Resources, Conservation and Recycling 104 (2015) 19–30

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Review

Geospatial and AHP-multicriteria analyses to locate and rank suitable sites for groundwater recharge with reclaimed water

Khadija Gdoura, Makram Anane*, Salah Jellali

Wastewater Treatment Laboratory, Water Researches and Technologies Centre, Technopark Borj Cedria, Carthage University, Tunisia

ARTICLE INFO

Article history:
Received 8 May 2015
Received in revised form 8 September 2015
Accepted 9 September 2015
Available online 11 November 2015

Keywords:
Wastewater
Groundwater recharge
AHP
GIS
Multi-criteria analysis
Nabeul–Hammamet
Sensitivity analysis

ABSTRACT

The reuse of reclaimed water in arid and semi-arid regions to recharge aquifers contribute to reduce pressure on conventional water. An appropriate site selection preceding the construction of the basins is required to insure the success of the process. The aim of this research is to develop a methodology to locate and rank suitable sites for groundwater recharge with reclaimed water based on a combination of geospatial and multicriteria analyses. Seven constraints were chosen to identify the suitable areas for aquifer recharge with reclaimed water. A vector spatial layer of each was obtained and the feasible areas were delineated by an intersection operator. To rank these areas three main criteria were identified having technical, economical and environmental aspects, from which twelve sub-criteria were derived. All of them were organized in a decision hierarchy structure and weighted using Saaty pair-wise comparison matrixes. A raster spatial layer of each sub-criterion was obtained and their values were standardized using fuzzy logic functions. A weighted linear combination was carried out to get the decisional index layer from which the suitable sites were ranked. Finally a sensitivity analysis was carried out in order to quantify the influence of the criteria weights on the resulting decision spatial layer. The study area selected to develop the methodology is the Nabeul–Hammamet shallow aquifer. The feasible area for aquifer recharge with reclaimed water is about 5160 ha. This area exceeds by far the needed 39 ha to absorb the total effluents of the SE3 and SE4 wastewater treatment plants present in the case study. The best 39 ha are located in the north west of the city of Nabeul for SE3 and in the northern west and the south west of the city of Nabeul for SE4. For best management and cost reduction it is preferable to gather these sites in a unique area located in the north west of the city of Nabeul in an agricultural region and far from the urban zones.

Contents

---

* Corresponding author. Tel.: +216 95535738.
E-mail addresses: kgdoura1@gmail.com (K. Gdoura), makram.anane@certe.rnrt.tn (M. Anane), salah.jallali@certe.rnrt.tn (S. Jellali).

http://dx.doi.org/10.1016/j.resconrec.2015.09.003
0921-3449/© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Groundwater is an essential freshwater source in Tunisia offering about 45% of total available water for domestic, agriculture, and recreational use (Chaabane, 2014). During the last decades withdrawals have increased causing groundwater level decline and quality deterioration, limiting future development of many shallow aquifers over the country. This unsuitable situation requires new approaches for groundwater management policy and consideration of non conventional water as an additional source of water. Reclaimed water, as a non conventional source, presents an interesting solution to cover part of the growing groundwater demand through managed aquifer recharge. It is cost-effective and continuously available all over the year. Currently the Tunisian wastewater treatment office (ONAS) is running 110 urban wastewater treatment plants (WWTP) producing an annual amount of 286 Mm^3 (ONAS, 2013). Only about 25% is reused and the remaining amount is disposed of in the sea and rivers.

Despite it raises a controversy to use reclaimed water to recharge a managed aquifer (Nijhawan et al., 2013), it has many advantages such as reducing the amount of wastewater disposed of in nature also increasing the groundwater level and reducing its salinity and increasing water reserves easily accessible if needed. Aquifer recharge with reclaimed water is widely used all over the world (Ghayoumian et al., 2005). United State via the Environment Protection Agency is one of the pioneers adopting this practice (Schmidt et al., 2013). Two techniques are mainly used to recharge aquifers with reclaimed water; injection wells and infiltration basins. The former is simple to implement and assures an instantaneous aquifer supply. It is used in areas presenting impermeable strata between the surface and the aquifer or in areas where land for infiltration basins is limited (EPA, 2014). However this technique provides little or no protection against possible groundwater contamination. So before injection, wastewater should undergo an advanced treatment (EPA, 2014). On the other hand, the infiltration basins technique assures an additional treatment of the wastewater when crossing the unsaturated zone but it needs a larger area and more time for wastewater infiltration and percolation along with an additional cost for basins constructions and maintenance. In this case three types of basins are mainly used (Detay, 1997). The first is the bare bottom basin. It is the most adopted worldwide and consists of a simple cavity dug on the surface. It requires a hydraulic loading ratio between 0.3 and 1 m/day and it is subjected to rapid clogging risk, if it is not regularly scarped and plowed. The second type is the basin with vegetation. Vegetation protects the structure from erosion and improves infiltration, unpacking and denitrification. This type requires a hydraulic loading ratio between 0.2 and 0.6 m/day. The wastewater should have a low content of suspended material in order to avoid rapid clogging and maintain normal vegetation growth. This kind of basins provides the highest infiltration ratio but it is limited to sites with vertical infiltration ratio of 2×10^{-6} m/s (Bouwer, 1982). The third type is the sandy basins consisting of covered cavities with graded sandy layers. The hydraulic loading ratio is between 2 and 5 m/day. This type is the most expensive and it requires a high level of maintenance. It is mainly implemented when groundwater is used for drinking. In Tunisia the first experience for aquifer recharge with reclaimed dates back to 1985, with construction of bare bottom basins at Nabeul region to raise availability of groundwater for irrigation (DGRE, 2005). In 2008 a second site was managed at Korba region in order to deter seawater intrusion into the *Côte Orientale* freshwater aquifer (Ouelhazi et al., 2014).

The first operational phase for managed aquifer recharge with reclaimed water is site selection. Selection of the feasible areas requires consideration and interaction of multiple factors, such as topography, soil type, groundwater quality, and distance and elevation from wastewater treatment plants (EPA, 1984). The most adapted technique to combine and put together factors with technical, economic and environmental characteristics is the multicriteria decision analysis (MCDA). Many MCDA methods were developed, such as ELECTRE, TOPSIS, MAUT, PROMTHEE, and AHP for plenty of applications such as to assess ecological suppliers (Shen et al., 2013), to rank the best sites for treated wastewater (Kim et al., 2013), to structure and assess the idea and opinion of stakeholders on the environmental impacts of solid waste disposal (Abba et al., 2013), to dispose solid waste (Ghoseiri and Lessan, 2014), to select material for industry (Anojkumar et al., 2014) to select windows for buildings (Chen, 2014), to rank municipal solid waste treatment solutions (Antonopoulos et al., 2014) and to find the best regulation solution for waste management (Bonnina et al., 2015). A review of the most important methods and their applications could be found in Belton and Stewart (2002) and Kiker et al. (2005). The geospatial aspect of site selection emphasizes the use of Geographical Information Systems (GIS) in combination with MCDA in order to treat and analyze spatially the involved factors and generate site suitability maps. Several studies benefit of the advantage of MCDA and GIS combination for sites selection and land allocation. Nasiri et al. (2013) integrated GIS and PROMETHEE II-AHP for selecting suitable sites for flood spreading, Malekmohammadi and Rahimi Blouchi (2014) combined GIS and AHP to classify zones with different ecological risk and Jha et al. (2014) to identify suitable zones for different rainwater harvesting structures. Neshat et al. (2014) used GIS and AHP to evaluate groundwater vulnerability. However, only recently scientific papers have evaluated these techniques to select feasible sites for aquifer recharges with reclaimed water. Kallali et al. (2007) and Pedrero et al. (2011) used conjunctive screening to identify the suitable sites however they neither classified nor ranked them. Rahman et al. (2013) classified the sites using AHP-OWA Regular Increasing Monotone Quantifier. Anane et al. (2008) ranked the sites using AHP to determine the weights of criteria, fuzzy functions for criteria standardization and weighted linear combination for aggregation. However they did not achieve the sensitivity analysis in order to show how the ranking of the sites is sensitive to the changes on the weights of the criteria.

In this paper a methodology was established to map and rank suitable sites for aquifer recharge with reclaimed water

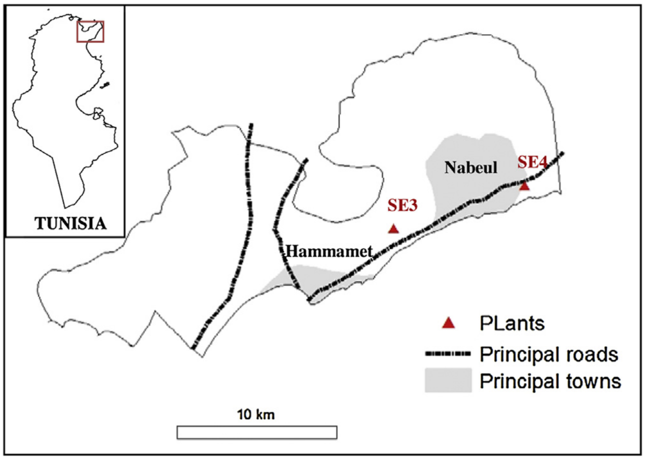

Fig. 1. Location map of Nabeul–Hammamet shallow aquifer.

using MCDA combined with GIS. The methodology constitutes the first step in the process of implementation of basins for aquifer recharges, prior to detailed field investigations, basins design and maintenance.

2. Material and methods

2.1. Characterization of the study area

The selected study area is the Nabeul–Hammamet shallow aquifer (Fig. 1). It is located at 50 km south-east of Tunis (Tunisia) and extends to 286 km^2. The climate is semi-arid with about 400 mm of yearly mean rainfall and 19 °C of yearly mean temperature. The altitude varies from 0 to 247 m and the unsaturated zone depth is between 4 and 31 m. The geology is Quaternary and Pliocene, essentially made of conglomerates, sandstones and clay. The wastewater in the study area is treated by two Wastewater Treatment Plants (WWTP); SE3 and SE4. The nominal flow rate of SE3 and SE4 is respectively 3500 m^3/day and 9585 m^3/day. The treatment process used for SE3 is oxidation ditches and for SE4 is mean load activated sludge and anaerobic digestion (ONAS, 2011).

Currently SE4 is under extension aiming to increase the amount of treated wastewater and improve its quality. The Commission's regional agricultural development of Nabeul "le commissariat regional du developpement agricole de Nabeul (CRDA-Nabeul)" expects that the total effluents volume for both plants will be 4.8 Mm^3/year in 2025 (CRDA, 2008).

2.2. Methodology overview

In order to determine a specific site for recharging aquifer with reclaimed water, a set of multicriteria techniques were used in an environment GIS. The overall methodology involves the following major steps:

(1) Identify constraints and feasibility/unfeasibility thresholds,
(2) Obtain for each constraint a polygonal spatial layer using boolean logics and apply conjunctive screening to get the constraints map delineating the feasible/unfeasible sites,
(3) Select criteria and sub-criteria to rank feasible sites,
(4) Organize the decisional problem in a hierarchical structure and determine weights for the criteria and sub-criteria through pair-wise comparison matrixes,
(5) Spatialize sub-criteria in raster-based format,
(6) Normalize sub-criteria layers using fuzzy functions,
(7) Aggregate sub-criteria spatial layers using weighted linear combination and get the ranked feasible sites spatial layer,
(8) Estimate the land area required to infiltrate the entire available amount of SE3 and SE4 treated effluents,
(9) Extract the most suitable sites on a map,
(10) Establish a sensitivity analysis to determine how the change in the criteria weights impacts the most suitable sites location (Fig. 2).

2.3. Constraints map building

2.3.1. Constraints identification and thresholds

Location of feasible sites for aquifer recharge with reclaimed water was achieved according to seven constraints, which are slope, soil texture, distance from water bodies (hill dams and reservoirs), distance from residential areas, distance from roads, unsaturated zone depth, geology and groundwater quality for human consumption. Their identification was based on consulting national experts, examination of international guidelines and reviewing technical and scientific documents (EPA, 1984; Kallali et al., 2007; Anane et al., 2008; Pedrero et al., 2011; Rahman et al., 2013). The rationale behind selecting these constraints and their unfeasibility/feasibility thresholds are given hereafter. *Topography* is an essential element for the structure stability. A slope of 12% was considered the maximum permitted value above which basins built-up, operation and maintenance become complicated and vertical water infiltration may not be guaranteed. *Soil* is the first layer the reclaimed water crosses from the basins toward groundwater. Its texture should be sufficiently permeable to ensure infiltration of reclaimed water, in which suspended and organic matter content is much higher than in conventional water. Soil textures with up to 10% of clay were considered suitable. *Unsaturated zone* ensures an additional purification of wastewater and attenuation of their compounds before reaching the aquifer through biodegradation, mechanical filtration, sorption, volatilization and dispersion. Most of organic matter is retained during the first centimeters of the unsaturated zone (Drewes, 2009) and more than 50% of DOC is removed from the first 1.5 m (Sharma et al., 2008). In order to guarantee a good purification of treated wastewater even after mounding a minimum thickness of 5 m of the unsaturated zone depth is required. *Geology* determines the media types constituting the unsaturated zone. This media should be sufficiently permeable to permit reclaimed water infiltration and percolation. All geological formations consisted of clay, sandstone or limestone were considered not feasible for aquifer recharge with reclaimed water. *The aquifer*, which groundwater is used for human consumption, was considered unfeasible for recharge with reclaimed water in order to avoid groundwater quality deterioration. Many researches were carried out on groundwater quality quantification for drinking based on aggregation of different chemical parameters. The number of the included parameters is very disparate from one study to another. For example, Gorai and Kumar (2013) considered 12 parameters which are Calcium, Magnesium, Iron, Manganese, Nitrate, Turbidity, pH, Sodium, Potassium, Alkalinity, Total Hardness and Total Dissolved Solids (TDS). Ambiga et al. (2013) considered nine parameters, which are Calcium, Magnesium, Nitrate, pH, Sulphates, Chlorides, Fluorides, Total Hardness and TDS. Saidi et al. (2009) selected five parameters (Electrical Conductivity, Calcium, Sulphates, Chlorides, Nitrate) on the base of the guidelines and technical documents published in WCCR (1991), Anon (2003) and WHO (2006). Stigter et al. (2006) considered Calcium, Sulphates, Chlorides, and Nitrate. They didn't include other parameters for redundancy reduction. They considered calcium an indicator of hardness, chlorides an indicator of salinity, and nitrates indirectly include pH; nitrite and phosphorous

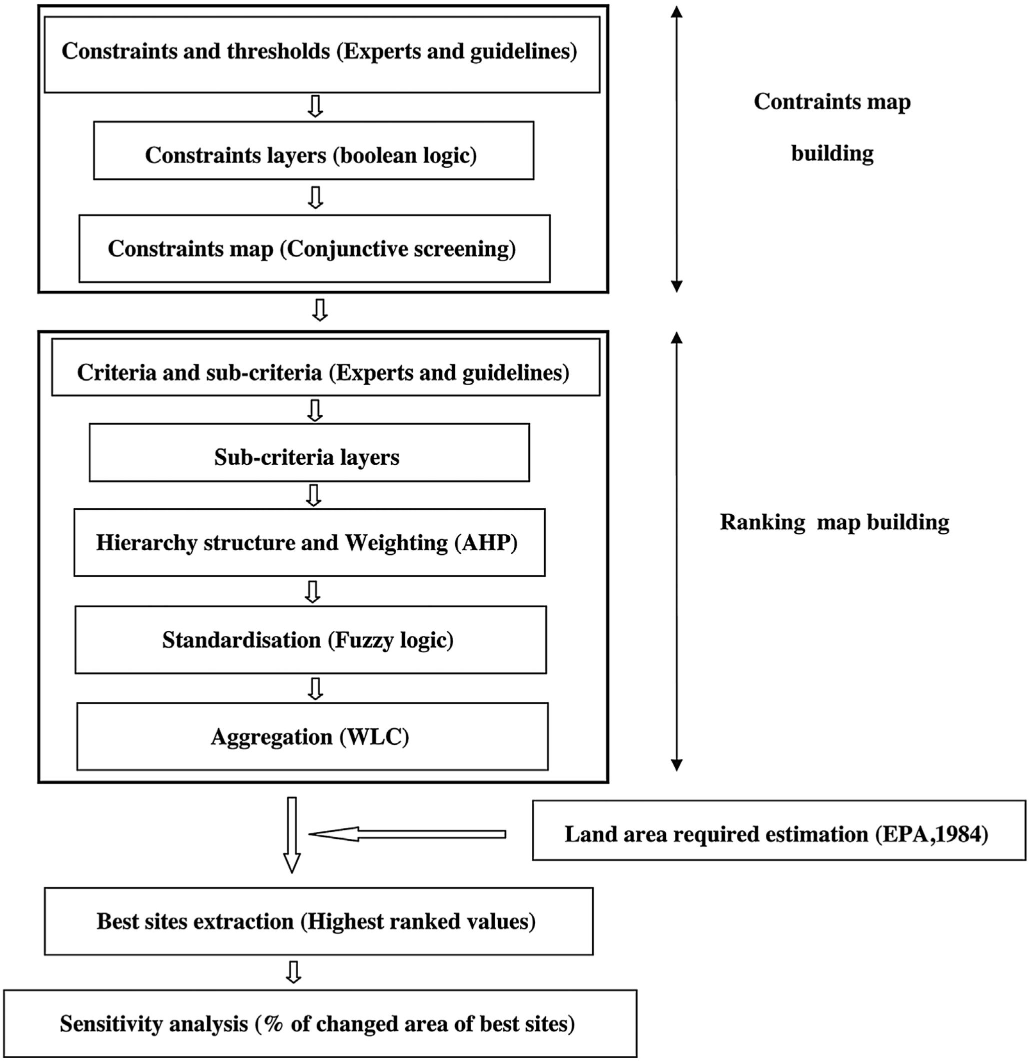

Fig. 2. Methodology flowchart.

contents. They didn't consider pesticides or their metabolites, because of the lack of available information. On the other hand, Rahman et al. (2013) considered only Chlorides and Nitrates for groundwater quality characterization in order to classify suitable sites for aquifer recharge with reclaimed water. In our case Electrical Conductivity, Calcium, Sulphates, Chlorides, Nitrates were considered. The other parameters were discarded for redundancy reduction or for unavailability of data. The thresholds chosen for these parameters correspond to the maximal concentration admitted by Tunisian standards for permissive drinking water. Accordingly, the groundwater under the unfeasible area has to contain simultaneously Dissolved Salts lesser than 2.5 g/L; Nitrates lesser than 45 mg/L, Chlorides lesser than 600 mg/L, Sulphates lesser than 600 mg/L and Calcium lesser than 300 mg/L (Ambiga et al., 2013). Consequently, if the threshold is exceeded for a minimum one of these parameters so that the site is considered suitable for aquifer recharge with reclaimed water. *Distance from water bodies*: A buffer zone is required to protect the surface water from any likelihood contamination with reclaim water. In this case a buffer of 500 m is chosen. *Distance from residential areas*: A safeguard distance is required to avoid any direct contact with citizens and to avoid possible harm caused by mosquitoes and smell. This distance should not be less than 200 m. *Distance from roads*: The roads with a buffer of 50 m are excluded.

2.3.2. *Constraints layering by GIS*

Each constraint was represented by a spatial thematic layer. They were derived from satellite images, official spatial data and conventional field data as well as hard copy maps. The analysis and treatment of these geospatial data was carried out using the commercial ArcGIS software with spatial analyst and geostatistical analyst extensions. The description of data sources and analysis procedures is detailed hereafter. Slope was derived from Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) 30-m resolution. Soil texture layer was extracted from the soil spatial layer of "La Carte Agricole" of Nabeul governorate. Soil layer is a polygon shapefile data having a scale of 1/50,000 and a projection reference system Carthage UTM Zone 32 N. "La Carte Agricole" is an official spatial database owned by the Tunisian Ministry of Agriculture (Ministry of Agriculture, 2000). The geology spatial layer was obtained from three official geological map sheets (Bensalem, 1991; Colleuil and Bensalem, 1991; Johan and Krivy 1969) after scanning, georeferencing and digitizing them on screen. The scale of these maps is 1/50,000. Distance from water bodies, from residential areas and from roads were obtained through digitization on screen from GoogleEarth map the water bodies, the settlements and the roads. A geospatial analysis was processed in order to get a layer representing the smallest distance from these structures. Depth of unsaturated zone and aquifer quality parameters were mapped based on 2005 water level data of 37 wells and piezometers reported by Jomâa et al. (2005). The data were captured and stored in point layer and then converted to grid through interpolation operators. Several deterministic and geostatistical interpolation were tested (completely regularized spline interpolation, inverse distance weighting and ordinary kriging, . . .). The selection of the model was based on the root-mean-square prediction error determined through the cross-validation process. The best model should have the smallest root-mean-square prediction error (ESRI, 2003).

2.3.3. *Conjunctive screening*

Each constraint layer was obtained in polygonal layer using Boolean logics. All area meeting the condition of feasibility according to the thresholds previously established was coded 1 and the remaining area was coded 0. Afterwards the conjunctive screening rule was applied to get the constraints map, combining all Boolean maps by means of intersect operator. A site is considered potential for aquifer recharge with reclaimed water when it fulfills simultaneously the feasibility condition for the seven constraints. The result is a map defining the feasible and unfeasible sites for Nabeul–Hammamet shallow aquifer recharge with reclaimed water.

2.4. *Ranking feasible sites*

2.4.1. *Criteria and sub-criteria selection*

In order to rank feasible sites for aquifer recharge with reclaimed water three main criteria were selected, which are technical, economic and environmental. Each is made up of several sub-criteria. Their identification was based on consulting national experts, examination of international guidelines and reviewing technical and scientific documents (EPA, 1984; Anane et al., 2008; Pedrero et al., 2011; Rahman et al., 2013). The rationale behind selecting these criteria and the sub-criteria are given hereafter (Anane et al., 2008, 2012).

2.4.1.1. Technical criterion. The technical criterion represents the factors that determine the basins installation and construction. They are highly related to field characteristics. Six sub-criteria are derived from it: soil texture, geology, depth of the unsaturated zone, slope and soil salinity. Soil texture and geology should be sufficiently permeable, with low clay content and high sand content to guarantee infiltration but not excessively permeable to permit natural purification. Depth of unsaturated zone should be as deep as possible in order to have enough area thickness for complementary purification. Slope should be as gentle as possible to favor water infiltration and reduce effort and cost for basins installation. Soil salinity should be as low as possible to avoid significant groundwater quality deterioration.

2.4.1.2. Economic criterion. The economic criterion encompasses the factors influencing cost of the wastewater transfer and installation. It involves three sub-criteria; difference of elevation and distance from wastewater treatment plant and land use. Difference of elevation from wastewater plant should be as low as possible to reduce pumping expenses. Distance from SE3 and SE4 should be as short as possible for pipes expenses and the land cost should be as cheap as possible. This cost is designed by the land use. Bare soil land is the cheapest, followed successively by the non irrigated land, the irrigated land and finally the forested land, which characterized by a high environmental cost.

2.4.1.3. Environmental criterion. The environmental criterion includes two sub-criteria; distance from urban area and groundwater quality. The basins should be as far as possible from urban areas to avoid the harmful impact of reclaimed water on citizens related to odor and insects. Four sub-criteria compose groundwater quality which are salinity, chloride, sodium, and nitrate content. The three former reflect the quality of available groundwater for irrigation, which is the main goal of aquifer recharge with reclaimed water. Excess soluble salts reduce the plant available water and increase plant stress (Lesch and Suarez, 2009). Groundwater salinity should not have high values (no possibility for groundwater recovery for agricultural use). Chlorides and sodium may have a toxic effect on plant roots and may stunt or stop their growth (FAO, 1994). Thus, the lesser is the groundwater concentration with these elements the better is the site is for aquifer recharge with reclaimed water. Nitrates content reflects the environmental impact of the reclaimed water on groundwater. In fact, in Tunisia the most important groundwater pollutant compound is nitrate, which they come mainly from fertilizing agricultural lands. Being an additional source of pollution it is sounder to favor recharging sites with reclaimed water with low nitrate content. Below 13 mg/L nitrate is considered naturally present in groundwater (McLay et al., 2001). Higher contents are consequences of anthropogenic activities (McLay et al., 2001; Babiker et al., 2004; Andrade and Stigter, 2009). Lower groundwater concentrations with nitrate are considered best sites for aquifer recharge with reclaimed water.

2.4.2. *Sub-criteria layering by GIS*

Each sub-criterion was represented by a spatial grid thematic layer with 30 m cell size. Soil salinity was derived from the soil map of "La Carte Agricole" of Nabeul governorate. Land Use was digitized using Landsat images, GoogleEarth data and Landuse vector layer of the year 2000 obtained from "La Carte Agricole". Distance from residential areas was obtained by digitizing GoogleEarth map. A proximity algorithm was applied to get the distance of each point from the closest residential area. Distance from WWTPs were gotten by locating the SE3 and SE4 position using a handheld Global Positioning System (GPS). Then a spatial layer representing the distance from each plant was derived. Difference of elevation was processed by subtracting the plant elevation from the SRTM DEM. The procedure to get slope, soil texture, distance from water bodies, distance from roads, unsaturated zone depth, geology and groundwater quality parameters was detailed previously in Section 2.3.2.

2.4.3. *Hierarchy structure and weighting*

The weighting process was carried out using the Analytic Hierarchy Process (AHP) method. In a first step the decisional problem was organized in a four-level hierarchical structure (Fig. 3). The upper level expresses the study purpose which is ranking feasible sites for shallow aquifer recharge with reclaimed water. The second level presents the main criteria and the last two levels display the sub-criteria (Fig. 3).

Then, for each group of elements a pair-wise comparison matrix was applied through Saaty (1980) method. The pair-wise comparison matrix uses a semantic 9-point scale for attributing priority values (a_{ij}); 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.

$$(a_{ij})_{1\le i,j\le n}\begin{cases} a_{ij}: \text{takes values in } \{1,\ldots,9\} \\ a_{jj}=1; \\ a_{ji}=\dfrac{1}{a_{ij}} \end{cases}$$

The priority values was attributed based upon international guidelines, technical reports and experts' opinions. Afterwards the pair-wise comparison matrix was normalized according to the

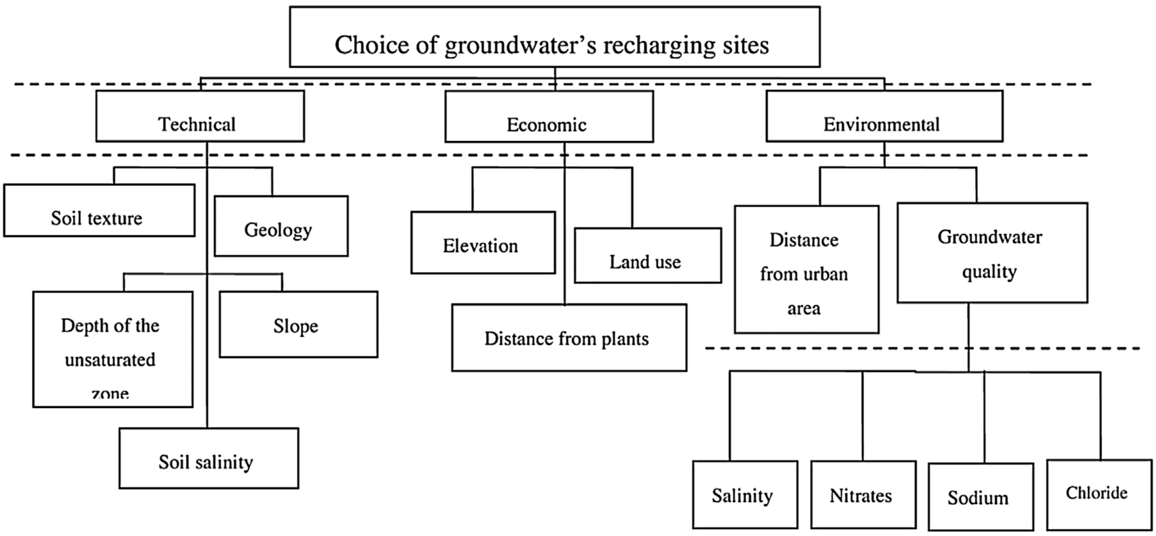

Fig. 3. Decision hierarchy structure.

formula $n_{ij} = a_{ij}/\sum_{i=1}^{n} a_{ij}$. Then, the local weights (w_i), presenting the matrix eigenvalues, were obtained as follow:

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

The consistency of the local weights was evaluated using the consistency ratio (c_r). c_r is the quotient between the consistency index (c) and the random index (r_i). It is defined as follows:

$$C_r = c/r_i$$

where $C = \lambda_{\max} - n/n - 1$ and $\lambda_{\max} = \sum_{i=1}^{n} \mathrm{PS}_i/w_i/n$. PS_i is the priority sum, $\mathrm{PS}_i = \sum_{j=1}^{n} q_{ij}/n$ being $q_{ij} = a_{ij}/w_i$.

The random index (r_i) is established from the bibliography (Saaty, 1980). For c lesser than 0.1, the priorities allocated are judged satisfactory, otherwise they are considered incoherent to produce weights and should be reviewed. Then, the global weight of each sub-criterion was obtained by multiplying its local weight by the local weight of the corresponding higher-levels sub-criterion and/or criterion (Table 1).

2.4.4. Sub-criteria standardization

The standardization process consisted in conversing cell values of the sub-criteria layers into a common [0–1] scale. The minimum 0 corresponds to the less desirable condition with regards to aquifer recharge with reclaimed water and 1 the most desirable condition. The cell values of all continuous numerical sub-criteria (e.g. slope, soil salinity and unsaturated zone depth) were rescaled using fuzzy linear membership functions. For categorical layers (e.g. soil texture, land use and geology) the categories were first grouped into classes according to their potential for aquifer recharge. Then, they were pair-wise compared using Saaty matrix (Gomez and Barredo, 2005). The resulting values were rescaled linearly into [0–1] interval. Tables 2–5 present the classes for soil texture, soil salinity, Land use, geology and groundwater quality and their corresponding values obtained using Saaty matrix.

2.4.5. Aggregation of standardized sub-criteria

A final composite map depicting the ranked feasible sites for aquifer recharge with reclaimed water was obtained through the calculation for each pixel (i) of the composite decision value (R_i) using the weighted lineal combination method. The corresponding formula is as follows:

$$R_i = \sum_{k} w_k r_{ik}$$

where w_k is the weights of the sub-criterion k and r_{ik} the standardized value of the pixel (i) in the map of the sub-criterion k. R_i values are between 0 and 1, being 0 is the least feasible for recharging shallow aquifer withy reclaimed water and 1 is the most feasible.

2.5. Estimation of the required area

To estimate the area required to infiltrate the effluents of SE3 and SE4 we adopted the equation developed by the United States

Table 1
The AHP weights for ranking suitable sites to aquifer recharge with reclaimed water.

Criterion		Sub-criterion	Local weight	Sub-criterion	Local weight	Global weight
Technical	0.33	Soil texture	0.290			0.095
		Geology	0.290			0.095
		Depth of unsaturated zone	0.290			0.095
		Soil salinity	0.086			0.028
		Slope	0.042			0.014
Economic	0.33	Distance from WWTP	0.591			0.195
		Elevation	0.334			0.110
		Land use	0.0074			0.025
Environmental	0.33	Distance from urban zone	0.800			0.264
		Water quality	0.200	Salinity	0.714	0.135
				NO_3	0.145	0.034
				SO_4	0.088	0.021
				Cl	0.053	0.010

Table 2
Pair-wise comparison matrix and weights to transform categorical classes of soil texture to numerical classes.

	Sand	Sandy and sandy–loam	Loam–sandy	Loam	Balanced	Sandy-clay	Loam-clay	Weights
Sand	1	2	3	4	5	6	7	0.35
Sandy and sandy-loam	1/2	1	2	3	4	5	6	0.24
Loam -sandy	1/3	1/2	1	2	3	4	5	0.16
Loam	1/4	1/3	1/2	1	2	3	4	0.10
Balanced	1/5	1/4	1/3	1/2	1	2	3	0.07
Sandy-clay	1/6	1/5	1/4	1/3	1/2	1	2	0.05
Loam-clay	1/7	1/6	1/5	1/4	1/3	1/2	1	0.03

Table 3
Pair-wise comparison matrix and weights to transform categorical classes of soil salinity to numerical classes.

	Non-saline soil	Slightly saline soil	Moderately saline soil	Saline soil	Very salty soil	Weight
Non-saline soil	1	2	4	7	9	0.47
Slightly saline soil	1/2	1	2	5	7	0.27
Moderately saline soil	1/4	1/2	1	3	5	0.16
Saline soil	1/7	1/5	1/3	1	2	0.06
Very salty soil	1/9	1/7	1/5	1/2	1	0.04

Table 4
Pair-wise comparison matrix and weights to transform categorical classes of land use to numerical classes.

	Parcour and bare soil	Non irrigated annual cultures	Non irrigated arboriculture	Irrigated annual cultures	Irrigated arboriculture	Weight
Parcour and bare soil	1	3	5	7	9	0.51
Non irrigated annual cultures	1/3	1	3	5	7	0.25
Non irrigated arboriculture	1/5	1/3	1	3	5	0.14
Irrigated annual cultures	1/7	1/5	1/3	1	3	0.07
Irrigated arboriculture	1/9	1/7	1/5	1/3	1	0.04

Environmental Protection Agency (EPA, 1984). The equation considers the bare bottom basin as basins type and it is based on the hydraulic loading rate, the number of wetting/drying cycles and the outflow. The equation is expressed as follow (EPA, 1984):

$$A = \frac{PQ10^{-4}}{NL} \tag{1}$$

where A is the required area expressed in [ha], P is the number of season days expressed in [day], Q is the outflow expressed in [m^3/day], N is the cycles number of each season per year [cycle] and L is the hydraulic loading rate per cycle [m/cycle]. A cycle is an alternation of wetting and drying periods. A drying period is needed to avoid basin clogging and assure water infiltration. This period is larger during winter than summer because of difference in climatic conditions, (e.g. evapotranspiration and rain). The number of cycles of each season per year is calculated as follow:

$$N = \frac{\text{Number of days perperiod}}{\text{Number of days percycle}} \tag{1a}$$

Days number per season, dry period, wet period and cycle period according to Nabeul–Hammamet climate are presented in Table 6.

The hydraulic loading of wastewater L is estimated to be 10% of the hydraulic loading of clean water (L_{cw}) (EPA, 1984). L_{cw} could be obtained experimentally or using the EPA (1984) following empirical the following equation:

$$L_{\text{cw}}\ [\text{m/year}] = \frac{K_v\ [\text{cm/h}]\ 24\ [\text{h/day}]\ 365\ [\text{day/am}]\ 1\ [\text{m}^2]}{100\ [\text{cm/m}]} \tag{1b}$$

where K_v is the soil hydraulic conductivity. In our study the hydraulic conductivity was obtained by averaging the hydraulic conductivity of the feasible soils for Nabeul–Hammamet aquifer recharge with treated wastewater according to the following equation:

$$K = \frac{\sum S_i K_i}{S} \tag{1c}$$

where K is the hydraulic conductivity [cm/h], i is the index of the soil texture (Fig. 4c), S_i is the surface of the soil (i) [ha] obtained from (Fig. 4c), K_i is the hydraulic conductivity of the soil (i) [cm/h], S is total feasible surface obtained from to the soil texture constraint layer (Fig. 4c). Based on Saxton and Rawls (2005), Clavet (2003), Rawls et al. (1998) and Clapp and Hornberger (1978) a K_i value was assigned to each soil texture in Nabeul–Hammamet region (Table 7).

Accordingly, for Nabeul–Hammamet region K is estimated to be equal to 2.6 cm/h and then L_{ww} is 22.69 m/year. So the total surface needed for SE3 and SE4 is respectively 5 ha and 14 ha during the summer period and is, respectively, 8 ha and 22 ha during the winter period. Then the needed areas considered for recharging the outflow of SE3 and SE4 are respectively 8 ha and 22 ha. These areas

Table 5
Pair-wise comparison matrix and weights to transform categorical classes of geology to numerical classes.

	Sandy Marne	Cultivated soil	Fossil	Alluvium	Marl	Weight
Sandy Marne	1	3	5	7	9	0.50
Cultivated soil	1/3	1	3	5	7	0.26
Fossil	1/5	1/3	1	3	5	0.13
Alluvium	1/7	1/5	1/3	1	3	0.07
Marl	1/9	1/7	1/5	1/3	1	0.03

Table 6
Days number per season, dry period, wet period and cycle period according to Nabeul–Hammemat climate.

	Season period	Wet period	Dry period	Cycle period
Winter	151 [Oct.–Feb.]	2	12	14
Summer	214 [Mar.–Sep.]	2	7	9

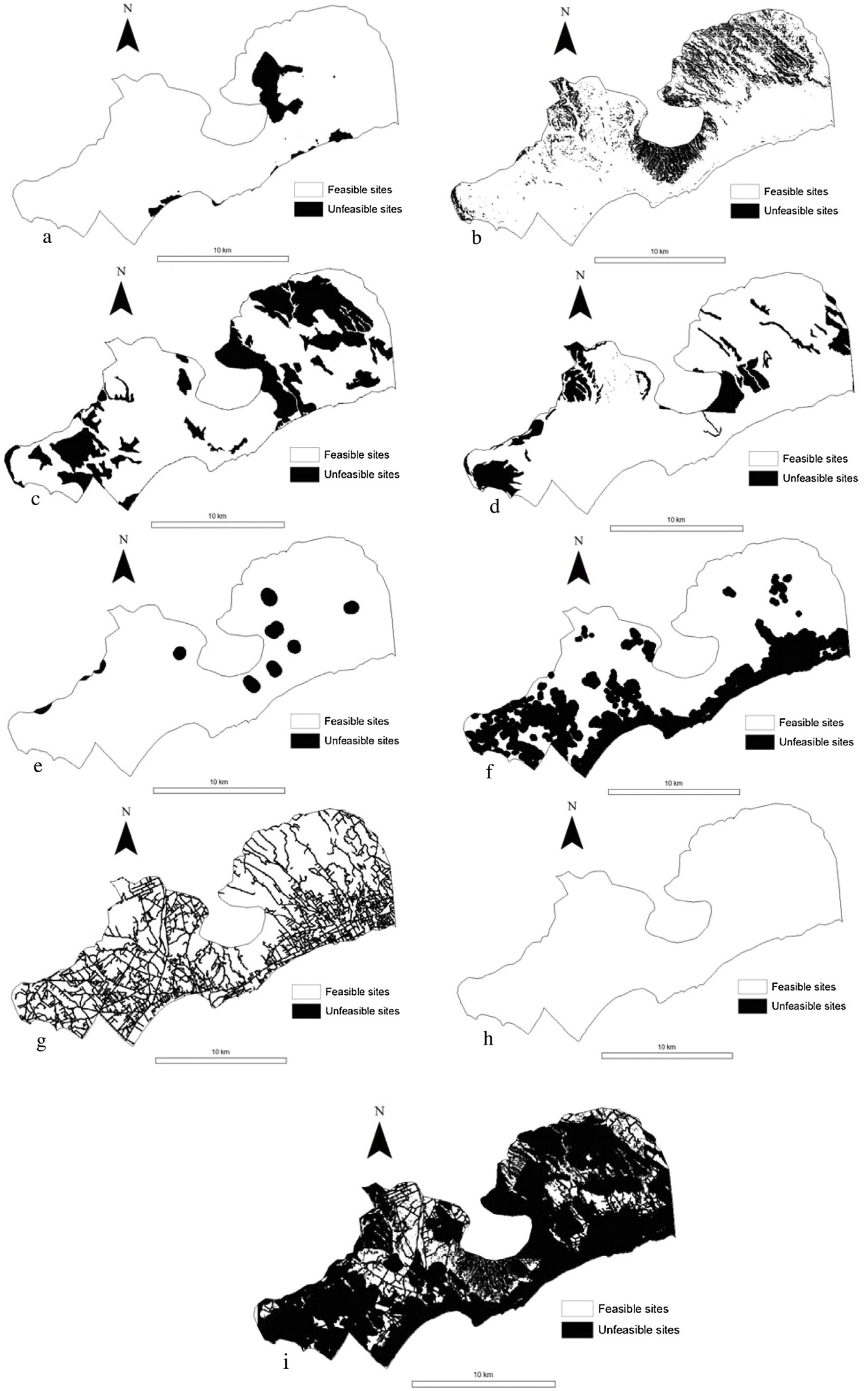

Fig. 4. Feasible/unfeasible sites to recharge Nabeul–Hammamet shallow aquifer with reclaimed water according to the constraint, (a) depth of the unsaturated zone, (b) slope, (c) soil texture, (d) geology, (e) distance from lakes and hill, (f) distance from residential areas, (g) distance from roads, (h) water quality, (i) conjunction of constraints.

Table 7
The area of each soil texture class feasible for Nabeul–Hammamet aquifer recharge and the corresponding hydraulic conductivity.

Soil texture	Surface [ha]	K_i
Sandy	1327.8	7.2
Sandy/Sandy–loamy	6323.8	4.57
Loamy	855.58	0.61
Balanced	2916.48	0.9
Loamy–clay	5082.24	0.24
Clay–sandy	57.58	0.11

were incremented by 30% as safeguard and protection zone. Then the total areas required to recharge the Nabeul–Hammamet aquifer with the outflow of SE3 and SE4 are respectively 11 ha and 28 ha, summing 39 ha.

2.6. *Location of best required land*

The cells of the ranked map corresponding to the best sites were those owning the highest R_i values and summing an area equal to the required land to infiltrate the effluents of SE3 and SE4, previously estimated using EPA equation.

2.7. *Sensitivity analysis*

The sensitivity analysis aims to quantify how any change applied on the input variables impacts the output results. In this study we quantified the change in the selected best sites caused by a progressive change in the weight of the criteria (technical, economic and environmental). The process was as follow:

(1) Different weights varying from 0 to 0.80 (00; 0.20, 0.25; 0.3; 0.35; 0.40; 0.5; 0.6 and 0.8) were assigned to the criterion *i*. The other two criteria share equally the remaining value to sum 1. For example if the weight 0.4 is assigned to the technical criteria then the environmental and economic criteria will have 0.3 each. Table 8 presents the weights distribution for the different possible scenarios.
(2) The multicriteria analysis was conducted for each set of weights and the corresponding ranking map and the best sites map were obtained. A total of 27 maps were obtained for each WWTP.

Table 9
Feasible area for Nabeul–Hammamet shallow aquifer recharge with reclaimed water per constraint and conjunction between constraints given in (ha) and (%).

Layer	Feasible area [ha]	Feasible area [%]
Depth of the unsaturated zone	27,140	94.9
Slope	23,800	83.21
Soil texture	20,300	70.98
Geology	25,400	88.81
Distance from residential areas	18,400	64.34
Distance from roads	19,800	69.23
Water quality	28,652.65	100
Final map	5,160	18.04

(3) The common area between the best sites of each scenario and the original model was obtained and the percentage (P) of the common area was calculated according to the equation

$$P = S_i/S \times 100$$

where, S_i is the common area between the best sites obtained by *scenario i* and the original model and S is the total area required to infiltrate the SE3 and SE4 effluents; higher is the value of P more stable is the model.

3. Results and discussions

3.1. *Constraints map building*

The resulting map of conjunctive screening identifies 5161 hectares feasible to recharge the Nabeul–Hammamet shallow aquifer with reclaimed water, representing 18% of the total area. They are situated in and out of cultivated lands, with different distances from SE3 and SE4 and have a large range of soil textures, slopes, etc. Distance from urban area is the most restrictive constraints. The total feasible area is 64% of the total Nabeul–Hammamet aquifer limits (Table 9). Quality of groundwater for human consumption is the less restrictive constraint fulfilling 100% of the study area. The location of these feasible areas according to each constraint and the conjunctive screening result are presented in Fig. 4.

Table 8
Weights considered for the sensitivity analysis.

	Case 1	Case 2	Case 3	Case 4	Original	Case 5	Case 6	Case 7	Case 8
Criterion I	0.0	0.20	0.25	0.30	0.33	0.40	0.50	0.60	0.80
Criterion II	0.50	0.40	0.37	0.35	0.33	0.30	0.25	0.20	0.10
Criterion III	0.50	0.40	0.37	0.35	0.33	0.30	0.25	0.20	0.10

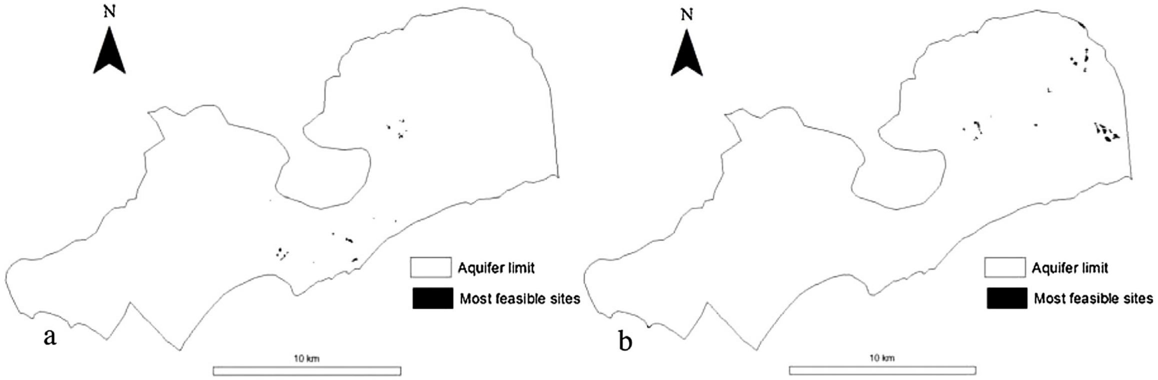

Fig. 5. Best sites for recharging Nabeul–Hammamet shallow aquifer with the effluents of (a) SE3 and (b) SE4.

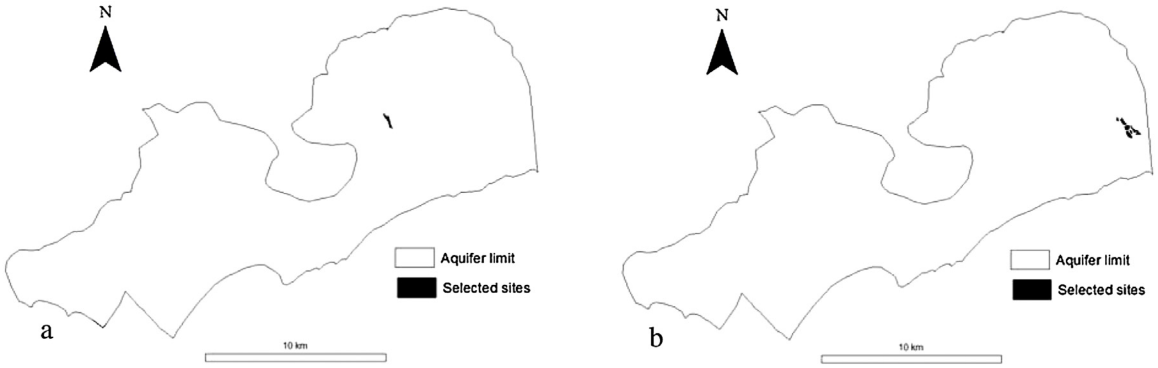

Fig. 6. Selected sites to recharge Nabeul–Hammamet shallow aquifer with the effluent of (a) SE3 and (b) SE4.

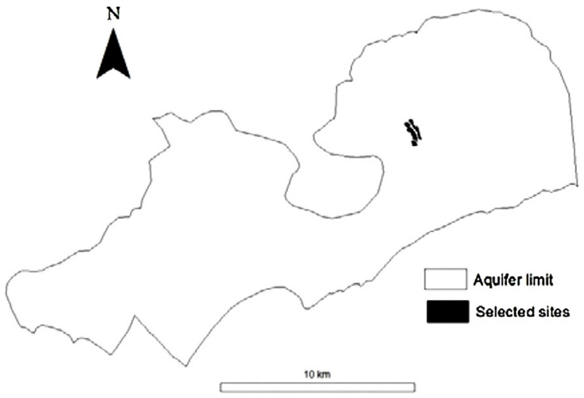

Fig. 7. Selected sites to recharge Nabeul–Hammamet shallow aquifer when collecting together the effluents of SE3 and SE4.

3.2. Feasible sites ranking

The R_i employed to rank the 5160 ha feasible areas for aquifer recharge with reclaimed water varies from 0.14 to 0.55 for SE3 and from 0.12 to 0.51 for SE4 (Fig. 5). The difference between both plants in the R_i range, average (about 0.35) and standard deviation (about 0.06) is very low so that the position and elevation differences between the plants does not a substantial impact on R_i values.

3.3. Location of best required land

The cells of the ranked map corresponding to the best 11 ha of SE3 possess R_i values from 0.49 to 0.52. The best 28 ha for SE4 have values from 0.48 to 0.51. The selected sites are made up of several plots situated in different locations. For SE3 they are scattered in the center of the study area around the Hammamet city, in an agricultural areas, non saline soil and where the groundwater salinity is around 2 g/L (Fig. 5a). For SE4 these selected sites are clustered in two zones at the extreme West of the study area located in agricultural areas and 2.5 to 7 km far from the treatment plant. The groundwater salinity is about 2.5 g/L (Fig. 5b).

In practice it is not useful managing several parts for aquifer recharge with reclaimed water. It is worthy grouping the dispersed plots into one big area to reduce construction expenses and to facilitate operation and maintenance tasks. Thus, the dispersed plots for each plant are clustered in one single site after checking the R_i values of the replaced areas, allowing only a slight decrease in the R_i values between the shifted sites (Fig. 6). Accordingly, the selected R_i go down to 0.48 for SE3 and to 0.46 for SE4.

Furthermore, it could be more cost-effective and environmentally friendly solution collecting together the effluents of both plants to recharge Nabeul–Hammamet aquifer in one single site. The best scenario to perform this objective is to convey SE4 effluent close to the SE3 best sites. This is due to two reasons: (i) availability of sufficient sites with high R_i values (varying from 0.45 to 0.48) close to SE3 best sites to infiltrate the entire SE4 outflow and (ii) absence of feasible sites for SE3 close to SE4 best sites (Fig. 7).

3.4. Sensitivity analysis

The percentages of common area between the best sites of each scenario and the original model (Section 2.7) are presented in Fig. 8.

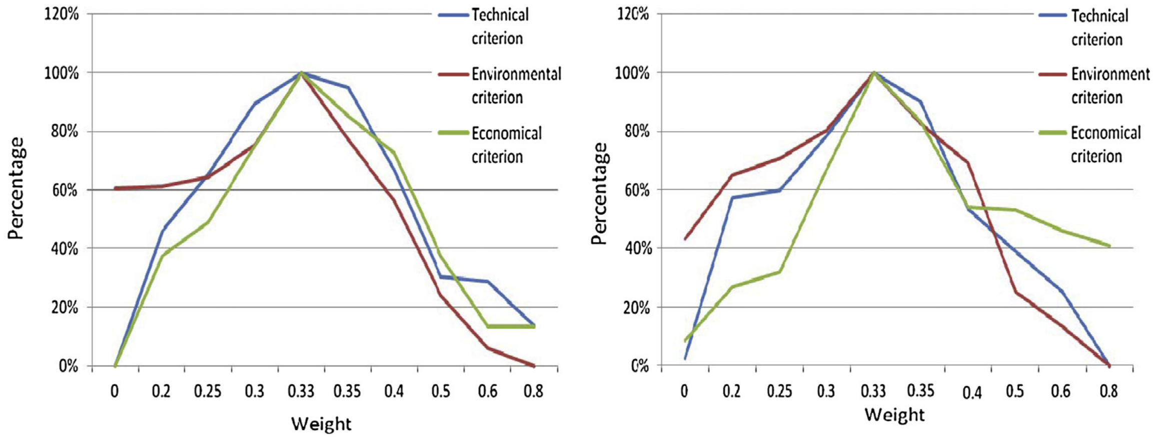

Fig. 8. Percentage of common surfaces between the original case of ranking suitable sites (multicriteria analysis study) and each layer of the sensitivity analysis cases (a) SE3 case, (b) SE4 case.

Whatever the criterion considered the shape of the sensitivity analysis curve is parabolic. The summit, presented by 100% of common area, corresponds to the weight of 0.33, given to the original model. The common area drops down to 80% for a change of ±3% in the weight and to about 50% for a change of ±7%. At this interval of weights the main selected plots are conserved indicating a certain stability of the established multicriteria model. At higher variations in the weights a considerable decrease of the common area is observed. The economic and technical criteria are the most sensitive to the low weights than the environmental criterion. Indeed, the elimination of the layers constituting the economical and the technical criteria (a weight of zero is assigned) the percentage of common area is dropped down to less than 10%. However, the elimination of the layers constituting the environmental criterion, 50% of a common area is conserved unchanged.

4. Conclusion

The developed methodology based on the multicriteria AHP method integrated with a GIS allows the identification and ranking of feasible sites for recharging Nabeul–Hammamet shallow aquifer with reclaimed water. The seven constraints identified and combined in a conjunctive screening process reveal that 19% of the Nabeul–Hammamet shallow aquifer is suitable to be recharged with reclaimed water, exceeding by far the 39 ha required to make use of the entire SE3 and SE4 effluents. The decision index values of the ranked feasible sites using Saaty pair-wise comparison matrixes, fuzzy logic functions and weighted linear combination, vary from 0.12 to 0.52 for SE3 and from 0.14 to 0.55 for SE4. The highest index values covering the required 11 ha for SE3 effluents and the 28 ha for SE4 effluents are respectively [0.49–0.55] and [0.48–0.51]. The corresponding sites are scattered over a large area with isolated and small plots, which prevent the wastewater transfer to all of them and complicate operation and maintenance. The simultaneous consideration of the pixels values and their neighbors ensures the selection of clustered areas for aquifer recharge, which reduces structure building cost and eases its operation and maintenance. These clustered areas for SE3 are located in the center of the aquifer between Nabeul and Hammamet cities and are located in the north east of Nabeul city for SE4. The sensitivity analysis shows that the model established is relatively stable conserving the best area unchanged up to ±7% of variation in the main criteria weight. The developed methodology offers a useful technical help for decision makers to manage Nabeul–Hammamet shallow aquifer. However, elaboration of a hydrogeological model remains an important step before basins building in order to estimate the impact of the projected recharge with reclaimed water on the quality and amount of groundwater.

References

Abba, A.H., Noor, Z.Z., Yusuf, R.O., Din, M.F.M.D., Abu Hassan, M.A., 2013. Assessing environmental impacts of municipal solid waste of Johor by analytical hierarchy process. Resour. Conserv. Recycl. 73 (2013), 188–196.

Ambiga, K., Anna Durai, R., 2013. Use of geographical information system and water quality index to assess groundwater quality in and around Ranipet area, Vellore district, Tamil Nadu. Int. J. Adv. Eng. Res. Stud. II/IV (July–Sept.), 73–80.

Anane, M., Bouziri, L., Limam, A., Jellali, S., 2012. Ranking suitable sites for irrigation with reclaimed water in the Nabeul–Hammamet region (Tunisia) using GIS and AHP-multicriteria decision analysis. Resour. Conserv. Recycl. 65, 36–46.

Anane, M., Kallali, H., Jellali, S., 2008. Ranking suitable sites for Soil Aquifer Treatment in Jerba Island (Tunisia) using remote sensing GIS and AHP-multicriteria decision analysis. Int. J. Water 4 (1/2), 121–135.

Andrade, A.I.A.S.S., Stigter, T.Y., 2009. Multi-method assessment of nitrate and pesticide contamination in shallow alluvial groundwater as a function of hydrogeological setting and land use. Agric. Water Manage. 96, 1751–1765.

Antonopoulos, I.S., Perkoulidis, G., Logothetis, D., Karkanias, C., 2014. Ranking municipal solid waste treatment alternatives considering sustainability criteria using the analytical hierarchical process tool. Resour. Conserv. Recycl. 86 (2014), 149–156.

Anojkumar, L., Ilangkumaran, M., Sasirekha, V., 2014. Comparative analysis of MCDM methods for pipe material selection in sugar industry. Expert Syst. Appl. 41, 2964–2980.

Anon, 2003. Système d'évaluation de la qualité des eaux souterraines SEQ—Eaux Souterraines. In: Rapport de présentation, version 0.1—Août 2003 (75 pp).

Babiker, I.S., Mohamed, M.A., Terao, H., Kato, K., Ohta, K., 2004. Assessment of groundwater contamination by nitrate leaching from intensive vegetable cultivation using geographical information system. Environ. Int. 29, 1009–1017.

Belton, V., Stewart, T., 2002. Multicriteria Decision Analysis: An Integrated Approach. Kluwer, Boston, MA.

Bensalem, H., 1991. Geological Map of Tunisia (Hammamet) Scale 1:50 000. Sheet No 37. Geological Service of Tunisia, Tunis.

Bonnina, M., Azzaro-Pantela, C., Domenecha, S., Villeneuveb, J., 2015. Multicriteria optimization of copper scrap management strategy. Resour. Conserv. Recycl. 99 (2015), 48–62.

Bouwer, H., 1982. Renovation of wastewater with rapid infiltration land treatment systems. In: Asano, T. (Ed.), Artificial Recharge of Groundwater. California State Water Resources Control Board, Sacramento, CA, pp. 249–282 (Chapter 8).

Chaabane, N.H., 2014. L'eau en Tunisie: Une crise occultée! Nawaat—Tunisia (24 September 2014): ⟨http://nawaat.org/portail/2014/09/24/leau-en-tunisie-une-crise-occultee/⟩.

Chen, T.Y., 2014. The extended linear assignment method for multiple criteria decision analysis based on interval-valued intuitionistic fuzzy sets. Appl. Math. Model. 38, 2101–2117.

Clapp, Roger B., Hornberger, G.M., 1978. Soil Information for Environmental Modelling and Ecosystem Management, Soil Info Home: ⟨http://www.soilinfo.psu.edu/index.cgi?soil_data&conus&data_cov&texture⟩.

Clavet, R., 2003. Le Sol: Propriétés et Fonction, Tom2, Phénomène physique et chimique, Applications agronomiques et environnementales. Editions France Agricole, ⟨http://books.google.fr/books?id=5I7g5L8×5VgC&printsec=frontcover&hl=fr#v=onepage&q&f=false⟩. (P 63–135–137).

Colleuil, B., Bensalem, H., 1991. Geological Map of Tunisia (Nabeul) scale 1:50 000. Sheet No 30. Geological Service of Tunisia, Tunis.

CRDA, 2008. Etude de la gestion intégrée des ressources hydrauliques de Cap Bon Phase II: Elaboration des scenarios de développement. Rapport général. BICHE.

Detay, M., 1997. La gestion active des aquifers. Masson, Paris, Milan, Barcelona.

DGRE, 2005. Recharge artificielle des nappes de Tunisie. Technical Report. DGRE, Tunis, pp. 102 (ISSN: 0330-8383).

Drewes, J.E., 2009. Groundwater replenishment with recycled water–water quality improvements during managed aquifer recharge. Groundwater 47 (4), 502–505.

EPA, 1984. U.S. Environmental Protection Agency Center for Environmental Research Information Cincinnati, Process Design Manual for Land Treatment of Municipal Wastewater Supplement on Rapid Infiltration and Overland Flow. EPA, Cincinnati, Ohio.

EPA, 2014. ⟨http://www.epa.gov/region1/eco/drinkwater/pc_groundwater_discharges.html⟩ (last access December 2014).

ESRI, 2003. Using Arc GIS Geostatistical Analyst, Printed in the USA Johan Z, Krivy M (1969) Geological map of Tunisia (Bouficha) scale 1:50 000. Sheet No 36. Geological Service of Tunisia.

FAO, 1994. Water Quality for Agriculture, FAO Irrigation and Drainage Paper, 29, No. 2. FAO, Rome.

Ghayoumian, J., Ghermezcheshme, B., Feizinia, S., Noroozi, A.A., 2005. Integrating GIS and DSS for identification of suitable for artificial recharge, case study Meimeh Basin, Isfahan, Iran. Environ. Geol. 47, 493–500.

Ghoseiri, K., Lessan, J., 2014. Waste disposal site selection using an analytic hierarchal pairwise comparison and ELECTRE approaches under fuzzy environment. J. Intell. Fuzzy Syst 26 (2), 693–704.

Gomez, M., Barredo, J.L., 2005. Sistemas de Informacion Geografica y Evaluacion Multicriterio en la Ordenacion del Territorio, second ed. Ra-Ma.

Gorai, A.K., Kumar, S., 2013. Spatial distribution analysis of groundwater quality index using GIS: a case study of Ranchi Municipal Corporation (RMC) area. Geoinf. Geostat. 1 (2), 3–12 (An Overview).

Jha, M.K., Chowdary, V.M., Kulkarni, Y., Mal, B.C., 2014. Rainwater harvesting planning using geospatial techniques and multicriteria decision analysis. Resour. Conserv. Recy. 83, 96–111.

Jomâa, S., Jellali, S., Kallali, H., Souissi, A., Oueslati, M.N., 2005. Caractérisation hydrodynamique et qualitative de la nappe côtière Nabeul–Hammamet, 30ème. In: Journées du Groupe Francophone d'Humidimètrie et des transferts en Milieux Poreux GFHN.

Kallali, H., Anane, M., Jellali, S., Tarhouni, J., 2007. GIS-based multicriteria analysis for potential wastewater aquifer recharge sites. Dessalination 215, 111–119.

Kiker, G.A., Bridges, T.S., Varghese, A., Seager, T.P., Linkov, I., 2005. Applications of multicriteria decision analysis in environmental decision making. Integr. Environ. Assess. Manage. 1 (2), 95–108.

Kim, Y., Chung, E.S., Jun, S.M., Kim, S.U., 2013. Prioritizing the best sites for treated wastewater instream use in an urban watershed using fuzzy TOPSIS. Resourc. Conserv. Recycl. 73, 23–32.

Lesch, S.M., Suarez, D.L., 2009. A short note on calculating the adjusted sar index. Am. Soc. Agric. Biol. Eng. 52 (2), 493–496.

Malekmohammadi, B., Rahimi Blouchi, L., 2014. Ecological risk assessment of wetland ecosystems using Multi Criteria Decision Making and Geographic Information System. Ecol. Indic. 41, 133–144.

McLay, C.D.A., Dragten, R., Sparling, G., Selvarajah, N., 2001. Predicting groundwater nitrate concentrations in a region of mixed agricultural land use: a comparison of three approaches. Environ. Pollut. 115, 191–204.

Ministry of Agriculture, 2000. Carte Agricole: CD-support of Many Data Layers Related with Agriculture and Water Sectors of Nabeul District.

Nasiri, H., Boloorani, A.D., Sabokbar, H.A.F., Jafari, H.R., Hamzeh, M., Rafii, Y., 2013. Determining the most suitable areas for artificial groundwater recharge via an integrated PROMETHEE II-AHP method in GIS environment (case study: Garabaygan Basin, Iran). Environ. Monit. Assess. 185, 707–718.

Neshat, A., Pradhan, B., Dadras, M., 2014. Groundwater vulnerability assessment using an improved DRASTIC method in GIS. Resour. Conserv. Recycl. 86, 74–86.

Nijhawan, A., Labhasetwar, P., Jain, P., Rahate, M., 2013. Public consultation on artificial aquifer recharge using treated municipal wastewater. Resour. Conserv. Recycl. 70 (2013), 20–24.

ONAS, 2011. Rapport Annuel 2010, ⟨http://www.onas.nat.tn/Fr/upload/telechargement/telechargement99.pdf⟩ (Last access, June 2012).

ONAS, 2013. Rapport Annuel 2012.

Ouelhazi, H., Lachaal, F., Charef, A., Challouf, B., Chaib, H., Horriche, F.J., 2014. Hydrogeological investigation of groundwater artificial recharge by treated wastewater in semi-arid regions: Korba aquifer (Cap-Bon Tunisia). Arabian J. Geosci. 7, 4407–4442.

Pedrero, F., Albuquerque, A., Marecos do Monte, H., Cavaleiro, V., Alarcón, J.J., 2011. Application of GIS-based multi-criteria analysis for site selection of aquifer recharge with reclaimed water. Resour. Conserv. Recy. 56, 105–116.

Rahman, M.A., Salah Uddin, B., Rusteberg, M., Lutz, A., Abu Saada, M., Sauter, M., 2013. An integrated study of spatial multicriteria analysis and mathematical modeling for managed aquifer recharge site suitability mapping and site ranking at Northern Gaza coastal aquifer. J. Environ. Manage. 124, 25–39.

Rawls, W.J., Gimenez, D., Grossman, R., 1998. Use of soil texture, bulk density and slope of the water retention curve to predict saturated hydraulic conductivity. Trans. ASAE 41, 983–988.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York, NY.

Saidi, S., Bouri, S., Ben Dhia, H., Anselme, B., 2009. A GIS-based susceptibility indexing method for irrigation and drinking water management planning: application to Chebba-Mellouleche aquifer, Tunisia. Agric. Water Manage. 96, 1683–1690.

Saxton, K.E., Rawls, W.J., 2005. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J., ⟨http://hydrolab.arsusda.gov/SPAW/Soil%20Water%20Characteristics-Paper.pdf⟩ (published by Soil Science of America).

Stigter, T.Y., Ribeiro, A.M.M., Carvalho Dill, L., 2006. Application of a groundwater quality index as an assessment and communication tool inagro-environmental policies—two Portuguese case studies. J. Hydrol. 327, 578–591.

Schmidt Jr., H.E., BCEE, P.E., Weatherby, Michael P.G, 2013. Aquifer recharge and reclaimed water—a new vision for managing your valuable resources. In: Water Environment Federation (WEFTEC), pp. 1715–1728.

Shen, L., Olfat, L., Govindan, K., Khodaverdi, R., Diabat, A., 2013. A fuzzy multi criteria approach for evaluating green supplier's performance in green supply chain with linguistic preferences. Resour. Conserv. Recycl. 74 (2013), 170–179.

Sharma, S.K., Harun, C.M., Amy, G., 2008. Framework for assessment of performance of soil aquifer treatment systems. Water Sci. Technol. 57 (6), 941–946.

WCCR, 1991. Official Paper. Ankara, No. 19919.

WHO, 2006. Guidelines for Drinking-water Quality. Recommendations, vol. 1., third ed., ISBN 92 4 154696 4 (595 pp).