Sources of Salinity in Ground Water from Jericho Area, Jordan Valley

by Amer Marie[1] and Avner Vengosh[2]

Abstract

One of the major problems in the lower Jordan Valley is the increasing salinization (i.e., chloride content) of local ground water. The high levels of salinity limit the utilization of ground water for both domestic and agriculture applications. This joint collaborative study evaluates the sources and mechanisms for salinization in the Jericho area. We employ diagnostic geochemical fingerprinting methods to trace the potential sources of the salinity in (1) the deep confined subaquifer system (K2) of Lower Cenomanian age; (2) the upper subaquifer system (K1) of Upper Cenomanian and Turonian ages; and (3) the shallow aquifer system (Q) of Plio-Pleistocene ages.

The chemical composition of the saline ground water from the two Cenomanian subaquifers (K1 and K2) point to a single saline source with $Na/Cl \sim 0.5$ and $Br/Cl \sim 7 \times 10^{-3}$. This composition is similar to that of thermal hypersaline springs that are found along the western shore of the Dead Sea (e.g., En Gedi thermal spring). We suggest that the increasing salinity in both K1 and K2 subaquifers is derived from mixing with deep-seated brines that flow through the Rift fault system. The salinization rate depends on the discharge volume of the fresh meteoric water in the Cenomanian Aquifer. In contrast, the chemical composition of ground water from the Plio-Pleistocene Aquifer shows a wide range of Cl^- (100–2000 mg/L), Na/Cl (0.4-1.0), Br/Cl ($2\text{-}6 \times 10^{-3}$), and SO_4/Cl (0.01–0.4) ratios. These variations, together with the high SO_4^{2-}, K^+, and NO_3^- concentrations, suggest that the salinity in the shallow aquifer is derived from the combination of (1) upconing of deep brines as reflected by low Na/Cl and high Br/Cl ratios; (2) leaching of salts from the Lisan Formation within the Plio-Pleistocene Aquifer, as suggested by the high SO_4^{2-} concentrations; and (3) anthropogenic contamination of agriculture return flow and sewage effluents with distinctive high K^+ (80 mg/L) and NO_3^-(80 mg/l) contents and low Br/Cl ratios (2×10^{-3}). Our data demonstrates that the chemical composition of salinized ground water can be used to delineate the sources of salinity and hence to establish the conceptual model for explaining salinization processes.

Introduction

Ground water quality is essential for the health, economy, stability, and development in the Middle East. Inhabitants in the lower Jordan Valley (Figure 1) solely depend on local ground water, in particular for irrigated agriculture. Furthermore, due to the anticipated increase in tourism in the near future, economic growth and viability are linked to the preservation and the increase in sustainable water sources. Yet, the only source of fresh water in the area is derived from ground water, which is tapped from the aquifer systems of the shallow Plio-Pleistocene and the deep Cenomanian (Eastern Mountain) aquifers (Table 1). With the Oslo agreement, the Palestinian population gained the right to tap additional water from this basin. Unfortunately, the ground water quality of the shallow aquifer system has been deteriorating in this area for some time. In the Jericho region, for example, dissolved chloride concentrations have increased to more than 2000 mg/L during the last 30 years. Continued ground water deterioration threatens the water sources linked to the success of current and future agricultural and domestic economies.

An understanding of the origin of the ground water salinity and the salinization mechanisms is crucial for future water management plans, including the design and drilling of new wells, withdrawal of fresh water before it becomes saline, and the use of brackish water for desalinization. Previous studies (Golani 1972; Rosenthal 1978; Shaliv 1980; Rosenthal and Kronfeld 1982; Kronfeld et al. 1992; Guttman 1997, 1998; Guttman and Rosenthal 1991; Hotzl and Wolfer 1999; Wishahi and Khalid 1999) have reconstructed the hydrogeological framework of the area, hydrochemistry, and possible flow paths of fresh ground water in the Cenomanian Aquifer. In this paper we evaluate the possible sources of salinity in the ground water by investigating the chemical composition of the ground water from the Jericho area. We posit that each of the potential salinity sources has a distinguished chemical fingerprint that can be delineated by studying the ratios of the dissolved constituents of the salinized ground water.

Analytical Procedure

The hydrological data is based on water levels and chloride content variations from files and the computer data base of the Hydrological Service of Israel. The piesomeric levels represent minimum autumn levels of the particular years noted, whereas chloride measurements were carried out in samples taken in the summer months. The chemical data are based on water samples taken during 1995, 1996, and 1997, which then were analyzed in the laboratory of the Hydrological Service. Chemical data was also taken from the water well archives in the Hydrological Service. Chemical

[1]Department of Applied Earth and Environmental Sciences, Al Quds University, Jerusalem, P.O.Box 20002, Palestinian Authority; marei@planet.edu

[2]Department of Geological and Environmental Sciences, Ben-Gurion University of the Negev, P.O. Box 653, Beer Sheva 84105, Israel; avnerv@bgumail.bgu.ac.il
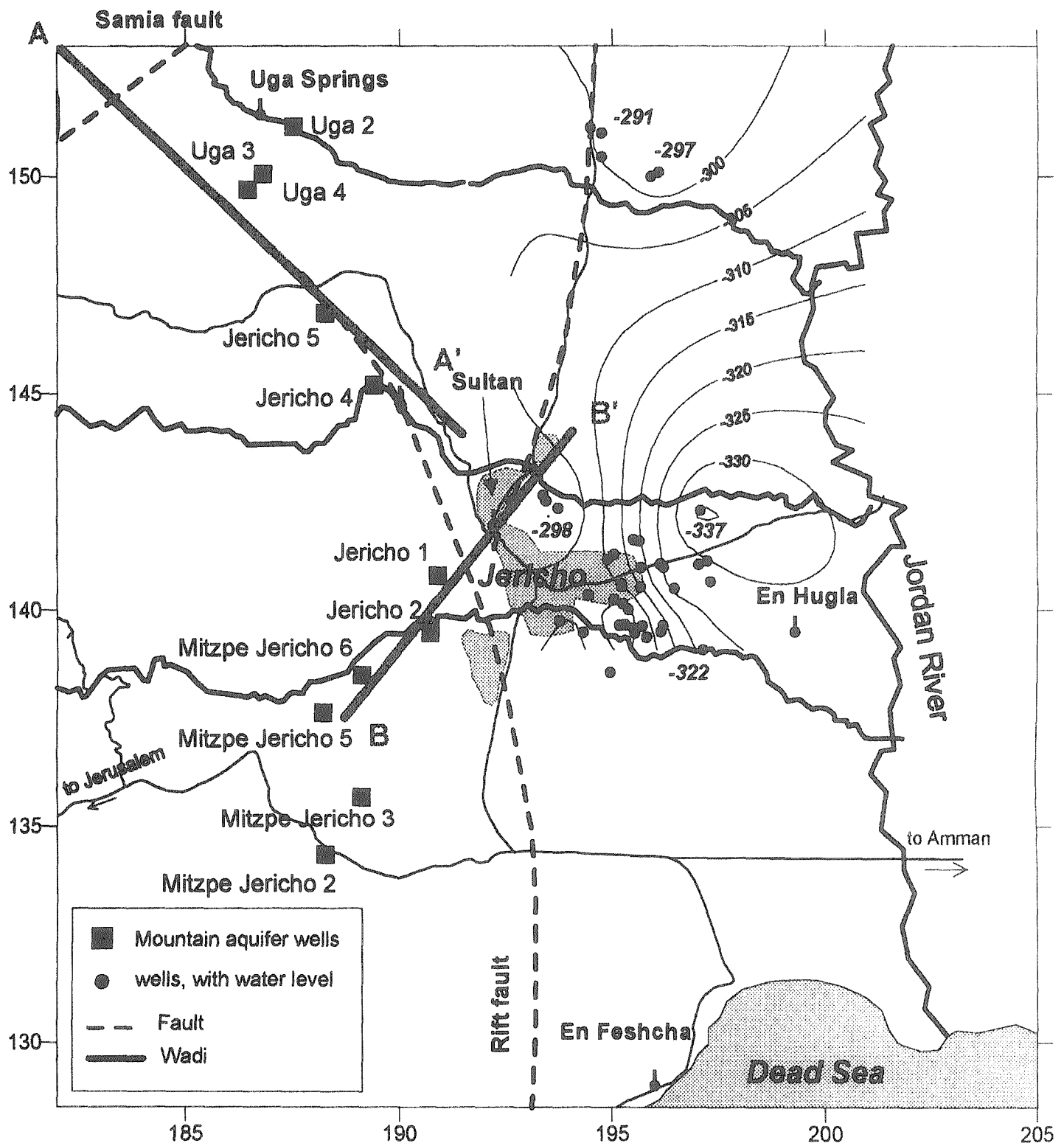
Figure 1. Location map of springs and wells in Jericho area. The Cenomanian (Mountain Aquifer) wells are marked by squares whereas the Plio-Pleistocene wells by circles. The water level contours refer to water levels of the Plio-Pleistocene Aquifer that were measured during fall 1997. Note the locations of Jericho 1, 2, 4, and 5 wells, the major rift faults (marked by dashed line), and the urban area of Jericho city. Lines A-A′ and B-B′ represent hydrogeological cross sections that are illustrated in Figure 3.

analyses were carried out in the analytical laboratory of the Hydrological Service in Jerusalem. Potassium and sodium were analyzed by a Perkin Elmer AA instrument, calcium and magnesium by EDTA titration, chloride by titration with silver nitrate, sulfate by turbidimetry, bicarbonate by titration with HCl, and nitrate by a Corning 476134 specific electrode adjusted to chloride concen-

trations for the pre-1995 water samples and by flow injection ion analyzer (QuickChem 8000) for the post-1995 water samples. Bromide concentrations were determined by a flow injection ion analyzer (QuickChem 8000) (Vengosh and Pankratov 1998). Balance error did not exceed 5%.

Table 1
List of Wells, Depth, and Hydrological Data of the Cenomanian Aquifer

Well	Coordination (m)	Depth (m)	Level[1] (mg/L)	Chloride[2] (mg/L)
Upper Cenomanian (K1)				
Jericho 1	19090/14080	243	–320.3	507
Jericho 2[3]	19072/13948	603	–326.2	498
Mitzpe Jericho 2	18826/13434	493	–345	68
Mitzpe Jericho 3[4]	18911/13567	427		200/6200[4]
Mitzpe Jericho 5	18820/13770	475		69
Mitzpe Jericho 6	18912/13850	417		74
Lower Cenomanian (K2)				
Jericho 4	18940/14520	621	–306.5	176
Jericho 5	18825/14685	731	–309.9	212
Uga 2	18751/15150	615	–255.9	40
Uga 3	18680/15005	738	–252.8	36
Uga 4	18645/14968	650	–260.2	35

[1]Level of fall 1997.
[2]Chloride (mg/L) measured in summer 1997.
[3]In well Jericho 2 saline water (Cl = 13,000 mg/L) was discovered at the lower aquifer (K2). This section was sealed, and pumping was carried out from the upper aquifer K1.
[4]In well Mitzpe Jericho 3 saline water (Cl = 6200) was discovered at the lower K2 aquifer, whereas the overlying K1 aquifer was fresh (200 mg/L). The lower section was sealed, but could not prevent salinization of the upper section (600–700 mg/L).

Results and Discussion

Geology and Hydrogeology

The arid Jordan Valley receives less than 200 mm/y of rain in its northern part to about 100 mm/y in the south at the shore of the Dead Sea. The area (Figure 1) is characterized with the geological features of the Jordan Rift valley. The aquifer system is composed of (1) the Upper Cretaceous carbonate aquifer, and (2) Quaternary alluvial, gravel, marls, and evaporites sediments of Plio-Pleistocene age with unknown depths that fill the valley. The main structural feature in the study area is the north-south fault system in which the Senonian chalk and Upper Cretaceous limestone and dolomite blocks are located along the western shoulder of the valley (Figures 2 and 3).

The Cenomanian Carbonate Aquifer of the Eastern Mountain is composed mainly of permeable limestones and dolomites. The aquifer is divided into two principle subaquifers, the Turonian and Upper Cenomanian subaquifer (K1) and the confined Lower Cenomanian subaquifer (K2; Table 1; Figure 2). The marls and marly limestone of the low permeable Moza, Beit Meir, and Yorqe'am (Yatta) formations form an aquiclude that causes a hydrogeological separation between the upper (K1) and lower (K2) parts of the aquifer system. This is reflected by different piesometic ground water levels and in some cases also by significant salinity differences (Guttman and Rosenthal 1991). The main recharge zones for the Mountain Aquifer are located in Jerusalem and the Ramallah Mountains, which receive annually about 540 mm

Period	age	Group	Formation (Hebrew)*	Formation (Arabic)**	Lithology	Hydrogeology
Quaternary	Pliocene-Pliestocene	Dead Sea	Lisan / Samra	Lisan / Samra		aquifer (Q)/aquiqlude (200-300 m)
Upper Cretaceous	Senonian-Paleocene	Mt. Scopus	Taqiye Ghareb Mishash Menuha	Abu Dis		aquiclude (S) (100-300 m)
Upper Cretaceous	Turonian	Judea	Nezer	Jerusalem		aquifer K1 (230-300 m)
Upper Cretaceous	Turonian	Judea	Shivta	Jerusalem		aquifer K1 (230-300 m)
Upper Cretaceous	Turonian	Judea	Derorim	Jerusalem		aquifer K1 (230-300 m)
Upper Cretaceous	Cenomanian Upper	Judea	Weradim			aquifer K1 (230-300 m)
Upper Cretaceous	Cenomanian Upper	Judea	Kefar Shaul	Bet Lehem		aquifer K1 (230-300 m)
Upper Cretaceous	Cenomanian Upper	Judea	Aminadav	Hebron		aquifer K1 (230-300 m)
Upper Cretaceous	Cenomanian Lower	Judea	Moza/En Yorqe'am BeitMeir	Yatta		aquiclude
Upper Cretaceous	Cenomanian Lower	Judea	Kisalon	Upper Bet Kahil		aquifer K2 (200-270 m)
Upper Cretaceous	Cenomanian Lower	Judea	Soreq	Upper Bet Kahil		aquifer K2 (200-270 m)
Upper Cretaceous	Cenomanian Lower	Judea	Giva't Ye'arim	Lower Bet Kahil		aquifer K2 (200-270 m)
Upper Cretaceous	Cenomanian Lower	Judea	Kefira	Lower Bet Kahil		aquifer K2 (200-270 m)
Lower Cretaceous	Albian		Qatana	Qatana		aquitard/aquiclude
Lower Cretaceous	Albian		Ein Qinya	Ein Qinya		aquitard/aquiclude
Lower Cretaceous	Albian		Tamun	Tamun		aquitard/aquiclude

Lithology Legend
- congolomerate/sandstone
- clays
- chalks
- Limestone
- Dolomite
- Marl
- Dolomitic marls
- Limestone marls

* Hebrew terminology
** Arabic terminology

Figure 2. Generalized geological columnar section indicating the aquiferial characteristics of the various formations in the study area. Note the distinction between Hebrew and Arab terminology for the formation names. Note the distinction between the deep confined K2 and the upper K1 Cenomanian subaquifers.
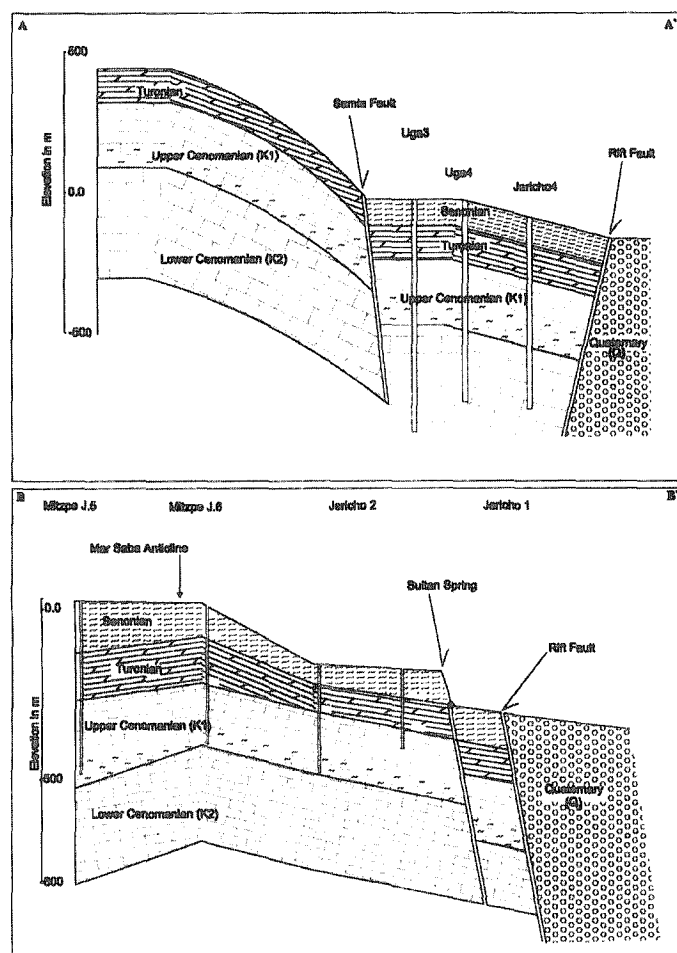
Figure 3. Schematic hydrogeological cross sections in the northern (line A-A'; see location in Figure 1), and central (line B-B') areas of the study area. Modified from Rosenthal (1978). Note the two sub-aquifers K1 and K2 of the Upper and Lower Cenomanian ages.
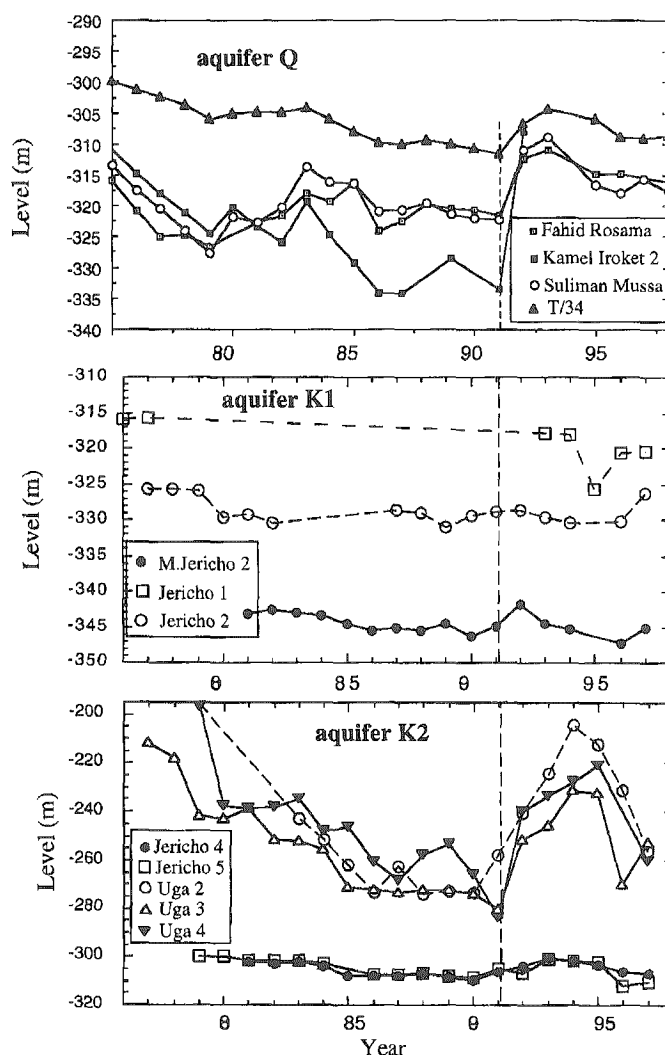

Figure 4. Water level (m, relative to sea level) and chloride (concentrations in mg/L) variations in wells from the K1 and K2 subaquifers and the Plio-Pleistocene Aquifer. The dash line represents the unusual wet year of 1991–1992.

of precipitation. The water level along the Ramallah anticlinal axes is about +450 m and declines eastward in the direction of the Jordan Valley to levels of about −300 m and −345 m in the lower (K2) and upper (K1) subaquifers, respectively (Table 2, Figures 3). The replenishment of ground water in the Eastern Mountain basin is estimated as 75 to 116×10^6 m^3 (Shaliv 1980). West of Jericho, faulted blocks of the impermeable Senonian chalk (Mt. Scopus Group) prevents lateral flow of ground water from the Upper Cretaceous to the Plio-Pleistocene shallow aquifer system (Golani 1972). Yechieli et al. (1995) showed, however, that water from the Upper Cretaceous Aquifer leaks into the Plio-Pleistocene Aquifer along the Dead Sea.

The shallow unconfined Plio-Pleistocene Aquifer consists of alluvial deposits, clay silts, conglomerate, chalk, marl, and gypsum layers of the Lisan Formation. Local aquifers are usually located as lenses of pebble-size sediments in the vicinity of modern and paleo wadis that cut through the Jordan Valley. The recharge to this system takes place mainly through flooding in the wadis during the wet months in the winter.

Based on our and previously published data (Golani 1972; Rosenthal and Kronfeld 1982; Kronfeld et al. 1992; Guttman and Rosenthal 1991) we distinguish between four hydrogeological units (Table 1; Figures 2, 3, and 4):

1. The deep confined subaquifer (K2) of Lower Cenomanian age experienced significant decline of water levels during the

1970s and 1980s and a remarkable recovery during the unusual wet year of 1991–1992 (total precipitation of 1200 mm relative to annual mean of 540 mm in the Jerusalem area). The general flow direction in the study area is southeast. The chloride level of the K2 aquifer varies from low values (~30 mg/L) in Uga wells, which are located in the northern part of the study area, to slight saline water in wells Jericho 4 and 5 (Cl = 270 mg/L) that are located near the major fault system. The latter showed an increase in Cl⁻ during the 1980s followed by a decrease after 1991–1992, in contrast to the water level variations that show a significant increase after this unusual wet year. High saline ground water in the K2 subaquifer was also revealed in wells Jericho 2 (13,000 mgCl/L) and Mitzpe Jericho 3 (Cl = 6200 mgCl/L).

2. The upper subaquifer (K1) of Upper Cenomanian age shows no significant variations in water level through time. The piesometic level of K1 is lower than that of K2. Ground water flows from west to east and toward the southeast. The chloride concentration of the K1 subaquifer varies from fresh water (~70 mg/L) in Mitzpe Jericho 2, 5, and 6 wells to saline water in the wells of Jericho 1 and 2 (500 mg/L). The latter wells showed a slight increase in Cl⁻ during the 1980s, which stopped after the wet year of 1991–1992.
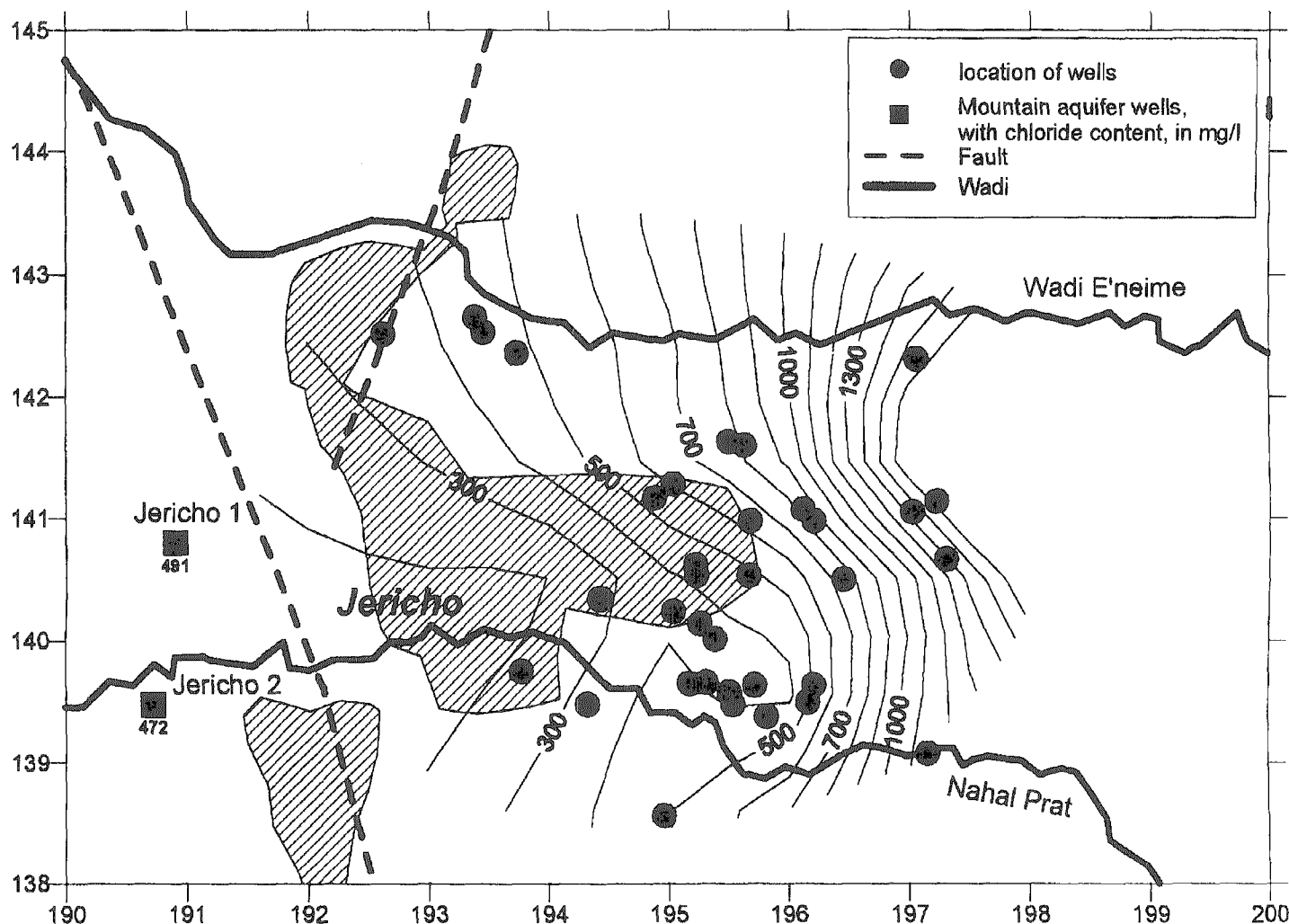
Figure 5. Chloride distribution (in mg/L) of ground water from the Plio-Pleistocene Aquifer. Note the west-east increase of the salinity toward the central part of the Jordan Valley, the Cl⁻ content of ground water from the adjacent Cenomanian Aquifer (Jericho 1 and 2), and the urban area of Jericho city.

3. The springs systems (Figure 1) emerge from the upper section (Toronian age) of the K1 subaquifer (Table 1; Rosenthal and Kronfeld 1982; Kronfeld et al. 1992). The major springs are Uga (average annual discharge of $7 \times 10^6 \text{m}^3/\text{y}$), Fazel (~$0.6 \times 10^6 \text{m}^3/\text{y}$), Kilt and Fawar (~$5 \times 10^6 \text{m}^3/\text{y}$), and springs in the vicinity of Jericho (Duke, Nuweima, and Sultan springs with total discharges of ~$14 \times 106 \text{m}^3/\text{y}$). In the case of the Sultan Spring, it is associated with the major fault system (Figure 3). All of the springs are characterized by low Cl⁻ content of ~30 mg/L.

4. The Plio-Pleistocene (Q) Aquifer shows piesometic level variations between −300 m to −337 m (Figure 1). The ground water flows from west to east and also toward the southeast. Water levels show a general decrease, while the chloride in some wells gradually increases with time (Figure 4). The Cl⁻ concentration in ground water increases from a level of about 100 mg/L in the western margin of the aquifer to about 2000 mg/L in the central part of the Jordan Valley (Figure 5).

Salinity in the Cenomanian Aquifer

The linear correlation between chloride and other dissolved ions of the Cenomanian ground water (Figure 6) suggests a single salinity source. Previous studies suggest that the salinity process in the Cenomanian Aquifer may be derived from (1) lateral flow from the east of saline water from the Plio-Pleistocene (Q) Aquifer; and (2)

the fresh ground water overlies on proto Dead Sea brine that was formed during the high water levels of the Lisan lake and was not washed out from the Cenomanian units, particularly those of the lower K2 subaquifer (Guttman 1997, 1998; Guttman and Rosenthal 1991). The chloride distribution in the Q Aquifer, presented in Figure 5, suggests that the first possibility is not correct because the Cl⁻ content along the hydrogeological contact with the Cenomanian Aquifer is rather low and increases only eastward toward the central part of the valley (Figure 5). Moreover, Golani (1972) showed that the faulted blocks of the impermeable Senonian chalk prevent hydrological connections between the Upper Cretaceous and the Plio-Pleistocene aquifers.

In order to asses the second possibility, we compare the chemical composition of the saline ground water with theoretical mixing combinations of the Dead Sea brine (Cl⁻ = 220,000 mg/L; Na/Cl = 0.28) and fresh water (Cl⁻ = 100 mg/L). The results of these calculations suggest that ground water with Cl⁻ of >1000 mg/L would have a Na/Cl ratio of <0.32, whereas ground water with Cl⁻ of 500 mg/L would have a Na/Cl ratio of 0.38. Similarly, calculations for Br/Cl ratios reveal that mixing between the Dead Sea and fresh water would form saline water with a Br/Cl ratio of 9×10^{-3} for Cl⁻ of 500 mg/L. Our data (Table 2) shows that brackish ground water from the Cenomanian Aquifer has typically a Na/Cl ratio of ~0.5 and Br/Cl ratio of ~7×10^{-3}, which are different from the
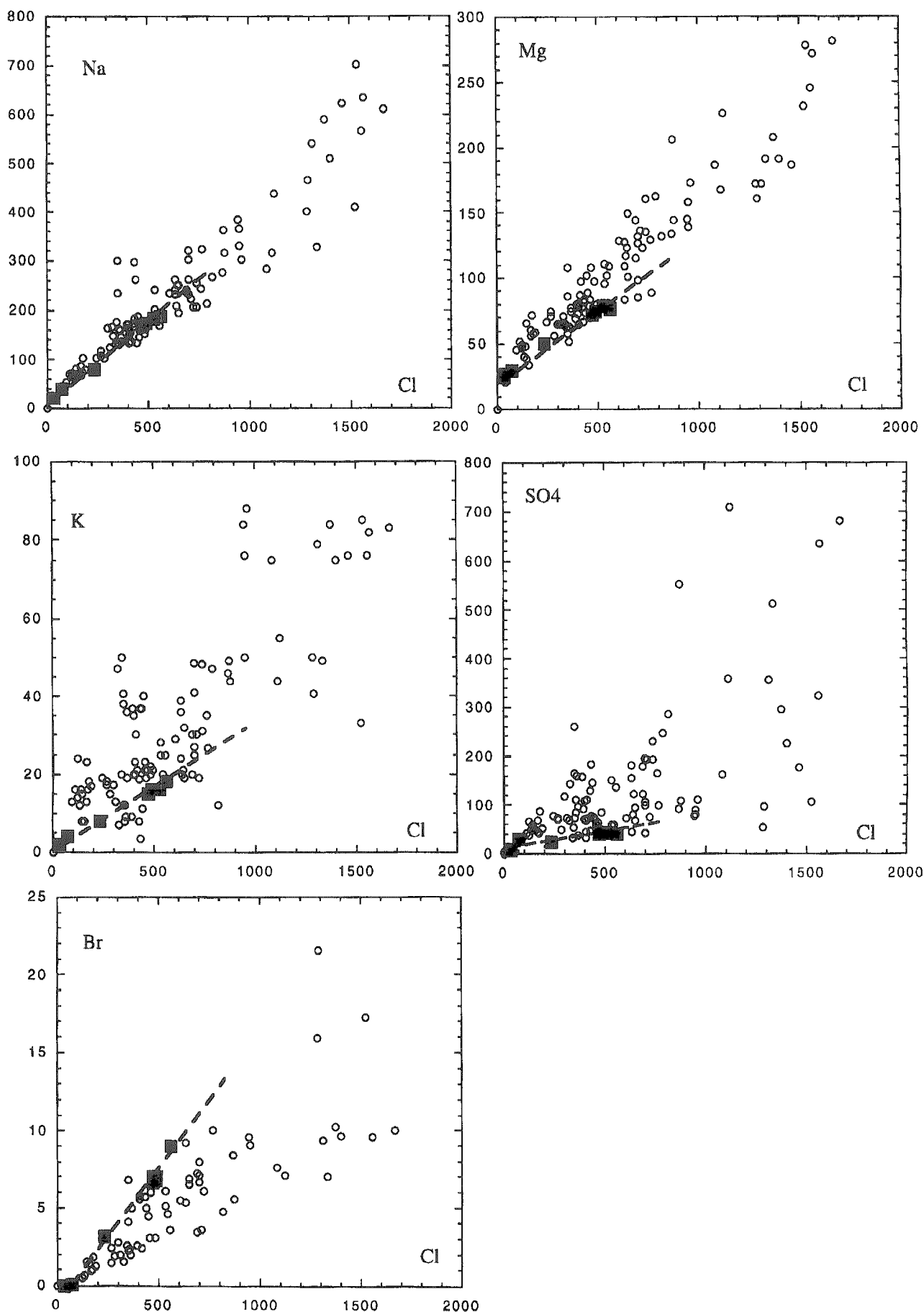
Figure 6. Chemical composition (in mg/L) of ground water in the Jericho area. Note the distinction between ground water from the deep Cenomanian Aquifer (closed squares) that show a linear correlation between Cl⁻ and other ions and ground water from the shallow Plio-Pleistocene Aquifer (open circles) with more scatter relationships.

Table 2
Chemical Composition (in mg/L) and Ionic Ratios (Molar Units) of Typical Brines in the Vicinity of the Dead Sea, Selected Wells from the Cenomenian Aquifer, and from the Plio-Pleistocene Aquifer

Name	Date	Ca	Mg	Na	K	Cl	SO$_4$	HCO$_3$	NO$_3$	Br	Na/Cl	SO$_4$/Cl (×10^{-3})	Br/Cl (×10^{-3})
Hypersaline Brines													
Dead Sea		17600	42120	41300	7600	224200	280	200		4500	0.28	0.7	10
En Gedi spring		7950	10500	23170	2200	80190	1150	169		1590	0.45	5.3	8.8
Hammei Yesha		9813	18086	27361	3520	114510	1078	107		835	0.37	3.5	9.0
En Feshcha (north)		1640	390	1340	125	4221	1200	70		65	0.48	100	6.8
Cenomanian Aquifer													
Mitzpe Jericho 3	18/6/86	490	578	1700	110	4950	105	275	62	83	0.52	16	7.4
Jericho 1	30/11/97	112	75	173	16	491	42	324	11	7.0	0.54	31.6	6.3
Jericho 1	18/3/87	124	79	183	16	528	42	290	10	—	0.53	29.4	—
Jericho 2	30/11/97	112	75	173	16	491	42	324	11	6.7	0.54	64.2	6.2
Jericho 2	31/8/86	128	76	188	18	564	40	317	11	9.0	0.51	26.2	7.1
Jericho 4	30/11/97	85	50	80	8	231	23	284	9	3.2	0.53	73.5	6.1
Plio-Pliestocene Aquifer													
En Hugla	30/11/97	222	162	212	47	788	245	264	42	—	0.41	115	—
Geodat Shasha 4	24/11/97	164	206	363	49	872	553	308	60	5.6	0.64	468	2.8
Mussa Alami 64/1	24/11/97	156	208	590	84	1372	295	363	29	10.2	0.66	159	3.3
Jericho Alami 11	24/11/97	336	471	729	82	2418	1040	233	12	13.5	0.46	318	2.5
Mussa Almi 81/20	24/11/97	114	145	384	84	947	77	415	26	9.6	0.63	601	4.5
Gintisi Sabin Hantan	25/11/97	200	246	567	76	1558	322	338	3	9.6	0.56	153	2.7
Pahad Namari 49-1	25/11/97	203	132	266	12	819	286	251	60	4.8	0.50	258	2.6
Hanna Haldan 58/1	26/11/97	115	126	320	41	702	99	494	33	6.7	0.70	104	4.2
Marg Nagaia 10	26/11/97	110	85	301	25	698	106	245	21	7.9	0.66	112	5.1

theoretical values based on simple mixing between the Dead Sea and fresh water.

Katz and Kolodny (1989) and Stein et al. (1997) showed that Lake Lisan was a hypersaline water body with a sharp density stratification of fresh water overlying hypersaline brines. Their leaching experiments showed that the bulk chemical composition of Lisan salts is indistinguishable from that of the modern Dead Sea. Thus, the chemical signature of the late Pleistocene ancestor of the Dead Sea was similar to the modern Dead Sea. Consequently, if the salinization phenomenom in the Cenomanian Aquifer is derived from unflushed residual brines from the Lisan Sea (Guttman 1997) we would expect to have Na/Cl and Br/Cl ratios that are typical to the Dead Sea brines.

Other potential saline fluids in the vicinity of the Dead Sea are listed in Table 2. Starinsky (1974) showed that thermal springs along the western shore of the Dead Sea have typically high Na/Cl and low Br/Cl ratios relative to the Dead Sea brines. This was interpreted as reflecting earlier stages in the evolution of the Dead Sea brines that were derived from residual evaporated sea during the Neogene period (Starinsky 1974; Starinsky et al. 1979; Vengosh et al. 1991; Stein et al. 1997). Based on ^{36}Cl/Cl and ^{14}C data, Yechieli et al. (1996) argued that similar brines could also have formed during post-Neogene evaporite phases in several evaporation stages. Thus, the distinguished chemical composition only indicates the mechanism of brine formation rather than the specific age of the evaporation phase. During evaporation of sea water, the Na/Cl and Br/Cl ratios of the residual brines decrease and increase, respectively, due to precipitation of halite (McCafferey et al. 1987). Thus, these ratios are excellent indicators for brine evolution.

We propose that the chemical composition of the saline ground water in the Cenomanian Aquifer reflects mixing with brines of similar origin (e.g., En Gedi thermal spring; Table 2). Since the thermal brines are derived from underlying deep sources and their flowpaths are controlled by the Rift fault systems, we suggest that the salinization in the Cenomanian Aquifer in the vicinity of Jericho are also derived from upconing of deep brines along the faults in the area. The fact that salinization occurs in both K1 and K2 sub-aquifers, particularly in wells that are adjacent to the major fault (e.g., Jericho 1, 2, 4, and 5), suggests upconing of deep hypersaline brines that flow through the fault system of the Rift valley. This mechanism of salinization is known in the northern part of the country, in the vicinity of the Sea of Galilee (Goldshmidt et al. 1967; Starinsky 1974; Gvirtzman et al. 1997). Consequently, any future drilling program in the Eastern Mountain Aquifer should take into consideration the possible salinization in areas adjacent to the Rift fault system.

Salinity in the Plio-Pleistocene Aquifer

The salinity in the shallow aquifer system of Plio-Pleistocene age could be derived from the following sources: (1) upconing of deep underlying brines; (2) in situ dissolution of salts, particularly from the marls of Lisan Formation; and (3) anthropogenic sources such as agriculture return-flow and local waste water of Jericho city. The geochemical fingerprinting criteria of each of these sources are used in order to provide tools to delineate their impact on the ground water.

The chemical composition of ground water from the Jericho area is presented in Table 2 and Figure 6. We compare the chemi-
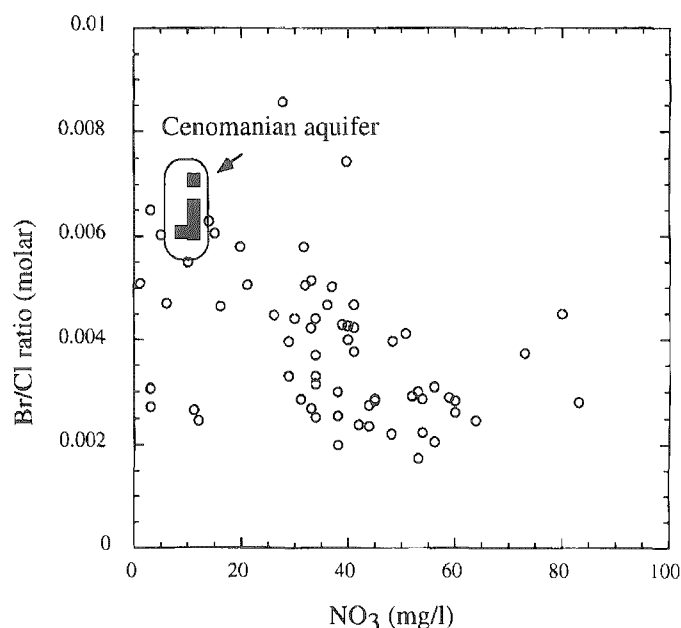
Figure 7. Nitrate concentration versus Br/Cl ratios of ground water from the Plio-Pleistocene Aquifer. Note the association of high NO_3^- with low Br/Cl ratios that suggests that sewage is an important source of the salinity and that the high Cl^- is not derived from halite dissolution.

cal composition of deep ground water from the Cenomanian Aquifer with the shallow ground water from the alluvial Plio-Pleistocene Aquifer. The chemical variations (Figure 6) suggest two distinctive patterns: (1) a linear correlation between Cl^- and other ions in ground water from the pre-Pleistocene and also in some of the Plio-Pleistocene aquifers; and (2) scatter variations in the Plio-Pleistocene Aquifer with ratios that are different from those of the Cenomanian ground water. Thus, some of the saline ground water in the Plio-Pleistocene units are enriched in Na^+, Mg^{2+}, K^+, NO_3^-, and SO_4^{2-} and depleted in Br^- relative to ground water from the Cenomanian Aquifer. Vengosh and Keren (1996) and Vengosh and Pankratov (1998) showed that domestic waste water is characterized by Na/Cl>1, SO_4/Cl and K/Cl> marine ratios while the Br/Cl ratio is typically low (~1 × 10^{-3}) due to the dissolution of NaCl salts and detergents in sewage effluents. The wide range of Na/Cl (0.4-1.0), Br/Cl (2-6 × 10^{-3}), and SO_4/Cl (0.01-0.4) ratios, together with high SO_4^{2-}, K+, and NO_3^- concentrations of the shallow aquifer, suggest that anthropogenic sources (more than one) also affect the water quality in the Plio-Pleistocene Aquifer in the Jericho area. The high NO_3^- and K+ concentrations are attributed to agriculture return flows whereas high NO_3^- and SO_4^{2-} coupled with the low Br^- (low Br/Cl ratios) are related to contamination of domestic waste water. Dissolution of halite mineral within the Lisan Formation may also reduce the Br/Cl and increase the Na/Cl ratios. The association of low Br/Cl (2 × 10^{-3}) and high NO_3^- (up to 80 mg/L; Figure 7), however, suggests sewage contamination.

It should be emphasized that a large fraction of the Plio-Pleistocene ground water has a chemical composition that is identical to that of the Cenomanian Aquifer, indicating a natural source of salinization. This source can be either upconing of brines or leaching of salts from the Lisan marls. As previously noted, Katz and Kolodny (1989) showed that the bulk salt composition that is leached from the Lisan Formation is identical to that of Dead Sea brines. Thus, the distinction between underlying saline sources and salt-leaching based on major ion chemistry is limited.

Nevertheless, we argue that the high sulfate content and the high SO_4/Cl ratios observed in some wells and in particular in the spring of En Hagla (Figure 1, Table 2) indicates dissolution of gypsum mineral within the Lisan units.

Conclusions

The hydrological and geochemical data presented in this study show that salinization of ground water occurs in three aquifer units in the vicinity of the Jericho area: (1) the lower subaquifer (K2) of Lower Cenomanian age; (2) the upper subaquifer (K1) of Middle-Upper Cenomanian age; and (3) the shallow aquifer (Q) of Plio-Pleistocene age. The chemical composition of the saline (Cl^- up to 5000 mg/L) ground water in the Cenomanian Aquifer points to a single saline source with Na/Cl ratio ~0.5 and Br/Cl~7 × 10^{-3}. This composition is similar to that of thermal hypersaline springs that emerge along the western shore of the Dead Sea. We argue that the increase in Cl^- in both K1 and K2 subaquifers is derived from mixing of fresh ground water with upconing of deep-seated brines with similar chemical composition. The deep-seated brine flow through the Rift fault systems and their mixing proportions are dependent upon the fresh water discharge of the Eastern Mountain Aquifer.

The chemical composition of ground water from the shallow Plio-Pleistocene Aquifer suggests that the high Cl^- (up to 2000 mg/L), particularly in the eastern part of the aquifer, is derived from several sources. These include: (1) upconing of deep brines; (2) leaching of salts within the aquifer; and (3) anthropogenic contamination of agriculture return flow and waste water infiltration. The anthropogenic geochemical signal of ground water in the Jericho area indicates that pollution prevention can be one of the key factors in remediation activities in the lower Jordan Valley. The shallow depth of the unconfined Plio-Pleistocene Aquifer makes it sensitive to surface contamination. Under the extreme arid conditions of the lower Jordan Valley, recycling of salts through pumping and irrigation can further increase the salinity of the local ground water.

The chemical results presented in this study provide the basic tools for delineating the possible sources of the salinity and hence for understanding the salinization processes in other areas of the Jordan Valley. This evaluation is crucial for management and future exploitation of any aquifer in which salinization occurs. Our data suggests that future utilization of the two hydrological systems, the deep Cenomanian and the shallow Plio-Pleistocene aquifers, will further increase the salinization rates. In both systems, the degradation of water quality will require special remediation measures. Moreover, salinization rates are expected to increase further if water will be extensively utilized from the deep aquifer for large-scale desalinization. Future planning of any desalinization plant should, therefore, take into consideration this expected rise of salinity.

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