



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

Dorsaf Aloui¹ · Anis Chekirbane² · Catalin Stefan³ · Robert Schlick³ · Mohamed Haythem Msaddek⁴ · Ammar Mlayah¹

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Abstract

Suitability mapping for managed aquifer recharge is recently gaining more attention because of its potential in producing comprehensive maps easily interpreted and used by policy makers. In front of the divers existing methodologies, an adapted approach for the arid and semi-arid conditions of Tunisia was developed to generate a managed aquifer recharge (MAR) suitability and feasibility maps within a participatory approach with stakeholders. A Geographical Information Systems coupled with multi-criteria decision analysis (GIS-MCDA) was applied to establish the suitability and feasibility of MAR in Enfidha plain, NE of Tunisia. Selected criterions were spatialized under GIS thematic layers, and they were standardized based on literature and experts' opinions regarding their importance in MAR implementation. Weights of each criterion were determined using analytic hierarchy process (AHP). Intrinsic suitability map was obtained using weighted linear combination (WLC) by the mean of ArcGIS software and via the INOWAS (innovative web-based decision support system for water sustainability under a changing climate) platform. It shows that more than 80% of the total plain area is intrinsically suitable and highly suitable for MAR. MAR feasibility map was established by overlaying intrinsic suitability, recharge water availability, and water demand maps of the region. It reveals that almost the fifth of the plain has high MAR feasibility potential. A decision support system (DSS) web-portal, namely, INOWAS, was finally used as an effective tool to store, share, and establish the MAR suitability maps with the concerned stakeholders.

Keywords MAR · GIS-MCDA · Feasibility · DSS web-portal · Tunisia

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✉ Anis Chekirbane
anis.chkirbane@inat.u-carthage.tn

- ¹ Water Research and Technologies Center, Borj Ceria Technopark, Borj Cedria, Tunisia
- ² National Institute of Agronomy of Tunisia, University of Carthage, Tunis, Tunisia
- ³ Research Group INOWAS, Technical University of Dresden, Dresden, Germany
- ⁴ Faculty of Sciences of Tunis, University of Tunis El Manar, Tunis, Tunisia

Introduction

Rapid population growth and development of industry and agriculture have led to a dramatic use of fresh water resources, especially groundwater. In fact, more than 70% of groundwater is used in irrigation (Margat and van der Gun 2013) and half of the world irrigated crops are relying on groundwater for irrigation (Famiglietti 2014; van der Gun 2021). Aquifers are also among the first sources of drinking water supply (Gorelick and Zheng 2015). Among the feasible measures to reduce water stress and to increase its availability for diverse usages, the reuse of water, either direct or indirect, is one of the main options. Direct reuse consists usually in the direct use of recycled water, while the indirect use occurs when the recycled water is released in natural freshwater bodies, and withdrawn downstream in a different point after dilution and/or natural reclaiming processes.

Indirect reuse into aquifers, named managed aquifer recharge (MAR), was defined by Dillon et al. (2009) as “purposeful recharge of water to aquifers for subsequent recovery or environmental benefits.” MAR represents a wide and growing range of measures to support active management of groundwater resources at the local and basin level, to make more efficient use of water resources, assist conjunctive management of surface and groundwater resources, to buffer against increasing intensity of climate extremes, particularly drought, and to protect and improve water quality in aquifers (Dillon et al. 2019). MAR is an innovative practice spread globally (Stefan and Ansems 2018; Page et al. 2018) that includes a set of techniques to increase the availability of good quality groundwater or for the qualitative and quantitative rehabilitation of groundwater resources and is practically operated through a variety of different schemes.

In Tunisia, MAR has become a priority in water management plans since 1970s (Bouri and Dhia 2010). Since this date, several techniques have been adopted and most of them are using different setups to infiltrate surface water into aquifers. The commonly used techniques are dry well, recharge release, infiltration pond, soil aquifer treatment, and percolation tank. The total recharge amount in Tunisia is estimated to range between 14 and 66 millions m^3/yr in the period 1992–2015 (DGRE 2015). The choice of MAR techniques was not based on solid scientific knowledge. In fact, most of the implemented MAR projects were response to the pressure of overexploitation and quantitative and qualitative groundwater deterioration only; there is no previous suitability mapping procedure before projects implementation. Consequently, a clear sustainability problem is affecting most of MAR projects in Tunisia. For instance, the MAR project in Korba aquifer, CapBon peninsula (NE of Tunisia), using infiltration basins of treated wastewater did not exceed 7 years lifetime (2008–2015) because of clogging, lack of treated wastewater, and limited size of the MAR infrastructure compared to the existing piezometric depression (Gaaloul et al. 2012; Mekni and Souissi 2016). Also, the MAR project in Khairat watershed (coastal region in NE of Tunisia) using released dam water and in-channel modifications was almost ineffective just after 5 years implementation (2006–2011) because the wrong choice and dimensioning of check dams and their destruction after the 2011 flooding (Belghith Triki et al. 2014).

Additional information is needed to identify potential MAR locations and increase the result’s validation, such as field observation, and referring to databases of thematic layers like soil, geology, land use and land cover, slope, drainage, and lineament density (Masciopinto 2013). As a result, application of MAR is still marginal in Tunisian coastal aquifers and the current state of knowledge on MAR in these areas is limited. To better understand the potential for MAR in these zones, it is prudent to understand which

MAR approaches can be applied in coastal and semi-arid area in general. The Enfidha aquifer system located in a semi-arid coastal region in NE of Tunisia is a typical example where artificial recharge is applied almost without solid knowledge. To identify suitable locations for MAR sites in the Enfidha aquifer system, MAR suitability and feasibility maps must be developed. Many MAR suitability mapping methodologies exist (Sallwey et al. 2018; Ajjur and Baalousha 2021). Most of them are based on multi-criteria decision analysis (MCDA) which comprises a collection of methods and tools used to integrate spatially distributed geographical data with respect to established preferences and value-judgments (Fathi et al. 2020). It is however not clear which method should be applied in coastal context of semi-arid region and which parameters must be taken into account. To the authors’ best knowledge, application of GIS-MCDA method to establish a MAR feasibility map for Enfidha plain was not previously established. Thus, optimizing an adapted method to map MAR suitability in the Tunisian coastal context and sharing results with water resources managers will be the first step of enhancing MAR as sustainable solution to cope with water scarcity in arid and semi-arid regions in Tunisia. Therefore, the overall objective of this research is to evaluate the suitability and feasibility of the managed aquifer recharge (MAR) techniques in the Tunisian environmental conditions throughout developing a GIS-based methodology applied to Enfidha Aquifer System (Sahel of Tunisia) as pilot zone and providing a web-based decision support system (DSS) to help water resources managers in selecting suitable and feasible MAR sites.

Study area

The study area is the Enfidha Aquifer System which is located in Sousse governorate (NE of Tunisia) in the eastern flank of the Tunisian Dorsal between latitudes $36^{\circ}5'$ and $36^{\circ}10'N$ and longitudes $10^{\circ}10'$ and $10^{\circ}28'E$ (Fig. 1).

With an elevation ranging between 110 m a.s.l in upstream and 0 m in downstream coastal region and a mean average precipitation of 354 mm, the Enfidha plain is characterized by a semi-arid climate. The geology of this area is dominated by tertiary and quaternary deposits.

Enfidha Aquifer System is subject of intensive exploitation for irrigation and drinking purposes of the Sahel of Tunisia. As consequence, severe groundwater table drawdown of -6 m has appeared between 1990 and 2018 and was associated to aquifer salinization especially in the coastal part of the plain (Furukawa 2012; El Euch 2016). It is unreasonable to expect the aquifer replenishment alone to reverse the impacts of excessive groundwater extraction. Therefore, as tentative remedy, artificial recharge strategy was implemented since 2002 using

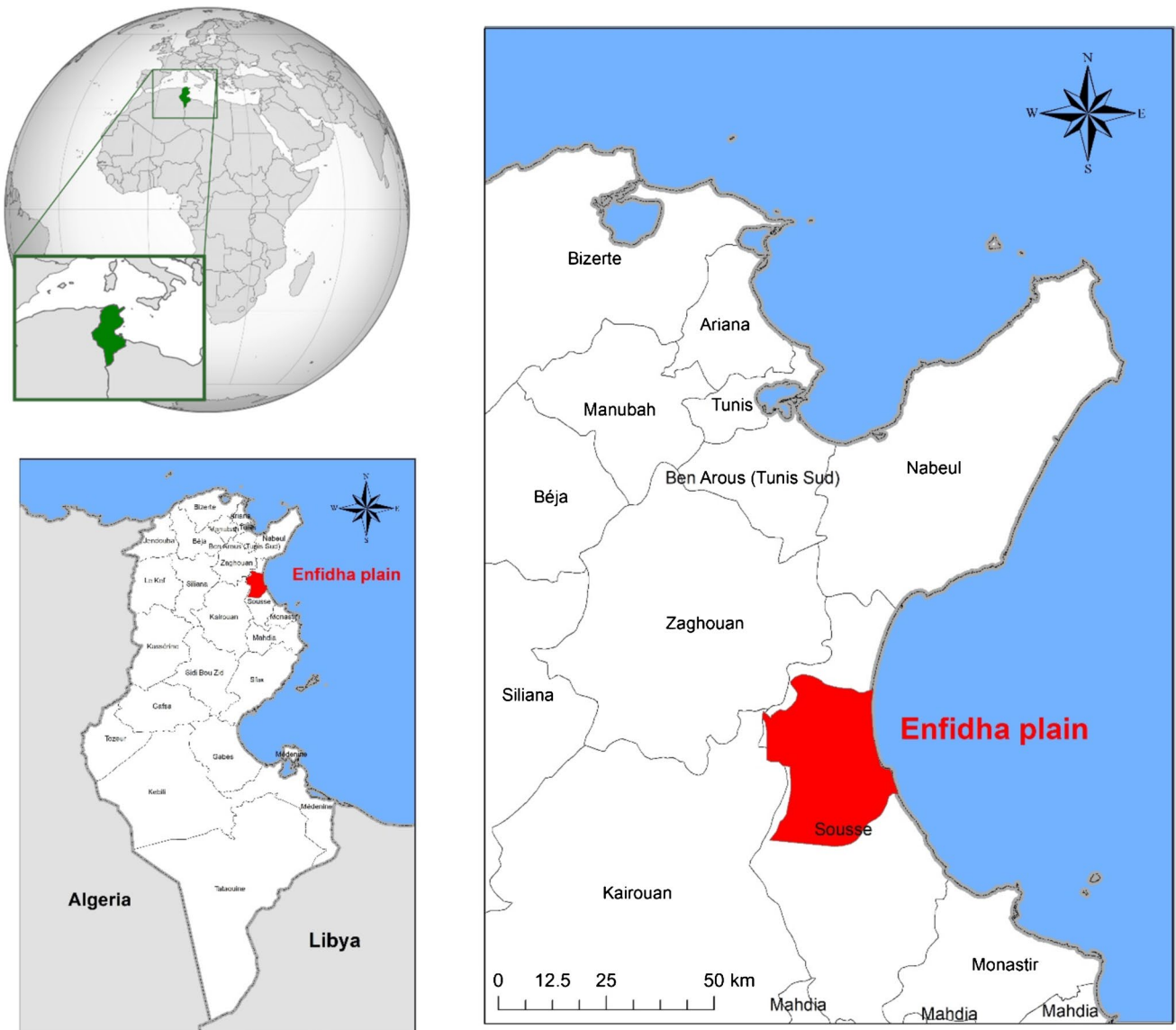


Fig. 1 Geographical location of the study zone

mainly hill dam water release and in-channel modification. Many previous studies have focused on these MAR schema impact on groundwater resources using a simple qualitative approach (Manaa et al. 1996; Ketata et al. 2014; Belghith Triki et al. 2014; Zammouri et al. 2018). The implemented MAR projects in the study area were not sustainable, and their lifetime do not exceed in general 10 years (Chekirbane et al. 2018, 2019). A problem of choice of the suitable and feasible MAR technique in the most effective zone of aquifer recharge was clearly recognized. Therefore, conducting a MAR suitability and feasibility map for the Enfidha Aquifer System and providing a DSS for the local and central water managers is becoming

a priority to cope with water scarcity and to secure a large part of the region’s need in irrigation and drinking water.

Methodology

The proposed methodology to reach the assigned objectives of this project is mainly composed of 3 parts (Fig. 2). The first one includes a review and analysis of the applied MAR techniques in the target zone (problem definition of MAR implementation in Enfidha plain) as well as the preparation of a GIS database comprising thematic layers of surface and subsurface parameters. The second part is Geographical Information System-multi-criteria decision analysis

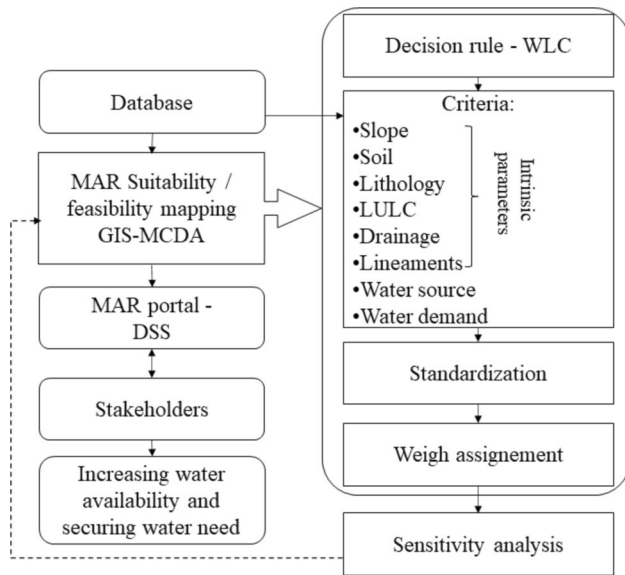


Fig. 2 Methodology flowchart

(GIS-MCDA). It constitutes an essential tool to solve many environmental problems. Geographical Information System (GIS) is typically involving a large set of feasible alternatives defined by multiple, conflicting, and incommensurate evaluation criteria (Malczewski 2006). Decision-makers require information and tools to incorporate their value judgments and understand the inherent trade-offs of a spatial problem (Greene et al. 2011). MCDA comprises a wide

range of methodologies, techniques, and procedures that guide the decision-making process (Malczewski and Rinner 2015; Bonilla Valverde et al. 2016). The third part is a web DSS portal throughout which the obtained MAR suitability and feasibility maps will be shared and discussed with stakeholders.

Database

The intrinsic MAR suitability map was generated based on 6 thematic layers: land use/land cover (LULC), slope (SL), top soil texture (ST), drainage density (DD), lineaments density (LD), and lithology (LIT). MAR feasibility map was generated through combining the intrinsic suitability, recharge water availability (rainfall, dam water and transferred water), and water demand (irrigation, drinking and ecosystem needs) in the study site. Characteristics and origins of the used data in MAR feasibility analysis are summarized in Table 1.

GIS-MCDA

GIS-MCDA, which is the core part of MAR suitability and feasibility, was used to rank the available areas based on decision rules that define how the standardized criteria are integrated. It includes the following steps:

- Decision rule: the decision rule is principal part of mapping MAR suitability, and GIS-MCDA will be per-

Table 1 Characteristics of the used data

Thematic layer	Source	Resolution	Link
Slope	ASTER GDEM data	30 × 30 m	https://earthexplorer.usgs.gov/ (Accessed in December 2020)
Soil	National agronomic database of Tunisia	Vector	Available at the regional departments of Agriculture Development (CRDAs)
Lithology	Geological map of Tunisia (Ben Haj Ali et al 1985)	Vector	Available at the National Office of Mines (ONM)
LULC	National agronomic database of Tunisia	Vector	Available at the regional departments of Agriculture Development (CRDAs)
Drainage	Derived from ASTER GDEM data	Vector	https://earthexplorer.usgs.gov/ (Accessed in December 2020)
Lineament	Derivated from Landsat 8 map	Vector	https://earthexplorer.usgs.gov/ (Accessed in December 2020)
Precipitation	Ministry of Agriculture, Fisheries and Hydraulic Resources	Table	http://www.agridata.tn/group/donnees-climatiques (Accessed in December 2020)
Irrigated perimeters	National agronomic database of Tunisia	Vector	Available at the regional departments of Agriculture Development (CRDAs)
Population density	World population database adjusted with UN and local statistics	125 × 125 m	WorldPop: www.worldpop.org (Accessed in December 2020)
Wetlands, hill dams, transferred water schemas	National agronomic database of Tunisia	Vector	Available at the regional departments of Agriculture Development (CRDAs)

formed based on weighted linear combination (WLC). WLC includes the linear accumulation of the result of weighting criteria and values. It consists of the linear aggregation of the product of criterion weights and values (Magesh et al. 2012).

- Criteria: factors which govern groundwater occurrence, recharge and movements depend upon geology, geomorphology, land cover, drainage density, lineament density, and natural precipitation. MAR feasibility depends basically from: (i) intrinsic MAR suitability of the site, (ii) recharge water availability, and (iii) water demand. These data were furnished by the Regional Office of Agriculture Development of Sousse governorate, and we stored them in GIS database. Constraint criteria will typically be represented by a Boolean statement of suitability for the decision considered, where the criterion is described by a binary system (true/false, 1/0...). This type of criterion serves to limit the alternatives under consideration by defining restrictive features for which an area will necessary be considered unsuitable. Constraint criteria are typically represented on a map with a separate mask layer (Bonilla and Stefan 2019; Fathi et al. 2020).
- Standardization: same scale is needed to be assigned in order to explain the relative level of the criteria. Transformation of criteria into comparable scale is standardization. There are two reliable methods which are used for standardization, stepwise, and linear functions. The former described by Rahman et al. (2012) will be applied to standardize combined criteria.
- The assignment of different weight for the integration of the criteria is necessary because they do not have the same degree of influence (Shaban et al. 2006). In this study, the analytic hierarchy process (AHP) will be used for the explanation and assignment of the weight. The AHP method was described by Saaty (1990) who stated that the relationships between the criteria are established either in matrix or in a graphical way.
- Sensitivity analysis: sensitivity analysis in MCDA is defined by Malczewski and Rinner (2015) as a set of methods for assessing uncertainty in the multi-criteria model output and the importance of the model input factors as the criterion values and weights. Criteria values and weights are the main sources of uncertainties in GIS-MCDA analysis (Feizizadeh and Blaschke 2014). In this study, sensitivity analysis will be performed by changing the criteria weights and evaluating its effect on the final MAR suitability index. The amount of the change will be defined by varying the weight within its standard deviation, thus altering the decision rule by small variations in the pairwise matrix method.

Results and discussion

Intrinsic MAR suitability mapping

Thematic layers

The intrinsic MAR suitability represents the hydrological aptitude of the study site to host an artificial recharge schema capable of water banking. It is performed using intrinsic criteria of the site which are land use/land cover (LULC), slope (SL), top soil texture (ST), drainage density (DD), lineaments density (LD), and lithology (LIT).

LULC is an important criterion since it plays an essential role in evapotranspiration as crucial component of the hydrological balance. Besides, it gives an idea about the available land for installing MAR systems. Many authors have considered it in MAR suitability studies under arid and semi-arid environments (Sener et al. 2005; Mukherjee et al. 2012; Fenta et al. 2015). Enfidha plain is dominated by seasonal crop plantation in its central part and pasture, olive trees, and bare soils in the other regions. Abundant pasture and bare soils constitute suitable zone for MAR implementation (Mahmoud 2014). The coastal and southwestern parts host wetlands (sebkha) (Fig. 3a).

Slope is one of the most considered criteria in MAR suitability mapping. In fact, the higher is the slope, the lower will be the aquifer recharge especially for spreading methods. This criterion was also considered in many studies in different arid and semi-arid locations (e.g., Andreo et al. 2008; Alraggad and Jasem 2010; Karami et al. 2016). Enfidha is flat plain in its majority with a gentle slope less than 5° which increase infiltration rate and favor the artificial recharge (Rahman et al. 2012). Only its northwestern part is characterized by higher slopes comprised between 2 and 15° (Fig. 3b).

Top soil texture is the first horizon which recharge water will cross. Coarse texture allows a better recharge water infiltration. It was also reported in many studies (e.g. Oikonomidis et al. 2015; Msaddek et al. 2017; Souissi et al. 2018). Enfidha plain is characterized by a dominant coarse top soil texture mainly composed by alluvium, sand, and sandstone. Fine texture, which is represented by clay and marl, is found in the central and north parts of the plain (Fig. 3c).

Drainage and lineament networks constitute favorable pathways for recharge water to replenish the aquifer. They were used as well in many arid and semi-arid regions to appreciate aquifer recharge (e.g. Chenini et al. 2010; Karami et al. 2016; Zghibi et al. 2020). Drainage density is more developed in the nonwestern part of the plain associated to outcropping reliefs (Fig. 3d and e). Natural

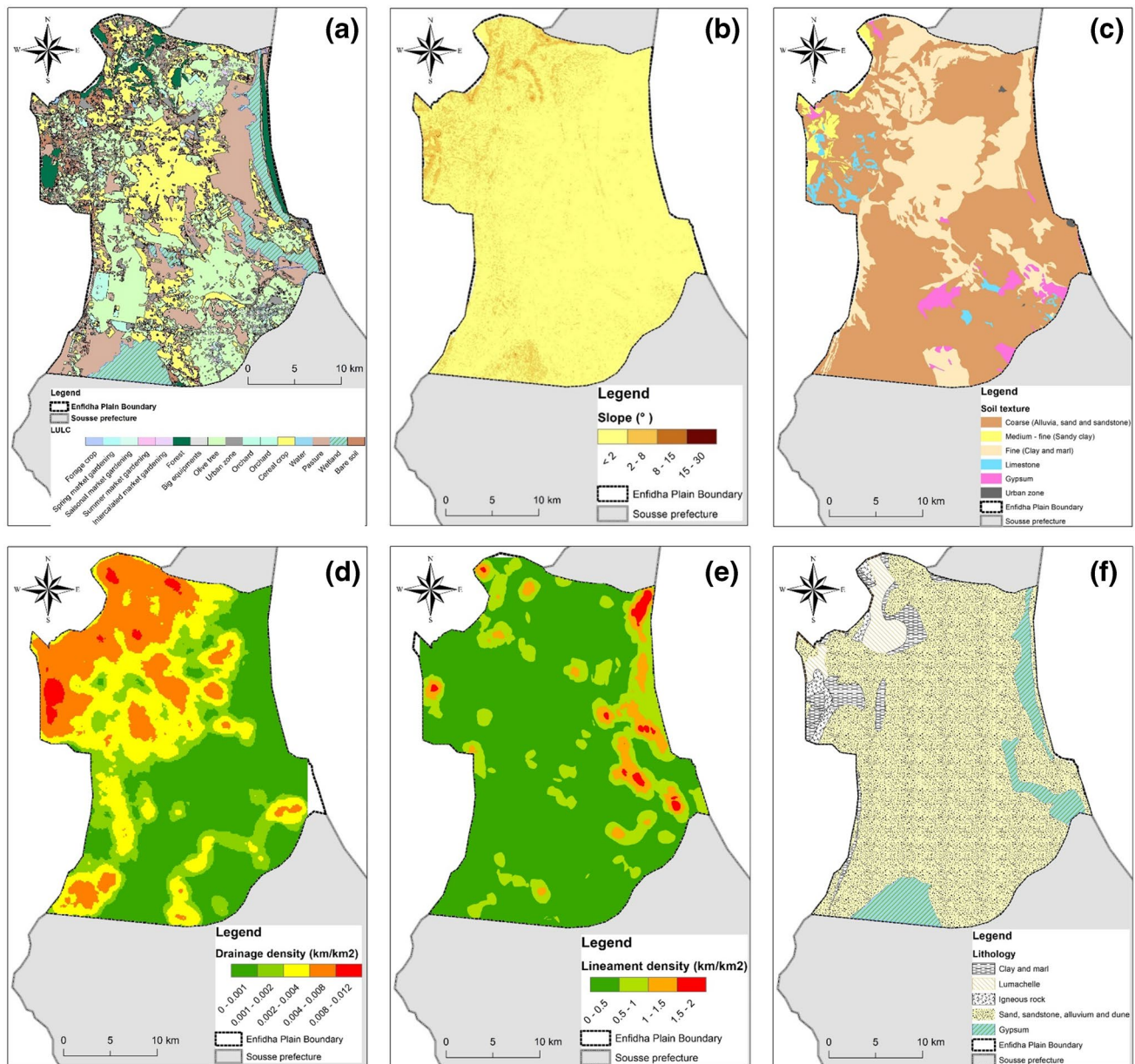


Fig. 3 Thematic layers of the MAR intrinsic suitability analysis: **a** LULC; **b** slope; **c** top soil texture; **d** drainage density; **e** lineament density; **f** lithology

recharge in this region might be more abundant, while lineaments are denser near the coast line since their occurrence is correlated to the tectonic activity in the region. In these regions, rainfall water infiltration is supposed to be easier and aquifer recharge facilitated.

Finally, lithology is obviously used in most of artificial recharge studies since the geological structure and parameters are the first influencers of this process. The main geologic outcrop in most parts of Enfidha plain is Quaternary deposits of alluvium, sand, and sandstone. Gypsum is abundant near the wetlands, and hard igneous

rocks are associated to steep reliefs in the northwestern part (Fig. 3f).

Standardization and weight assignment

The six thematic layers were standardized in 1 to 5 scale regarding their influence on artificial groundwater recharge (Table 2). An area with 1 value does not have any influence on MAR implementation, while an area with value of 5 have a very high MAR potential. Other values (2, 3 and 4) are used for intermediate MAR potential. Standardized values were

Table 2 Standardization of the criterions

Criteria	Suitability classes					References
	1. Unsuitable	2. Low suitable	3. Moderately suitable	4. Suitable	5. Highly suitable	
LULC	Artificial area, wetland, water body, bare rock	Forest	Permanent crop, heterogenous agricultural area	Arable land, pasture	Scrub and herbaceous, Spare vegetation	Sener et al. (2005), Adham et al. (2010), Fenta et al. (2015)
SL	> 30°	30–10	10–5	5–2	< 2°	Chowdhury et al. (2010), Msaddek et al. (2017), Souissi et al. (2018)
ST	Clay	Silty clay	Clayey silt	Sand-silt	Sandy to coarse	Singh et al. (2013), Pedrero et al. (2011), Sukumar and Sankar (2010)
DD	< 0.1 km/km ²	0.1–0.17	0.17–0.24	0.24–0.32	> 0.32 km/km ²	Chenini et al. (2010), Msaddek et al. (2017), Zghibi et al. (2020)
LD	0–0.5 km/km ²	0.5–1	1–1.5	1.5–2	> 2 km/km ²	Chenini et al. (2010), Karami et al. (2016), Zghibi et al. (2020)
LIT	Unfractured, clay	Sedimentary in clay matrix	Permeable sedimentary	Fractured, weathered	Sand and gravel	Kallali et al. (2007), Gdoura et al. (2015)

chosen based on detailed literature review in similar condition zones, international guidelines, and reports and expert’s opinions.

The weighting process was carried out using the analytic hierarchy process (AHP) based on pairwise comparison matrix method. Priority values were assigned through Saaty (1990) method. The pair-wise comparison matrix uses a semantic 9-point scale for attributing priority values 1, 3, 5, 7, and 9 correspond respectively to equally important, moderately important, strongly important, very strongly important, and extremely important criterion when compared with another. The intermediate values 2, 4, 6, and 8 could be used when compromise is needed (Saaty 1990). After that, the matrix is normalized using Eq. 1:

$$n_{ij} = a_{ij} / \sum_{i=1}^n a_{ij} \tag{1}$$

a_{ij} is the assigned priority value throughout Saaty’s classification.

Then, local weights (w_i) are calculated based on Eq. 2:

$$w_i = \sum_{i=1}^n n_{ij} / n \tag{2}$$

Consistency of the calculated weights is evaluated through consistency ration (Cr) based on Eq. 3:

$$C_r = CI / r_i \tag{3}$$

r_i is the random index determined from literature (Saaty 1990) and CI is the consistency index determined by Eq. 4:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

λ_{max} is the principal eigenvalue.

A consistency ration less than 10% means satisfying judgment, and the calculated weights can be then utilized in calculating the MAR suitability index.

Pairwise comparison matrix and calculated criterions weights of the present study are presented in Table 3. Consistency ratio is equal to 4.6%. Subsurface lithology and topsoil texture criterions have the most important weights (43.8% and 24.5%, respectively) since they constitute the core of MAR concept. Terrain slope and LULC have together 20% of the total influence on MAR suitability. Finally, drainage and lineaments density have the least weight with 10%.

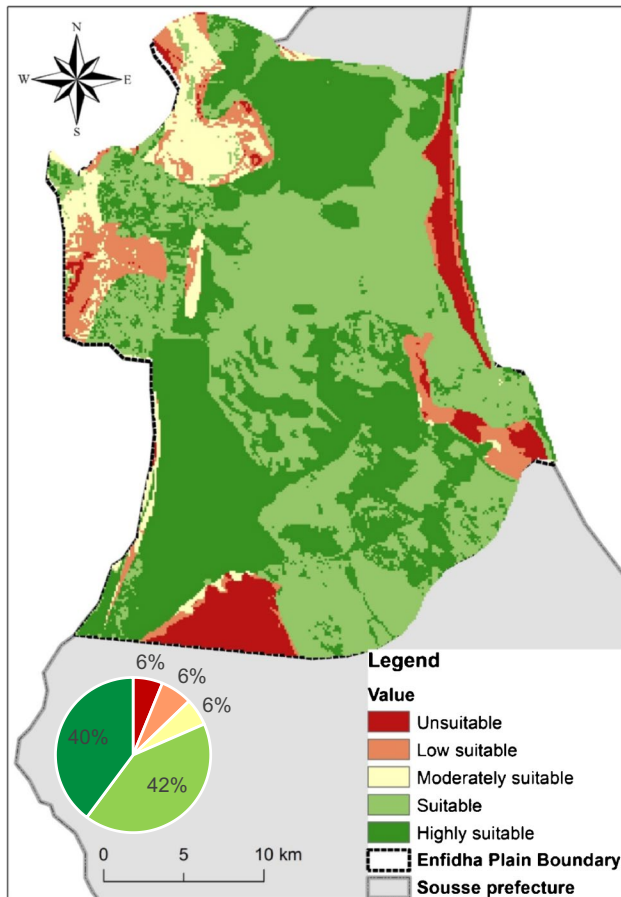
Intrinsic suitability map

Intrinsic suitability index of Enfidha plain is calculated based on Eq. 5:

$$S = \sum_{i=1}^n w_i \cdot x_i \tag{5}$$

Table 3 Pairwise comparison matrix with calculated criterions weights and standard deviation

	LULC	SL	ST	DD	LD	LIT	Weight	STD ± -
LULC	1	3	1/3	2	2	1/5	12.1%	5.5%
SL	1/3	1	1/4	2	2	1/5	8%	2.9%
ST	3	4	1	4	4	1/3	24.5%	7.2%
DD	1/2	1/2	1/4	1	1	1/5	5.8%	1.5%
LD	1/2	1/2	1/4	1	1	1/5	5.8%	1.5%
LIT	5	5	3	5	5	1	43.8%	16.9%

**Fig. 4** Intrinsic MAR suitability map of Enfidha plain

w is the weight of the criterion and x is the standardized value of criterion.

The weighted linear combination (WLC) was carried out using raster calculator module in ArcGIS software. The obtained intrinsic suitability map of Enfidha plain is illustrated in Fig. 4. It reveals that 82% of the plain area is suitable to highly suitable to implement MAR systems. These zones cover the north, center, and southeast of the plain. They are characterized by gentle slope, coarse texture, alluvial deposits, and abundant pasture and bare soils. This finding is similar to the results of Rahman et al. (2012) and Mahmoud (2014). Zones classified “moderately suitable”

represent 6% of the total area. They are mainly located in the northwestern part of the plain dominated by high lands and forests but also with high drainage density and acceptable hydrogeological parameters (natural recharge zones). Low suitability and unsuitable zones represent together 12% of the total plain area. They are retrieved in coastal and southern regions and associated with the wetlands. They cover also limited zones in the northwestern part of the plain in the piedmonts of the high lands where impermeable formations are dominant.

Sensitivity analysis

The calculated weights of criterions were associated with standard deviation (Table 3). The variation of every criterion weigh from maximum (+) to minimum (–) with keeping others without change generated 12 scenarios with different decision rules (Fig. 5). The twelve scenarios are compared with the original reclassified WLC, and the analysis is done throughout the percentage of change in every suitability class. Sensitivity analysis reveals that the intrinsic MAR suitability model is particularly sensitive to top soil texture and lithology criterions. Scenario 5 (–ST) shows a decrease of “suitable” class by around 20% and an increase in “highly suitable” class by the same absolute value. If we keep priorities for these two classes together, the same suitability will practically remain under (–ST) scenario and the intrinsic suitability model can be considered low sensitive to change in top soil texture criteria, whereas lithology criteria scenarios produce considerable changes in intrinsic MAR suitability classes. In fact, under scenario 11 (–LIT), “low suitable” class area decreases by 20%. However, “suitable” class decreases by the same amount considering scenario 12 (+LIT). In addition, the last scenario engenders an increase by 10% in the area of “highly suitable” class. In summary, except scenario 11, variation in suitability classes is not exceeding globally 10% and the noticeable changes in the most important classes (“suitable” and “highly suitable”) are compensating each other since their absolute values of change are almost the same. Therefore, the proposed intrinsic MAR suitability model is considered only sensitive when undervaluing lithological criteria which lead to an underestimate of the MAR suitability.

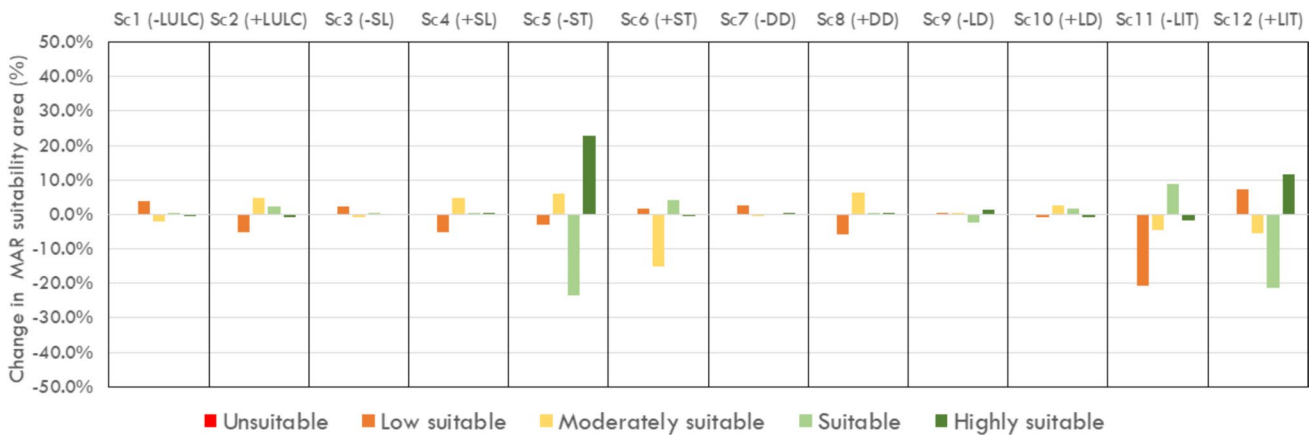


Fig. 5 Sensitivity analysis result

MAR feasibility map

MAR feasibility is a wider concept which includes intrinsic suitability of a site, the available water for recharge, and the water demand.

Recharge water availability

A MAR system cannot be implemented without water dedicated to recharge. Therefore, possible source waters were screened in Enfidha plain. They include hill dam water which is already used in the zone (in-channel modification (Fig. 6a), harvested rain water (Fig. 6b), and transferred water (Fig. 6c). The last water source is available throughout

the North water transfer canal which passes through Enfidha plain towards coastal and south part of the country. This water is mainly used for drinking purpose. Aloui (2019) have demonstrated the existence of a seasonal water surplus by comparing the transferred and consumed canal water. These quantities can be used in MAR of Enfidha plain.

Similar to the intrinsic suitability mapping process, these three criteria were standardized, reclassified, and weighed to produce the map of recharge water availability. Reclassification procedure is presented in Table 4.

After that, a pairwise comparison matrix was performed to calculate the weighs of the criterions (Table 5). Its consistency ratio is equal to 0.4% which means that the obtained weighs are reliable.

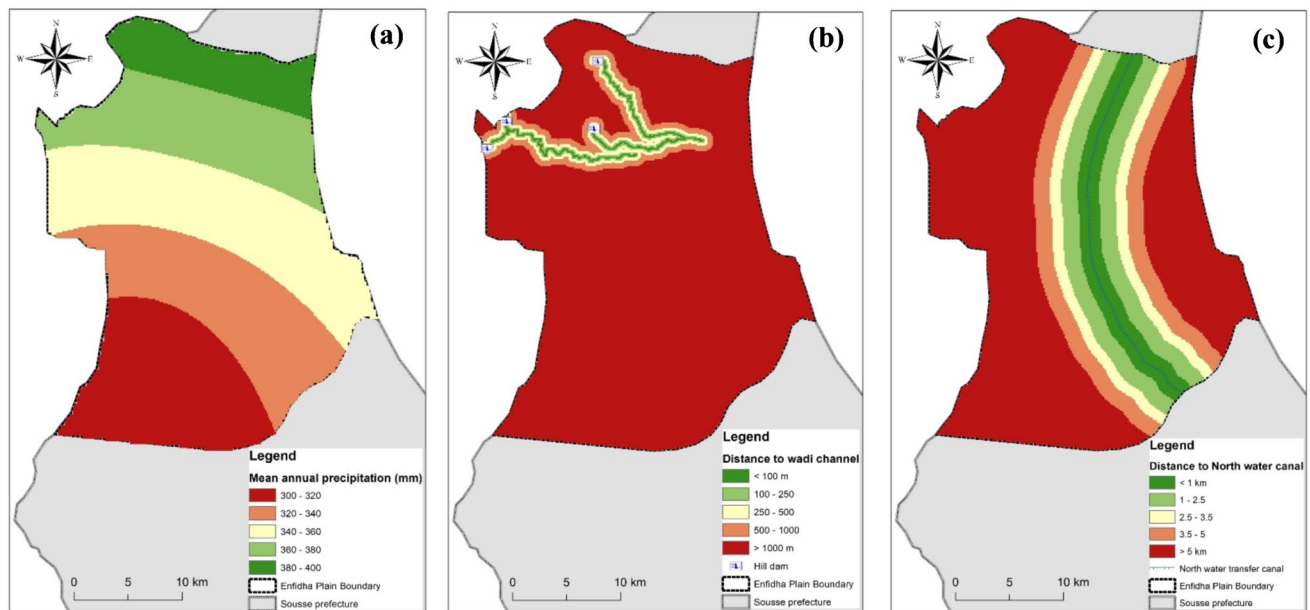


Fig. 6 Available water for MAR in Enfidha plain. **a** Mean annual precipitation; **b** distance to wadi channel; **c** distance to North water canal

Table 4 Standardization of the recharge water availability criterions

Criteria	Availability classes				
	1. Unavailable	2. Low available	3. Moderately available	4. Available	5. Highly available
Hill dam (distance to wadi channel)	> 1000 m	1000–500	500–250	250–100	< 100 m
Transferred water (distance to transferred water canal)	> 5 km	5–3.5	3.5–2.5	2.5–1	< 1 km
Rainfall (annual precipitation)	< 150 mm/yr	150–250	250–350	350–450	> 450 mm/yr

Table 5 Pairwise comparison matrix and weights of the used criterions for recharge water availability

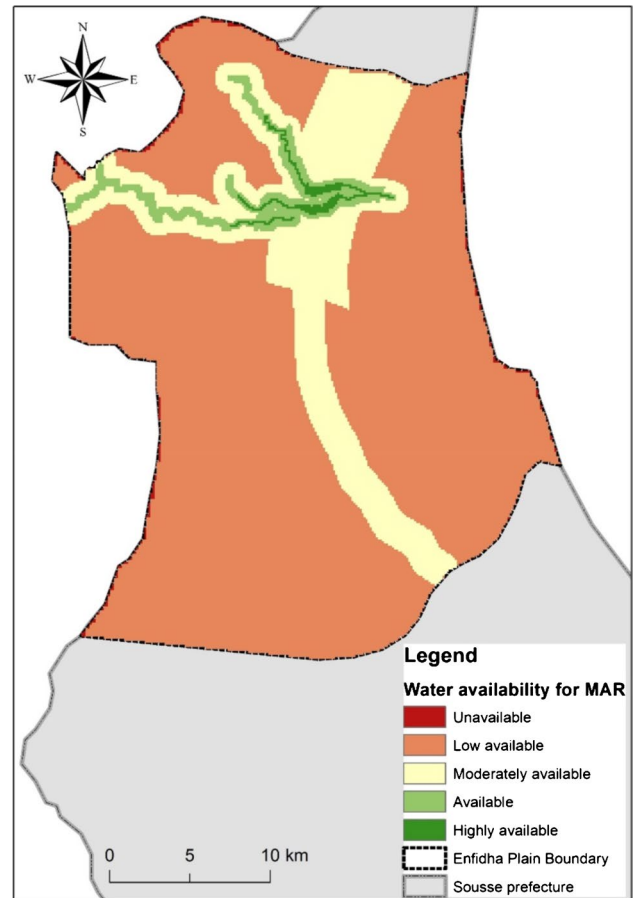
	Rainfall	Transferred water	Hill dam water	Weight
Rainfall	1	1/2	1/5	12.2%
Transferred water	2	1	1/3	23%
Hill dam water	5	3	1	64.8%

The generated map of recharge water availability is illustrated in Fig. 7. It shows clearly the influence of both hill dams and transferred water. Recharge water is low available in the major part of Enfidha plain. Its availability becomes moderate in the vicinity of the transfer canal and in some distance from wadis. However, the classified “available” to “highly available” zones are particularly in low distance from the wadis where the dam water release is undertaken.

Water demand

MAR systems are usually implemented to contribute in satisfying water demand. Without water consumers, MAR is meaningless. In Enfidha plain, tremendous water need is not satisfied right now with the existent water resources. In fact, the main demand poles are constituted by irrigation (Fig. 8a), drinking water supply (Fig. 8b), and ecosystems needs (Fig. 8c). The study area hosts many public and private irrigated perimeters (exceeding 5000 ha) with huge irrigation water demand. Abundant rural and urban zones are also existing in the plain with important population densities especially around Enfidha city. Many locations are still missing adequate connection to drinking water supply systems. Humid zones (sebkha) are existing in both coastal and southwestern parts of the plain. They constitute huge ecosystems refuting a diversity of fauna and flora which depend from existing water for their developments. They constitute the natural outlets of the aquifers. Thus, any variation in groundwater resources will inevitably affect these vulnerable ecosystems.

The 3 criterions were classified according to areas of the irrigated perimeter, population density, and proximity

**Fig. 7** Map of recharge water availability in Enfidha plain

to wetlands for irrigation, drinking, and ecosystem needs, respectively (Table 6).

The chosen criteria were weighted using pairwise comparison matrix. The obtained weights are 67.2%, 26.5%, and 6.3% for irrigation, drinking, and ecosystem demands, respectively. The consistency ratio of the analysis is equal to 3%. Thus, the obtained weights can be adopted to generate the water demand map of Enfidha plain (Fig. 9). The obtained map shows that the most important demand is located primarily in the northern part of the plain within the intersection of the largest irrigated perimeter with the

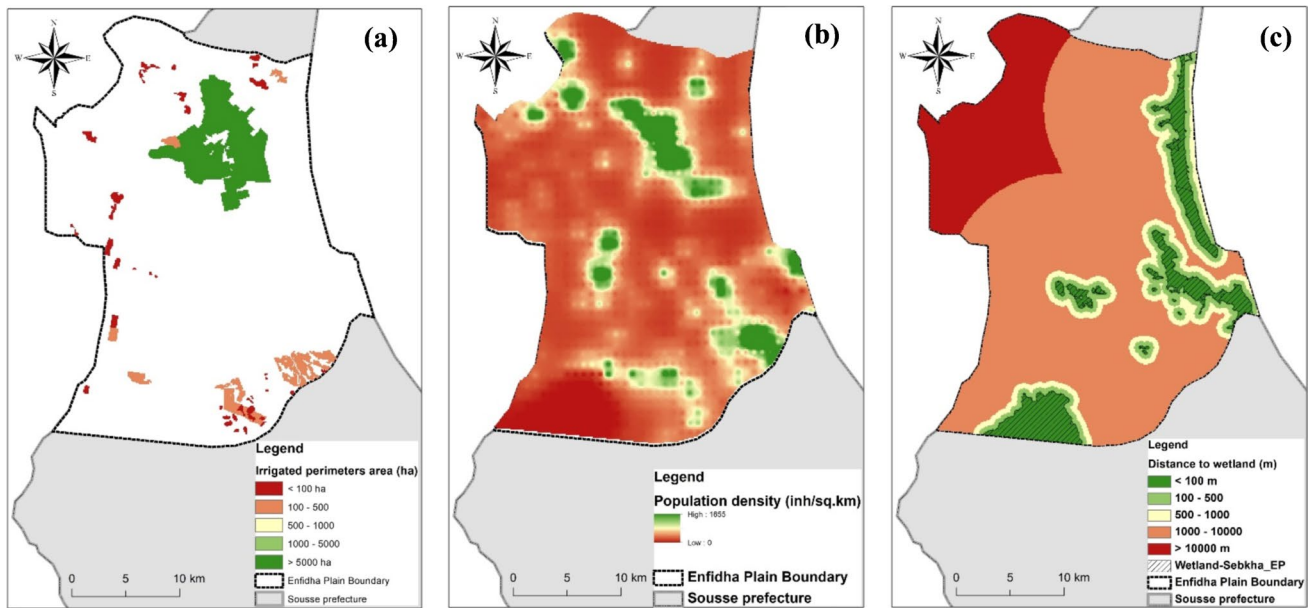


Fig. 8 Thematic layers of water demand in Enfidha plain. **a** Irrigated perimeters area; **b** population density; **c** distance to wetlands

Table 6 Standardization of the water demand

Criteria	Water demand classes				
	1. No demand	2. Low demand	3. Moderate demand	4. Demand	5. High demand
Population density (inhabitant per sq km)	< 50 inhab/km ²	50–250	250–500	500–750	> 750 inhab/km ²
Irrigated perimeters (IP surface)	< 100 ha	100–500	500–1000	1000–5000	> 5000 ha
Ecosystem needs (distance to wetlands)	< 100 m	100–500	500–1000	1000–10,000	> 10,000 m

densest population zone (Enfidha city). Some spots of moderate demand are also existing in the southern part and are correlated to the existing scattered irrigated perimeters.

MAR feasibility in Enfidha plain

MAR feasibility map is the result of overlay of the MAR intrinsic suitability, recharge water availability, and water demand maps. The obtained MAR feasibility map of Enfidha plain shows that only 18% of the total area where MAR is feasible and highly feasible (Fig. 10). These zones are mainly located in the northern part of the plain near Enfidha city and its largest irrigated perimeter and where recharge water is available from the hill dams. Furthermore, a strip that runs along the plain from its central part to its southern part, following the transferred water canal, is also categorized “suitable” for MAR systems implementation. Zones classified “unfeasible” and “low feasible” (12%) are particularly overlaid with wetlands (sebkha) where none intrinsic suitability neither water availability are fulfilled. The remaining plain area (70%) is classified “moderately feasible.” Implementing

a MAR project in these zones is not profitable and may face failure and permanent ineffectiveness.

Until now, MAR feasibility maps are considered as the result of an equal contribution of the three maps of intrinsic suitability, recharge water availability, and water demand. Some authors agreed that the equal weighs are the most convenient (Bonilla and Stefan 2019). However, to be more rigorous, these assigned weighs need to be adapted to every case according to the importance of each parameter.

Web-based DSS portal: INOWAS platform

Once achieved, thematic layer maps and data need to be shared and discussed with stakeholders. MAR intrinsic suitability, recharge water availability, and water demand maps can be generated in harmony with decision makers throughout specialized web-based DSS portal. Basic data and raster data were deployed within INOWAS DSS web portal (<https://inowas.com/>) which was developed by the Research Group INOWAS (“Innovative web-based decision support system for water sustainability under a changing climate”, <http://tu-dresden.de/uw/inowas>) at the Technical

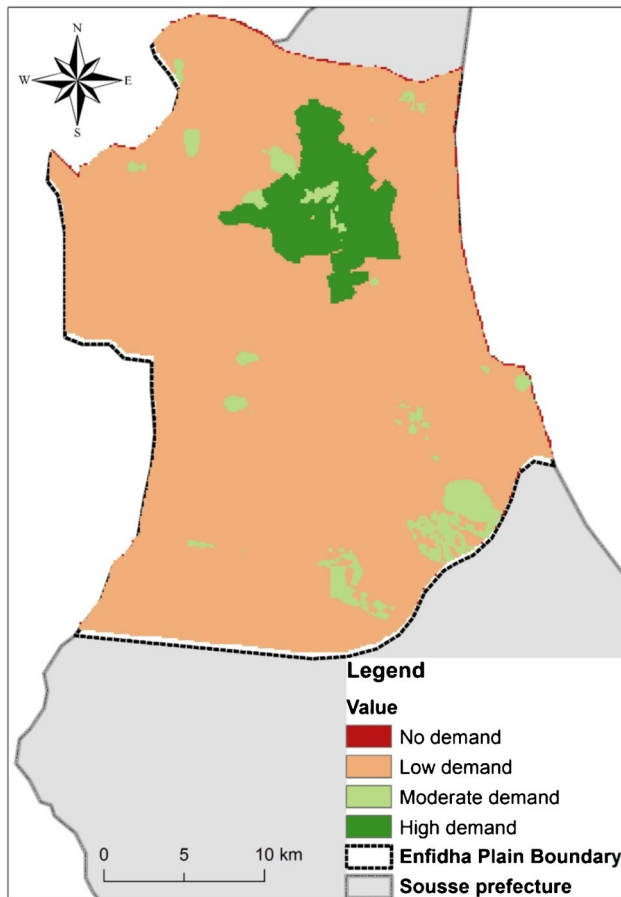


Fig. 9 Map of the water demand in Enfidha plain

University of Dresden, Germany. INOWAS is a platform that is accessible by most of the internet browsers. It is based on open-source collection of empirical, analytical, and numerical web-based models focusing on the planning, management, and optimization of MAR applications. Users can create accounts to establish, store, and share their MAR maps. The database query tool “T05 GIS multi-criteria decision analysis” was used to manipulate the data of Enfidha plain.

The tool offers the possibility to use all the conventional steps of a GIS-MCDA from criteria identification until generating the MAR suitability map.

The MAR intrinsic suitability map of Enfidha plain was established using INOWAS portal using the six criteria previously described; a pairwise comparison matrix and an online WLC method to overlay the weighed criterions (Fig. 11). The obtained spatial distribution of suitability classes is compatible to the result of the commonly used commercial software like ArcGIS 10.

INOWAS web-based DSS portal offers an easy-to-use tool to study MAR suitability. With the increased interest in free and open-source tools, this portal has a promising role in promoting sustainable water resources management

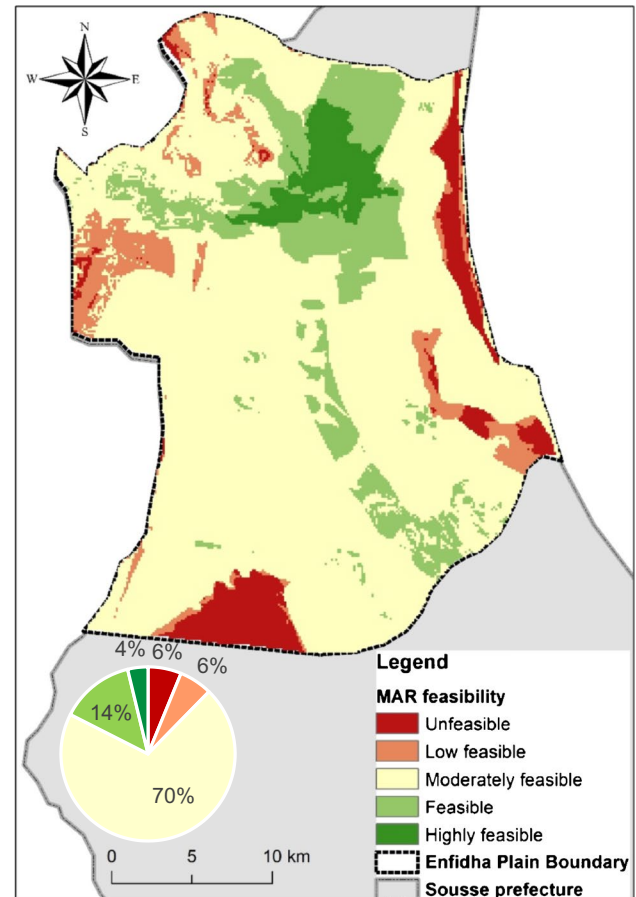


Fig. 10 MAR feasibility map of Enfidha plain

throughout its capacity of effective participatory decision making.

Conclusion

This study was performed within the framework of enhancing the use of geospatial and web-based methods in finding new pathways to reduce water scarcity in arid and semi-arid environments of Tunisia. The present work demonstrates GIS-MCDA-based approach as useful tool for MAR suitability and feasibility mapping in Enfidha plain as an experimental site which hosts one of the most stressed aquifer systems in the eastern part of Tunisia.

An adapted methodology for the choice of criteria and calculation of their weights was used in comparison to selected previous studies which have dealt with similar characteristics as well as from the expertise of the stakeholders and their deep knowledge about the plain main issues. A developed sensitivity analysis revealed that that intrinsic suitability of the site depends mainly from an underestimation of the geological factor. Detailed exploration of the

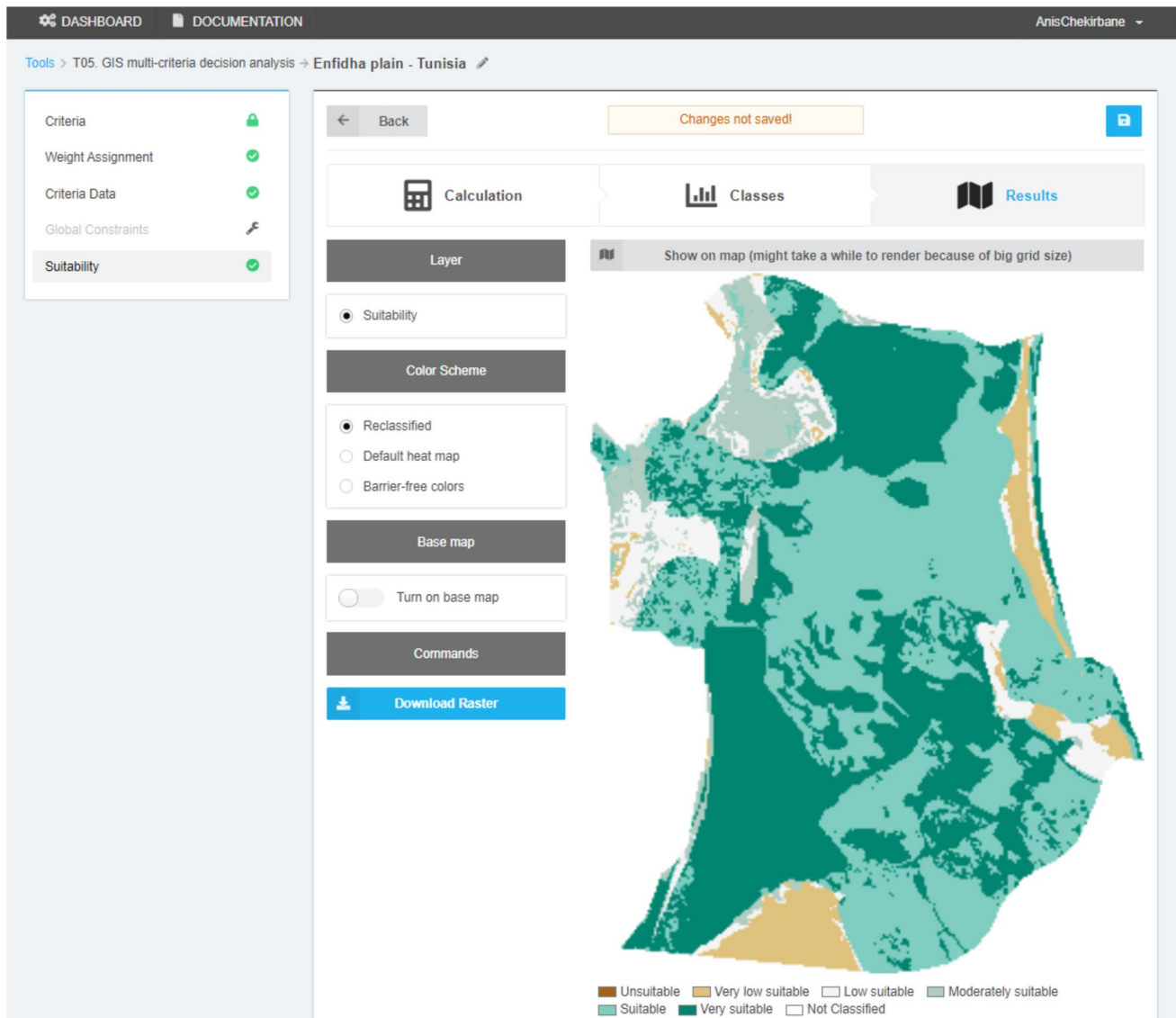


Fig. 11 MAR intrinsic suitability map of Enfidha plain obtained from INOWAS web tool

subsurface geology based on multidisciplinary approaches including field observations, geophysics, and boring data will be an asset to reduce the model sensitivity to this criterion.

The MAR intrinsic suitability of Enfidha plain shows that more than 80% of its total area is classified suitable highly suitable especially near the central part which is dominated by porous formations and spare vegetation. Sebkhha (wetlands) and high lands are the least suitable zones. MAR feasibility requires in addition to the intrinsic site suitability an analysis of recharge water availability and an identification of water demand poles. The obtained MAR feasibility of Enfidha plain shows that only around the fifth of its total areal have good to high potential for implementing a MAR system. This class is mainly located in the junction

between the most intrinsically suitable area (central part), the area with most available recharge water (dams and transferred water), and the most important water consumer pole (Enfidha irrigated perimeter and Enfidha city). Zones with least feasibility potential are mainly located within the wetlands and high lands.

The INOWAS web-based DSS portal offers a good opportunity to map MAR suitability and feasibility in a participatory approach. The whole process going from thematic layers to standardization and weight assignment until generating the final maps can be shared, discussed, and modified in agreement with the stakeholders (technicians, policy makers, and final beneficiaries). Therefore, the proposed approach in this work can constitute the corner-stone of a sustainable groundwater resources management and one of the steps of

coping with water scarcity in arid and semi-arid environments of Tunisia.

Author contribution We would like to state that regardless their order in the authors list, first (Dorsaf Aloui) and second authors (Anis Chekirbane) have equally contributed to this paper preparation.

Declarations

Conflict of interest The authors declare no competing interests.

References

- Adham MI, Jahan CS, Mazumder QH, Hossain MMA, Haque AM (2010) Study on groundwater recharge potentiality of Barind Tract, Rajshahi District, Bangladesh using GIS and remote sensing technique. *J Geol Soc India* 75(2):432–438
- Ajjur SB, Baalousha HM (2021) A review on implementing managed aquifer recharge in the Middle East and North Africa region: methods, progress and challenges. *Water Int* 46(4):578–604
- Aloui D (2019) Etude hydrogéologique du système aquifère de Chegarnia-Sidi Abiche (Enfidha, Sousse) : bilan hydrique et possibilités de recharge artificielle. Master degree dissertation, Faculty of Sciences of Bizerte, University of Carthage, p 105
- Alraggad M, Jasem H (2010) Managed aquifer recharge (MAR) through surface infiltration in the Azraq basin/Jordan. *J Water Resour Prot* 2(12):1057
- Andreo B, Vías J, Durán JJ, Jiménez P, López-Geta JA, Carrasco F (2008) Methodology for groundwater recharge assessment in carbonate aquifers: application to pilot sites in southern Spain. *Hydrogeol J* 16(5):911–925
- Belghith Triki L, Boughrara L, Maalel F, Soussou A, Mattoussi R (2014) Contribution de la recharge artificielle à l'amélioration de la situation piézométrique du système aquifère de l'oued El Khairat. Internal report, Publ. General Direction of Water Resources, Ministry of Agriculture, Hydraulic Resources and Fisheries, Tunisia, p 32
- Ben Haj Ali M, Jedoui Y, Dali T, Ben Salem H, Memmi L (1985) Geological map of Tunisia at the scale 1/500 000, ed. Serv. Géol., Tunisia
- Bonilla JP, Stefan C (2019) Utilization of spatial analysis techniques for the identification of potential MAR areas: challenges and opportunities. Event report, 10th International Symposium on Managed Aquifer Recharge (ISMAR10). Madrid, Spain, May 20–24, 2019
- 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* 8(9):391
- Bouri S, Dhia HB (2010) A thirty-year artificial recharge experiment in a coastal aquifer in an arid zone: the Teboulba aquifer system (Tunisian Sahel). *C R Geosci* 342(1):60–74
- Chekirbane A, Aloui D, El Euch I, Mejri S, Lachaal F, Khadhar S, Mlayah A (2018) Assessment of managed aquifer recharge by hill dam water release: case of the groundwater flow systems at Wadi Saadine and Wadi Khairat watersheds, NE of Tunisia. Sixth International Water Forum Conference 2018. March 19–21, Hammamet, Tunisia
- Chekirbane A, Aloui D, El Euch I, Mejri S, Khadhar S, Lachaal F, Tsujimura M, Zghibi A, Mlayah A (2019) Tunisian experience in Managed Aquifer Recharge (MAR) by hill dam water release: case of some groundwater flow systems in North of Tunisia. 10th International Symposium for Managed Aquifer Recharge ISMAR 10. 20 – 24 May, Madrid, Spain
- Chenini I, Mammou AB, El May M (2010) Groundwater recharge zone mapping using GIS-based multi-criteria analysis: a case study in Central Tunisia (Maknassy Basin). *Water Resour Manage* 24(5):921–939
- Chowdhury A, Jha MK, Chowdary VM (2010) Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS and MCDM techniques. *Environ Earth Sci* 59(6):1209
- DGRE (General Direction of Water Resources DGRE) (2015) Artificial recharge of Tunisian aquifers. Internal report. Publ. Ministry of Agriculture, Hydraulic Resources and Fisheries, Tunisia
- Dillon P, Stuyfzand P, Grischek T, Lloria M, Pyne RDG, Jain RC, Bear J, Schwarz J, Wang W, Fernandez E, Stefan C (2019) Sixty years of global progress in managed aquifer recharge. *Hydrogeol J* 27(1):1–30
- Dillon PJ, Pavelic P, Page D, Beringen H, Ward J (2009) Managed aquifer recharge. An introduction waterlines report series. (13)
- El Euch I (2016) Evaluation de la recharge de la nappe de l'underflow d'oued El Khairat à partir des lâchers de barrage. [Groundwater recharge assessment in Khairat aquifer from dam water release]. *Master thesis*. National Institute of Agronomy, University of Carthage, Tunisia
- Famiglietti JS (2014) The global groundwater crisis. *Nat Clim Chang* 4(11):945–948
- 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
- Feizizadeh B, Blaschke T (2014) An uncertainty and sensitivity analysis approach for GIS-based multicriteria landslide susceptibility mapping. *Int J Geogr Inf Sci* 28(3):610–638
- Fenta AA, Kifle A, Gebreyohannes T, Hailu G (2015) Spatial analysis of groundwater potential using remote sensing and GIS-based multi-criteria evaluation in Raya Valley, northern Ethiopia. *Hydrogeol J* 23(1):195–206
- Furukawa M (2012) Groundwater and surface water cycle system in inland and coastal watersheds, northern Tunisia. Master thesis. Faculty of Life and Environmental Sciences, University of Tsukuba, Japan
- Gaaloul N, Pliakas F, Kallioras A, Schuth C, Marinos P (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
- Gdoura K, Anane M, Jellali S (2015) Geospatial and AHP-multicriteria analyses to locate and rank suitable sites for groundwater recharge with reclaimed water. *Resour Conserv Recycl* 104:19–30. <https://doi.org/10.1016/j.resconrec.2015.09.003>
- Gorelick SM, Zheng C (2015) Global change and the groundwater management challenge. *Water Resour Res* 51(5):3031–3051
- Greene R, Devillers R, Luther JE, Eddy BG (2011) GIS-based multiple-criteria decision analysis. *Geogr Compass* 5(6):412–432
- Kallali H, Anane M, Jellali S, Tarhouni J (2007) GIS-based multi-criteria analysis for potential wastewater aquifer recharge sites. *Desalination* 215(1–3):111–119
- Karami GH, Bagheri R, Rahimi F (2016) Determining the groundwater potential recharge zone and karst springs catchment area: Saldoran region, western Iran. *Hydrogeol J* 24(8):1981–1992
- Ketata M, Gueddari M, Bouhlila R (2014) Hydrodynamic and salinity evolution of groundwaters during artificial recharge within semi-arid coastal aquifers: a case study of El Khairat aquifer system in Enfidha (Tunisian Sahel). *J Afr Earth Sci* 97:224–229
- Magesh NS, Chandrasekar N, Soundranayagam JP (2012) Delineation of groundwater potential zones in Theni district, Tamil Nadu,

- using remote sensing GIS and MIF techniques. *Geosci Front* 3(2):189–196
- Mahmoud SH (2014) Delineation of potential sites for groundwater recharge using a GIS-based decision support system. *Environ Earth Sci* 72(9):3429–3442
- Malczewski J (2006) GIS-based multicriteria decision analysis: a survey of the literature. *Int J Geogr Inf Sci* 20(7):703–726
- Malczewski J, Rinner C (2015) *Multicriteria decision analysis in geographic information science*. Springer, New York, pp 90–93
- Manaa M, Chaieb H, Amri R (1996) Etude par modèle hydrogéologique de la nappe alluviale d'Oued El Khairat. [A study by hydrogeological model of the alluvial aquifer of Wadi Khairat], Internal report, Publ. General Direction of Water Resources, Ministry of Agriculture, Hydraulic Resources and Fisheries, Tunisia, p 31
- Margat J, Van der Gun J (2013) *Groundwater around the world: a geographic synopsis*. CRC Press/Balkema. <https://doi.org/10.1201/b13977>
- Masciopinto C (2013) Management of aquifer recharge in Lebanon by removing seawater intrusion from coastal aquifers. *J Environ Manage* 130:306–312
- 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(2):264
- Msaddek MH, Souissi D, Moumni Y, Chenini I, Dlala M (2017) Integrated multi-criteria evaluation and weighted overlay analysis in assessment of groundwater potentiality in Segui Region, Southern Tunisia. In: *Euro-Mediterranean Conference for Environmental Integration*. Springer, Cham, pp 631–632
- Mukherjee P, Singh CK, Mukherjee S (2012) Delineation of groundwater potential zones in arid region of India—a remote sensing and GIS approach. *Water Resour Manage* 26(9):2643–2672
- Oikonomidis D, Dimogianni S, Kazakis N, Voudouris K (2015) A GIS/remote sensing-based methodology for groundwater potentiality assessment in Tirnavos area, Greece. *J Hydrol* 525:197–208
- Page D, Bekele E, Vanderzalm J, Sidhu J (2018) Managed aquifer recharge (MAR) in sustainable urban water management. *Water* 10(3):239
- Pedrero F, Albuquerque A, do Monte HM, Cavaleiro V, Alarcón JJ (2011) Application of GIS-based multi-criteria analysis for site selection of aquifer recharge with reclaimed water. *Resour Conserv Recycl* 56(1):105–116
- Rahman MA, Rusteberg B, Gogu RC, Ferreira JL, 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
- Saaty TL (1990) How to make a decision: the analytic hierarchy process. *Eur J Oper Res* 48(1):9–26
- Sallwey J, Bonilla Valverde JP, Vásquez López F, Junghanns R, Stefan C (2018) Suitability maps for managed aquifer recharge: a review of multi-criteria decision analysis studies. *Environ Rev* 27(2):138–150
- Sener E, Davraz A, Ozcelik M (2005) An integration of GIS and remote sensing in groundwater investigations: a case study in Burdur, Turkey. *Hydrogeol J* 13(5–6):826–834
- Shaban A, Khawlie M, Abdallah C (2006) Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon. *Hydrogeol J* 14(4):433–443
- Singh A, Panda SN, Kumar KS, Sharma CS (2013) Artificial groundwater recharge zones mapping using remote sensing and GIS: a case study in Indian Punjab. *Environ Manage* 52(1):61–71
- Souissi D, Msaddek MH, Zouhri L, Chenini I, El May M, Dlala M (2018) Mapping groundwater recharge potential zones in arid region using GIS and Landsat approaches, southeast Tunisia. *Hydrol Sci J* 63(2):251–268
- Stefan C, Ansems N (2018) Web-based global inventory of managed aquifer recharge applications. *Sustain Water Resour Manage* 4(2):153–162
- Sukumar S, Sankar K (2010) Delineation of potential zones for artificial recharge using GIS in Theni district, Tamilnadu, India. *Int J Geomatics Geosci* 1(3):639
- van der Gun J (2021) Groundwater resources sustainability. In: Mukherjee A, Scanlon BR, Aureli A, Langan S, Guo H, McKenzie AA (eds) *Chapter 24 - global groundwater*. Elsevier, pp 331–345. <https://doi.org/10.1016/B978-0-12-818172-0.00024-4>
- Zammouri M, Brini N, Horriche FJ (2018) Assessment of artificial recharge efficiency against groundwater stress in the El Khairat aquifer. In: *Groundwater and Global Change in the Western Mediterranean Area*. Springer, Cham, pp 305–312
- Zghibi A, Mirchi A, Msaddek MH, Merzougui A, Zouhri L, Taupin JD, 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* 12(9):2525