall	0.03	1
Groundwater level	0.09	3
Slope	0.22	7
Soil	0.10	3
Land use	0.03	1
Distance F	0.18	6
Distance G	0.18	6

from the dam of Faneromeni. The dam is located northwest of the study area (blue circle, Figure 5(b) and 5(d)); therefore, the areas to the east are not suitable as they are in scenario 1.

- for scenario 3 (Figure 5(c)), the highest suitability for MAR spreading methods in Geropotamos basin covers the western part and some areas in the central part of the region (Agios Ioannis, Mires, Petrokefalo, Platanos, Dionysi, Stavies, Kasteli, Mitropoli, Flathiakes, Vagionia), particularly around the Geropotamos River. The result of scenario 3 is very similar to that of scenario 1, in terms of the most suitable areas, with the difference that in scenario 3 the most suitable areas around the river Geropotamos have increased.
- for scenario 4 (Figure 5(d)), the highest suitability for MAR spreading methods in Geropotamos basin covers the western part of the region (Agios Ioannis, Kalyvia, Mires). The most suitable areas in scenario 4 are almost common with those of scenario 2. This is logical as looking at the maps of scenario 2 and scenario 3, we notice that they have some parts in common in which the suitability is greatest. Table 8 shows the results of the four scenarios.

The present study used the GIS-MCDA method to identify suitable sites for implementing MAR type spreading method in Geropotamos basin. If we consider all the factors assessed in the study area at the locations where the suitability is greater for each scenario separately, we observe the following:

Scenario 1:

- The percentage slope is 0.00059–1.09318 (the smallest slope of the study area).
- These areas are mainly agricultural, which makes sense as the region's economy relies on the agricultural sector.
- In terms of hydrogeology, there are granular alluvial deposits mainly with ranging hydraulic conductivity (P1).
- Rainfall is the lowest we encounter in the Geropotamos basin.
- The GL in the areas that came out more suitable is the lowest in the Geropotamos basin.
- The soil texture is alluvial with REGOSOLS

Scenario 2:

For scenario 2, the same applies as for scenario 1 for each factor separately in the areas with the highest suitability, with the difference that the areas that are more suitable have been greatly reduced as the distance factor from the Faneromeni dam has

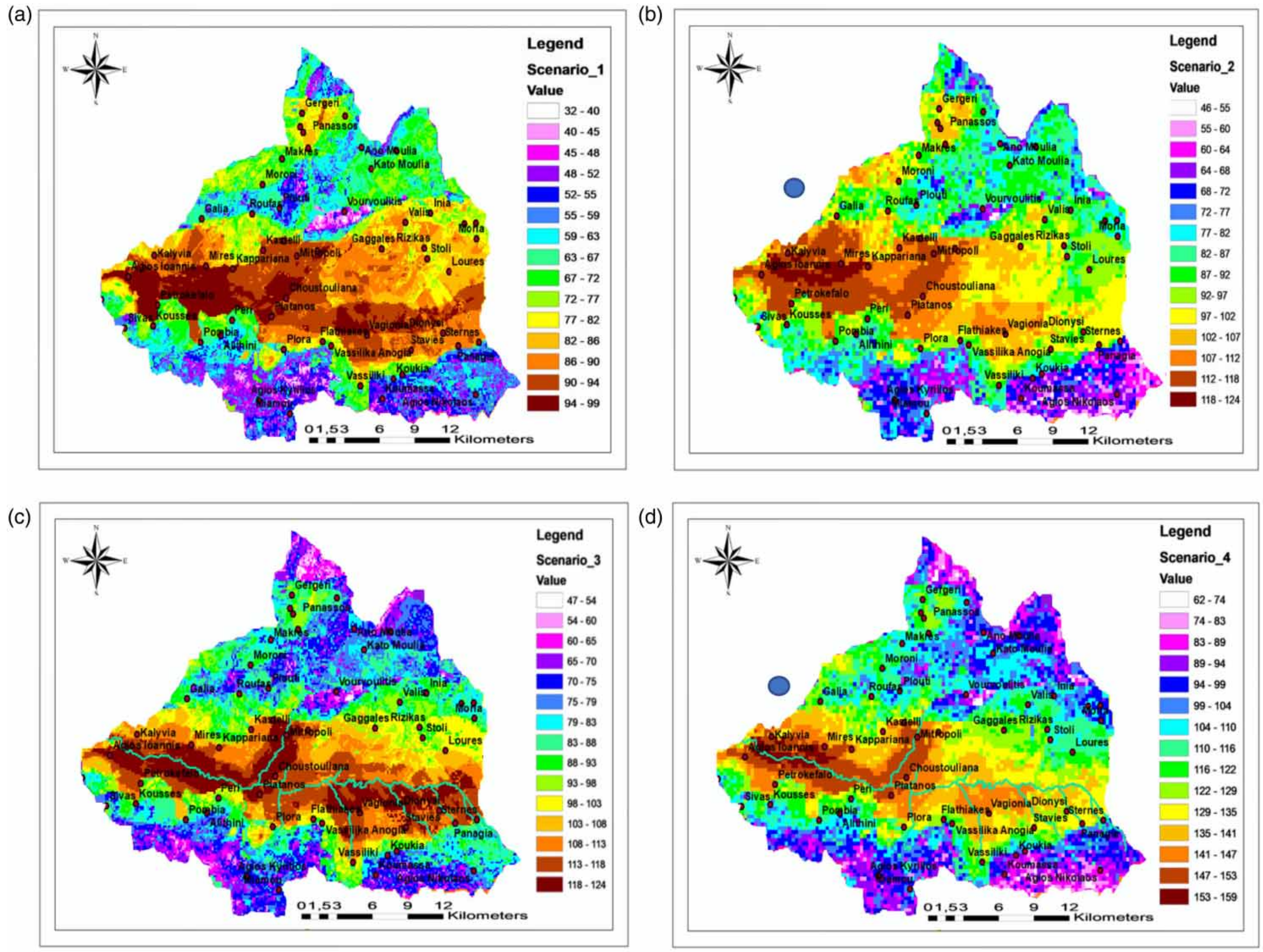

Figure 5 | Suitability map for MAR spreading methods in Geropotamos basin; (a) Scenario; 1 (b) Scenario 2 considering Distance to Faneromeni dam; (c) Scenario 3 considering Distance to Geropotamos river; (d) Scenario 4; blue dot denotes the dam location.

Table 8 | Results

Scenario	Criteria combination	Suitable areas
1	6H + R + 3GL + 5Sl + 4So + LU	Agios Ioannis, Petrokefalo, Kousses, Vagionia, Choustouliana, Platanos, Mitropoli, Kappariana
2	5H + R + 3GL + 6Sl + 3So + LU + 6D	Agios Ioannis, Mires, Kalivia, Kappariana
3	5H + R + 3GL + 6Sl + 3So + LU + 6D	Agios Ioannis, Mires, Petrokefalo, Platanos, Dionysi, Stavies, Kasteli, Mitropoli, Flathiakes, Vagionia
4	5H + R + 3GL + 7Sl + 3So + LU + 6D.F + 6D.G	Agios Ioannis, Kalivia, Mires

been added. Thus, the most suitable areas are those that are closer to the Faneromeni dam, but combining all the above characteristics.

Scenario 3:

For scenario 3, the same applies as for scenario 2, with the difference that the most suitable areas are those that are closer to the river of Geropotamos.

Scenario 4:

For scenario 4, the same applies as for scenario 2. This is logical as looking at the maps of scenario 2 and scenario 3, we notice that they have some parts in common in which the suitability is greatest.

Overall, we observe that the method worked very well as the areas that seem to be the most suitable for aquifer recharge are the most suitable for each factor separately. The proposed suitable areas for MAR applications agree with previous hydrogeological works in the area (Kritsotakis 2010; Ioanidou 2016; Special water secretariat of Greece 2017).

4. CONCLUSIONS

The most suitable technique for planning the aquifer recharge was selected according to the area characteristics. The spreading method was assessed as the most suitable technique based on the area characteristics that should typically have a source of excess water available nearby, be located in a relatively flat area with permeable soils and be underlined by an unconfined aquifer. Suitability maps provide a useful starting point for identifying areas where additional field tests need to be performed to accurately locate suitable locations for MAR application. The outcome of this work is a simple framework methodology for selecting the most suitable recharge locations of the underlying aquifers that can be easily linked for socioeconomic and environmental analysis. This simple methodology could be used as an efficient visual tool to raise awareness on the wide applicability of MAR and encourage water authorities to consider MAR more often for water resources management strategies. The results of this work will assist local authorities to consider the applicability of aquifer recharge in the Messara valley while it consists of a framework for efficient planning of similar applications in other Mediterranean regions.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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