5th International Conference on Water Resources and Arid Environments (ICWRAE 5): 171-181
7-9 January 2013, Riyadh, Saudi Arabia

GIS-Based AHP-Multicriteria Decision Analysis to Rank Suitable Sites for Irrigation with Reclaimed Water in the Nabeul-Hammamet Region (Tunisia)

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Abstract: The present study describes an innovative methodology to rank suitable sites for irrigation with reclaimed water using fuzzy-AHP based on GIS where the Nabeul-Hammamet aquifer catchment (Tunisia) is selected as the target area. The model is relatively simple and is extendable worldwide. Several influential parameters are identified considering simultaneously technical, social, economical and environmental aspects. They are grouped in five main criteria, namely land suitability for irrigation, resources conflicts, cost effectiveness, social acceptance and environmental impact. Each criterion is subdivided into several sub-criteria. A pair-wise matrix is used to compare these criteria and sub-criteria and to rank them according to their relative importance for site evaluation. Using GIS, geographical layers are obtained for the sub-criteria, leading to mapping and ranking the suitable sites for irrigation with reclaimed water. The results show that the total suitable area covers 11426 ha which represents 31% of the total Nabeul–Hammamet aquifer watershed. This constitutes quite a large zone that can absorb the entire volume of available treated wastewater, thereby increasing the region's agricultural production. The best sites to receive the surplus amount of reclaimed water, produced by the treatment plants of the region, are located near these plants and inside agricultural lands. In addition, all these sites are located around the districts already irrigated by reclaimed water, which underlines the role these districts may play in encouraging neighbouring farmers to change their attitude towards reclaimed water and to accept it as an alternative resource for irrigation.

Key words: AHP · GIS · Wastewater · Irrigation · Mapping · Tunisia

INTRODUCTION

Tunisia, as well as several countries around the world, is facing the problem of water scarcity due to its arid and semi-arid climate, where the estimated available freshwater is only about 450 m^3/citizen/year, which is relatively low compared to the international standards (1000 m^3) [1]. To tackle water penury and to fulfil growing population needs as well as agricultural, industrial and touristic sectors demand, Tunisia has made a remarkable investment in hydraulic resources mobilization. Thus, the available freshwater is mostly mobilized and is managed through various structures such as dams, channels, wells, hill dams and hill reservoirs and cisterns to harvest rainwater from houses roofs. In addition, water harvesting structures built on runoff watercourses and in the foothills areas (locally called jessours and tabias) are set up to meet olive trees and cereals water demand despite their location at Sahara limits [2, 3].

Growing attention within the last thirty years has been paid to the treated wastewater (TWW) use, which has been considered as an important part of Tunisia's overall water resources balance [4]. Currently the Tunisian wastewater treatment office (ONAS) is running 106 urban wastewater treatment plants (WWTP) producing an annual total volume of 238 Mm^3 [5]. This volume can irrigate up to 30000 ha of cultivated lands, however only 9555 ha have been allocated [5]. Some irrigated districts failed in the start-up or in the long-term viability because of an inappropriate site selection.

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In Tunisia, the irrigated land with TWW is commonly selected as the nearest agricultural area to the WWTP [6]. However, more criteria should be included to ensure a sound site selection where technical, economical, social and environmental characteristics interconnect. For instance, it is important to consider the negative impact of the practice on the environment [7-9] in addition to the farmers' reticence, still considering treated wastewater as sewage [10].

Considering the necessity of TWW use and its importance as a fast-growing practice (the allocated area is projected to reach 44000 ha by 2021 [5]), the establishment of a methodology to locate the best sites becomes a need. This methodology would be applied each time a WWTP's outflow is projected for use whatever the region. Thus, a better benefit of this non conventional water is ensured along with the increasing availability of the national water and the reduction of the negative impact on environment.

On the other hand and according to a search made in *scopus* database, there is no scientific work published on site selection for TWW irrigation. However, site selection has been applied for many other applications such as aquifer recharge [11], solid waste disposal [12], airport site selection [13], gas stations [14], etc. Site selection techniques lead to the identification of the suitable sites and generate their suitability map through the integration of Multi-Criteria Decision Analysis (MCDA) into a Geographical Information System (GIS). MCDA combines technically feasible, economically viable, socially acceptable and environmental friendly criteria with respect to their importance to suitability. These criteria are then analyzed using GIS and treated spatially to generate sites suitability maps.

Several MCDA techniques have been used in many fields for site selection and land allocation such as ELECTRE, PROMETHEE, AHP, TOPSIS, AIM, etc. [15-19]. However, only few of them are integrated into GIS [20-23], where Analytic Hierarchy Process (AHP) is the most applied [24-26]. AHP was established by Thomas Lorie Saaty in the 1970s [27] and used to determine the priority for different decision alternatives via pair-wise comparisons with respect to common criteria.

The present study aims to establish an innovative methodology to map and rank suitable sites for irrigation with treated wastewater. It integrates a single-objective AHP method into a GIS model to select the most suitable sites for irrigation according to the available volume of TWW. The methodology uses easy-to-get data from Tunisian official institutions and available satellite images. The Nabeul–Hammamet aquifer watershed is selected as a study site to check the feasibility of the methodology.

MATERIALS AND METHODS

Characterization of the Study Area: The study area corresponds to the Nabeul–Hammamet aquifer watershed. It is located at 'Cap Bon' peninsula at the North Eastern part of Tunisia and belongs to Nabeul District (Fig. 1). It covers 365 km^2 of surface area, with a length of 34 km and a width ranging from 6 to 16 km. The climate is semi-arid with 400 mm as annual average precipitation at Nabeul city and 19°C as average temperature. The altitude varies between 0 m and 500 m. Geologically, the region is Pliocene and Quaternary, mainly composed by sandstones, conglomerates and clay. The depth of the aquifer varies from 4 to 31 m. The economic activities are mainly based on tourism and agriculture.

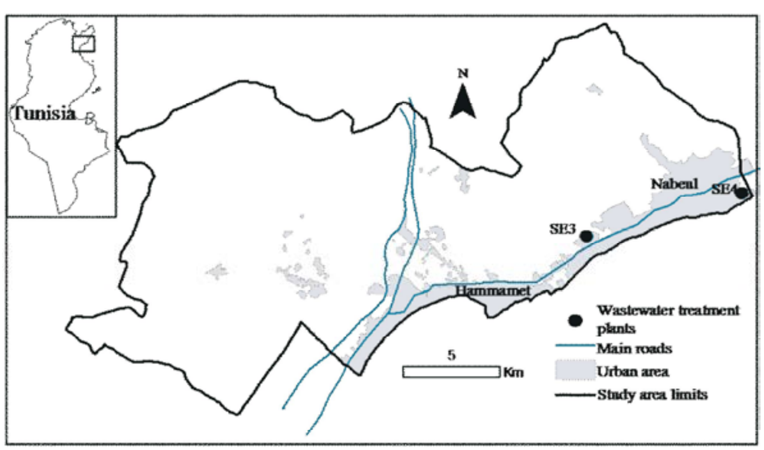

Fig. 1: Location map of Nabeul-Hammamet aquifer catchment showing urban areas, wastewater treatment plants and main roads.

Table 1: Constraints and their corresponding discarding conditions for wastewater irrigation suitability

Constraint	Discarding conditions
Soil Texture	Sandy and coarse-textured soils and soils with very high content of clay
Soil Depth	<25cm
Soil Salinity	Halomorph soils and saline soils
Slope	> 15%
Land Use	Urban, Forest, Irrigated by TWW, water bodies
Farness from residential areas	<200m
DRASTIC	Very vulnerable

Two wastewater treatment plants are operating in the area, namely SE3 and SE4. The first WWTP uses oxidation ditches as treatment process, with a nominal flow rate of 3500 m^3/d [28, 29]. The second WWTP uses mean load activated sludge and anaerobic digestion as a treatment process, with a nominal flow rate of 9585 m^3/d [28, 29]. Currently, 1.8 Mm^3 mainly from SE4, are already reserved to irrigate five districts located around Nabeul city: Souhil, Bir Romana, Messadi, Beni Khiar and Hawaria.

The *Commisariat Regional de Développement Agricole* of Nabeul (CRDA-Nabeul) predicts that the SE4 outflow will reach 3 Mm^3/year in 2025 [6]. The future surplus produced SE4 effluent (about 1.5 Mm^3/year) is able to irrigate 566 ha [6].

Methodology Overview: To locate the best area suitable for irrigation with the 3 Mm^3/year outflow, an Analytic Hierarchy Process (AHP) combined with a GIS was used. The methodology involved the following major steps:

- Select criteria, sub-criteria and constraints,
- Develop a decision hierarchy structure and identify priorities (weights) for each decision criterion and sub-criterion using a pair-wise comparison matrix,
- Extract the geographic layers corresponding to each sub-criterion and constraints using GIS
- Standardize each sub-criterion to make possible their combination and then calculate the composite decision value (CDV),
- Extract most suitable sites based on their CDV and the surface of the land requirement.

Constraints Identification: The constraints considered to delineate the suitable areas for irrigation with reclaimed water in the Hammamet-Nabeul aquifer catchment are: soil texture, soil depth, soil salinity, land slope, land use, farness from residential areas and aquifer vulnerability (Table 1). The rationale behind selecting these constraints is presented hereinafter.

For *soil texture,* sandy and coarse-textured soils and soils with very high content of clay are not suitable for wastewater irrigation. The former does not conserve water in the root zone and the latter avoids water infiltration from the surface to the root zone [30]. Only intermediate textures are considered suitable for irrigation with reclaimed water. According to *Soil salinity,* Wagesho [31] states that 8 mmhos/cm should be the upper threshold of soil salinity to be suitable for irrigation. Suitable soils should have a lower salinity to offer the cultivation appropriate chemical conditions to grow up. As for *Soil depth*, Wagesho [31] shows that 25 cm is the threshold value under which the depth does not permit a good development of the roots and absorption of water and nutrients. Then, to be suitable for irrigation a soil should be deeper than 25 cm. The constraint *slope* depends on irrigation method. It could vary from less than 1% for certain surface irrigation to 15% for centre pivot sprinkler and could reach 20% in extreme cases with localized irrigation [30-32]. Then for this study, slopes greater than 15% are considered unsuitable for irrigation by TWW. As for *land uses,* residential, industrial and touristic areas, water bodies and forests are unsuitable for wastewater irrigation. The agricultural area already irrigated with wastewater is also excluded from the analysis since the purpose of this analysis is to find new suitable sites, whereas the remaining agricultural land and bare soil areas are considered suitable. For the constraint *farness from residential areas*, a 200 m buffer zone from residential, touristic and industrial areas is considered unsuitable to avoid a continuous contact of residential people with TWW and then social complaints. The last constraint considered is *Shallow aquifer vulnerability to pollution*. Each site defined as very vulnerable to pollution using DRASTIC method is not suitable for TWW irrigation. By this way, groundwater quality is protected from potential pollution brought by reclaimed water.

Criteria Selection: Four criteria were selected to rank suitable sites for TWW irrigation, which are (i) land suitability criteria, (ii) resources conflicts criteria, (iii) economic criteria, (iv) social criteria and (v) environmental criteria. These criteria, the derived sub-criteria and the rationale behind selecting them are detailed hereafter.

Land Suitability Criteria: Successful irrigation requires a suitable physical medium for an appropriate crop development. The land suitability for irrigation includes soil characteristics and land slopes. Texture, depth and salinity define soil characteristics. *Soil texture* is determined by the size of soil particles and it affects water storage, infiltration and holding capacity [33]. *Soil depth* refers to the thickness of the soil materials which provide structural support, nutrients and water for plants [32]. Depth is an important factor that offers a medium to the roots to develop and influences the amount of water available to the crop. Shallow soils require more frequent irrigations while deep soils require less frequent irrigations allowing the roots to penetrate deeper [33]. As for salinity, plants are sensitive to *soil salinity* because it delays or prevents crop germination. It also reduces the plant growth due to the high osmotic pressures between the soil-water solution and the plants, which affect the plant ability to absorb water [33]. When salinity exceeds a certain value it harms crops. According to *land slope,* it influences runoff and soil drainage and determines the erosion hazard to which the field is exposed [32]. Furthermore, farmlands management and irrigation techniques depend on the slope.

Resources Conflicts Criteria: Natural resources are limited and conflicts between different uses are often occurring. The main conflicts could happen on land and with freshwater, if available:

Land Use: Many uses are competing with agriculture on land such as urban areas and forests. Agricultural areas are the main potential sites for TWW irrigation. Among them, those employing restrictive cultivations, such as olives, citrus trees, fodder and cereals are the most suitable areas.

Freshwater Availability: Freshwater availability in a given region could reduce or prevent TWW demand since it is more socially acceptable and is not restricted to any kind of cultivation. Surface water and groundwater are the two forms of freshwater. In the Nabeul-Hammamet aquifer catchment there are 11 hill reservoirs and dams that retain surface water for irrigation purposes [6]. Distance to these structures is the sub-criterion considered to reflect the available surface water in the MCA process. As for groundwater, the shallow aquifer currently used for irrigation suffers in parts from a salinization process. Salinity is the most determinant factor for groundwater use in irrigation purposes whether in the specific study area or in Tunisia in general. This factor is taken as the sub-criterion that reflects groundwater availability in the MCA process.

Economic Criteria: Cost effectiveness depicts the fees needed to transfer wastewater from the treatment plant to the farmland as well as the closeness of the land to the roads for accessibility.

WW Transfer: Water transfer costs include adduction (distance from WWTPs) and pumping from wastewater treatment plant to the suitable irrigated areas (difference of elevation from WWTPs). The *distance from WWTP* reflects necessary pipe length and afferent costs to convey wastewater from source to destination. The *difference of elevation from WWTP* reflects the necessary wastewater pumping devices and related costs.

Closeness to the Roads: Farmers should have a good accessibility to the parcels for equipments convey and farm production marketing.

Social Criteria: Social criteria are twofold:

Farness from Residential Areas: A safeguard distance of urban agglomerations and touristic areas has to be respected in order to avoid social complaints.

Closeness to the Already Irrigated Districts with TWW: Successful TWW irrigation requires the farmers' agreement and acceptability to use reclaimed water. In many regions in Tunisia there is somewhat reluctance to irrigate with WWTPs outflow, considering it as sewage. This perception changes drastically if the practice is already well-established somewhere nearby and especially if it presents a tangible positive economical and social impact. It is the case of many irrigated districts located in the study area around Nabeul city such as Souhil and Bir Rommana.

Environmental Criteria: Using TWW in irrigation could be considered as source of diffuse pollution due to its high concentration of some pollutants mainly nitrogen compounds. The reclaimed water could reach the aquifer via infiltration through unsaturated zone altering the groundwater quality and reducing its value. The quality alteration and the value reduction is tributary of two parameters; the aquifer intrinsic vulnerability and the current quality of the shallow groundwater.

Intrinsic Vulnerability of the Shallow Aquifer: Some parts of groundwater are more exposed to pollution than others because of the aquifer-related physical characteristics. The magnitude of exposure defines the intrinsic vulnerability of the aquifer. Various methods have been established to determine and map such vulnerability [34, 35]. The most used is DRASTIC [36, 37], which is the adopted method in this study. It consists on combining the parameters, depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity, using the following formula:

Intrinsic vulnerability = $D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w$ where D, R, A, S, T, I and C are the seven parameters and the subscripts r and w are the corresponding rating and weights, respectively. More details about DRASTIC could be found in many works such as Fritch *et al*. [36] and Secunda *et al*. [37].

Current Quality of the Shallow Aquifer: The groundwater resource is used for a multitude of purposes, such as potable supply, irrigation, livestock watering and for industry. Higher the quality more uses are possible, being potable purpose the most demanding. Irrigating with TWW could reduce the quality of groundwater beneath and then reduces its multi-use. The most determinant compounds to define the groundwater quality in Tunisia are salinity and nitrate concentration. The first element is previously taken into consideration in the groundwater availability criteria. In this section Nitrate is taken as the most influential element for groundwater quality. According to Tunisian standards groundwater is potable up to 50 mg/l of nitrate concentration.

Data Analysis

Hierarchy Structure and Weighting: The hierarchy structure in AHP method consists to organize the decision problem in a number of levels. In this case four levels hierarchy structure is developed (Fig. 2). The first one defines the objective of this study which is ranking suitable sites for irrigation with TWW. The next levels consist in organizing the influential parameters on site aptitude for TWW irrigation. The former presents the criteria previously mentioned, whereas the last two levels display the sub-criteria.

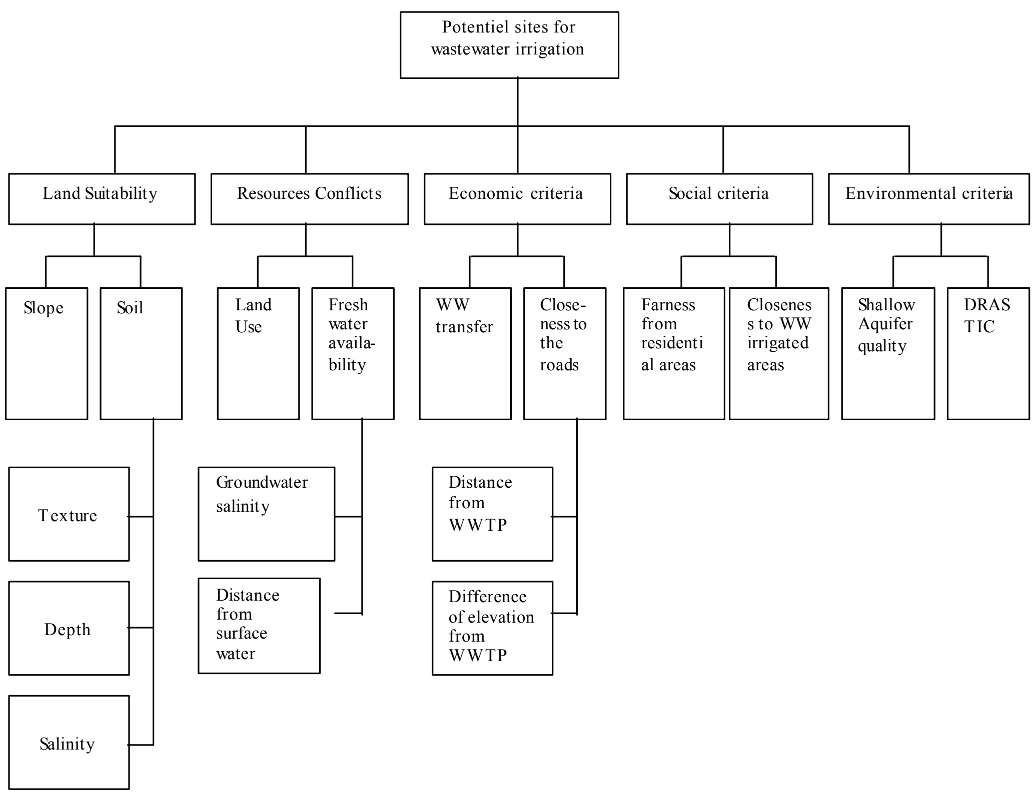

Fig. 2: Decision hierarchy structure.

Table 2: Hierarchy weights for potential irrigation wastewater sites

Main Criteria	Sub Criteria 1	Sub Criteria 2	Total weight
Land suitability for irrigation *w=0.2*	Soil *w=0.83*	Texture *w=0.33*	0.05478
		Depth *w=0.33*	0.05478
		Salinity *w=0.33*	0.05478
	Slope *w=0.17*		0.034
Resources conflicts *w=0.2*	Availability of other sources of water *w=0.5*	Groundwater *w=0.1*	0.01
		Distance from Surface water *w=0.9*	0.09
	Land Use *w=0.5*		0.1
Economic critria *w=0.2*	Wastewater transfer *w=0.9*	Difference of elevation from WWTP *w=0.5*	0.09
		Distance from WWTP *w=0.5*	0.09
	Closeness to the roads w=0.1		0.02
Social criteria *w=0.2*	Farness from residential areas *w=0.13*		0.026
	Closeness to the current irrigated areas by WW *w=0.87*		0.174
Environmental criteria *w=0.2*	DRASTIC *w=0.83*		0.166
	The aquifer current pollution *w=0.17*		0.034

In order to rank the suitability of a given area, a weight for each sub-criterion is assigned. Weighting expresses the criterion degree of relevance or preference relatively to the others. The process is achieved through the pairwise comparison between the elements for each hierarchical level [27]. Indeed, a pairwise matrix for the main decision criteria is obtained. Five other pairwise matrixes are obtained for level 3 and three others for level 4.

The pairwise comparison employed a semantic 9-point scale for the assignment of priority values where 1, 3, 5, 7 and 9 correspond respectively to equally, moderately, strongly, very strongly and extremely important criterion when compared with another. 2, 4, 6 and 8 are intermediate values. The assignment of preference values are based upon experts consulting and reviewing of international published guidelines and technical documents. Then each matrix consistency is checked out through the calculation of consistency ratio (c_r) which is defined as the quotient between the consistency index (c_i) and the random index (r_i) as follows:

$$c_r = \frac{c_i}{r_i}$$

The consistency index (c_i) is determined using the following quotient:

$$ci = \frac{(\lambda_{\max} - n)}{(n-1)}$$

where λ_{max} the maximum value of eigenvector and n is the criteria number.

The random index (r_i) is obtained from a table established by Oak Ridge National Laboratory for matrix with rows going from 1 to 15 [27]. For c_r lesser than 0.1, the priorities assigned are considered satisfying, otherwise they are judged not consistent to generate weights and have to be revised and improved. The final weight for each sub criterion is calculated by the multiplication of the resulted weights of all the hierarchy levels (Table 2).

Sub-Criteria and Constraints Layering by GIS: Spatial analysis to identify suitable sites for irrigation with wastewater starts with representing each selected sub-criterion by a thematic layer in which each point takes a value or a qualification according to that criterion. In order to layer all the criteria, data are gathered from satellite images and official sources at different available forms (digital and hard copy maps, tables and charts). Then, they are analyzed and treated using GIS and geostatistical tools. Each layer is obtained in raster data model. The description of data sources and analysis procedures is detailed hereafter.

Spatial data on *soil texture*, *salinity* and *depth* are obtained from “La Carte Agricole” of Nabeul district, which is the Tunisian official source of agricultural spatial database. Data are already available in digital format with 1/50000 scale. *Slope* layer was derived from Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) with a 90m-resolution. *Land Use* was digitized using three Landsat TM images of 2009/2010, GoogleEarth data and Land use map of the year 2000 obtained from

"La Carte Agricole". *Distance from surface water* is obtained by digitizing from GoogleEarth map the hill reservoirs and hill dams used for irrigation. The vocation of these structures is given by CRDA [6]. A geospatial analysis is applied to get the minimum distance from these structures. *Aquifer salinity* is obtained by the interpolation of measured groundwater concentration of 35 wells [38]. Many deterministic and geostatistical methods (Inverse distance weighting, Radial basis functions and kriging) are tested while varying the number of measured points to use within the neighbourhood. The spline with tension using 17 neighbourhood points had the lowest root-mean-square prediction error when performing cross-validation. The smaller the root-mean-square prediction error is the closer the predictions are to their true values and better is the interpolation method [39].

Distance from wastewater treatment plants is obtained by visiting the WWTPs SE3 and SE4 and identifying their geographical location by a GPS. Then the distance layer from each plant is derived using a spatial operator. *Difference of Elevation* is obtained by subtracting the plant elevation from the SRTM DEM. *Closeness to the roads* is derived from the road layer using a proximity algorithm. The road layer is obtained from "La Carte Agricole" and updated using GoogleEarth. *Farness from residential areas* map is layered through digitization on screen the residential area from GoogleEarth image and then processing a distance algorithm. *Closeness to the current irrigated areas by TWW* is mapped using a proximity algorithm of the irrigated areas by TWW. These areas are identified and delimited using GoogleEarth maps, field visit and a joint consultation with the staff of "Groupement de Developpement Agricole" (GDA) of Mesaadi and Souhil. *Current quality of shallow aquifer* is obtained by Ordinary Kriging interpolation of measured groundwater nitrogen compounds concentration of 32 wells [38]. Many deterministic and geostatistical methods (Inverse distance weighting, Radial basis functions and kriging) are tested while varying the number of measured points to use within the neighbourhood. The Inverse quadric using 15 neighbourhood points had the lowest root-mean-square prediction error when performing cross-validation. To map *intrinsic vulnerability using DRASTIC,* seven layers are required, namely Depth to water, Soil media, Topography, net Recharge, Impact of vadose zone, Aquifer media and hydraulic Conductivity. Depth to water, Soil media and Topography are obtained using the same data as explained above. Net recharge is performed using Williams and Kissel method [40]. This method requires climatologic data, obtained from meteorological stations in the region from 1952 to 2005 and soil data gotten from "La Carte Agricole". The impact of vadose zone is mapped through assembling and digitalizing on screen three scanned geological map sheets at 1/50000 scale. Aquifer media is obtained from 24 logs distributed inside the study area and 6 outside. A proximity operator is applied to expand the information all over the study area. The hydraulic conductivity is obtained from the data contained in the logs, assigning to each lithology the corresponding hydraulic conductivity value according to Freeze and Cherry [41] and Rodriguez *et al*. [42].

On the other hand, for each constraint, a Boolean map is obtained in which all area meeting the condition of suitability is coded 1 and the remaining area is coded 0. The constraints map is performed combining all Boolean maps by means of intersect operator. Then, a site is considered suitable for wastewater irrigation when it fulfils the suitability of all the constraints. The result is a map which contains all potential sites suitable for wastewater irrigation related to these constraints.

Sub-Criteria Standardization: The process of potential wastewater irrigation sites choice deals with sub-criteria of heterogeneous types (qualitative and/or quantitative), different forms (continuous or discrete) and different domains of measurement. In order to combine these heterogeneous data, it is crucial to standardize all sub-criteria by bringing them into a common domain of measurement. Thus, pixel values of all sub-criteria raster layers are transformed on a scale of suitability ranging from 0 to 255 using fuzzy membership functions to support soft decision-making. Sub-criteria values are processed differently depending on their continuous or discrete form. For continuous criteria, such as slope, aquifer depth, groundwater salinity and distances from WWTP, values are stretched over 0-255 interval using increasing, decreasing or symmetric sigmoid function where 0 is assigned to the least suitable for wastewater irrigation and 255 to the most suitable. For discrete values, soil texture, depth, salinity and land use, the classes are grouped relatively to their capacity to be irrigated by TWW. Then, their weights are assigned to each class by means of Saaty matrix [43]. The obtained weights are stretched linearly from 0 to 255.

Table 3: Suitable area in (ha) and in% obtained for each constraint and the conjunction between them. UNCLEAR TITLE, PLEASE EXPLAIN THE RELATION BETWEEN THESE CRITERIA AND THE PRESENTED PERCENTAGES

Constraint	Suitable area (ha)	%
Soil texture	35160	96%
Soil salinity	34847	95%
Soil depth	18643	51%
Slope	32848	90%
Land use	20508	56%
Distance from urban area	30135	82%
Aquifer vulnerability	36543	100%
Total	11426	31%

The Composite Decision Value Calculation: A final composite map of the study area is obtained by calculating the composite decision value (R_i) for each pixel (i) as follows:

$$R_i = \sum_k w_k r_{ik}$$

where w_k is the multiplication result of the weights of all the hierarchy levels (Table 3) and r_{ik} the standardized value of the pixel i in the map of the sub-criterion k.

R_i varies between 0 and 255 where 0 is the least suitable value for wastewater irrigation and 255 is the most suitable value.

RESULTS AND DISCUSSION

Suitable Areas Identification: The total suitable area for irrigation by TWW, obtained from the multiplication of the constraints, occupies 11426 ha which corresponds to 31% of the total watershed area (Table 3). This constitutes quite a large area that can absorb all the amount of treated wastewater and contributes to increase the agricultural production of the region. The total suitable area is made by enclaves ranging from less than 1 ha to more than 1000 ha, sketched out mainly by the most restrictive constraints, namely *soil depth* and *land use*. The total unsuitable areas meeting these constraints represent 49% and 44%, respectively.

The remaining constraints limit the unsuitable area to less than 18% of the watershed, being the least restrictive *aquifer vulnerability*. These suitable sites have various characteristics. They are located inside and outside agricultural areas, with different distances from WWTPs and urban areas and present a large interval of slopes and soil textures, etc.

Suitable Areas Ranking: The composite decision values (R_i) used to rank the 11426 suitable areas for treated wastewater irrigation varies from 124 to 231. The suitability map for reclaimed water is presented in Fig. 3.

The most extended area corresponds to the interval [150-170] with 41% of the total area followed by [170-190] with 30% then [0-150] and [190-210] with 14% and 12% respectively. The less extended is the interval > 210 with 2% of the total area..

Location of the Best Required Land: As previously estimated, the total areas requiring to be irrigated by SE4 treated wastewater is 566 ha. The best areas among the 11426 ha suitable sites, are those having the highest scored composite decision values. To cover the required 566 ha the R_i should go down from 231 to 207.

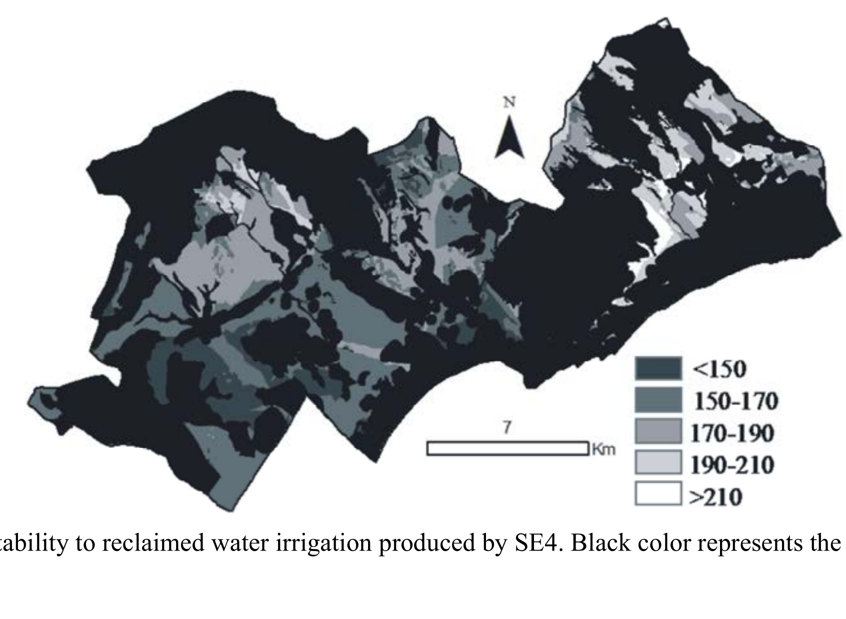

Fig. 3: Map of suitability to reclaimed water irrigation produced by SE4. Black color represents the unsuitable area.

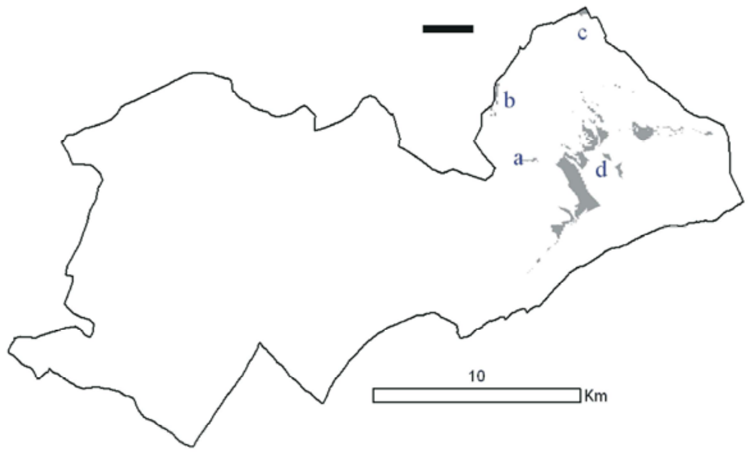

Fig. 10: Maps of best suitable areas for irrigation able to receive SE4 effluent to the horizon of 2025.

The best-suitable areas are made up by one big plot and some scattered ones, most of them located at North West of Nabeul city and adjacent to the already irrigated area by TWW (Fig. 4). These plots are 1–12 km far from SE4 and 200 m to 3500 m far from residential areas. They are located in agricultural zones partially irrigated by groundwater while the other part contains non-irrigated olive trees and cereal crops. These plots are easily accessible, mostly located in a flat non-saline zone and deep soils. The aquifer vulnerability in these zones is low.

This map shows that the selected suitable 566 ha are highly dispersed. In practice irrigating so many scattered small pieces is very costly. It is mandatory grouping these plots in two or three big ones to be cost-effective so that water conveying fees decrease and irrigated districts management becomes easier. These plots are grouped visually and through checking the R_i values of the replaced areas. For instance, the small and scattered plots a, b and c are replaced by the plot d, assuring a slight difference between R_i values of these replaced plots (Fig. 4).

Fig. 10. Maps of best suitable areas for irrigation able to receive SE4 effluent to the horizon of 2025. PLEASE UNITE THE TERM EFFLUENT OR TRATED OR RECLAIMED WASTEWATER

CONCLUSIONS

In the present work, a single-objective AHP integrated with a GIS was carried out to identify and rank potential sites for irrigation with treated wastewater in the Nabeul-Hammamet aquifer watershed. Many criteria were selected, taking into account technical, environmental, social and economical aspects.

Constraints analysis shows that 31% of the Nabeul-Hammamet aquifer watershed is suitable for irrigation by TWW, which exceeds the required land for the reuse of the total SE4 outflow. Soil depth and land use represent the most restrictive constraints whereas aquifer vulnerability is the least constraining. Ranking these suitable sites, using AHP integrated in a GIS, reveals that the best sites are close to the already irrigated districts by treated wastewater, which underlines the role that these districts may play in encouraging neighbouring farmers to change their attitude towards TWW and to accept it as an alternative resource for irrigation.

This methodology uses available and easy-to-get data from Tunisian official institutions and satellite images. Hence, it is easily extendable to other Tunisian regions and other countries.

This work constitutes a helpful technical support for decision-makers for a better integrated water management in the Nabeul-Hammamet aquifer watershed. Further developments could be achieved by multi-objectives analysis, including other options to reuse treated wastewater such as shallow aquifer recharge or urban green spaces watering.

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