GIS-Based Model for Vulnerability and Seawater Intrusion Risk Assessment by Combined Chemical Indicators and GALDIT Tools: The Case of a Coastal Aquifer in Monastir, Tunisia

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Abstract Due to an increase in population and agricultural activities in coastal areas, seawater intrusion is a major threat to the rapidly depleting groundwater resources around these areas. This research was refined with local inputs to study one of the most sensitive Tunisian coastlines, Monastir. With the aim of tackling the groundwater degradation problem, an approach combining a survey of some dissolved ions and the Geographical Information System (GIS)-based hydrogeological index, named the GALDIT method, was applied to evaluate the aquifer's vulnerability, as a technique for assessing seawater intrusion potential. This allowed to prepare thematic maps for seawater indicators and to develop a final vulnerability map. The derived map illustrates that the most affected areas in our case are the coastal zones of the aquifer and the northeastern part in the proximity of the Moknine sabkha, having the highest GALDIT Index, between 70 and 90. This study aims to propose some agricultural policies to conserve groundwater resources and groundwater management alternatives for this coastal aquifer. It could also serve as a scientific basis for sustainable groundwater planning and management in Monastir.

Keywords Monastir aquifer · Hydrochemical indicators · Seawater intrusion modelling · GIS technique · Groundwater management

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1   Introduction

The coastal aquifer is made up of a different composition of water-bearing permeable rocks and unconsolidated materials like gravel, sand, and silt [1, 2]. In recognition of the need for efficient methods for protecting groundwater resources from future contamination, and especially from seawater intrusion, resource managers have sought to develop different models and methods for determining which areas are more contaminated like the GALDIT method [3, 4]. This work will attempt to integrate the GALDIT model and the analysis of hydrochemistry maps, with aims to assess the groundwater vulnerability in the Monastir coastal aquifer. In addition, the integration of such approaches can be a more effective and consistent way of assessing the extent and magnitude of seawater intrusion. To overcome the problem associated with groundwater decline and quantify the degradation using the map of vulnerability to seawater intrusion, it is crucial to know and quantify the vulnerable areas of the coastal phreatic groundwater of Monastir, as a support that can focus on the most important causes of resource degradation and which will be utilized to set up preliminary management options in the study area [5, 6].

2   Materials and Methods

This article presents the analytical results of 37 samples collected in October 2018 from shallow wells. The geographical coordinates of each well were captured using a handheld Garmin e-Trex GPS receiver. The analyzed water quality parameters include salinity, conductivity, and concentration ions mainly concerning the anionic elements chloride ($\mathbf{Cl^-}$), sulfate ($\mathbf{SO_4^{2-}}$), bicarbonates ($\mathbf{HCO_3^-}$), and nitrate ($\mathbf{NO_3^-}$), while cationic ($\mathbf{Ca^{2+}}$), sodium ($\mathbf{Na^+}$), magnesium (Mg^{2+}), and potassium ($\mathbf{K^+}$) were estimated in the accredited and certified Water Analysis Laboratory of Tunisian Environment (PPE laboratory), using atomic absorption spectrometry. Bicarbonates were determined by the volumetric method, ($\mathbf{Cl^-}$) was determined using the Mohr Method and finally ($\mathbf{SO_4^{2-}}$) was spectrophotometrically determined.

3   Results

Based on Table 1, the GALDIT map shows three classes, depicts the different degrees of the aquifer's sensitivity to seawater intrusion along the Monastir coastal aquifer. In fact, the GALDIT Index ranges from 26 to 96. The highest class of vulnerability covers particularly the northeastern part and the eastern part of the aquifer (the coast) (Fig. 1f). The aquifer system in Monastir is lodged in Mio-Plio-Quaternary clastic deposits, essentially composed of sand and clayey sand levels with variable permeability. The aquifer is mainly semi-confined and the rating of groundwater

Table 1 Classes according to the GALDIT method [8]

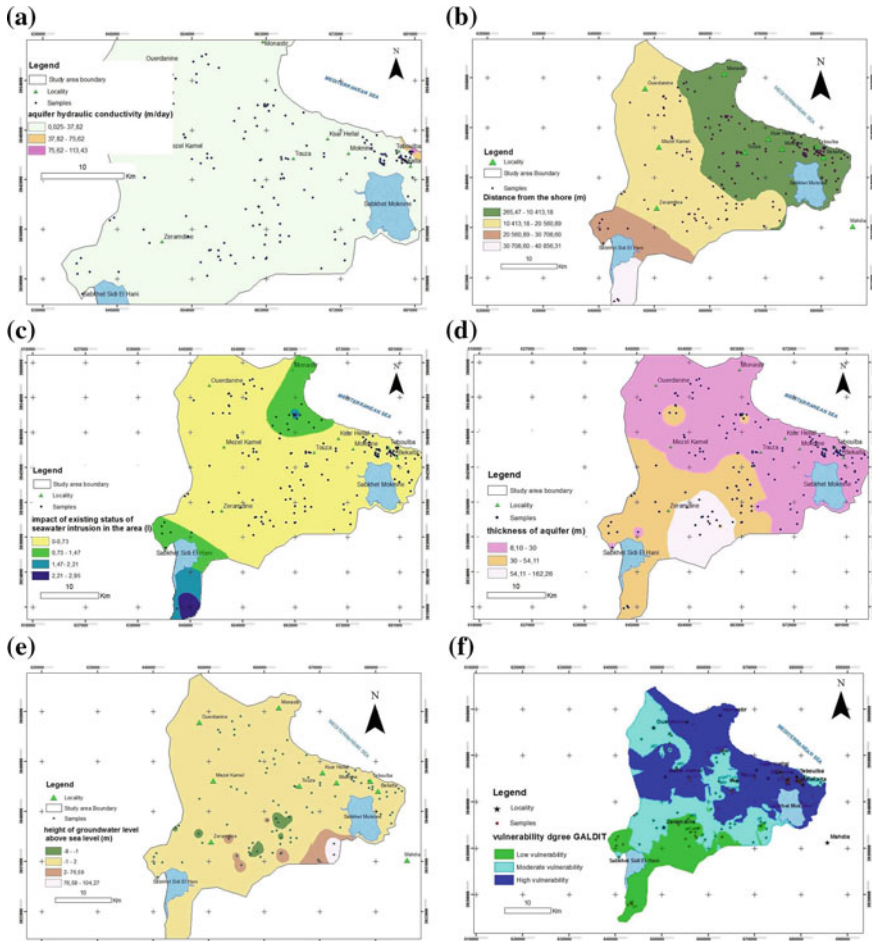| GALDIT index	Vulnerability class
30–50	Low vulnerability
50–70	Moderate vulnerability
70–90	High vulnerability

Fig. 1 The GALDIT model parameters raster maps

occurrence corresponds to the highest weight values of G_w given (8, 9, 10). The hydraulic conductivity data (A) were extracted from the pumping test and ranged from 0.025 to more than 75.62 m/day (Fig. 1a). The highest hydraulic conductivity value has been recorded in the quasi-totality of the study area with values exceeding the international norms. The height of groundwater above mean sea level (L) was

drawn in the current study from the piezometric curve level of 106 groundwater well measurements during 2006. The values ranged from −8 to 104.27 m (Fig. 1e). The distance from the shore (D), according to the GALDIT procedure, was estimated according to three distances to the coastline ranges (500, 750, and 1000 m) (Fig. 1b). The impact of the existing status of seawater intrusion (I), the ratio ($Cl^-/(HCO_3^-$ $+ CO_3^-$)) is often used as a criterion to identify the extent of seawater intrusion into coastal aquifers [3–5]. The values of (Cl^-/HCO_3^-) are almost within a single interval (>4) and, therefore, a single score (10). The remaining area shows a ratio greater than one, indicating the presence of seawater intrusion. This is why the ratio (SO_4^{2-}/Cl^-) was considered as an additional parameter for assessing the impact of existing marine intrusions (Fig. 1c). This ratio was used as a natural tracer of the residence time of seawater in the aquifer. The Monastir aquifer thickness (T) ranges from 8.10 to 162.26 m (Fig. 1d).

4 Discussion

The aquifer vulnerability method requires validation to reduce the subjectivity in the selection of rating and to increase reliability [7]. For this reason, by applying a simple linear regression analysis between TDS concentration and EC values versus GALDIT index, it is proved that there is a quite satisfactory correlation ($r^2 = 0.8$ and $r^2 = 0.77$, respectively). Consequently, the applied index is well validated by the field measurements and chemical analyses. Besides, the seawater intrusion phenomenon is considered to be important and alarming in that case. This would result in further groundwater salinization (toward inland). Therefore, groundwater would become inappropriate even for resistant cultivations. Furthermore, the seawater intrusion phenomenon will become irreversible due to the high permeability (unconfined aquifer), the high hydraulic conductivity (20 m/day), the shallow groundwater table (<8 m), the high Cl^- concentration (hence a low $SO4^-/Cl^-$ ratio), the thin aquifer (<10 m), and the relatively low-distance separating wells from the sea (<1,000 m). As a consequence, in this area, we should allow neither additional wells nor high-risk activities in order to preserve the groundwater resource and reduce the environmental pollution hazard.

5 Conclusions

The groundwater of coastal Monastir is an aquifer system formed by Mio-Plio-Quaternary deposits. The GALDIT method and GIS techniques, added to hydro-chemical analyses of the groundwater, are used to evaluate the impact of the increase of salt level, as well as to assess potential seawater intrusion in the study area, particularly in the coastal areas. Six environmental parameters—which are ground-water occurrence, aquifer hydraulic conductivity, height of groundwater level above

sea level, distance from the shore, impact of existing status of seawater intrusion, and thickness of aquifer—were used to represent the hydrogeological setting of the study area. Consequently, the southern part of the aquifer will be more suitable for the implantation of potential anthropogenic activities and the northern part should be considered by the managers in order to minimize the groundwater contamination by seawater intrusion.

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