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Application of nuclear techniques to arid-zone hydrology: 1 - present recharge and groundwater salination in the Gefara Plain (Libyan Arab Jamahiriya)

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ABSTRACT. — In the plain south of Tripoli, the environmental isotopes indicate present recharge by rainfall of the shallower aquifers, combined with a deep supply of old waters flowing from the south. Moreover aquifer stratification is deducible in all piezometers from the tremendous increasing in total dissolved salt, mainly sulphates and chlorides. In a few wells the salinity is typical of brine (NaCl > 200 g/l). This water can be explained as a remnant of a Pliocene sea water, as noted in all great coastal plains of the Central Mediterranean basin.

Key words: isotope hydrology, Gefara Plain, brines, groundwater salination.

RIASSUNTO. — Gli isotopi ambientali indicano la presenza di una ricarica attuale degli acquiferi più superficiali, nella piana a Sud di Tripoli; l'apporto meteorico avviene unitamente a quello profondo dai sottostanti acquiferi. La stratificazione degli acquiferi è messa in evidenza in quasi tutti i punti d'acqua da un forte incremento della salinità specialmente in solfati ed in cloruri. In alcuni piezometri il tenore in cloruro di sodio supera i 200 g/l e la salamoia può essere considerata come «reliquia» di un paleomare di inizio Pliocene come anche osservato in altre pianure costiere del bacino mediterraneo.

Parole chiave: idrologia isotopica, Piana del Gefara, acquiferi, incremento della salinità.

Introduction

Arid conditions are said to exist in a region when the potential evapotranspiration is greater than the precipitation for most of the year. The difference determines the degree of aridity. In some very arid zones, such as the Central Sahara area and the Arabian Peninsula, it exceeds 2 metres per year; in semi-arid regions (southern side of Mediterranean basin and Sahelian belt), it is usually less or close to 1 metre. Long periods of aridity, drastically, change the face of the land so that it has a different hydrological response to atmospheric inputs and incoming radiant energy.

Conventional methods of calculating the main hydrological parameters cannot be relied upon to give accurate values when applied to arid and semi-arid zones, and it is generally agreed that isotope hydrology offers most significant results. Its most promising applications are:

- assessment of the occurence and mechanism of modern recharge. This generally takes place mainly through alluvial wadi flooding rather than through direct infiltration of rainfall in sand-dunes;
- investigation of the occurence, characteristics and frequency of past recharge and of paleogroundwaters, on which to base long term water resource estimations;
- provision of evidence of underground recharge through leakage or interconnections between aquifers.

All these applications are quite complex. The isotopic data must therefore be interpreted together with the hydrological, hydrogeological and hydrochemical data.

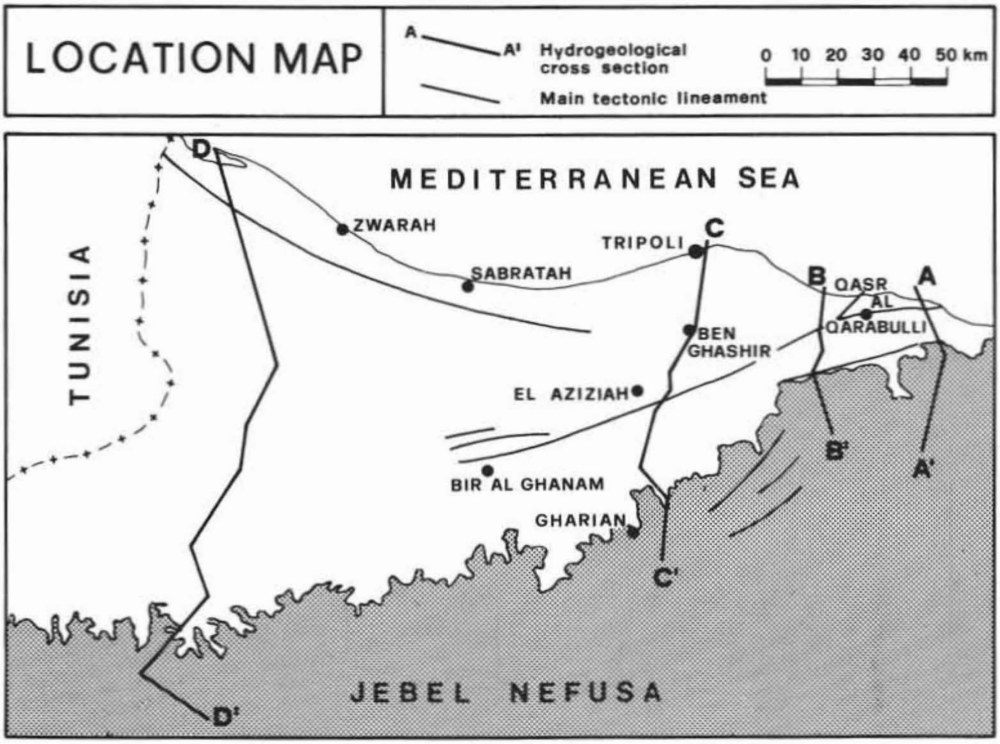

Fig. 1. — Gefara plain: localities map, hydrogeological cross section (see Figure 2) and main tectonic lineament visible on the satellite imagery (from Pallas Ph. 1978).

Hydrogeology of Gefara plain

The problem

Heavy exploitation for municipal, industrial and agricultural supplies has lowerest the aquifer water level by several metres during the few last decades; for instance, in the Ben Gashir area the piezometers show a decline of more than 40 metres during the last 25 years, excluding the short recovery when the pumping rate is reduced during the rainy season (Pallas Ph., 1978). However, the water level of some wells in the Sabratah and Tajura areas does not fall despite heavy exploitation, since sea water is replacing the extracted groundwater and the quality is naturally impaired.

Geomorphological sketch

The Gefara plain is a triangular area of about 20.000 km², bounded on the north by the Mediterranean coast, on the south by the Jebel el Nefusa and on the west by the Tunisian border (Fig. 1). It is a low lying area rising gently from sea level along the coast to 200 m at the foot of the hill escarpment, and the sharply to more than 750 m.

Rainfall and surface runoff

The annual rainfall varies from 300 m (Tripoli) to less than 100 mm in south-west of the plain, with an increase to 250 mm at the highest elevation of Jebel el Nefusa. The hydrographic network flowing nortward is the only one that drains a significant amount of runoff water every year through many wadis not usually more than a few kilometers long.

Geology and hydrogeology

The Gefara Plain is underlain by stratified marine and continental rocks of Tertiary and

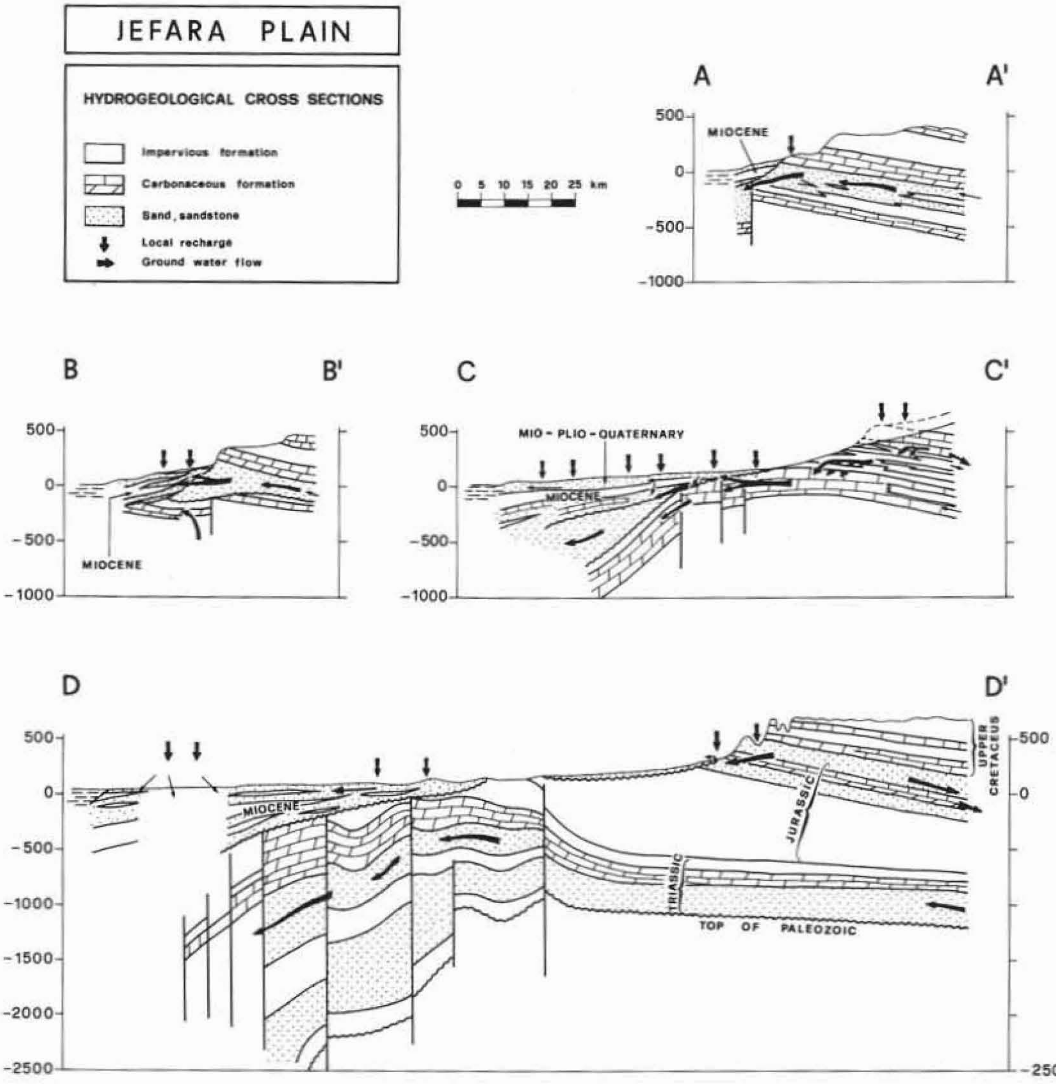

Fig. 2. — Gefara plain: hydrogeological cross sections (modified from Pallas Ph. 1978).

Quaternary age. The oldest rocks outcropping in the area are principally limestones interbedded by gray marl, clay and sandstone. These Miocene deposits lie at the surface in the south of the plain. Near the coast, they are mantled by Quaternary deposits, most loosely cemented sandstone. Along the Mediterranean shore, these deposits are covered by recent dunes of unconsolidated sand. The total thickness of the Mio-Plio-Quaternary formations can reach 600 m along the coast. In the south, it is less near the Jebel, where thin Quaternary marble covers upper Jurassic and Triassic deposits (Fig. 2). The aquifers which play an important role in the groundwater flow and storage in the Gafara Plain are:

— Quaternary-Plio and Upper Miocene aquifers: the saturated thickness varies from 10 to 150 m. The groundwater flows from south to north under unconfined conditions. The recharge area should be located approximately in the Jebel escarpment according to the geological and topographical conditions.

The reservoir seems to be recharged directly by infiltration of runoff from the wadis, and by direct infiltration of rainfall. The water of this aquifer is generally of good quality with a conductivity less than 2.500 μmho/cm (about 1.700 ppm as T.D.S.). However, in Sabratah the water quality deteriorates rapidly and becames saline. Along the coast, higher salinity can be observed owing to from sea water intrusion.

— Cretaceous and Upper Jurassic aquifer: Kicla formation. It is very important in the central part of the Plain. This thick complex of sandstone forms a single, usually confined hydraulic unit. The groundwater flow is in continuity with the general south-north flow. The recharge area is the same as that for the previous aquifer, from which it is separated by Middle Miocene clay deposits. The thickness of the Kicla aquifer ranges from 100 to 350 m. The water quality is generally good with a conductivity ranging from 1.500 and 2.500 μmho/cm and T.D.S. from 1.000 and 2.000 ppm.

— Middle Triassic aquifer: Aziziah formation, essentially composed of dolomitic limestone locally interbedded with evaporitic layers. This formation hosts an important aquifer. In the western and north-eastern part of the Plain, where its depth does not exceed 300 - 1.100 m, sebkhas may be originated by the artesian discharge. The water is usually of medium to poor quality with conductivity higher than 4.000 μmho/cm (PALLAS PH., 1978; SALEM O. et al., 1980).

Sampling and analyses

Isotopic and selected chemical groundwater data are reported in Table 1. The environmental isotopes evaluated were Deuterium (^2H or D), Oxygen-18, Carbon-13, Sulphur-34 and Tritium (^3H) and Carbon-14.

Some of the isotopic results used in this paper were obtained at the I.A.E.A. Isotope Hydrology Laboratory but additional analyses were performed in other laboratories.

The stable isotope results are expressed in the usual ways i.e. as differences in parts per mille with respect to SMOW (Standard Mean Ocean Water) for ^{18}O and D, with respect to PDB (marine carbonate) for ^{13}C and with respect to C.D. (meteorite of Cañon Diablo) for ^{34}S. The tritium results are expressed Tritium Units (T.U.) 1 T.U. being equal to 1 atom of tritium for 10^{18} atoms of hydrogen. Carbon-14 is expressed in per cent of modern ^{14}C, i.e. Carbon-14 content of modern plants before 1950. The analytical reproducibility of the measurements is 0.1% for $\delta\ ^{18}O$ and for $\delta\ ^{13}C$, 0.4% for $\delta\ ^{34}S$ and 1% for δ D (at 1 σ level). The analytical errors associated with the tritium and ^{14}C measurements are reported together with the results when available. The age of groundwater is evaluated from the ^{13}C and ^{14}C data by using the formulas:

$$t \text{ (years)} = 8.270 \ln (A_o/A_t)$$

$$A_o = \frac{100\ (\delta - \delta_C)}{\delta_G - \delta_C + \epsilon} \times (1 + \frac{2\ \epsilon}{1.000})$$

where A_t is the ^{14}C activity in the sample and A_o is the «initial» one, corrected for changes due to water-rock interaction; δ is the ^{13}C content in dissolved bicarbonate; δ_C is that of the aquifer matrix carbonate; δ_G is that of the gaseous phase in the soil at the recharge time; ϵ accounts for the isotopic fractionation which occurs when dissolved CO_2 gives a bicarbonate. The values adopted for the calculation are:

$$\delta_G = -25\%, \delta_C = 0\%, \text{ and } \epsilon = 7.5\%$$

Carbon-14 dating is valid for the periods of 1.000 to 30.000 years. It is therefore especially applied to waters in confined aquifers. The mixture of waters of very different ages means that the ^{14}C age is less, (sometimes much less) than their average age.

Groundwater data

Stable isotopes

An important characteristic of these groundwaters is their very broad ^{18}O and ^2H spread.

If a single, confined aquifer existed with recharge from a single source, much smaller

TABLE 1
Chemical and isotopic data

Code	Date	Area	Aquifer	Depth of sample a.s.l.	D‰	^{18}O‰	TU	^{14}C%	^{13}C‰	^{34}S‰	$^{18}O_{(SO_4^{-2})}$‰	Temp	pH	Cond	Cl mg/l	SO_4 mg/l
GEF- 1	1979	Janzur	Quater.	- 5	-29.6	-4.80	7.0±1.0					21.6	7.60	1650	316	
GEF- 2	1979		Quater.	- 25	-31.1	-4.86	5.6±1.0					22.0	7.65	1600		
GEF- 3	1979		Quater.	- 77	-33.4	-5.31						22.5	7.45	1730	294	
GEF- 4	1979	Jud Daim	Quater.	- 82	-39.2	-5.70						23.7	7.31	3800	411	
GEF- 5	1979	Swiman	Quater.	- 2	-31.8	-5.01	5.1±1.0			+14.56	+ 9.50	21.9	8.30	2800	631	
GEF- 6	1979			- 15	-34.1	-4.95	1.7±1.0			+16.54	+ 9.85	22.2	8.10	5010	1336	
GEF- 7	1979			- 25	-31.9	-4.32	0.5±1.0			+17.37	+15.40	22.5	7.65	32000	10174	
GEF- 8	1979			- 85	-20.7	-1.97						23.7	7.40	82000	37542	
GEF- 9	1979	Sabratah	Quater.	- 5	-30.1	-4.30				+14.34	+ 8.00	21.8	7.38	12600	4254	
GEF-10	1979		Sea water		+ 3.2	+1.33	6.2±1.0			+20.26	+10.26	21.2	8.50	51060	21128	
GEF-11	1979	Ajaylat	Mesozoic	-679	-47.0	-6.93		0.6-0.3	-6.52			44.5	7.05	5000	461	
GEF-12	1979	Sabratah	Mesozoic	-652	-42.9	-6.53						33.8	7.50	4900"	780	
GEF-13	1979	Tajwra	Miocene	-478	-37.1	-6.14		0.1-0.5	-3.35			43.0	6.85	4900	933	
GEF-14	1979	W. Ramil	Trias	-574	-37.3	-6.07		2.9-0.3	-3.39			37.8	6.80	2700	344	
GEF-15	1979	Ajaylat	Quater.	- 9	-30.0	-4.87	0.0±1.0			+15.40	+11.68	21.4	7.40	12790	4715	
GEF-16	1979	Sabratah	Quater.	- 12	-27.0	-4.76	0.0±1.0			+15.12	+12.48	21.7	7.40	6610	1819	
GEF-17	1979	Ajaylat	Quater.	- 15	-24.7	-4.08	0.0±1.0					21.8	7.20	6370	1996	
GEF-18	1979	Bu Jsa	Quater.	- 75	-28.5	-5.21						20.8	7.30	1150	163	
GEF-19	1979	Surman	Quater.	- 5	-28.3	-4.87						22.2	7.30	1250	308	
GEF-20	1979	Zawiyah	Quater.	+ 3	-28.9	-4.97						22.8	7.40	785	142	
GEF-21	1979	Zawiyah	Quater.	- 13	-20.0	-3.69						22.5	7.2	14660	6026	
GEF-22	1979	Qargaresh	Quater.	- 5	-28.7	-5.07						20.6	7.40	2220	507	
GEF-23	1979	Qargaresh	Quater.	- 10	-30.1	-5.47	0.0±1.0					20.3	7.40	545	99	
GEF-24	1979	Fornaj	Quater.	- 18	-28.8	-5.35	0.0±1.0						7.60	415	64	
GEF-25	1979	Jum'ah	Quater.	0	-26.1	-4.55							7.40	7530	2659	
GEF-26	1979	Tajura	Quater.	- 26	-31.6	-5.23	0.0±1.0						7.10	3490	727	
GEF-27	1979	Tajura	Quater.	- 6	-26.6	-4.96						21.0	7.00	7770	2942	
GEF-28	1979	Tajura	Miocene	-299	-39.2	-6.17							6.50	4895	893	
GEF-29	1979	Tajura	Quater.	- 9	-31.1	-5.44						21.8	7.20	550	74	
GEF-30	1979	W. Ramil	Quater.	+ 10	-33.4	-5.49						22.5	7.10	1370	191	
GEF-31	1979	W. Ramil	Quater.	+ 7	-25.9	-4.94						22.2	7.20	580	113	
GEF-32	1979	Q. Khiyar	Mesozoic	-248	-38.2	-6.30						27.0	7.00	2800	408	
GEF-33	1979	Q. Khiyar	Quater.	+ 1	-26.0	-5.16						21.8	7.40	630	99	
GEF-34	1978	Bu Jsa	Quater.	- 6	-27.3	-4.82	3.3±0.5					21.0		19160	5050	
GEF-35	1978	Bu Jsa	Quater.	- 5	-28.1	-4.79	7.8±1.2					21.2	7.40	11120	3150	
GEF-36	1978	Bu Jsa	Quater.	- 7	-29.4	-4.95	3.5±0.3					21.3	7.00	7500	1410	
GEF-37	1978	Bu Jsa	Quater.	- 5	-31.6	-5.40	1.8±0.3					21.7	7.20	5300	938	
GEF-38	1978	Bu Jsa	Quater.	- 10	-27.7	-5.04	0.2±0.3					21.8	7.20	645	135	
GEF-39	1978	Bu Jsa	Quater.	- 11	-27.5	-5.20	1.2±0.2					21.7	7.30	500	86	
GEF-40	1978	Tarfass	Miocene	- 90	-36.8	-6.00						25.2	7.20	5075	495	
GEF-41	1978	Tarfass	U. Pleist.	- 41	-39.7	-6.08						24.9	7.20	6075	512	
GEF-42	1978	Bu Jsa	Sea Water		+ 7.5	+0.94						14.3	8.30	58860	21700	
GEF-43	1978	Bu Jsa	Sea Water		+ 7.8	+0.97				+20.6	+10.4	14.3	8.40	58880	21800	
GEF-44	1982	Sabratah	Quater.	- 15	-31.0	-4.45	0.3			+14.7	+10.2	20.5	7.45	6390	1920	1970
GEF-45	1982	Sabratah	Mesozoic	-650	-46.0	-6.93		0.4±0.3	-5.3	+18.3	+18.4	34.5	7.50	5140	750	740
GEF-46	1982	Zwarah	Quater.	- 5	-29.3	-4.20				+18.3	+ 9.6	21.9	7.25	12330	4230	1520
GEF-47	1982	Zwarah	Quater.	- 8	-27.2	-4.83	0.2					21.0	7.20	7580	2380	2030
GEF-48	1982	Qarabulli	Quater.	- 15	-28.4	-5.25	1.5					23.0	7.60	1059	208	200
GEF-49	1982	Qarabulli	Mesozoic	- 80	-38.3	-6.47		4.0±0.3	-3.5	+15.6	+17.2	38.0	6.90	2880	382	425
GEF-50	1982	W. Ramil	Trias	-570	-39.2	-5.90		3.2±0.3	-3.5	+15.4	+17.0	38.2	7.10	2780	370	403
GEF-51	1982	W. Ramil	Quater.	0	-34.7	-5.35	6.0					18.9	7.60	990	185	208
GEF-52	1982	Tajwra	Mioc.	-421	- 6.25			1.0±0.5	-2.1			42.0	6.90	5120	880	810
GEF-53	1982	Al Ghanam	Quater.	- 5	-32.0	-5.50				+14.2	+ 9.2	21.9	7.90	1790	400	220
GEF-54	1982		Quater.	- 15	-33.1	-5.01				+14.5	+10.1	22.4	8.10	5200	1390	290
GEF-55	1982		Quater.	- 30	-25.4	-3.25				+17.1	+15.2	22.7	7.70	35000	11700	280
GEF-56	1982		Quater.	- 80	-18.8	-1.70				+18.2	+16.8	23.5	7.50	91000	48000	280
GEF-57	1982	W. Ramil	Quater.	> 0	-36.1	-5.65	4.0			+19.0	+14.0	21.8	7.30	740	135	150
GEF-58	1982	W. Ramil	Quater.	> 0	-34.4	-5.51	16.0			+20.2	+14.8	22.4	7.20	580	110	97
GEF-59	1982	W. Ramil	Quater.	> 0	-34.0	-5.40	20.2					22.5	7.30	400	95	80
GEF-60	1982	Jabratah	Quater.	- 5	-29.4	-4.18				+16.0	+ 9.0	22.0	7.40	13200	4370	1500

variations would be expected. On closer inspection, different groundwater bodies with rather well defined compositions can be recognised; the isotope contents do not vary at random as emphasized by Fig. 3 which shows a probability vs ^{18}O plot. Group A includes samples collected in Tertiary and Mesozoic aquifers as well as Quaternary aquifers.

The latter samples were collected in the southern area between the piedmont of Jebel el Nefusa and the sebkhas line. Their mean values are — 5.17 ± 0.24 and — 30.3 ± 3.1 respectively for Oxygen-18 and Deuterium, compared with — 6.08 ± 0.41 and — 40.6 ± 3.7 for the pre-Quaternary aquifers. Group

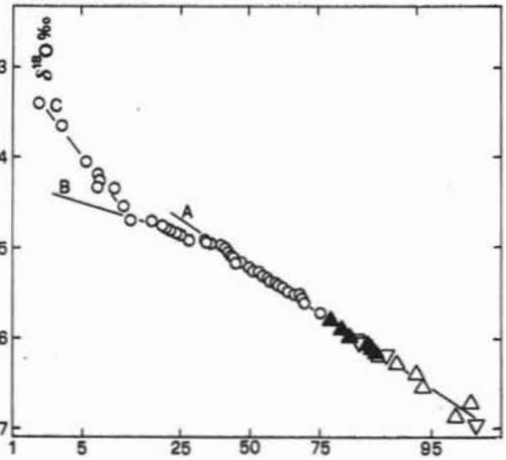

Fig. 3. — Cumulative probability distribution of $\delta^{18}O$ for all wells studied. It clearly shows that wells in Gefara plain belong to three different families. The symbols are as follows: Inverse triangles - Trias. Normal triangles - Cretaceous. Filled triangles - Miocene. Circles - Quaternary wells.

B includes samples collected near the sebkhas; they show a relatively high uniformity with mean values of — 4.80 ± 0.10 for Oxygen-18 and — 28.2 ± 1.1 for Deuterium. Group C mainly includes samples collected between the sebkhas line and the Mediterranean Sea with an average value in Oxygen-18 of — 4.30 ± 0.35 and in Deuterium of — 26.7 ± 5.4. Table 2 illustrates the probability that these groups are isotopically different. It is clear that sample GEF 8 does not belong to these families.

When the results are plotted on the classical diagram $\delta D - \delta^{18}O$ the samples generally cluster on the line (Fig. 4)

$$\delta D = (7.25 \pm 0.61)\, \delta^{18}O + (4.26 \pm 5.15)$$

This is calculated without GEF-10 and GEF-42, 43 (sea water samples). If points that are 2 σ out of the regression line (GEF-6, 7, 8, 9, 17, 21, 53, 54, 55, 56) are also excluded, this relation becomes

$$\delta D = (8.03 \pm 0.57)\, \delta^{18}O + (15.38 \pm 3.06)$$

This line is very similar to that of meteoric waters collected in North Africa. The least-squares-fit line for $\delta D - \delta^{18}O$ relationship for precipitation in the Alexandria and Tunis areas is:

$$\delta D = (7.82 \pm 0.42)\, \delta^{18}O + (15.85 \pm 4.15)$$

The other points are on a line with the following characteristics:

$$\delta D = (4.11 \pm 0.54)\, \delta^{18}O - (18.23 \pm 2.32)$$

Some evaporation phenomena take place, mainly in the Sabratah region. The equation gives the $\delta D - \delta^{18}O$ relationship in samples resulting from mixture of fresh and saline, evaporated waters.

Origin and mechanism of groundwater recharge

Several processes affecting groundwaters can be deduced from this non-uniform distribution of values:

— direct infiltration of precipitation on the Jebel el Nefusa affecting locally the outcropping pre-Quaternary aquifers;
— direct infiltration of precipitation on Gefara Plain or of wadi water in the Jebel piedmont, affecting Quaternary aquifers;
— leakage from underlying formations.

Less well-defined at present is the recharge of the pre-Quaternary aquifers. However, previous work in the region (SALEM O. et al., 1978; ALLEMOZ M. et al., 1978; SRDOC D. et al., 1978) suggests that on the Jebel el Nefusa their Oxygen-18 value is around — 7.00%. They all display more positive δ-values than

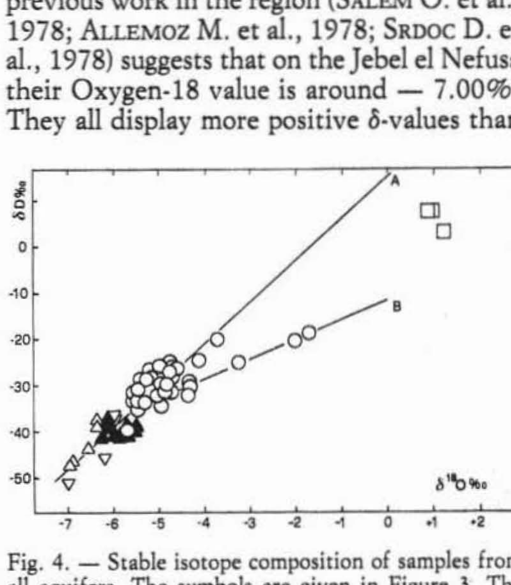

Fig. 4. — Stable isotope composition of samples from all aquifers. The symbols are given in Figure 3. The squares represent sea water samples. The straight line A represents the best fitting of all data excluding the sea water samples.
Line B represents the best fitting of samples (GEF 6, 7, 8, 9, 21) resulting from mixing between fresh and saline, evaporated waters.

those in the same aquifers in the south. The contribution of local precipitation to their recharge is presumably between 30 and 70%.

In the Gefara Plain, their isotopic content is more positive than on the Jebel. These values are most probably characteristic of locally recharged groundwater (about — 5% for Oxygen-18 and — 30% for Deuterium). As way of comparison, the average isotopic composition at Tunis-Carthage for 11 years of observations is — 3.97 and — 24.1 for ^{18}O and ^{2}H respectively. In winter when the precipitation is heaviest (close to 85% of the total amount in the period November-April), the mean is — 4.96 and — 28.6. In the light of these values and the — 7.00 for the Jebel el Nefusa, the contribution of precipitation directly or through the Quaternary shallower groundwater to the recharge of pre-Quaternary aquifers would be about 45%. The leakage from the surface to the underlying aquifers is very well distinct, for instance, between Rjaylat and Sabratah in the Mesozoic sandstones aquifer and in the southern Gefara Plain. However, the dominant hydrogeological feature of the area is an extensive east-west direct fault system extending vertically to the pre-Quaternary strata. These faults and the correlated fissures provide the channels through which deep waters may reach the Quaternary aquifers.

Some wells in Quaternary aquifers in the southern Gefara Plain have an isotopic content more depleted in Oxygen-18 than the local precipitation, and sometimes very close to that of waters from the Miocene aquifer. However, assuming the mean values of — 5.17 for Quaternary and — 6.08 for pre-Quaternary aquifers (see Section 4.1), and — 4.96 for winter precipitations, the contribution of present precipitation to the Quaternary aquifers would be at least 80%.

The chemical data confirm the participation of the deeper aquifers in the Quaternary recharge with an high supply of calcium sulphate waters. The chloride content in the water samples collected in the deeper aquifers is between 700 and 1.500 mg/l, depending on the local lithological variations. The usual dilution equation indicates that the contribution of meteoric waters is between 90% (in the first case) and 50% (in the second).

TABLE 2

Comparison of isotopic values between groups (t - test)

Groups	Degree of freedom	$\Delta\delta^{18}O$	$t(^{18}O)$	% probability of being different	$\Delta\delta D$	t (D)	% probability of being different
Pre-Quaternary vs Quaternary Group A	39	0.91	7.78	99.9	10.3	8.42	99.9
Quaternary Group A vs Quaternary Group B	37	0.37	4.83	99.9	2.1	2.15	95.0
Quaternary Group B vs Quaternary Group C	22	0.50	4.52	99.9	1.5	0.91	50.0

Occurrence of present recharge and groundwater dating

Tritium analyses of groundwater samples (Table 1) performed in the study area reveal a small variation (0 - 9 TU).

The plot of Tritium content versus ^{18}O values for all the groundwater samples from Quaternary aquifers is shown in Fig. 5, it provides an overall view of the Tritium data and an easy classification of the groundwater samples in terms of their isotopic content.

As shown in Figure 5, the wells can be divided into those with TU $>$ 3 (group 1 and TU $<$ 2 (group 2).

The choice of more or less than 3 is, of course, arbitrary. Nevertheless it reflects the

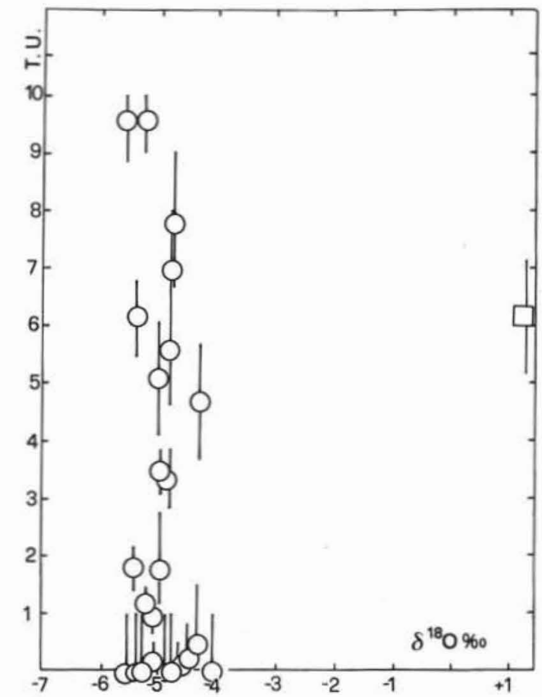

Fig. 5. — Tritium content versus $\delta\ ^{18}O$ values for all groundwater samples from Quaternary aquifers.

groundwaters replenishment time and opens the way to a semiquantitative interpretation. In group 1, recharge has occurred since 1952 (i.e. during the period of nuclear tests in atmosphere) and at least pastly over the last 20 years. In group 2, the recharge (if any) just have taken place before 1952. The minimum period during which there has been replenisment rate is thus rather slow.

It should be noted that the very low Tritium content observed in the Gefara Plain wells may be partly due to diluition by the substantial contribution from the deep aquifers, since the upward leaking water would contain no Tritium in view of its very old age. Their present recharge by rainfall may, thus, be higher than these apparent values. In the unconfined pre-Quaternary aquifers, the exhibited low Tritium content is also attributed to exchange with atmospheric vapour rather than rain or to soil water.

Examination of the topographical variations in the groundwater ^3H reveals that most group-1 wells are near Sabratah and other areas west of Tripoli, or in wadis alluvia, whereas those in group 2 are mainly located in the eastern part of the Gefara plain. Recharge of the upper aquifer by direct rainfall is mainly governed by the temporal and spatial variations or significant storm events (winter precipitations decrease southward). However, at the foot of the Jebel, water samples collected in the Wadi el Ramil basin, those that wadi floods are of great importance.

In winter, the stream flow of the intermittent Wadi el Ramil recharges the alluvial aquifer; in this case, the groundwater salt content decreases as the flood contribution increases (Fig. 6). Moreover, the presence of recent waters in the discharge of alluvium aquifer indicates that the storage is high and that the superficial porous medium contributes to the recharge, as expected from sedimentological criteria (large content of sand). Further to the systematic study of groundwater TU, it is now admitted that aquifers may be considered as well-mixed reservoirs (Simpson E. et al., 1976) underground mean residence times (τ) can be evaluated.

If the ^3H content of the recharge is known, that of the groundwater permits calculation of the recharge coefficient α (annual recharge/volume of the reservoirs) and inference of the mean residence time of water $\tau = \frac{1}{\alpha}$. Soil and wadis alluvia with a TU

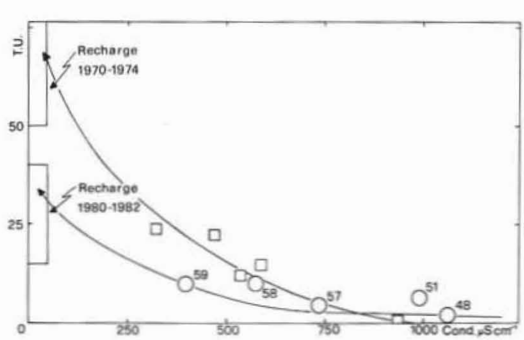

Fig. 6. — Tritium Units versus salt content of groundwaters: T.D.S. decreases with the increasing of flood contribution.
Squares are refered to groundwater samples collected in 1973 (from Allemoz M. et al., 1978).

values between 2 and 25 (ALLEMOZ M. et al., 1978) indicate a recharge coefficient between 10^{-3} and 10^{-2}, which corresponds to an average residence of 150 - 1.000 years. The tracer velocity is between 10^{-4} and 10^{-5} and the storage coefficient 10%.

TU values are regularly distributed in fonction of depth throughout the Gefara Plain. Tritium occurs in the shallower strata of the wells up to 10 m approximately and decreases suddently with depth in parallel with a salinity increase. Because of the lack of wells with screens set at specific horizons it is not possible to fully delineate the vertical differences.

The low Tritium content in the Quaternary wells may thus be due to the severe exploitation of the shallower aquifer resulting in drainage of Tritium-free water from the deeper.

An exception is provided by two piezometers close to the sebkhas line (Swiman, Gef 5-8; Al Ghanamm Gef 53-56). In the same aquifer, a kind of water stratification occurs as a consequence of a tremendous increase in total dissolved salt that reaches values typical of brines. In this case the different environmental isotopic content may reflect local climatic variations during the Quaternary.

Some selected wells were sampled for ^{14}C analysis to provide an additional tracer to support the stable isotope findings with regard to the question of a difference between the recharge of the Mesozoic and Tertiary as opposed to the Quaternary aquifers (Table 3).

For the former, groundwater age ranges from 8.800 (GEF-14) to more than 40.000 years (GEF 13). This confirm the observations of SALEM et al. (1978), SRDOC et al. (1978) in the Tawurgha region and ZUPPI et al. (1980) in the Benghazi area. The last most important period of recharge for the Mediterranean regions of Africa is fixed at about 8.000 years ago during the last fluvial period.

The absence of ^{13}C values in the literature precludes age calculations for the groundwater in samples collected prior to 1978 in Quaternary aquifers. However, their higher ^{14}C contents is in line with admixture with more recent waters on the way up to the surface, as indicated by ^{3}H data.

TABLE 3
Groundwater age

Sample	Aquifer	Age
11	Mesozoic	15400-5800
13	Miocene	40000
14	Trias	8800-4700
45	Mesozoic	35700-3900
49	Mesozoic	13700-5700
50	Trias	15500-5500
52	Miocene	21000-3500

Salination problem

The δ ^{18}O versus Cl plot of Fig. 7 shows the presence of a saline water contribution to some wells. Line A is the mixing line for the fresh water with sea water (samples GEF 10, 42, 43). The plot of TDS versus Cl (Fig. 8) shows that most wells do not cluster on the theoretical mixing line. The increase in TDS indicates that these wells have a higher sulphate concentration than would occur if the salinity was only derived from mixing with sea water. A plot of δ ^{18}O versus the ratio Cl/SO_4 shows that a correlation between these parameters exists; the Oxygen-18 decreases in the Quaternary wells parallel to a gently decrease in the ion ratio.

This implies that the «sulphate excess» is not due to concentration by evaporation but to dissolution of sulphates in the aquifers underneath the Quaternary (Fig. 9).

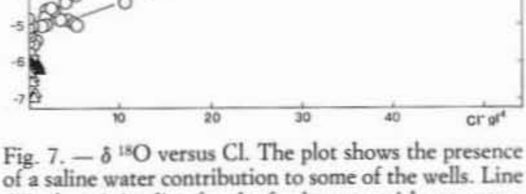

Fig. 7. — δ ^{18}O versus Cl. The plot shows the presence of a saline water contribution to some of the wells. Line A is the mixing line for the fresh water with sea water. Line B represents the water evolution in the Swiman piezometer (GEF 6, 7, 8). The symbols are given in Figure 3.

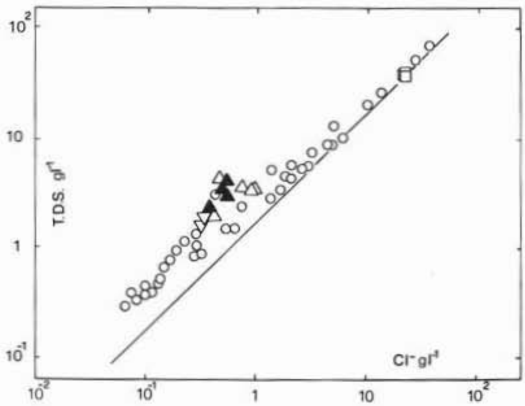

Fig. 8. — T.D.S. versus chloride content. The plot shows that most of the wells do not cluster on the theoretical mixing line between fresh and sea waters. The symbols are given in Figure 3.

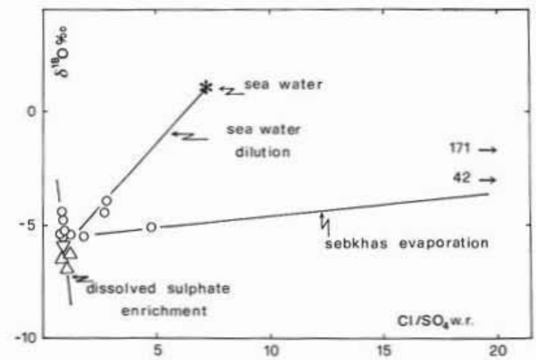

Fig. 9. — δ ^{18}O versus chloride - sulphate ratios. The symbols are given in Figure 3. The plot shows that a correlation exists between these parameters: the Oxygen-18 decreases with a slight of the ratio in Quaternary wells.

With regard to sea water intrusion, the highest contribution is evident for wells GEF 21, 25, 46 e 60. These are located relatively close to the coast, where sea water encroachment could be expected. Their sea water contribution is about 10% (Fig. 10).

The origin of the dissolved sulphates was determined from their isotope contents. Their ^{34}S varied between + 14.2 and + 20.6‰, whereas their ^{18}O ranged from + 8.0 to + 14.0. These values are far from those of typical present marine sulphates (^{34}S + 20.43‰, ^{18}O + 10.33‰) determined in two samples of Mediterranean sea water.

Our data can be compared with those for sebkhas sulphates reported by ROUSE J.E. et al. (1980) from the Tawurgah region.

In addition to sea water intrusion, an alternative origin for these dissolved sulphates may be sought in groundwaters from Mesozoic (Triassic and Cretaceous) or Miocene (Messinian) sediments, all of which mainly consist of calcite, dolomite, anhydrite and shale beds, the latter providing the most likely source of the negative electrical potential. Starting from the original sulphates, a succession of geochemical processes (partial reduction and probably a slight reoxydation) takes place during underground circulation of waters. The enrichment ratio Δ ^{34}S / Δ ^{18}O is constant for all the geochemical processes affecting these waters and has a value of 1.0 and 3.0 respectively for Messinian and Mesozoic aquifers.

Admixing of these two sources and the consequent parallel reduction phenomena are reflected in the isotopic composition of sulphates dissolved in waters from Quaternary aquifers, which reflects local climatic variations during the Quaternary, when the higher groundwater level permitted easier dissolution and a fast remobilization of sulphates from underlying aquifers.

An exeception is offered by GEF 46 and 60, where sulphates are depleted in Oxygen-18 but enriched in Sulphur-34. In these cases, the dissolved sulphates originated from mixing between present sea water and leached messinian sulphates. Both are clearly affected by slight reduction processes.

The isotopic values of dissolved sulphates for the deeper Quaternary samples (GEF 8 and 56), although 2 and 3‰ (heavier than those collected on the shallow horizons of groundwater), do not conflict with this conclusion. Their enrichment in heavier isotopes is probably due to bacterial sulphate reduction enriching the residual dissolved sulphate stratified under the tremendous increase in T.D.S.; at the same time, a depleted sulphide originated.

The samples collected at the depth of the Swiman piezometer and in the Al Ghanam

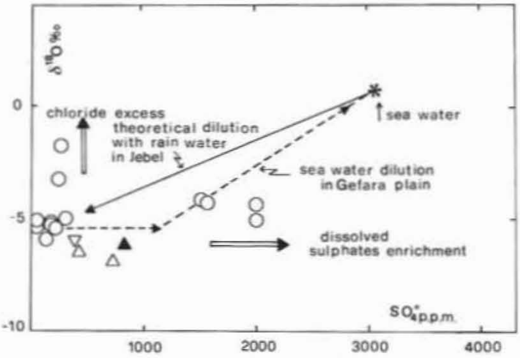

Fig. 10. — δ ¹⁸O versus sulphate content. The sea water contribution to the wells located close to the coast should in the range of 10%.

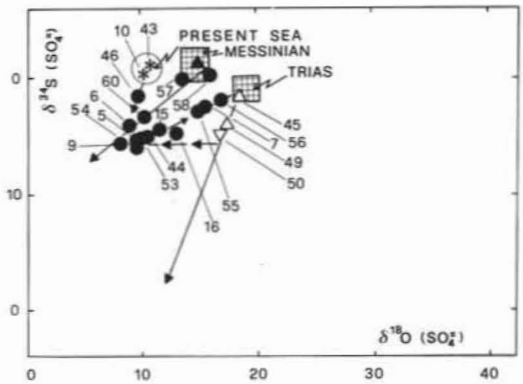

Fig. 11. — δ ³⁴S versus δ ¹⁸O in the dissolved sulphates. Besides sea water intrusion, there are two possible sources of dissolved sulphates: Mesozoic and Messinian sediments.

well (GEF 8 and 56) are thus an excellent key to the origin of the brines and sebkhas in the Gefara Plain. The dissolved salt content higher than that of sea water, the presence of evaporated water, and the dissolved sulphates of «continental» sedimentary origin can be explained only as a remnant of an old pre-Quaternary water, presumables related to old sebkhas covered during the Quaternary by new sediments as a consequence of sea level changes. This «fossil water» can be closely compared with the similar brines of Pliocene age in the great coastal plain of the Mediterranean basin (COGGIOLA F. et al., 1986; NANNI T. et al., 1986).

Conclusions

The figures reported in this paper indicate that the shallower aquifer in the Gefara Plain is being recharged at present.

This recharge is mainly subject to differences in the time and place of significant storm events and the important wadi floods thus produced. However the lower Tritium content of the Quaternary aquifer with respect to that of the precipitations is due to its severe exploitation and hence drainage of tritium - free water from the deeper aquifers (Mesozoic an Cenozoic), for which the groundwater age ranges between, 8.800 and 45.000 in connection with the last pluvial period.

Moreover the environmental isotopes point water stratification, in the Quaternary aquifer, since there is a tremendous increase in total dissolved salt reflecting local climatic variations during the Quaternary, when the higher groundwater level dissolved sulphates in the underlying aquifers, as indicated by the ^{34}S data. An exception is provided by two water points where the dissolved salt content is typical of brines; the presence of evaporated water and dissolved sulphates can only be explained only as a remnant of an old pre-Quaternary water from sebkhas, covered during the Quaternary, by new sediments as a consequence of sea level changes.

Similar brines are another example of the presence of this kind of fossil water in the great coastal plain in the Mediterranean basin.

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