

Geochemical and Isotopic Study of the Origin of Salinization in an Unconfined Coastal Aquifer of Cap Bon (Tunisia)

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ABSTRACT

In the Plio-quaternary aquifer of the eastern coast of Cap Bon (Tunisia), the groundwater quality is deteriorating. Different methods using geochemistry (ions Na⁺, Cl⁻, Ca²⁺, Mg²⁺, Br⁻) and isotopes (¹⁸O, ²H) are compared with the hydrodynamic information for identifying the main processes involved in the increase in salinization. Along the coast, the seawater intrusion resulting from the groundwater overexploitation is identified but is not the only cause of the qualitative degradation: the irrigation development that induces the soil leaching and the fertilizers transfer to groundwater over the whole aquifer extent is another major reason of the salinization increase.

INTRODUCTION

As many other semi-arid regions, the Cap Bon peninsula (N.E. Tunisia) shows a parallel increase in overexploitation and mineralization of groundwater resources. Because of the regional situation along the seashore, the seawater intrusion in the unconfined Plio-quaternary aquifer is an obvious explanation for the rising salinity but other processes may also intervene. Surveys including level measurements, hydrochemical and isotopic samplings were performed in 2001, 2002 and 2003 and results were compared with previous information. The study area is 45 km long and 17 km wide at the most, with a mean annual rainfall of about 500 mm and potential evapotranspiration of about 1100 mm. The landscape is a coastal plain slightly sloping (3%) towards the sea. The Plio-quaternary aquifer extends over 475 km² and its thickness varies between 30 and 150 m. Groundwater flows from NW, at the foot of a mountain range, to SE in the coastal plain. Two deeper aquifers exist but they are separated from the Plio-quaternary aquifer by an impervious clayey layer.

METHODS AND RESULTS

Piezometric and salinity maps of the Plio-quaternary aquifer were established. The continuous increase in pumping has created several depressions in the water table, up to 12 m below msl and induced a deterioration of the water quality. The temporal changes in water-table level and salinity are often similar which suggests a strong link between them. Several geochemical approaches were performed to identify the importance of the marine intrusion in the increase in mineralization.

The chloride is strongly correlated to the sodium for the majority of the samples (Fig. 1). The predominance of sodium and chloride is explained by the proximity of the sea, via the spray and/or a progress of seawater intrusion. Even for points far from the sea, the Na⁺/Cl⁻ molar ratio (meq/l) does not significantly differ from the Mediterranean ratio (0.86). This indicator is then of a limited interest for distinguishing the origins of the mineralization. The contents of Ca²⁺ and Mg²⁺ in meq/l are very variable. In most cases, Ca²⁺ is higher than Mg²⁺ but for 4 samples (11635, 11637, 11281, 11828) where the Ca²⁺/Mg²⁺ ratio lower than 1 (Fig. 2) indicates a mixing with the seawater (marine ratio 0.2). These points are close to the sea in the region where the mineralization is the highest.

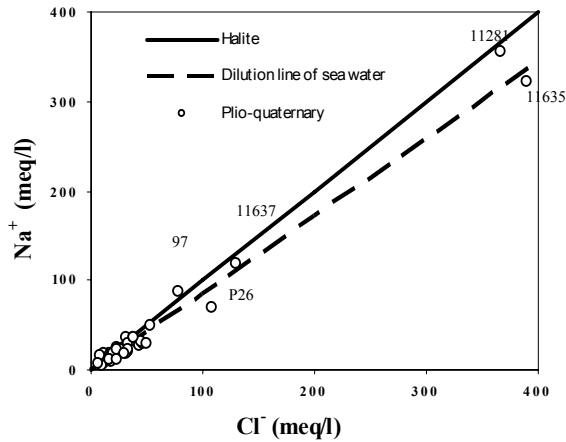


Figure 1. $[Na^+]/[Cl^-]$ correlation

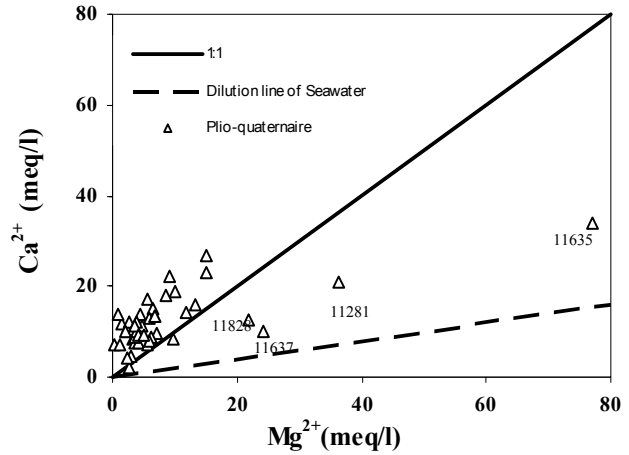


Figure 2. $[Ca^{2+}]/[Mg^{2+}]$ correlation

The Br^-/Cl^- ratio is often used for identifying a possible seawater intrusion because of its relatively constant value ($1,5 \cdot 10^{-3}$) in the present sea water. In the Plio-quaternary aquifer, the Br^-/Cl^- ratio is in general lower than the marine ratio (Fig. 3). The few points close to the dilution line of seawater may trace a mixing with the recent seawater intrusion.

Other samples, with a lower Br^-/Cl^- ratio, suggest the existence of other pole of water with a different mineralization. This suggests a contribution of superficial water and possibly returns of water irrigation into the aquifer and an evaporation of water during the infiltration within the aquifer formation. The points which the ratio Br^-/Cl^- are located over to the line of dilution of sea water are outside of the seawater intrusion.

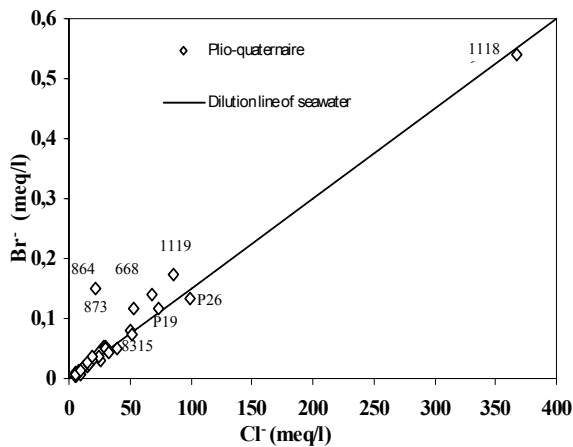


Figure 3. Content in Br^- and Cl^-

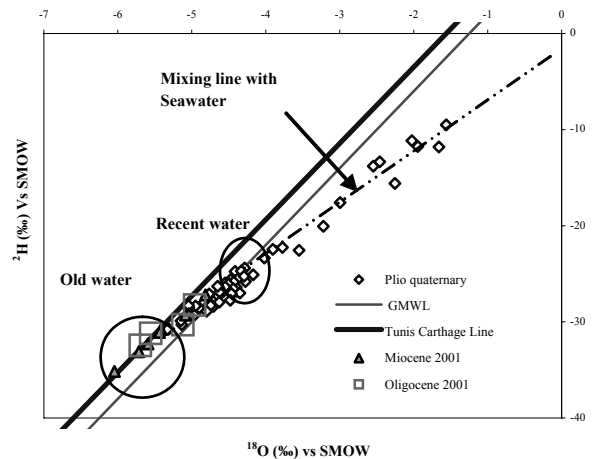


Figure 4. Isotopic content (^{18}O , 2H)

The Br^-/Cl^- ratio identifies also points which seem contaminated by seawater. These points differ sometimes from those distinguished by the Ca^{2+}/Mg^{2+} ratio. These two approaches are complementary but imperfectly discriminating.

The graph ^{18}O vs. 2H shows three groups (Fig.4). The first one (^{18}O between -4.3 and -5.5 ‰) is between the global meteoric water line (GMWL) and the local meteoric line of Tunis-Carthage (LMWL). This reveals the important contribution of the present rain to the groundwater recharge. These points are situated all over the plain and especially close to the temporary rivers.

The second group, along the mixing line with the seawater, corresponds to wells in the piezometric depression (P19, 11281, 11635, 8684, P3, 5729, 6077, 5610), but two exceptions (3002, 5994). The recent seawater contamination is then clearly identified. The third group with isotopic values lower than the mean present rainfall (^{18}O between -4.82 and -6.05 ‰) is made of wells in Miocene and Oligocene aquifers with a probable mixing between present and old waters.

DISCUSSION AND CONCLUSIONS

In the old measurements, typical of the natural state, the upstream part of the Plio-quadernary aquifer was more mineralized than downstream. This implies that the rainfall infiltration in aquifer outcrops is significantly complemented by the infiltration from temporary rivers floods when they reach the plain. Recent observations confirm the importance of the present recharge: after rainy years, as 2003 and 2004, the decrease in mineralization is clear. In this region, the $^{18}\text{O}/^2\text{H}$ study is the most efficient geochemical tool for characterizing the seawater intrusion. As the most depressed areas are not systematically the most mineralized or contaminated by the seawater, other processes modifying the Plio-quadernary chemistry are to be searched for. An upward leakage from the Miocene aquifer is very weak or even nil: its mineralization is lower (less than 1 g.l^{-1} for 90 % of the samples), even in the depressed area. The return of irrigation water to the Plio-quadernary water-table affects the whole region, whatever the thickness of the unsaturated zone (1 to 31 m), as shown by the NO_3^- content (median value of 90 mg.l^{-1} in 2001). The absence of correlation between content of nitrate and thickness of the unsaturated zone indicates that all the area can be contaminated by this pollution. This a fundamental driver of the geochemistry changes for the coming decades.

The determination the contribution of seawater in the plio-quadernary aquifer has been based on the calculation of the mass balance of the chloride. The contribution of seawater in the plio-quadernary aquifer has been estimated to be between 4 and 10% and may reach a maximum of 70 % depending on location translating the heterogeneity of the process of salinization in this region.

The table summarizes the various approaches applied for the distinction of the origin of salinity. With for the rows all the water samples and for the columns all the geochemical methods and the hydrodynamic information, this table highlights in each cell, if the method gave in this point information on the origin of the salinization and also the degree of certainty of the information (no doubt yes, no doubt not, possible yes, possible not, no idea). Confrontation between the various approaches permits to highlight the efficient methods, the methods requiring a confrontation with other methods and the methods insufficient for the determination of the origin of salinity. All around the Mediterranean sea, the human modifications of the natural water cycle are now superimposed over the large natural hydrological variability, following asynchronous dynamics. Even in apparently simple cases as this present study, a cautious and critical approach is necessary. Only the comparison of different methods at different spatial and temporal scales can lead to the pertinent identification of main processes at work. However, the variability of the results obtained according to the methods underlines the difficulty of interpretations. The overlap of different processes, the limitations related on the data and interpretations make particularly delicate the quantification of the evolutions of the next decades.

Sample No	Piez.Lev (m)	Salinity (mg/l)	$\delta^{18}O$ ‰	δ^2H ‰	Na/Cl meq/l	Ca/Mg meq/l	Br/Cl Meq/l	Hydro	Salinity	Isotopes	Na/Cl	Ca/Mg	Br/Cl	Origin of salinization
P1	33	2144	-4,84	-28	0,83	3,06	1,14E-03	NDN	PN	NDN	PY	NDN	PN	No Seawater intrusion
P 3	1,2	2035	-1,95	-11,8	1,11	2,60	1,41E-03	PY	PY	PY	PN	PN	PY	Possible mixing with seawater
P19	3,5	3520	-3,55	-22,6	0,75	2,32	1,58E-03	PY	PY	NDY	NDY	PN	PY	Possible mixing with seawater
P26	8,3	8371	-1,56	-9,5	0,63	1,79	1,36E-03	PN	PY	PY	NDY	PN	NDY	Evaporation + dissolution
97	3,7	7296	-4,46	-27,1	1,11	1,54	1,63E-03	PN	PY	PN	PN	PN	PN	Evaporation + dissolution
892	-7,7	3469	-4,39	-26,9	0,61	1,88	1,85E-03	NDY	PY	PN	NDY	PN	PY	Possible mixing with seawater
996	13,6	2650	-4,9	-28,6	0,82	2,35	1,76E-03	PN	PN	PN	PY	PN	PN	No Seawater intrusion
1129	27,3	2067	-5,05	-29,1	0,93	2,15	1,78E-03	NDN	NDN	NDN	NDN	NDN	PN	No Seawater intrusion
3093	40,9	1265	-4,7	-27,5	0,77	4,12	1,85E-03	NDN	NDN	NDN	PY	NDN	PY	Fresh water-No Seawater intrusion
3113	5,6	1153	-5,31	-30,8	0,86	36,08	1,44E-03	PN	NDN	NDN	PY	NDN	PN	Fresh water-No intrusion
3190	52,9	2451	-4,71	-28,4	0,84	3,13		NDN	NI	NDN	NDN	NDN		Dissolution by irrigation return flow
3202	47	1920	-1,66	-11,8	1,62	1,36	1,58E-03	NDN	NDY	NDY	NDN	NDN	PN	Evaporation
4814	102	3417	-4,48	-25,6	1,10	2,22	1,46E-03	NDN	NDN	NDN	NDN	NDN	PN	Evaporation
5610	-1,6	1293	-3,78	-22,3	0,90	1,83	8,30E-04	NDY	PY	NDY	PN	PN	PN	very weak mixing with sea water
5729	10,9	1510	-2,03	-11,2	0,66	0,87		NDN	NDN	NDY	NDY	NDY		very weak mixing with sea water
5743	28,8	2400	-4,42	-24,8	1,06	1,37		NDN	PN	NDN	NDN	NDN		Dissolution by irrigation return flow
5972	40,2	1485	-4,55	-26	0,60	8,21	1,63E-03	NDN	NDN	NDN	PY	NDN	NDN	Fresh water-No Seawater intrusion
5994	25,8	1862	-2,55	-13,8	0,92	3,96		NDN	NDN	PY	PN	PN		Evaporation
6077	15,6	1613	-3	-17,6	0,84	4,53		PN	PN	PY	PY	NDN		Possible mixing with seawater
6686	38,1	1702	-4,77	-27,1	0,87	4,36		NDN	NDN	NDN	PY	NDN		Fresh water
8088	50,4	1958	-4,68	-27,6	0,82	4,57		NDN	NDN	NDN	PY	NDN		Fresh water-No Seawater intrusion
8315	4,8	4762	-4,65	-27,3	0,93	1,22	1,41E-03	PY	PY	PN	PN	PN	PY	Possible mixing with seawater
8346	0,4	2323	-5,14	-30,3	0,92	3,28		PY	PY	NDN	PN	NDN		No Seawater intrusion
8377	72,4	2010	-4,95	-28,4	0,92	3,28		NDN	PN	NDN	PN	PN		No Seawater intrusion
8400	4,7	1971	-5,04	-28,5	0,88	2,42	1,65E-03	PN	NDN	NDN	NDN	NDN	NDN	Fresh water-No Seawater intrusion
8403	10,4	3648	-4,28	-25,8	0,85	2,42	1,71E-03	NDN	PY	PN	PY	PN	PY	Possible mixing with seawater
8420	-0,4	2413	-4,5	-26	0,81	2,65	1,58E-03	NDY	PY	PN	NDY	PN	PY	Seawater intrusion
8647	2	1696	-5,15	-29,9	0,48	3,13	7,04E-03	NDN	NDN	NDN	PY	NDN	NDN	Fresh water-No Seawater intrusion
8684	4	3232	-2,46	-13,4	0,92	1,27	2,04E-03	PY	PY	NDY	PN	PN	PN	Seawater intrusion
8737	0,8	3578	-4,42	-25,7	0,63	2,12	2,19E-03	PY	NDY	PY	PY	PN	PN	Possible mixing with seawater
8774	1,6	2995	-4,76	-28,2	0,60	1,23	1,37E-03	PY	PY	PN	PY	PN	NDY	Possible mixing with seawater
8820	40,6	1453	-5,05	-28,3	1,94	1,70	1,39E-03	NDN	NDN	NDN	NDN	NDN	PN	Fresh water-No Seawater intrusion
8894	-2,8	2848	-4,6	-26,6	0,58	3,12		NDY	PY	PN	PY	PN		Possible mixing with seawater
10959	-2	1162	-4,44	-26,6	0,73	0,76		NDY	PN	PN	PY	PY		Possible mixing with seawater
10995	-0,2	3226	-4,02	-23,4	0,71	13,80		PY	PY	PY	PY	NDN		Possible mixing with seawater
10996	1,6	1023	-5,33	-30,8	0,52	5,48	1,30E-03	PY	NDN	NDN	PY	NDN	PN	Fresh water-No Seawater intrusion
11186	3,7	3802	-4,55	-26,4	0,92	2,21	1,47E-03	PY	PY	PN	PN	NDN	PY	Possible mixing with seawater
11191	6,4	2355	-4,35	-27	0,64	1,33	2,03E-03	PN	PY	PY	PY	PN	PN	Possible mixing with seawater
11635	0,4	27160	-2,26	-15,6	0,82	0,44		NDY	NDY	NDY	NDY	NDY		Seawater intrusion
11637	0,8	10430	-4,36	-25,4	0,90	0,42		NDY	NDY	PY	PY	NDY		Seawater intrusion
11650	4,3	2331	-4,65	-26,3	0,93	4,95		PN	PN	PN	PY	PN		Dissolution, irrigation return flow
11829	6,8	2432	-4,33	-24,7	0,63	2,01	1,58E-03	PN	PN	PN	PY	PN	PY	Possible mixing with seawater
11269	-8,7	1702	-4,47	-27,1	0,68	1,82		NDY	PY	PN	PY	PN		Possible mixing with seawater
11281	1	36315	-3,22	-20,1	0,97	0,58		PY	NDY	NDY	PY	NDY		Seawater intrusion
11828	4,3	4090	-4,48	-27,8	0,58	0,57	1,68E-03	PN	NDY	PN	NDY	NDY	PY	Possible mixing with seawater
11869	3,2	858	-4,8	-28,9	0,99	1,89		NDN	NDN	NDN	NDN	NDN		Fresh water, No Seawater intrusion
13143	-1,05	21050			0,5675	0,6667		NDY	NDY		NDY	NDY		Seawater intrusion
13207	-0,66	9960			0,6475	0,875		NDY	NDY		NDY	NDY		Seawater intrusion

No doubt yes : NDY

No doubt non: NDN

Possible yes: PY

Possible non: PN

No idea : NI

require confrontation with other methods

efficient method for samples near the sea

adequate method

insufficient method

require confrontation with other methods

require confrontation with other methods

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