



Site selection for artificial recharge with treated wastewater with the integration of multi-criteria evaluation and ELECTRE III

Marwa Mahmoudi^{1,2} · Abdelwaheb Aydi³ · Hatem Ibrahim³

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Abstract

The suitable location selection for artificial recharge with treated wastewater is an important issue, especially in arid and semiarid countries as a result of rapid population growth, increasing water demand, excessive use of groundwater resources, and mismanagement of limited freshwater resources. However, the determination of suitable sites is a complex process affected the environment, social, and economic concerns. This study shows the integration of the geographic information system (GIS) and the multi-criteria evaluation (MCE) to determine a suitable artificial recharge site with treated wastewater for Ariana, Tunisia. According to the literature review, data available on artificial recharge and regional characteristics, thirteen constraints and five factors were determined to choose the best potential site for artificial recharge. The constraints helped the determination of unsuitable sites with Boolean logic, while factors, standardized using fuzzy logic and weighted with the analytic hierarchy process (AHP), helped to identify suitable locations. All criteria were overlaid on a decision structure after two scenarios based on environment and economic were identified with a weighted linear combination (WLC) that selects the suitable sites for artificial recharge. The results indicated that three potential sites were suitable for artificial recharge with treated wastewater. Finally, the ELECTRE III method was used to classify the three determining potential areas to order the best locations for aquifer recharge with treated water according to their characteristics from higher to lower weighted: distance from the road, geometric form of the site, cost of the site, and distance from wetlands.

Keywords Multi-criteria evaluation · Analytical hierarchy process · Weighted linear combination · Artificial recharge · Treated wastewater

Introduction

Tunisia is an arid to a semiarid country with a total surface area of about 164,000 km². The freshwater available annually is about 450 m³ per citizen. The overexploitation of groundwater has caused decreasing groundwater levels because most

of the irrigation and drinking water needs are met from wells sourced by underground water in Tunisia. In recent years, artificial recharge has been increasingly used to outbalance the negative impacts on groundwater (Pedrero et al. 2011; Anane et al. 2012; Gdoura et al. 2015; Salar et al. 2018; Sallwey et al. 2018). There are plenty of recharge techniques including in-channel modifications (IM); well, shaft, and borehole recharge (WSB); rainwater and runoff harvesting (RWH); and induced bank filtration. These techniques have been used to recover the groundwater level, improve its quality, and serve as a barrier to salinity intrusion (Rahman et al. 2012). Moreover, it allows for the additional polishing of the wastewater through soil aquifer treatment as water flows through aquifers and soils (Asano et al. 2007). Therefore, the artificial recharge site selection has an important role in sustaining and controlling the quantity and quality of groundwater resources in risky areas. However, the selection of suitable artificial recharge sites is based on many factors,

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✉ Abdelwaheb Aydi
abdelwaheb_2000@yahoo.fr

¹ Department of Geology, Faculty of Sciences of Tunis, University of Tunis EL Manar, 2092 Tunis, Tunisia

² Lab.-3G “ LR18ES37 ”, Faculty of Sciences of Tunis, University of Tunis EL Manar, 2092 Tunis, Tunisia

³ Department of Earth Sciences, Faculty of Sciences of Bizerte, University of Carthage, Jarzouna, 7021 Bizerte, Tunisia

including environmental, geological, social, and economic concerns (Pedrero et al. 2011, Anane et al. 2012, Gdoura et al. 2015, Salar et al. 2018). There is still a large variation in the criteria applied for the selection of artificial recharge with reclaimed water site (i.e., topography, vegetation cover, geology, pedology, geomorphology, water quality, surface and sub-surface hydrology, etc.). Most of them rely on variations and combinations of indirect recharge and direct sub-surface techniques (Ghayoumian et al. 2005; Huang et al. 2013). Direct-surface techniques are the most widely used, including surface flooding, long narrow excavation for drainage, and furrow systems (Ghayoumian et al. 2007), even though the recharge techniques were applied to manage and sustain the groundwater resources. Recently, several studies have been put into effect using different new techniques for the detection of suitable areas for artificial groundwater recharge. The common methods are multi-criteria decision system (MCDA) combined with geographic information system (GIS) to solve spatial problems because GIS-based techniques help to manage large dataset, to eliminate conflicting policy objectives and to quickly calculate and combine a lot of information (Kallali et al. 2007; Ahmadi et al. 2017, Ghasemi et al. 2017). Previous studies used different GIS-based techniques to determine suitable location selection for artificial recharge with treated wastewater. In Tunisia, Kallali et al. (2007) combined the GIS-based MCDA with Boolean logic to safely recharge the aquifer. Gdoura et al. (2015) developed a methodology to select a suitable site using GIS and analytic hierarchy process (AHP) with a pairwise comparison. The combination of Boolean logic with GIS-based technique was tested on Egyptian semiarid climate by Riad et al. (2011) and on Saudi arid climate by Zaidi et al. (2015). Unlike the former, the latter additionally applied the overlay weighted methods to determine criteria weight. In Tehran, Iran, Ghasemi et al. (2017) suggested GIS-based fuzzy logic as another suitable approach for the location selection of artificial recharge with treated wastewater. Recently, Ahmadi et al. (2017) applied GIS-based multi-criteria evaluation techniques and remote sensing techniques as a decision support system to identify a potential location for groundwater recharge with treated municipal wastewater. Singh et al. (2011) combined the MCDA, AHP, and weighted linear combination (WLC) as a case study in India. The main aspects considered in the study are as follows: (1) the climate of the studied areas are arid or semiarid, (2) they have limited freshwater sources, (3) water use is dependent on groundwater resources, (4) water management is important for sustainable water use, and (5) GIS-based MCDA techniques were applied in all the test cases.

The main objective of this study is to identify the suitable location for artificial recharge with treated waste water in the semiarid region of Ariana, Tunisia, by applying a combination of GIS-based MCDA techniques, including Boolean logic, fuzzy set theory, AHP pairwise comparison, and WLC. The

study is pioneered with classifying and ranking the suitable possible areas using the AHP-ELECTRE III method. The research serves as a useful guide for decision-makers to recharge treated wastewater into the groundwater safely and to sustainably manage the water use in the Ariana region, Tunisia.

Materials and methods

Study area

The target area selected to conduct the research is the Ariana region in the north-east of Tunisia with a surface area of 482 km² (Fig. 1). It is a crowded region with more than 510,500 inhabitants, which represent 4.8% of the country’s population. The population density of Ariana is 876 citizens per km². Of the population, 90.8% lives in urban areas while

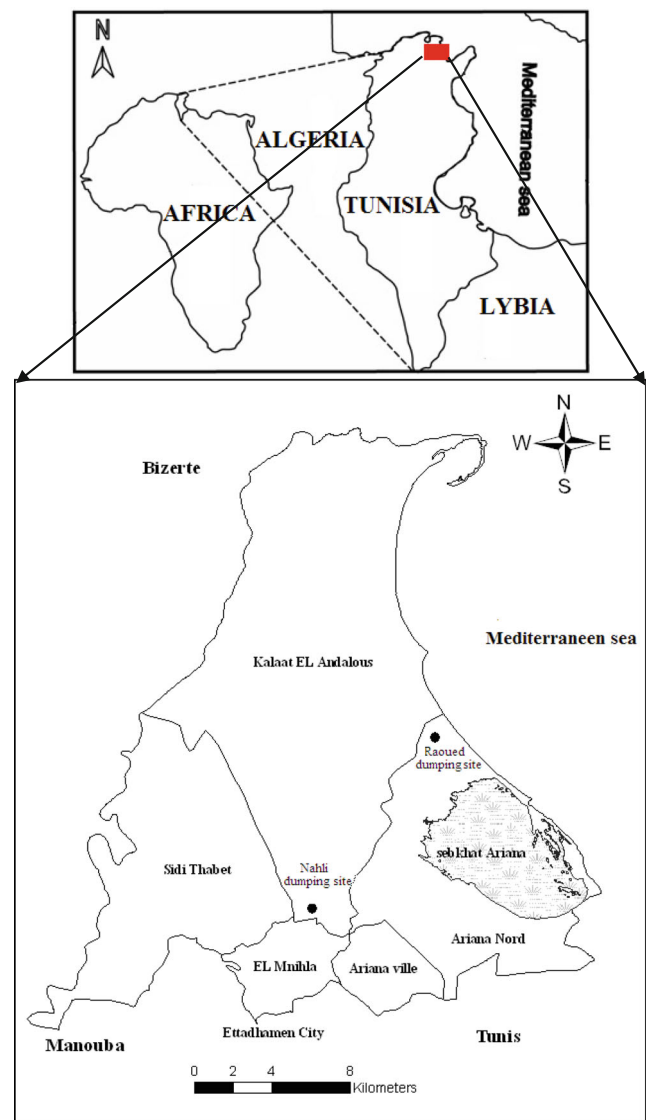


Fig 1 Location map of Ariana (The blue color indicates the study area.)

9.2% lives in rural areas. The climate is semiarid with an estimated annual precipitation of about 460 mm and an average annual temperature of 19 °C. The region of Ariana has an increasing shortage of water resources caused mainly by over-consumption, the decrease of rainfall, and poor management of the scarce water sources. The limited availability of water and high consumption creased the deficits. Reclaimed water is reused as an alternative source for agricultural, industrial, and domestic purposes. Wastewater in the Ariana region is treated by two wastewater treatment plants (WWTP), known as Chotrana I and Chotrana II. Chotrana I and II covered 50 ha and were commissioned in 1986. It has undergone several extensions and rehabilitations since 1998. Chotrana I and II treatment plants operate continuously throughout the year and treat 103,543 m³/day of sewage, which is equivalent to the daily water consumption of about 1035,430 inhabitants (Khouja et al. 2010). The treated water is discharged to the sea via Oued El Khalij (Dahmouni et al. 2019).

In order to quantify the organic pollutants, all the analyses and measurements are performed in accordance with the Tunisian Norms NT 106.002 and NT 106003, which are similar to the French Norm (AFNOR). The up-to-date regulations for treated wastewater and sludge (NT 106.03 and NT 106.20) visibly determine the limits for chemical and bacteriological elements.

Table 1 shows the difference between the physicochemical parameters of wastewater before and after treatment. The treated water was characterized with low heavy metal concentrations. Flows from the Chotrana WWTP (ONAS 2017) comply with the Tunisian standards on the discharge of wastewater into the receiving environment and rules on the use of wastewater for agricultural purposes. This is an indication of the proper functioning of the Chotrana WWTP (Table 1) (ONAS 2017). It also shows that the treated water does not have any adverse effects of discharging into groundwater sources.

Irrigation is practiced only 6 months a year. The recovered water is not stored during the non-irrigation season. A vast amount of treated water is discharged to the sea in Raoued for forage crops in the Bourj Touil area. This situation is a fundamental problem that needs to be resolved in terms of the

efficient use of treated water. Therefore, the main reasons why the Ariana jurisdiction was chosen as the study area are summarized below:

- The majority of the water used depends on groundwater resources
- The need for water management due to the limited water resources and inefficient water management
- To decide for a suitable wastewater recharge site selection because of discharging most of the treated wastewater into the sea instead of underground water sources.

To carry out this study, influential criteria were selected based the regional characteristics of the study area, data availability, and the literature review. Hence, the data relating to land use, slope, road network, urban area, rivers, water supply, wetlands, the location of groundwater wells, soil types, and protected area maps were collected from the Regional Commission for Agricultural Development of Ariana at a scale of 1:50,000 in shape file format and a projection reference system Carthage UTM Zone 32 N. The groundwater depth was obtained from piezometers using the inverse distance weighted (IDW) interpolation in ArcGIS 10.1.

Methodology overview

In ArcGIS environment, all the thematic maps were transformed on raster on raster grid with cells of 50 × 50 m² and exported to the IDRISI software. The influential criteria adopted were distinguished as constraints and factors. For the constraints, a Boolean approach was applied to differentiate the suitable areas (assigned the values of 1) for an aquifer recharge with treated water from the unsuitable areas (assigned the values of 0) under any conditions. After that, the factors influenced were standardized to a continuous scale, weighed, and then combined using the AHP methods. The weighted linear combination (WLC) method is applied to overlay constraints and factors. The suitable candidate areas are ranked using ELECTRE III method (Fig. 2).

Table 1 The annually averaged values of the main physicochemical parameters

Parameters	Wastewaters	Reclaimed water	NT 106002
pH	7.36	7.86	6.5 < pH < 8.5
Electric conductivity (µs/cm)	3677	4003	-
Suspended matter (mg/l)	391.25	26.75	30
COD (mgO ₂ /l)	900	86	90
BOD ₅ (mgO ₂ /l)	433	29	30
PO ₄ (mg/l)	10.37	2.71	0.1
N (mg/l)	92.48	32.64	30

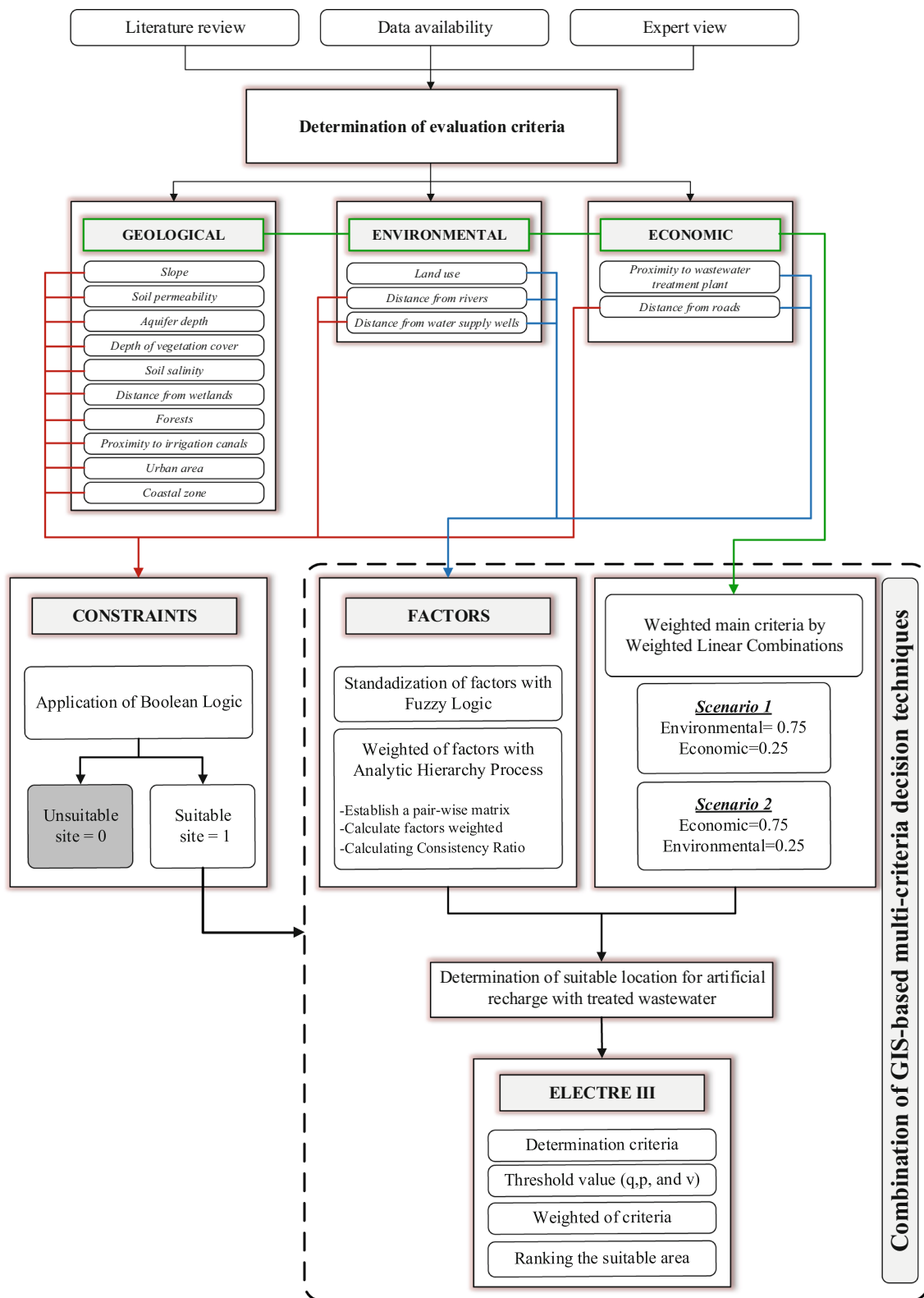


Fig. 2 The flowchart illustrating the methodology used in artificial recharge with reclaimed water

Table 2 The hierarchical structure of decision criteria for the selection of suitable artificial recharge site with wastewater treatment

Objective	Main Criteria	Sub-criteria	Constraints	Factors	
To select suitable sites for artificial recharge with wastewater treated	Geological	Slope	*		
		Soil permeability	*		
		Aquifer depth	*		
		Depth of vegetation cover	*		
		Soil salinity	*		
		Distance from wetlands	*		
		Forests	*		
		Proximity to irrigation canals	*		
		Urban area	*		
	Coastal zone	*			
	Environmental	Land use			*
		Distance from rivers	*		*
		Distance from water supply wells	*		*
	Economic	Proximity to wastewater treatment plant			*
		Distance from roads	*		*

Determination of decision criteria

The suitable location for artificial recharge sites with treated water decisions is a comprehensive study that requires a detailed analysis including environment, social, economic, and geological aspects. The determination of the right criteria is important for the suitable site selection because the artificial recharge site should

be positioned such that it minimizes the damage to the environment and the social life at the lowest possible cost. In this study, fifteen decision criteria related to geological, economic, and environmental aspects were selected. Also, thirteen criteria were applied for the suitable site selection according to the regional characteristics of the study area and the data availability upon the consultation of national experts and reviewing the relevant

Table 3 Fuzzy set memberships and membership functions with control points used for artificial recharge site selection

Main criteria	Factors	Standardization of factors	
		Control point	Fuzzy membership function
Environmental	Land use (no units)		
	Urban areas		0
	Protected area		0
	Wetlands		0
	Water		0
	Vine		2
	Mariachi culture		2
	Cereals		3
	Olive trees		3
	Forager culture		4
	Course		6
	Naked soil		10
	Economic	Distance from rivers	100 and 400 m
Distance from water supply wells		500 and 800 m	Sigmoidal increasing
Distance from roads		50 and 300 m	J-shaped decreasing
Proximity to wastewater treatment plant		800 and 2000 m	J-shaped decreasing

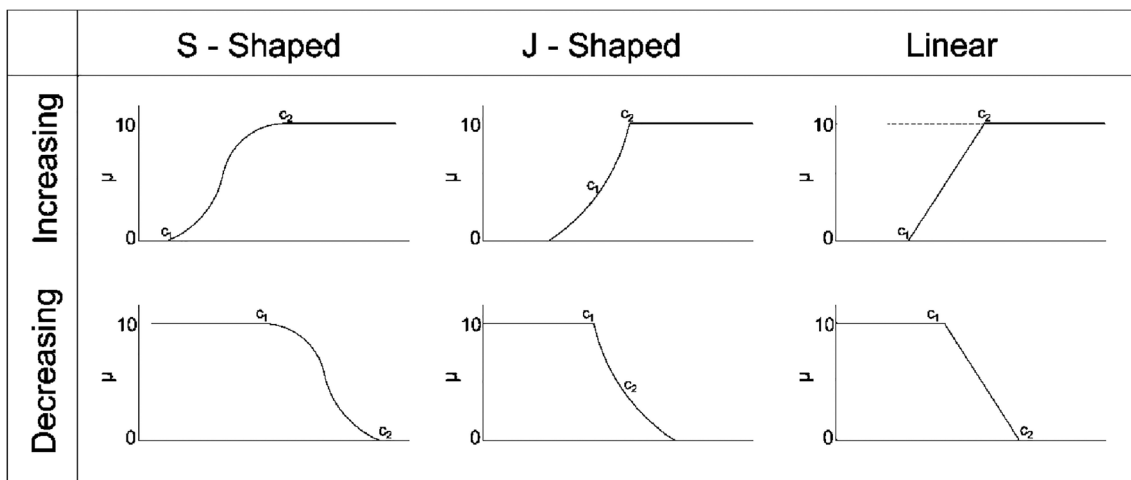


Fig. 3 Fuzzy membership functions for the standardization of factors

literature (EPA 1984; Kallali et al. 2007; Anane et al. 2008; Pedrero et al. 2011; Rahman et al. 2013; Gdoura et al. 2015; Ribeiro et al. 2010). The hierarchical structure of the decision criteria for the selection of suitable artificial recharge sites with wastewater treatment comprises five levels (Table 2). The first represents the objective of the study, ranking feasible areas for artificial recharge with treated wastewater. The second level shows the main criteria, including geological, environmental, and economical concerns. The third level shows the fifteen sub-criteria, which were divided into two groups: (i) constraints and (ii) factors, as shown in the last two levels of Table 3. Thirteen sub-criteria were defined as constraints; area considered as not suitable for the artificial recharge site. On the contrary, the factors, including five sub-criteria, determine a few degrees of suitability for the geographic areas. They allow an evaluation of the different alternatives from the previous step (Aydi et al. 2013).

Three criteria (distance from rivers, distance from waters, and distance from roads) were included in both constraints and factors groups. While the artificial recharge site should not be located in a constrained area to protect the environment and to minimize cost, it should be located at a rational distance to a decreased cost. Therefore, constraints, factors, and threshold values need to be well-defined before the suitable site decision.

Definition of decision criteria

Slope

The slope is an essential criterion for the anticipation of groundwater retention potential (Razandi et al. 2015; Aluko and Igwe 2017). Pedrero et al. (2011) and Anane (2012) stated that slopes higher than 15% are considered unsuitable sites. In this study, the limit slope value was set to 15%. Sites with slope values higher than 15% were excluded.

Soil permeability

Based on the geological characteristics of the region, this criterion was divided into three categories: very low, medium, and high permeability rates. The first and second categories are considered as unsuitable sites for artificial recharge with treated wastewater. High permeability is considered as one of the most appropriate criteria for artificial recharge (Gdoura et al. 2015; EPA 2006; Asano et al. 2007).

Groundwater depth

Groundwater depth shows the elevation of the top of the water surface in an aquifer (Salar et al. 2018). As for groundwater contamination, aquifers should be deep to prevent the excessive rise of the groundwater table due to penetration. The lower static groundwater level is 5 m, which is accepted for treated wastewater infiltration because it has a sufficiently large vadose zone for the last purification (State of California 1992; Pescod 1992; Pedrero et al. 2011; Asano et al. 2007).

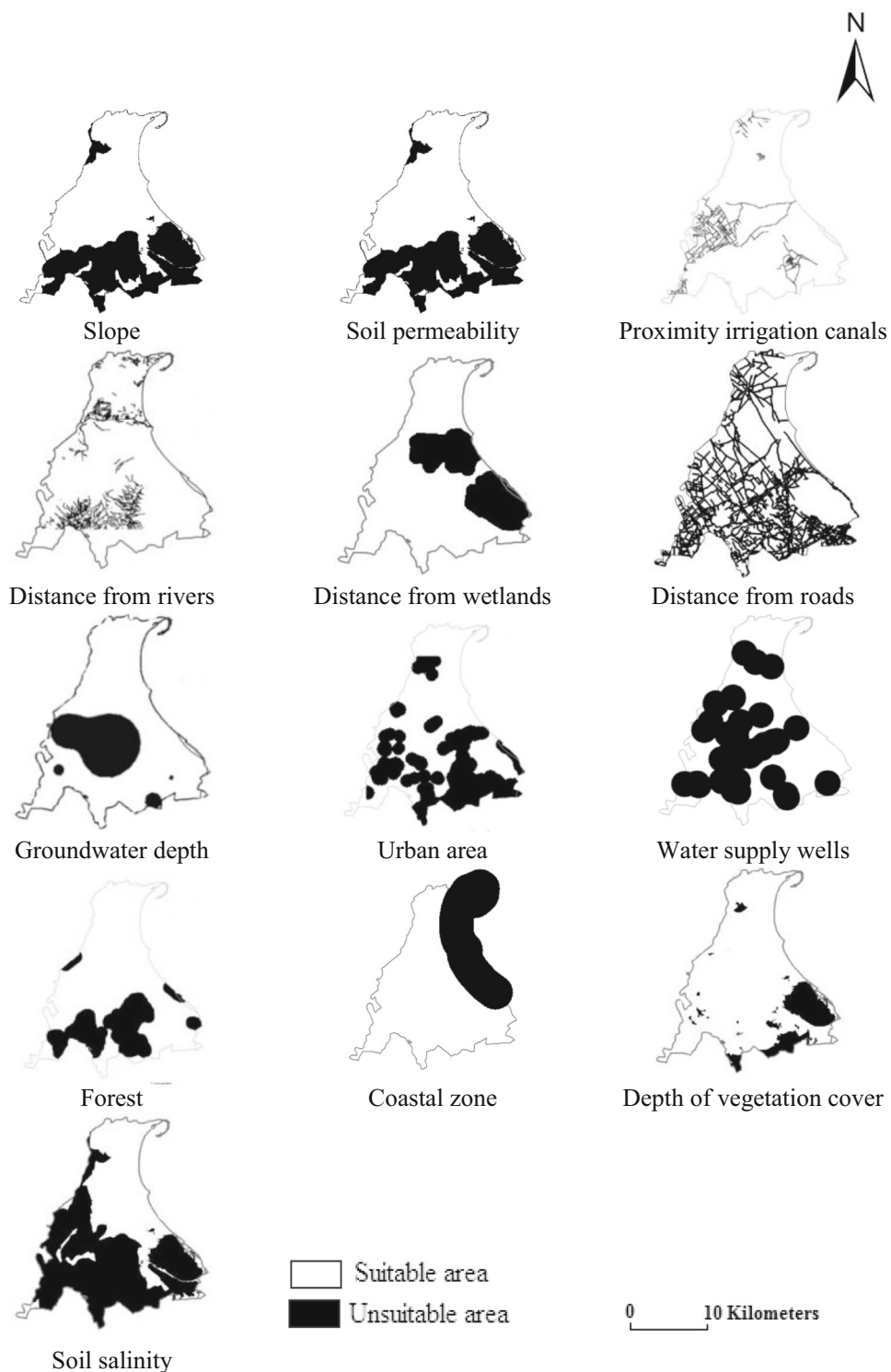
Depth of the vegetation cover

Wagesho (2004) stated that 25 cm is the maximum value that allows for proper absorption of water and nutrients. However, the vegetation cover depth should be under 25 cm to select a suitable site for artificial recharge.

Soil salinity

Groundwater should not have high salinity values. Wagesho (2004) showed that 8 mmhos/cm is the maximum soil salinity suitable for artificial recharge site selection to avoid aquifer salinization by leaching (Anane et al. 2012).

Fig. 4 Boolean images of constrained maps



Wetlands

The artificial recharge site must not be near swamps or lakes. Therefore, a buffer of 1000 meters is applied around the wetlands to avoid their overlap by reclaimed water infiltration (Singh et al. 2013).

Forests

According to the Tunisian legislation, disposal liquid wastes of any kind in natural ecological reserves, such as forests, are prohibited. Therefore, artificial recharge sites should be at least 1000 m away from the forest areas (Aydi et al. 2013).



Fig. 5 Artificial recharge site with reclaimed water obtained from constraint criteria

Proximity to irrigation canals

The artificial recharge site must be located far from irrigation canals to minimize the risk of contamination by the treated wastewater. Hence, a 100-m buffer distance from irrigation canals was selected in this work.

Urban area

Since an artificial recharge site should not be located near an urban area, a buffer distance of 1000 m was set around urban areas in order to avoid direct contact of the treated water with the inhabitants and livestock (Aydi et al. 2013).

Coastal area

The artificial recharge site should be a certain distance from the coastline to avoid any leakage of treated wastewater into the sea. According to Aydi (2013), a safety distance of 3000 m from the shoreline is suitable to protect the harmful effects of treated wastewater on the coastal areas.

Rivers

The artificial recharge site should be located away from rivers to prevent the contamination of the river due to treated wastewater infiltration and thereby accidental leaks of untreated water in case of a treatment plant failure. Therefore, a buffer distance around streams was determined as 100 m (Pedrero et al. 2011).

Water supply wells

An artificial recharge site should be away from wells used as irrigation and drinking water sources, because of its negative effect on the environment. To protect the wells from the runoff of treated water, a buffer distance of 500 m was chosen (Anane et al. 2012).

Roads

The artificial recharge site must be easily accessible and well connected to the road networks to facilitate the commute and reduce transportation costs. In addition, convenient road accesses to the infiltration sites facilitate maintenance and operation on the basins. Consequently, sites situated at more than 50 m from roads were excluded (Ribeiro et al. 2010; Pedrero et al. 2011; Anane et al. 2012).

Site suitability analysis combining GIS-based techniques

Subtraction of constraints with Boolean logic

The first step of the location selection decision is the exclusion of the unsuitable areas from the study area by applying Boolean logic. This method was first applied by Boole (1854) with a binary code classification system including zero “0 = unsatisfactory” and one “1 = satisfactory.” In other words, the main idea of Boolean logic is that all values are either true or false. Moreover, it is a logical, simple, and well-known method which is commonly used in the GIS model for thematic layers integration. To integrate the different thematic layers, data, and values, it has three primitive operations known as “Or,” “And,” and “Not” (Zaidi et al. 2015). In this study, the constraints and their threshold values were defined, and the “NOT” Boolean operator was used to exclude unsuitable areas from the decision map. Each constraint was ranked as zero “0 = unsuitable site” and one “1 = suitable site” in a GIS environment according to their threshold values. The potential artificial recharge site with treated water is obtained by the overlaying of all constraints criteria.

Standardization of factors by fuzzy logic

The second step of the location selection decision process is the standardization of factors by fuzzy logic because of having two different types of data, numerical and nominal. To these types of data, one of the most preferred and suitable methods is fuzzy logic, introduced by Lotfi Zadeh in 1965 (Saaty 1980, 1990, 2008). On the contrary to traditional Boolean logic with the concept of “completely true” and “completely false,” fuzzy logic adopts the concept of partial truth (Gorsevski et al. 2006). Moreover, it has been proved that the application of fuzzy logic in multi-criteria decision-making and GIS-based environmental management process has a significant impact (Forman and Selly 2002; De Feo and De Gisi 2010; Shabou et al. 2009; Unal et al. 2020). There are four types of fuzzy set membership functions shown in IDRISI, such as J-shaped, sigmoidal, linear, and user-determined (Eastman 1993). The selection of appropriate fuzzy membership functions is instrumental as it affects the final decision, but is subjective. Some types of membership functions depend on only two control points (c_1 and c_2) (Fig. 3) (Eastman 2001). In the case of linearly increasing functions, for instance, the first control point (c_1) shows zero “0 = unsuitable,” while the second control point (c_2) indicates ten “10 = most suitable.” The fuzzy membership function, and so the site suitability degree, linearly increase from the first to the second control point.

Linear decreasing membership functions behave in a similar fashion with the sole difference in that they decrease in values instead of increase. The fuzzy membership in the user-defined function can be linearly interpolated between any two control points (Gorsevski et al. 2006). In this study, the threshold values of the control points and the selection of the appropriate fuzzy functions depended on the local literature review and the expert knowledge.

Weighting of factors by AHP

The third step of the location selection decision is assigning the factor weights, because each factor has a different importance level that affects the decision process, and it can be specified according to individual factors, regulation, and expert opinion. In this study, the analytic hierarchy process (AHP) method, proposed by Saaty (1980), was used to determine the weight coefficients of the factors applied according to some knowledge base. The AHP method facilitates the decision-making process, and it is a highly approved decision-making technique built on pairwise comparisons to order the factors from the most to the least importance level (Saaty 2008). In the building of a pairwise comparison matrix, an equal number of rows and columns are placed. Each possible factor pair is compared with each decision factor based on a scale of increasing importance values 1/9, 1/8, 1/7, 1/6,

Fig. 6 Standardized maps for environmental and economic factors

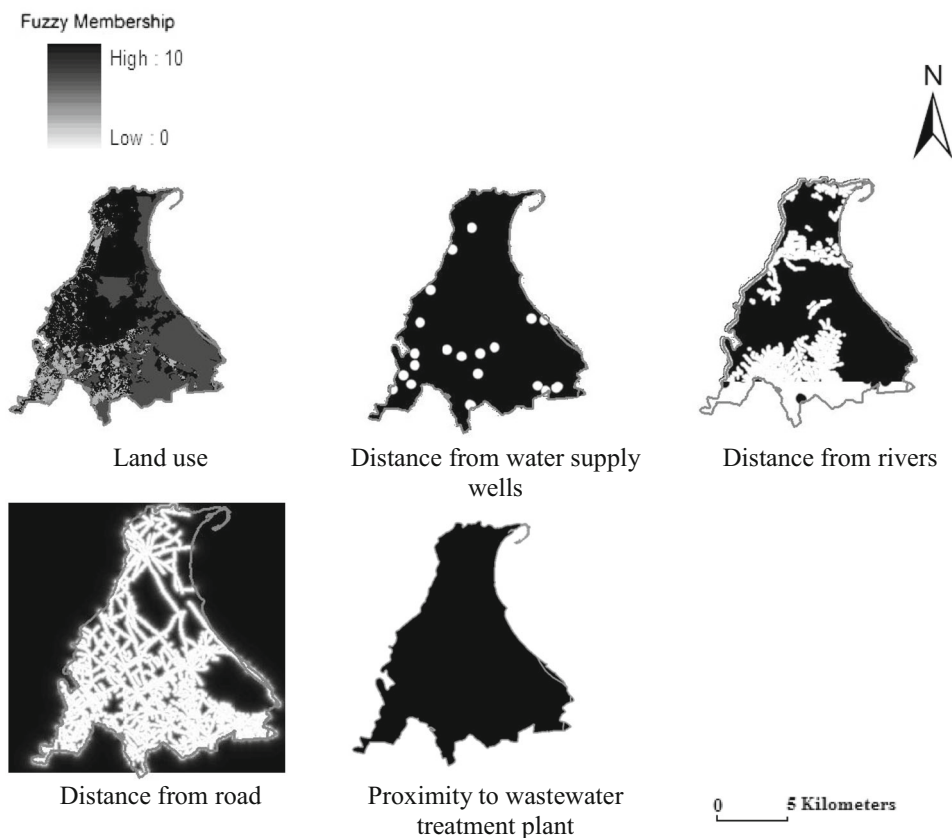


Table 4 Pairwise comparison matrix for assessing the weights of environmental factors

	Land use	Distance from rivers	The proximity to water supply wells	Eigenvector	Weight
Land use	1	1/5	3	0.44	0.11
Distance from rivers	5	1	1/3	2.44	0.63
The proximity to water supply wells	3	1/3	1	1	0.2

1/5, 1/4, 1/3, 1/2, 1, 2, 3, 4, 5, 6, 7, 8, and 9 (Saaty 1977, 2000). After the determination of factor weights, the consistency ratio (CR) was calculated to control the consistency of the pairwise comparison matrix. The CR should have a value of less than 10% to indicate a coherence of the judgments (Kontos et al. 2005). Consequently, the results of standardized and weighted maps can be used as WLC input data (Jiang and Eastman 2000).

Weighting the main criteria by WLC

The last step of the location selection decision is weighting the main criteria with weighted linear combination (WLC). It is applied to the aggregate suitability maps generated by each factor after the determination of standardization and the weighting of each factor. The selected weights are employed with their pen pal individual standardized criteria as input for the WLC aggregation. In the WLC method, each criterion is multiplied by its weight obtained from the pairwise comparison. The corresponding formula is as follows:

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

where *S* is the suitability index, *w*₁, ..., *w*_{*n*} are the weights of the criteria normalized to sum up to 1, and *x*_{*i*} is the standardized score of the criteria *i* (Aydi et al. 2013).

Ranking the suitable candidate areas with ELECTRE III method

The mathematic-based ELECTRE method, which emerged in the late 1960s, is one of the multi-criteria decision-making techniques. ELECTRE can find solutions to the selection, ranking, and assignment problems that require a multi-

criteria decision. While ELECTRE I and ELECTRE IS methods are used in selection problems, ELECTRE II, III, and IV methods are used in ranking problems, while the ELECTRE TRI method is used in assignment problems (Maystre et al. 1994).

ELECTRE III method, developed by Bernard Roy in 1978, is the most widely used method among ELECTRE methods. This method selects the best alternative and orders the others from best to the worst based on comparing each alternative (Soner and Onut 2006). In the ELECTRE III method, three different threshold values are used for each criterion: indifference (*q*), preference (*p*), and veto (*v*). These threshold values are used in the creation of compatibility and incompatibility matrices to be used to rank the superiority of the alternatives. Threshold values can be either determined by giving fixed numbers or defined as a function of the alternatives according to the criteria. While creating the model, these thresholds should be defined by decision-makers for all criteria and the weight value indicating that the degree of importance for each criterion should also be determined (Rogers 2000).

The meaning of threshold values used in ELECTRE III is as follows (Pena et al. 2007):

- *q*: The difference between the criteria scores to have poor preferability between the two alternatives.
- *p*: The difference between the criterion scores to have a strong preferability between the two alternatives.
- *v*: Unacceptably significant difference between criteria values when comparing two alternatives

The following steps of the ELECTRE III algorithm are applied sequentially (Hokkanen and Salminen 1997).

- Step 1: creating the compatibility matrices
- Step 2: cumulative the compatibility matrix

Table 5 Pairwise comparison matrix for determining the weights of economic factors

	The proximity to wastewater treatment plant	Distance from roads	Eigenvector	Weight
The proximity to wastewater treatment plant	1	5	2.23	0.83
Distance from roads	1/5	5	0.45	0.17

Table 6 Pairwise comparison matrix for determining the weights of factors concerning two scenarios

Decision factor	Environmental	Economic	Eigenvector	Weight
Scenario 1 (environmental > economic)				
Environmental	1	3	1.73	0.75
Economic	1/3	1	0.57	0.25
Scenario 2 (economic > environmental)				
Environmental	1	1/3	0.57	0.25
Economic	3	1	0.173	0.75

- Step 3: creating mismatch matrices
- Step 4: creating the credibility matrix
- Step 5: distillation (ranking) process

Results

In order to select a suitable location for artificial recharge with treated wastewater in the semiarid region of Ariana, Tunisia, fifteen criteria were selected. These criteria were divided into two groups: constraints (13 sub-criteria) and factors (5 sub-criteria) depending on geological, environmental, and economic factors. Constraints defined the unsuitable areas, which are not adequate for an artificial recharge site with treated wastewater. Three sub-criteria, including the distance from

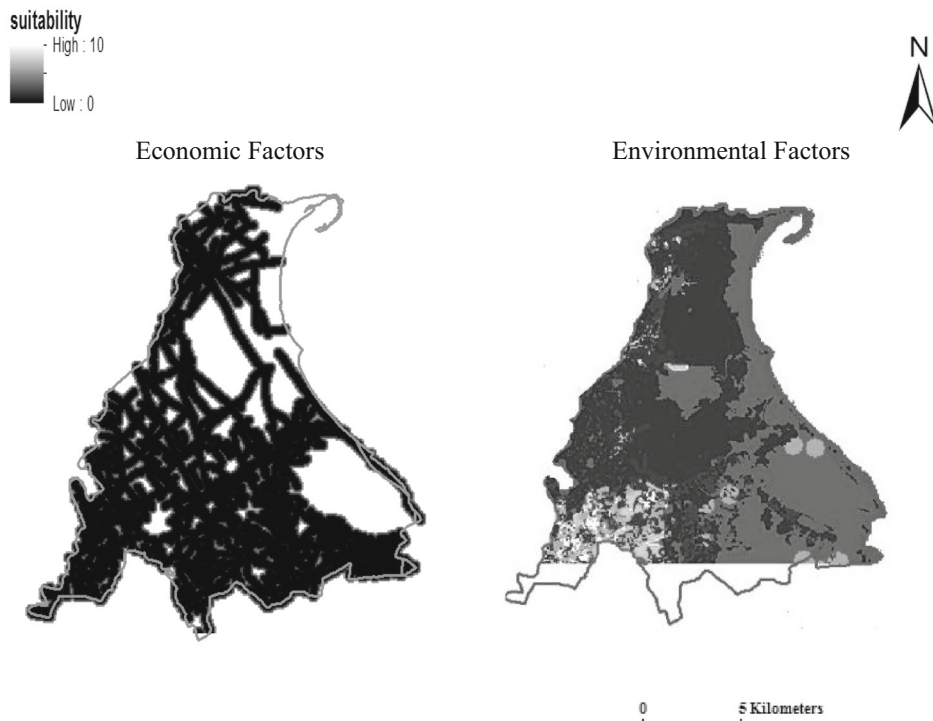
rivers, distance from water supply wells, and the distance from roads, were common in the two groups. They are constraints due to their negative impact on the environment and economy. On the other hand, they are factors because the suitability analysis depends on factors. For example, an artificial recharge site should be located within a close proximity from the road network for easy access and reducing transportation costs. However, it should also be not too close not to affect the scenic quality. Therefore, suitable and unsuitable areas were determined using Boolean logic according to the threshold value of each constrain and were mapped in the GIS environment (Fig. 4). All thematic layers were overlaid; thus, it is defined as the unsuitable area, which is not located in the artificial recharge area with treated wastewater (Fig. 5).

After the constrained areas were removed as unsuitable areas in the study, the areas that could be suitable were determined in line with the factors. However, the factors need to be standardized due to the difference in data type. While four factors (i.e., distance from rivers, distance from water supply wells, distance from roads, and proximity to wastewater treatment plant) are numerical data, one factor (i.e., land use) is a nominal data. All factors were standardized using fuzzy logic using truth degrees ranging from 1 to 10. The suitability of factors was determined according to fuzzy membership functions (Table 3).

The fuzzy membership functions and standardization values of factors are as follows:

The economic factor involves two sub-criteria, namely the distance from roads and the proximity to the WWTP. The

Fig. 7 Multi-criteria aggregation of factors by WLC



standardization of the road proximity was performed using a J-shaped monotonically decreasing fuzzy function defined by two control points ($c_1 = 50$ m and $c_2 = 300$ m), where distances nearest to 50 m correspond to the most suitable and furthest to 300 m denote unsuitable locations. The proximity to the WWTP was also standardized by using a J-shaped monotonically decreasing fuzzy function defined by two points ($c_1 = 800$ m and $c_2 = 2000$ m), where distances below 800 m are the most appropriate and those above 2000 m are inappropriate.

The environmental criteria include three sub-criteria, including proximity to rivers, land use, and proximity to water supply wells. The distance from rivers was calculated by applying a sigmoidal monotonically increasing fuzzy function characterized by two control points (c_1 100 m and c_2 400 m) where distances lower than 100 m are not suitable (full membership) and higher than 400 m are the most suitable locations. The distance from water supply wells was standardized by a sigmoidal monotonically increasing fuzzy function whose control points are (c_1 500 m and c_2 800 m) where lengths lower than 500 m are not suitable, and those higher than 800 m are the most suitable potential areas. The land uses were standardized basis on their suitability and were classified from the least to the most suitable land use with the score of 0 to 10 (Table 3). The protected

areas, urban regions, water, and wetlands were given a score of 0 and not considered as suitable land use to locate artificial recharge sites. The vine and mariachi cultures are considered to be the least suitable lands with scores between 2 and 6. Naked soils are assigned a score of 10 to signify the most suitable land for an artificial recharge site with treated wastewater (Fig. 6).

The next step is the determination of factor weights. AHP pairwise comparison was applied to attribute weights and present the benefits of economic and environmental factors. The literature review and the knowledge of a local expert were determined the factors weighs. Table 4 and Table 5 show the pairwise comparison matrix of relative significance and weights related to the environmental and economic factors, respectively. The weights of the environmental factors are calculated that the highest weight is 0.63 for distance from rivers, while the lowest weight is 0.11 for land use. The consistency ratio for the environmental factors is calculated as 0.03, showing an excellent consistency of the judgments applied for the comparison.

On the other hand, the weights of the economic factors are set to 0.83 for the proximity to the wastewater treatment plant and 0.17 for the distance from roads. The consistency ratio of 0 was obtained, which indicated that the judgments were consistent. The sum of the factors weights in each main criterion is equal to 1. The weighted factors and standardization are used as input data for WLC.

WLC is used to compute the possible artificial recharge sites with treated wastewater for the economic and environmental set of criteria, applying the attributed weight to the main criteria (Table 6). Two scenarios were developed by considering the different proportions of weights for the main criteria (Fig. 7). For instance, the first scenario assigns a weight of 0.75 to the environmental factors and 0.25 to the economic ones. The second scenario assigns a weight of 0.75 to the economic factors and 0.25 to the environmental ones. The consistency ratio is acceptable for both scenarios with a value of less than 0.01.

Figure 7 shows that the environmental factors are favored over the contribution to the economic factors for the environmental aspect of our project (scenario 1). Applying an equal interval classification, the artificial recharge site values of the Ariana region were categorized into 3 classes (Fig. 8):

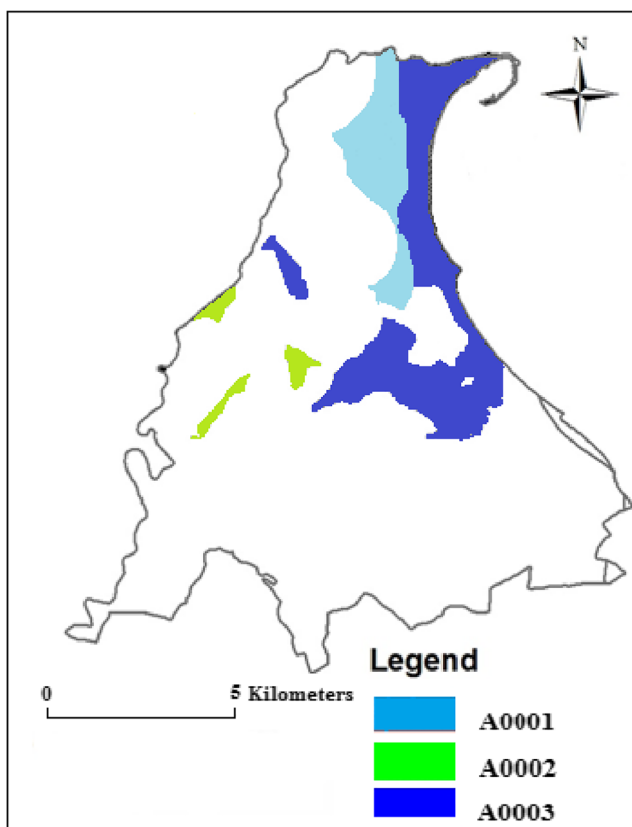


Fig. 8 Possible suitability maps derived by both factors using scenario 1: (environmental > economic)

Table 7 Family and criteria

Family	Criteria	Direction
Social	Cr ₁ : distance from road (km)	Min
	Cr ₂ : distance from wetlands (km)	Max
Geometric	Cr ₃ : geometric form of the site (scores 1–10)	Max
Economic	Cr ₄ : cost of site (\$/m ³) (scores 1–10)	Min

Table 8 Synthesis performances matrix based on the environmental scenario

Site	Cr ₁	Cr ₂	Cr ₃	Cr ₄
A0001	1.5 km	5.6 km	10	1
A0002	1.7 km	1.7 km	1	10
A0003	1.3 km	3.2 km	5	5

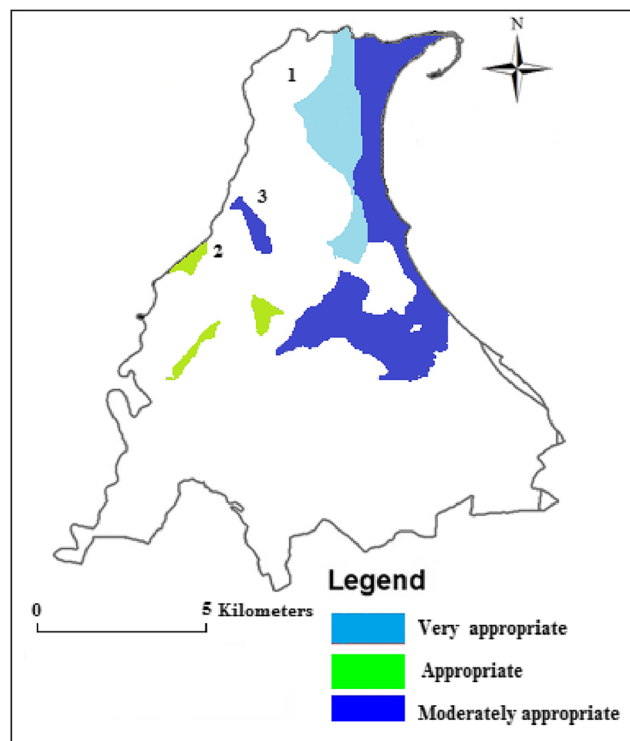
- Class 1: Cells with a score less than or equal to 3 are assigned as a site that is moderately suitable for artificial recharge.
- Class 2: Cells with a score between 3 and 7 are assigned as the suitable site for artificial recharge.
- Class 3: Cells with a value greater than or equal to 7 are classified as very suitable for artificial recharge with treated wastewater.

Finally, depending on the classification of environmental scenario results, the selected sites were reclassified in a predefined class by applying the ELECTRE III method. To reclassify the suitable locations, four evaluation criteria were defined as the distance from roads, the geometric form of the area, the distance from wetlands, and the site. While the distance from the road and the cost of the site may be minimized to reduce cost, the distance from wetlands should be maximum to protect the environment (Table 7). Moreover, the geometric form of the site should be maximum because aquifers do not have sharp boundaries or geometric shapes such as rectangular or square. It means that the number of sides is high when the suitability of the site is high. While a square or a rectangular shape was considered as the least suitable with a grade of 1, the elongated and circular shapes of the candidate site were attributed a grade of 10 (best case). In other shapes, an intermediate grade of 1 to 10 was assigned. The characteristic features of each potentially suitable area were ranked according to evaluation criteria (Table 8).

The indifferences, preferences, and veto values were calculated for each criterion in ELECTRE III. After the criteria were established, we defined the weights to indicate the

Table 9 Weights, thresholds, and directions of criteria

Site	Cr ₁	Cr ₂	Cr ₃	Cr ₄
Indifference	1.5 km	4.5 km	2	2
Preference	1.4 km	2 km	7	8
Veto	0	0	0	0
Weight	40	10	30	20
Direction	Min	Max	Max	Min

**Fig. 9** Final artificial recharge suitability map showing the selected sites based on the environmental scenario

relative value accorded to every criterion (Table 9). The weight of the criteria ranged from 10 to 40. The criteria that scored the lowest to the highest value are, the distance from wetlands with a score of 10, the cost of the site with a value of 20, the geometric form of the site with a score of 30, and distance from the road with a fitness of 40. This evaluation then makes it possible to classify these sites according to their ascending/descending distillation.

Discussions

Although there are plenty of GIS-based location selection studies, the studies about suitable location selection for artificial recharge with treated wastewater were limited. Thus, developing a suitable technique is important to choose a potential location before deciding on arid and semiarid areas with limited water resources. Previous studies mainly used one or a combination of two or three multi-criteria decision methods, including Boolean logic, fuzzy logic, AHP pairwise comparison, and WLC. Such studies were carried out on arid and semiarid cities with limited water resources, such as Tunisia (Kallali et al. 2007; Anane et al. 2008; Gdoura et al. 2015), Egypt (Riad et al. 2011), India (Singh et al. 2011), Saudi Arabia (Zaidi et al. 2015), and Iran (Ahmadi et al. 2017; Ghasemi et al. 2017). To manage the limited freshwater resource, they determined the evaluation criteria about technical, economic, and environmental concerns.

In this work, we conducted a study to select suitable artificial recharge sites with treated wastewater for the semi-arid region of Ariana, Tunisia. The study differs from the previous attempts proposed in the literature in terms of the number of influencing criteria grouped as constraints and factors and combining the five multi-criteria methods, including Boolean logic, fuzzy logic, AHP pairwise comparison, and WLC. Moreover, what makes this research quite unique is that it also provides the ranking of the suitable areas using ELECTRE III method which sorts the sites by prioritizing environmental and economic factors. This makes the applied methodology generic enough so that it can be applied to locally and internationally. Considering the threshold value, suitable and unsuitable sites for all constraints were mapped, and unsuitable sites were eliminated from the study area. Factors were standardized using fuzzy logic and were weighted with the analytic hierarchy process (AHP). All factors and constraints maps were overlaid on a decision structure, after weighted main criteria with weighted linear combination (WLC) to select the environmentally and economically suitable sites. The ELECTRE III method was used to classify, in descending order, the best site for aquifer recharge with treated water. The final ranking of the selected sites is shown in Fig. 9. These candidate areas were ranked by applying the ELECTRE III method according to the two distillations and were classified as suitable, moderately suitable, and very suitable.

This technique shows a clearway to explain the figure legend. Three candidate sites (1, 2, and 3) were recommended as the artificial recharge site since the GIS and AHP methods defined these areas as highly suitable areas. Site numbers 2 and 3 represent, respectively, the suitable and moderately suitable areas for artificial recharge with treated wastewater. Site number 1 is the most suitable for the artificial recharge site.

It is essential to note that the most suitable areas are mostly gathered in the N and NW part of the study area, which contains poor land use and permeable and halomorphic soils. Slopes of less than 15% characterize them.

However, a few researchers indicated that their maps must not be the main basis for a final decision for the selection of artificial recharge sites and operational strategies but rather an orientation tool to concentrate on specific zone for further investigation. A site that has been selected as suitable for artificial recharge with reclaimed water should be investigated with subsequent in situ measurements to characterize the hydrology and hydrogeology of the site (Jamali et al. 2014; Satapathy and Syed 2015; Selvam et al. 2016). The last decision on the selection of the artificial recharge site requires hydrogeological analyses to be carried out for the protection of six groundwater as well as geotechnical studies. The combination of GIS-based AHP techniques was helpful and has great significance for decision-makers to manage water resources.

Conclusion

The present work shows an original methodology to identify suitable areas for artificial recharge with treated wastewater by applying the Boolean logic, fuzzy set theory, AHP, and WLC built on GIS. The region of Ariana (Tunisia) was chosen as the object area. Fifteen critical criteria were selected in this study, taking into consideration geological, economic, and environmental aspects. GIS was applied for displaying and analyzing geospatial data. The literature review and expert knowledge were used for the identification of suitable fuzzy functions and their checkpoints. The proposed method includes five factors and thirteen constraints. These criteria were grouped into three main groups involving environmental, economic, and geological concerns. The constraints criteria applied in this work encompass coastal zone proximity, soil salinity, soil permeability, groundwater depth, slope, proximity to forests, water supply wells, wetlands, rivers, irrigation canals, urban regions, and roads, as well as the depth of the vegetation cover. The proximity from rivers, the distance of water supply wells, and land use were regarded as the components of the environmental factor. The economic factor consisted of the proximity to the WWTP and the distance from roads. The association of different numbers of factors depending on the environmental scenario showed three possible artificial recharge areas. The most suitable areas are gathered in the north and northwest of the region of Ariana. These sites contain poor land use in the less populated residential areas and permeable and halomorphic soils. They are characterized by slopes of less than 15%. The ELECTRE III method was used to classify the candidate areas and identify the best option.

This study represents a useful guide for decision-makers to incorporate into water management in the region of Ariana. However, the last decision on the selection of the artificial recharge site requires hydrogeological analyses to be carried out for the protection of groundwater as well as geotechnical studies. Further evolution may be obtained by a multi-objective analysis according to another alternative to reapply the treated water as irrigation of shallow urban green spaces.

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- Conceptualization: Marwa Mahmoudi, Abdelwaheb Aydi, Hatem Ibrahim
- Methodology: Marwa Mahmoudi, Abdelwaheb Aydi, Hatem Ibrahim
- Analysis and interpretation: Marwa Mahmoudi, Abdelwaheb Aydi
- Writing original draft, review, and revision: Marwa Mahmoudi, Abdelwaheb Aydi

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