Assessment of water qualities and evidence of seawater intrusion in a deep confined aquifer: case of the coastal Djeffara aquifer (Southern Tunisia)

Adel Kharroubi, Soumaya Farhat, Belgacem Agoubi and Zouhir Lakhbir

ABSTRACT

Geochemical analyses of groundwater samples from the Djeffara confined aquifer (Southern Tunisia) were performed. The distribution of saline waters was investigated to identify the origin of the groundwater contamination. The aquifer was shown to be affected by an abnormal increase in groundwater salinity. Near the recharge zone, the groundwater salinity does not exceed 2.5 g l^{-1} but reaches 7 g l^{-1} in the northeast of the study area. Due to over pumping, groundwater level decline is so important that it disturbs the equilibrium between fresh and saline waters. The salinity distribution coupled with the structure and geology of the Djeffara aquifer suggest current seawater intrusion is possible through the deep fault systems affecting the zone. The groundwater level was shown to be highly correlated with the sea level fluctuation in the area near the fault systems, suggesting a communication between the sea and the confined aquifer. Groundwater salinization is probably related to infiltration of seawater through the faults. However, an intrusion on the side of the discharge area of the aquifer may also be possible. The bromide and chlorine analyses coupled with the SO_4/Cl ratio confirmed that the mixing between fresh and saline waters is the main origin of groundwater salinization.

Key words | aquifer, fault systems, groundwater, seawater intrusion

Adel Kharroubi
Soumaya Farhat
Belgacem Agoubi (corresponding author)
Higher Institute of Water Sciences and Techniques,
University of Gabes,
Tunisia,
Cité Erryadh 6072,
Gabes,
Tunisia
E-mail: *Belgacem.Agoubi@isstegb.rnu.tn*

Zouhir Lakhbir
Société Nationale d'Exploitation et de Distribution d'Eau (SONEDE),
Direction Production,
Jerba,
Tunisia

INTRODUCTION

In arid and semi-arid regions, groundwater is the main source of fresh water. It is required for drinking purposes, tourism and agricultural activities. The increasing demands for fresh water lead to groundwater pumping intensification. High pumping rates cause groundwater levels to decline and therefore change the flow direction, which comes from the sea towards the aquifer. When demanding groundwater withdrawals from aquifers exceed the recharge rate, seawater intrusion occurs. With excessive pumping, the natural hydraulic gradient towards the sea may be reversed and the intrusion can then extend to the pumping borehole which becomes saline.

Numerous studies deal with groundwater salinization (Kim *et al.* 2003; Ghabayen *et al.* 2006; Rosenthal *et al.* 2007; Gattacceca *et al.* 2009; De Montely *et al.* 2008; Kouzana *et al.* 2009; Martos *et al.* 2002). The mixing between groundwater and seawater can be diagnosed using many techniques such as geochemical analyses, minor elements and isotopic tracers. In many cases, tracers like Sr and Br can be used to identify the origin of groundwater salinization when a single process occurs (Boluda-Botella *et al.* 2008; Kim *et al.* 2003). Cl^-/Br^- and I^-/Cl^- ratios and spatial distribution of chlorine are generally used to determine the source of salinity, especially when the seawater intrusion is the main source of groundwater contamination (Rao *et al.* 2005; Kim *et al.* 2003). When groundwater salinization results from several processes, the isotopic analyses of δ^2H, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ are more efficient in identifying the possible origins of saline groundwater (Jorgensen *et al.* 2008). Seawater intrusion processes may be considered as a

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multivariate problem, which involves several parameters such as hydrochemical properties, cationic exchanges and transport parameters (Boluda-Botella *et al.* 2008).

The objective of this study is to recognize and identify the groundwater salinization origins of the Djeffara confined aquifer using hydrochemical and hydrodynamic analyses. Expected results shall be of paramount importance in a region characterized by an arid climate and fresh water scarcity.

STUDY AREA

The Djeffara aquifer located in Southern Tunisia (Figure 1) constitutes the main water reserve in this region. Southeastern Tunisia is characterized by weak rainfall, with an average annual precipitation of less than 250 mm. Rainfall runoff is torrential causing more streaming and very low infiltration. Unlike temperate zones, the studied area is characterized by high temperature, and a high rate of evaporation. Intensive groundwater abstraction during the last decades has caused aquifer piezometric level decline and groundwater quality degradation. Since the year 2000, two desalinization units (Jerba, Zarzis) have been pumping together about 50,000 m^3 day^{-1} from the Djeffara aquifer. Moreover, numerous hotels in the region pump groundwater via their own private wells to satisfy their water requirements. Extremely low recharge rates of the aquifer and the groundwater overexploitation resulted in fresh water/salt water mixing and therefore groundwater salinization.

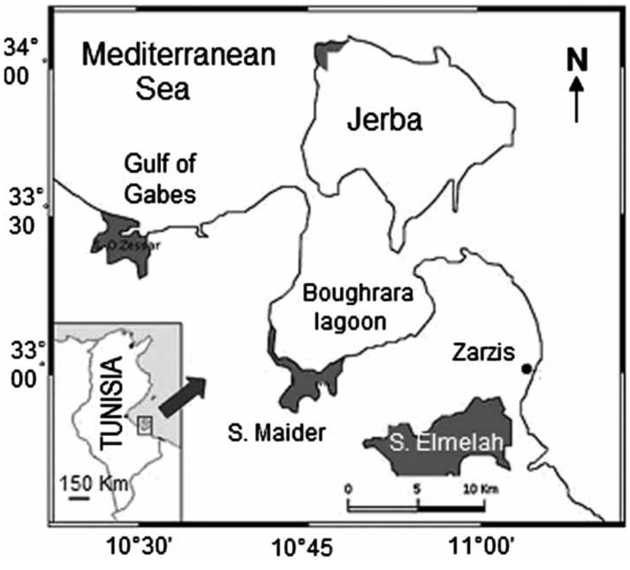

Figure 1 | Location map of the study area (southeast Tunisia).

Geological, structural and hydro-geological contexts

The coastal Djeffara aquifer is logged in Mio-Pliocene sands. Trapped between marls and clays, the aquifer thickness varies from 25 to 80 m, with a maximum in the coastal area (Trabelsi *et al.* 2009). The depth of water-bearing horizons does not exceed 300 m. The recharge of the Djeffara aquifer mainly comes from the 'Continental Intercalaire (C.I)' Aquifer through the Elhamma and Medenine faults (Figure 2). It is assured by lateral flow into upper cretaceous and pontien layers. Recent recharge is limited and constitutes a small fraction of the aquifer resources (Mamou *et al.* 1988). The groundwater piezometric maps showed that groundwater flows mainly in the South-West North-East direction. The study region is affected by numerous faults orientated NW–SE (Figure 2) (Floridia 1965; Busson 1967; Perthuisot 1977; in Jedoui 2000). Their extension in depth remains to be identified. These faults seem to affect the continuity and the geometry of the aquifer. Two faults concern the sea area between Jerba Island and Jorf. A communication between the aquifer and the sea through these faults is a strong possibility (Figure 3).

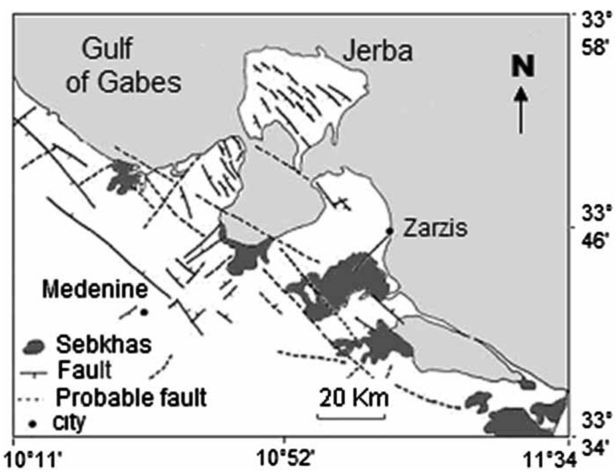

Figure 2 | Structural map of Tunisian Djeffara showing the fault system with predominant orientation; northwest–southeast.

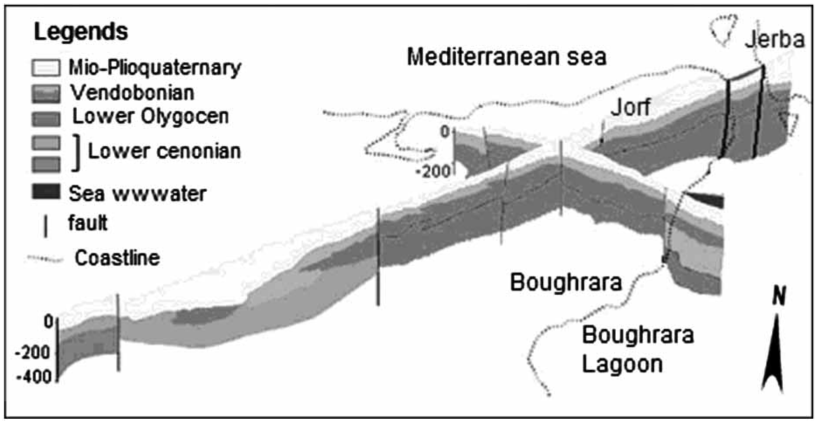

Figure 3 | Geological cross-section of studied area highlighting the fault systems as well as their depth extension (Mekrazi (1974), modified).

Sampling and analysis

Field investigations were carried out from January to March 2010. In total, 24 groundwater samples were taken from wells located all over the study area. A particular interest was attached to areas suspected to suffer seawater intrusion. Groundwater temperature and electrical conductivity (EC) were measured in the laboratory using a thermometer and conductivity electrodes, respectively. Water salinity was calculated using EC. Major elements and Br concentrations were analyzed using ionic liquid chromatography. Groundwater level fluctuation was continually measured by an automatic piezometer installed in the well.

RESULTS AND DISCUSSION

Decline of the aquifer piezometric level

Groundwater piezometric data of the Djeffara aquifer have been measured with respect to mean sea level since 1950. Data used to establish piezometric maps were provided by the 'Regional Agricultural Department of Medenine'. Groundwater piezometric level maps for the years 1950 and 1970 (Figures 4(a) and 4(b), respectively) and the present groundwater level observed in several wells allowed us to establish the groundwater level decline of the aquifer. In fact, because of permanent pumping in Jerba Island, mainly to supply water drinking demands, it is near impossible to establish a groundwater level map describing its present state. Comparing a few isolated values of the present groundwater level to the 1950 piezometric map, groundwater level decline is shown to be about 27.5 m between 1950 and 2010. In areas where the water table is declining, the hydraulic head drops may promote seawater intrusion. Fresh water salinization is explained by mixing between groundwater and seawater: (a) at the aquifer outlet, assumed to be northeast of Jerba Island, (b) through the numerous faults located in the marine area between Jerba Island and the continent.

Seawater intrusion mechanism

Analytical solutions to approximate the seawater intrusion behavior have been derived since 1901. Under hydrostatic conditions, assuming an homogenous aquifer and steady-state freshwater flow, the depth of freshwater/saltwater interface can be shown by a model called the Ghyben–Herzberg relation. Assuming that seawater intrusion comes mainly through faults and taking into account the groundwater level, the depth of the aquifer, fresh water density and seawater density (Figure 5), the groundwater piezometric level at which a new equilibrium of the sharp interface is re-established can be determined. The equilibrium piezometric level (H*) can be expressed, using the Ghyben–Herzberg relation, by the following equation:

$$H^{*} = \left(\frac{\rho_1}{\rho_2} - 1\right) H_1$$

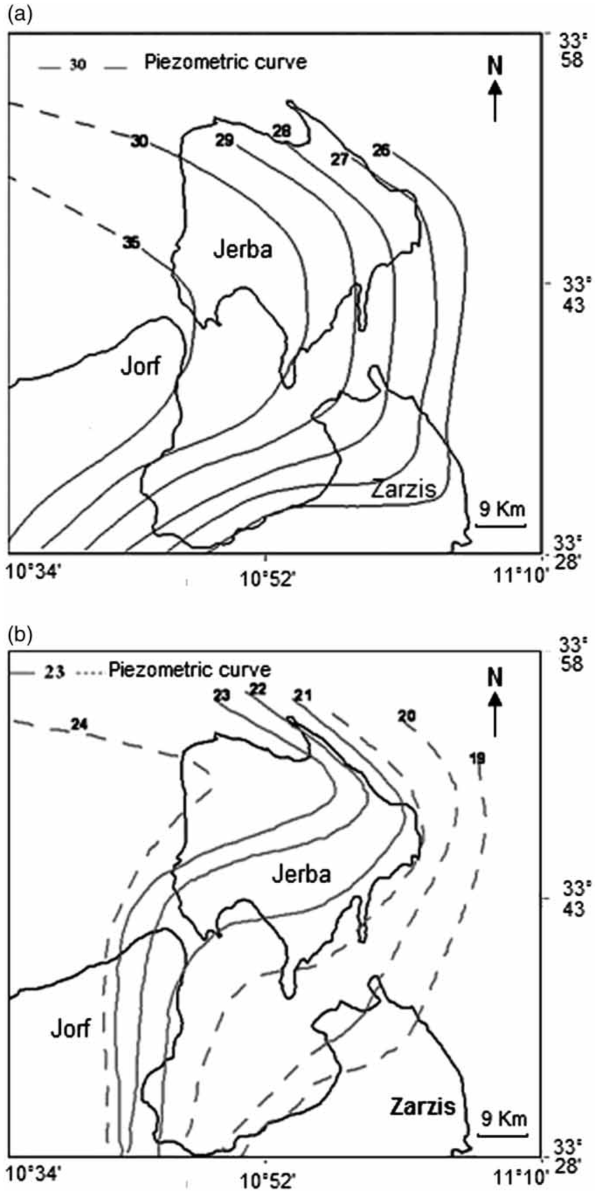

Figure 4 | (a) Groundwater piezometric map for the year 1950 established using piezometric data collected in wells of the study area. (b) Groundwater piezometric map for the year1970 established using piezometric data collected in wells of the study area.

where H_1 is the distance between sea level and the aquifer (m), ρ_1 is the seawater density ($kg\,m^{-3}$) and ρ_2 is the fresh water density ($kg\,m^{-3}$).

The Ghyben–Herzberg relation is an analytical model which describes the mixing between fresh water and sea water. It assumes that under hydrostatic conditions, the pressure of a unit freshwater column extending from the water table to the interface is balanced by a saltwater column extending from the sea level to the same depth. The transition zone between sea water and the aquifer fresh water is not a distinct boundary but a transition zone characterized by a mixing of fresh and saline waters.

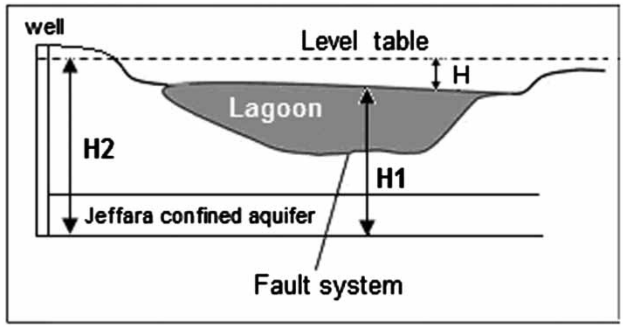

Figure 5 | Seawater intrusion mechanism scheme showing the communication process between the aquifer and the lagoon.

The Ghyben–Herzberg model is used to understand the salinization process of the Djeffara confined aquifer. It can be deduced that when the piezometric level (H) in the aquifer is greater than H^*, the flow is from the aquifer to the sea. Otherwise, the flow is from the sea to the aquifer and seawater intrusion occurs. In the case of the Djeffara aquifer, $H_1 = 300$ m, $\rho_1 = 1{,}032\ kg\,m^{-3}$, and $\rho_2 = 1{,}003.5\ kg\,m^{-3}$. Thus, $H^* = 9.44$ m.

It can be concluded, therefore, that seawater intrusion occurs through the faults system when the piezometric level is less than 9.44 m. The actual groundwater level in the study area is less than 8 m. The weight of the fresh water cannot balance the weight of saltwater and the flow is from the sea to the aquifer.

Communication between the aquifer and the sea evidence

The seawater intrusion in the aquifer can be confirmed based on the groundwater level fluctuation observed in some wells near the faults (Figure 6). Two wells, located at approximately 800 m from the faults, showed that groundwater level fluctuations are closely linked to sea level variations. Simultaneous measurements of the sea wave and the groundwater level in well No. G12, show that

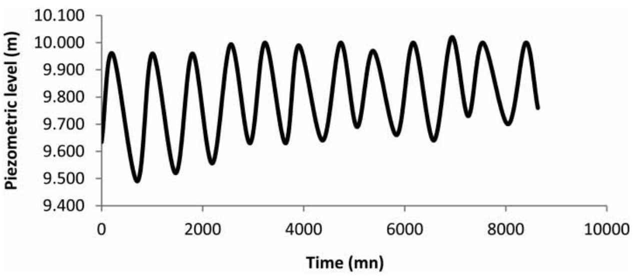

Figure 6 | Piezometric level fluctuation in a well near the sea. Fluctuation in the groundwater level decreases going to the backwaters.

these two phenomena are perfectly correlated (Figure 7). The fluctuation of the groundwater level which is only observed for the nearest two wells, disappears away from the fault system. This behavior can be explained by the fact that the amplitude of the fluctuation is gradually damped with increased distance from the source of the signal. Thus, it seems that the assumption of seawater intrusion in the Djeffara confined aquifer through faults is quite credible and warrants more detailed investigations to be definitively demonstrated.

The fluctuation of the groundwater level depending on the tide cannot be the result of a pumping effect. Indeed, the additional stress due to the increase of the water level in the lagoon is too small to justify such a fluctuation of the piezometric level in the aquifer.

Salinity

The groundwater salinity map established using EC values (Figure 8), shows the distribution of water salinity of the aquifer. High values are observed in the northern and the eastern sides of the study area. Groundwater near the coast is associated with the highest salinity, with a maximum of 7 $g\,l^{-1}$. Abnormally high salinity values are observed in areas of low hydraulic heads and near the presumed aquifer outlet. Relatively fresh waters (2.2 $g\,l^{-1}$) are found mainly in the southern part near the recharge zone. Water salinity remains almost constant within a radius of about 70 km from the recharge zone. Beyond this distance, a sudden increase in salinity is found predominantly in the northern part of Jerba Island and Zarzis Region. High salt content in the groundwater is probably due to seawater intrusion because of the excessive extraction rates from the Djeffara aquifer.

Origin of salinization

Geochemical analysis is considered to investigate the origin of groundwater salinization. Chlorine can be used to distinguish between several mixing mechanisms of fresh water and saline water (Kim *et al.* 2003). The concentration of some minor elements such as Br is considered to be a good marker of seawater intrusion. It can be used to separate salinity of marine and non-marine origins (Andreasen & Flek 1997). The Br/Cl ratio remains constant when salinization of fresh water is related to seawater and groundwater mixing. When the Br/Cl ratio exceeds the normal seawater range (0.0036), potential sources of Br other than seawater may be responsible for water salinity. Groundwater samples from selected wells were collected and analyzed to determine principally Br and Cl content. The analysis (Table 1) showed that most of the treated samples present a significant Br concentration.

The principal origin of Br in hydrogeological systems is seawater because rock bromide concentrations do not exceed 6 ppm. High Br concentration in the groundwater indicates the evidence of mixing between fresh and saline waters. The Br/Cl diagram (Figure 9) was established to determine the origin of groundwater salinity. As Br is a good marker of seawater intrusion, high Br concentration in the Djeffara aquifer coupled with the abnormal salinity values indicate a seawater intrusion to a large extent. A Br/Cl ratio close to 0.0036 characterizes a fresh aquifer water contamination. Figure 8 shows that the majority of points are near the mixing line, implying thereby that Cl and Br have the same origin. Areas affected by marine intrusion are distinguished by Br/Cl ratios similar to those of seawater. Therefore, bromide analyses showed that groundwater salinity is mainly explained by freshwater/seawater mixing. Groundwater containing a significant amount of Br is located beyond the fault system (Figure 10). This finding highlights the major role of faults in the transport process of salt waters from the sea to the aquifer.

SO_4^{2-}/Cl^- ratio has been recognized to be a good natural indicator of seawater intrusion in coastal aquifers (Pulido-leboeuf *et al.* 2003; Kouzana *et al.* 2007; Zouhri

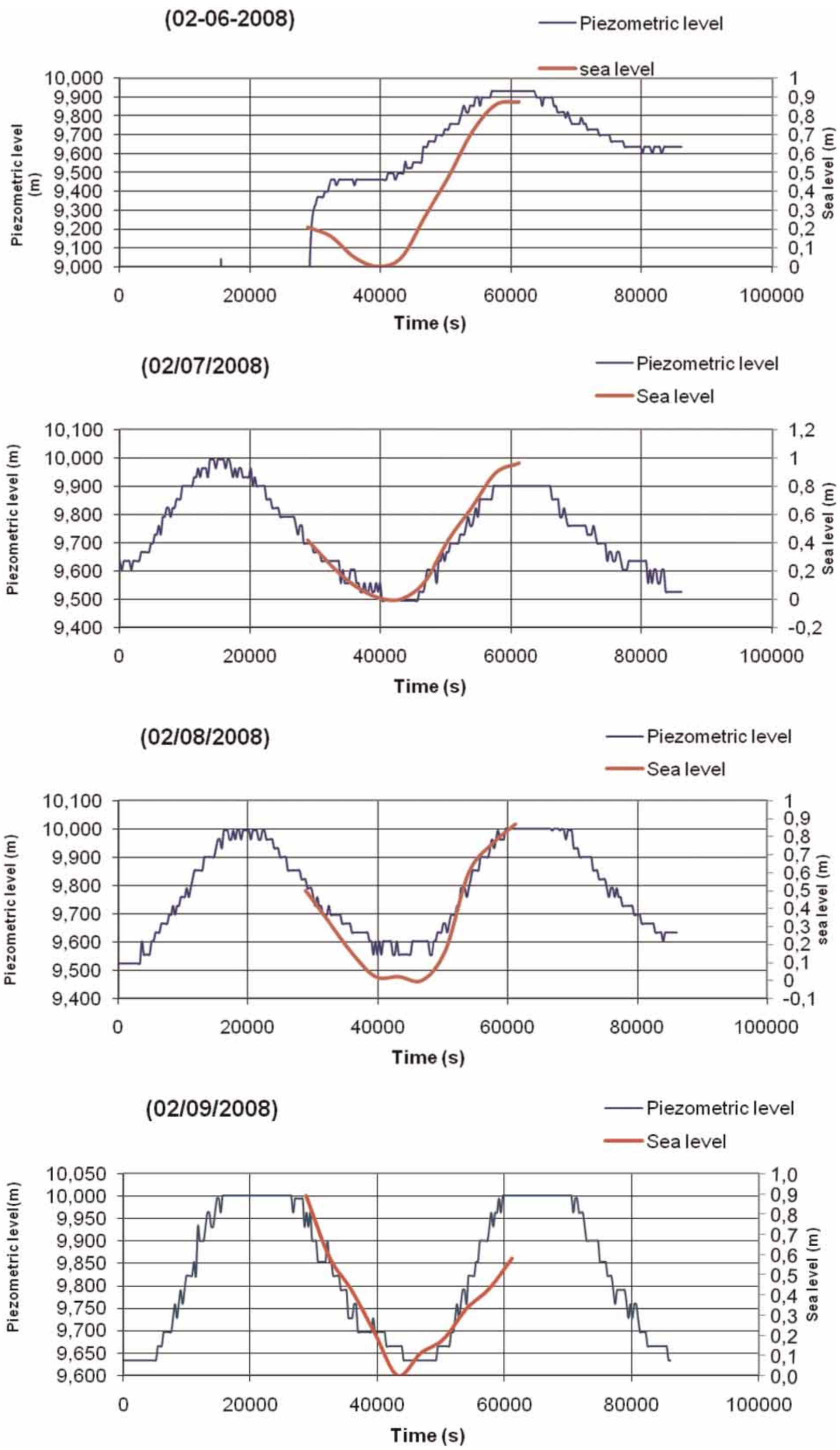

Figure 7 | Piezometric level and sea level measured simultaneously to show the correlation between the tide and the piezometric level of the aquifer.

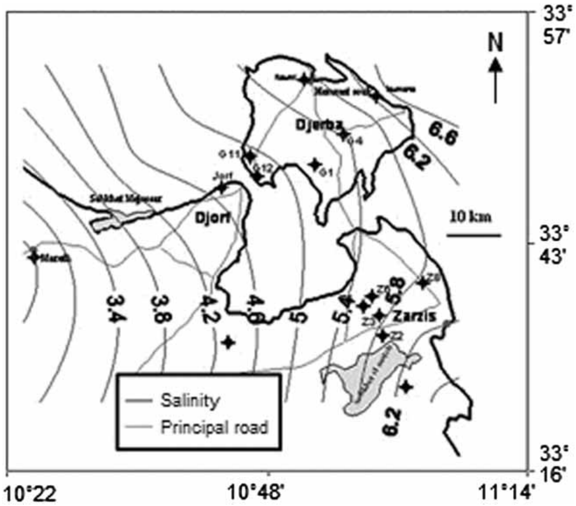

Figure 8 | Groundwater salinity map showing a marked increase in salinity values ranging from the recharge area to the suspected outlet.

Table 1 | Br, Cl, SO_4, Na and Ca concentrations in the Djeffara aquifer

Sample	Chloride (ppm)	Bromide (ppm)	Sulfate (ppm)	Sodium (ppm)	Calcium (ppm)
GB1	612	0	1,723	528	182
MR1	629	0	1,570	542	187
KT1	590	0	1,640	512	168
JF1	1,696	4.98	2,550	1,240	212
BG1	1,502	5.21	2,589	980	227
G1	1,794	5.23	2,406	1,318	281
G2	1,437	5.09	1,906	1,347	265
G4	1,964	6.82	2,248	1,546	369
G6	1,769	5.36	1,872	1,358	208
G7	2,195	7.44	2,191	1,583	117
G8	2,282	6.1	2,234	1,600	281
G9	2,492	0	2,151	1,700	300
G10	1,690	5.03	2,406	1,107	369
G11	1,641	5.1	2,191	1,108	393
G12	1,618	5.02	2,204	1,093	371
BR1	2,405	7.75	2,366	1,900	381
TM1	3,201	9.96	2,061	2,059	361
ZR2	2,235	6.15	2,247	1,420	320
ZR3	2,279	7.58	2,442	1,470	288
ZR4	2,082	5.77	2,579	1,360	264
ZR5	2,158	6	2,701	1,415	248
ZR6	2,333	6.51	2,481	1,524	269
ZR7	2,423	8	2,865	1,620	296
ZR8	2,352	6.16	2,236	1,560	212

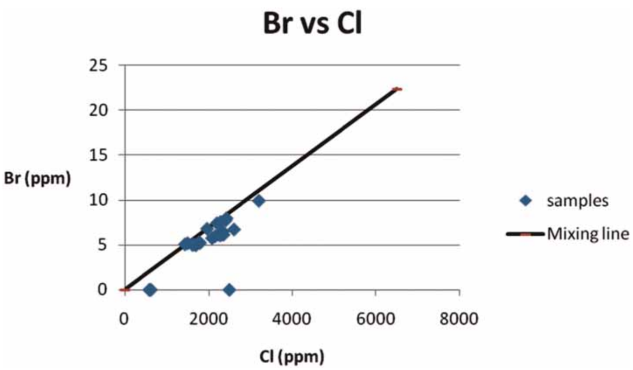

Figure 9 | Bromide versus chlorine concentrations established for the aquifer waters collected from wells located in the study area.

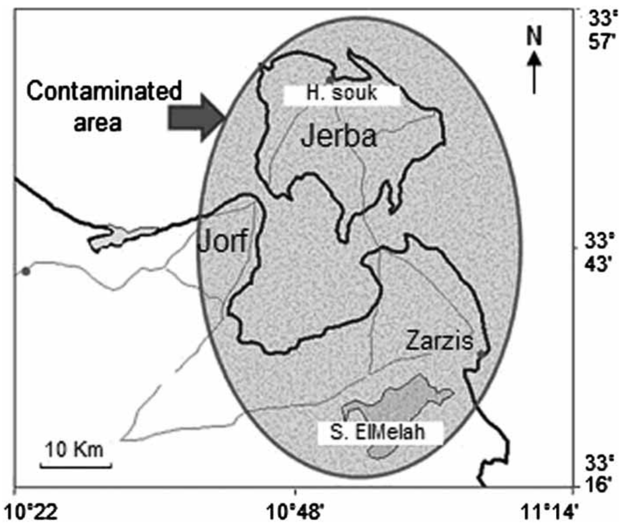

Figure 10 | Localization of seawater intrusion area in the Djeffara confined aquifer.

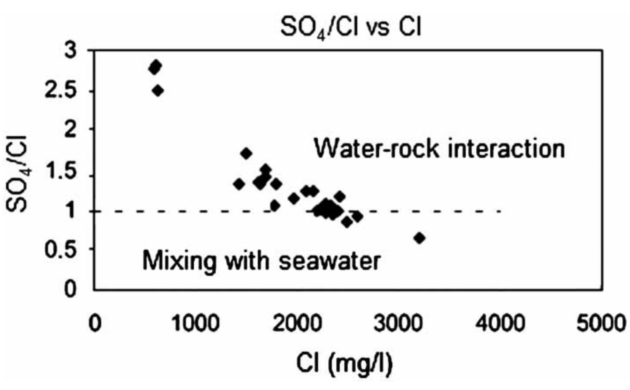

Figure 11 | SO_4/Cl ratio versus Cl concentration in aquifer water. This highlights the contributions of the rock and sea water to underground water mineralization process.

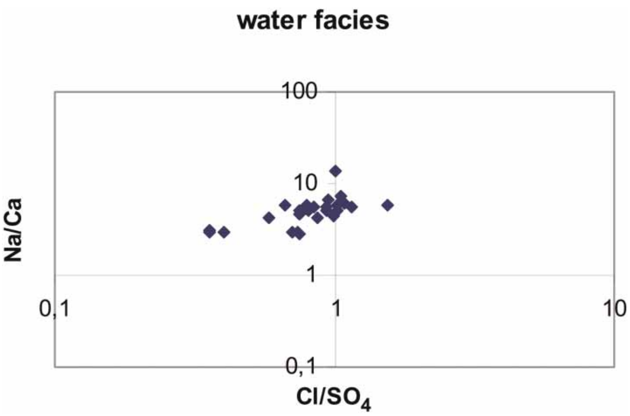

Figure 12 | Chemical facies of underground waters sampled in the Djeffara deep aquifer.

et al. 2010). This ratio decreases when the proportion of seawater in the aquifer increases. Low SO_4^{2-}/Cl^- ratios (Figure 11) indicate evidence of saltwater/freshwater mixing in some parts of the aquifer. However, a plot of Cl^-/SO_4^{2-} as a function of Na^+/Ca^{2+} leads to identification of $Na\text{-}SO_4$ and Na-Cl chemical facies of underground water (Figure 12). The sodium chloride pole demonstrates the evidence of seawater/freshwater mixing. Although the current contamination level seems to be not very significant, the high pumping rates in the aquifer may magnify the seawater intrusion phenomenon in the coming years.

CONCLUSION

The Djeffara aquifer abnormal salinization is mainly related to seawater intrusion and freshwater/seawater mixing. High pumping rates disturb the natural equilibrium between fresh and saline waters, resulting in the subsidence of the groundwater table below sea level, which causes seawater intrusion into the aquifer. Although seawater intrusion at the aquifer outlet is not excluded, the fault system is believed to be predominant in the process of groundwater salinization. Seawater intrusion in the aquifer through the fault system was confirmed based on the groundwater level fluctuation observed in wells near the faults. Hydrochemical analyses, based on Cl and Br ions, showed that changes of groundwater quality and high degrees of groundwater salinization are especially controlled by the mixing process. Seawater intrusion was confirmed by the obtained Br/Cl and SO_4/Cl ratios, which are close to those of seawater. Areas of the aquifer downstream of the fault system were shown to be highly contaminated, thereby preventing any groundwater use. Therefore, seawater intrusion and groundwater quality shall be monitored to establish integrated water management strategies and preserve the limited water resources of the region.

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