

Article

Using a Mamdani Fuzzy Inference System Model (MFISM) for Ranking Groundwater Quality in an Agri-Environmental Context: Case of the Hammamet-Nabeul Shallow Aquifer (Tunisia)

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Abstract: Using an adaptive Mamdani fuzzy inference system model (MFISM), the purpose of this paper is mainly to assess and rank the assessment and ranking of water quality for irrigation occurring in the Hammamet-Nabeul (Tunisia) shallow aquifer. This aquifer is under Mediterranean climate conditions and affected by intensive and irrational agricultural activities. In the current study, the Mamdani fuzzy logic-based decision-making approach was adapted to classify groundwater quality (GW) for irrigation. The operation of the fuzzy model is based on the input membership functions of electrical conductivity (EC) and sodium absorption ratio (SAR) and on the output membership function of the irrigation water quality index (IWQI). Validation of the applied MFISM showed a rate of about 80%. Therefore, MFISM was shown to be reliable and flexible in quality ranking for irrigation in an uncertain and complex hydrogeological system. The results demonstrated that water quality contamination in the aquifer is affected by the overlaying of three types of negative anthropogenic practices: the excess use of water for irrigation and chemical fertilizers, and the rejection of partially treated wastewater in some areas. The implemented approach led to identifying the spatial distribution of water quality for irrigation in the studied area. It is considered a helpful tool for water agri-environmental sustainability and management.

Keywords: groundwater; Mamdani fuzzy inference system model; MFISM; USSL diagram; irrigation water quality index; treated wastewater; agri-environmental; Hammamet-Nabeul shallow aquifer; Tunisia



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1. Introduction

Groundwater is a major contributor to abstraction for agriculture uses. In view of the increasing number of human populations, agricultural development is expected to aggravate the conflict between water supply and demand. Groundwater (GW) quality assessment is considered a very important component of water resources sustainability. Generally, the quality of GW is related to changes in its chemical composition, it is controlled by many factors, including the following: rock-water interactions, seawater intrusion, and water mixing between aquifers [1]. Along with these processes, water-borne pathogens and, toxic and nontoxic pollutants, are the major water quality parameters [2].

In addition, there is bad human behavior to ensure agricultural needs such as the intensive use of water for irrigation and the use of fertilizer applications in agricultural fields. The irrigation return flow concentrated the strong evaporation and by flushing of fertilizers can lead to degradation of water quality degradation [3,4].

Furthermore, the use of partially treated wastewater for artificial GW recharge of GW can lead to GW such as pathogenic and toxic contamination. However, this could be minimized by irrigation with well-treated wastewater [5]. In addition, the application of nitrogen as a fertilizer is well known throughout the world and its overuse has caused high nitrate concentrations of nitrates in aquifers [6]. Additionally, the high extraction rate of GW for irrigation can have dangerous effects in coastal areas, such as the risk of seawater intrusion. This is especially known in the Mediterranean regions, where there is a high water demand and dry periods. Because of uncertainties in measurement and analysis, a lot of effort was made to find a comprehensive and representative index for water quality. For this task, there are many indices: individuals such as SAR, EC, %Na, Permeability index (PI) and integrated parameters. The most widely used parameter is the Water Quality Index (WQI) [7,8], which is used to answer many questions about the quality of GW for irrigation [8–12]. However, this index suffers from several problems mainly when values with different distances from a boundary have the same effect on the final index score [13]. For this reason, growing attention has been paid to use Artificial Intelligence-(AI)-based approaches. Methods, such as neural networks, genetic algorithms, fuzzy logic, Fuzzy-AHP, and Fuzzy VIKOR method were proposed [14–16]. They seemed to be efficient because they can show a better ranking of GW quality.

Fuzzy logic was first introduced by L. Zadeh [17] and has become one of the most known approaches to be appropriate for developing environmental indices. These approaches can easily reflect human thoughts and expertise in the indices [18]. It also allows users to enter a wide range of parameter values, including both qualitative and quantitative variables. Indeed, the Fuzzy model led to the facilitating, identifying, representing, processing, performing interpretation, and using data and information that are vague and uncertain [13,16,19–26].

The case study focuses on Hammamet-Nabeul (HN) shallow aquifer which suffers from GW quality degradation, mainly, due to agricultural practices in the region. This aquifer was the subject of several previous studies that have—through different methods—highlighted many agri-environmental problems. For instance, Ben Moussa et al. [27–29] used hydrochemical, geochemical and isotopic approaches to identify the origin of both natural and anthropogenic mineralization in the study area. Anane et al. [30,31] applied the AHP-Multicriteria Decision analysis method for the selection of favorable sites for irrigation by treated wastewater. Anane et al. [28] also worked on the assessment of agricultural pollution from agricultural sources using GIS-based DRASTIC, the pesticide DRASTIC, and the susceptibility index. Furthermore, Trabelsi [32] and Trabelsi et al. [33] used geophysics methods to assess the marine intrusion phenomena.

Numerous processes are found to occur in the HN shallow aquifer. An attempt is made to determine the actual state and spatial distribution of each process in the aquifer. In addition to the combination of hydrochemical and statistical analysis used to assess factors that control the quality of GW quality for irrigation, the objective of the present study is to adapt a fuzzy model for irrigation water suitability that is representative of water quality with practical and easy parameters to measure.

2. Materials and Methods

Assessing GW quality for irrigation in HN shallow water is based on: (i) individual parameter calculation and (ii) the Mamdani Fuzzy Inference System Model (MFISM) vs. the classification method using United States Salinity Laboratory (USSL) diagram).

2.1. Study Area

The HN basin extending approximately 450 km² belongs to the Cap Bon peninsula, northeastern Tunisia. It is located between latitudes 40°40' and 40°60' North and longitudes 9°10' and 9°30' East, and it is bordered by the Grombalia basin in the North, by the oriental coastal plain in the East, by the Gulf of Hammamet in the South and by the Bouficha basin in the West. The study area is presented in Figure 1.

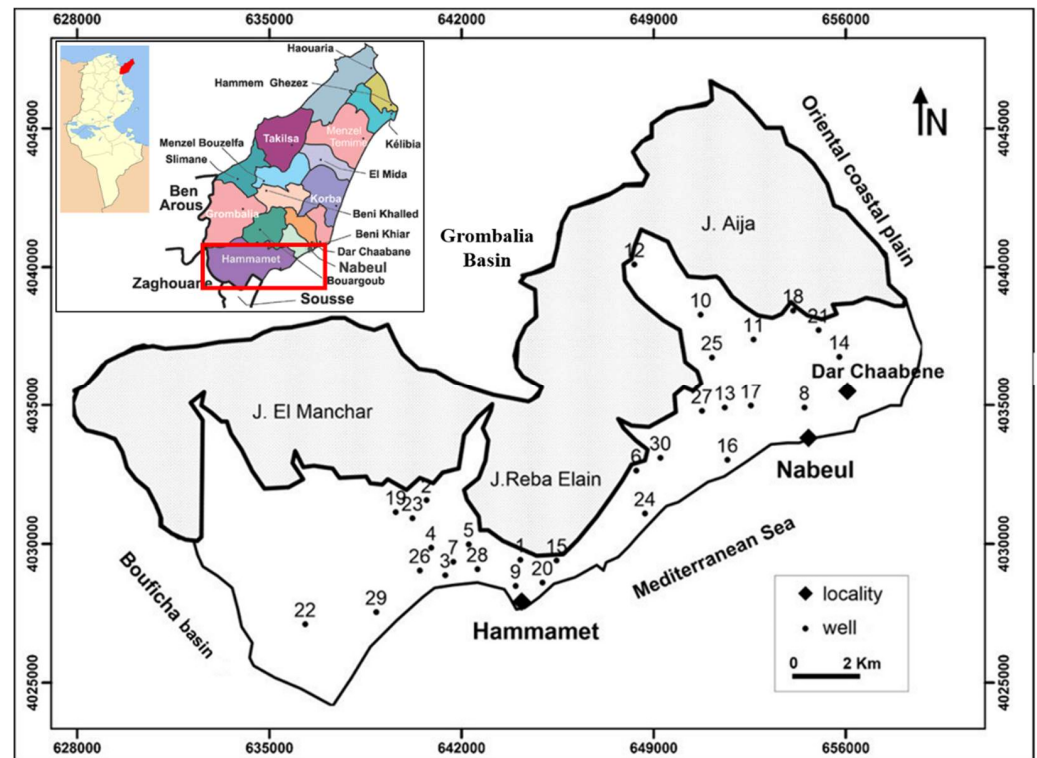


Figure 1. Location map of Hammamet-Nabeul shallow aquifer and groundwater sampling positions.

The climate of the study area is semiarid to arid, characterized by long hot summers and short cold winters with a mean annual rainfall of 425 mm. The potential evapotranspiration is approximately 1166 mm/year. The mean annual temperature is approximately 19° [29].

From a geological point of view, the oldest outcropping formations are in the lower Eocene age and the most recent are in the Quaternary age [34]. This later covers almost the entire basin with mainly sandy clayey deposits.

The HN region is limited by two main structures, the Oriental coastal plain in its eastern part and the Grombalia basin with NNW-SSE direction in its western part. These structures are the result of the movement between the African and the Eurasian plates [35]. The structures of the NE-SW fold are the result of the Pliocene–Quaternary tectonic activities. These are combined with E-W to N120 dextral reverse faults and NE–SW faults [35].

The HN main aquifers consist of four principal entities: the Plio-Quaternary aquifer, the Miocene aquifer, the Oligocene aquifer and the Eocene aquifer [32]. However, the most important regional shallow aquifer is the Plio-Quaternary, which covers an area of about 110 km² and is the purpose of this study. In fact, the thickness of this aquifer varies between 20 and 300 m and it is mostly sandy clayey as mentioned in the hydrogeological chart as presented in Figure 2 [32]. Hydraulic conductivity is between 0.5×10^{-5} m/s and 0.6×10^{-5} m/s, while transmissivity values range from 0.4×10^{-4} m²/s to 2.5×10^{-3} m²/s [27].

Age	Stage	Formation		Lithology	(aquifer/ substratum)
Quaternary	Holocene	Alluvions		sandy-silty deposits	Aquifer
		Agriculture soil		Sandy deposits	Aquifer
		screen of sand		Sandy pack	Aquifer
				Calcareous crust	
				Sandy limestone	
				Conglomerates sand and clay	Aquifer
				Clay, gravel, sand, sandstone	Aquifer
Pliocene	Upper pliocene			Sandy with sandstone bars	Aquifer
	Middle pliocene			Clayey deposits	Substratum
	Lower Pliocene	Yellow sand of Nabeul		Sandy deposits	Aquifer
		Potters clay		Clayey deposits	Substratum

Figure 2. Hydrogeological chart of the Plio-Quaternary reservoir.

The piezometric levels range from 0 to 55 m, as indicated in Figure 3. At the level of the HN plain, the recharge of the shallow aquifer is carried out by the direct infiltration of rainwater through the unsaturated zone. Wadis also contribute to the recharge of the water table by the surface water collected at the level of the border reliefs. The contributions of these wadis are important, in particular in the eastern part of the basin.

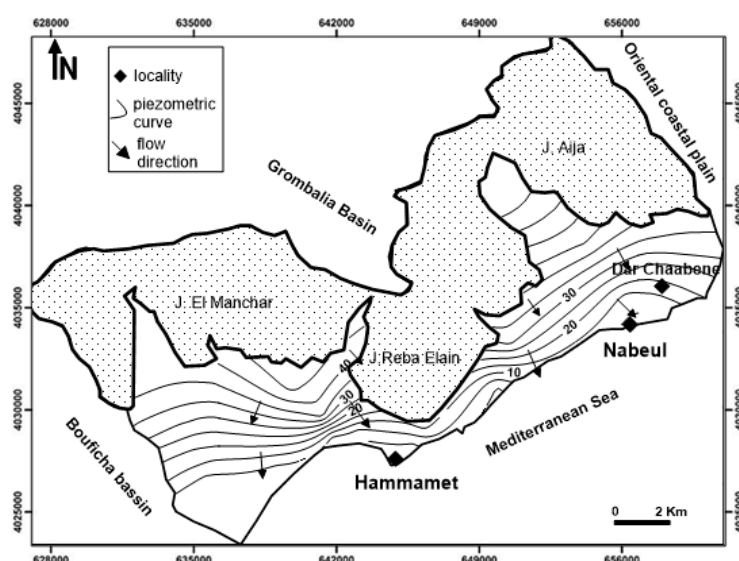


Figure 3. Piezometric map of HN shallow aquifer (2016).

2.2. Sampling and Chemical Analyses

To perform the present work, a total of thirty water samples from water wells tapping shallow aquifers are investigated (Figure 1). These wells are used by inhabitants or by the Regional Commission for Agricultural Development of Nabeul. The water samples were collected in two clean 0.5L bottles. All of the water samples were taken from the continuously used surface wells. In situ, the samples were measured for pH, EC, and temperature. Before laboratory analysis, the samples were stored at a temperature below 4 °C. The chemical analyses were performed in the Laboratory of Radio Analyses and Environment (LRAE) in the National School of Engineers (Sfax, Tunisia). Analysis of the main elements (Cl^- , SO_4^{2-} , HCO_3^- , NO_3^{2-} , Na^+ , Mg^{2+}) was performed using HPLC Waters equipped with IC-Pak TM CM/D columns for cations, using EDTA and nitric acid as eluent, and on a Metrohm chromatograph equipped with CI SUPER-SEP columns for anions, using phthalic acid and acetonitrile as eluent. Total dissolved solids (TDS) measurements were performed by evaporating 100 mL of groundwater sample at 105 °C for 24 h.

2.3. Individual Parameters

The quality of GW is studied through five indices such as in [8,36]: electrical conductivity (EC), permeability index (PI), sodium adsorption ratio (SAR), sodium percent (%Na) and magnesium hazard (%MH). The detail of each index is mentioned in Table 1.

Table 1. Individual criteria for classification of GW quality for irrigation (meq/L).

Quality Indices	Reference	Category	Range
EC ($\mu\text{S}/\text{cm}$) (measured in situ)	[7]	Low	0–250
		Moderate	250–750
		High	750–2250
		Very High	>2250
$PI = 100 \times \frac{[Na] + \frac{\sqrt{[HCO_3]}}{2}}{[Na] + [Ca] + [Mg]}$	(1) [37]	Suitable Moderate Unsuitable	>75% 25–75% <25%
$SAR = \frac{Na^{2+}}{\sqrt{([Ca^{2+} + Mg^{2+})/2)}} \times 100$	(2) [38]	Suitable Moderate Unsuitable	0–3 3–9 >9
$MH = \left(\frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \right) \times 100$	(3) [39]	Suitable Unsuitable and Harmful	<50% >50%
$Na^+ \% = (Na + K) \times 100 / (Ca + Mg + Na + K)$	(4) [37]	Good Permissible Doubtful Unsuitable	20–40% 40–60% 60–80% >80%

Firstly, the determination of salinity content is carried out by EC calculation in order to identify the effects on soil. Second, the PI, which is expressed in Equation (1), is used to assess the GW for irrigation. The excess sodium concentration in GW affects the properties of the soil and reduces the soil permeability; therefore, SAR should be calculated. This ratio, expressed in Equation (2), measures the risk of alkali–sodium for crops and informs about the tendency of water to cation exchange reactions in the soil. Third, MH, which is expressed in Equation (3), is one of the most important qualitative criteria for assessing the quality of GW quality for irrigation [7]. Excess magnesium affects soil quality and can decrease productivity [39]. Finally, the %Na presents a relevant factor to assess the water quality for agricultural purposes. This index is calculated according to Equation (4) which is expressed as the percentage of sodium and potassium compared to all cationic concentrations [40,41].

2.4. Fuzzy Logic Model Background

The Fuzzy Logic Model was introduced by Zadeh in 1965 [17] in order to create systems closer to human thinking. According to many previous works such as in [20,21] and [24], this method was proven to be efficient in treating complex systems under uncertain conditions.

A fuzzy controller system consists of three operations: fuzzification, inference and defuzzification as shown in Figure 4. In the Fuzzy Inference System (FIS), human knowledge is presented as a set of fuzzy linguistic rules that would make approximate decisions. In fact, the human expert can be replaced by a combination of a fuzzy rule-based system (FRBS) and a block called a defuzzifier.

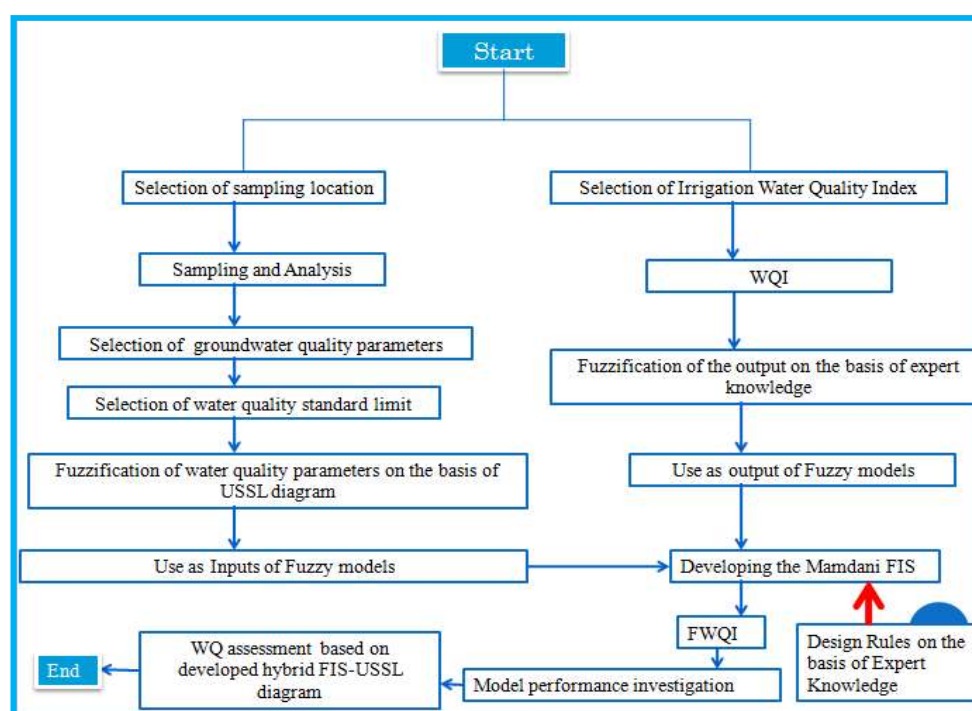


Figure 4. The proposed Fuzzy Model flowchart.

2.4.1. Fuzzification: Membership Functions

Fuzzification is the process of decomposing a system input and/or output into one or more fuzzy sets. A fuzzy set is defined in terms of a membership function that maps the domain of interest, e.g., concentrations of major elements, onto the interval [0, 1]. The shape of the curves shows the membership function for each set (it can be expressed in various forms such as trapezoidal, triangular, Gaussian, etc.). In fact, the membership function represents the degree, or weighting, that the specified value belongs to the set [24].

The membership function of set A defined over a domain X takes the form:

$$\mu(A): X [0; 1]$$

The set A is defined in terms of its membership μ function by the Equation (5)

$$\mu(A) \begin{cases} = 1, & \text{if } x \text{ is full member of } A \\ \in [0; 1] & \text{if } x \text{ is partial member of } A \\ = 0, & \text{if } x \text{ is not member of } A \end{cases} \quad (5)$$

The fuzzy set for a trapezoidal membership function f is developed according to Equation (6).

$$f(x, a, b, c, d) = \begin{cases} 0, & \text{if } x < a \text{ or } x > d \\ \frac{(a-x)}{(a-b)}, & \text{if } a \leq x \leq b \\ 1, & \text{if } b \leq x \leq c \\ \frac{(d-x)}{(d-c)}, & \text{if } c \leq x \leq d \end{cases} \quad (6)$$

In this work, a trapezoidal fuzzy logic function is used as in [14]. The trapezoidal curve (Figure 5) is a function of a vector, x , and depends on four scalar parameters a , b , c and d , as given by Equation (6). Parameters for membership function used in the fuzzy inference system are a and d located in the “feet” of the trapezoid and the parameters b and c located in the “shoulders”.

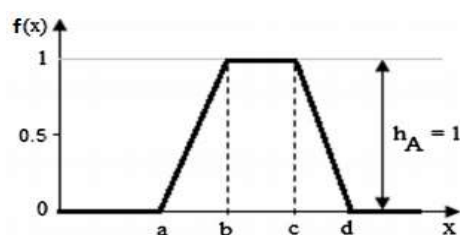


Figure 5. The trapezoidal curve.

2.4.2. Fuzzy Set Operations

Different fuzzy set operators are used in the development of different fuzzy-rule-based systems. There are three basic operators [15] include the following. (1) Intersection (AND), (2) Union (OR), and (3) Negation (NOT).

2.4.3. Inference Rules

The inference rules reflect the relationships between the subsets of the inputs and the outputs. Inferences rules should produce a new output subset. Each rule is composed of two parts: the “if” part and the “then” part. For more details about these rules, the reader can consult Ross [42].

2.4.4. Defuzzification

The defuzzification procedure is the final step in FIS processing. This process allows one to convert the results obtained as fuzzy sets into numerical values. The center of gravity, the average of the maximums and the smallest of the maximums are widely used as defuzzification methods [15].

2.5. USSL Diagram

The USSL diagram is a well-known diagram for classifying irrigation water [38,43]. This diagram shows both risk effects of sodium and salinity, using the SAR and the EC values as coordinates [38], the corresponding points are located on the diagram indicating the water quality class. Water samples are grouped into 16 classes as mentioned in Figure 6.

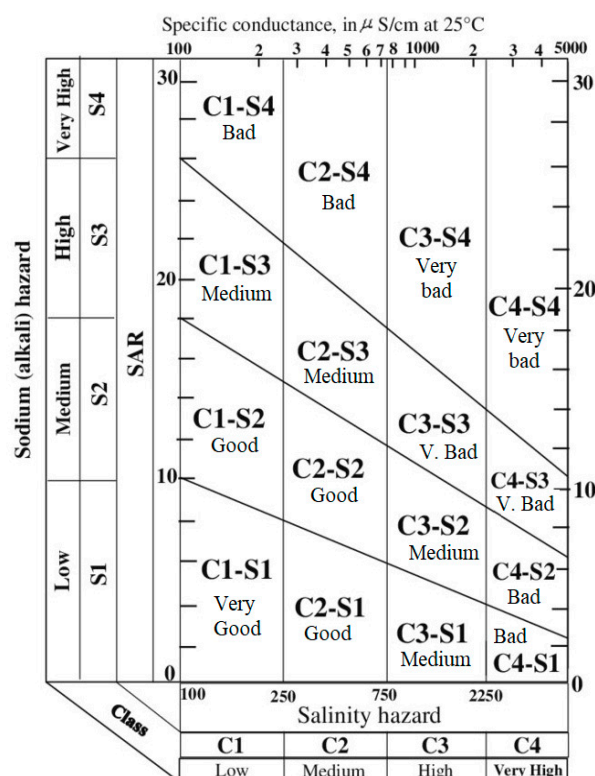


Figure 6. USSL Diagram for the classification of irrigation waters.

3. Results and Discussion

3.1. Hydrochemical Results

The results of the chemical analysis are summarized in Table 2. The ionic balance for all samples in this study is within 5%. The geochemistry of HN shallow water is dominated by sodium chloride (Na-Cl) and slightly (Ca-SO₄) facies (Figure 7). This is corroborated by saturation indices distribution (Figure 8).

Table 2. Descriptive statistics for 30 samples in the Hammamet-Nabeul shallow aquifer.

<i>n</i> = 30	Na (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	NO ₃ (mg/L)	SO ₄ (mg/L)	HCO ₃ (mg/L)
Max	770.3	202.8	360	938	347.2	1190.4	475.8
Min	51.1	25.2	40	68	0	57.6	183
Average	304.2	77.32	157.4	426.8	103.54	393.7	297.47
SD	188.94	43.89	86.84	253.55	94.75	317.66	71.61

In fact, all samples show negative indices with respect to mainly Halite and secondly gypsum, indicating undersaturation and dissolution of these minerals. Indeed, some samples show the dominance of sodium, which, for the vast majority, exceed 60% of the wells, while the others show a trend towards the mixed water type. On the other hand, the majority of the samples indicate the predominance of chloride whose grades can exceed 70% with a slight tendency towards the mixed water type. (Ca²⁺) can be affected by cation exchange and the calcite equilibrium [6]. Concentrations of Cl and partly SO₄^{2−} anions increase in the coastal aquifer, probably due to seawater intrusion.

Furthermore, the order of the relative abundance of major cations in GW of the shallow water of HN is Na⁺ > Ca²⁺ > Mg²⁺ their concentrations represent an average of 57%, 29%, and 14%, respectively. Concerning anions, the order of their contribution is Cl[−] > SO₄^{2−} > HCO₃[−] > NO₃^{2−} with percentages of 35%, 32%, 24% and 9%, respectively.

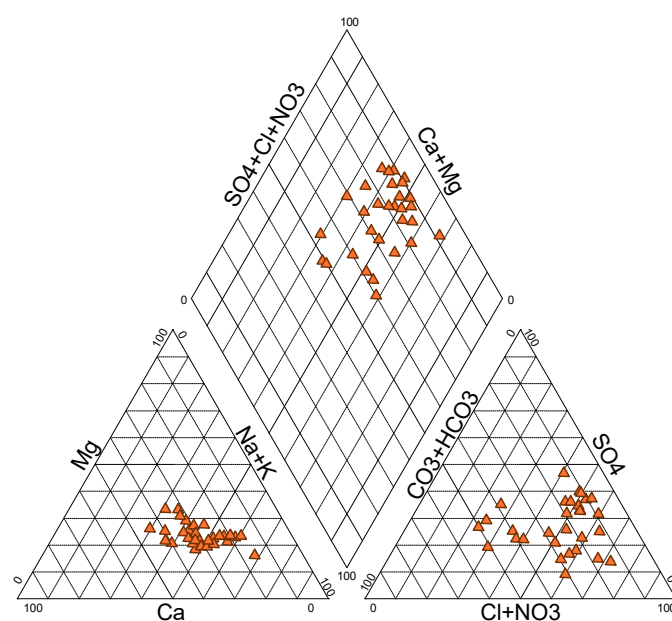


Figure 7. Piper diagram for groundwater samples from the study area.

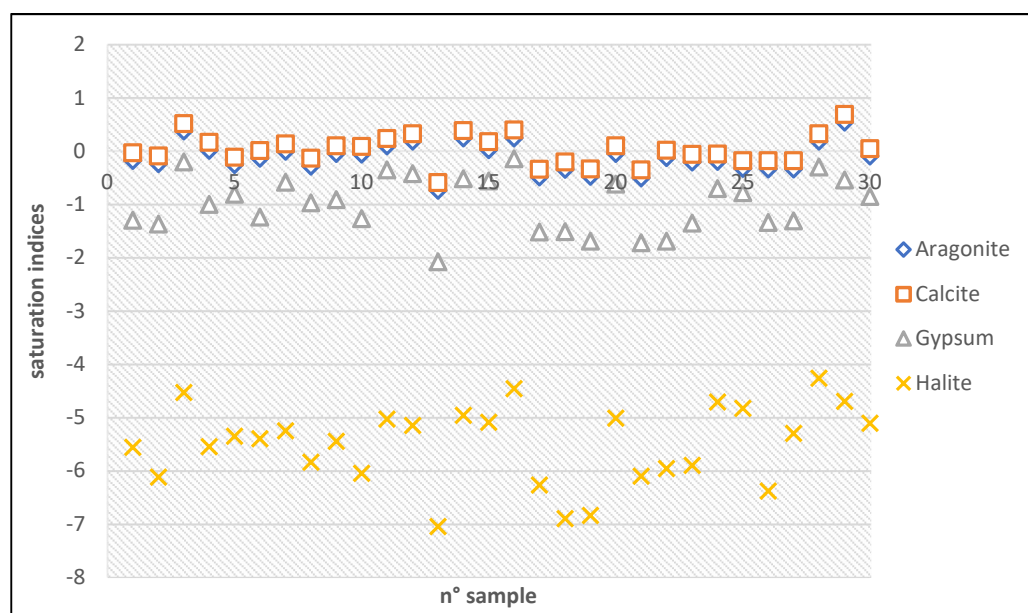


Figure 8. Saturation indices diagrams of groundwater samples from the study area.

Furthermore, the average ratios between Ca/Na (0.69), Mg/Na (0.54) and HCO_3^-/Na (0.54) suggest that the chemical composition of the reservoir is mainly under the combined influence of evaporation and silicate weathering [44] (Figure 9), as carbonate-dominated reservoirs have a Ca / Na ratio around 50, Mg/Na around 10 and HCO_3^-/Na ratio near to 120 [45–47]. At the average, the $((\text{Na}/\text{K})/\sum(+))$ ratio of 0.46 (with $\sum(+)$ represents total cations) also confirms that silicate weathering might be the major source of cations [48]. Furthermore, the area is characterized by a semi-arid climate with a high rate of evaporation leading to the formation of salt layers which are leached from the soil surface to formation waters through circulating water. The high irrigation activities of the area are also responsible for the increase in salinity of GW. In fact, irrigation increases the salinity of irrigation return flow from three to ten times that of applied water [49].

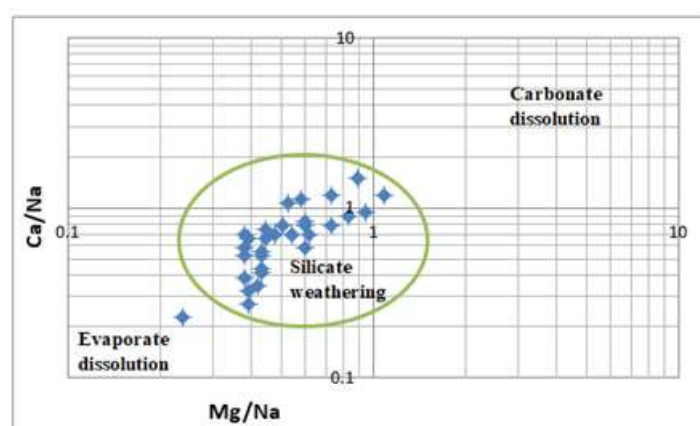


Figure 9. Weathering type on the basis of Na-normalized Ca and Mg (meq/L).

3.2. Impact of Agricultural Activities

Agriculture has been a major influence on the economy of many areas for centuries [50], especially in arid and semi-arid regions such as Tunisia. Olive, almond and fig trees dominate agricultural lands in the study area. At the end of the nineteenth century, irrigation was introduced and became more and more intensive. Horticulture and citriculture are the dominant land use in Cap Bon Tunisia, particularly in the HN region [51]. In terms of nitrate, Figure 10 perfectly demonstrates the same behavior between the NO_3/Ca and NO_3/SO_4 ratios in all samples.

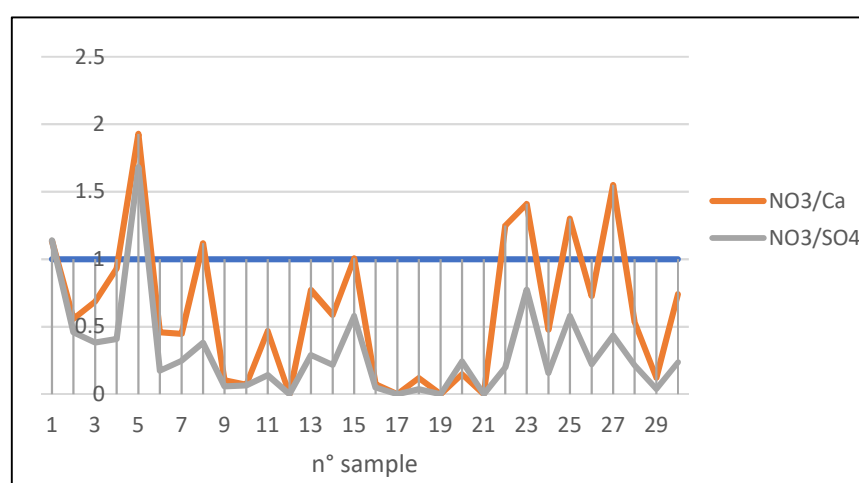


Figure 10. Variation of NO_3/Ca and NO_3/SO_4 in the shallow aquifer of Hammamet-Nabeul shallow aquifer).

These two ratios are calculated to test the impact of the fertilizer on GW composition. In fact, a general excess of both Ca and SO_4 is indicated by NO_3/Ca and NO_3/SO_4 ratios below 1 except in boreholes n° 1, 4, 5, 8, 15, 23, 25 and 27. The excess of NO_3 in these locations may derive from the excessive use of fertilizers especially with the chemical formula the $\text{Ca}(\text{NO}_3)_2$, $(\text{NH}_4)_2\text{SO}_4$ as presented by [27,52].

Moreover, these observations belonging to areas with the highest concentrations of nitrate are located in irrigated perimeters (Figure 11).

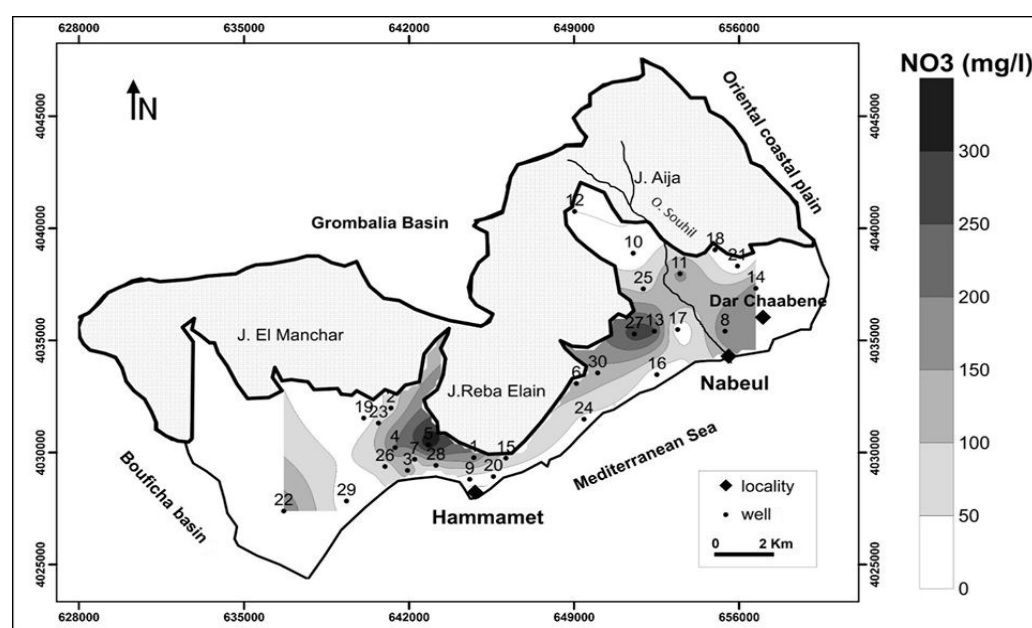


Figure 11. Spatial distribution of nitrate concentrations in the study area (mg/L).

3.3. Ranking of Groundwater Quality for Irrigation

3.3.1. Using Individual Parameters

Classification of GW quality for irrigation based on individual parameters as EC, PI, SAR, MH and %Na, allows obtaining the following results (Table 3).

Table 3. Groundwater quality ranking according to individual parameters.

Parameters	Class
EC	3% moderate
	43% high
	54% very high
PI	100% suitable
SAR	3% unsuitable
	20% suitable
	77% moderate
MH	6% unsuitable
	94% suitable
Na%	3% doubtful
	70% permissible
	27% good

• CE

In this study, 54% of the water samples belong to the very high salinity class, 43% of the area belongs to the high salinity, and 3% of the water samples indicate a moderate rate of salinity (Figure 12). High salinity values ($>750 \mu\text{S}/\text{cm}$) are recorded in (1) downstream of the aquifer (water–rock interaction), (2) in the irrigation perimeter in the west of the study area where there is a return flow (wells n° 22, 26), which contributes to the increase on water and soil, (3) in the two sides of Wadi Souhil (in the east of the study area). In fact, the bottom of the Wadi Souhil is characterized by the abundance of sandy soil that is sufficiently permeable to allow the infiltration of surface water, which contributes to the recharge of the aquifer. As a result, the bed of this Wadi is considered a good site of artificial recharge by treated wastewater (TWW) [28]. In this context, although reuse of TWW for agricultural purposes can be a sustainable solution to water scarcity, as in [29,53–55], the

effluent must be continuously monitored to avoid contamination, which is not the case in the present zone [28]. So, the very high salinity recorded in wells n° 11, 17, 25, 27, 29 ($>2250 \mu\text{S}/\text{cm}$), located in both sides of the Souhil Wadi, may be attributed to the rejection of partially treated wastewater in this Wadi.

- PI

In this study, the values of the permeability index (PI) values range from 37.43 to 64.23%. All PI values are included between 25 and 75%, showing that the water belongs to class II related to suitable quality for irrigation (Table 1).

- SAR

This ratio shows values ranging from 1.53 to 11.92. Then, 20% of water samples are suitable for irrigation, 77% of samples belong to the moderate class and 3% of water samples are unsuitable for irrigation. Mapping based on the kriging technique shows the spatial distribution of this parameter in the HN aquifer (Figure 13). Areas with maximum values corroborate the cultivated area and with maximum NO_3 values. This is in agreement with the impact of agricultural activities in the study area.

- MH

In the study area, approximately 94% of the water samples show MH values less than 50%. So, these waters are suitable for irrigation. Whereas, the remained samples (6% with an $\text{MH} > 50\%$) are unsuitable for irrigation.

- %Na

In this study, the % Na values range from 29.47% to 60.21%. A total of 27% of the water samples are good for irrigation while 3% are doubtful and 70% are permissible for irrigation (Table 3).

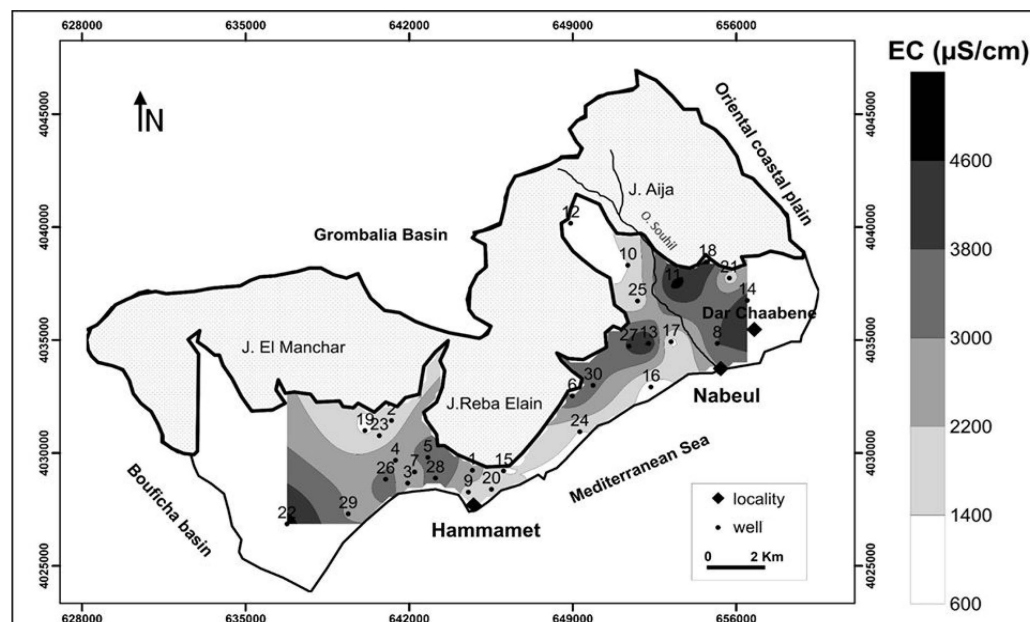


Figure 12. Spatial distribution of electrical conductivity in the study area.

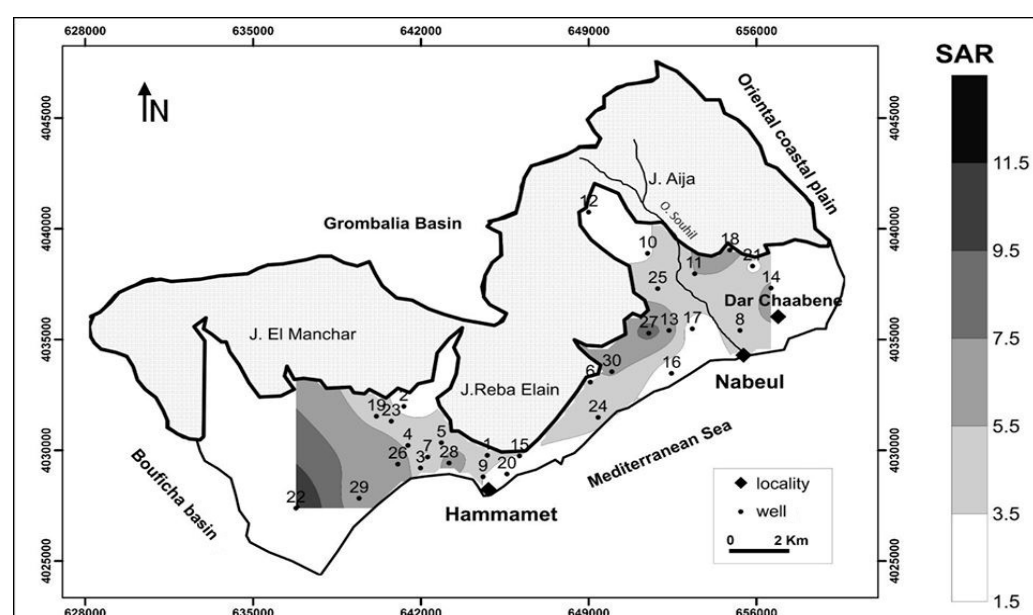


Figure 13. Spatial distribution of the sodium adsorption ratio in the study area.

Moreover, statistical analysis is performed to identify the most relevant parameters intervening in the IWQI. In fact, according to the average values (Table 4). The highest parameter on average is the PI (average = 49.22%). This indicates that this parameter represents the greatest risk on water quality [36].

Furthermore, Table 4 shows that the SAR and EC variables highly contribute greatly to the variability of water quality for irrigation (VC = 46.55% and 49.28%, respectively).

Table 4. Descriptive statistics of individual parameters of water quality for irrigation.

	PI	%Na	MH (%)	SAR	EC ($\mu\text{S}/\text{cm}$)
Min	37.43	29.47	29.41	1.53	765.00
Max	64.23	60.21	55.36	11.92	4973.00
Average	49.22	44.55	42.24	4.79	2697.30
Standard Deviation (SD)	6.10	7.14	5.59	2.22	1328.82
Variation coefficient (VC) in%	12.41	16.03	13.23	46.55	49.28

3.3.2. IWQ Ranking Using the USSL Diagram

Obtained results and the projection of water points in the USSL diagram (Figure 14) showed that almost all the GW samples have very high salinity and alkalinity hazard values. Water quality could be categorized into classes C4S4 and C4S3 (very bad), C4S2 (bad), (C3S1) (medium), and C2S1 (good). They accounted for 20%, 33.33%, 43.33% and 3.33%, respectively, of the total water samples. For samples, which were classified as C4S2 and C4S3 and C4S4 with a very high salinity hazard, the GW does not indicate that the GW is not suitable for irrigating soils. Samples belonging to category C3S1 with a high salinity hazard could be used to irrigate soils with good permeability [55]. While the sample alone (n°12) which is classified as C2S1 is considered safe for irrigation use. It belongs upstream of the aquifer corresponding to the lowest concentration of salinity.

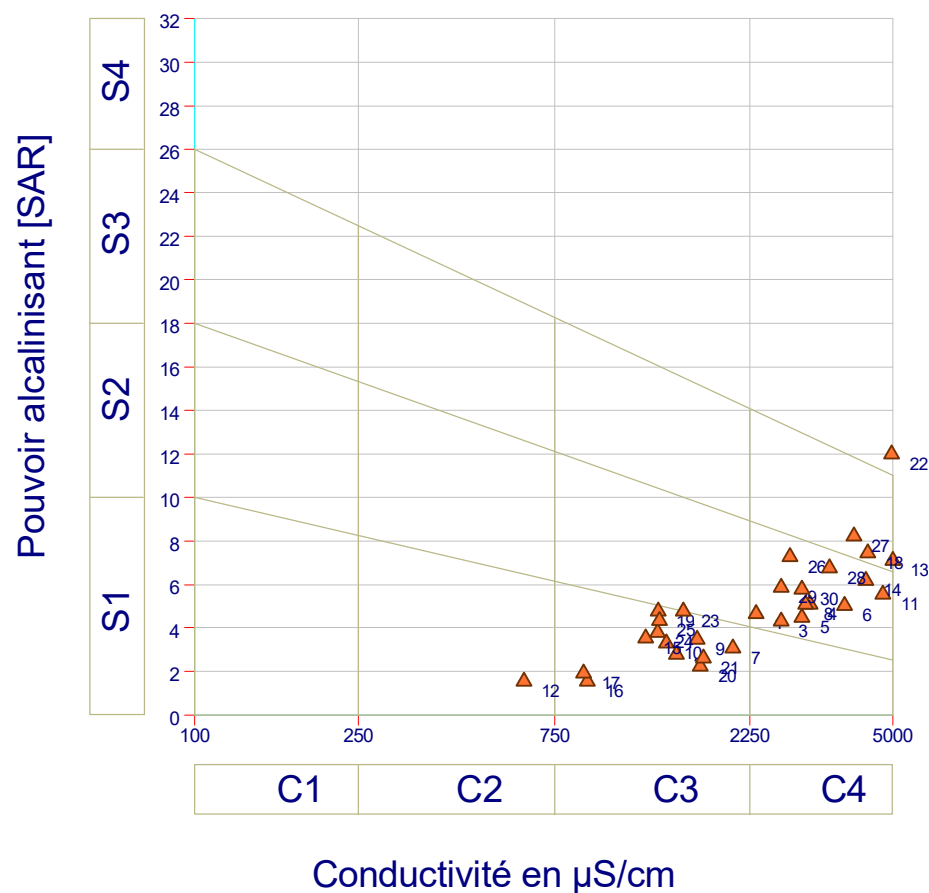


Figure 14. USSL diagram (SAR vs. EC) for the Hammamet-Nabeul shallow aquifer.

3.3.3. Classification of IWQ Using MFISM According to the Determination of the Membership Function Determination

In this research, MFISM is performed using the fuzzy logic toolbox of MATLAB (7.0). It was selected for the evaluation and classification of the quality samples available from GW for irrigation purposes. According to the statistical analyses described above, the two inputs EC and SAR are selected to express irrigation water quality for irrigation (IWQI), which is the output of the MFISM (Figure 15). The model is used to evaluate and classify the IWQI samples in the HN shallow aquifer. Based on the membership functions considered for inputs, the MFISM has $4 \times 4 = 16$ rules.

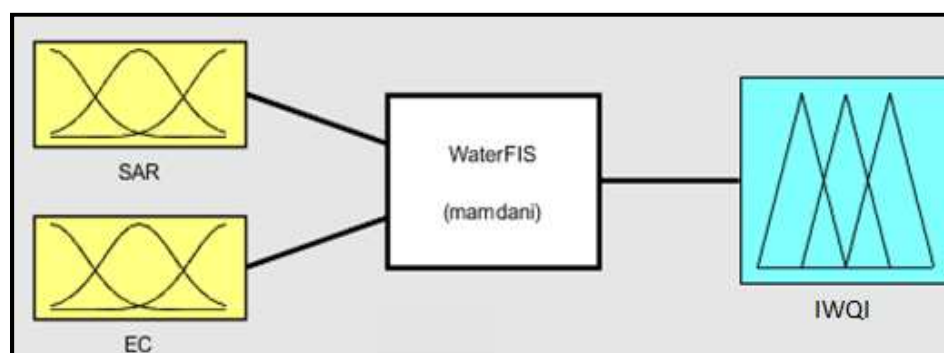


Figure 15. Fuzzy Inference System of the present study.

Membership functions were assigned to two variables inputs (EC and SAR) and one output (IWQI = WQ).

1. Inputs' membership function for SAR variable;
The SAR values are classified as follows (Figure 16):
(0–9): Low value of SAR refers to Good IWQI
(2–17): Med value of SAR refers to Medium IWQI
(6–25): A high value of SAR refers to Bad IWQI
(11–35): Very high value of SAR refers to very bad IWQI
2. Inputs' membership function for EC variable;
The EC values are classified as follows (Figure 17):
(0–250): Low value of EC refers to Good IWQI
(200–750): Med value of EC refers to Medium IWQI
(600–2500): High value of EC refers to Bad IWQI
(2200–5000): Very High value of EC refers to Very Bad IWQI
3. Output Membership function for IWQI variable;
The output membership function was chosen for the IWQI evaluation (Figure 18).
The irrigation water quality index values are classified as follows:
(0–0.3): Very Bad IWQI
(0.15–0.45): Bad IWQI
(0.3–0.7): Medium IWQI
(0.55–0.85): Good IWQI
(0.7–1): Very Good IWQI

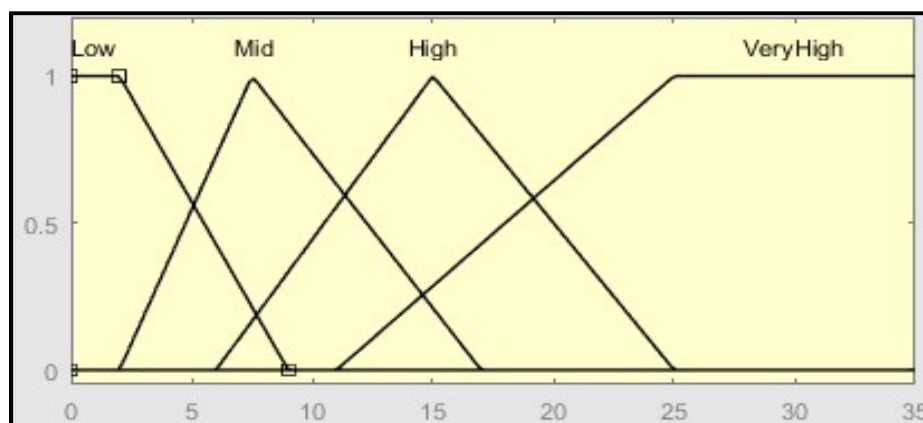


Figure 16. SAR membership function.

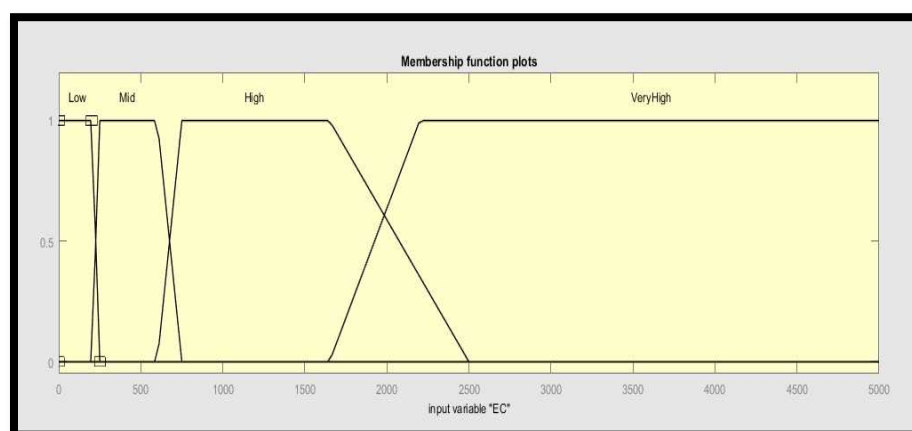


Figure 17. EC membership function.

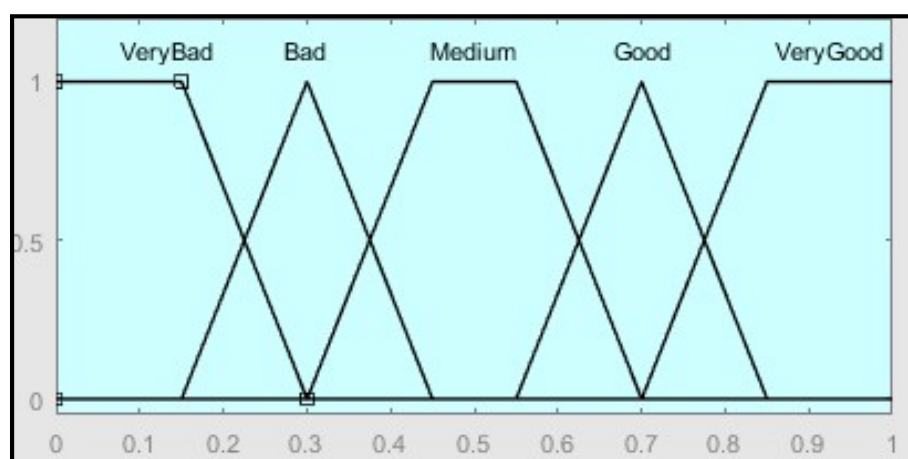


Figure 18. IWQI membership function.

To display the interaction between input variables and their contribution to the output variable evolution, the fuzzy surface is used as a three-dimensional view graphical user interface (GUI) tool (Figure 19). It shows that the lowest are the “SAR” and “EC” values, the highest is the IWQI. Therefore, the GW quality for irrigation is better.

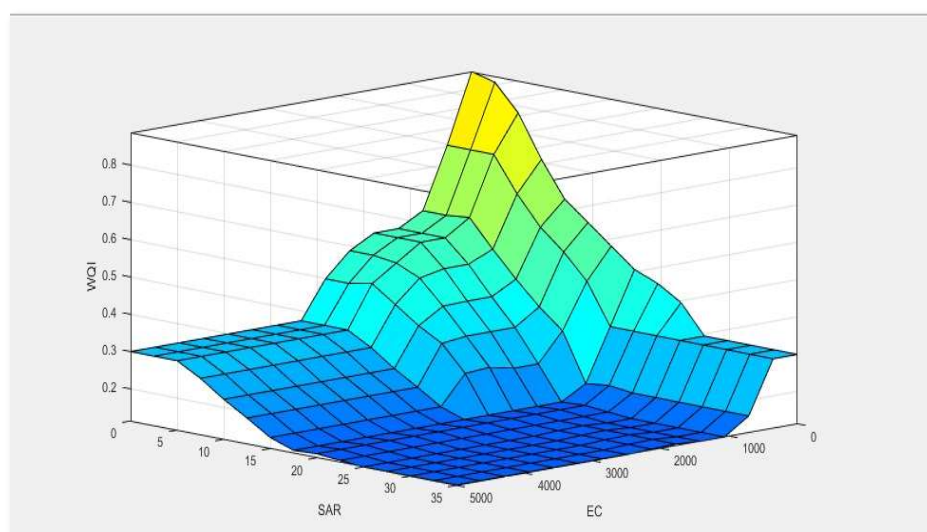


Figure 19. Three-dimensional view graphical user interface of membership in MFISM in the study area.

3.3.4. Classification of IWQ Using MFISM According to the Fuzzy Rules’ Determination

In the Mamdani fuzzy inference system, the rules (If/and/then) are the representation of the experts’ knowledge and opinion on the classification of water quality for irrigation purposes referring to IWQI (WQ), following four classes of the two parameters: SAR and EC. Therefore, rules based on expert knowledge for the presented model consist of 16 rules (Figure 20).

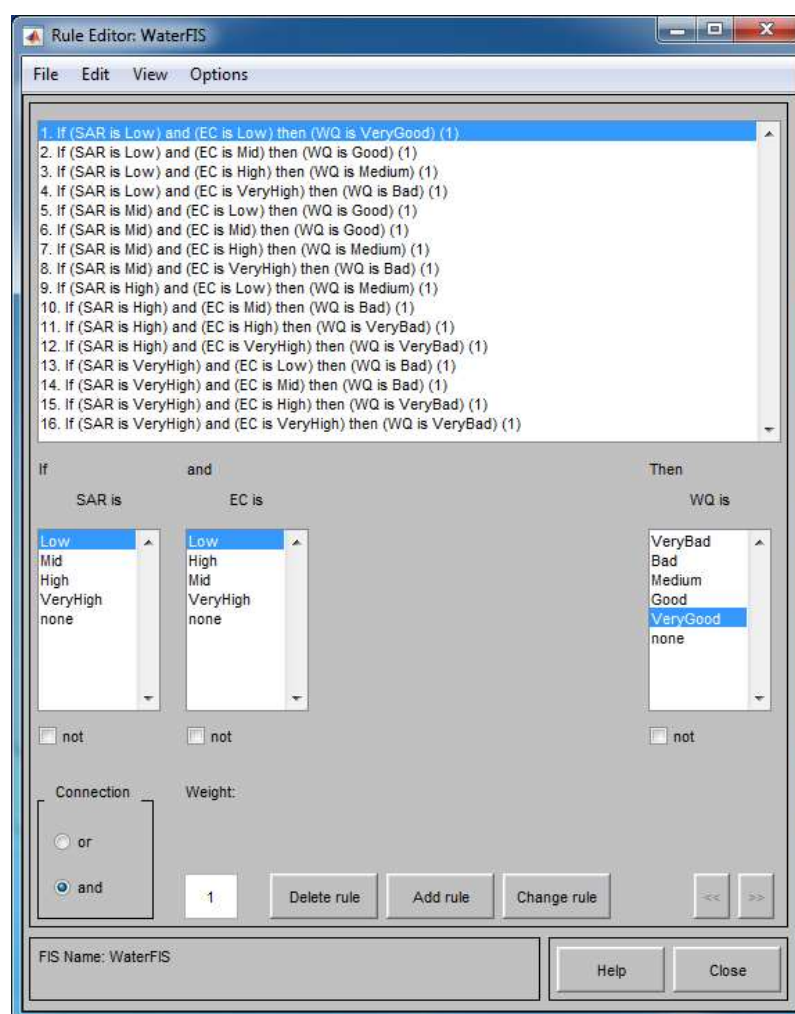


Figure 20. Fuzzy rules.

3.3.5. Model Validation with USSL Diagram after Defuzzification

During the defuzzification step, the score assigned for IQWI ranges from 0 to 1. The closer this score is to 1, the more the quality of irrigation water quality (Table 5). An important step in the development of the model is the assessment of the concordance between the results obtained by the MFISM and the knowledge of experts. This means that the system must provide an adequate answer to the different conditions that may be introduced. The comparison between the results of the USSL diagram and those of MFISM in (Table 5) showed that the MFISM is proven as an efficient method for ranking water quality with 79.78% general agreement. Besides, the overview of the table demonstrates that MFIS allows improving GW quality ranking. For example, in the USSL classification, samples n° 7, 20 are “100% medium” class, while they are modified to “80% medium and 20% bad” type following the MFISM. The same reasoning is valid for points 26 and 27 which belong to the class “100%very bad” according to the USSL diagram. Though, they are 10% and 17% very bad, respectively, following the MFISM. So, thanks to MFSIM, a new more exact ranking for IQWI is created.

Table 5. Evaluation results of MFISM and USSL diagram.

Sample Num	USSL Class	USSL Diagram Evaluation	Fuzzy Score	Fuzzy Evaluation	Agreement Evaluation%
1	C4-S2	bad	0.30	100% bad	100
2	C3-S1	medium	0.46	100% medium	100
3	C4-S2	bad	0.30	100% bad	100
4	C4-S4	very bad	0.30	100% bad	0
5	C4-S2	bad	0.30	100% bad	100
6	C4-S2	bad	0.30	100% bad	100
7	C3-S1	medium	0.39	80% medium	80
8	C4-S2	bad	0.30	100% bad	100
9	C3-S1	medium	0.46	100% medium	100
10	C3-S1	medium	0.50	100% medium	100
11	C4-S2	bad	0.30	100% bad	100
12	C2-S1	good	0.52	100% medium	0
13	C4-S3	very bad	0.27	10% very bad	10
14	C4-S2	bad	0.30	100% bad	100
15	C3-S1	medium	0.50	100% medium	100
16	C3-S2	medium	0.50	100% medium	100
17	C3-S1	medium	0.50	100% medium	100
18	C4-S3	very bad	0.27	40% very bad	40
19	C3-S1	medium	0.50	100% medium	100
20	C3-S1	medium	0.39	80% medium	80
21	C3-S1	medium	0.50	100% medium	100
22	C4-S4	very bad	0.19	63.3% very bad	63.3
23	C3-S1	medium	0.50	100% medium	100
24	C3-S2	medium	0.50	100% medium	100
25	C3-S1	medium	0.50	100% medium	100
26	C4-S2	very bad	0.27	10% very bad	10
27	C4-S3	very bad	0.25	17% very bad	17
28	C4-S2	bad	0.28	93.3% bad	93.3
29	C4-S2	bad	0.30	100% bad	100
30	C4-S2	bad	0.30	100% bad	100
					79.78

3.4. Mapping Spatial Distribution of Water Quality for Irrigation Purpose

Finally, mapping IWQI based on the MFISM allows identifying two zones (Figure 21) (A) and (B): Zone (A) is located in the West of the study area, influenced by irrigation return flow and by flushing fertilizers in excess. Zone (B) is situated on both sides of the Souhil Wadi affected mainly by infiltration of partially treated wastewater through the Wadi. This water is enriched with nutritive elements; hence, it is characterized by a high level of NO₃, EC, and SAR. In fact, spatial variation of these parameters is in good agreement with the IQWI assessment (Figures 11–13 and 21).

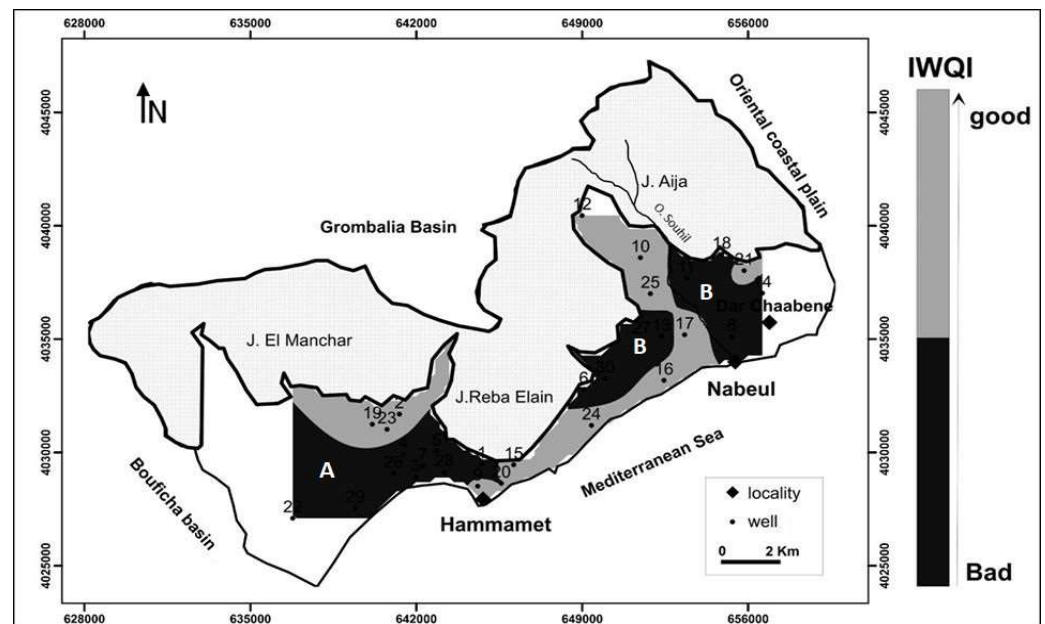


Figure 21. IWQI Spatial distribution in Hammamet-Nabeul shallow aquifer (A) irrigated perimeter and (B) two sides of Wadi Souhil (recharge area by partial treated wastewater).

4. Conclusions

The assessment of GW quality in the Hammamet-Nabeul shallow aquifer was performed based on the hydrochemical characteristics. The results show that the mineralization of GW is mainly highlighted by the leaching of minerals, basically hyalite and Gypsum. The high GW salinity rate expressed on electrical conductivity can be attributed to excess irrigation return flow combined with evaporation and leaching fertilizer. In fact, high NO_3 contents are related to (i) the return of irrigation water, (ii) intensive use of artificial fertilizers, especially on agricultural land, and (iii) rejection of partially treated wastewater in Wadi Souhil. It should be noted that treated wastewater can be used for irrigation with respect to optimal quantity values for the plant and with permanent biological control of effluent quality to avoid contamination.

The water quality for irrigation was evaluated in two ways: (i) individual parameters (EC, SAR, Na%, MH, and PI), (ii) Mamdani fuzzy logic inference model (MFISM) based on irrigation water quality index (IWQI) calculation. The model built based on EC and SAR emerged as the most significant for parameters in water quality for irrigation evaluation. It was developed using the trapezoidal membership function and defining sixteen rules. With 80% agreement between the MFISM results of MFISM and USSL diagram in 30 wells, the results revealed that the MFISM is useful for improving the ranking water quality by creating new classes in the same class defined previously by the USSL diagram. In addition, it helps minimize the probable errors and uncertainties caused by the field data and hydrochemical analyses. Furthermore, the IWQI that was successfully simulated with MFISM could provide even more reliable and confidential results. In fact, this accurate model can be extended by using additional parameters. Current IWQI spatial distribution could be enhanced by using an integrated Fuzzy-GIS system. This study provides a reference point for future studies of the hydrochemical characteristics and GW quality in other similar areas. It could be helpful in the task of decision-making for building strategic plans for water resources management and sustainability.

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Abbreviations

The following acronyms and notation are used in this manuscript:

%Na	Sodium percent
%MH	Magnesium hazard
AI	Artificial Intelligence
EC	Electrical Conductivity
FIS	Fuzzy Inference System
FRBS	Fuzzy Rule-Based System
Fuzzy-VIKOR	Fuzzy Vlekkriterijumsko KOMPromisno Rangiranje
Fuzzy-AHP	Fuzzy Analytic Hierarchy Process
GIS	Geographic Information System
GW	Groundwater
HN	Hammamet-Nabeul
IWQI	Irrigation Water Quality Index
LRAE	Laboratory of Radio Analyses and Environment
MFISM	Mamdani Fuzzy Inference System Model
PI	Permeability Index
SAR	Sodium Absorption Ratio (SAR)
SD	Standard Deviation
TDS	Total Dissolved Solids
TWW	Treated Waste Water
USSL	United States Salinity Laboratory
VC	Variation Coefficient (VC)
WQI	Water Quality Index

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