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The seawater intrusion assessment in coastal aquifers using GALDIT method and groundwater quality index: the Djeffara of Medenine coastal aquifer (Southeastern Tunisia)

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Abstract

The Djeffara of Medenine coastal aquifer (Southeastern Tunisia) is threatened by the seawater intrusion (SWI). This region is characterized by a notable increase in population and spreading of agricultural activities (increasing of groundwater pumping), which makes it under tremendous stress of SWI. So, the groundwater quality degradation is caused by both anthropogenic activities (pumping) and natural hazards (sea level rise (SLR) and storm surge). Hence, assessing the groundwater vulnerability to SWI is highly crucial to protect this resource. The assessment of SWI represents the principal aim of this study. To achieve this objective, firstly, a parametric method of vulnerability assessment "GALDIT" was applied. It considers six parameters which interfere with each other and determine the SWI effects. Obtained results show three degrees of vulnerability (low, moderate, and high). Most of the coastal broadline represents high classes. In addition to the hydrogeological parameters, these results are closely related to the piezometric level (− 10 to 15 m) and the distance from the shore (< 500 m) parameters. Secondly, a groundwater quality index for seawater intrusion (GQI_{SWI}) was developed in order to identify the groundwater type. This method shows that the Djeffara of Medenine groundwaters is classified as mixed water. The validation procedure of these two applied models was performed based on water electrical conductivity (EC). It shows a significant correlation coefficient. Obtained maps may be used as a scientific basis allowing the water management and protection in coastal aquifers threatened by saline waters.

Keywords Seawater intrusion · GALDIT · Groundwater quality index · Djeffara of Medenine · Shallow aquifer

Introduction

During the last decades, the coastal aquifer systems are under numerous pressures since they serve as a major resource used for the human's activities satisfaction. Almost 44% of the world's population lives inside 150 km of the coast line (Atlas 2010; Reed 2010). The industrial, economic, and agriculture sector development and the drastic population growth lead to the groundwater resources degradation. Moreover, the coastal regions were characterized by a high demographic density which provides an intensive pumping that may possible the seawater intrusion (SWI). These regions are also affected by the Sebkhas' influences. In coastal aquifers, the equilibrium interface between freshwater and seawater can be modified by natural and anthropogenic imposing, such as overexploitation which leads to the sea level rise decrease and limited recharge (variation of the precipitation regime). Worldwide, the SWI is a serious problem in several coastal aquifers (Dentoni et al. 2015). So, it is one of the main threats to freshwater resources in coastal areas. For this reason, the protection and the management of these resources against the SWI become indispensable essentially in arid and semi-arid regions where these vital resources are limited and overexploited.

Since the saltwater intrusion becomes a problem of the last decades, researchers try to develop models which explain this phenomenon in order to better prepare and mitigate the negative effects. Several studies have showed that the overexploitation and the incontinence of humans lead to the groundwater

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quality modification and the increase of the salinization (Ben Hamouda et al. 2011). Numerous authors applied several models and used several tools to assess the groundwater vulnerability to SWI such as the following: (i) Zeng et al. (2016) have assessed the SWI in Laizhou Bay region by applying a numerical model of seawater intrusion process which was built by using SEAWAT4, (ii) Arslan (2013) has evaluated the groundwater quality against seawater intrusion in Bafra Plain, Turkey, based on multivariate statistical techniques, (iii) Klassen and Allen (2017) have assessed the risk of saltwater intrusion in coastal aquifers especially by mapping hazards in combination with the aquifer susceptibility, and (iv) Kura et al. (2015) have assessed the seawater intrusion in a small tropical island using geophysical, geochemical, and geostatistical techniques. Moreover, the SWI was almost assessed using experimental models such as the following: (i) Boluda-Botella et al. (2014) have used three sets of obtained results of column experiments realized in laboratory to determine the SWI effects using two programs: the ACUAINTRUSION program to determine the instabilities and the PHREEQC program to prove the simulations performed with the other software. These models were always used to minimize the differences between the experimental and the simulated data and the computational time, and (ii) Robinson et al. (2015) have developed a novel methodology to quantify SWI parameters in a sandbox experiment using image analysis.

Usually, authors desire to use numerical models to address the SWI problem. They announce that, nevertheless their wide usage, the numerical model application poses numerous challenges such as limited process understanding, limited availability of data, or conceptual issues (Carrera et al. 2010; Werner et al. 2013; Walther et al. 2017). The main used model was based on the vulnerability maps which can be created to indicate areas that may be highly susceptible to contamination. To assess the groundwater vulnerability to seawater intrusion, some modifications and/or new parameters were added to a based model. For example, the sea level rise parameter was added to the parametric method "DRASTIC" (this acronym is formed from the highlighted letters of seven parameters: Depth to groundwater, net Recharge, Aquifer permeability, Soil types, Topography, Impact of the vadose zone, and hydraulic Conductivity parameters) and it will be named modified DRASTIC model (Özyurt and Ergin 2010). Furthermore, the GALDIT parametric model was developed by Chachadi and Lobo-Ferreira (2001) specifically for assessing the spatial vulnerability of hydrogeological settings to SWI. The GALDIT acronym is formed by the first letters of six factors. It groups the most physical and chemical parameters determining the SWI which are the following: Groundwater occurrence, Aquifer hydraulic conductivity, Depth to groundwater, Level above the sea, Distance from the shore, Impact of existing status of seawater intrusion, and Thickness of the aquifer. Like every method, this model shows some drawbacks and advantages. The main drawback is the unawareness of the pumping effect on the seawater intrusion process. On the other hand, this model can be applied in several regions, due to its numerous parameters and the easier collection of data. It gives relatively precise results for widespread regions characterized by a complex geological structure, notwithstanding the absence of specific parameter measurements (Panagopoulos et al. 2006). However, the parametric method GALDIT was successfully applied in several studies in order to assess the SWI using geographic information system (GIS) such as Chachadi (2005); Lobo Ferreira et al. (2005); Shetkar and Mahesha (2010); Mahesha et al. (2011); Saidi et al. (2013); Sophiya and Syed (2013); Recinos et al. (2015); and Allouche et al. (2017).

Moreover, groundwater chemistry has been almost operated as a significant tool to outlook water quality for several purposes. These methods were classified into traditional methods which consist on the comparison of existing guidelines with experimentally determined parameter values and groundwater quality index (GQI) methods (Boyacioglu 2007). The GQI method helps in understanding the extent of saltwater intrusion. A new saltwater intrusion-specific model (GQI) was established by El-Fadel et al. (2013). It takes into account various water quality indicators. Furthermore, a new storage based on water quality parameters indicative of seawater intrusion was developed to obtain a representative index for seawater intrusion (GQI_{SWI}) (Tomaszkiewicz et al. 2014). It provides a comprehensible format that allows spatial analysis for the results (vulnerability maps).

The focus of the present paper deals with the application of the parametric model "GALDIT," Piper diagram ($GQI_{Piper(mix)}$ and $GQI_{Piper(dom)}$), and the groundwater quality index for seawater intrusion (GQI_{SWI}) in order to assess the effect of the seawater intrusion in the Djeffara of Medenine coastal aquifer. The combination of numerous approaches can be an effective and consistent way of assessing the amount and degree of seawater intrusion. The saltwater intrusion is always controlled by the aquifer type (unconfined, leaky confined, and confined), the aquifer hydraulic conductivity, the depth to groundwater level above the sea, the distance from the shore, the impact of existing status of saltwater intrusion, and the aquifer thickness.

Study area

The Djeffara of Medenine coastal aquifer (Southeastern Tunisia) is the purpose of this study. It is covering around 3100 km^2 of superficies (Fig. 1). This zone is bordered on the east by the Mediterranean Sea, on the west by Dhaher Djebel, on the north by the boundary of the Gabes governorate, and on the south by the Ben Guerdene city. The study area is composed of 11 watersheds which are Djorf peninsula, Zeuss-Om Zessar, Sidi Makhlouf, El Fje, Om Ettamer, Smar

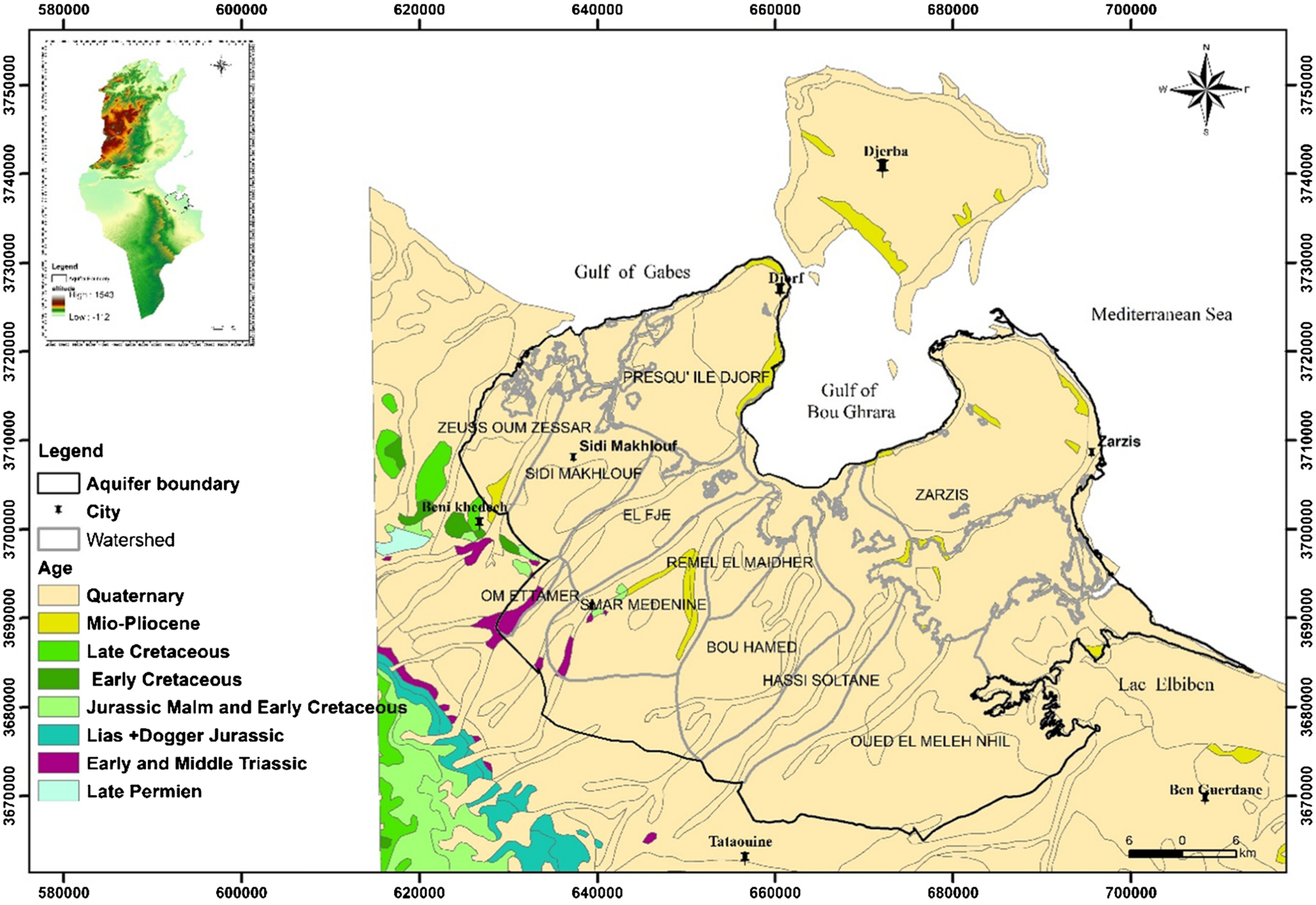

Fig. 1 Presentation of the study area map

Wadi, Remel El Maidher, Bou Hamed, Hassi Soltane, El Maleh Wadi, and Zarzis peninsula.

The Djeffara region was almost classified among the region of arid and hot upper arid climate. The temperature average varies between 12.4 and 30.1 °C in winter and summer, respectively, while the mean annual rainfall does not exceed 149 mm/year for 47 years (1968–2015).

The outcrop of the study area is characterized by a notable variety of soil types (Fig. 2). Most of the study area is covered by the soil with little evolution type which is a material transported and deposited by water, characteristics of alluvial plains. These are characterized by a fine texture (clay-silty or clay). These soils present specific physical properties; they have a good superficial aeration and especially a high porosity (Duchaufour 1965). Moreover, we notice the spreading of the Isohumic soil type which represents a sandy to sandy-clay texture. Furthermore, the halomorphic soil type settles at the level of Sebkhas. They develop at the level of depressions, at the level of the watershed outlets where evaporation contributes to the salty soil formation.

Going deeper, this coastal aquifer is included in the Mio-Plio-Quaternary deposits which were mainly alluviums, limestones, gypsum, conglomerates, sands, and coastal dunes. In order to more understand this lithological variation, two hydrogeological cross sections were established (Figs. 3 and 4).

The AA′ section with NNE-SSW direction correlates nine drilling wells (Fig. 3). This correlation illustrates the important subsidence of Jurassic at CFPA El Fje drilling well located at the central part of the study area. This subsidence may be due to the effect of El Fje fault. It shows a thickness variation of the shallow aquifer. Especially, an important decrease of thickness was noted at the "Tmasent 2" deep well, located at Djorf region (coastal part). Furthermore, a second hydrogeological section BB′ was achieved with N-S direction (Fig. 4). This section shows positive structure (a dome) at Zarzis region resulting of the two faults (the graben and horst structure). These faults cause a depression at the coastal part of Zarzis peninsula. At this region, an absence of the Jurassic and Triassic deposits was noted. The Djeffara of Medenine aquifer is almost characterized by a high lithologic complexity.

On the other hand, the study area is characterized by an intense hydrographic density (Fig. 5).

The piezometric map of the Djeffara coastal aquifer was obtained after a head value calculation based on the static level and altitude measured in 2017 on 46 wells (Fig. 5). It shows

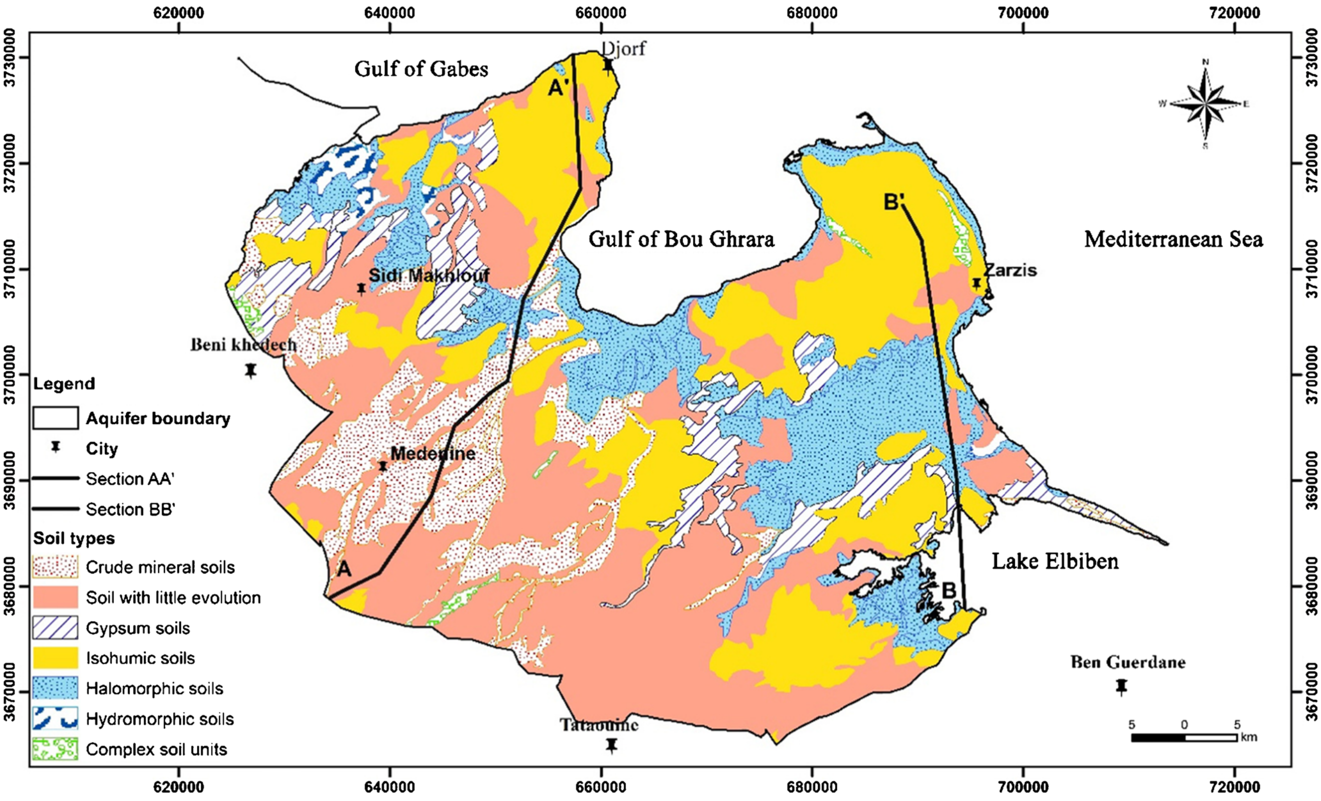

Fig. 2 Pedology map of the Djeffara of Medenine

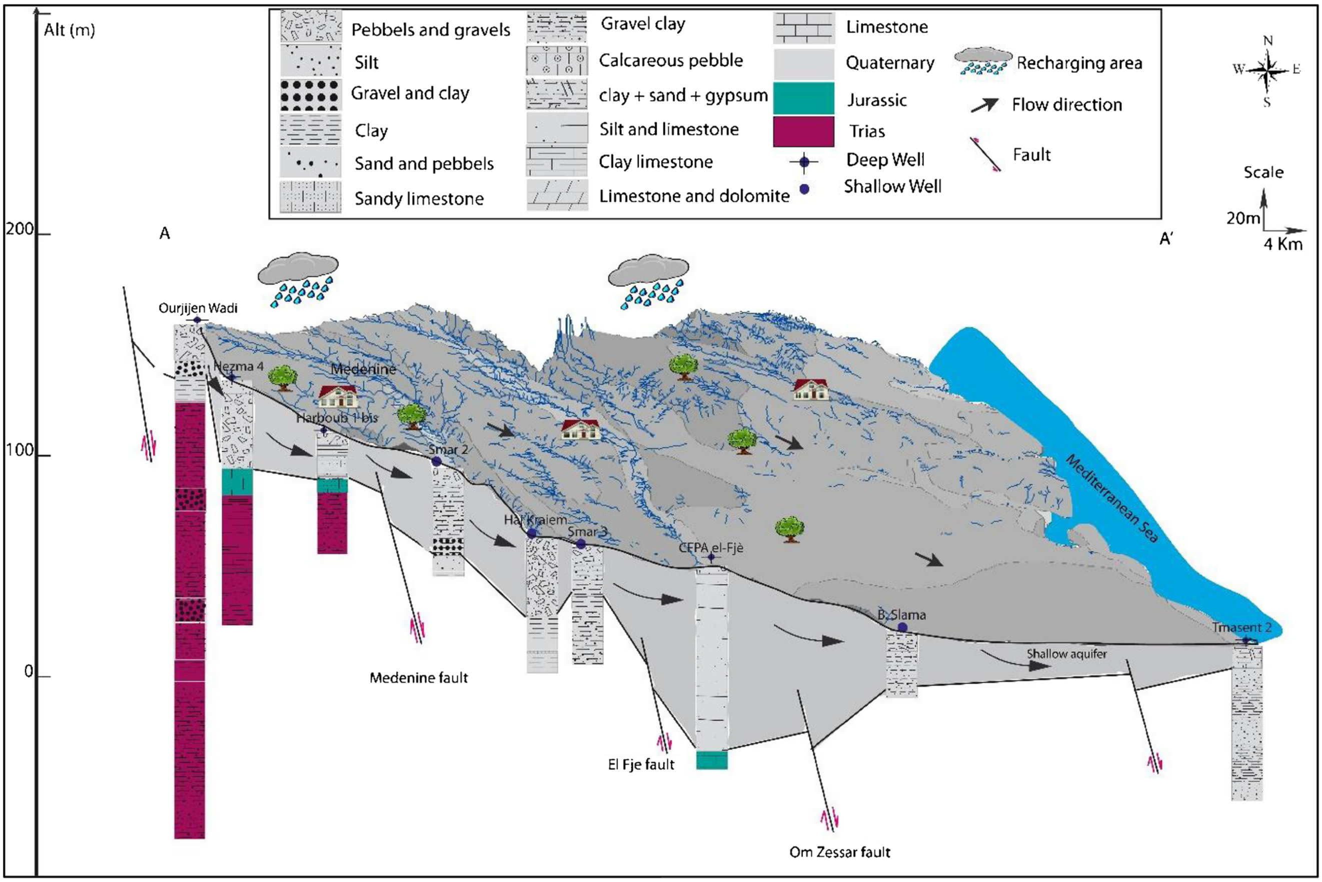

Fig. 3 Hydrogeological section AA′ of the Djeffara of Medenine

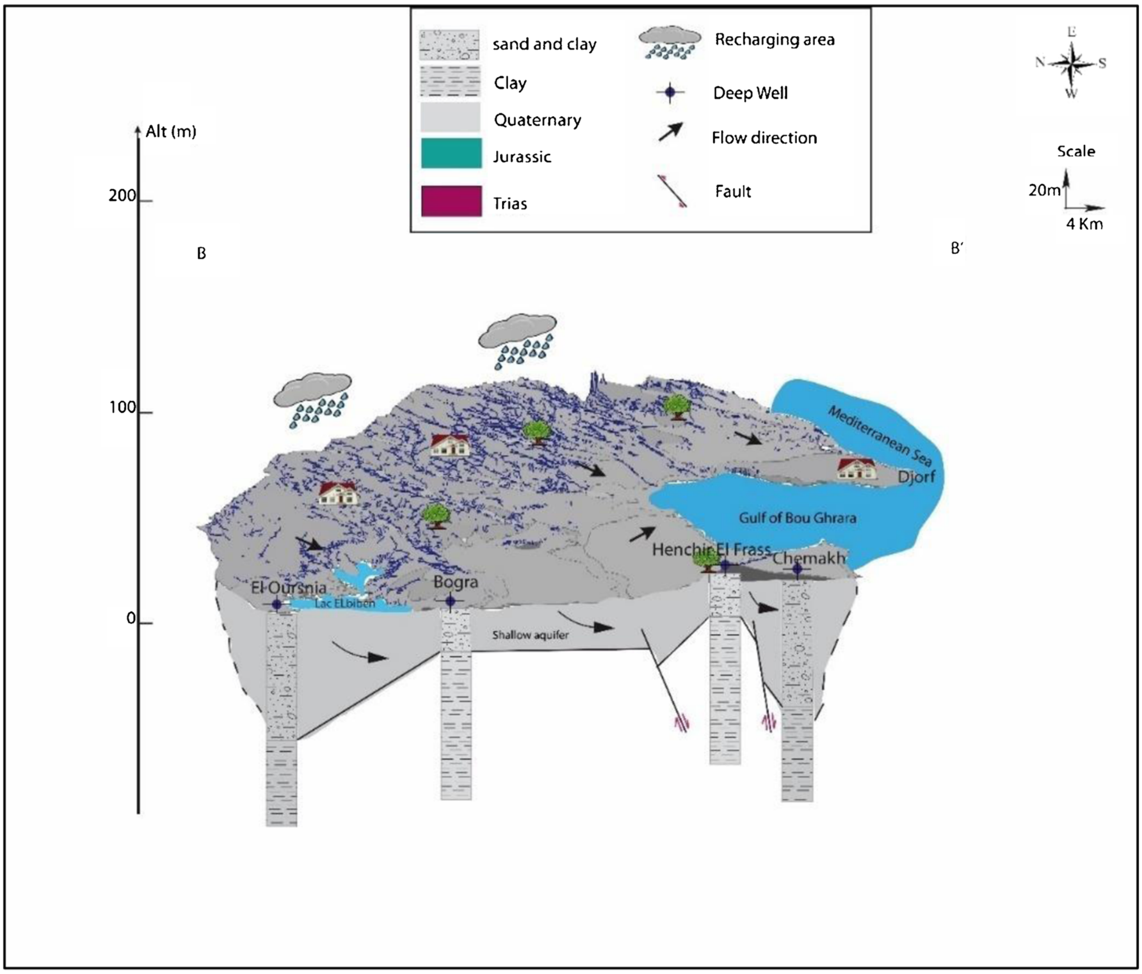

Fig. 4 Hydrogeological section BB′ of the Djeffara of Medenine

head values ranging between − 10 and 110 m. The low values were located at the coastal areas (Djorf, Bou Ghrara Gulf, and Zarzis), while the high ones were noted at the recharge area in the southwestern part. Generally, the flow direction was oriented from the southwest to the northeast. Likewise, it shows a piezometric depression localized at the Djorf Bou Ghrara Gulf, and Zarzis regions (coastal regions) which may induce a saltwater intrusion (Agoubi et al. 2013). Moreover, a measure of salinity for 47 samples (depth of samples ranges from 5 to 40 m) was performed. In fact, the Djeffara of Medenine groundwater was characterized by a high salinity value which reaches 11.53 g/l (Fig. 6). The lower salinity value (1.5 g/l) appears in the southwest areas (recharge area), whereas the higher salinity values (> 5 g/l) belong to the:

– northeastern zones where the groundwater salinization is a result of the Sebkhas effects in addition to the dissolution of Triassic deposits outcropping at the Tebaga dome;
– southeastern areas (Bou Ghrara Gulf, El Maleh Sebkhas, and Zarzis) where the presence of salinity high values is related to the groundwater mixing with seawater;
– southwestern zones (around the Elbiben Lake) where the presence of salinity high values is related to the groundwater salinization by the Sebkhas effects and the mixing with deep waters coming from the Triassic groundwaters at the level of Medenine fault.

Materials and methods

Data description

The assessment of the seawater intrusion in the Djeffara of Medenine coastal aquifer was manifested by using several methods. The first step consists to collect the data base. In fact, to achieve this purpose and determine the groundwater chemistry, 47 samples were collected and were analyzed at the “Water Sciences Laboratory” at the Higher Institute of Water Sciences and Technology of Gabes, Tunisia, in May 2016. These samples were characterized by a homogeneous

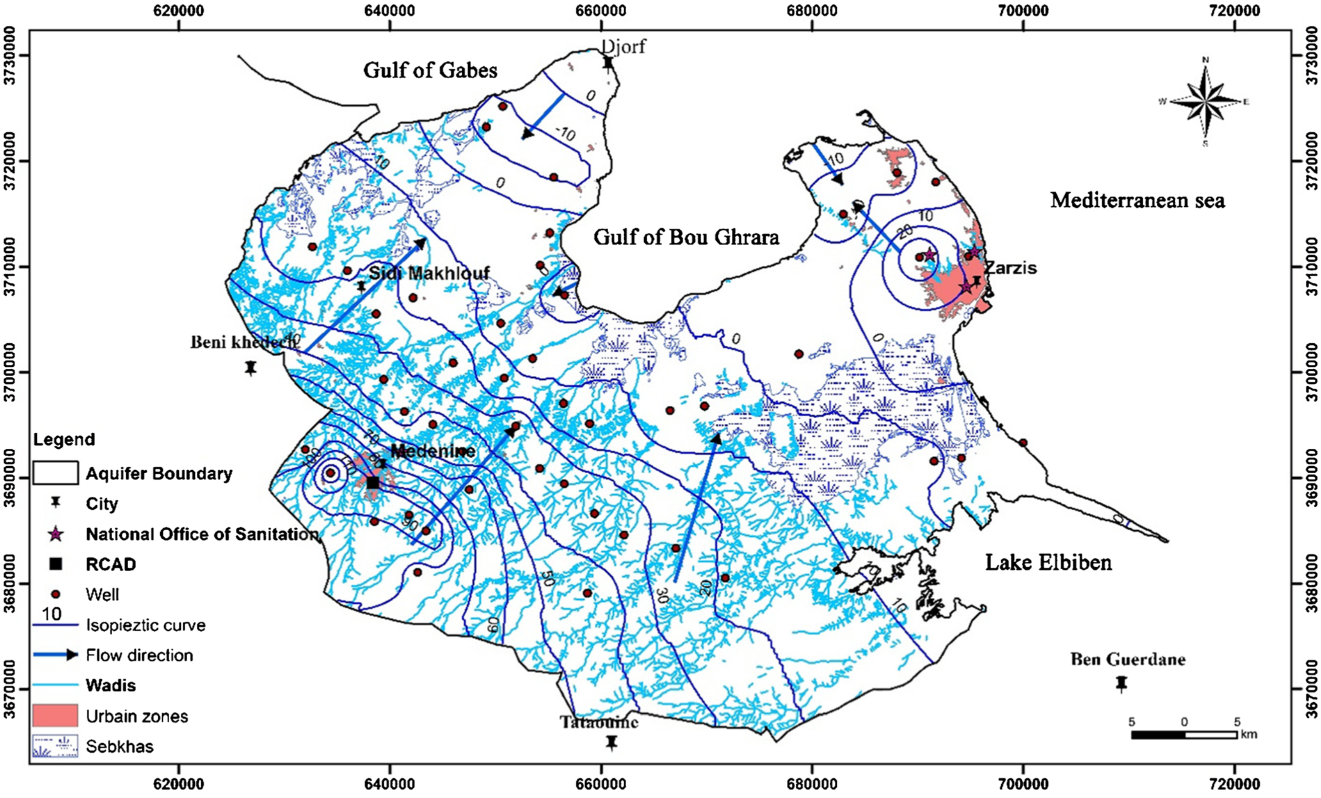

Fig. 5 Piezometric map (in 2017)

spreading (Fig. 5). To assess the seawater intrusion, the electrical conductivity (EC), the total dissolved salt (TDS), and the several cations and anions were used. Sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulfate (SO_4^{2-}), brome (Br^-), and bicarbonate (HCO_3^-) are considered the major elements. The static level of the groundwater was measured in field surveys conducted in May 2016. The depths of these samples range between 5 and 40 m. Concerning the reservoir delimitation, it was founded by the lithostratigraphic logs collection from the direction of water resources of Medenine (CRDA-Medenine).

Ionic ratio

In order to determine the seawater intrusion effects in the groundwater resources, several ratio correlations were performed. The ionic ratio method was successfully applied by numerous researchers in order to determine the origin of the groundwater mineralization in coastal sides such as the following: Leboeuf et al. (2003) have used the SO_4/Cl and Ca/Mg ionic ratios; El Moujabber et al. (2006) have used the Na/Ca, Mg/Ca, HCO_3/Cl, Na/Cl, and SO_4/Cl ionic ratios; Lee and Song (2007) have used the Cl/(HCO_3+CO_3), the Br/Cl, and the SO_4/Cl ionic ratios; Mondal et al. (2011) have used the Cl/HCO_3 and the Mg/Ca ionic ratios; and Arslan (2013) has used the Ca/Na, Cl/HCO_3, Ca/Cl, Mg/Cl, Mg/Ca, and SO_4/Cl ionic ratios. In the present study, the main ionic ratios developed are the Mg/Ca, SO_4/Cl, Ca/Na, Mg/Cl, Ca/Cl, and the Cl/HCO_3. These ratios were used to determine the origin of groundwater mineralization in the Djeffara of Medenine coastal aquifer.

Vulnerability assessment: GALDIT method

In the present study, the vulnerability assessment was performed based on a parametric method named "GALDIT." This model was created in order to evaluate the seawater intrusion in coastal aquifers (Chachadi 2005). This method consists to subdivide obtained values for each factor to some of classes (ranges) then to accord to each class a determined rate then it will be assigned with a significant weight. This procedure will be determined according to each parameter intervention in groundwater contamination (SWI). Each parameter has a relative rate varying from 1 to 10 and weigh varying from 1 to 4. This model is characterized by its system of ranges, ratings, and weights. The GALDIT indexes were obtained by using the following equation (Gorgij and Moghaddam 2016):

$$\text{GALGIT index} = \frac{(1\times G)+(3\times A)+(4\times L)+(4\times D)+(1\times I)+(2\times T)}{15} \tag{1}$$

where G, A, L, D, I, and T are the parameters sited above.

Once the GALDIT index has been calculated, the identification of areas that are affected by SWI is possible (Table 1)

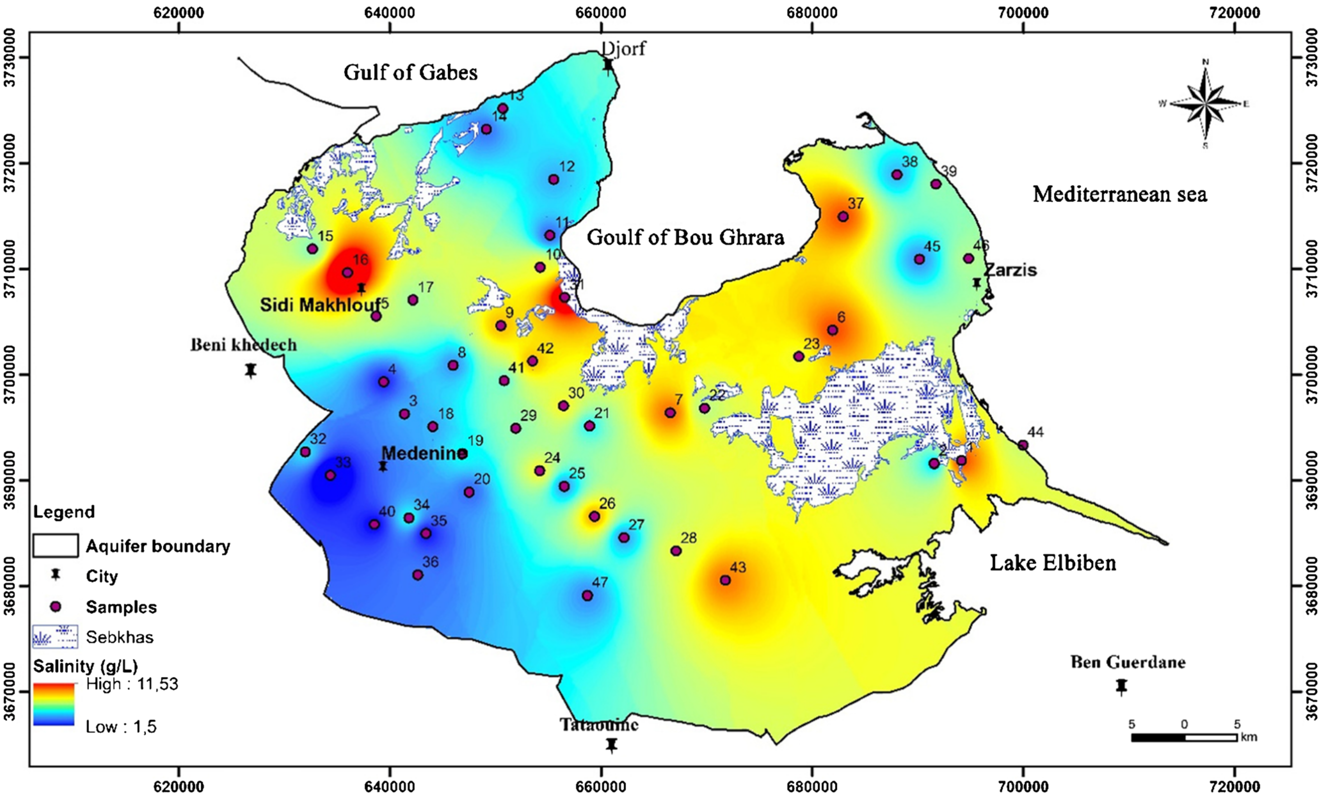

Fig. 6 Groundwater salinity map (in 2016)

(Agarwadkar 2005). The final GALDIT map was created using the spatial analyst extension of ArcMap 10.1 software (Fig. 7).

Analytical procedure to vulnerability map generation was presented in fig. 7.

Groundwater quality index for seawater intrusion

The vulnerability assessment for seawater intrusion was almost treated basing on GALDIT method and groundwater quality index for seawater intrusion (GQI_{SWI}) created by Tomaszkiewicz et al. (2014). This method takes into account the quality parameters revealing the SWI. Generally, the hydrochemistry difference between the seawater and the freshwater was categorized by anion and cation concentrations. In fact, the freshwater is characterized by the abundance of calcium and bicarbonate, while the seawater is categorized by its chloride and sodium dominance (Kreitler 1993). The mixing of these two water types can be determined based on the chloride concentration, which is explained by the conservative nature of anions (Panteleit et al. 2011). For this reason, the fraction of seawater (f_{sea}) can be calculated by the following formula (Appelo and Postma 2004):

$$f_{\text{sea}} = \frac{m_{\text{Cl(sample)}} - m_{\text{Cl (freshwater)}}}{m_{\text{Cl(seawater)}} - m_{\text{Cl (freshwater)}}} \qquad (2)$$

where $m_{\text{Cl(sample)}}$ is the Cl^- concentration of the sample, $m_{\text{Cl(seawater)}}$ is the Cl^- concentration of the Mediterranean Sea, and $m_{\text{Cl(freshwater)}}$ represents the Cl^- concentration of the fresh water. When Cl^- is not available for Mediterranean Sea, it can be assumed to be equal to 0 and 566 meq/l for freshwater and seawater, respectively (Tomaszkiewicz et al. 2014).

To identify the SWI, another simple tool was used which is the $GQI_{f\text{sea}}$ index. These values range from 0 to 100, whose fresher waters possessing a lower f_{sea}.

$$GQI_{f_{\text{sea}}} = (1 - f_{\text{sea}}) \times 100 \qquad (3)$$

Moreover, the groundwater quality indices were manifested based on the Piper diagram results which have a determined diamond field for water types. This diagram can be divided into six distinct domains: I, II, III, IV, V, VI, representing Ca-HCO_3, Na-Cl, mixed Ca-Na-HCO_3, mixed Ca-Mg-Cl, Ca-Cl, and Na-HCO_3 water types, respectively (Fig. 8) (Sarath Prasanth et al. 2012). Domain I typifies the freshwater, whereas domain II characterizes seawater and saline water.

Table 1 Degrees of vulnerability GALDIT (Chachadi 2005)

Index classes	Vulnerability degrees
< 5	Low
5–7.5	Moderate
> 7.5	High

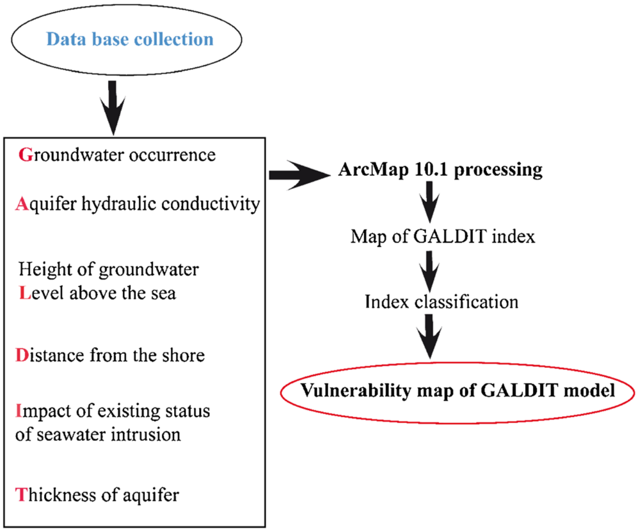

Fig. 7 Flow chart of methodology

The seawater and freshwater mixing is represented by a horizontal line across the diagram center. It is numerically expressed by $GQI_{Piper(mix)}$ as stated in the following equation:

$$GQI_{Piper(mix)}(meq/l) = \left[\frac{(Ca^{2+}+Mg^{2+})}{\text{Total cations}} + \frac{HCO_3^-}{\text{Total anions}}\right] \times 50 \quad (4)$$

The $GQI_{Piper(mix)}$ index ranges between 0 which represents highly saline water (domain II) and 100 which designs fresh water (domain I) (Table 2).

Furthermore, the other domain definition can be accomplished when $GQI_{Piper(mix)}$ is used simultaneously with another index which is $GQI_{Piper(dom)}$ (Eq. 5). Equally, it arrays from 0 (Ca-Cl water, domain V) to 100 ($NaHCO_3$ water type, domain VI) (Table 2).

$$GQI_{Piper(dom)}(meq/l) = \left[\frac{(Na^{+}+K^{+})}{\text{Total cations}} + \frac{HCO_3^-}{\text{Total anions}}\right] \times 50 \quad (5)$$

A new index (Eq. 6) was developed named groundwater quality index for seawater intrusion (GQI_{SWI}). This model translates the Piper diagram information (Eqs. 4 and 5) and the seawater fraction (Eq. 3) to develop a new two-stage numerical indicator for seawater intrusion (Tomaszkiewicz et al. 2014). The obtained GQI_{SWI} index can be transformed to map by using the "interpolation" function in ArcMap 10.1 framework. This map consists a meaningful tool of knowledge and presents a significant spatiotemporal representation and distribution of GQI_{SWI} index.

$$GQI_{SWI} = \frac{GQI_{Piper(mix)} + GQI_{f_{sea}}}{2} \quad (6)$$

Generally, the GQI_{SWI} values vary between 0 and 100, where "100" indicates the freshwater and "0" presents the seawater, while the obtained $GQI_{Piper(mix)}$ index ranges from 0 (representing saltwater) to 100 (representing freshwater) (Table 3).

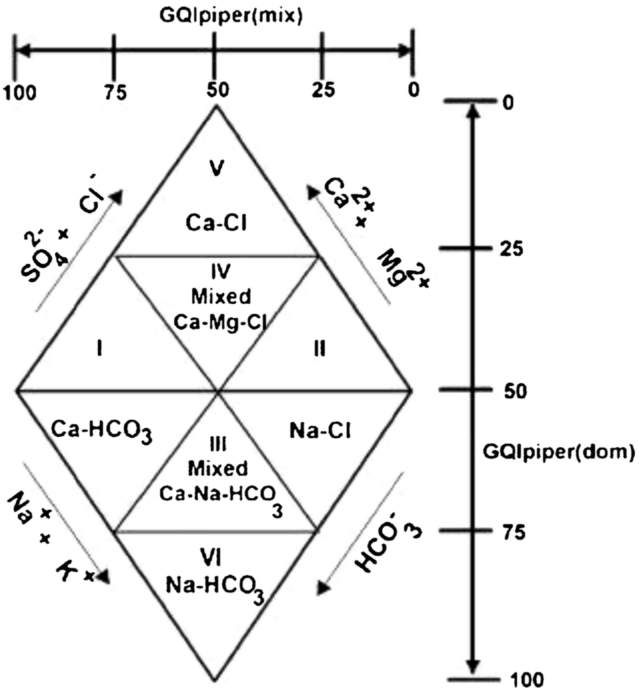

Fig. 8 Piper domain development based on $GQI_{Piper(mix)}$ and $GQI_{Piper(dom)}$ indexes (Tomaszkiewicz et al. 2014)

In the present study, the GQI_{SWI} was calculated using the Excel-based algorithm 2016.

Model validation

Usually, any results should be validated for determining the result reliability. The vulnerability map obtained by each method (GALDIT and GQI_{SWI}) was virtually illustrated basing on the hydrochemical analysis results (Ribeiro et al. 2017). In the present study, the validation procedure was achieved by the superposition of electrical conductivity (EC) values and vulnerability maps. The selection of this parameter is founded on the aim of this study which is the assessment of seawater intrusion; well, the high values of EC are a characteristic of seawater. The EC values were obtained from the 47 collected samples (depth, 5–40 m).

Results and discussion

Ionic ratio

In order to identify the origin of groundwater salinization in the Djeffara of Medenine shallow aquifer, many ratios, versus chloride, were calculated (Fig. 9).

The Mg/Ca and SO_4/Cl ratios were used as natural tracers for seawater time residence (Leboeuf et al. 2003). According

Table 2 The corresponding domain of $GQI_{Piper(mix)}$ and $GQI_{Piper(dom)}$ (Hussien 2015)

Domain	$GQI_{piper(mix)}$	$GQI_{piper(dom)}$
I	50–100	25–75
II	0–50	25–75
III	25–75	50–75
IV	25–75	25–50
V	25–75	0–25
VI	25–75	75–100

to El Moujabber et al. (2006), the Mg/Ca ratio is around 5 and varies between 0.2 and 1.5 for the seawater and the freshwater, respectively. In the case study, the Mg/Ca ratio calculated for the 47 samples was always close or superior to 1 (Fig. 9a). These values were designated by a positive correlation. In fact, the increase of this ratio means the increase of Cl concentration, hence the importance effect of SWI.

The SO_4/Cl molar ratio arrays between 0.99 and 1.62. This ratio reveals a negative correlation with Cl concentrations where R-squared value is equal to 0.03 (Fig. 9b).

Figure 9c shows the Ca/Na correlation versus Cl concentrations. It illustrates the decrease of the Ca/Na ratio when the Cl concentration increases. This correlation reveals a moderately negative correlation ($R^2 = 0.6$). The higher Cl concentration may indicate the degree of seawater influences in the coastal aquifer.

Other correlation was established between the Mg/Cl ratio and Cl concentrations. It shows a negative correlation ($R^2 = 0.4$) (Fig. 9d). The low values of Mg/Cl indicate the seawater intrusion influence. The Mg ion is a characteristic of freshwater. It is negatively correlated with the Cl ion.

Moreover, the variation of Ca/Cl molar ratio versus Cl concentrations shows a strong negative correlation ($R^2 = 0.7$) (Fig. 9e). Furthermore, the effect of salinization was performed by using the Cl/HCO_3 molar ratio correlation with the Cl concentrations (Fig. 9f). According to Revelle (1941), three states of groundwater were distinguished: unaffected (< 0.5), slightly or moderately affected (0.5–6.6), and strongly affected by SWI (> 6.6). The Cl/HCO_3 values vary between 0.22 and 6.20. This correlation reveals a strong positive correlation ($R = 0.8$) and a groundwater slightly and moderately affected by SWI.

GALDIT method

The groundwater vulnerability assessment against seawater intrusion was developed by applying the parametric model "GALDIT."

The relative maps showing the variation of the six parameters in the GALDIT model were derived by using the function "Interpolation" in ArcMap 10.1 interface and projected in "BWGS 1984 UTM Zone 32N."

Groundwater occurrence

The groundwater occurrence parameter (*G*) designs the confinement degree of the aquifer: unconfined, leaky confined, and confined. The saltwater intrusion level depends on the original nature of the aquifer media. So, a confined aquifer would be less threatened by seawater intrusion comparing to an unconfined aquifer. Furthermore, the aquifer type affects the degree of advancement of the marine water into the groundwater (Satishkumar et al. 2016).

In the case study, the *G* parameter was determined basing on the pedologic map obtained from the Regional Commissionership for the Agricultural Development of Medenine "RCSAD." The Djeffara of Medenine coastal aquifer was classified into two aquifer types (Fig. 10): (i) unconfined aquifer which covers the main surface of the study area This aquifer was categorized by its coarse and moderate grain sizes (sandy-clayey, silt, clay-sandy), and (ii) leaky confined aquifer located essentially at the coastal part of Zarzis and Djorf regions and at the Sebkhas zones. This aquifer type was characterized by a coarse grain size formed essentially by sands and sandy-silty. The assessing rates attributed to these two types are 9 and 8, respectively. This parameter will be multiplied by a relative weigh equal to 1 when calculating GALDIT index.

Aquifer hydraulic conductivity

The aquifer hydraulic conductivity parameter (*A*) was used as the measure of the water flow rate through the saturated zone in the horizontal direction in the aquifer. The magnitude of seawater movement is directly controlled by the hydraulic conductivity. When this latter is important, the seawater inland movements are more significant (Tasnim and Tahsin 2016). In

Table 3 The corresponding domain of $GQI_{Piper(mix)}$ and $GQI_{Piper(dom)}$ (Hussien 2015)

Water type	GQI_{SWI} based on worldwide literature			Typical GQI_{SWI}	
	Min	Max	Mean	Min	Max
Fresh water	73.5	90.1	82.7	75	100
Mixed groundwater	47.8	79.9	63.4	50	75
Saline groundwater	4.8	58.8	27.5	10	50
Seawater	3.1	9.2	5.8	0	10

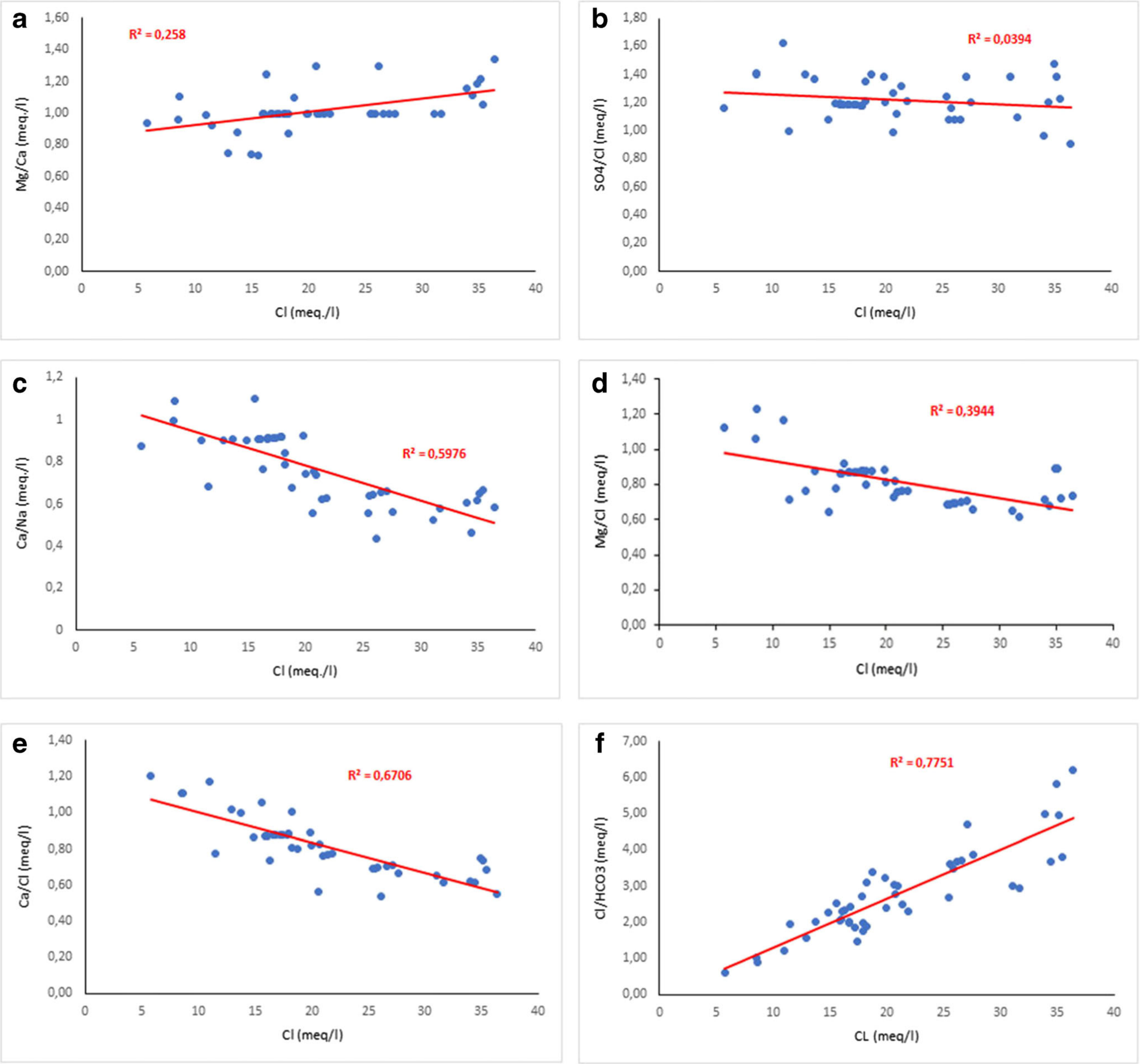

Fig. 9 Molar ratio correlation versus Cl concentrations

the present study, the aquifer hydraulic conductivity was considered as the aquifer permeability. It was calculated using the lithostratigraphic logs obtained from the Regional Commissary for Agricultural Development of Medenine (RCAD). The aquifer permeability was considered by applying the Castany formula (Castany 1982):

$$K_{\mathrm{mh}} = K_{\mathrm{eq}} = (h_1 k_1 + h_2 k_2 + \dots h_i k_i)/H \qquad (7)$$

where K_{mh} is the average of the horizontal permeability (m/s), H is the total thickness of the aquifer (m), h_i is the thickness of layer i (m), and k_i is the permeability of layer i (m/s).

The relative map of the *A* parameter (Fig. 11) shows some of permeability values varying from 10^{-5} to 2.6 10^{-1} m/s. The main permeable aquifer is located at the coastal part especially at Zarzis and Djorf peninsulas and near the borderline of Elbiben Lake. The Djeffara of Medenine coastal aquifer is formed mainly by permeable lithology (sands, gravels). It was possible to subdivide these values into five significant intervals. Each one of these intervals will be assigned by a relative rate varying from 2 to 9 according to their influences in the aquifer vulnerability. When calculating the GALDIT index, the *A* parameter will be multiplied by a weight equal to 3.

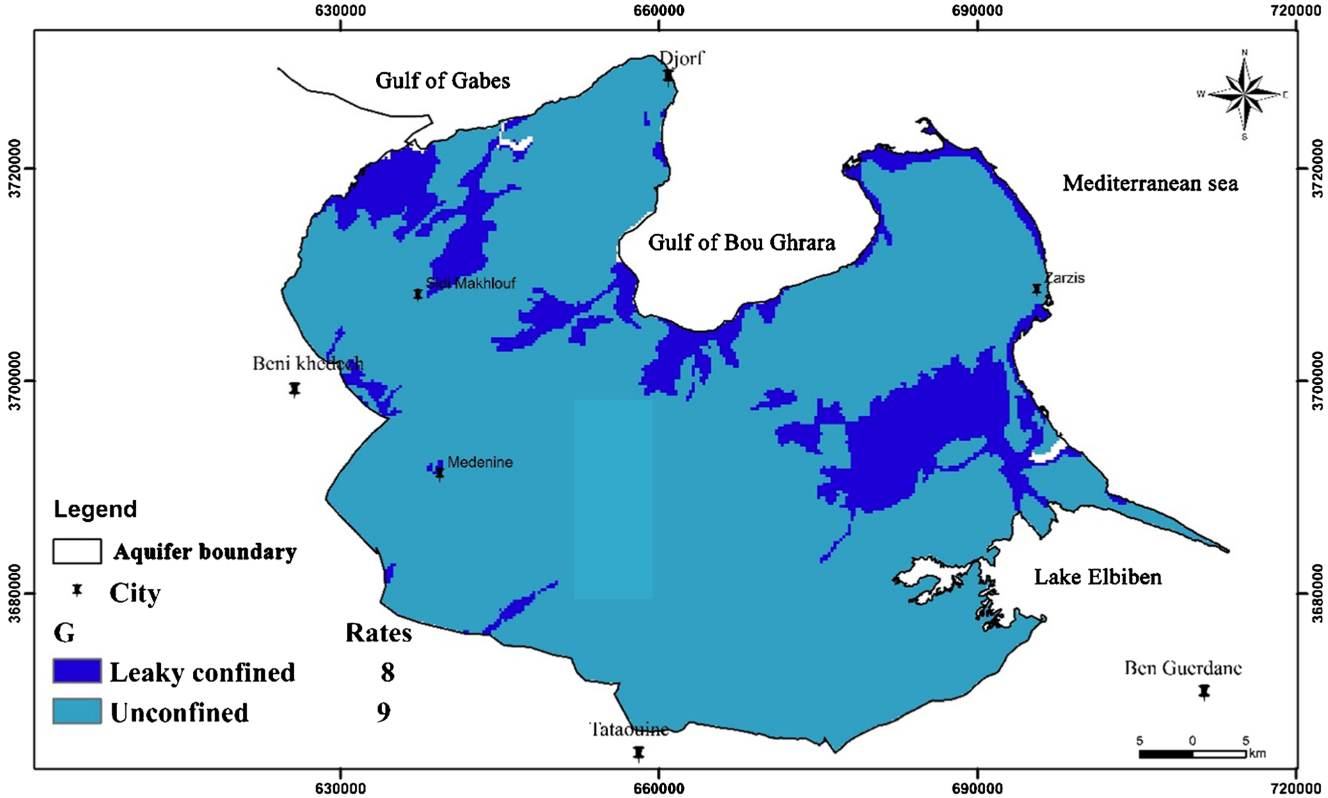

Fig. 10 Groundwater occurrence (*G*) map

Height of groundwater level above the sea

The height of groundwater level above the sea (*L*) designs the groundwater elevation compared to the mean sea elevation. The *L* parameter determines the hydraulic pressure eventually able to push back the seawater front (Gorgij and Moghaddam 2016). The more the piezometric level is low, the higher risk of seawater intrusion threats the aquifer.

In the case study, the *L* parameter was performed by calculating the piezometric level for inventoried 46 wells. Figure 12 shows the *L* factor spatial distribution after an interpolation with ArcMap 10.1 software. The *L* values oscillate between − 10 and 110 m. The low piezometric levels were observed at the coastal and the central regions of the Djeffara shallow aquifer ($-10 < L > 15$ m). These low values were obtained according to the extensive groundwater uses (overexploitation) at these regions especially for agriculture purposes satisfactions (Djorf, Gulf of Bou Ghrara, Zarzis, Smar). These regions are more vulnerable to the SWI than others, while the high values were noted at the recharge areas which are located at the southwestern part of the study area. Furthermore, depth to groundwater values greater than 15 m are located at the Djorf, the central part, and the southwestern areas of the study area. In these regions, there is more hydraulic pressure to push back the seawater front.

Seven significant intervals were distinguished where their rates vary from 1 to 10. The *L* factor was assigned by a weight of 4.

Distance from the shore

Generally, the seawater intrusion impact decreases when moving perpendicularly to the shore towards the interior. The distance from the shore factor (*D*) was evaluated according to meaningful distances which were measured perpendicular to the line of the coast (Tasnim and Tahsin 2016; Gorgij and Moghaddam 2016). According to Recinos et al. (2015), the most important rate (10) was adopted to distance less than 500 m from the shore. Concerning the distance values greater than 1001 m, a rate of 2.5 was adopted for all. Usually, the rating system declines relatively with an increase in the perpendicular distance from the coastline. It is noticeable that the more the aquifer is near to the shore, the saltwater intrusion reaches its maximum amount without neglecting the hydrogeological conditions.

According to the distance from the shore (*D*) map, four significant intervals were distinguished (Fig. 13). Their relative rates vary from 2.5 to 10 by going from the farthest point

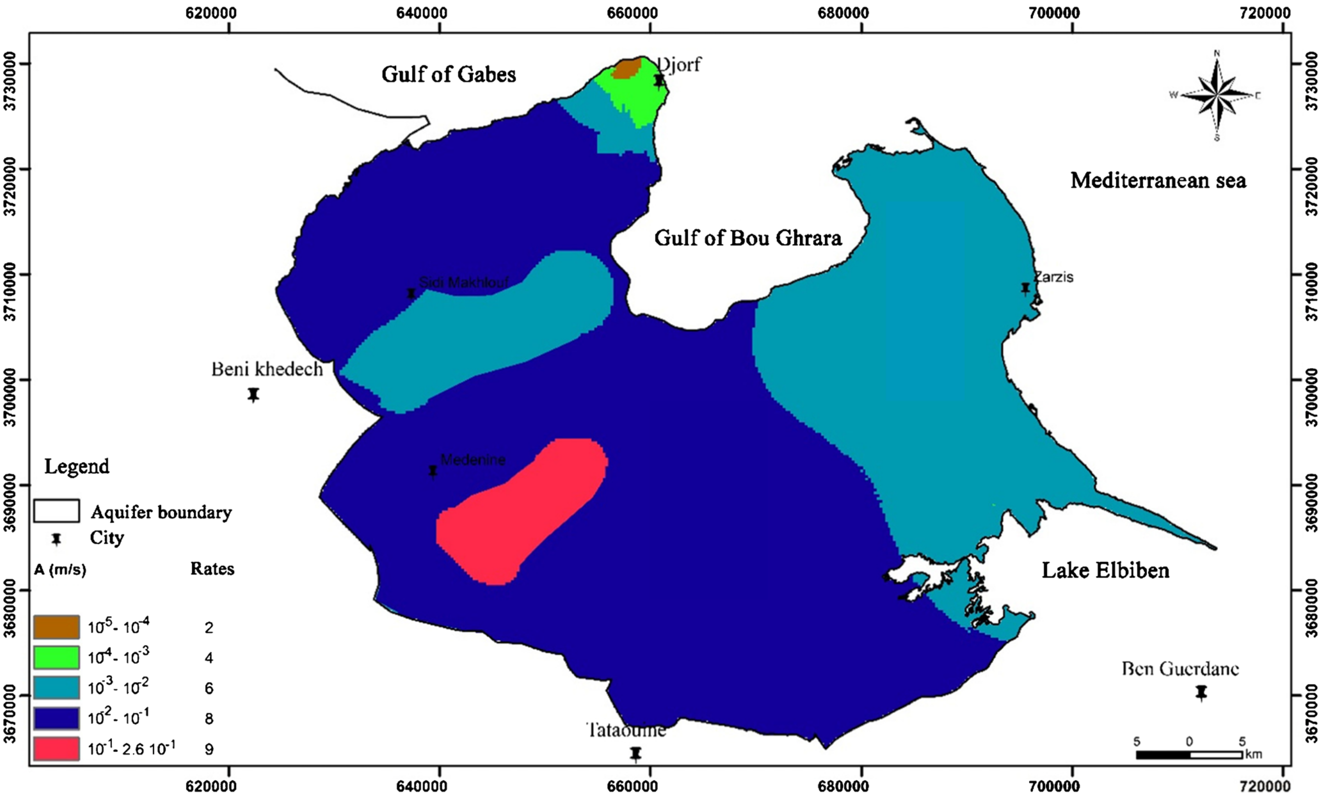

Fig. 11 Aquifer hydraulic conductivity (*A*) map

to the closest of the coastal line, respectively. The wells located at the shore line are the more exposed to the seawater intrusion and make it more vulnerable. This parameter will be multiplied by a weight of 4 when calculating the GALDIT index.

Impact of existing status of seawater intrusion

Usually, the chloride concentration of groundwater describes the extent of saltwater intrusion.

In this study, two ratios were used to determine the impact of existing status of seawater intrusion (*I*) factor. The Cl/HCO_3 ratio was used. Generally, chloride ion dominates in the seawater; nevertheless, it is available in small quantities in groundwater. It is to highlight that when Cl/HCO_3 is greater than 1.5, the groundwater may be considered to be contaminated by seawater intrusion (Mahesha et al. 2011). Figure 14 presents the *I* parameter obtained by calculating the Cl/HCO_3 ratio. These values oscillate between 0.22 and 6.19. It was possible to classify them into 10 intervals whose their relative rates vary from 1 to 10. Furthermore, the *I* parameter was provided by the determination of the SO_4/Cl ratio. The SO_4 is a characteristic of the fresh groundwater. If the SO_4/Cl is below 1, the aquifer is affected by the SWI (Saidi et al. 2013). The *I* parameter map shows only three classes where the values range from 0.9 to 1.75. The smallest value was multiplied by a rate of 10 (Fig. 15). The assigned weigh to this parameter when calculating the GALDIT index is equal to 1.

Thickness of the aquifer

In coastal regions, the SWI magnitude is influenced by the thickness or saturated thickness of an unconfined aquifer (Chachadi 2005). Obviously, the larger the aquifer thickness, the greater will be the SWI volume (Sophiya and Syed 2013). The rate system assessed to the *T* parameter increases when the aquifer thickness upsurges.

The measurement of the aquifer thickness (*T*) in the study area shows values varying from 10 to more than 20 m. Five significant intervals were distinguished and were multiplied by a rate ranging between 6 to 10, going from the lowest to the highest thickness values (Fig. 16). The Djeffara of Medenine coastal aquifer is manifested by a thickness greater than 20 (covers almost the entire of the areas) which makes the aquifer vulnerability to the SWI more significant.

Vulnerability map using GALDIT method

Once the six parameters were determined, the superposition of these relative layers was possible. The GALDIT index was calculated by applying Eq. 1 using "Map Algebra" function in ArcMap 10.1 software. The index distribution makes

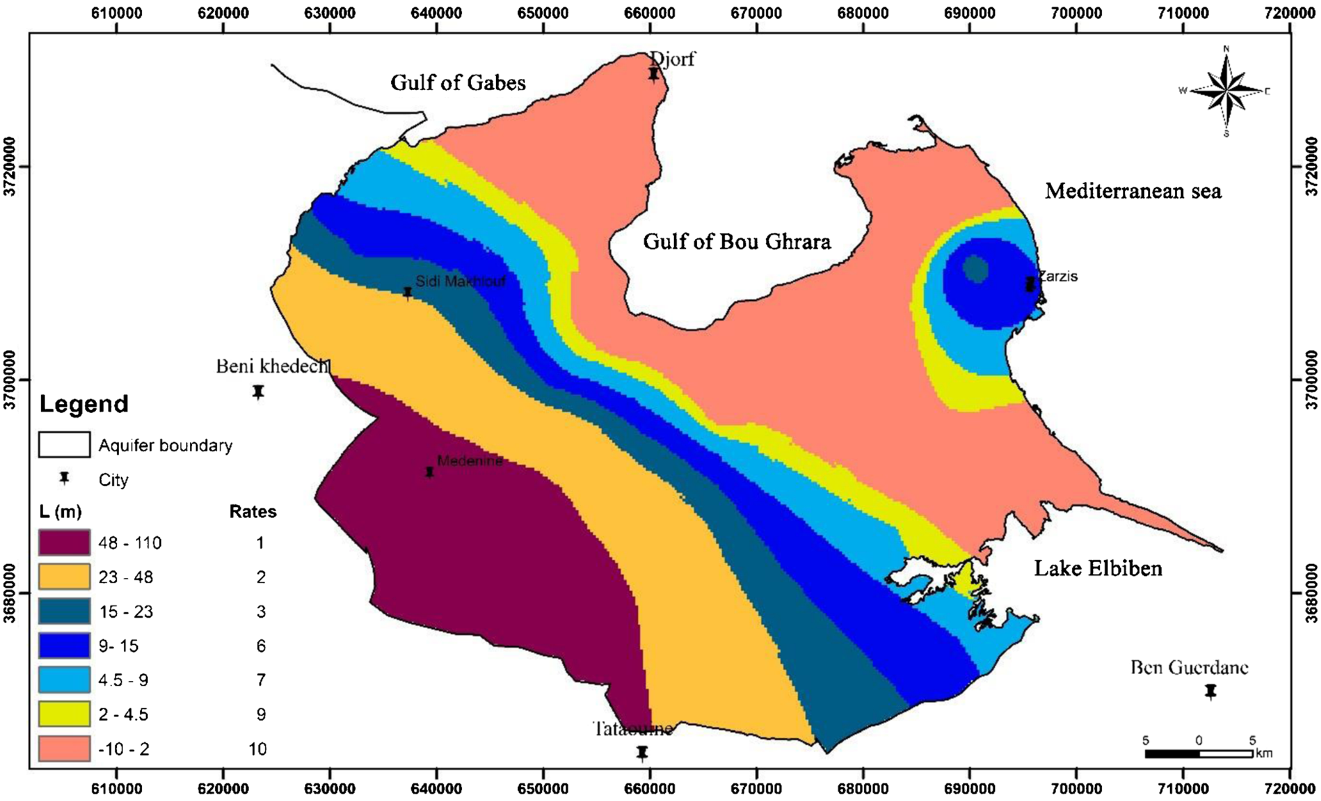

Fig. 12 Height of groundwater level above the sea (*L*) map

possible the identification of the areas more likely to be affected by the SWI.

GALDIT model using the Cl/HCO$_3$ The obtained vulnerability map (1/500000) using GALDIT model for the Djeffara of Medenine coastal aquifer shows a GALDIT index varying between 3 and 9 (Fig. 17). It was possible to classify these indices into three classes of vulnerability: low (3–5), moderate (5–7.5), and high (> 7.5). This assessment proves the spatial spreading of the GALDIT index in the study area. The high degree of vulnerability characterizes mainly the coastal areas (discharge areas). These areas are characterized by an unconfined aquifer type, a high hydraulic conductivity (sand and gravel, conglomerate), an important groundwater level above the sea (− 10 to 2 m), and an impact of existing status of seawater intrusion (Cl/HCO$_3$) which oscillates between 0.22 and 6.19. While, the low vulnerability classes categorize the western (recharge areas) and the central areas of the study area which are far from the coast. As a result, the possibility of the SWI becomes very high for the coastal regions.

GALDIT model using SO$_4$/Cl The second GALDIT map for the SWI of the study area was developed by determining the impact of existing status of seawater intrusion parameter using SO$_4$/Cl. The corresponding vulnerability map (Fig. 18) shows also three degrees of vulnerability: low, moderate, and high where the relative index classes were 4–5, 5–7.5, and 7.5–9, respectively. This classification is due to the high permeability (unconfined aquifer), the high hydraulic conductivity, the low piezometric level (< 15 m), the low SO$_4$/Cl ratio, the relatively small distance from the sea (< 1000 m), and the important aquifer thicknesses.

On the other hand, the spreading of the moderate and high degrees was also in relation with the impact of the Sebkhas.

One notices that the obtained vulnerability maps, using the Cl/HCO$_3$ and SO$_4$/Cl ratios, are almost similar. This similitude proves the success using of these two ratios.

The groundwater quality index

The evaluation of seawater intrusion in the Djeffara of Medenine coastal aquifer was assessed by using Piper diagram ($GQI_{Piper(mix)}$ and $GQI_{Piper(dom)}$). The obtained results of $GQI_{Piper(mix)}$ show values varying from 29.75 to 61.57. The groundwater belongs to domain IV (mixed CaMgCl) which means that the study area groundwater was classified as mixed water. This index may possible the indication of early signs of seawater intrusion. The $GQI_{Piper(dom)}$ results show that values vary between 23.05 and 41.89. These values were classified into two water domains (IV and V), which illustrate the mixed water types Ca-Mg-Cl and Ca-Cl, respectively. The corresponding $GQI_{Piper(mix)}$ and $GQI_{Piper(dom)}$ indices confirm that the values fall within designated ranges for each domain.

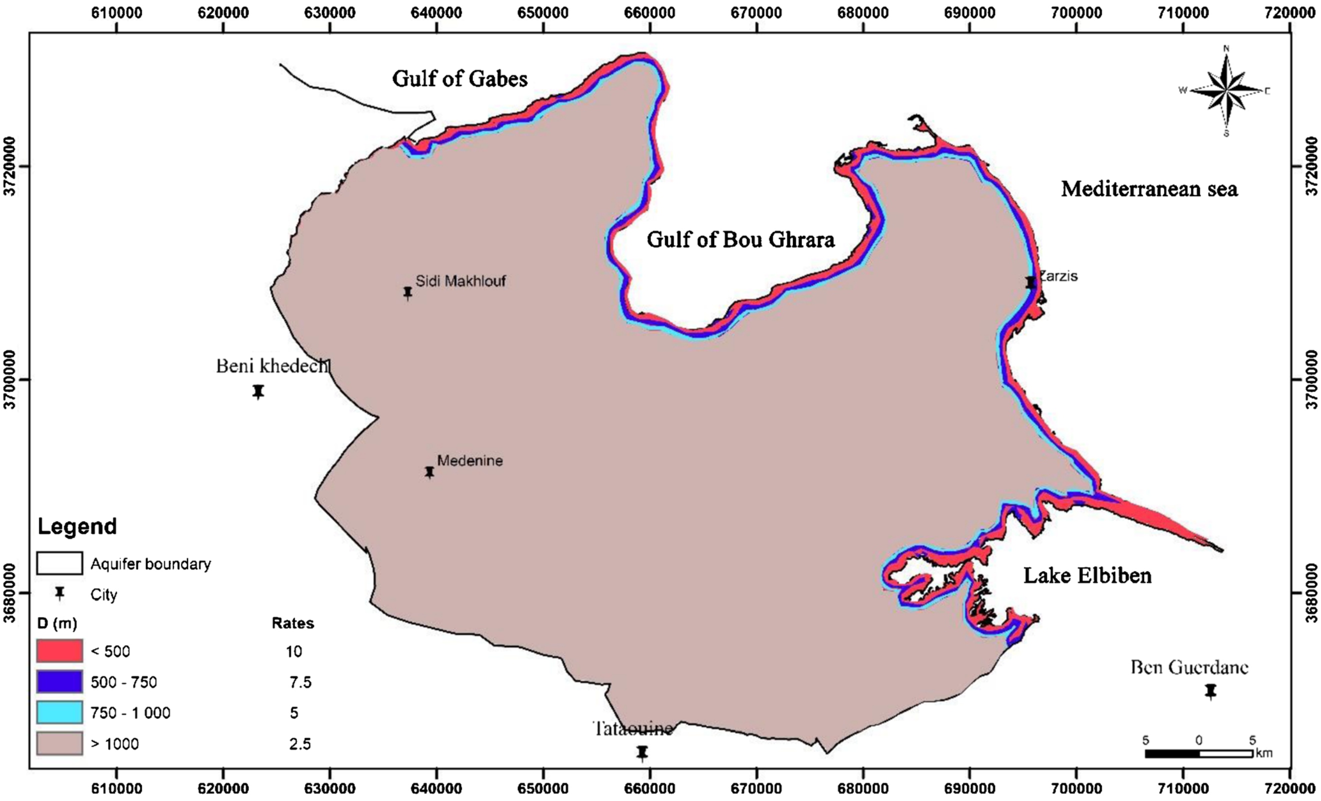

Fig. 13 Distance from the shore (*D*) map

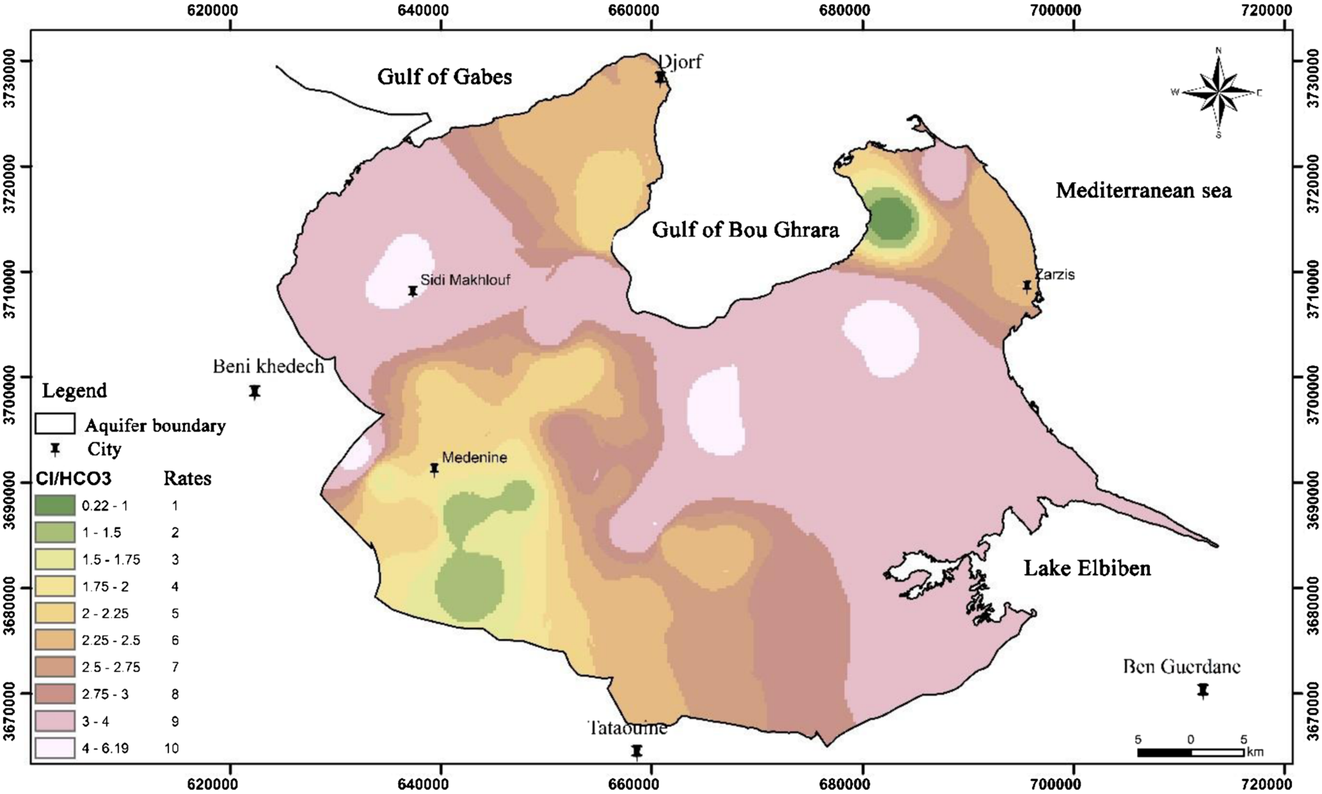

Fig. 14 Impact of existing status of seawater intrusion map using Cl/HCO_3

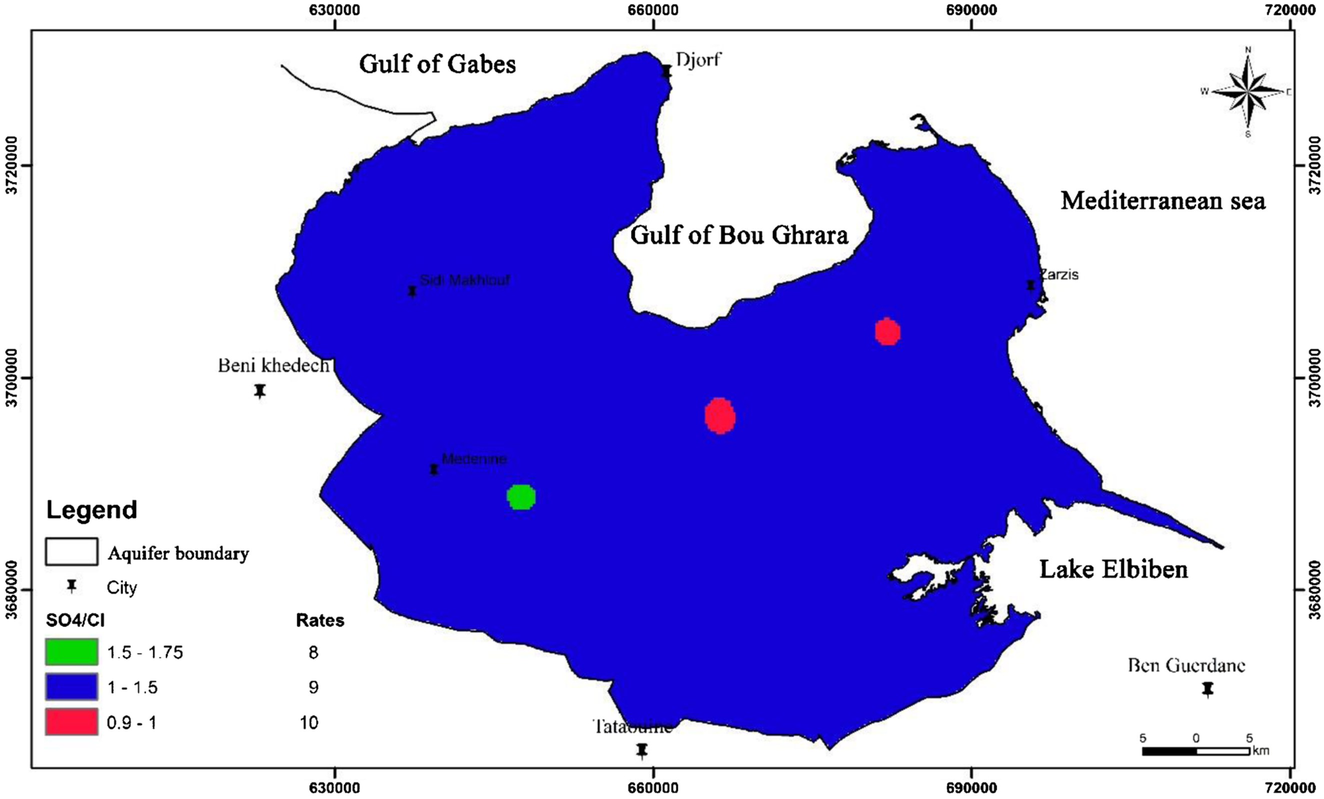

Fig. 15 Impact of existing status of seawater intrusion map using SO_4/Cl

In addition, the groundwater quality index for seawater intrusion (GQI_{SWI}) was used to evaluate the actual state of the SWI. It was calculated based on the chemical composition concentrations. Based on comparison with the literature results (Table 3), the index values which are above 75 characterize freshwater and those below than 50 categorize saline groundwater and seawater. Values ranging between 50 and 75 characterize the mixed type. Usually, the GQI_{SWI} and $GQI_{Piper(mix)}$ increases when the f_{sea} decreases.

In the study area, the GQI_{SWI} values range between 61.8 and 74.5 (Fig. 19). Based on this model, the Djeffara of Medenine groundwaters was classified as mixed water to fresh water. The low values, located at the coastal regions and around the Sebkhas zones, indicate the impact of the groundwater salinization.

Using this model, the obtained results corroborate these obtained by the GALDIT model. Then, the GALDIT, GQI_{SWI} maps, and hydrochemical indicator results obviously support the presence of seawater intrusion in the Djeffara of Medenine coastal aquifer, chiefly in the east and southeastern part of the study area where the Sebkhas influence was notable and the coastal strip areas. However, the spreading of saline water as far as the Sabkhas noticed in the central zones of the study area can be attributed to the water quality deterioration more than to seawater intrusion. It may be caused by the leaching of Triassic deposits located at Tebaga and Dhaher Djebel, also to the Triassic outcrop at several Wadis. So, the existing saline water in these regions can be explained by water-rock interaction.

As deduction, the GALDIT and GQI_{SWI} approaches provide a better understanding of the SWI processes in the aquifer.

Model validation

Since the electrical conductivities (EC) values are a significant index to identify the seawater intrusion, they were used to validate the obtained results for this study. The GALDIT model was validated by superposing the EC values and the GALDIT vulnerability map using the Cl/HCO_3 (Fig. 17) and the GALDIT vulnerability map using the SO_4/Cl (Fig. 18). These correlations show that the high EC values coincide with the areas characterized by a moderate to high degrees of vulnerability, whereas the low values characterize the central and the southwestern parts of the study area, that are characterized by a low vulnerability class. We note the presence of some high EC values far to the coastal line in areas with low vulnerability degree. This is due to the dissolution of evaporitic deposits.

Moreover, the superposition of the EC values and the GQI_{SWI} map (Fig. 19) shows a significant correlation. The high EC values coincide with the low index values.

These results prove that these models were successfully applied to the Djeffara of Medenine coastal aquifer. This

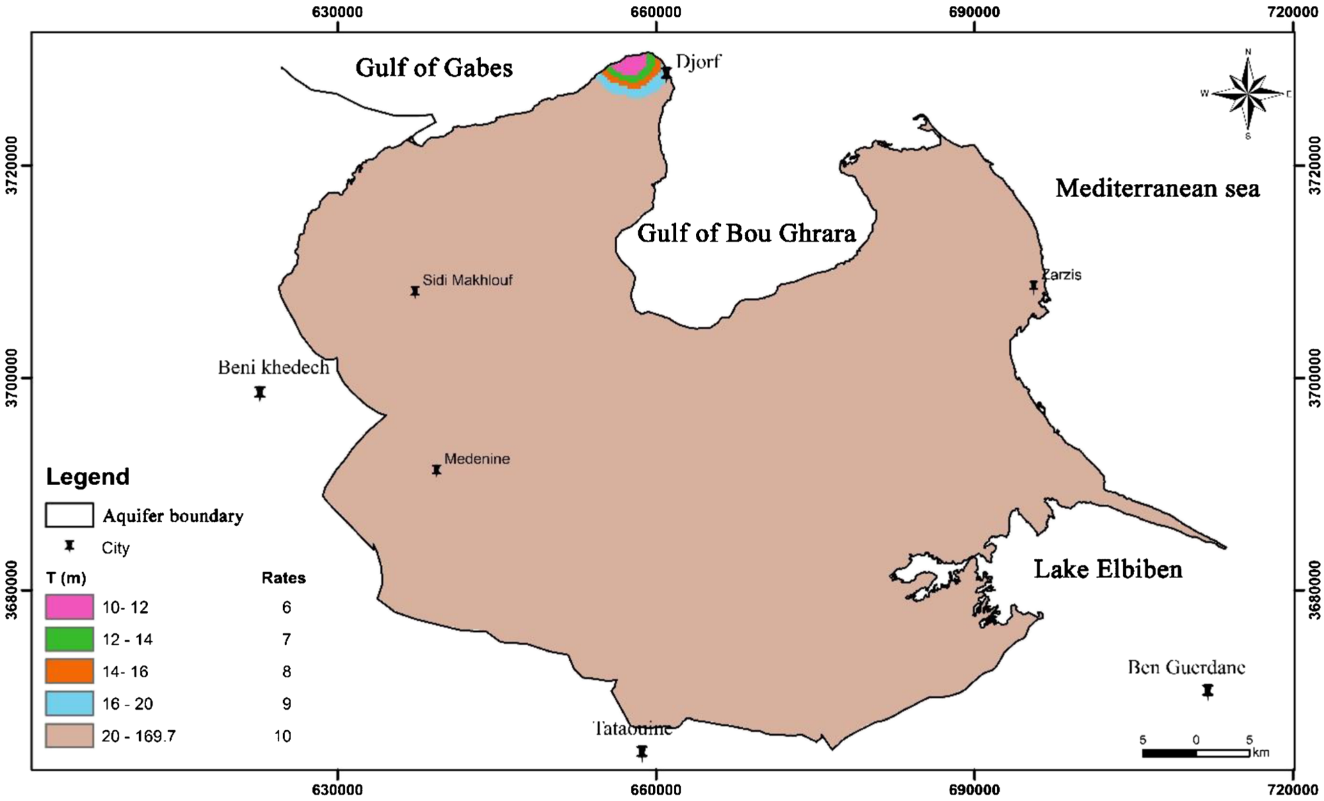

Fig. 16 Thickness map of the aquifer (*T*)

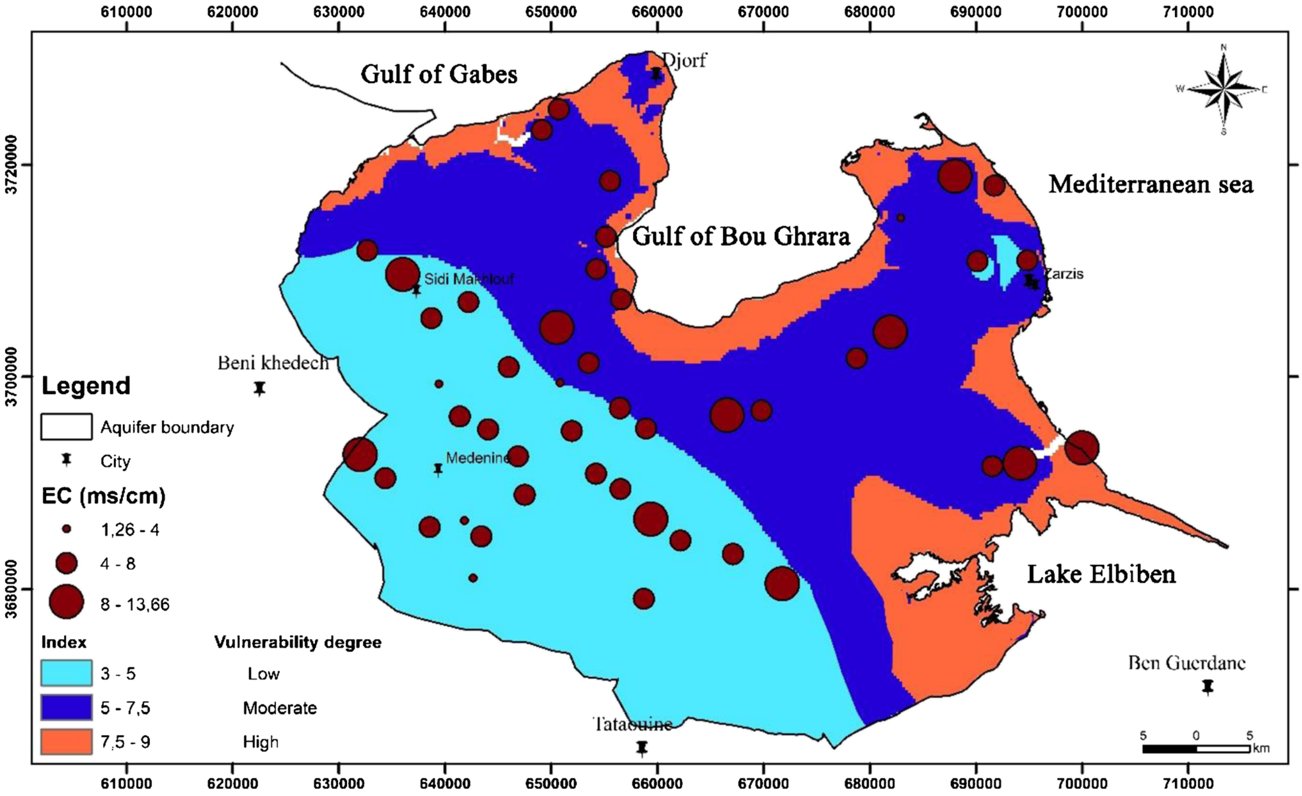

Fig. 17 GALDIT map using Cl/HCO_3 validation with EC values

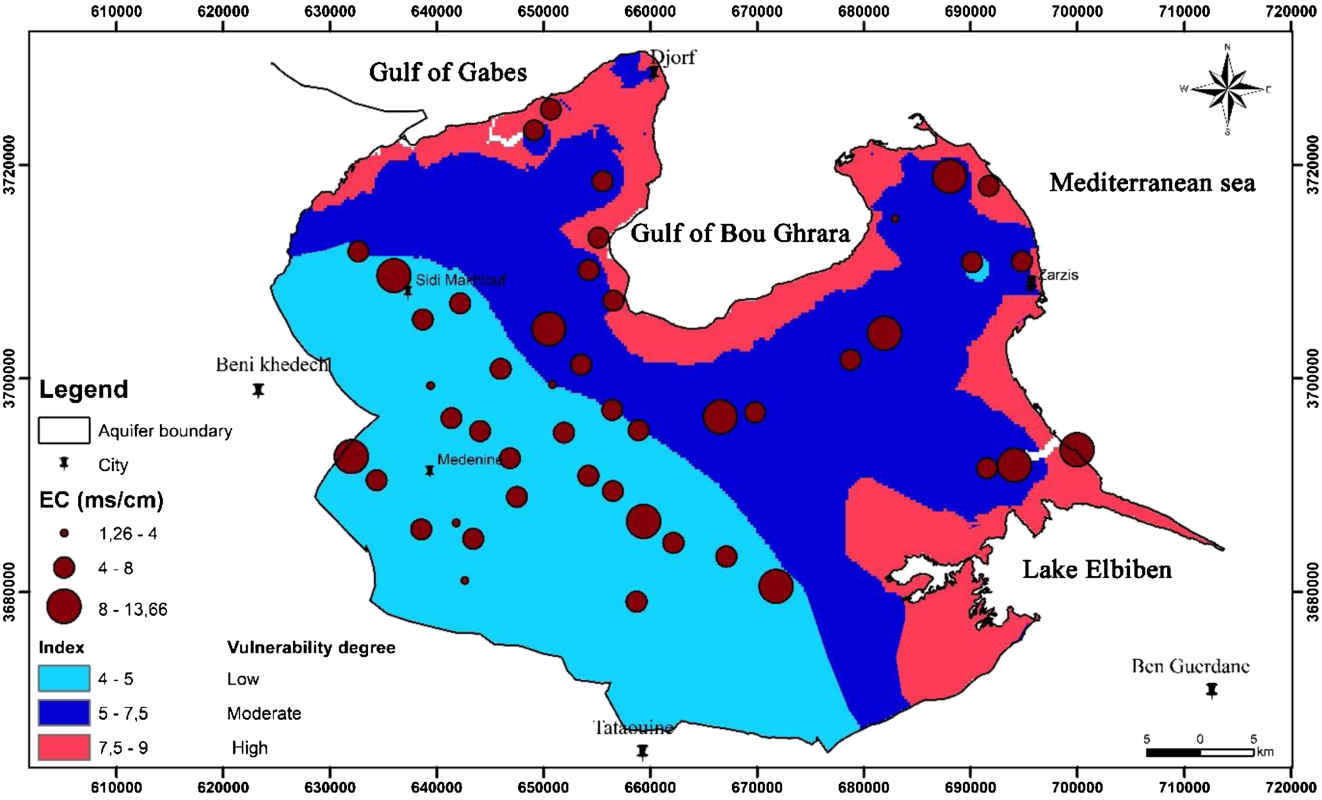

Fig. 18 GALDIT map using SO_4/Cl validation with EC values

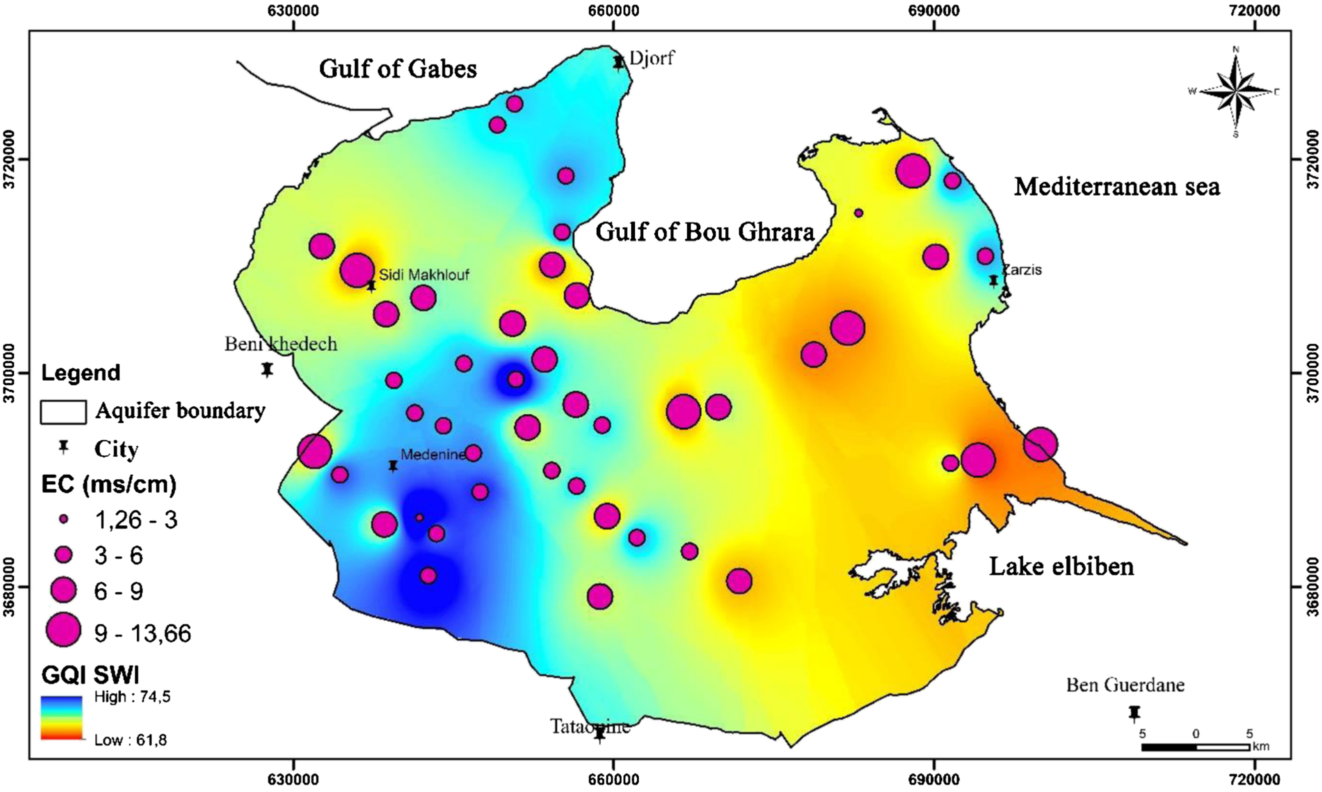

Fig. 19 GQI_{SWI} map validation using EC values

aquifer is threatened by both seawater intrusion and groundwater salinization caused by the Sabkhas influences.

According to this study, the use of such models to assess the groundwater vulnerability against seawater intrusion is recommended.

Conclusion

This study investigated the assessment of groundwater vulnerability against seawater intrusion, based on three recently proposed methods to recognize and understand the spatial evolution of saltwater intrusion in the Djeffara of Medenine coastal aquifer. All these methods were applied using GIS techniques. Firstly, the GALDIT method was applied. The vulnerability models show three degrees: low (< 5), moderate (5–7.5), and high (> 7.5). They indicate that the moderate to high vulnerability class covers the coastal regions of the study area.

Secondly, the groundwater quality index for seawater intrusion was calculated by using the $GQI_{\mathrm{Piper(mix)}}$ and $GQI_{\mathrm{Piper(dom)}}$ indices. Then, it was possible to compare Piper results with those of other methods. Results show that the study area groundwater has almost mixed water types Ca-Mg-Cl (domain IV) and Ca-Cl (domain V). The groundwater quality index for seawater intrusion (GQI_{SWI}), resulting by the combination of the seawater fraction index ($GQI_{f\mathrm{sea}}$) and the $GQI_{\mathrm{Piper(mix)}}$ of the Piper diagram, was used. It shows more representative performance over each method. The obtained results indicate that most of groundwater samples still fell into the same type (mixed water).

The GALDIT and GQI_{SWI} revealed that the coastal zones are the most threatened by the seawater intrusion. The obtained results can be used as a synthetic document for realistic management of groundwater quality.

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