

# GIS-based multi-criteria analysis for potential wastewater aquifer recharge sites

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## Abstract

GIS and expert knowledge are used as a decision support system to determine adequate potential soil aquifer treatment (SAT) sites for groundwater recharge of Hammamet–Nabeul aquifer located in ‘Cap Bon’ peninsula in North East of Tunisia. These sites are identified using a single-objective multi-criteria analysis. All criteria selected are assumed to be constraints. The acceptable range of each criterion is determined by a critical threshold value, corresponding to standards or normative statements. Based on these acceptable ranges, all criteria are expressed in a Boolean map: excluded areas are coded 0 and those open for consideration are coded 1. Multi-criteria evaluation were performed combining all Boolean maps by means of intersect operator in order to select sites meeting all the criteria. The selection of criteria and acceptable ranges is based on national expert consulting and international published guidelines and technical documents. The resulting map of this GIS-based multi-criteria analysis shows extended potential sites for SAT, exceeding 1000 ha, which indicates a possible use of treated wastewater for groundwater recharge; 8 ha could be supplied by Hammamet Sud plant, 764 ha by SE3 and 347 ha by SE4. 109 ha of these areas could be supplied by both SE3 and SE4. These potential sites are mostly located at rivers banks, around Grand-Nabeul urban area and in some agricultural domains and coastal dunes.

*Keywords:* GIS; Multi-criteria; Soil aquifer treatment; Wastewater reuse

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## 1. Introduction

Water resources scarcity constitutes a major problem in almost all agriculture areas in

Tunisia. Certainly, since 1960, a big effort has been deployed for hydro-agricultural development, which allowed mobilizing 88.5% of 4.84 billions m<sup>3</sup> potential water resources in 2005 [1,2]. However, taking into account the increase in water needs, groundwater overexploitation

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(105.4% of 0.74 billion m<sup>3</sup> potential shallow groundwater) and resource vulnerability to long drought periods, the occasional deficit affecting the offer-demand equilibrium tends to be chronic [3].

At most Tunisian regions, irrigation is subject to problems as groundwater overexploitation, river beds drying, frequent decreases of dams' replenishment rates and water resources salinization, contamination and usage conflicts. Thus, classic water management and traditional regulating approaches have reached their limits. The current situation needs an integrated approach to manage the fresh and non conventional water resources use. In as much as the latter reaches a volume of 200 millions m<sup>3</sup> in 2005 and is tending to increase [1,2].

Hammamet–Nabeul area has one of the Mediterranean coastal aquifers mostly threatened by groundwater use. Indeed, pumping rate can reach 175% in some cases [1]. Many remedial measures were taken to face this threat as prohibition of new wells construction (since 1946, it was decreed as safeguard region) and North water adduction to the region by the Mejerda open Channel. However, more efforts are needed to reach a secure groundwater level.

The study area and its vicinity, corresponding to the limits of Hammamet–Nabeul aquifer, contain three wastewater treatment plants (WWTP) with a total treatment capacity of 28,976 m<sup>3</sup>/day. This treated wastewater is regularly available and its amount follows the urban and tourism development trend. Its reuse for the recharge of the local aquifer could increase the available groundwater and improve also the quality of the wastewater disposed through filtration. Unfortunately, almost all of the wastewater produced is discharged to the sea or wadi (only 21% is reused in agriculture).

Near Nabeul city at Souhil Wadi region, a pilot project of treated wastewater by soil aquifer treatment (SAT) technique has been implemented in order to study the capacity of this technique to safely recharge the aquifer. The results obtained

show the effectiveness of the method in respect to groundwater level improvement. However the technique success is strongly related to an appropriate site selection, correct design and continuous maintenance.

This work aims at identifying potential sites for SAT for groundwater recharge of Hammamet–Nabeul aquifer by GIS-based single-objective multi-criteria analysis. GIS techniques were used and integrated in a multi-criteria analysis to benefit of its capacity to elaborate and to analyse spatial data. It constitutes the first step, prior to field investigations, in the process of implementation of SAT basins in order to avoid additional efforts and expenses. Employing this method, engineers will be able to subsequently carry out more detailed studies that 'fine-tune' the implementation of a SAT system [4].

## **2. Case study area**

The case study area corresponds to Hammamet–Nabeul aquifer limits. It is located at 'Cap Bon' peninsula at the North Eastern part of Tunisia and belongs to Nabeul District (Fig. 1). It covers 195 km<sup>2</sup> of surface area, 34 km long and a width ranging from 8 to 14 km. The climate is semi-arid with 400 mm as mean annual precipitation at Nabeul city, and 19°C as mean temperature. The altitude varies between 200 m and 0 m. Geologically the region is Pliocene and Quaternary, mainly composed by sandstones, conglomerates and clay. The depth of the aquifer varies between 4 and 31 m. Dominant economic activities are tourism and agriculture with some agro-industries. Three wastewater treatment plants are operating in the area, called SE3 and SE4 for Nabeul and "Hammamet Sud" for Hammamet City. Table 1 presents the characteristics of these plants.

## **3. Methodology**

For the identification of treated wastewater SAT potential sites for Hammamet–Nabeul

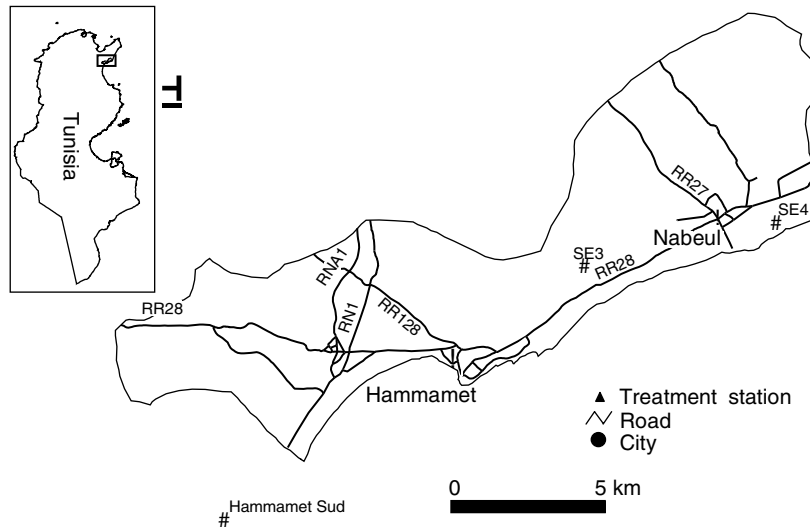


Fig. 1. Location of main cities, roads and WWTPs in the study area. Aquifer limits were taken from Ref. [10].

aquifer recharge, we applied a single-objective multi-criteria analysis methodology involving the following major steps: (i) identification of criteria and of their suitable ranges for SAT; (ii) Collection of necessary geographic data; (iii) Spatial representation of the criteria using GIS tools; (iv) Obtaining Boolean maps of each criterion; (v) Calculation of the composite decision criterion for all potential sites.

### 3.1. Criteria and acceptable ranges

Various sustainability criteria are found in literature [4–7]. The differences originate from

the various goals and scopes of the researches as well as the various sustainability principles on which the selection of criteria is based. Sustainability criteria often used are based on end user-technology-environment-interactions, where environment includes physical, economic, social and cultural environments [5].

Taking into account this general scheme, we defined three sets of criteria:

- *technical criteria* including soil and ground-water characteristics,
- *economic criteria* such as affordability and costs,
- *environmental criteria* covering urban management and fresh water resources vulnerability.

Table 1  
Characteristics of WWTPs located in the study area and nearby (from National Sewerage Authority)

	Year of operation	Nominal flow rate (m <sup>3</sup> /d)	Pollutant load (kg BOD/d)	Person equivalent	Treatment technique
Hammamet Sud	1995	11,386	2722	76,000	Extended aeration activated sludge
SE3 Nabeul	1979	3500	720	23,243	Oxidation ditches
SE4 Nabeul	1979	9585	5870	81,400	Mean load activated sludge + anaerobic digestion

Being aware of the importance of the selection of criteria affecting the site choice process, we adopted the most critical aspects but when we considered the sub-criteria in each aspect, we selected only these which have easy to get data. For instance, in the technical criteria, as done by US Environmental Protection Agency [6] we include consideration of soil and groundwater conditions, grades, existing land use and flood potential. For the economic factors, we take into account costs related to pumping from the community to the SAT site. All these criteria are considered as constraints. An acceptable range of each criterion regarding feasibility of SAT was set by critical threshold values, corresponding to standards. These normative statements are gathered after consulting national experts and reviewing international guidelines and technical documents published especially by [6,8–13].

### 3.1.1. Technical criteria

Five technical criteria were considered: slope, soil texture, soil salinity, geology and aquifer depth.

- (1) Slope: Infiltration percolation plant site should be feasibly constructed in slope ranging between 0 and 12%. Higher slopes increase runoff, soil erosion and thus soil instability, which risks basin safety and increases refilling costs.
- (2) Soil texture: Suitable soils should have a very low clay fraction in order to firstly be permeable enough to allow wastewater infiltration and secondary perform good complementary wastewater purification. In this respect, soils with greater than 10% clay fraction would exclude SAT construction.
- (3) Soil salinity: Suitable soils must have salinity under 4 mmhos/cm in order to avoid aquifer salinization by leaching.
- (4) Geology: Suitable site must have enough permeable subsoil with low salty layers in

order to permit wastewater to reach the aquifer with low salinity.

- (5) Aquifer depth: Suitable site must have static groundwater level at least 5 m depth in order to have a sufficient vadose zone for wastewater purification. With this minimum aquifer depth, we expect overcoming aquifer mounding regardless of its transfer rate.

### 3.1.2. Environmental criteria

Three environmental criteria were considered affecting SAT site suitability: distance from urban agglomerations, tourist areas and hill reservoirs. A safeguard distance of at least 200 m of urban agglomerations and tourist areas has to be respected in order to avoid direct contact with human settlements, and a safeguard distance of at least 500 m of hill reservoirs to avoid their possible contamination by wastewater infiltration.

### 3.1.3. Economic criteria

The economic criteria considered include water transfer costs (adduction and pumping) from wastewater treatment plant to SAT basins. The first criterion is how far is the potential site to WWTPs? This reflects necessary pipe length in meters and afferent costs to convey wastewater from source to destination. The economic feasible distance must not exceed 8 km. The second criterion is how the potential site is elevated regarding WWTPs? This criterion reflects the necessary wastewater pumping devices and related costs. The economic feasible elevation difference must not exceed 15 m.

## 3.2. GIS analysis

Spatial analysis for suitable SAT sites identification is realised through a representation of each selected criterion by a thematic layer. Each point in this layer takes a value or a qualification according to that criterion. The layers were

derived from geographical data obtained from official sources or generated using satellite images, GIS and geostatistical tools. ArcView software is used for visualisation, treatment and analysis of these spatial data. Description of data sources and analysis procedures is presented hereafter.

Slopes were derived from Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) 90-m resolution after its projection from geographic to UTM Carthage. The study area was firstly clipped and reclassified into two categories: one with values less than 12%, coded 1 and another with higher values coded 0. Then we applied a  $5 \times 5$  majority filter in order to smooth the distribution and to discard sites with significant and numerous changes in relief that increase significantly costs. The raster layer obtained is converted to vector format (Fig. 2a).

Soil texture and soil salinity spatial data were obtained from “La Carte Agricole” of Nabeul district, which is an official source of agricultural spatial database. Data are in digital format with UTM Carthage projection and 1/50,000 scale. The soil texture map of the study area was clipped and all polygons with very low clay fraction (sand and sandy-loam) were assembled together and coded 1. The rest of polygons were coded 0 (Fig. 2b). By the same procedure, the region soil salinity map was clipped and all polygons with salinity less than 4 mmhos/cm, open for consideration, were assembled and coded 1 and the rest of polygons were coded 0 (Fig. 2c).

Geological data were obtained by digitalizing on screen two scanned official map sheets covering the study area. The scale of these maps is 1/50,000. Then, all polygons of stream sediments, Miocene sand, dune sediments and Pliocene sand were assembled and coded 1. The rest of the area, coded 0, was excluded from consideration (Fig. 2d).

For aquifer depths, 37 wells and piezometers has been considered. In order to draw the isolines, we tested several deterministic and geostatistical methods (completely regularized spline

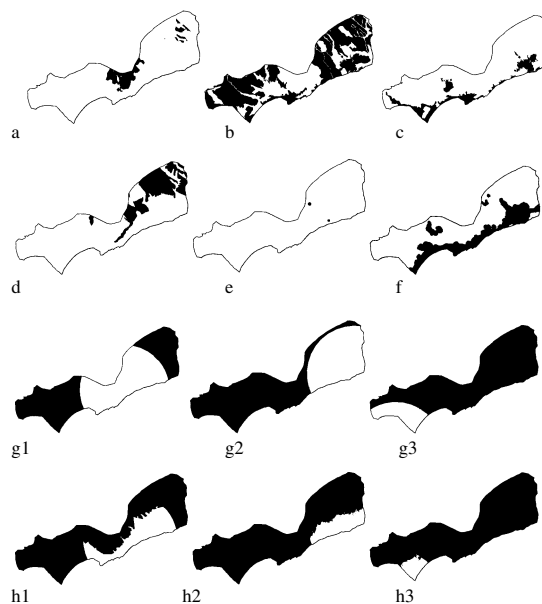


Fig. 2. Suitable area according to the criterion (a) slope; (b) soil texture; (c) soil salinity; (d) geology; (e) aquifer depth; (f) distance to residential areas and fresh water resources; (g1) distance from SE3; (g2) distance from SE4; (g3) distance from Hammamet Sud; (h1) difference in elevation from steps SE3; (h2) difference in elevation from steps SE4; (h3) difference in elevation from steps Hammamet Sud. White color presents the suitable area and the black the unsuitable.

interpolation (CRSI), inverse distance weighting, Radial basis functions and kriging). CRSI that has the lowest root-mean-square prediction error when performing cross-validation has been adopted. Indeed, the smaller the root-mean-square prediction error the closer the predictions are to their true values and better is the interpolation method [14].

Urban and tourist areas and hill reservoir maps were obtained by digitising on screen Landsat ETM 2001 image using RGB 453 false colour. A 90 m perimeter buffer zone from these areas, coded 0, was determined. Code 1 was assigned to the rest of the area (Fig. 2f).

The map of distances and elevations from wastewater treatment plants was obtained as follows: we visited SE3, SE4 and Hammamet

Sud plants, and registered their coordinates by GPS. Then, we introduced these coordinates in Arcview and converted them to point layer in UTM Carthage projection. Elevation of each point was taken from SRTM DEM. A buffer of 8 km was applied to each point. Inside this buffer, each area which is elevated less than 15 m over the WWTP altitude is considered suitable for infiltration percolation and coded 1 and the rest is coded 0 (Fig. 2g and h).

### 3.3. Multi-criteria evaluation

Multi-criteria evaluation was performed combining all Boolean maps by means of intersect operator in order to let all sites meeting the matching criteria. Indeed, a site will be considered suitable for SAT if it fulfils all technical, environmental and economical criteria. The result is a map which contains all potential sites suitable for SAT related to each WWTP.

### 3.4. Validation

The map was evaluated using Souhil Wadi pilot site for SAT, located near Souhil stream at 2 km from Nabeul city. The water table there is around 10 m in depth. Site lithology consists of unconsolidated sand and gravel at upper layers and consolidated silt and clay beds substratum [15,16]. Permeability in saturated state varies from  $10^{-4}$  to  $10^{-5}$  m/sec for sand and gravel and less than  $10^{-9}$  m/s for silt and clay [16,17]. Supplied by SE4 treated wastewater, the pilot plant is composed of four square SAT basins with area varying from 330 to 347 m<sup>2</sup>.

## 4. Results and discussion

The multi-criteria analysis resulting map identifies a total area suitable for wastewater SAT of about 1011 ha, representing 5% of the aquifer limit under study. This constitutes a quite large area which can absorb big amounts of treated

Table 2  
Suitable areas obtained for each criterion

Criterion	Area (ha)	% From the total area
Slope	17,874	92
Soil texture	7850	40
Soil salinity	17,147	88
Geology	15,492	79
Aquifer depth	55,938	99
Urban, tourist and hill reservoirs area	15,505	73
Distance from WWTPs	14,956	77
Difference in elevation with WWTPs	6218	32
Total	1011	5

wastewater and contributes significantly in Nabeul–Hammamet aquifer recharge. Suitable sites involve different areas with diverse landscapes: rivers banks, around Grand-Nabeul urban area, agricultural domains and coastal dunes. They are scattered into plots varying between 0.01 and 256 ha.

Economic and soil texture are the most restrictive criteria to wastewater SAT. The total areas meeting these two criteria represent only 32% and 40% respectively of the total Nabeul–Hammamet aquifer catchment. Aquifer depth is the less restrictive criterion fulfilled by more than 99% of the study area. The rest of criteria are met by 73 and 92% of the area (Table 2).

In regard to results by WWTP (Fig. 3), only 8 ha could be supplied by Hammamet Sud plant. Indeed, this plant is outside the study area and the nearest landscape is mainly saline, urban or tourist area. SE3 could supply the highest area (764 ha) because of its location in the middle of the study area and its high elevation (26 m above sea). A relative smaller area (347 ha) could be fed by SE4 since it is situated at about 2 km from study area east limit and has low elevation (6 m above sea). About 109 ha of these areas could be supplied by both SE3 and SE4.

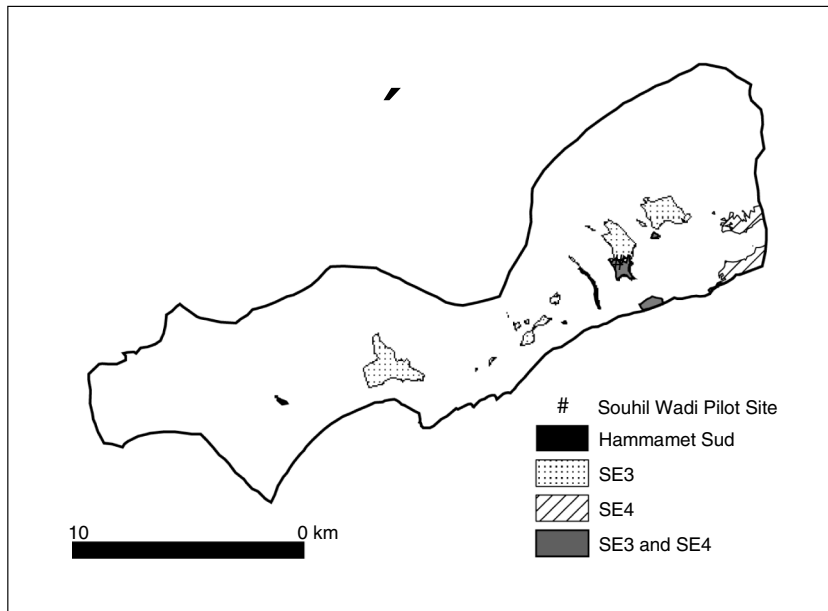


Fig. 3. Potential sites for infiltration percolation related to WWTPs and location of the Souhil Wadi pilot plant.

As pointed out in Fig. 3, Souhil Wadi pilot plant fits in a potential site for wastewater SAT supplied by SE4, which is a preliminary results validation.

When we estimate the land requirements for recharging the aquifer by treated wastewater produced by all the WWTPs, using the design methodology introduced by Kallali et al. [16], we obtain a total required area of 115 ha split by WWTP as follows: 53 ha for Hammamet Sud, 17 ha for SE3 and 45 ha for SE4.

Matching these results with suitable areas for each WWTP, we notice that Hammamet Sud needs more area than available whereas SE3 and SE4 need quite lower area. Thus, for Hammamet Sud case, we can either check the availability of sites at the nearby region of Bouficha — not included in the study area — or use the available 8 ha for recharge and reuse directly the remaining treated wastewater in agriculture. Otherwise economical sub-criteria thresholds should be extended in respect to social development and environmental sustainability. The revised distance (more than 8 km) could be determined by the

decision maker according to the investment cost he is willing to concede. For SE3 and SE4 cases, we can attempt to determine the most suitable area among the identified ones or set recharge purposes priority: suitable shore lands could be used to mitigate existing marine intrusion problem, whereas pieces of land near irrigated area permit easy uptake of the groundwater for unrestricted irrigation.

In implementing these technical options, we have to bear in mind that although the percolate from SAT systems is of high quality, it may not in some cases satisfy all factors in state groundwater requirements. In these situations, we have to either design for percolate recovery or demonstrate via a hydrogeological survey and analysis that all of the percolate will not adversely impact the in-situ aquifer [3].

## 5. Conclusions and perspectives

In this work a single-objective multi-criteria analysis was carried out to identify potential sites for SAT technique. Many criteria were selected

which have technical, environmental, social and economical aspects. Soil type and economical criteria were the most restrictive and the aquifer depth the less restrictive one.

An important area was suitable for infiltration percolation (<1200 ha), which exceeds the needed area to absorb the total treated wastewater of SE3 and SE4 WWPTs (located inside the study area), and covers a part of the needed area for Hammamet Sud plant (located at 4 km from the study area). Being situated near coasts and irrigated areas, potential sites can be used to mitigate existing marine intrusion problem facing Nabeul–Hammamet aquifer and increase groundwater availability for irrigation by pumping.

To select, among the suitable area, best wastewater SAT sites for SE3 and SE4 further work is needed: ranking potential areas according to their suitability and considering other activities that compete with SAT for land, such as irrigation and bathing.

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