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ORIGINAL ARTICLE

Environmental isotope study of seawater intrusion in the coastal aquifer (Syria)

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Abstract Seawater intrusion into the shallow aquifer in the Syrian coast, north of Latakia (Damsarkho, Ras Ibn Hani) and south of Tartous (Al Hamidieh, Ein Zarka) was studied using hydrochemical and isotopic techniques. The electrical conductivity (EC) distribution map north of Latakia revealed that mixing in this area is the consequence of a frontal intrusion of seawater within the fresh groundwater aquifer which, in turn, results from intensive pumping since the 1960s which has lowered the water table inland below sea level. In Ein Zarka, south of Tartous, in contrast,the EC distribution revealed that seawater intrusion is due to local up-coning as a result of intensive pumping. The deuterium and oxygen-18 relationship is that of a mixing line with a slope of 5.55, indicating an intrusion between freshwater and seawater. In addition, the relationship between oxygen-18 and chloride reveals that the mixing has a dominant role compared to evaporation process. The mixing ratios are estimated to be between 6 and 10% north of Latakia, while they do not exceed 3% south of Tartous. A tritium model was applied to compute the ‘‘mean transit time’’, which is estimated to be around 10 years, on average, to reach the equilibrium that existed originally between the fresh groundwater and seawater, provided that severe pumping is completely halted and the aquifer is naturally recharged by rainfall and deep percolation of irrigation water, thereby allowing the restoration of the hydraulic gradient.

Keywords Environmental isotope · Mediterranean · Mixing ratio · Seawater intrusion · Syria · Transit time

This paper is dedicated to the memory of Dr. Y. Yurtsever.

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Introduction

Seawater intrusion is widespread along the Mediterranean coastlines of Turkey, Cyprus, Egypt, Tunisia, Lebanon and Syria (FAO 1997). These phenomena are also observed at two locations along the Syrian coast, north of Latakia (Damsarkho, Ras Ibn Hani) and south of Tartous (Al Hamidieh, Ein Zarka), where human settlements and urban and agricultural activities are concentrated, and water demands for domestic and industrial as well as for irrigation are increasing. These two locations represent the area under study in this report (Fig. 1).

Severe pumping in these areas has increased the salinity of the shallow aquifer, and subsequent irrigation with this saline water has caused a great deal of damage to olive and lime orchard trees. As a result, the soil has become saline in many places.

Several studies have provided a general description of this problem in the coastal area of Syria [Malakani 1979, 1997; Sekhozpromexport 1979; General Company of Water Study (GCWS) 1987; Ministry of Irrigation 1979, 1985, (unpublished); Abed Rabu 2000; Abou Zakhem and Hafez 2002]. In the 1960s a number of wells were drilled within 3 km of the beach to supply drinking water to Latakia City, Da'atour and Dams-

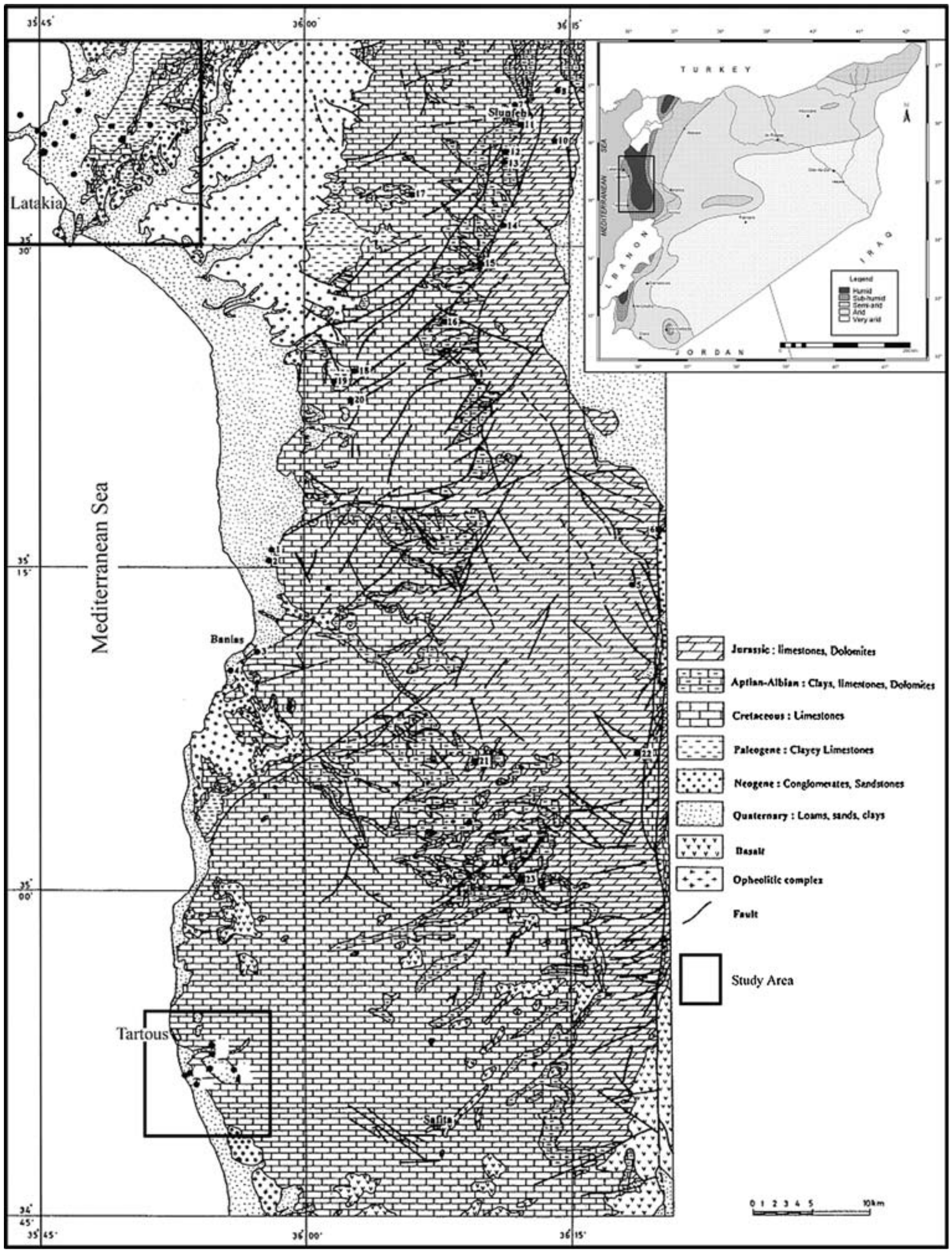


Fig. 1 Geological map and sample location (modified from Ponikarov 1966)

arkho. Over the years, groundwater salinity has gradually increased due to seawater intrusion (Malakani 1997).

The purpose of the investigation reported here was to study the geology, climate, hydrology, hydrogeology and hydrochemical composition of the groundwater in a coastal area of Syria. Stable isotopes were used to identify seawater intrusion, and the tritium model was applied to evaluate the mixing ratio between fresh and seawater and to estimate the required time for reconstruction of the hydrostatic equilibrium between fresh and seawater, provided all pumping activities completely ceased. This study was performed in cooperation with the International Atomic Energy Agency (IAEA), within the framework of the regional project RAW/8/002 entitled ''Isotope hydrology techniques in water resources management''.

Environmental background

The study area is characterized by a Mediterranean climate with a wet winter (November–April) and a dry summer. The average rainfall varies from 800 to

1000 mm/year (Selkhozpromexport 1979). The coastal mountain range comprises Jurassic, Cretaceous and Neogene sedimentary rocks. Cretaceous sediments are widespread in the area, represented by limestone, dolomite, marl and chalky marls. The Tertiary comprises marls and marly limestone of the Paleogene age. Neogene sediments are composed of marls, limestone, conglomerates and basalt (Fig. 1) (Ponikarov 1966). Quaternary sediments occur along the shoreline, represented by coastal marine formations and sand dunes of conglomerate and sandstone. Ras Ibn Hani represents a typical marine terrace composed of sand, clay and gravel, while in the center of the Damsarkho depression, extending along an axis of 150 km^2, the Quaternary formation consists of continental alluvium containing sand, clay and pebble. These formations overlay Pliocene marls and form a good aquifer with a thickness of 25 m (Malakani 1997; Khouri and Droubi 1981).

The coastal region is characterized by a well-developed hydrographic network. There are several springs and rivers varying in size, all flowing westerly towards the sea, without the formation of deltas.

The main rivers in the area are:

- Al Kabir Ashamali River, the biggest river in the coastal area with a large catchment area with intensive drainage network (180 km^2). It discharges into the Mediterranean Sea, south of Latakia. The river flow rate increases during the flood periods (January–May). The Al Kabir Ashamali dam is located upstream of the river, 20 km from the coastal line.
- Al Abrash River, the largest water resource with a catchment area of 250 km^2. It discharges into the Mediterranean Sea, south of Hamidieh village. Al Abrash dam is located 16 km east of the coastal line.

Hydrogeology of the shallow aquifer

Northern Latakia

The piezometric map of the shallow groundwater shows that the water is flowing towards Al Kabir Ashamalli River from both sides, which represents the main natural discharge area of this aquifer (Fig. 2). However, north of Latakia the groundwater flows towards the sea from the Sitmarkho area to Ras Ibn Hani area. Nevertheless, this movement is rather slower than the flow of water to the river. The recharge of this aquifer comes primarily from direct infiltration of rainfall and the deep percolation of excess irrigation and surface water and partially from underground recharge from the eastern part of the aquifer. Figure 2 shows that the groundwater levels are below sea level in the eastern and southern parts of the Ras Ibn Hani area within an area 3–5 km inland. Another depression extends from northern Latakia to Damsarkho. These depressions of groundwater level reverse the hydraulic gradient direction from west to east, as clearly illustrated in Fig. 2 which is based on data collected during 1997 (Ministry of Irrigation 1997, unpublished). A comparison of the data collected from the mid-1980s by GCWS (1987) indicate that the situation has not changed significantly.

A water divide line passes from Latakia to Sitmarkho dividing the area into two parts. Seawater intrusion is only encountered north of Latakia to Damsarkho and Ras Ibn Hani.

South Tartous area

The study area extends from south Tartous (Hamidieh) to Ein Zarka, along the AL Abrash River to include an area for 8 km in width in the direction towards Hora village. The groundwater level map of the shallow aquifer shows that isolines are closer in the eastern part near Hora village and farther apart towards the coast (Fig. 3). The pattern of these isolines is strongly correlated to the hydrographic network, where the groundwater discharges into the rivers in some places and is recharged by the rivers in other places. The zero line bends slightly towards the east between Al Abrash River and Ein Zarka, and is less obvious than in the area to the north of Latakia.

Chemical characteristics

Electrical conductivity maps

Northern Latakia area

Based on the electrical conductivity (EC) map (Fig. 4), it was possible to divide the area into two zones. The first zone is located between Sitmarkho and B. Kassab, where the EC is less than 1000 µS/cm and no mixing process is observed (the intrusion zone limit). The second zone is located between Damsarkho and Ras Ibn Hani, which is characterized by higher EC values – reaching 6000 µS/cm – with a mixing ratio between 2 and 10%.

The dense EC isolines indicate a significant seawater intrusion between the Romanah and Ras Ibn Hani sector, whereas it appears to be more gradual in the Damsarkho area.

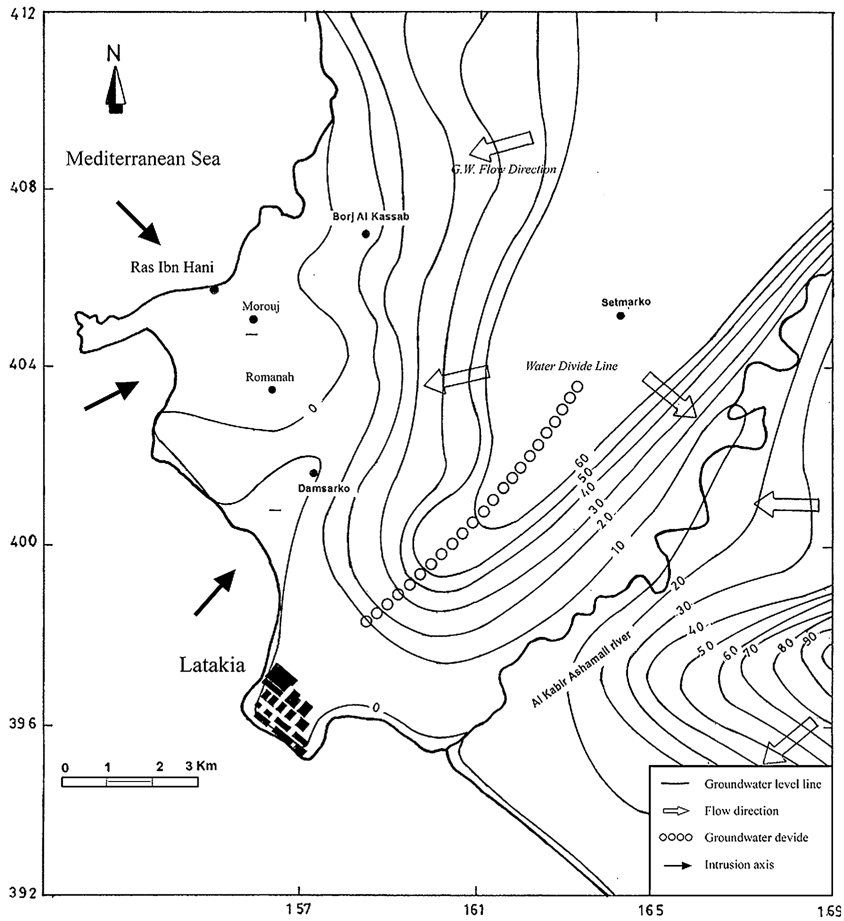


Fig. 2 Water level map of shallow groundwater in the coastal area, Latakia

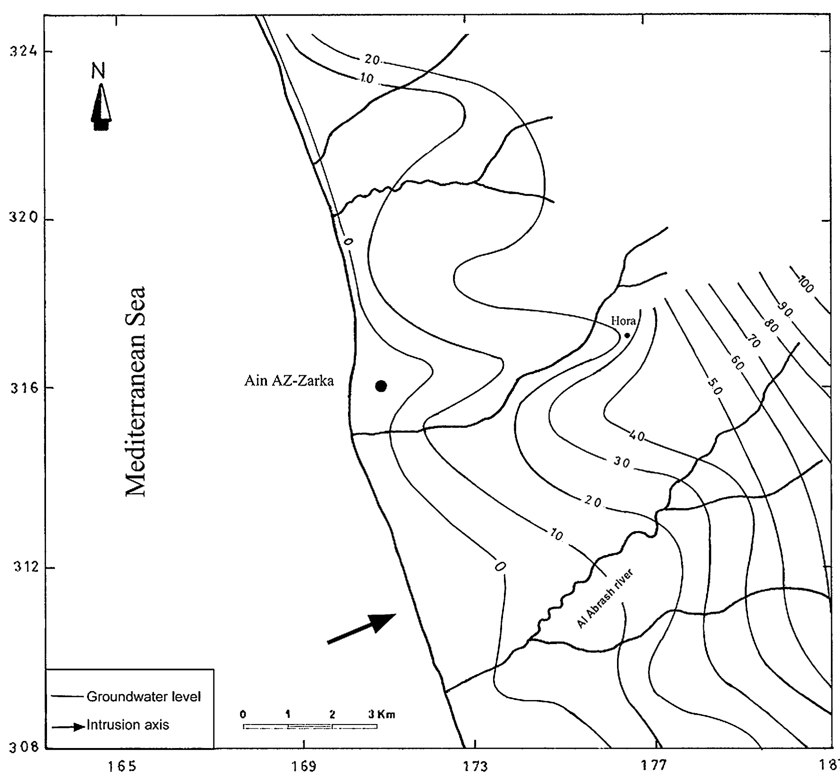
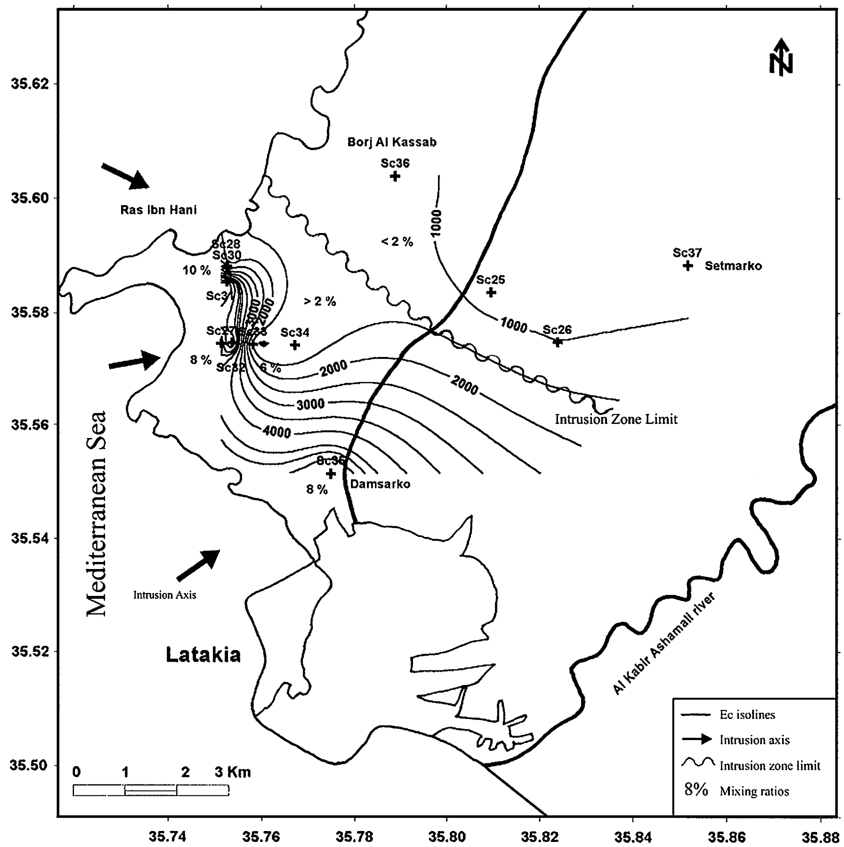


Fig. 3 Water level map of shallow groundwater in the coastal area, Tartous

Fig. 4 Map of EC (µS/cm), distribution in the coastal area (Latakia, June 1994)



The intrusion has a frontal aspect with three axes. The first one extends from Ras Ibn Hani to the east (well Sc31); the second is in southern Ras Ibn Hani, towards the Romaneh area (well Sc32); the third stretches from north Latakia to Damsarkho (well Sc35). These intrusions correspond to the groundwater level (Fig. 2), which indicates that seawater intrusion occurs in areas where the water level is below zero. The main cause of the lowered water level is the intensive pumping that occurred during the 1960s, leading to an advanced stage of seawater intrusion. Figure 4 shows the mixing ratios calculated using Hydrowin software; these are around 10% in the Mourouj (Sc31) area, 8% in the Romaneh (Sc32) area and Damsarkho, decreasing to 6% towards the east. These ratios are comparable to the 10–15% estimated by Yurtsever and Payne (1978) in Qatar. The map shows that the intrusion ratio decreases towards the east and northeast to less than 2%. The intrusion line was drawn approximately northwest–southeast, dividing the area into two zones, as mentioned.

Southern Tartous area

The EC map allowed us to define a freshwater area with an EC lower than 600 µS/cm (Sc45, Sc43 wells) (Fig. 5). The salinity increases towards the west, reaching the highest value, 2300 µS/cm, in the Sc41 well located south of Ain Al Zarka. The mixing ratio was estimated to be 3%, which is lower than that recorded in northern Latakia. Nevertheless, the mixing pattern was somehow different, probably due to the up-coning movement of saline seawater as a result of intensive pumping. Although this mixing is spatially limited, there is a possibility of spreading to northern Latakia if extensive pumping were to continue.

Chemical analyses

Piper diagram

The chemical composition of shallow groundwater from northern Latakia and southern Tartous is shown in the Piper diagram (Fig. 6).

Figure 6 shows that freshwater represented by two reference samples collected from the Al Kabir Ashamali and Al Abrash river dams (Sc1, Sc2) are of the calcium-bicarbonate type. Reference seawater sample (Sc29) (Table 1) collected 3 km inland of the Ras Ibn Hani coastline is of the sodium chloride type (Cl^- = 26,000 mg/l). The samples taken at the other points are a mixture of fresh and seawater types, their

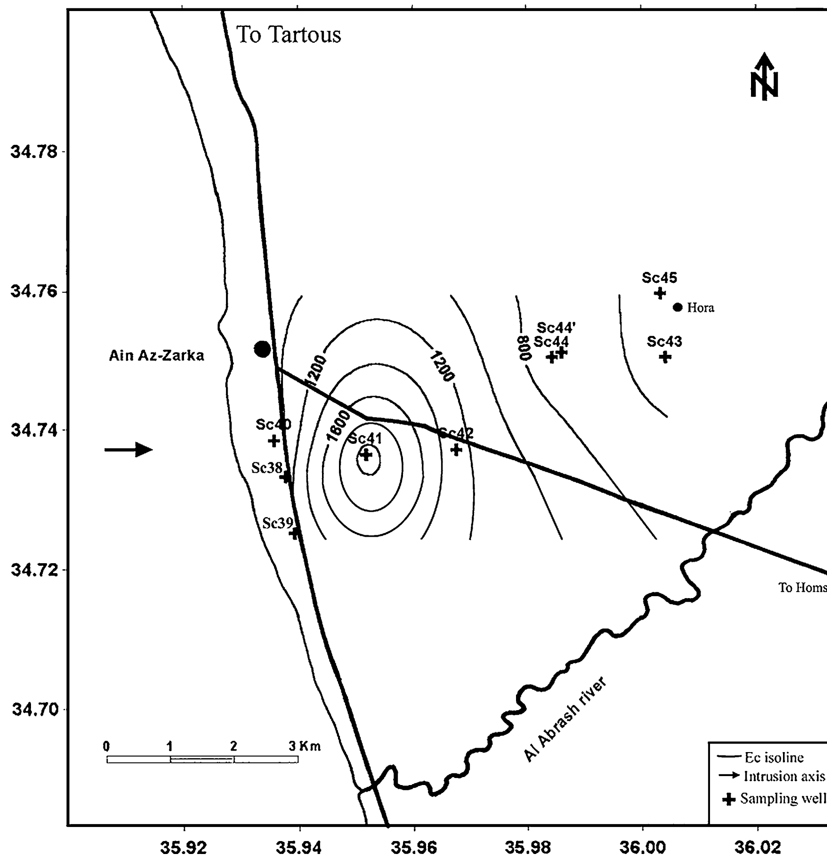


Fig. 5 Map of electrical conductivity (μS/cm) distribution in the coastal area (Tartous, June 1994)

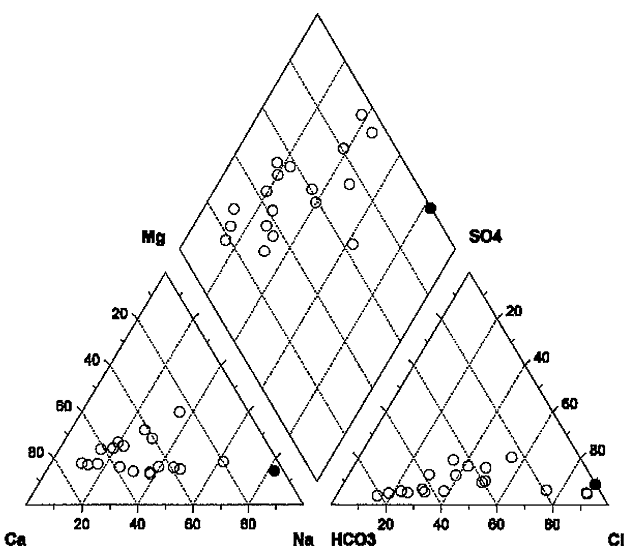


Fig. 6 Piper diagram, coastal area, April 1998

composition depending on the mixing ratios. The concentration of chloride in the seawater along the Syrian coast varies between 23,000 and 31,000 mg/l(average: 27,000 mg/l) (Al-Charideh 2004); along the coast of Lebanon, the average chloride concentration of sea water is 26,400 mg/l (Ayoub et al. 2002),and in Turkey, at Marmaris, it is 28,872 mg/l (δ^2H = 10.9‰, δ^{18}O = 1.82‰) and at Oren, 20,945 mg/l (Kurttas et al. 1996).

Isotopic analyses

Environmental isotopes were also used to investigate the seawater intrusion in the study areas. The continental water is depleted in the stable isotopes (negative values of δ^{18}O, δ^2H). These delta values are around 0‰ in mean ocean water. The Mediterranean Sea, however, represents a semi-closed basin characterized by high evaporation and, consequently, the delta values are positive (δ^2H = 13.2‰, δ^{18}O = 1.3‰) (Table 1).

The relationship between deuterium and oxygen-18 provides a clear picture of the mixing process between fresh water and seawater along the straight line of the two mixing poles, with fresh water of the aquifer at one end and seawater at the other end (Gat and Confiantini 1981; Gonfiantini and Simonot 1987; Payne 1983; Custodio and Bruggeman 1987; Gonfiantini and Araguas 1988; Custodio et al. 1989, 1993; Ho et al. 1992; Ahn et al. 1992; FAO 1997). The slope of the line

Table 1 Isotopic composition of shallow groundwater in the study areas (21 April 1998)

Location	Sample code	*t* (°C)	EC (μS/cm)	Cl^- (mg/l)	pH	δO-18‰	δD‰	T (TU)
Kanjara-W	Sc25	20	756	84.1	7.39	–4.78	–21.4	1.4
Jinata-W	Sc26	18.4	1,005	65.4	7.18	–4.8	–21.8	4.3
H. Maya-W	Sc27	19.2	4,650	1,374.1	6.88	–4.43	–20.2	7.4
I. Hani-W1	Sc28	20.4	2,030	360	6.87	–5.77	–29	4.8
M. Sea	Sc29	25.4	67,600	26,000	8.17	1.29	13.2	1.9
I. Hani-W2	Sc30	21	1,379	220	7.67	–5.99	–31.5	6
Mourouj-W1	Sc31	20.9	6,740	2,300	6.8	–4.53	–20.3	9
Romanah-W	Sc32	19.5	6,270	2,300	6.72	–4.42	–19.8	9.8
Mourouj-W2	Sc33	19.6	913	84	6.53	–4.93	–22.8	8.5
S. Mousa-W	Sc34	19.5	1,017	120	6.58	–4.98	–23.6	10.5
Damsarkho-W	Sc35	20.2	5,530	2,100	6.55	–4.89	–22.4	8.4
Qassab-W	Sc36	21.6	1,300	240	7.22	–5.17	–26.2	5.6
Setmarkho-W	Sc37	18.9	783	60	6.67	–5.42	–26	4.8
Tartous-W1	Sc38	21	1,270	210	6.54	–3.84	–17.4	7.4
Tartous-W2	Sc39	22.1	947	100	7.4	–5.15	–22	0
Tartous-W3	Sc40	22.5	770	80	7.04	–5.55	–26.5	2.4
Tartous-W4	Sc41	21.4	2,120	530	7	–4.52	–21	5.2
Tartous-W5	Sc42	20.9	1,258	80	6.81	–4.31	–22.5	8.6
Tartous-W6	Sc43	23.4	499	36	6.96	–5.32	–26.5	8.8
Tartous-W7	Sc44	20.4	671	36	6.3	–5.29	–28.2	10.3
Tartous-W8	Sc45	20.3	546	26	6.51	–5.73	–27.6	8.8
AlAbrash Dam	Sc1	18.5	460	84.1	8.3	–5.2	–24.5	4.5
K. Ashamali Dam	Sc2	22.3	493	80.0	8.59	–4.5	–21	4

connecting the aquifer and seawater is sometimes similar to the line that is based on the evaporation process. In this case, we can use the relationship between oxygen-18 and chloride to verify the real effect of the mixing process.

The relation between deuterium and oxygen-18

All data points are distributed around the mixing line characterized by a slope of 5.55 (Fig. 7) and given by the equation:

$$\delta^2\mathrm{H} = 5.55\delta^{18}\mathrm{O} + 3.35.$$

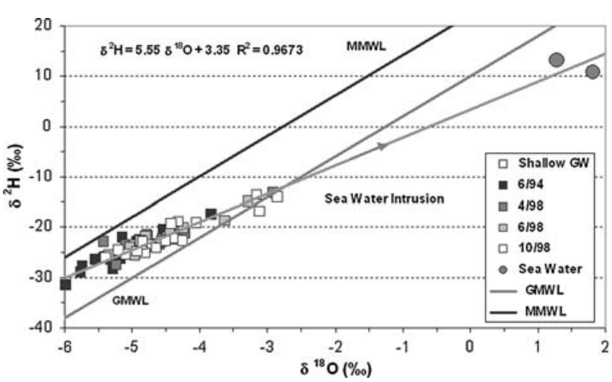


Fig. 7 Correlation between deuterium and oxygen-18 (δ^{18}O) (*GW* ground water, *GMWL* global meteoric water line, *MMWL* Mediterranean mean water line)

This line connects seawater with groundwater, and along the line those points shifting towards seawater have a higher mixing ratio. The distribution of these points around this line may be attributed either to the mixing process between the freshwater and seawater or to the evaporation of the shallow groundwater through the unsaturated zone which has the same enrichment and slope.

The relationship between δ^{18}O and chloride

As shown in Fig. 8a the points are distributed around the mixing line linking fresh water with seawater are expressed by the formula:

$$\delta^{18}\mathrm{O} = 2.33 \times 10^{-4}\mathrm{Cl}^- - 4.7751 R^2 = 0.8333.$$

Figure 8b shows the detailed distribution of the samples around the mixing line. The samples from Al Abrash River and Al Kabir Ashamali river dams represent standard fresh surface water (taken in 1998) that is used for irrigation. Groundwater from Setmarkho (Sc37) and Tartous (Sc 45) represents fresh groundwater samples, with no effect of seawater intrusion. Based upon the theoretical plot of δ^{18}O and Cl^-, the samples related to different mixtures of fresh and saline water should be located on a straight line connecting the two ends, with the original freshwater of the aquifer at one end and local seawater at the other.

If the groundwater is affected by evaporation, the samples will be distributed around an exponential line. However, an increase in the chloride concentration without any variations of oxygen-18 indicates the dissolution or leaching of the geological formation (Gonfiantini and Araguas 1988).

It can be seen in Fig. 8b that the groundwater samples are not distributed around the exponential evaporation line, indicating a very limited effect of evaporation and that the groundwater salinization is mainly due to mixing with seawater. The line also shows that seawater intrusion north of Latakia is more pronounced than south of Tartous. This will be clearly expressed by the mixing ratio of salt and fresh water.

Mixing ratios between fresh and saline water

To calculate the theoretical mixing ratios of seawater and fresh groundwater we have used non-affected groundwater from Setmarkho (Sc37) and Tartous-W8 (Sc45) and seawater samples taken 3 km away from Ras Ibn Hani (Sc29).

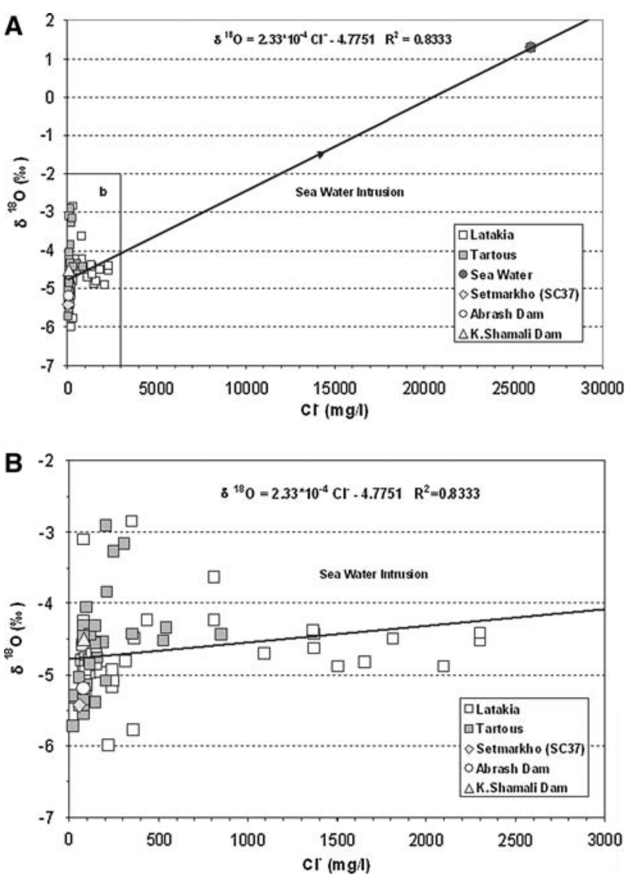


Fig. 8 Correlation between $\delta^{18}O$ and chloride in shallow groundwater (**a**, **b**). **b** Zoom of the *b* sector

Based on the conservative mass balance of the chloride concentration, the theoretical mixing could be calculated in the following equation:

$$F = \frac{[Cl^-_{MIX}] - [Cl^-_{GW}]}{[Cl^-_{SEA}] - [Cl^-_{GW}]} \times 100(\%)$$

where

F: mixing ratio expressed as the percentage of seawater (%);
Cl^-_{MIX}: chloride concentration in the mixing groundwater;
Cl^-_{GW}: chloride concentration in Setmarkho groundwater;
Cl^-_{SEA}: chloride concentration in seawater.

Using the HYDROWIN program, all field parameters, chemical and isotopic compositions were included in the theoretical estimation of the optimized mixing ratios (Table 2). This calculation depends on the mixing of the seawater sample with fresh groundwater in Setmarkho and a comparison with the groundwater samples.

Table 3 shows the calculated mixing ratio for all samples with a mixing ratio of over 1%, and Cl^- at different seasons and years. The mixing ratio in Latakia can be seen to range from 2 to 9%, whereas in Tartous it ranges from 1 to 3%.

The relationship between the estimated mixing ratio and chloride concentration as shown in Fig. 9 for some samples was compared with the theoretical mixing line.

From periodical measurements between 1994 and 1998, we noticed that the mixing ratio gradually decreased from 9 to 5% in Mourouj w. Sc31, while in Damsarkho w. Sc35 it decreased from 8 to 4% then increased to 7% in October 1998 (Table 3). We attributed this development to the fact that some wells of high salinity became unsuitable for irrigation and pumping was stopped, whereas in others the salinity increased due to heavy pumping. The installation of an irrigation network from Al Kabir Ashamali dam at some places, which has been in operation since 1998, may be another contributing factor. These two factors have substantially contributed to a partial recovery of the previous groundwater hydraulic gradient.

The mixing ratios calculated in southern Tartous are generally less than 3% (in Sc41 well), and concentrated around well Sc41. This indicates a different mixing mechanism than that in northern Latakia. This type of mixing could be explained by local up-coning and has limited mixing effects.

Table 2 Theoretical optimized mixing ratios of seawater and fresh groundwater

F (%)	O[a]	2%	4%	6%	8%	10%	100[b]
K^+ (mg/l)	1	9.58	18.2	26.7	35.3	43.9	430
Mg^{++} (mg/l)	17	46.4	75.8	105.3	134.7	164.1	1,488
Ca^{++} (mg/l)	112	120.9	129.9	138.9	147.8	156.8	560
Na^+ (mg/l)	20	339.6	659.2	978.8	1,298.4	1,618	16,000
Cl^- (mg/l)	60	578.8	1,097.6	1,616.4	2,135.2	2,654	26,000
$SO_4^=$ (mg/l)	21	88.6	156.2	223.7	291.3	358.9	3,400
HCO_3^- (mg/l)	329	325.8	322.7	319.5	316.4	313.2	171
T (°C)	18.9	19	19.2	19.3	19.4	19.5	25.4
pH	6.67	6.7	6.73	6.76	6.79	6.82	8.17
EC (μS/cm)	783	2,119.3	3,455.7	4,792	6,128.4	7,464.7	67,600
NO_3^- (mg/l)	22	21.7	21.4	21.2	20.9	20.6	8
$\delta^{18}O$ (‰)	–5.42	–5.29	–5.15	–5.02	–4.88	–4.75	1.29
δ^2H (‰)	–26	–25.2	–24.4	–23.6	–22.9	–22.1	13.2
^3H (TU)	4.8	4.74	4.68	4.63	4.57	4.51	1.9

[a]Fresh groundwater (Setmarkho Sc37)

[b]Seawater

Table 3 The seawater:groundwater mixing ratio in a number of samples over a 4-year period

Wells	14 June 1994		21 April 1998		2 June 1998		28 October 1998	
Mixing water	Cl^- (mg/l)	Seawater (%)	Cl^- (mg/l)	Seawater (%)	Cl^- (mg/l)	Seawater (%)	Cl^- (mg/l)	Seawater (%)
Mourouj W1 (Sc31)	2300	9	1,505	6	1655	6	1365	5
Damsarkho (Sc35)	2100	8	1,095	4	1374	5	1815	7
Maya (Sc27)	–	–	1,374	5	–	–	–	–
Romanah (Sc32)	2300	8	813	3	813	3	351	2
I. Hani W2 (Sc30)	220	1	364	1.2	439	1.5	320	1
Tartous-W4 (Sc 41)	530	1.9	542	2	850	3.2	355	1.3

Groundwater transit time estimation

As the irrigation system has been in operation since 1998 and the pumping of groundwater has ceased, it is possible to reconstruct a positive hydraulic gradient towards the sea, particularly in the Damsarkho, Romaneh and Morouj areas, thereby allowing hydrostatic re-equilibrium between fresh and saline water.

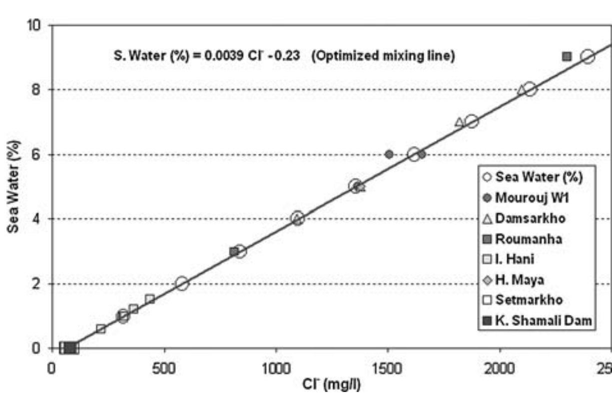


Fig. 9 Relationship between calculated mixing ratio (%) and Cl^- of shallow groundwater

The required re-equilibrium time can be estimated by applying the tritium model under the following conditions: pumping activities must be prevented in the high mixing areas, natural recharge of the aquifer from rainfall and irrigation must occur from the dams.

The tritium data can be used to estimate the "mean transit time" of groundwater in the aquifer. There are many mathematical models used for this calculation (Dancer and Payne 1971; ; Yurtsever and Payne 1978; Yurtsever 1979, 1983). We have selected the complete mixing model, which is the most appropriate in our case study. It is based on mathematical formulas using tracer input and output of the aquifer under steady-state flow conditions. The mathematical formulation is:

$$C_0(t) = \sum_{\tau=0}^{\infty} C(t-\tau) \times h(\tau) \times \mathrm{e}^{-\lambda t},$$

where

$C_0(t)$: tritium output;
$C(t\text{-}\tau)$: tritium input;
$h(\tau)$: transit time distribution;
$\mathrm{e}^{-\lambda t}$: radioactive decay correction factor;

t: time;
τ: transit time.

The exponential expression to describe the response factor system is as follows:

$$h(\tau) = \frac{1}{\tau_0} \times \mathrm{e}^{-\left(1/\tau_0\right)t}$$

where τ_0 is the "mean transit time":

$$\tau_0 = V/Q$$

in which V is the volume of the aquifer and Q is the base flow.

The tritium data of the Bet Dajan meteorological station located near the Mediterranean coastline (32°00″N, 34°82″E) is used as input signal for the years 1960–1990 (IAEA 1992). The theoretical tritium output curves were computed using the complete mixing model for the transit time of 5, 10, 15 and 20 years, as shown in Fig. 10, with selected groundwater wells that have been affected by high salinity.

The measured tritium content in seawater is 1.9 TU, while the mean tritium content in precipitation for the period between 2000 and 2002 is 4.5 TU; in comparison, the content in Al Kabir Ashamali and Abrash dams is 4.2 and 4 TU, respectively. We have selected the wells of high salinity values and high tritium contents.

Tritium amounts in samples Sc31, Sc32, Sc33, Sc35, Sc42 were between 8.4 and 9.8 TU, with an average of 8.9 TU for 1994; in 1998, tritium amounts ranged from 4.6 to 7.1 TU, with an average of 6.3 TU (Fig. 10). These averages correspond to the computed line of a 10-year mean transit time, which represents the required time to re-establish the balance between fresh and seawater under the above-mentioned conditions.

Accordingly, we suggest chemical and isotopic monitoring at 4- to 5-year intervals in order to verify the return of the ground water to conditions that existed before the intensive pumping period.

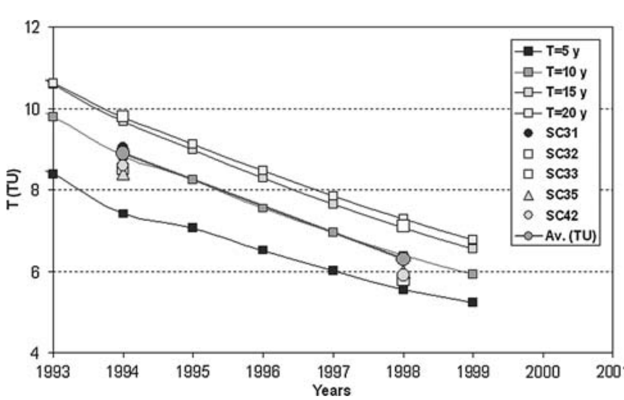


Fig. 10 Computed tritium output concentration of Bet Dagan station, compared with measured tritium in the coastal area

Conclusion

The mixing mechanism in northern Latakia is the result of the frontal intrusion of seawater into the shallow aquifer. This intrusion process is caused by a reverse hydraulic gradient and flow direction of seawater towards the coastline as a result of a fall in the water table level below zero. In contrast, the mixing mechanism south of Tartous is an up-coning, represented by a vertical upward movement of saline water into the fresh water aquifer. This type of mixing has localized effects compared with the frontal intrusion in northern Latakia.

The Piper diagram shows that the water is of the calcium-bicarbonate type in non-affected areas. This water gradually becomes a sodium-chloride type towards the sea, reflecting the increase in the mixing ratio.

The relationship between deuterium and oxygen-18 indicates that all points are scattered around the mixing line with a slope of 5.55 linking the fresh water with seawater.

The relationship between oxygen-18 and chloride proves that evaporation has very limited effects, whereas the groundwater salinization is mainly due to seawater intrusion. Seawater intrusion in the north of Latakia is more pronounced than that in the south of Tartous.

The mixing ratios in northern Latakia are around 9% in the Mourouj area near Ras ibn Hani and 8% in Damsarkho and Romanah, while in the south of Tartous the mixing ratio does not exceed 3%. These results show that the mixing ratios have decreased from 1994 to 1998, primarilyas a consequence of pumping activities being stopped in some wells and the establishment of the irrigation network from the dams of Al Kabir Ashamali and Abrash Rivers in 1998. However, the mixing ratios in some wells has increased due to a continuation of over-pumping.

The required mean time to achieve re-equilibrium between fresh and seawater is estimated to be around 10 years on average – based on tritium modeling – provided that pumping activities are completely stopped and the natural recharge of the aquifer is re-established, thereby allowing for restoration of the groundwater hydraulic gradient towards the sea.

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