A multi-tracer approach to understand the hydrogeochemical functioning of a coastal aquifer located in NE Tunisia

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Abstract El Haouaria aquifer (northeast Tunisia) is one of the typical examples of semi-arid coastal aquifers which have been intensively exploited during the last few years. In order to implement a strategy of sustainable groundwater management of El Haouaria aquifer a proper understanding of the hydrogeological systems is necessary. In this context, a multi-tracer approach has been carried out in the El Haouaria aquifer system, based on major ions and stable isotopes analysis. The piezometric study confirms the overexploitation of the aquifer, especially at the centre of the aquifer, where the water table is lowered 2.5 m below sea level. The geochemical data was used to characterize and classify water samples and study the water–rock interaction based on a multitude of ion plots and diagrams. Stable isotopes were useful tools to provide valuable information about the origin and the circulation patterns, to understand the recharge processes, and to differentiate between mineralization origins.

Key words water resources; hydrogeochemistry; stable isotopes; multi-tracer; ephemeral coastal plain; Cap-Bon region; El Haouaria aquifer; Tunisia

INTRODUCTION

In arid and semi-arid regions, the intensive exploitation of groundwater resources is causing a decrease in groundwater levels, degradation of water quality (Lachaal *et al*., 2010, 2011; Liu *et al*., 2013), and seawater intrusion in coastal areas (Dokou & Karatzas, 2012). A proper understanding of the groundwater system behaviour and its assessment is essential in order to define a sustainable management plan which can cope with the future impact of the global change on water resources.

Aquifer complexity, as well as the lack of hydrologic data, requires more than a single and traditional hydrological investigation to understand the hydrogeochemical functioning of an aquifer system for its sustainable management. A multi-tracer approach integrating chemical and isotopic methods can be applied in order to clarify the schema of the aquifer's evolution.

Similar to other Middle East and North Africa countries, Tunisia is a water stressed country. It has an average of 486 m^3 per capita of renewable water availability. Tunisia has a semi-arid to arid climate with a mean annual rainfall of 230 mm $year^{-1}$ (INM, 2005). The water resources are estimated at about 4800 Mm^3 $year^{-1}$, divided into 2700 Mm^3 $year^{-1}$ (56.25%) of surface water, 1400 Mm^3 $year^{-1}$ (29.15%) of deep aquifers, and 700 Mm^3 $year^{-1}$ (14.6%) of shallow aquifers (DGRE, 2005). Excessive groundwater extraction in the coastal regions of Cap-Bon and Sahel has resulted in saline intrusion in many areas leading to the degradation of groundwater quality in many regions (Chkirbane *et al*., 2013). El Haouaria aquifer (northeast Tunisia) is one of the typical examples of coastal aquifers in semi-arid regions which have been intensively exploited during the last few years. In fact, the piezometric levels have decreased and the water quality has deteriorated.

The aim of the paper is to establish a good understanding of the hydrogeological systems, through a quantitative and qualitative assessment of groundwater resources and the identification of the major hydrogeochemical processes occurring in the aquifer, in order to implement a strategy of sustainable groundwater management of El Haouaria aquifer and to provide the prospective scenarios of groundwater evolution.

GEOGRAPHICAL AND HYDROGEOLOGICAL SETTING

The study area is located in the El Haouaria plain. It belongs geographically to Cap-Bon region (northeast Tunisia), with a total area of 500 km^2 between the 665000 and 690000 north parallels and the 4085000 and 4105000 east meridians (Universal Transverse Mercator System) (Fig. 1(a)). The study area is bound in the North by Jbel El Haouaria, in the South by Azmour fault, and in the West and East by the Mediterranean Sea (Fig. 1(b)).

The major geological outcrops in the study area are mainly Mio-Plio-Quaternary deposits (Fig. 1(c)). They are formed mainly by sandstone and marl deposits. The Pliocene outcrops in the El Haouaria plain are in an underlying position to the coastal and marine Quaternary deposits.

The study area is characterized by a Mediterranean semi-arid climate with an average annual precipitation of 420 mm (INM, 2005). The precipitation is characterized by a strong spatio-temporal variability; it fluctuates between 200 and 500 mm. The majority of precipitation (60%) is concentrated between November and March. The annual mean temperature in the region is about 17°C. The relative humidity varies between 71 and 81% (INM, 2005).

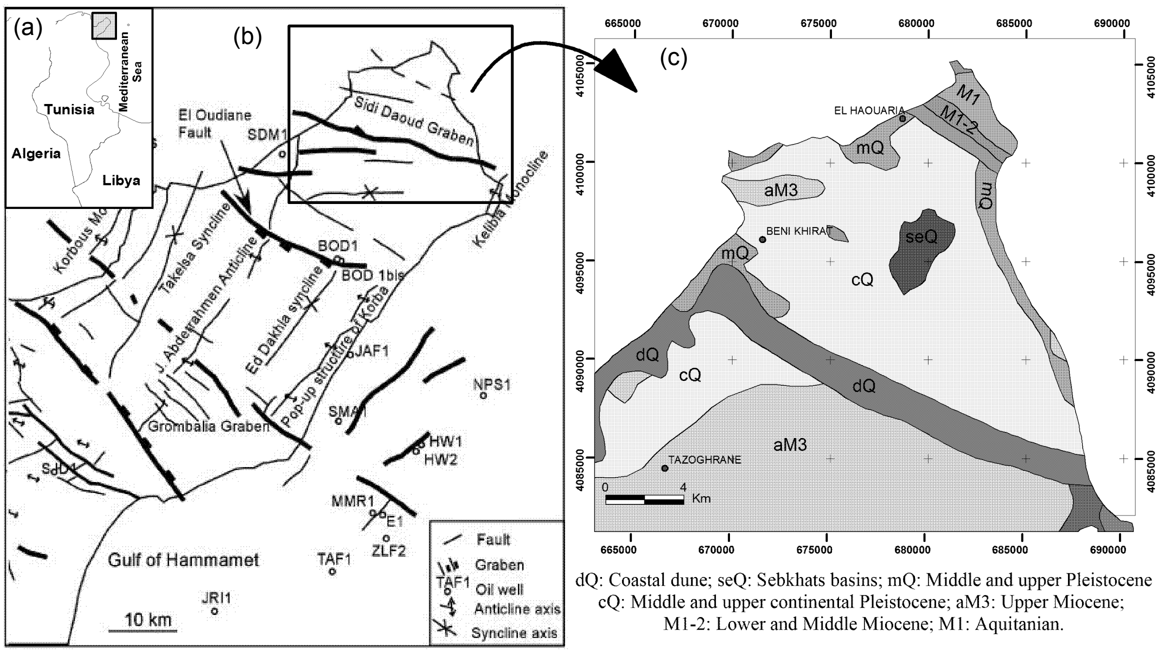

Fig. 1 (a) Geographical location, (b) structural features of the Cap-Bon region (Adouani & Aissaoui, 2003), and (c) geological map of the study area (Ben Haj Ali *et al.*, 1985).

HYDROGEOLOGY OF HAOUIRIYA AQUIFER

The Cap-Bon region is one of the most productive agricultural regions in Tunisia, which is reflected by the high water demand and consumption. The agricultural growth in the region was triggered by a spectacular increase of the tube wells used for irrigation dictated by the high-yielding varieties of crops. The water demand for irrigation is principally fulfilled from groundwater resources. El Haouria aquifer is one of the most important groundwater flow systems in the Cap-Bon region used principally for irrigation purposes.

From a structural view point, the El Haouaria aquifer is characterized by a synclinal depression bounded by the sea and by Oum Dhouil formation outcrops. The synclinal is covered by 200 m of Plio-Quaternary deposits (Aouadi, 2003). The aquifer consists of two hydrogeological systems: shallow and deep groundwater separated by a clayey semi-permeable layer (Aouadi, 2003).

Excessive withdrawal of groundwater for irrigation is causing declines in water levels throughout the region. The El Haouaria groundwater extraction increased from 12.5 Mm^3 $year^{-1}$ in 1973 to 71.75 Mm^3 $year^{-1}$ in 2002.

SAMPLING AND ANALYTICAL TECHNIQUES

In order to study the spatial and temporal piezometric evolution, and the result of the intense exploitation, we selected 74 piezometers and observed wells that cover all the groundwater area during the period of March 2013. The well altitudes are determined using GPS Trimble® R3, and static water levels are measured by piezometric probe.

To study the water chemistry, 19 groundwater samples were collected in the same period as the piezometric survey. These water samples were collected in clean polyethylene bottles. After sufficient time, which allowed the stabilization of the water electrical conductivity, the bottles were thoroughly rinsed 2–3 times with the sample water to be taken before the water was sampled. Temperature (T), electrical conductivity (EC), and pH were measured *in situ*. SO_4^{2-} concentration was determined using the gravimetric method. Cl^- was analysed using titration (Mohr method). HCO_3^- and CO_3^{2-} were measured by titration with sulphuric acid. Cations Ca^{2+}, Na^+, Mg^{2+} and K^+ were analysed by atomic absorption spectrometer. In addition, stable isotopes (^{18}O and ^2H) of 10 groundwater samples were analysed using an isotopic liquid water and vapour water analyzer (Picarro L1102-i).

The piezometric and salinity distribution maps were drawn using the kriging interpolation method, Surfer.10 software and ARC Info 10.0 software package.

RESULTS AND DISCUSSION

Piezometric behaviour

The piezometric map of 1971 is the oldest existing data for the El Haouaria aquifer (Fig. 2(a)). The map shows a piezometric level varying between 2.5 and 40 m. It shows a divergent flow from the Jbel El Haouaria in the north and the Azmour fault in the south. On the south side, the water flow is from the Azmour region in two directions northwest–southeast and southwest–northeast. In the north part, the flow direction is from the Jbel El Haouaria following a northeast–southwest direction.

The piezometric map of March 2013 was drawn based on the interpolation of 74 observation wells (Fig. 2(b)). The piezometric map shows the presence of three piezometric depressions located in the southeast, northeast and west parts. The maximum piezometric depression was registered in the aquifer centre where the piezometry is about 2.5 m below sea level. The groundwater recharge area is located in Jebel El Haouaria from the north and in the Azmour fault from the south. The water flows and converges from the recharge area to the piezometric depressions.

The comparison of the piezometric map of 1973 (Fig. 2(a)) and 2013 (Fig. 2(b)) shows the presence of a general lowering of the piezometric depression over the aquifer area. The drawdown exceeds 20 m (in the south of the aquifer).The piezometric depression is caused by the increase of

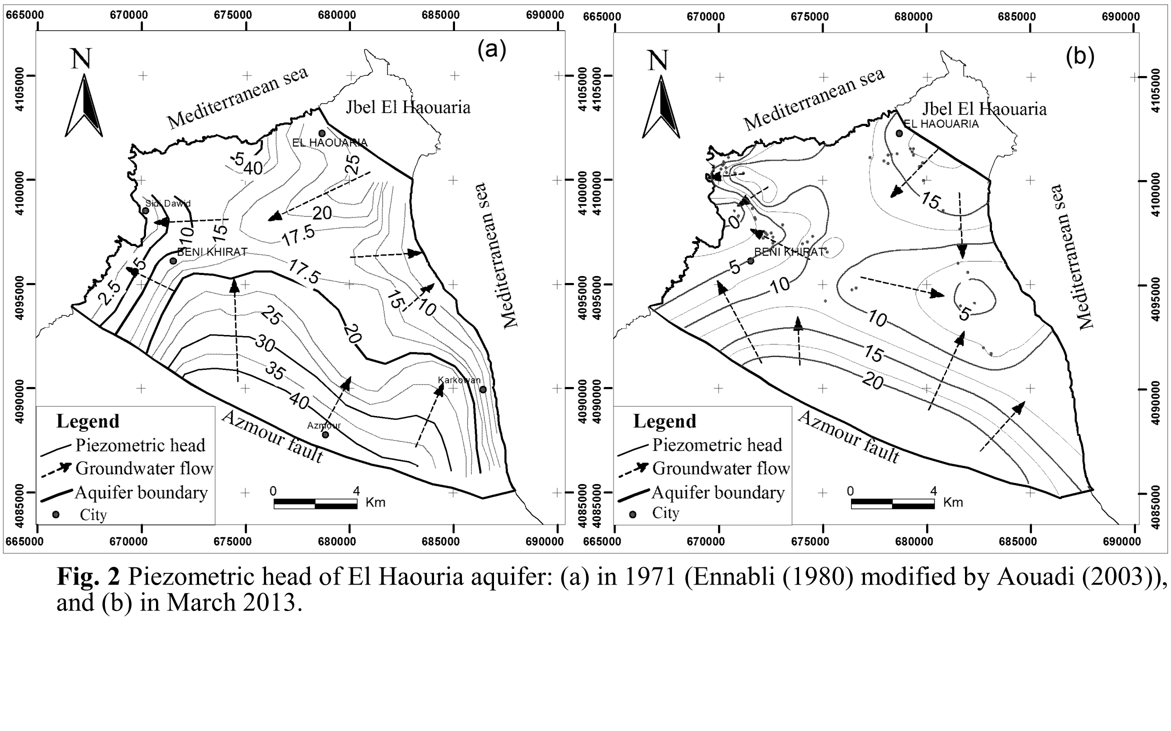

Fig. 2 Piezometric head of El Haouria aquifer: (a) in 1971 (Ennabli (1980) modified by Aouadi (2003)), and (b) in March 2013.

the groundwater pumping. The socio-economic consequence of the groundwater drawdown is the decline of economic viability of the irrigated farming due to the increased depth of the drilled wells and pumping costs. A programme of artificial groundwater recharge from surface waters has been initialized by the government in order to reduce the piezometric depression. The infiltrated artificial recharge began in 1999 by 0.053 Mm^3 $year^{-1}$ in Oued Melloul. Until 2008, a volume of 6.872 Mm^3 of waters was infiltrated to the aquifer (DGRE, 2009).

Groundwater quality

Physico-chemical parameters The El Haouaria aquifer water is characterized by pH values varying from 6.88 to 7.73 being in the range of natural waters standard. The EC is ranging from 1.15 to 10.2 mS/cm. The salinity of El Haouaria aquifer water varies between 0.3 and 3.2 g L^{-1} (Fig. 3). The salinity distribution map of March 2013 revealed the presence of a salinization gradient from east to west in the direction to the sea, corresponding to the main groundwater flow direction. This salinity increase could be explained by a longer contact-time with rocks during water circulation and to the abundance of halite and gypsum in this area. The high salinity is observed in the central and western side of the aquifer which coincides with the piezometric and exploitation anomalies.

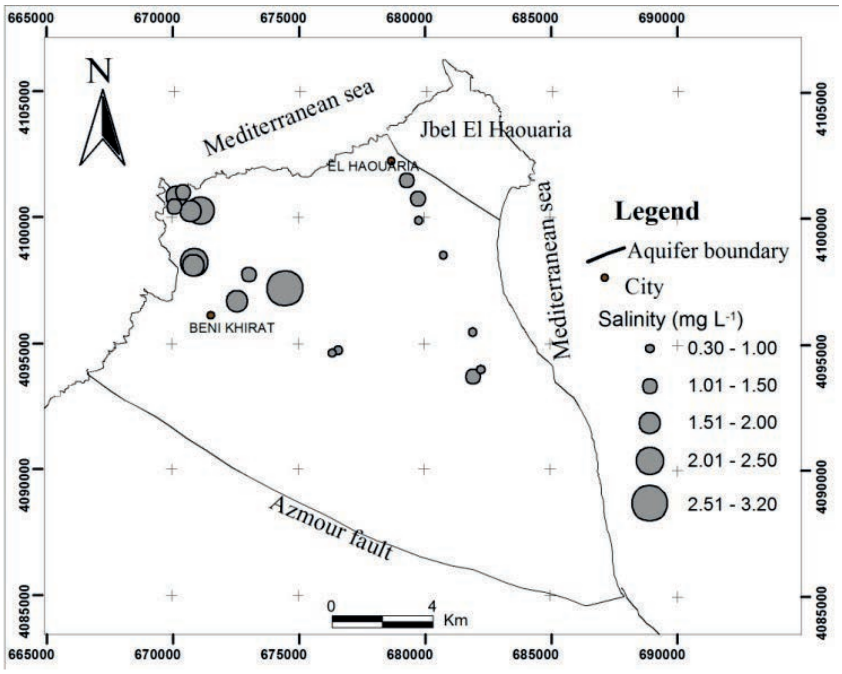

Fig. 3 Spatial distribution of the salinity in the EL Haouaria aquifer in March 2013.

Water types A Piper diagram is a trilinear representation of the major ions composing water samples in order to classify them according to their type or chemical facies. The Piper diagram for the groundwater samples from Haouaria aquifer (Fig. 4(a)) show that they are globally characterized by Cl-SO_4-Ca-Mg type with a relative increase in nitrate which reflects the effect of the chemical and organic fertilizers commonly used by the farmers in the study area.

Stiff diagrams are used to compare the ionic composition of water samples between different locations, depths, or aquifers. The Stiff diagram is a polygon created from three horizontal axes extended on both sides of a vertical axis. Cations are plotted on the left side of the axis and anions are plotted on the right side, both in meq/L. A greater distance from the vertical axis represents a larger ionic concentration. The cation and anion concentrations are connected to form an asymmetric polygon known as a Stiff diagram, where the size is a relative indication of the dissolved-solids concentration. The plotted Stiff diagrams of the water samples taken from El

Haouaria aquifer (Fig. 4(b)) show that most of the sampled wells are characterized by the same facies (Cl-SO_4-Ca-Mg). Nevertheless, they can be divided into two groups: the first is presenting a relatively low TDS, located in the upstream region near the recharge zone and the second showing a relatively high TDS, Na and Cl, generally located near the coastal part of the aquifer. The mineralization of the groundwater in the El Haouaria region is principally controlled by the geological effect and the residence time. In fact, in the upstream region, the groundwater recharge is mainly composed by the rapidly infiltrated rain water and as soon as the groundwater flows until its natural outlet (the Mediterranean Sea), the residence time of groundwater is increasing allowing more contact with the geological formations to enhance their dissolution.

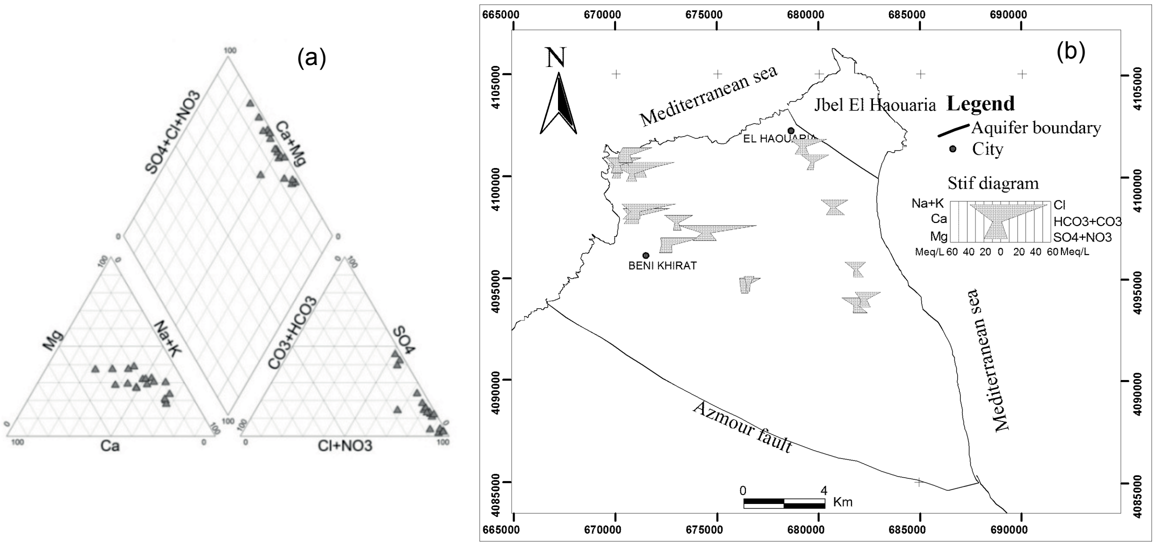

Fig. 4 Diagram representation for water samples of El Haouaria aquifer: (a) Piper diagram, and (b) Stiff diagram.

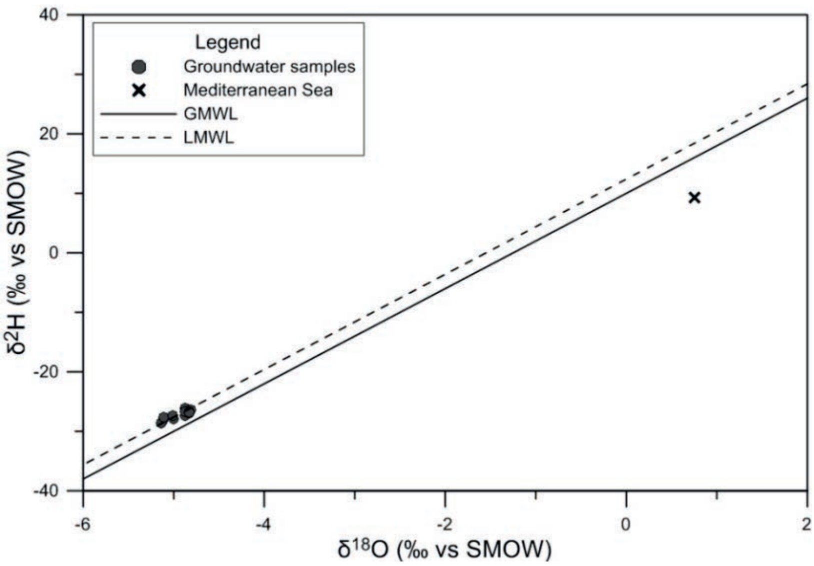

Fig. 5 Delta diagram.

Isotopic data and water origin Oxygen and hydrogen isotopes ($\delta^{18}O$ and δ^2H) are plotted in Fig. 5. The local meteoric water line (LMWL) is a fractionation line that represents the relationship between $\delta^{18}O$ and δ^2H in local rainwater. It was calculated from the weighted annual mean of precipitation in Tunis–Carthage station (no. 6071500), the nearest global network for isotopes in precipitation (GNIP) station. RMWL follows the linear regression: $\delta^2H = 8\delta^{18}O + 12.4$

(Ben Moussa *et al*., 2010). The $\delta^{18}O$ and δ^2H contents of the sampled groundwater varied from –5.14 to –4.81‰ and from –28.60 to –26.06‰, respectively. The samples fall between the regional meteoric water line (RMWL) and the global meteoric water line (GMWL) having the equation $\delta^2H = 8\delta^{18}O + 10$ (Craig, 1961). That could be explained by the fact that the origin of these waters is meteoric and non-evaporated water rapidly infiltrated to the saturated zone. Their different isotopic composition from sea water suggests the absence of any seawater intrusion.

CONCLUSION

In this study, a multi-tracer approach to understand the hydrogeochemical functioning of coastal aquifer used chemical and isotopic analysis. As a consequence of the intense groundwater pumping a piezometric drawdown (varying between 3 and 20 m) and an increase in water salinity were observed in the El Haouaria aquifer. However, the groundwater flow perturbation was recorded in the central part of aquifer, represented by a water flow direction variation from the recharge area to the piezometric depression. The water aquifer was characterised by Cl-SO_4-Ca-Mg facies. The stable isotopes analysis ($\delta^{18}O$ and δ^2H) showed the meteoric origin of water and the absence of seawater intrusion. As a consequence, it seems necessary to implement a sustainable water management programme in the region.

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