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CHEMICAL AND ENVIRONMENTAL ISOTOPE INVESTIGATION ON HYDRODYNAMICS OF A MONOMICTIC LAKE: A CASE STUDY ON QARAOUN DAM, LEBANON

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Hydrogeochemical and isotopic investigations have been carried out in a small basin in the Bekaa plain in Lebanon, to determine the exchange between Qaraoun Lake and the surrounding groundwater. Qaraoun lake is a warm monomictic lake. The poor vertical mixing of the lake is due to the temperature-induced seasonal stratification. There are few groundwater inflow points along fractures. The mineralization in the lake is higher than the surrounding groundwater, due to evaporation and anthropogenic inputs. The concentration of most chemical species decreases downgradient in groundwater with distance from the dam. Groundwater is recharged by a source other than the lake in this region. The isotopic composition of groundwater from observation wells, which are not influenced by the lake, lies on the local meteoric water line. The isotopic composition of the lake and of the wells that contain water from Qaraoun lake fall on the evaporation water line. The position of the points indicates the extent of mixing between locally infiltrated groundwater and lake water. The contribution of lake water diminishes with increasing distance from the lake. The mixing zone, delineated by combining the stable isotope data and hydrochemical parameters, is oriented to the southeast and its lateral extent is limited.

INTRODUCTION

The Litany River is the principal artery of Lebanon, exceeding 170 km in length with an estimated average annual discharge rate of over 750 million cubic meters (MCM). The river has multiple tributaries that flow from the slopes of the Lebanon and Anti Lebanon mountain ranges. The major water structure in the river basin is the Qaraoun Dam, completed circa 1956 which forms the Qaraoun reservoir, 12.3 km^2 in area. The river and reservoir are the most important lotic and lentic systems in Lebanon. The surface and groundwater resources in the river basin provide drinking water to over 350,000 habitants in more than 160 communities and serve as a fundamental component of the Bekaa Valley agricultural and industrial sectors (2003 report on water quality assessment of the Litany River). The Qaraoun reservoir has a maximum storage capacity of about 220 million cubic meters (MCM), of which approximately 70% is used per year for irrigation and hydropower. A minimum of 40 MCM is stored throughout the year. The dam itself (60 m height and 1.1 km long) is an impressive piece of engineering which has held up quite well over the past fifty years. In this study, establishing reservoir water – groundwater relationships and the associated groundwater flow pathways, which may be either through the walls and foundation of the dam or through natural geological formations, is important for evaluating the economic consequences of this surface water - groundwater interaction.

Environmental isotopes, along with hydrochemistry studies, are useful for identifying whether a groundwater body is receiving recharge from direct precipitation or from a surface water body (Krabbenhoft et al., 1990; Navada and Rao, 1991; Clark and Fritz 1997; Sinha et al., 2000; Zhu, 2000; Saravana Kumar et al., 2001; Murthy et al., 2002). In addition, comparison of stable isotope data of surface waters (including reservoir water) with those of precipitation and groundwaters from the same region has been used to evaluate infiltration of surface water to aquifers (Payne, 1983; Gat and Matsui, 1991).

In this context, the Qaraoun Lake has not received attention despite its importance in water storage. In a case study of stable isotopes in the Litany River from its headwaters to the estuary (Figure 1), Saad et al. (2006) observed that surface water mineralization increased continuously in the river course. They also reported that $\delta^{18}O$-δD relationship in the river course is similar to the local meteoric water line whereas an evaporative isotopic enrichment was seen in the Qaraoun reservoir. Even though the study demonstrated the potential of stable isotope measurements in the Litany River and Qaraoun Lake to characterize groundwater sources, it does not consider the seasonal variation in the lake water isotopic composition and its influence on groundwater recharge.

In an attempt to understand the hydrodynamics of Qaraoun Lake, we present a systematic environmental isotope characterization of the lake and the adjacent groundwater. The primary goal is to determine seasonal and spatial variations in the stable isotope compositions of Qaraoun Lake. Also groundwater was extensively sampled to delineate the area of recharge from the lake.

GEOLOGY OF THE CATCHMENT AREA

The Bekaa plain is a depression located at an average elevation of 900 meters between the Lebanon and the Anti-Lebanon mountain chains. The formations constituting the river basin include the Jurassic, Cretaceous, Tertiary and Quaternary periods. Most of the rocks of the Jurassic system, Cenomanian, and Eocene are limestone and dolomitic limestone. These rocks exhibit high permeability and are subject to erosion. In other locations, there are Cenomanian rock

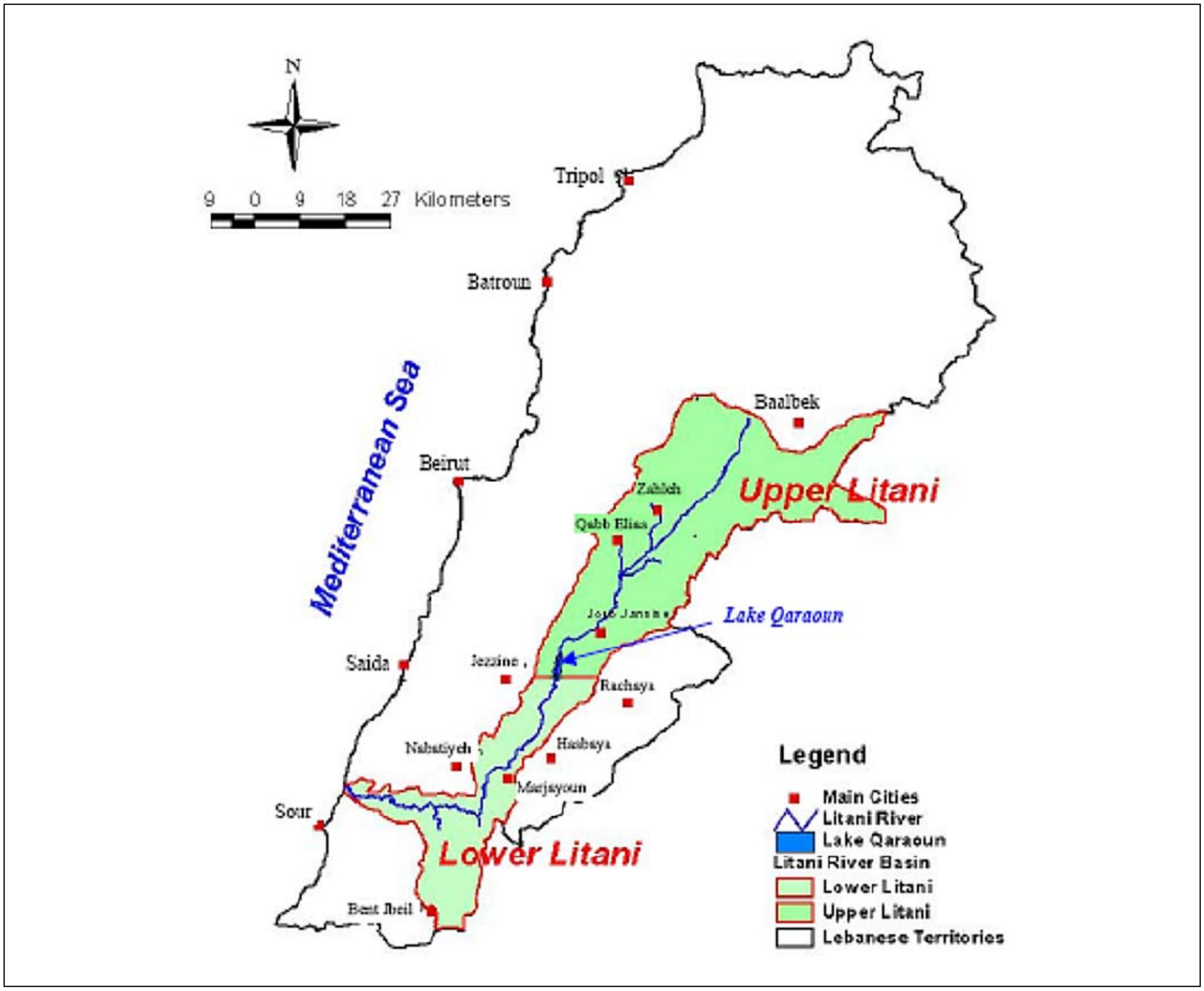

Figure 1. Location map of Litani River and Qaraoun Lake (from water quality assessment report for Litany, 2003).

outcrops, consisting mainly of chalky marl. Quaternary formations are of limited extent, comprised mainly of alluvial deposits of clay, silt, sand and gravel (Khair, 1993).

SAMPLING PROGRAM

A sampling program was carried out in August 2007 and February 2008 at different depths and locations in Qaraoun Lake for environmental isotope analysis ($\delta^{18}O$ and δD) and for hydrochemical parameters. Samples in locationS A and B were made respectively at 0, 5, 10, 15 and 20 m depth (Figure 2). Other sampling campaigns were made in 2007-2008 in 8 observation wells around Qaraoun reservoir and at the surface of the lake (location A) for comparison. These samples were analyzed for their stable isotopes (oxygen and hydrogen) and their chemical composition. They were collected in the dry (August) and rainy (February) seasons.

All water samples were filtered through a 0.45 $_{\mu}$m pore size cellulose acetate syringe filter (Millipore filters), then samples were acidified with nitric acid (15% v/v) and stored at 4°C before analysis. Major cations were measured using Atomic Absorption Spectrometry (Perkin Elmer analyst 100 Model A.A.S) using air-acetylene flame after addition of lanthanum chloride to minimize the interference phenomena. Anions were measured using an Ion Chromatograph (Dionex IC25). Each sample was measured in triplicate.

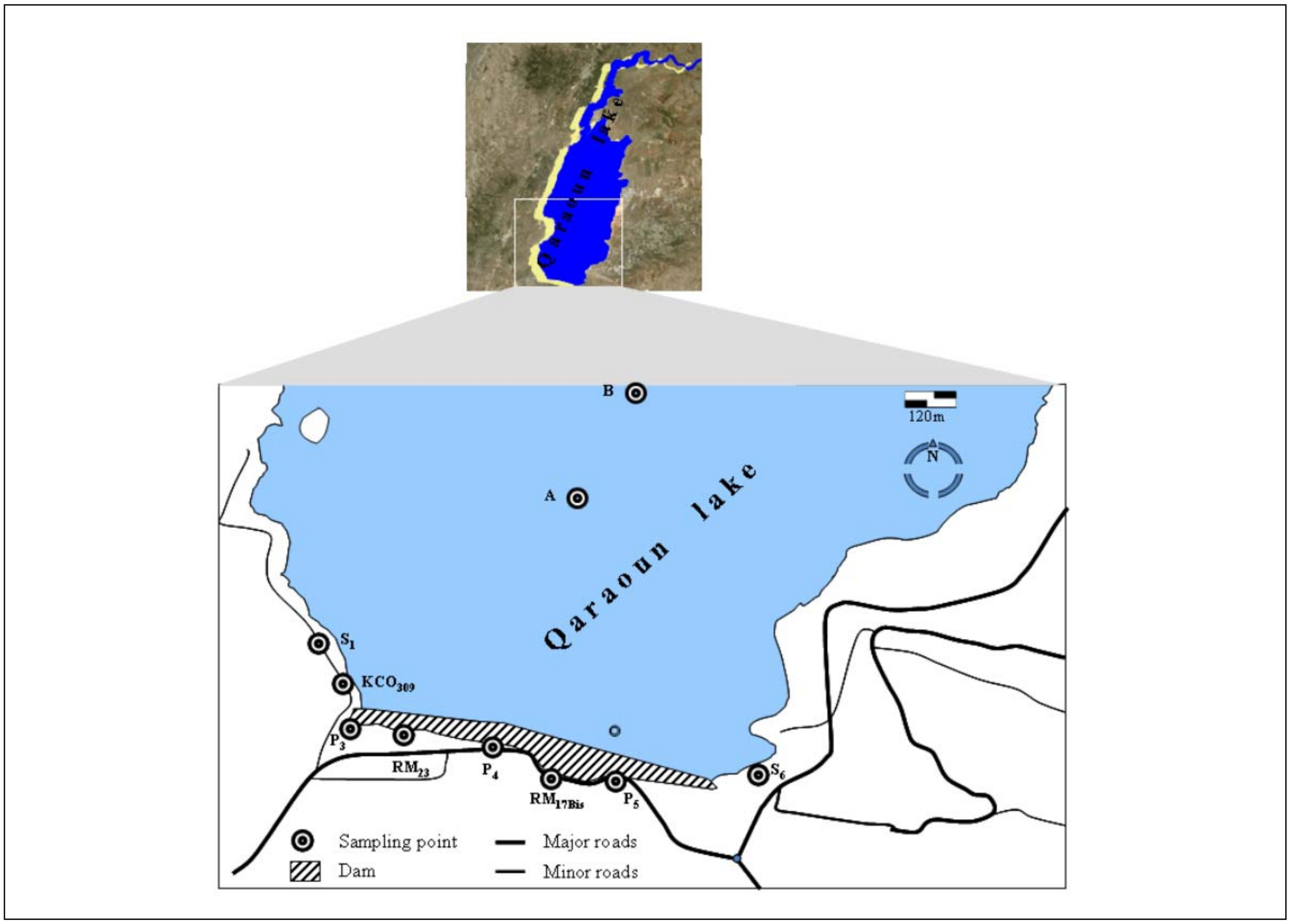

Figure 2. Location of water sampling sites in the Lake (location A and B) and in adjacent groundwater (S1, S6, P3, P4, P5, RM23, RM 17bis, KCO 309).

For stable isotope measurements, samples were collected in pre-cleaned 50 mL polypropylene bottles. These were rinsed at site with surface and groundwater to be collected and filled with water samples, tightly capped (to prevent evaporation and exchange with the atmosphere) and sent to the Syrian Atomic Energy Commission for isotopic analysis. The stable isotopic composition of the water samples was determined by the chromium technique (^{2}H) with an analytical precision of ±0.8‰, and the standard H_2O-CO_2 equilibration method (^{18}O) (Epstein and Mayeda, 1953) with an analytical precision of ±0.1‰ in an IRMS delta S (Finnigan MAT). The results of the hydrogen and oxygen isotope measurements are expressed as delta notations ($\delta^{18}O$ and $\delta^{2}H$), relative to the Vienna Standard Mean of Ocean Water (VSMOW).

RESULTS AND DISCUSSION

Surface-groundwater interaction

Patterns of major element variation in groundwater were inferred from the Ion Chromatograph analysis (Figure 3, Table 1). Variation of geochemical parameters helped to understand the reservoir-groundwater dynamics (Rank et al., 1983). In all sites, none of the groundwater samples had a major chemical compound higher than Qaraoun surface water (Figure 3, Table 1). Most of measured components confirmed that underlying groundwater is divided into two groups. The first, including sites P4, P5, RM-23 and S6, has a geochemical composition approaching that of Qaraoun lake water. The second is separated by large intervals from lake chemistry. As a result, groundwater seemed to lie between two end-members: the lake geochemistry and site KCO-309. The latter site

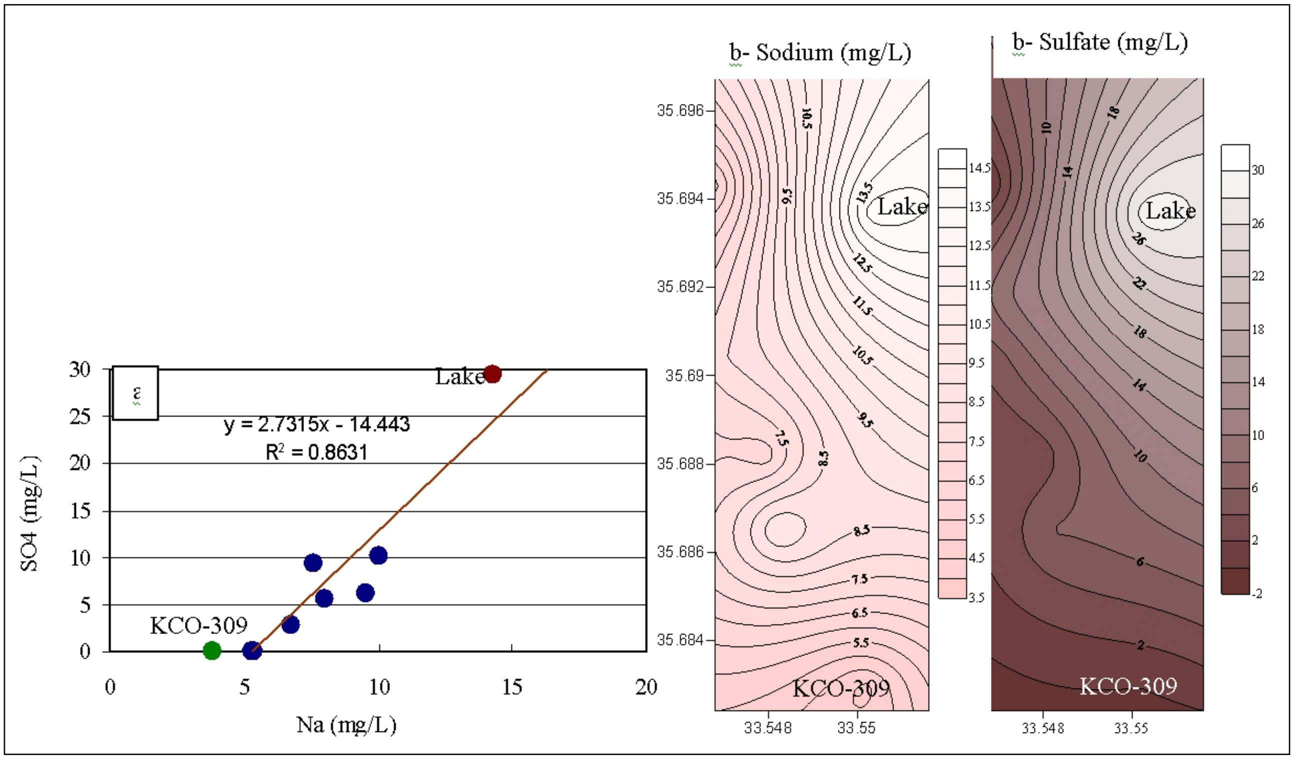

Figure 3. a- Variation of sulfate versus sodium in groundwater relative to lake water. b- Spatial variation of major ions showing gradual influence of lake water onto groundwater.

Table 1. Chemical data for pumped groundwater and Qaraoun surface water. Major elements are measured in mg/L. ND: Not Detected.

Sample site	Na^+	Mg^{2+}	Ca^{2+}	K^+	Cl^-	NO_3^-	SO_4^{2-}
S-6	10.051	3.39	9.984	0.607	11.23	2.66	10.04
P-3	5.28	6.958	6.823	0.958	11.49	1.38	ND
S-1	5.392	4.302	3.362	1.815	13.48	1.74	ND
RM-17	8	2.44	10.375	0.887	6.58	2.11	5.49
RM-23	9.559	ND	10.537	0.344	3.32	3.36	6.11
P-4	6.734	ND	7.363	0.376	18.01	1.48	2.76
P-5	7.591	ND	5.402	0.451	6.57	4.02	9.42
KCO-309	3.841	2.346	3.592	0.55	6.09	1.47	ND
Qaraoun reservoir - A	14.273	12.29	7.459	2.401	13.3	2.98	29.37

is taken as groundwater not influenced by the lake. Figure 3b shows the gradual decrease of both sodium and sulfate concentrations in groundwater from lake water.

Qaraoun Lake is a dynamic system, it receives major input from the Litany River and a minor inflow from underlying groundwater along extended faults and fractures in the Qaraoun basin (2003 report on water quality assessment of the Litany River). Current results add important information by considering the artificial recharge from surface water into underlying groundwater in the overall dynamic system of the lake.

In a later step, Oxygen-18 and deuterium isotopes were used to investigate the interrelation between lake water and underlying groundwater (Rank et al., 1983; Turner et al., 1984; Saravana Kumar et al., 2008; Krabbenhoft et al., 1990). It is important to find out if isotope technique will support the findings made for groundwater recharge by the reservoir by using geochemical parameters. In fact, oxygen-18 and deuterium are conservative in nature and therefore are considered to be ideal environmental tracers. Besides the evaporation process, that is accompanied by significant isotopic fractionation, monitoring environmental isotopes of Qaraoun water makes possible the evaluation of lake dynamics, specifically the seepage to the adjacent groundwater as the latter process is not accompanied by isotopic fractionation.

Figure 4a shows the environmental isotopes ($\delta^{18}O$ and deuterium) distribution in both lake water and underlying groundwater sampled from piezometers by the Litany River Authority. Deuterium content of water samples are plotted relatively to $\delta^{18}O$ in Figure 4b which also shows the Local Meteoric Water Line LMWL and both Mediterranean and Global Meteoric Water Lines (MMWL and GMWL). Results show again the two end-members of lake water and piezometer KCO-309. Surface water is isotopically enriched with $\delta^{18}O$ = -5.37‰ and δD = -28‰. Whereas the second end-member, groundwater in site KCO-309, falls on the LMWL and thus is depleted relatively to lake water. All sampled groundwater falls in between the prescribed end-members. Only piezometers P4, P5 and RM-23 which are very close to the lake are affected by lake water recharge according to the highest values in both $\delta^{18}O$ and δD. In the proximity of the Qaraoun dam, the Litany River has typical values of $\delta^{18}O$ = -7.5‰ and δD = -35.48‰ (Saad et al., 2006). These values lie on the LMWL indicating that major origin of Litany water, in this part of the river, is meteoric. All piezometers lying on the LMWL are thus naturally recharged by the river and rain waters. The most depleted piezometers P4, P5 and RM-23, represent a mixture between different sources with the contribution of both enriched lake water and depleted river water. If we consider the mean isotopic composition of piezometers P4, P5 and RM-23 to represent the average groundwater affected by lake seepage, we can estimate the percentage of artificial recharge to the piezometers by the following equation:

$$\text{Artificial Recharge (\%)} = \text{Mean } \delta^{18}O_{groundwater} - \text{Mean } \delta^{18}O_{rain} / \text{Mean } \delta^{18}O_{lake} - \text{Mean } \delta^{18}O_{rain}$$

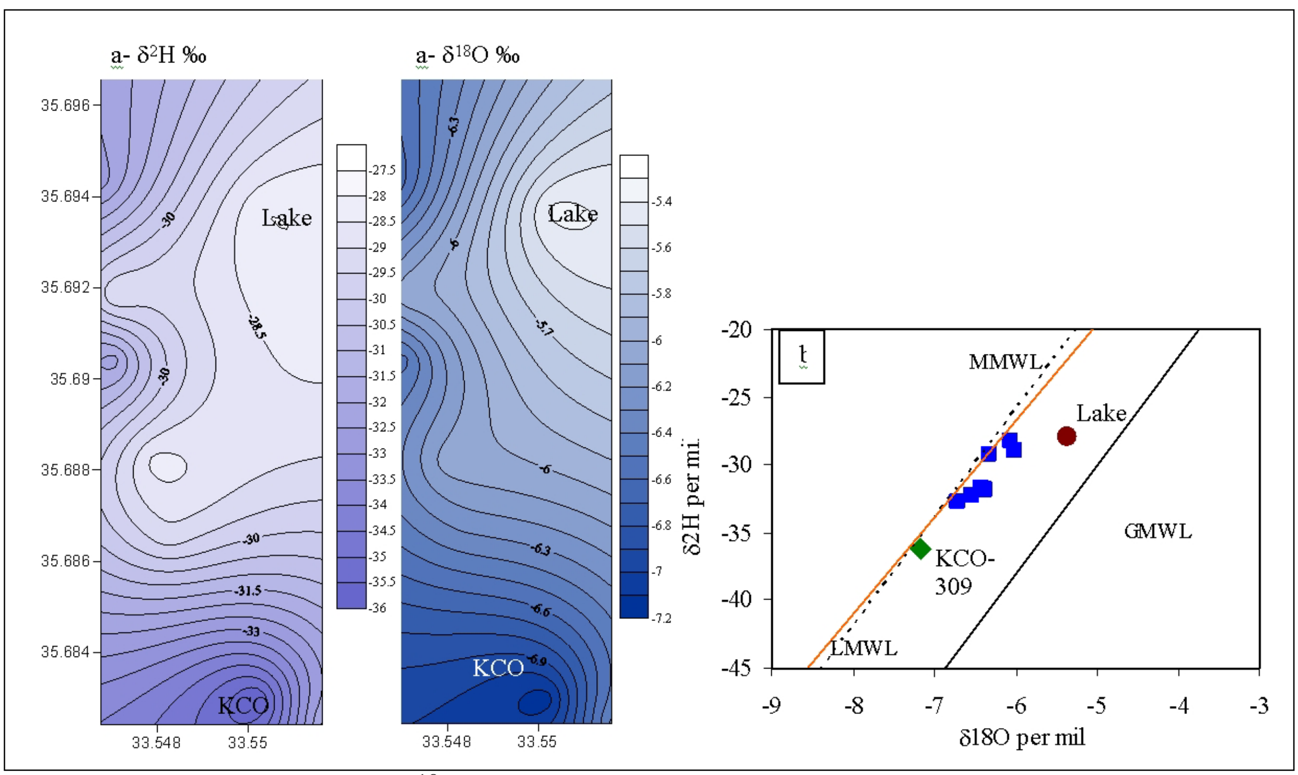

Figure 4. a- Spatial variation of $\delta^{18}O$ and δD in Qaraoun Lake and in groundwater. b- δD content of water samples relatively to $\delta^{18}O$.

(Technical documents in hydrology, 2001).

Considering the different δ values, the highest contribution of lake water to adjacent groundwater is estimated to be about 10%. Thus the concept of groundwater artificial recharge from lake contribution is confirmed by both geochemical and isotopic techniques.

Isotope geochemistry and annual stratification of Lake Qaraoun.

Besides the thermal contact with the atmosphere, the common exposure of lakes to seasons is the main reason for its geochemical evolution throughout the year. The temperature cycle is typical for lakes of the temperate climate zone (Imboden and Wüest, 1995; Boehrer et al., 2000). Consequently, it is important to investigate, in the case of Qaraoun Lake, the role of stratification, when it exists, on water isotope geochemistry and how environmental isotopes evolve during seasons (Turner et al., 1984; Michel and Kraemer, 1995). In this order, $\delta^{18}O$ and deuterium depth profiles were measured in two locations in the lake and during two different seasons (winter-February and summer-August). Water samples were collected every 5m along the profiles and were analyzed for environmental isotopes (Figure 5, Figure 6) and major ion composition (Figure 7). Both $\delta^{18}O$ and deuterium in lake water sampled in February remain relatively constant from the top to the bottom of the lake thus showing a low vertical gradient in isotope content (Figure 5). It is noted that isotope depth profiles did not vary with distance to dam since location A is closer than B and exhibits the same variation. These results confirmed the absence of stratification in lake water during February throughout depth profiles. Compared to August, both environmental isotopes showed a gradual increase from the bottom to the top of the lake (Figure 6). Almost a linear isotopic enrichment is established through the depth profile with an average degree of variation for $\delta^{18}O$ and deuterium of -0.32‰ / 5m and -2‰ / 5m respectively. This isotope fractionation effect could be explained by the fact that the epilimnion is relatively enriched due to evaporation in Lake Qaraoun in the summer season (Aly et al., 1993). The hypolimnion has more depleted values as water in the bottom of the lake is protected from the evaporation process. Also the density difference established in the lake due to the summer stratification locks the mixing and the homogenization in isotope fractionation (Boehrer et al., 2000; Murthy et al., 2002).

This isotope fractionation in depth profile supports the classification of Qaraoun Lake as monomictic with one circulation period in addition to the stratification period. Many lakes in temperate climates belong to this class.

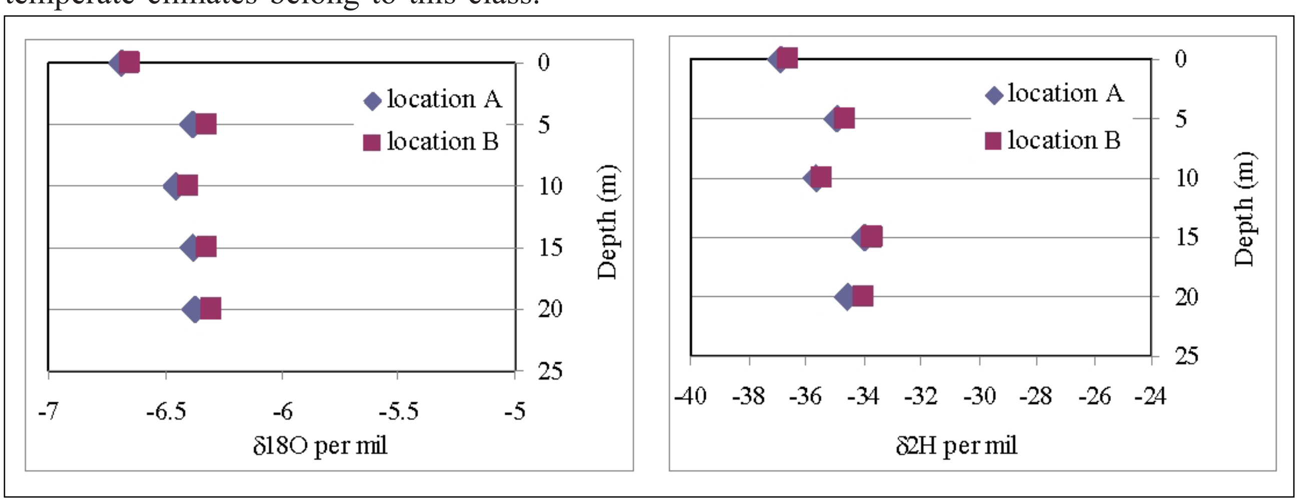

Figure 5. Vertical profile of $\delta^{18}O$ and deuterium content of Qaraoun lake water at two different locations

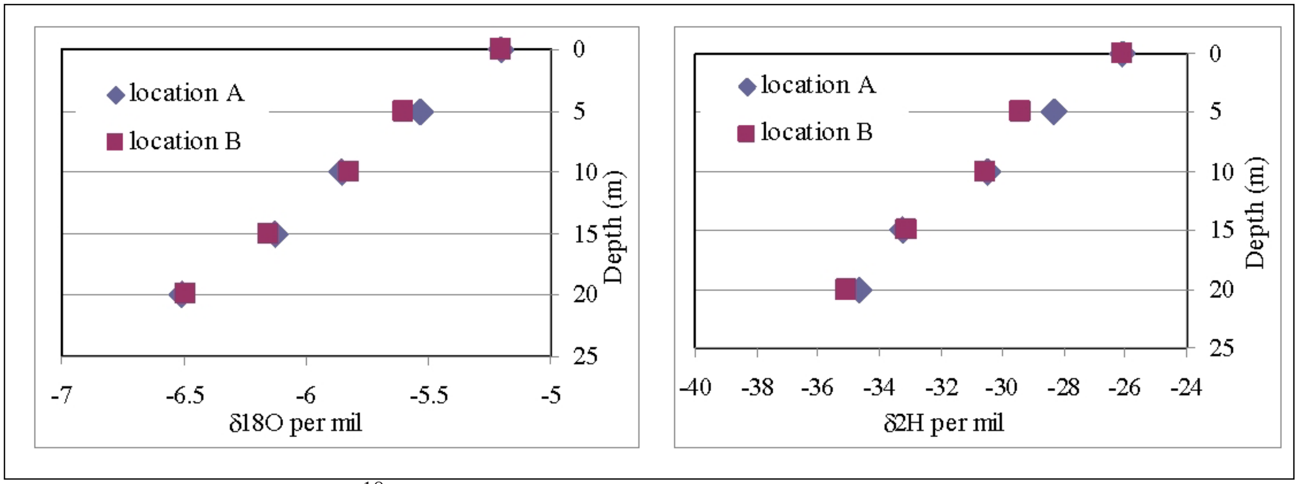

Figure 6. Vertical profile of $\delta^{18}O$ and deuterium content of Qaraoun lake water at two different locations (summer season).

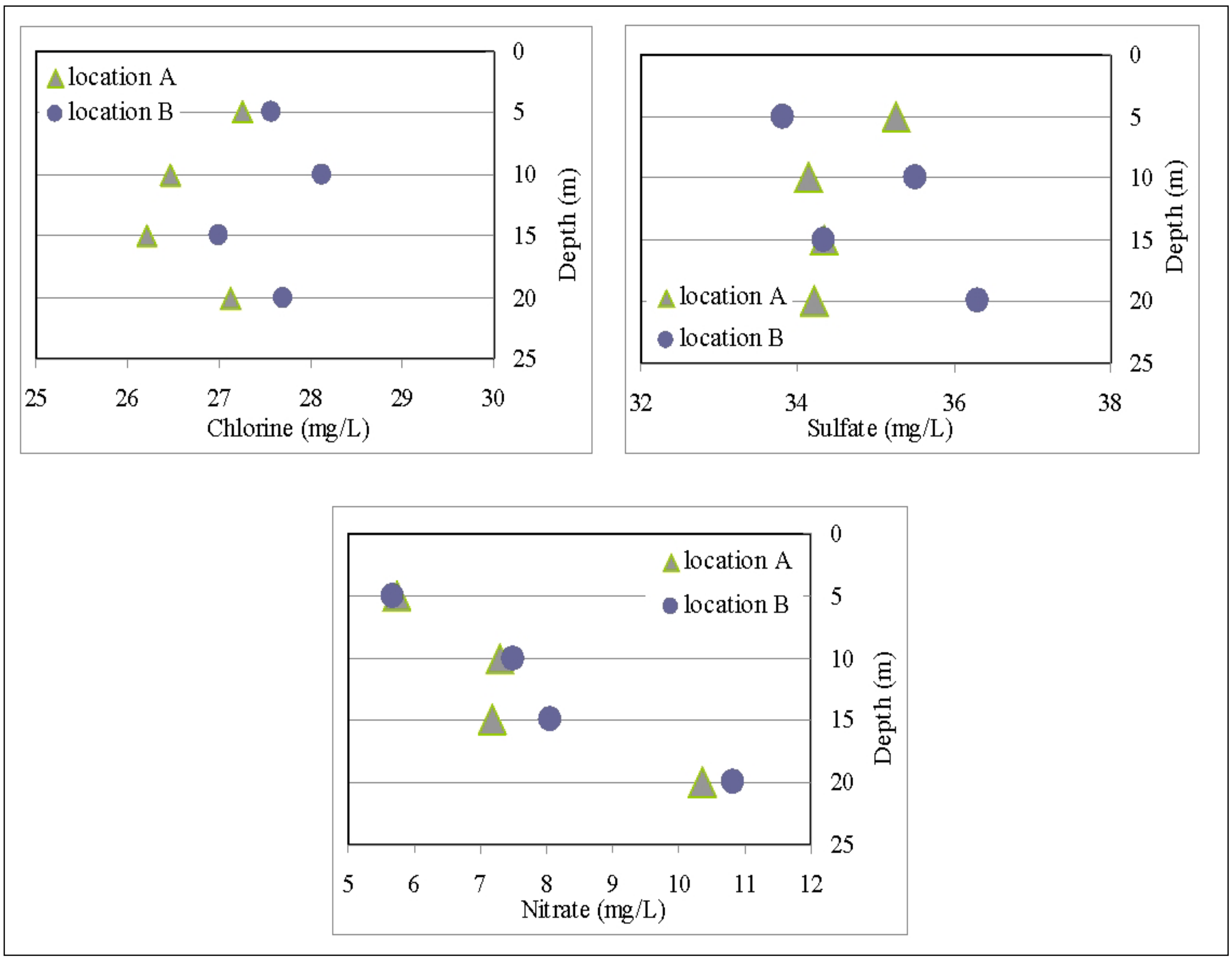

Figure 7. Depth profiles of major anions in qaraoun lake water at two different locations (summer season).

It was also important to determine the role of lake stratification in the summer season on water chemistry (Zeng and Rasmussen, 2005; Wand et al., 1997). Depth profiles for major anions, Cl^-, SO_4^{2-} and NO_3^- were determined at two locations A and B (Figure 7). It is clearly seen that lake stratification did not affect concentration of both Cl^- and SO_4^{2-}, which remain relatively constant throughout the depth profile.

Only nitrate enrichment is shown in deep waters as it increases from 6mg/L in shallower surface water to 11 mg/L in the deepest samples. Here again, horizontal chemical variation between the two locations was absent. Nitrate enrichment reflects the effect of density-dependent stratification in summer waters. In a previous study (Saad et al., 2006) it was shown that incoming water from the Litany River to the lake had high nitrate concentrations due to different anthropogenic activities besides the agricultural runoff in the basin. This source also plays a role in contributing nitrate to the lake and its concentration in deep dense water in the lake.

CONCLUSIONS

The use of isotope geochemistry is a powerful technique in the determination of Qaraoun lake dynamics as well as the study of recharge to adjacent groundwater from the lake. Environmental isotopes coupled with geochemical parameters have been used to determine the percentage of recharge and its areal extent, which is limited to the proximity of the dam in a southeast direction. Piezometers located far from the dam showed a gradual decrease in lake water seepage content. Also in this study, Qaraoun lake was classified as monomictic with summer stratification. Nitrate enrichment in the bottom cold and dense lake water is a result of the stratification process in the summer season.

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