



# A Participatory GIS-based Multicriteria Decision Analysis Approach to Map the Geospatial Feasibility of Managed Aquifer Recharge in a Tunisian Coastal Watershed

Anis Chekirbane<sup>1</sup> · Khaoula Khemiri<sup>1</sup> · Tiago N. Martins<sup>2</sup> · Catalin Stefan<sup>3</sup> · Constantinos F. Panagiotou<sup>4</sup>

Received: 17 December 2024 / Accepted: 16 April 2025 / Published online: 25 April 2025  
© The Author(s) 2025

## Abstract

Managed aquifer recharge (MAR) is essential for enhancing groundwater storage and ensuring long-term water sustainability, particularly in semiarid regions. This study focuses on identifying and mapping suitable MAR areas in the Chiba watershed, Tunisia, by integrating hydrogeophysical, hydrological, and socioeconomic criteria. The methodology combines geographical information systems (GISs), multicriteria decision analysis (MCDA), and hydrological modeling. A stakeholder-driven analytical hierarchical process (AHP) is used to assess the MAR suitability criteria. To capture seasonal variability, the feasibility assessment is conducted separately for wet and dry periods. Three thematic layers are considered: the intrinsic hydrogeophysical conditions of the site (IS), water availability (WA), and water demand (WD). The results indicate that water availability is the dominant factor (49.3%), followed by water demand (30%) and site conditions (20%). MAR feasibility maps show that areas classified ‘highly’ to ‘very highly feasible’ represent 19% of the total watershed area. The maps highlight also the coastal areas as highly suitable because of their optimal hydrogeological characteristics, surplus water resources, and high agricultural and ecological demands. In contrast, upstream areas are less feasible because of their limited recharge potential and lower water availability. The maps also suggest specific MAR typologies, such as using treated wastewater in coastal areas and infiltration basins upstream. In conclusion, this study provides a replicable framework for integrating MAR into water policies by aligning site selection with recharge objectives, available water sources, and socioeconomic factors. The findings emphasize the critical role of stakeholder engagement in MAR planning and its embedding in existing water policies, providing a replicable framework for improving groundwater management in semiarid regions.

## Highlights

- Managed aquifer recharge (MAR) suitable areas are identified and mapped.
- A participatory decision-making process is proposed to select feasible MAR areas.
- MAR-related criteria are grouped into three thematic layers.
- The recharge problem is formulated in terms of MAR typology.
- Stakeholders are engaged in different components of the decision-making process.

Extended author information available on the last page of the article

**Keywords** MAR typology · Stakeholder-adapted approach · Analytical hierarchical process · MAR planning · Decision-making

## 1 Introduction

Users of natural water resources are finding that optimal management of freshwater stocks is becoming crucial in light of current global changes (Ingrao et al. 2023). Because of the intense water demands that emerge in highly populated coastal zones, as well as their proximity to seawater, the water quality of existing coastal aquifers is often degraded due to the intrusion of seawater (Werner et al. 2013; Panagiotou et al. 2022b). The reuse of treated water is a practical way to increase water availability for irrigation while reducing direct or indirect water stress in these areas (Kumar and Yadav 2025; Huang et al. 2024; Çiftçiöğlü-Gözüaçık et al. 2023; Neto et al. 2018). For example, treated wastewater effluent is often intentionally infiltrated into underlying aquifers for future retrieval or for environmental benefits, a technique known as managed aquifer recharge (MAR) (Dillon et al. 2019). Consequently, MAR is a nature-based solution aimed at enhancing the replenishment of aquifers via a wide range of infiltration techniques, such as infiltration ponds, injection wells, and dam water release. The storage of water in aquifers is a key factor in the effective management of surface and subsurface porous systems and buffers the impacts of extreme hydroclimatic events, especially those associated with alternating flood and drought cycles, whereas it preserves and improves the quality status of an aquifer (Dillon et al. 2019). Currently, MAR is widely used on a global scale (Panagiotou et al. 2022a, b, c; Stefan and Ansems 2018) because of its ability to adapt to specific local contexts and needs (Fernández Escalante et al. 2022). However, there are a series of challenges related to the correct assessment of its technical, economic, environmental and social feasibility, which currently hinders further penetration of these nature-based solutions into the Integrated Water Resources Management (IWRM) framework. Among these bottlenecks, the identification of optimal locations for MAR implementation is crucial, as it depends on a plethora of interlinked criteria that must be balanced to maximize the potential benefits while minimizing the costs and resources needed for implementation and sustainable operation.

Numerous hydrogeological studies have combined MCDA with geographic information systems (GISs) (Rahman et al. 2012; Ravichandran et al. 2022; Sallwey et al. 2019; Slimani et al. 2024) to identify feasible regions for MAR installation. On the other hand, GIS makes it easier to visualize and analyze intricate spatial linkages, whereas MCDA offers a systematic decision-making framework for assessing the relative impact of various factors concerning a prespecified problem. GIS-based MCDA has been widely used to address groundwater problems, such as the identification of groundwater potential zones (Antonakos and Lambrakis 2021; Tiwari et al. 2017; Fathi et al. 2020; Sahu et al. 2022; Wijesinghe et al. 2023; Zghibi et al. 2020), groundwater quality assessment (Kavurmaci 2016; Srivastava et al. 2024), aquifer vulnerability assessment (Saravanan et al. 2023; Teixeira et al. 2023), and MAR suitability (Aloui et al. 2022; Sallwey et al. 2019; Soliman et al. 2022). It has also been applied in California, USA, where it effectively integrates biophysical and socioeconomic criteria to identify and prioritize suitable agricultural managed aquifer recharge (Ag-MAR) sites (Marwaha et al. 2021). However, the study lacked a participatory weighting process, which could have strengthened the analysis by incorporating stakeholder insights and local water management priorities. Similar studies have also been conducted in some European countries, such as in agricultural areas in northern

Greece (Papadopoulos et al. 2022). However, it does not consider any specific MAR typology, such as recharge objectives, techniques and water sources, which are essential for tailoring MAR feasible locations to local conditions and ensuring their practical feasibility.

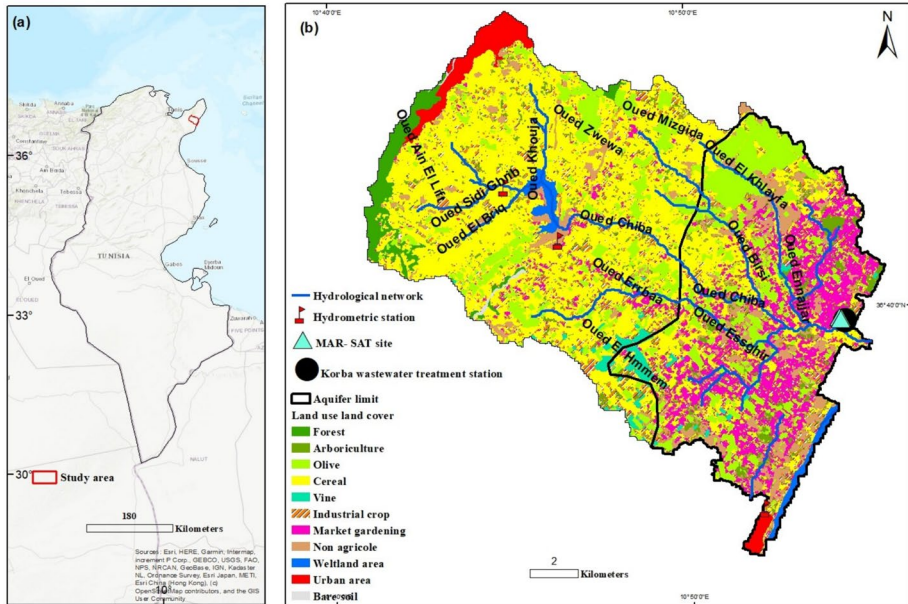
Despite significant advancements, existing studies still exhibit key limitations that hinder the optimal contribution of MAR solutions to sustainable water resource management. First, many approaches focus primarily on the intrinsic characteristics of MAR schemes, such as topography and hydrogeology, while often overlooking critical socioeconomic, institutional, and environmental factors that influence MAR feasibility and long-term success. Second, most studies fail to integrate decision-maker perspectives into the evaluation process, missing an opportunity to minimize potential conflicts and enhance stakeholder engagement during MAR implementation. Third, existing frameworks tend to apply a standardized set of criteria across the three components of MAR typology — the recharge objective, water source, and recharge techniques — despite their distinct regional variations and challenges. As a result, many recommendations lack adaptability and context-specific relevance.

To address these gaps, this study introduces an integrated and participatory GIS-MCDA framework that enhances MAR suitability assessments by: (1) incorporating both physical and nonphysical aspects, stakeholder-driven weighting, and region-specific criteria, ensuring a more robust and adaptable methodology; and (2) embedding a participatory approach that actively involves multiple actors at different stages of decision-making, improving acceptance and facilitating real-world implementation. Unlike previous studies, this study explicitly considers MAR typology in the suitability mapping process, offering a more nuanced and transferable methodology. By bridging hydrological science with stakeholder-driven decision-making, this research contributes a replicable framework that can be adapted to diverse hydrogeological and socioeconomic contexts worldwide, making it relevant for an international audience concerned with sustainable groundwater management.

## 2 Description of the Study Area

The Chiba watershed is located in the northeastern part of Tunisia, on the eastern side of the Cap-Bon peninsula (Fig. 1a). It covers an area of 204 km<sup>2</sup>, with terrain elevations varying from 2 to 483 m above sea level (m.a.s.l.). The region is characterized by a subhumid climate, with strong spatiotemporal variations in precipitation patterns. According to ground-based rainfall stations in the Chiba watershed, the average annual precipitation was  $468.7 \pm 75.6$  mm/year from 2009 to 2021. The Chiba Wadi serves as the primary drainage channel, extending from the mountains to the Mediterranean Sea. The Chiba dam, built in 1963 primarily for surface water retention for irrigation, covers 64 km<sup>2</sup> of the upstream area, which is in a natural state. Korba Lagoon runs along the coast and is approximately 8.5 km long, with erratic banks and a width that varies from 180 to 320 m. The lagoon surface area varies between 170 and 210 ha. The lagoon is isolated from the sea by a barrier beach. A channel that connects to the Sidi Othmane wadi is formed as the northern portion narrows (Fig. 1b).

The Chiba watershed has a complex geological morphology characterized by various sedimentary formations. The upper and middle-marine Pleistocene deposits (Tyrrhenian deposits) dominate large portions of the region, consisting primarily of sands and clays. Adjacent to these deposits, continental Pleistocene deposits include fluvial and aeolian sediments, contributing to the stratigraphic diversity of the region. The Marine Pliocene is

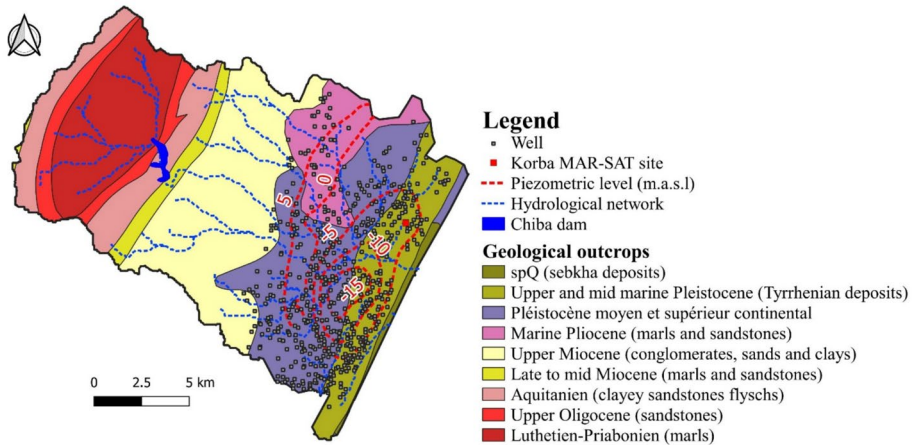


**Fig. 1** a Geographical location of the Chiba watershed; (b) general settings of the Chiba watershed including land cover and hydrological network

composed of alternating marls and sandstones, which form significant aquifer units. Further inland, the Upper Miocene consists of conglomerates, sands and clays, whereas the late to mid-Miocene formations are predominantly marls and sandstones. The Aquitanian unit is characterized by clayey sandstone flysch, indicative of a more consolidated geological history. Older deposits include the Upper Oligocene sandstones, which form deeper aquifer layers, and the Lutetien-Priabonien marls, which serve as more compact and less permeable substrate (Fig. 2).

The Chiba watershed is characterized by intensive agricultural activities that rely heavily on groundwater extraction from the Korba aquifer, with approximately 579 wells currently pumping nearly 54 Mm<sup>3</sup>/yr from the shallow unconfined aquifer (Ben Hamouda 2008; Ennabli 1980; Zghibi et al. 2013). The majority of this water is used for irrigation, placing significant pressure on the aquifer and leading to its overexploitation. The measured piezometric levels in the Korba aquifer revealed a pronounced decline, particularly in the downstream and coastal areas (Fig. 2). Historical data indicate a significant decrease from 0 m.a.s.l. in 1963 to – 15 m.a.s.l. in 2018, highlighting the effects of overexploitation (Gaaloul 2012; Chekirbane et al. 2013; Zghibi et al. 2019). This depletion has intensified seawater intrusion, particularly in coastal areas such as the Diar Hojje zone, where rising salinity levels have significantly deteriorated water quality. Recent studies indicate that the saltwater front has already migrated 0.8 km inland as of 2014, and projections suggest that by 2050, it could extend up to 1.8 km inland, advancing an additional 1 km over a 43-year period if current trends persist (Zghibi et al. 2019).

Water authorities are suggesting creating the Korba MAR site as a solution to these problems to address the lowering groundwater levels and poor quality of the water. This project, which is situated 1.5 km from the Mediterranean Sea and approximately 300 m north of the Korba wastewater treatment plant, uses secondary treated municipal wastewater



**Fig. 2** Geological and hydrogeological settings of the study area

(Fig. 1b). The existing MAR site uses a soil aquifer treatment (SAT) process based on three infiltration ponds, each covering an area of approximately 1500 m<sup>2</sup>, designed to achieve a recharge rate of 1500 m<sup>3</sup>/day. However, the ability of the MAR facility to increase groundwater levels is limited due to clogging, the use of treated wastewater with poor quality and the comparatively small size of the infiltration basins (Gaaloul 2012; Mekni and Souissi 2016). As a result, a significant sustainability challenge plagues most MAR initiatives in Tunisia overall, specifically within the Chiba watershed. The main reason behind the failure of these initiatives stems from the fact that these initiatives have been reactionary responses to the demands of both quantitative and qualitative degradation as well as over-exploitation of groundwater, without any prior evaluation of the suitability and viability of the MAR system.

### 3 Methodology

Figure 3 shows an overview of the participatory approach. The first step is to determine the key components of MAR typology, namely, the recharge objective, the recharge method, and the available amount of water source for MAR. Relevant constraints such as wetlands and forest zones were used to exclude unsuitable areas within the study region.

The second step focuses on determining parameters, referred to as criteria, that are pertinent to the selected MAR typology across three thematic layers: intrinsic hydrogeological characteristics, water availability for MAR implementation, and the water demand associated with aquifer-dependent services. An initial set of criteria was determined via a comprehensive literature review, consultations with MAR specialists, technical reports on existing MAR systems in Tunisia and the perspectives of the relevant stakeholders, which were collected via surveys. These criteria were validated through stakeholder workshops held in July 2023. Ultimately, eight criteria were selected to evaluate the intrinsic suitability of the study area: five criteria for water availability assessment and two for assessing water demand.

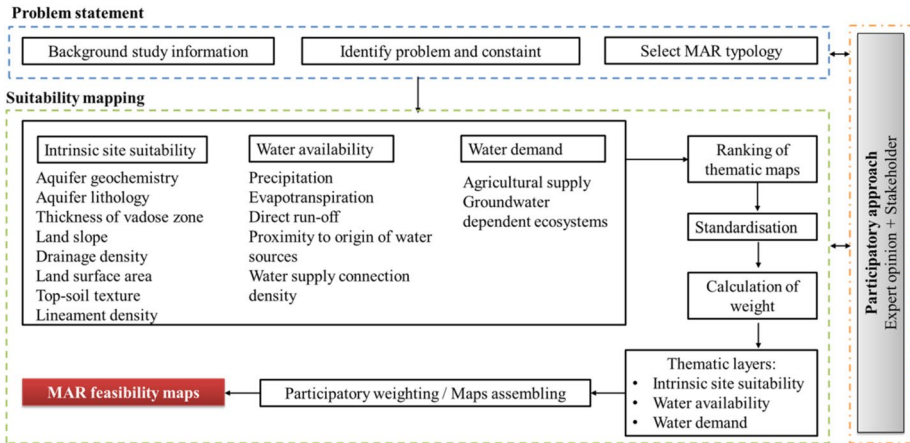


Fig. 3 Flowchart of the stakeholder-tailored feasibility process

The third step involves the harmonization of all criteria into a common grid and the standardization of the selected criteria to a scale of 0.2 to 1.0, ensuring consistency and reflecting significant variations in MAR suitability within the study area and facilitating comparison and integration in the analysis. For both continuous and discrete datasets, including slope, rainfall, soil texture classes or geological formations, stepwise discretization is used to categorize values into thematic groups. This approach allows for meaningful representation of diverse data types while maintaining consistency across the criteria. In this step, relevant stakeholders, including representatives from the national, regional and local water authorities, assigned weights to the criteria on the basis of their relevance to MAR typology. The weighting of the criteria is performed via an analytical hierarchical process (AHP), which adheres to the principles established by Saaty (1987) and was further refined in the work of Bozóki and Rapcsák (2008). These weights, combined with standardized maps, were used in the fourth step to produce thematic suitability maps. For each thematic layer, stakeholders assess the relative contribution of each pair of criteria via a numerical scale ranging from 1/9 to 9. In particular, the acceptable levels of importance are as follows: equal (1), weak (2 to 3), moderate (3 to 4), strong (5 to 6), and very strong (7 to 9). According to the reciprocal property, inverse scaling is applied for the less important parameters, thus ranging from 1/9 to 1 Saaty (1987). These scores are used to construct the pairwise comparison matrix, ensuring that each criterion is compared against all others within the same thematic category. The consistency of the pairwise comparisons is evaluated by the consistency ratio (CR) (Saaty 1987)

$$CR = \frac{CI}{RI} \tag{1}$$

where *CI* denotes the consistency index, and *RI* denotes the random index.

According to the literature (Bozóki and Rapcsák 2008; Saaty 1987), a *CR* value below 0.1 is considered acceptable, whereas higher values indicate the need to repeat pairwise comparisons. In the present work, all the *CR* values were lower than 0.1.

The pairwise elements are normalized via the following equation:

$$b_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n_c} a_{kj}} \quad (2)$$

where  $a_{ij}$  is an element of the pairwise matrix and  $n_c$  is the total number of rows (equal to the total number of criteria). Next, the weights ( $w_i$ ) are calculated via the following expression:

$$w_i = \frac{\sum_{q=1}^{n_c} b_{iq}}{\sum_{j=1}^{n_r} [\sum_{k=1}^{n_c} b_{jk}]} \quad (3)$$

For each thematic layer, the suitability index ( $SI$ ) is calculated by multiplying the weighting coefficients with their respective standardized scores ( $SS$ ) at each grid location ( $u_a$ ) via weighted linear combination (WLC):

$$SI(u_a) = \sum_{k=1}^p w_k \times SS_k(u_a). \quad (4)$$

The suitability indices of the three thematic layers are then combined to evaluate the MAR feasibility index at each location:

$$FI(u_a) = \sum_{j=1}^3 \tilde{w}_j \times SI_j(u_a). \quad (5)$$

The thematic weights ( $\tilde{w}_j$ ) were jointly determined with the relevant stakeholders during a dedicated workshop in July 2023.

## 4 Results and Discussion

### 4.1 Problem Definition, Constraints, and MAR Typology

An initial evaluation of key criteria was conducted on the basis of existing suitability maps for MAR, as well as other MCDA applications documented in various studies (e.g., Aloui et al. 2022; Bonilla Valverde et al. 2016; Rahman et al. 2012). The selection of criteria was motivated by a comprehensive database recently compiled by Panagiotou et al. (2022a, b, c).

The primary objectives of MAR in the Chiba watershed are twofold: 1) to enhance groundwater quality; and 2) to secure long-term groundwater storage. Stakeholders also played a pivotal role in identifying the most suitable MAR techniques for the region, particularly the use of ponds and infiltration basins, soil-aquifer treatment (SAT), and regulated water discharge from dams (Table 1).

The areas subjected to natural or regulatory constraints, such as regions where MAR is legally prohibited or where it is physically unfeasible (e.g., lakes), are identified and excluded from further consideration during the decision-making process. At this point, it is important to differentiate between constrained areas assigned zero values of the feasibility index and those with low feasibility levels. While low-feasibility areas may present technical, intrinsic, or socioeconomic challenges, they are not entirely unsuitable for MAR; rather, they offer a reduced likelihood of achieving the desired MAR objectives. In the case

**Table 1** MAR typology for the Chiba watershed

Overall goal	Specific objectives	Water source	MAR scheme	Other considerations
Long term storage of groundwater	Increase piezometric levels and groundwater storage	Conventional and nonconventional water resources	Infiltration ponds and SAT (costal region) and dam water release near the dam	Water availability and demand were estimated for dry and wet seasons
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 dry and wet seasons

of the Chiba watershed, only land use constraints, specifically dense urban zones, forests, and protected areas, were considered.

## 4.2 Criteria Selection

Expert opinions and stakeholder feedback were gathered through questionnaires and surveys to identify the relevant MAR feasibility criteria in the Chiba Basin. To ensure comprehensive coverage of the watershed, the most relevant physical criteria were selected on the basis of available spatial data for both the dry and wet seasons to capture seasonal variability. These criteria were then grouped into the three thematic layers.

Eight criteria were selected to assess the intrinsic suitability (IS) of the study area. In particular, topographic data were collected from Shuttle Radar Topography Mission (SRTM) with 30 m resolution, supplemented by drainage density, lineament, and terrain slope data. Agricultural and soil texture data were obtained from the Nabeul Governorate database, whereas geological data, provided by the Office of Mines, included fault density and subsurface lithology.

Regions in the Chiba watershed with salinity levels above 3 g/L are deemed suitable for MAR. However, several studies (Ennabli 1980; Kerrou et al. 2010; Paniconi et al. 2001) report that excessive groundwater extraction exceeding 50 million m<sup>3</sup> annually has intensified seawater intrusion, degrading the Korba aquifer (MARHP and DGACTA 2022).

Lithology strongly influences aquifer recharge by affecting permeability, porosity, land use, and drainage density (Al-Djazouli et al. 2021; Fathi et al. 2020; Zhang et al. 2023). The lithology of the watershed is categorized into five types, with sand and gravel deposits being highly suitable for MAR and unfractured/clayey formations being least suitable. Vadose zone thickness also plays a critical role in MAR, with zones thinner than 20 m rated highly suitable, as they increase infiltration but may limit storage (de Vries and Simmers 2002). The terrain slope, ranging from 2 to 20 degrees, influences runoff and infiltration. Steep slopes greater than 20 degrees lead to runoff, whereas low-slope areas downstream of the Chiba dam favor infiltration (Moharir et al. 2023; Zhang et al. 2023). Drainage density, varying between 0.1 and 0.32 km/km<sup>2</sup>, indicates recharge potential, with higher density near rivers being more favorable. Land use significantly affects infiltration and runoff (Aloui et al. 2022). Categories such as arable land and pasture promote infiltration, whereas artificial areas and wetlands reduce infiltration due to increased evaporation and runoff (Arumugam et al. 2023). The soil type also influences recharge, with calcareous brown soils covering 35.93% of the watershed (MARHP 1998). Finally, lineament density, ranging from 0 to 2 km/km<sup>2</sup>, improves groundwater movement and recharge, enhancing MAR suitability (Al-Djazouli et al. 2021; Rath and Hinge 2024) (Supplementary Material (SM), Fig. SM1).

Two key categories of water availability (WA) are considered: proximity to source water and hydrometeorological parameters. MAR systems depend on recharge water sources, which vary seasonally (Fig. SM2). In the Chiba watershed, potential sources include freshwater transfers from the Medjerda Basin to the Cap Bon canal, local dams (Korba, Diar Elhojjej, and Tafelloune, operational since 1999), and treated wastewater from the Korba plant (MARHP 2006). Hydrometeorological factors, such as precipitation, evapotranspiration, and direct runoff, influence natural water availability. Rainfall ranges from 300–500 mm in the wet season and decreases to less than 45 mm in the dry season, with heavy rains concentrated in the northwest, northeast, and central-southern areas. While evapotranspiration reduces water availability, direct runoff contributes positively to the MAR by flowing

into stream channels. A SWAT model (1985–2021) revealed maximum direct runoff near Chiba Wadi and decreased evapotranspiration from downstream to upstream. Runoff above  $0.1 \text{ m}^3/\text{s}$  indicates high availability, whereas evapotranspiration above 900 mm suggests low availability.

The water demand (WD) criteria are selected on the basis of the agricultural and ecological water needs of the Chiba watershed, where water shortages are significant. Approximately 8,000 hectares of irrigated farmland depend on reliable water supplies. Spatial analysis of crop water needs versus actual irrigation supply revealed high water demand during the dry season in coastal areas dominated by market gardening and moderate demand in upstream orchards during the wet season (Fig. SM3). Korba Lagoon, a groundwater-dependent wetland and natural aquifer outlet, requires a minimum water depth of 25 cm to maintain ecological balance and offset evaporation (Baccar et al. 2001). Consequently, MAR implementation near lagoons is essential for sustaining their habitat and ecological functions.

### 4.3 Standardization Approach

All criteria maps were first sampled onto the same numerical grid with 30 m resolution and then standardized to the same scale, ranging from 0.2 to 1.0. Two techniques were employed (Rahman et al. 2012). Particularly, linear functions were used to standardize the criteria that contain continuous data. With respect to discrete data, such as soil textures or geological formations, the ‘progressive discretization’ method was used instead. The details of the standardization scheme for each criterion are presented in Table 2.

Figure 4 presents the spatial distribution of the standardized criteria across all thematic layers. The aquifer characteristics, such as geochemistry, lithology, and depth, predominantly highlight the coastal region, where the shallow aquifer consists mainly of sufficiently porous media and is influenced by seawater intrusion, making it suitable for MAR.

Land surface attributes, including slope, drainage density, and lineament density, have high suitability scores in coastal areas and near the hydrological network. The LULC map identifies small-scale regions with very low scores, notably in urban areas, surface water bodies, and forests, which are excluded from the feasibility map after applying constraint factors.

In terms of water availability, precipitation and evapotranspiration exhibit high suitability scores, mainly in the northeastern section of the watershed (to the west of the Chiba River). In contrast, high direct runoff scores are present in the central part of the watershed, emphasizing the critical role of the existing hydrological network. As expected, regions close to the recharge sources received higher suitability scores than did more distant regions.

The zones most favorable for water demand, encompassing both agricultural and ecological needs, are located primarily in the coastal areas of the watershed. These areas feature intensive irrigation activities and include the Korba Lagoon, a groundwater-dependent ecosystem that serves as the natural outlet for the aquifer.

### 4.4 Criteria Weighting

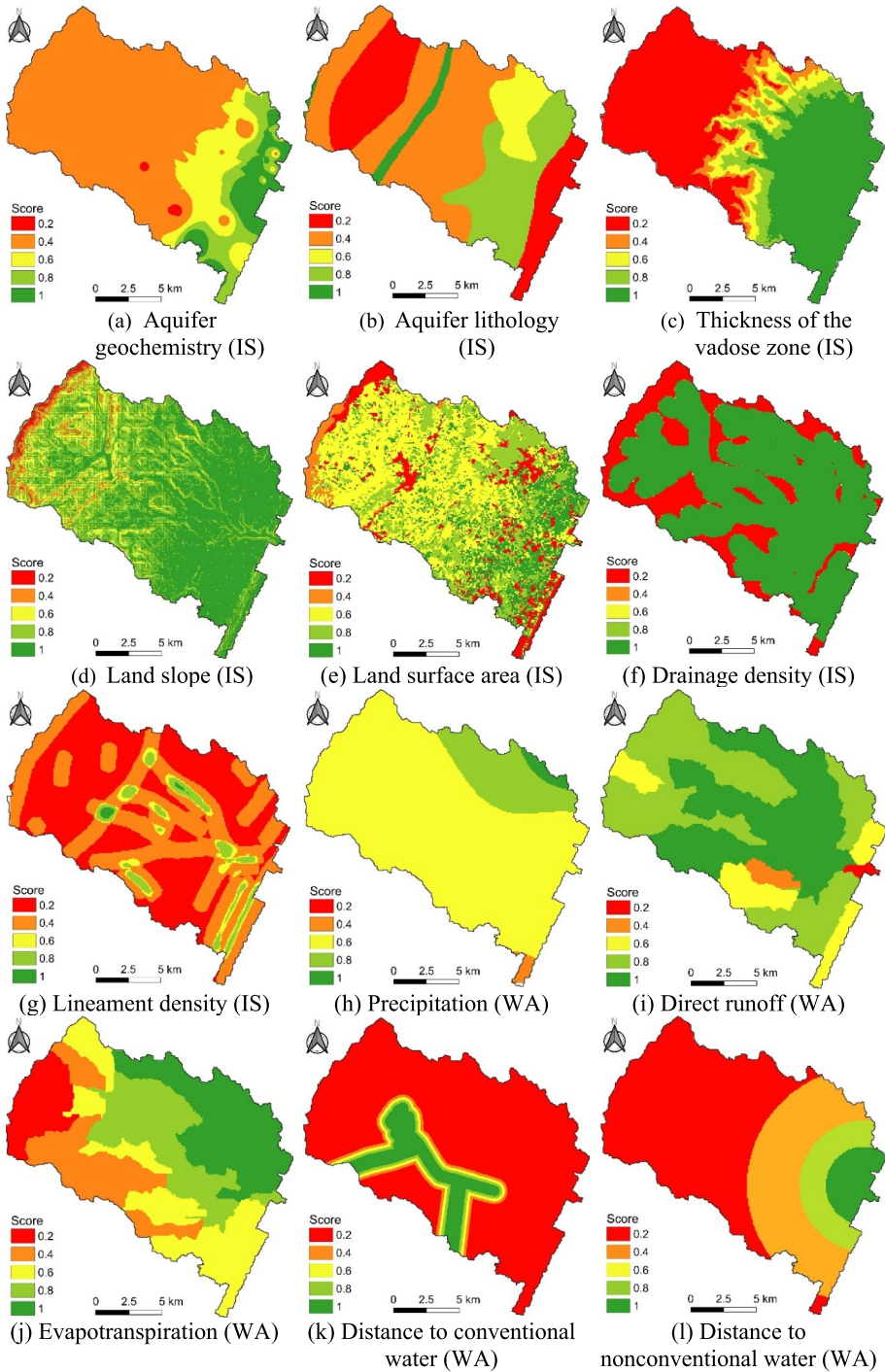
The weighting results for the MAR feasibility criteria are summarized in Fig. 5. The intrinsic site suitability criteria exhibit relatively uniform weights, ranging from 9 to 12%, with a slight emphasis on aquifer geochemistry, vadose zone thickness, and drainage density. This

**Table 2** Values for criteria standardization

Criteria	Data type	Description	Standardization approach
Intrinsic suitability			
Aquifer geochemistry	Discrete	Computed based on published salinity values of groundwater	Assigned values 0.2 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-SRTM30 m); 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-SRTM30 m); reclassification assumed that less than 0.1 km <sup>2</sup> /km <sup>2</sup> feasibility remains as 0.2	Assigned values 0.2 to 1
Lineament density	Discrete	Computed from surface topography (USGS-SRTM30 m) and Landsat 8 image reclassification assumed that less than 0.5 km <sup>2</sup> /km <sup>2</sup> feasibility remains as 0.2	Assigned values 0.2 to 1
Water availability			
Precipitation	Discrete	Spatial distribution of average precipitation (mm/yr) computed from the National Institute of Meteorology (INM) data (1980–2022)	Scaled between 0.2 and 1
Direct runoff	Discrete	Spatial distribution of average direct runoff (mm/yr) computed with SWAT model	Scaled between 0.2 and 1
Evapotranspiration	Discrete	Spatial distribution of average actual evapotranspiration (mm/yr) computed with SWAT model	Scaled between 0.2 and 1
Distance to source (conventional and nonconventional)	Discrete	Based on the classification conducted by Aloui et al. (2022)	Scaled between 0.2 and 1

**Table 2** (continued)

Criteria	Data type	Description	Standardization approach
Water supply connection density	Discrete	Based on the classification conducted by Aloui et al. (2022)	Scaled between 0.2 and 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 method ((Brouwer and Heibloom 1986)	Scaled between 0.2 and 1
Groundwater dependent ecosystems (supporting needs)	Discrete	Based on the diagnostic report of conservation sites for coastal wetlands and coastal ecosystems in Cap Bon (Baccar et al. 2001)	Assigned values 0.2 to 1



**Fig. 4** Spatial distribution of the standardized scores for the selected criteria across the three thematic layers: intrinsic suitability (IS), water availability (WA), and water demand (WD)

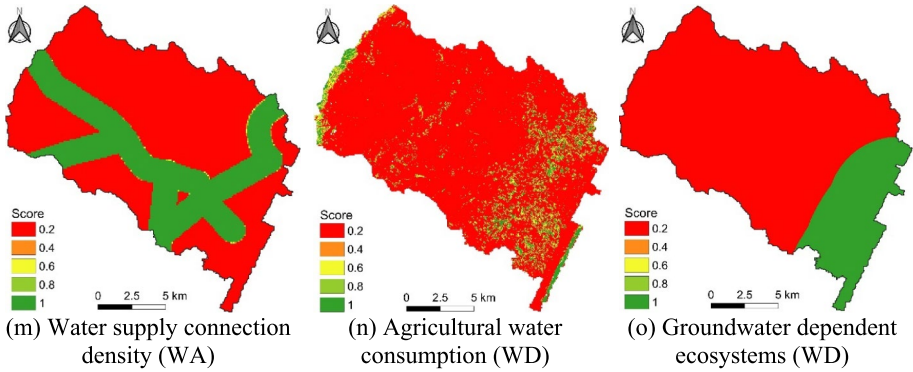


Fig. 4 (continued)

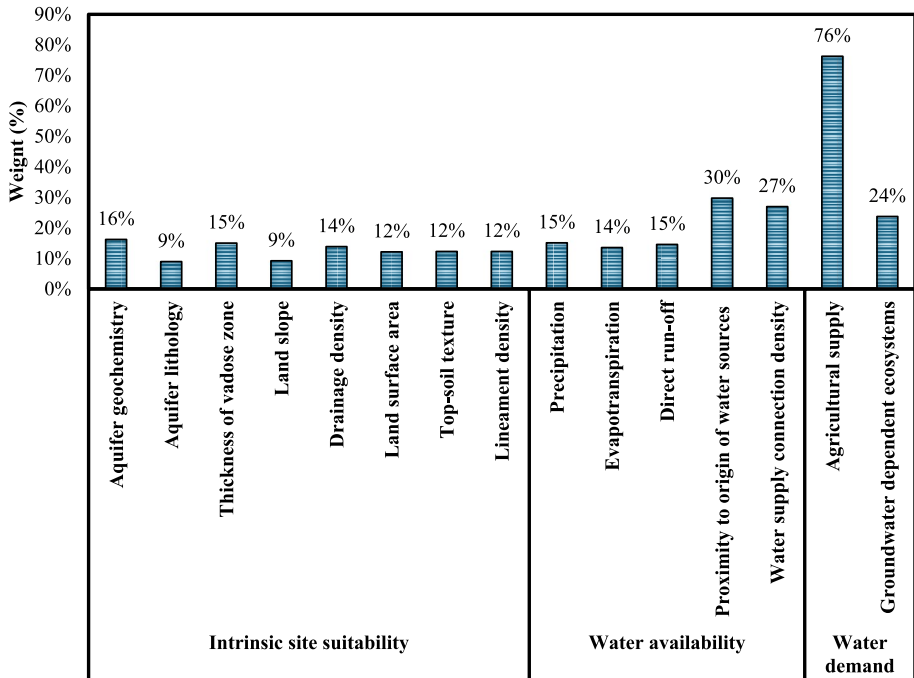


Fig. 5 Aggregated weights of physical criteria from stakeholders and experts

observation highlights the significance of these factors for MAR feasibility in the Chiba watershed, particularly when employing soil aquifer treatment (SAT) for treated wastewater (TWW) and dam water release via conventional water. For the WA thematic layer, the origin of recharge water emerges as a significantly more critical factor than hydrometeorological parameters. This finding underscores its importance as a key success factor for MAR feasibility while highlighting the vulnerability of hydrometeorological factors to climate change, which markedly impacts their availability. With respect to WD, the weighting coefficient of irrigation water demand is three times greater than the weight of meeting the

ecological needs of Korba Lagoon. This disparity reflects the significant priority placed by farmers on enhancing water reserves through MAR to ensure the security of their agricultural production.

#### 4.5 Development and Validation of Suitability Maps

The intrinsic site suitability map reveals that the most favorable regions for MAR installation are concentrated in coastal areas since these regions display favorable conditions for specific criteria. Specifically, the lithology in these zones predominantly consists of permeable and porous formations, which facilitate efficient water infiltration and storage. Furthermore, the drainage density in these areas is moderate to high, promoting the accumulation and channeling of runoff into recharge zones. Additionally, the vadose zone thickness is within an optimal range (less than 20 m), ensuring sufficient thickness to allow the purification of TWW and enough capacity for water infiltration without excessive evaporation losses. This combination of factors—favorable lithology, adequate drainage density, and suitable vadose zone characteristics—creates an ideal environment for MAR implementation. Figure 6 shows the spatial distributions of these intrinsic criteria, emphasizing the high suitability of coastal regions for sustainable groundwater recharge. This alignment underscores the strategic importance of prioritizing MAR interventions in these areas to maximize recharge efficiency and mitigate water scarcity challenges.

The resulting water availability maps for both the wet and dry seasons highlight coastal areas as the most favorable zones for MAR, particularly near the Korba wastewater treatment plant and the distribution network of the Chiba dam. These locations benefit from proximity to consistent water sources, supporting efficient recharge operations.

During the wet season, moderate water availability is also noted in the upstream regions, reflecting seasonal variability in water resources. However, upstream areas generally experience lower availability during the dry season because of limited water sources, which restricts MAR feasibility. This variation underscores the critical role of localized water infrastructure, such as dams and WWTPs, in enhancing recharge potential and addressing water scarcity across the watershed (Fig. 7). Prioritizing these areas for MAR initiatives can help optimize a region's water management strategy.

The MAR water demand map for the Chiba watershed reveals that demand is highest during the dry season, particularly in coastal regions dominated by irrigated crops, such as market gardens (Fig. 8). This is also true in regions where Korba Lagoon's ecological requirements significantly contribute to the overall demand. In contrast, moderate demand is observed upstream during the wet season, primarily in areas near Chiba dam, which are cultivated with orchards and cereals. These findings highlight a seasonal pattern, with peak demand occurring in the dry season in coastal areas. This underscores the urgent need for sustainable water resources in these regions to meet both agricultural and ecological needs effectively. Prioritizing MAR in these high-demand zones could help alleviate water shortages and support the watershed's diverse requirements.

#### 4.6 Compilation and Validation of the MAR Feasibility Maps

MAR feasibility maps were created during a workshop for stakeholders held at the National Agronomic Institute of Tunisia (INAT) in July 2024. Specifically, participants from the INAT team and relevant stakeholder representatives from the national, regional and local levels carried out a pairwise comparison matrix exercise, which was helpful in determining

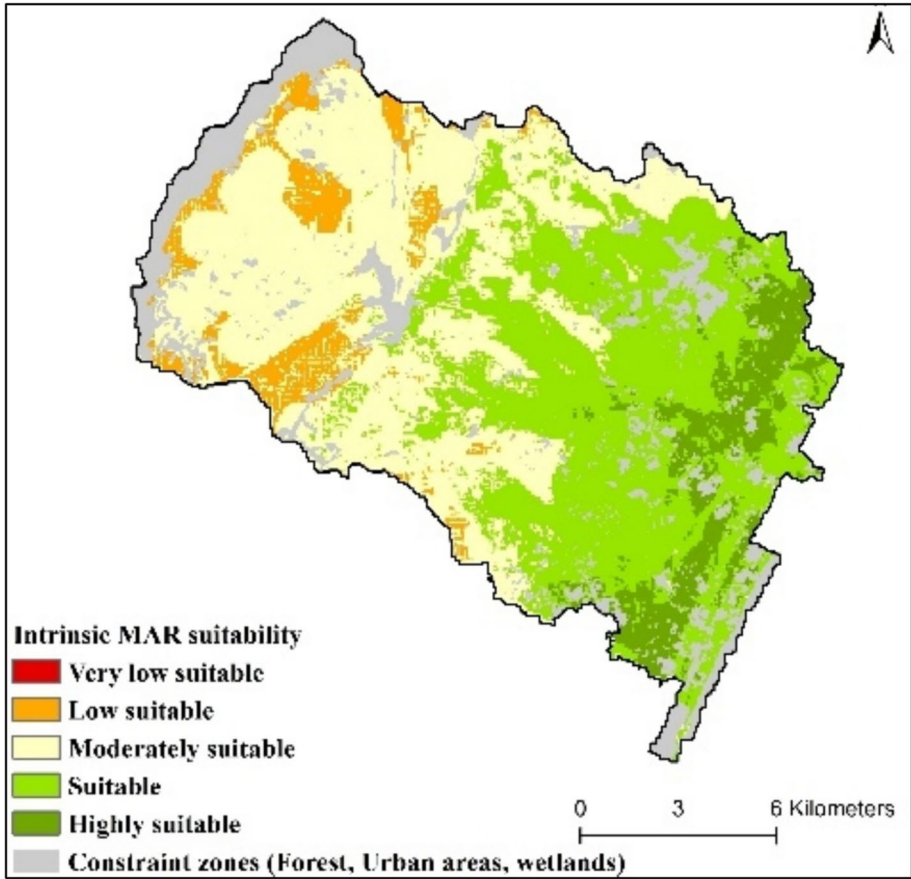


Fig. 6 Intrinsic site suitability map

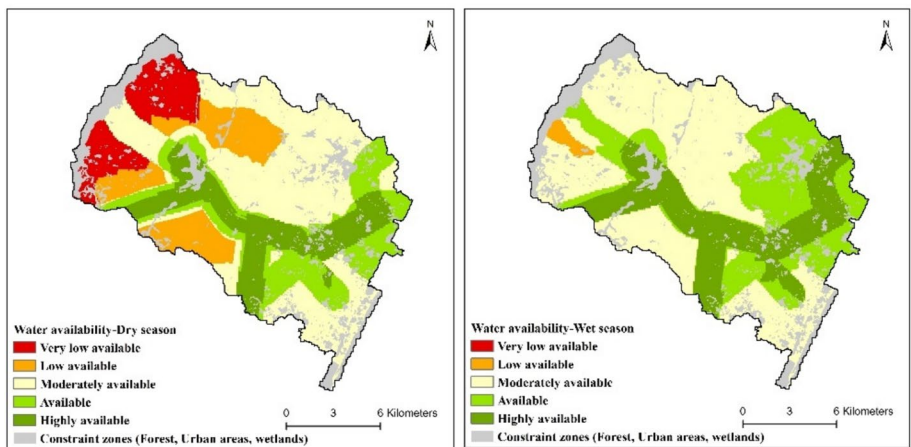
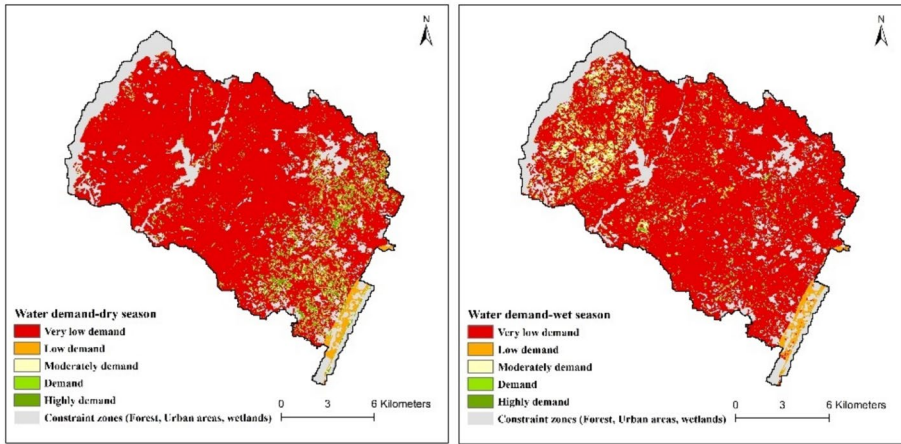


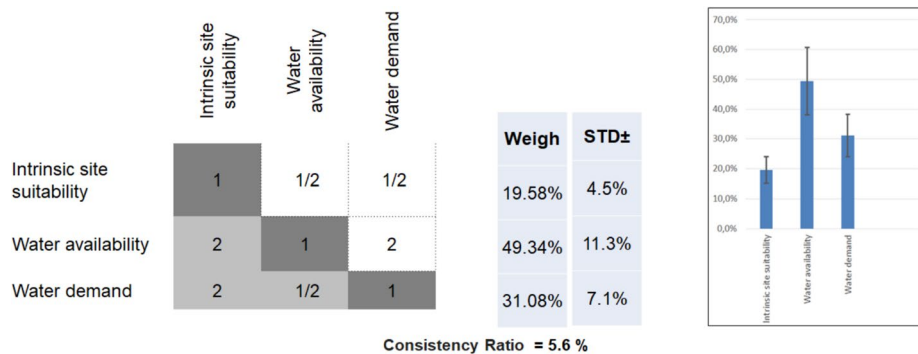
Fig. 7 Maps of water availability for the MAR (left: dry season; right: wet season)



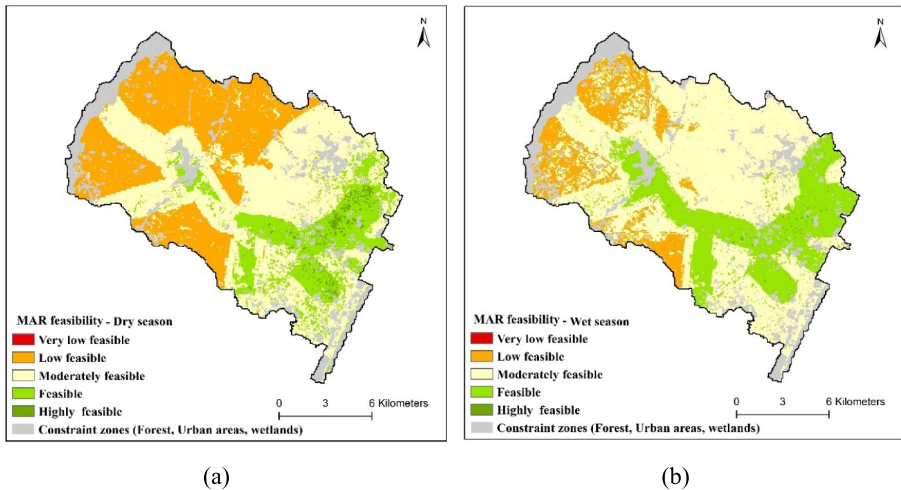
**Fig. 8** Maps of the water demand for the MAR (left: during the dry season; right: during the wet season)

the final weights of each thematic layer. Stakeholders choose the scenario prioritizing water availability, as it best corresponds to their preferences and priorities for MAR in the Chiba watershed. The obtained weights are as follows: intrinsic site suitability (IS): 19.6%; water availability (WA): 49.3%; and water demand (WD): 31.1% (Fig. 9).

The resulting feasibility maps exhibit similar patterns for both dry and wet seasons. Zones where the operation of MAR schemes is classified as feasible and highly feasible are located mainly near coastal regions because of favorable intrinsic site characteristics, the availability of conventional and nonconventional water resources for groundwater recharge, and high agricultural and ecosystem demands. The high feasibility levels of the areas close to the water supply network reflect the greater importance of water availability (49.34%) compared with the other thematic layers. Low feasibility zones are observed in the upstream part of the watershed where the intrinsic characteristics are less favorable (e.g., the terrain slope exceeds 20°), and recharge water is rare due to the absence of treated wastewater resources and limited conventional water resources, such as water from the Chiba dam (Fig. 10).



**Fig. 9** Weights calculated via the pairwise comparison matrix during the validation workshop at INAT, Tunisia



**Fig. 10** MAR feasibility maps of the Chiba watershed in Tunisia during dry (a) and wet (b) seasons

Considering the MAR typology of the Chiba watershed, the most relevant MAR scheme should consist of infiltration basins to enable soil-aquifer treatment (SAT) near the coastal region to mitigate seawater intrusion via treated wastewater from the Korba WWTP. However, for areas close to a dam, water release and the installation of check dams could be effective solutions for the long-term storage of groundwater. The existing dug wells in public irrigated perimeters could also constitute a MAR scheme on the basis of the concept of injection wells.

A broader comparison with international studies highlights both the strengths and areas for improvement in the methodology used in this research. Similar GIS-based MCDA approaches have been successfully applied to determine MAR feasibility in other semiarid regions, such as Lebanon (Itani et al. 2022), Egypt (Hani et al. 2023), Ethiopia (Yosef et al. 2024), India (Kodihal and Akhtar 2024), and Spain (Escalante et al. 2023). However, differences in parameter selection, weighting schemes, and stakeholder engagement processes suggest that methodological frameworks should be tailored to local conditions. In Spain, for example, Escalante et al. 2023 have employed the GIS-based MCDA to determine the fractional volume of water contributing to aquifer recharge from small dyke structures, providing valuable insights for sustainable groundwater management. In India, Jadav and Yadav (2023) have emphasized the integration of climate change and land cover dynamics together with GIS-MCDA mapping for long-term MAR sustainability. In Australia, advanced hydrological modeling has been used with MCDA to enhance MAR site selection (Fuentes and Vervoort 2020).

A key uniqueness of the present study is MAR feasibility mapping, which explicitly accounts for a specific MAR typology, which includes the recharge objective, the technique used, and the source of water for recharge. Unlike many previous studies that focused solely on hydrological and geological factors, the current approach provides a more practical and operational perspective by aligning MAR site selection with the intended recharge mechanism and available water sources. This distinction ensures that feasibility assessments are not only spatially relevant but also technically implementable, bridging the gap between scientific analysis and real-world application. Furthermore, the current research

includes socio-economic aspects in the weighting process. While socioeconomic factors such as land ownership, governance frameworks, and financial constraints are not explicitly mapped as standalone layers, they are indirectly embedded in the decision-making process through stakeholder input. By incorporating expert and local stakeholder perspectives in the weighting of criteria, this study implicitly reflects the influence of socioeconomic considerations on MAR feasibility, as highlighted in recent studies (Martins et al. 2024; Panagiotou et al. 2024). This approach enhances the applicability of MAR site selection outcomes by ensuring alignment with local priorities, institutional capacities, and water management needs.

Despite the robustness of the proposed methodology, the accuracy of the MAR feasibility maps is inherently dependent on the quality and resolution of the input data. The limited availability of high-resolution hydrogeological and hydrological data may introduce uncertainties in spatial analysis. Future research could address this issue by incorporating advanced remote sensing techniques and in-situ monitoring to refine data precision. Furthermore, while the study accounts for seasonal variations by analyzing wet and dry periods separately, it does not fully integrate long-term climate change projections, which could significantly impact water availability and MAR suitability over time. The incorporation of climate models and downscaled projections in future analyses would enhance the resilience of MAR planning.

Future amelioration pathways can explore hybrid methodologies that combine hydrological modeling with machine learning techniques to enhance predictive capabilities. Additionally, cross-regional comparative studies could provide insights into best practices for MAR implementation under varying climatic and institutional settings. By addressing these ameliorations and expanding the methodological framework, future research can further refine MAR site selection and contribute to the development of more sustainable groundwater management strategies globally.

## 5 Conclusions

This study proposed a comprehensive methodology that integrates expert-based knowledge and stakeholder opinions to map the MAR feasibility of the Chiba watershed. The MAR typology concept is introduced to illustrate the general applicability of the suggested method, which consists of the water supply, recharge mechanism, and MAR purpose. The perspectives of MAR experts and key stakeholders from the water sector were taken into consideration when selecting a set of sixteen parameter criteria that were considered in the multicriteria decision analysis.

The stakeholders identified water availability (~ 50%) as the most important consideration for MAR development in Tunisia, followed by water demand (~ 30%), which reflects the need to address increasing agricultural water needs. Intrinsic site suitability (~ 20%) was also highlighted, emphasizing the importance of selecting locations with favorable geological and hydrological conditions to ensure the efficiency and sustainability of MAR systems. The results indicate that MAR is feasible to highly feasible in 19% of the total area of the watershed, especially in the coastal region of the watershed, in areas close to the water conveyance and supply network and to the Korba WWTP. The MAR feasibility maps indicate that groundwater recharge via the SAT may be implemented in coastal regions utilizing treated wastewater and in the upstream section of a watershed via simple injection wells and dam water release coupled to an infiltration basin. The accuracy of these maps

depends on input data quality, with limitations in high-resolution hydrogeological and hydrological data introducing uncertainties. Future research should refine data precision using remote sensing and in-situ monitoring while integrating climate models to enhance MAR planning resilience.

This study underscores the critical role of stakeholder engagement in the assessment process, as their insights significantly shape the selection of parameters and the prioritization of criteria. By integrating local knowledge with advanced analytical techniques, this approach not only ensures the feasibility of MAR projects but also fosters shared ownership and support for their implementation. The findings emphasize the high potential for MAR in the Chiba watershed, offering a replicable model for other regions seeking sustainable groundwater management solutions.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s40710-025-00769-z>.

**Author Contributions** All the authors contributed to the study conception and design. AC: conceptualization, visualization, methodology, validation, investigation, formal analysis, data curation, writing-original draft, resources; KK: visualization, validation, investigation, formal analysis, data curation, writing-original draft; TNM: conceptualization, methodology, review and editing; CS: conceptualization, methodology, review and editing, resources; CFP: conceptualization, methodology, review and editing, resources.

**Funding** This research is in the framework of the AGREEMAR project which is funded by National Funding Agencies from Germany (Bundesministerium für Bildung und Forschung – BMBF), Cyprus (Research & Innovation Foundation—RIF), Portugal (Fundação para a Ciência e a Tecnologia – FCT), Spain (Ministerio de Ciencia e Innovación – MCI) and Tunisia (Ministere de l’Enseignement Supérieur et de la Recherche Scientifique – MESRS) 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.

**Data Availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing Interests** The authors declare no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

## References

- Al-Djazouli MO, Elmorabiti K, Rahimi A, Amellah O, Fadil OAM (2021) Delineating of groundwater potential zones based on remote sensing, GIS and analytical hierarchical process: a case of Waddai, eastern Chad. *GeoJournal* 86:1881–1894. <https://doi.org/10.1007/s10708-020-10160-0>
- Aloui D, Chekirbane A, Stefan C, Schlick R, Msaddek MH, Mlayah A (2022) Use of a GIS-multi-criteria decision analysis and web-based decision support tools for mapping and sharing managed aquifer recharge feasibility in Enfidha plain, NE of Tunisia. *Arab J Geosci* 15:658. <https://doi.org/10.1007/s12517-022-09893-8>

- Antonakos A, Lambrakis N (2021) Spatial interpolation for the distribution of groundwater level in an area of complex geology using widely available GIS tools. *Environ Process* 8:993–1026. <https://doi.org/10.1007/s40710-021-00529-9>
- Arumugam M, Kulandaisamy P, Karthikeyan S, Thangaraj K, Senapathi V, Chung SY, Muthuramalingam S, Rajendran M, Sugumaran S, Manimuthu S (2023) An assessment of geospatial analysis combined with AHP techniques to identify groundwater potential zones in the Pudukkottai District, Tamil Nadu, India. *Water (Basel)* 15:1101. <https://doi.org/10.3390/w15061101>
- Baccar I, Moussa M, Ben Hamza C (2001) Conservation des zones humides littorales et des écosystèmes côtiers du cap-bon. Rapport de diagnostic des sites partie relative à l'hydraulique des zones humides de Maamoura, Tazarka et Korba. [https://www.oieau.fr/eaudoc/system/files/documents/41/206554/206554\\_doc.pdf](https://www.oieau.fr/eaudoc/system/files/documents/41/206554/206554_doc.pdf). Accessed 12 October 2024
- Ben Hamouda MF (2008) Approche hydrogéochimique et isotopique des systèmes aquifères côtiers du Cap Bon: cas des nappes de la côte orientale et d'Haouaria. Dissertation, University of Carthage, Tunisia. <https://gnssn.iaea.org/main/NCP/Tunisia/LRAE/Documents/Student%20Programmes/Benhamouda%20Th%C3%A8se%20Intrusion%20Tunisie.pdf>. Accessed 24 Sep 2024
- Bonilla Valverde J, Blank C, Roidt M, Schneider L, Stefan C (2016) Application of a GIS multi-criteria decision analysis for the identification of intrinsic suitable sites in Costa Rica for the application of managed aquifer recharge (MAR) through spreading methods. *Water (Basel)* 8:391. <https://doi.org/10.3390/w8090391>
- Bozóki S, Rapcsák T (2008) On Saaty's and Koczkodaj's inconsistencies of pairwise comparison matrices. *J Global Optim* 42:157–175. <https://doi.org/10.1007/s10898-007-9236-z>
- Brouwer C, Heibloom M (1986) Irrigation water management: irrigation water needs. <https://www.fao.org/4/s2022e/s2022e00.htm>. Accessed 12 October 2024
- Chekirbane A, Tsujimura M, Kawachi A, Isoda H, Tarhouni J, Benalaya A (2013) Hydrogeochemistry and groundwater salinization in an ephemeral coastal flood plain: Cap Bon, Tunisia. *Hydrol Sci J* 58:1097–1110. <https://doi.org/10.1080/02626667.2013.800202>
- Çiftçiöğlü-Gözüaçık B, Omwene PI, Ergenekon SM et al (2023) Conforming to agricultural water reuse criteria: wastewater recovery by electrooxidation integrated with nanofiltration/reverse osmosis. *Environ Process* 10:11. <https://doi.org/10.1007/s40710-023-00629-8>
- de Vries JJ, Simmers I (2002) Groundwater recharge: an overview of processes and challenges. *Hydrogeol J* 10:5–17. <https://doi.org/10.1007/s10040-001-0171-7>
- Dillon P, Stuyfzand P, Grischek T, Lluria M, Pyne RDG, Jain RC, Bear J, Schwarz J, Wang W, Fernandez E, Stefan C, Pettenati M, van der Gun J, Sprenger C, Massmann G, Scanlon BR, Xanke J, Jokela P, Zheng Y, Rossetto R, Shamruk M, Pavelic P, Murray E, Ross A, Bonilla Valverde JP, Palma Nava A, Ansems N, Posavec K, Ha K, Martin R, Sapiano M (2019) Sixty years of global progress in managed aquifer recharge. *Hydrogeol J* 27:1–30. <https://doi.org/10.1007/s10040-018-1841-z>
- Ennabli M (1980) Étude hydrogéologique des aquifères du Nord-Est de la Tunisie pour une gestion intégrée des ressources en eau. Dissertation, University of Nice, France. <https://www.sudoc.abes.fr/cbs/DB=2.1/SRCH?IKT=12&TRM=04223428X>. Accessed 9 Nov 2024
- Escalante EF, Henaou Casas JD, San Sebastián Sauto J, Calero Gil R (2022) Monitored and intentional recharge (MIR): a model for managed aquifer recharge (MAR) guideline and regulation formulation. *Water (Basel)* 14:3405. <https://doi.org/10.3390/w14213405>
- Escalante EF, Casas JDH, Per CMdeG, Vera MDM, Valverde CM (2023) Unintentional recharge of aquifers from small dams and dykes in Spain: a GIS-based approach to determine a fractional volume. *Earth* 4:584–605. <https://doi.org/10.3390/earth4030031>
- Fathi S, Hagen JS, Haidari AH (2020) Synthesizing existing frameworks to identify the potential for Managed Aquifer Recharge in a karstic and semi-arid region using GIS Multi Criteria Decision Analysis. *Groundw Sustain Dev* 11:100390. <https://doi.org/10.1016/j.gsd.2020.100390>
- Fuentes I, Vervoort RW (2020) Site suitability and water availability for a managed aquifer recharge project in the Namoi basin, Australia. *J Hydrol Reg Stud* 27:100657. <https://doi.org/10.1016/j.ejrh.2019.100657>
- Gaaloul N (2012) Simulation of seawater intrusion in coastal aquifers: forty five-years exploitation in an eastern coast aquifer in NE Tunisia. *Open Hydrol J* 6:31–44. <https://doi.org/10.2174/1874378101206010031>
- Hani HM, El Din MMN, Khalifa A, Elalfy E (2023) Development of suitability map for managed aquifer recharge: case study, West Delta, Egypt. *AQUA — Water Infrastruct Ecosyst Soc* 72:868–884. <https://doi.org/10.2166/aqua.2023.177>
- Huang Y, Hu H, Zhu S et al (2024) An economical and efficient physico-chemical approach for the reuse of wastewater in small and medium scale paint enterprises. *Environ Process* 11:47. <https://doi.org/10.1007/s40710-024-00724-4>

- Ingrao C, Strippoli R, Lagioia G, Huisingsh D (2023) Water scarcity in agriculture: an overview of causes, impacts and approaches for reducing the risks. *Heliyon* 9:e18507. <https://doi.org/10.1016/j.heliyon.2023.e18507>
- Itani N, Harik G, Alameddine I, El-Fadel M (2022) Managed aquifer recharge in karstic systems: site suitability mapping by coupling multi-criteria decision analysis with remote sensing and hydrologic modeling. *J Environ Manage* 322:116162. <https://doi.org/10.1016/j.jenvman.2022.116162>
- Jadav K, Yadav B (2023) Identifying the suitable managed aquifer recharge (MAR) strategy in an over-exploited and contaminated river basin. *Environ Monit Assess* 195(8):1014. <https://doi.org/10.1007/s10661-023-11586-y>
- Kavurmaci M (2016) Evaluation of groundwater quality using a GIS-MCDA-based model: a case study in Aksaray, Turkey. *Environ Earth Sci* 75:1258. <https://doi.org/10.1007/s12665-016-6074-7>
- Kerrou J, Renard P, Tarhouni J (2010) Status of the Korba groundwater resources (Tunisia): observations and three-dimensional modelling of seawater intrusion. *Hydrogeol J* 18:1173–1190. <https://doi.org/10.1007/s10040-010-0573-5>
- Kodihal S, Akhtar MP (2024) Sustainable groundwater recharge potential zone identification: an AHP-OWA approach integrating future rainfall and land-use projections. *Water Resour Manage* 38:1079–1098. <https://doi.org/10.1007/s11269-023-03710-x>
- Kumar A, Yadav B (2025) Wastewater composition, resource assessment, and reutilization potential: a comparative analysis of various treatment systems in India. *Environ Process* 12:14. <https://doi.org/10.1007/s40710-025-00756-4>
- MARHP (1998) *Projet de Développement Agricole*. Internal report. Ministry of Agriculture, Hydraulic Resources and Fisheries. Tunis, Tunisia
- MARHP (2006) *Rapport Interne*. Ministry of Agriculture, Hydraulic Resources and Fisheries. Tunis, Tunisia
- MARHP, DGACTA (2022) *Etude de planification des aménagements de conservation des eaux et du sol*. Internal report. Ministry of Agriculture, Hydraulic Resources and Fisheries. Tunis, Tunisia
- Martins TN, Leitão TE, Oliveira MM, Panagiotou CF, Stefan C, Chkirbene A, Portela MM (2024) Proposal for a managed aquifer recharge feasibility index for southern Portugal using multi-criteria decision analysis. *Groundw Sustain Dev* 26:101280. <https://doi.org/10.1016/j.gsd.2024.101280>
- Marwaha N, Kourakos G, Levintal E, Dahlke HE (2021) Identifying agricultural managed aquifer recharge locations to benefit drinking water supply in rural communities. *Water Resour Res* 57:e2020WR028811. <https://doi.org/10.1029/2020WR028811>
- Mekni A, Souissi A (2016) The effectiveness of artificial recharge by treated wastewater in combating seawater intrusion—the case study of Korba-El Mida aquifer (Cape bon, Tunisia). *Int J Innov Appl Stud* 15:264–274
- Moharir KN, Pande CB, Gautam VK, Singh SK, Rane NL (2023) Integration of hydrogeological data, GIS and AHP techniques applied to delineate groundwater potential zones in sandstone, limestone and shales rocks of the Damoh district, (MP) central India. *Environ Res* 228:115832. <https://doi.org/10.1016/j.envres.2023.115832>
- Neto S, Camkin J, Fenemor A, Tan P-L, Baptista JM, Ribeiro M, Schulze R, Stuart-Hill S, Spray C, Elfithri R (2018) OECD Principles on Water Governance in practice: an assessment of existing frameworks in Europe, Asia-Pacific, Africa and South America. *Water Int* 43:60–89. <https://doi.org/10.1080/02508060.2018.1402650>
- Panagiotou CF, Kyriakidis P, Tziritis E (2022b) Application of geostatistical methods to groundwater salinization problems: a review. *J Hydrol (Amst)* 615:128566. <https://doi.org/10.1016/j.jhydrol.2022.128566>
- Panagiotou CF, Stefan C, Papanastasiou P, Sprenger C (2022c) Quantitative microbial risk assessment (QMRA) for setting health-based performance targets during soil aquifer treatment. *Environ Sci Pollut Res* 30:14424–14438. <https://doi.org/10.1007/s11356-022-22729-y>
- Panagiotou CF, Eisenreich S, Barouta OT, Chekirbane A, Martins T, Neophytides S, Khemiri K, Stefan C (2024) Identification of feasible regions for managed aquifer recharge in the Republic of Cyprus using a co-participative multi-criteria decision analysis. *Groundw Sustain Dev* 27:101323. <https://doi.org/10.1016/j.gsd.2024.101323>
- Panagiotou CF, Chekirbane A, Martins TN, Leitão T (2022a) AGREEMAR Deliverable D2.1: matrix of feasibility criteria for managed aquifer recharge. [https://agreemar.webspace.tu-dresden.de/wp-content/uploads/2022/11/AGREEMAR\\_D2.1.pdf](https://agreemar.webspace.tu-dresden.de/wp-content/uploads/2022/11/AGREEMAR_D2.1.pdf). Accessed 01 October 2024
- Paniconi C, Khlaifi I, Lecca G, Giacomelli A, Tarhouni J (2001) A modelling study of seawater intrusion in the Korba coastal plain, Tunisia. *Phys Chem Earth Part B: Hydrol Oceans Atmos* 26:345–351. [https://doi.org/10.1016/S1464-1909\(01\)00017-X](https://doi.org/10.1016/S1464-1909(01)00017-X)

- Papadopoulos C, Spiliotis M, Pliakis F, Gkioukhis I, Kazakis N, Papadopoulos B (2022) Hybrid fuzzy multi-criteria analysis for selecting discrete preferable groundwater recharge sites. *Water (Basel)* 14:107. <https://doi.org/10.3390/w14010107>
- Rahman MA, Rusteberg B, Gogu RC, Lobo Ferreira JP, Sauter M (2012) A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. *J Environ Manage* 99:61–75. <https://doi.org/10.1016/j.jenvman.2012.01.003>
- Rath S, Hinge G (2024) Groundwater sustainability mapping for managed aquifer recharge in Dwarakeswar River basin: integration of watershed modeling, multi-criteria decision analysis, and constraint mapping. *Groundw Sustain Dev* 26:101279. <https://doi.org/10.1016/j.gsd.2024.101279>
- Ravichandran R, Ayyavoo R, Rajangam L, Madasamy N, Murugaiyan B, Shanmugam S (2022) Identification of groundwater potential zone using analytical hierarchical process (AHP) and multi-criteria decision analysis (MCDA) for Bhavani river basin, Tamil Nadu, southern India. *Groundw Sustain Dev* 18:100806. <https://doi.org/10.1016/j.gsd.2022.100806>
- Saaty RW (1987) The analytic hierarchy process—what it is and how it is used. *Math Model* 9:161–176. [https://doi.org/10.1016/0270-0255\(87\)90473-8](https://doi.org/10.1016/0270-0255(87)90473-8)
- Sahu U, Wagh V, Mukate S, Kadam A, Patil S (2022) Applications of geospatial analysis and analytical hierarchy process to identify the groundwater recharge potential zones and suitable recharge structures in the Ajani-Jhiri watershed of north Maharashtra, India. *Groundw Sustain Dev* 17:100733. <https://doi.org/10.1016/j.gsd.2022.100733>
- Sallwey J, Bonilla Valverde JP, Vásquez López F, Junghanns R, Stefan C (2019) Suitability maps for managed aquifer recharge: a review of multi-criteria decision analysis studies. *Environ Rev* 27(2):138–150. <https://doi.org/10.1139/er-2018-0069>
- Saravanan S, Pitchaikani S, Thambiraja M, Sathiyamurthi S, Sivakumar V, Velusamy S, Shanmugamoorthy M (2023) Comparative assessment of groundwater vulnerability using GIS-based DRASTIC and DRASTIC-AHP for Thoothukudi District, Tamil Nadu India. *Environ Monit Assess* 195:57. <https://doi.org/10.1007/s10661-022-10601-y>
- Slimani FE, Zghibi A, Elomri A, Aloui S, Naeem K, Merzougui A, Msaddek MH, Chekirbene A (2024) Identification of groundwater potential recharge zones in a Tunisian anthropogenic coastal region: insights from multi-criteria decision-making techniques. *J Afr Earth Sc* 209:105108. <https://doi.org/10.1016/j.jafrearsci.2023.105108>
- Soliman K, Sallam OM, Schüth C (2022) Delineating MAR sites using GIS-MCDA for Nuweiba alluvial fan aquifer, Sinai, Egypt. *Water (Basel)* 14:475. <https://doi.org/10.3390/w14030475>
- Srivastava MK, Gaur S, Ohri A (2024) Analysing the effectiveness of MCDM and integrated weighting approaches in groundwater quality index development. *Water Conserv Sci Eng* 9:35. <https://doi.org/10.1007/s41101-024-00267-7>
- Stefan C, Ansems N (2018) Web-based global inventory of managed aquifer recharge applications. *Sustain Water Resour Manag* 4:153–162. <https://doi.org/10.1007/s40899-017-0212-6>
- Teixeira J, Chaminé HI, Martins Carvalho J, Pérez-Alberti A, Rocha F (2023) Insights from a comparative GIS-MCDA groundwater vulnerability assessment in a granitic and metasedimentary fractured rock media. *Discover Water* 3:16. <https://doi.org/10.1007/s43832-023-00040-2>
- Tiwari K, Goyal R, Sarkar A (2017) GIS-based spatial distribution of groundwater quality and regional suitability evaluation for drinking water. *Environ Process* 4:645–662. <https://doi.org/10.1007/s40710-017-0257-4>
- Werner AD, Bakker M, Post VEA, Vandenbohede A, Lu C, Ataie-Ashtiani B, Simmons CT, Barry DA (2013) Seawater intrusion processes, investigation and management: recent advances and future challenges. *Adv Water Resour* 51:3–26. <https://doi.org/10.1016/j.advwatres.2012.03.004>
- Wijesinghe DC, Mishra PK, Withanage NC, Abdelrahman K, Mishra V, Tripathi S, Fnaiss MS (2023) Application of GIS, multi-criteria decision-making techniques for mapping groundwater potential zones: a case study of thalawa division, Sri Lanka. *Water (Basel)* 15:3462. <https://doi.org/10.3390/w15193462>
- Yosef Z-M, Birhanu B, Suryabhagavan KV, Tsegay T (2024) GIS-based suitability mapping of Managed Aquifer Recharge (MAR) in Diredawa catchment, Eastern Ethiopia. *Int J River Basin Manag* 1–15. <https://doi.org/10.1080/15715124.2024.2361038>
- Zghibi A, Tarhouni J, Zouhri L (2013) Assessment of seawater intrusion and nitrate contamination on the groundwater quality in the Korba coastal plain of Cap-Bon (North-east of Tunisia). *J Afr Earth Sc* 87:1–12. <https://doi.org/10.1016/j.jafrearsci.2013.07.009>
- Zghibi A, Mirchi A, Zouhri L, Taupin J-D, Chekirbane A, Tarhouni J (2019) Implications of groundwater development and seawater intrusion for sustainability of a Mediterranean coastal aquifer in Tunisia. *Environ Monit Assess* 191:696. <https://doi.org/10.1007/s10661-019-7866-5>

- Zghibi A, Mirchi A, Msaddek MH, Merzougui A, Zouhri L, Taupin J-D, Chekirbane A, Chenini I, Tarhouni J (2020) Using analytical hierarchy process and multi-influencing factors to map groundwater recharge zones in a semi-arid Mediterranean coastal aquifer. *Water (Basel)* 12:2525. <https://doi.org/10.3390/w12092525>
- Zhang Z, Zhang S, Li M, Zhang Y, Chen M, Zhang Q, Dai Z, Liu J (2023) Groundwater potential assessment in Gannan Region, China, using the soil and water assessment tool model and GIS-based analytical hierarchical process. *Remote Sens (Basel)* 15:3873. <https://doi.org/10.3390/rs15153873>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## Authors and Affiliations

Anis Chekirbane<sup>1</sup> · Khaoula Khemiri<sup>1</sup> · Tiago N. Martins<sup>2</sup> · Catalin Stefan<sup>3</sup> · Constantinos F. Panagiotou<sup>4</sup>

✉ Constantinos F. Panagiotou  
constantinos.panagiotou@eratosthenes.org.cy

<sup>1</sup> Laboratory of Sciences and Techniques for Water and Environment (LST2E), Department of Rural Engineering, Water and Forests, INAT, University of Carthage, Tunis, Tunisia

<sup>2</sup> National Laboratory for Civil Engineering LNEC, Lisbon, Portugal

<sup>3</sup> Research Group INOWAS, Department of Hydrosociology, Institute of Groundwater Management, Technical University of Dresden, Dresden, Germany

<sup>4</sup> Department of Resilient Society, ERATOSTHENES Centre of Excellence, Limassol, Cyprus