

Using stable isotopes to delineate the relations between sub-aquifer systems in the eastern slope of Bethlehem-Hebron to the Dead Sea/Palestine

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Abstract This study used stable isotopes ^{18}O , ^2H , and ^3H in addition to hydro chemical and hydraulic data to explain the relations between different sub-aquifer systems in the Bethlehem-Hebron area. This area is suffering from high water shortage. The results indicate different recharge processes which occur within the upper and lower Aquifer systems of the mountain aquifer, and the structural features play an important role in this process. The isotopes emphasize the previous finding about the role of the structure, mainly, the extensive-folded anticlinorium that forces groundwater to flow through synclinal axes up- and downward, with different recharge mechanisms. While the lower aquifer received limited direct recharge from the exposed Bet Kahil formation in the upper part of the mountain, some of the upper aquifer groundwater seeping down through structural axes and faults fed the lower aquifer with additional amount of water. This process is attributed to the lowering of hydraulic head that varied seasonally. On the other hand, the direct recharge for the upper

aquifer can be enough unless a huge amount of water from the upper aquifer seeping down due to steep hydraulic gradient to the Dead Sea springs. This process is apparently responsible for the quick drawdown of the groundwater level besides depletion of some wells drilled recently during the last decade in the upper aquifer. Delineating the relations between different aquifer systems within the study area can give further explanation and help the stakeholders to manage the water shortage problem, taking into account the main finding about aquifer relations in the future plans.

Keywords Bethlehem-Hebron · Aquifer delineation · Isotope hydrology · Geological complexity

Introduction

South of the West Bank consists of Hebron and Bethlehem governorates. It has an area of about 1943 km², making 28% of the WB area (Palestinian Water Authority 2012). Moreover, it has the highest number of population compared to other governorates, the number of population reaching 772,000 persons in 2008 (Nazer et al. 2008). The cultivated area in the year 2007/2008 is about 285 km² from it (3%) from where rain-fed consist 97%, covering about 26% of the governorate areas. The area has an average rainfall of about 580 mm/year, with an average maximum of 140 mm in February and a minimum during the month of May (Nazer et al. 2008).

The study area is located to the southeastern part of the West Bank including Bethlehem and Hebron governorates as shown in Fig. 1, positioning over the main middle mountain chain of the West Bank. The difference in the elevation between the west highlands and the Dead Sea level eastwards is about 1100 m.

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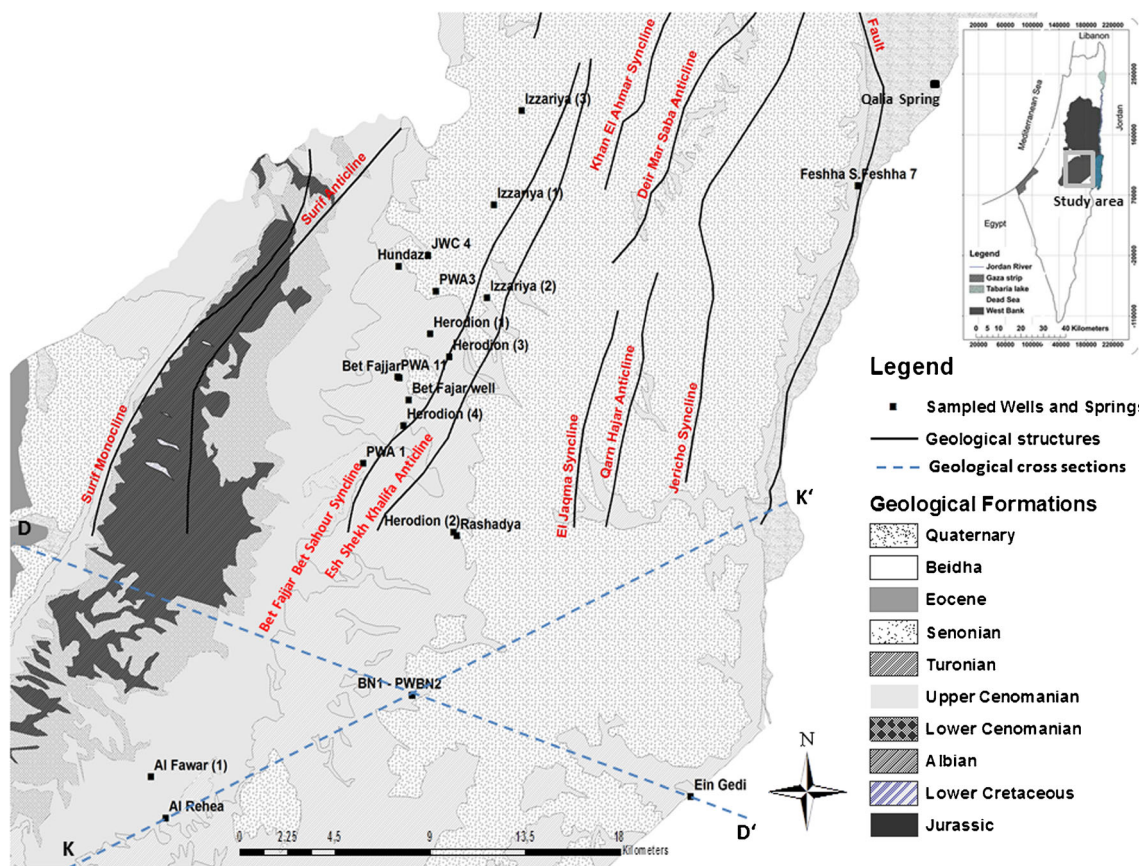


Fig. 1 Study area showing sampled wells and springs, major geological structures governing the area, and the locations of cross sections *D–D'* and *K–K'*

The area of eastern slope to the Dead Sea includes several wadis with very rare vegetation coverage where mainly natural small-spine bushels cover the slopes. These wadis are generally located within the rain-shadow area which dominate the eastern slopes of mountains.

There are some people settled in the wadi area who are mostly farmers distributed over 25 communities covering more than 17 km² with a population of more than 65,000. However, the residents in the lower part are mainly Bedouins raising livestock. The main crops planted are grapes, olive trees, and wheat; these are rain-fed crops that do not need irrigation, and they are mainly distributed among the upper part of the catchment area.

Due to population increase and improving life standard, both districts are suffering from extreme water shortage, so many wells were drilled in the study area to meet the increased drinking water demand. However, the predicted productions of those wells do not meet the current domestic water demand; on the other hand, few of those wells dried 3 years after operation. Some of those wells drilled in the upper aquifer show rapid decrease in water table during summer time, and then, it is completely dried by the end of summer period (personal measurements).

The integrated approach of using hydrogeochemistry and stable isotopes as tracers is a well-known method that is

conducted all over the world. Such tracer method has been proved to provide additional information about groundwater flow paths, potential sources, and recharge mechanism (Petitta et al. 2010; Barbieri et al. 2017). Hydrogeochemical and isotope analyses can test and fine-tune a conceptual hydrogeological model in the region. Furthermore, monitoring changes in stable isotopes over time and in space can give a better understanding of aquifer recharge and spring discharge that are essential for defining groundwater hydrodynamics. In addition, monitoring of stable isotopes proves to be a useful tool when urgent land planning decisions are to be made, such as those concerning conservation and management of water resources, as well as assessment of the quality of water for human use (Barbieri et al. 2005).

Geology and hydrogeology

In general, the oldest formation of Albian to Turonian ages crops out at the axis of the anticline, whereas the younger Paleogene series of Senonian age covers the eastern flanks of the anticline mainly in the southern and central parts of the study area (Fig. 1). The Upper Cretaceous carbonate sediments consist of thick alternating sequences of limestone, dolomite, marls, and marly limestone that build the upper

and lower parts of the mountain aquifer. On the other hand, the chalk unit of the Senonian age partially covers the limestone of Turonian age which is considered as impervious. Figure 1 illustrates various geologic formations of the study area. The main dominant formations are as follows as described by Rofe and Raffety in the hydro-geological survey they made in Palestine in 1963.

Abu Dees Formation (Senonian Age): It is approximately 200 to 450 m thick and composed of massive hard chalk unit inter-bedded with 2-m cherty layers in the lower part and is soft and un-bedded in its upper part. It covers the eastern slopes.

Jerusalem Formation (Turonian Age): This formation underlies the Abu Dees Formation and is approximately 70 to 130 m thick. Its lithology is characterized by highly fractured and karstified limestone. It crops out at the top of the mountain.

Bethlehem Formations (Upper Cenomanian Age): It consists of 30 to 115 m of limestone and marly limestone and is highly fractured and also karstified. The marly limestone and marl bands near the base act as an aquitard.

Hebron Formations (Upper Cenomanian Age): It consists of 105- to 260-m-thick bedded dolomite and limestone; it is highly fractured and karstified. This formation is cropped out at the top of the mountain chain.

Yatta Formation (Lower Cenomanian): It is composed mainly of marl and marly limestone; This formation is considered as an aquiclude that divides the mountain aquifer into upper and lower aquifers.

Upper Bet Kahel Formation (Albian): It consists of a 160- to 190-m-thick well bedded limestone and dolomite. The lower part of this formation is made up of limestone with thin layers of porous dolomite interchanging with marly limestone and calcitic massive limestone near the base.

Lower Bet Kahel Formation (Albian): It consists of gray limestone layers alternating with layers of shale and marl in the lower part, whereas the upper part is made up of gray to brown dolomite with clayey and marly limestone.

Aquifer systems: The rock formations of Jerusalem, Bethlehem, and Hebron make the upper aquifer system, whereas formations of upper and lower Beit Kahil make the lower aquifer. That formation is cropped out in an area with rainfall ranging from 450 to 650 mm/year. Table 1 summarizes the exposed area of the upper- and lower-forming formation.

Abu Dees formation covers 59 of 225 km² (which is about 25% of the catchment area) with neglected infiltration rate due to the chalk contents.

The considerable influence of the geological structure on groundwater flow regime is exhibited in the thick carbonate aquifer beneath the study area. According to Ben-Itzhak and Gvirtzman (2005a), the groundwater flow is diverted from the generally steep hydraulic gradient, creating a subsurface with “river-like” meandering flow pattern.

Groundwater originating in the mountains is driven by gravity down to the Dead Sea; enters this region from the west, mainly at the shallow Judea aquifer; and discharges to the Dead Sea shore.

The structure of the extensively folded anticlinorium forces groundwater flow through synclinal axes in the upper aquifer, and in certain places, it overflows from one syncline to an adjacent one. Groundwater outflows are the springs near the Dead Sea shore and by the sub-surface flow across the Graben faults towards the Dead Sea (Shalev and Yeichieli 2007). The sampled wells and springs in the study area are distributed mainly between the Surif anticline and the Esh Shekh Khalifa anticline, where most of them are distributed around the Bet Fajjar Bet Sahur syncline (Fig. 1).

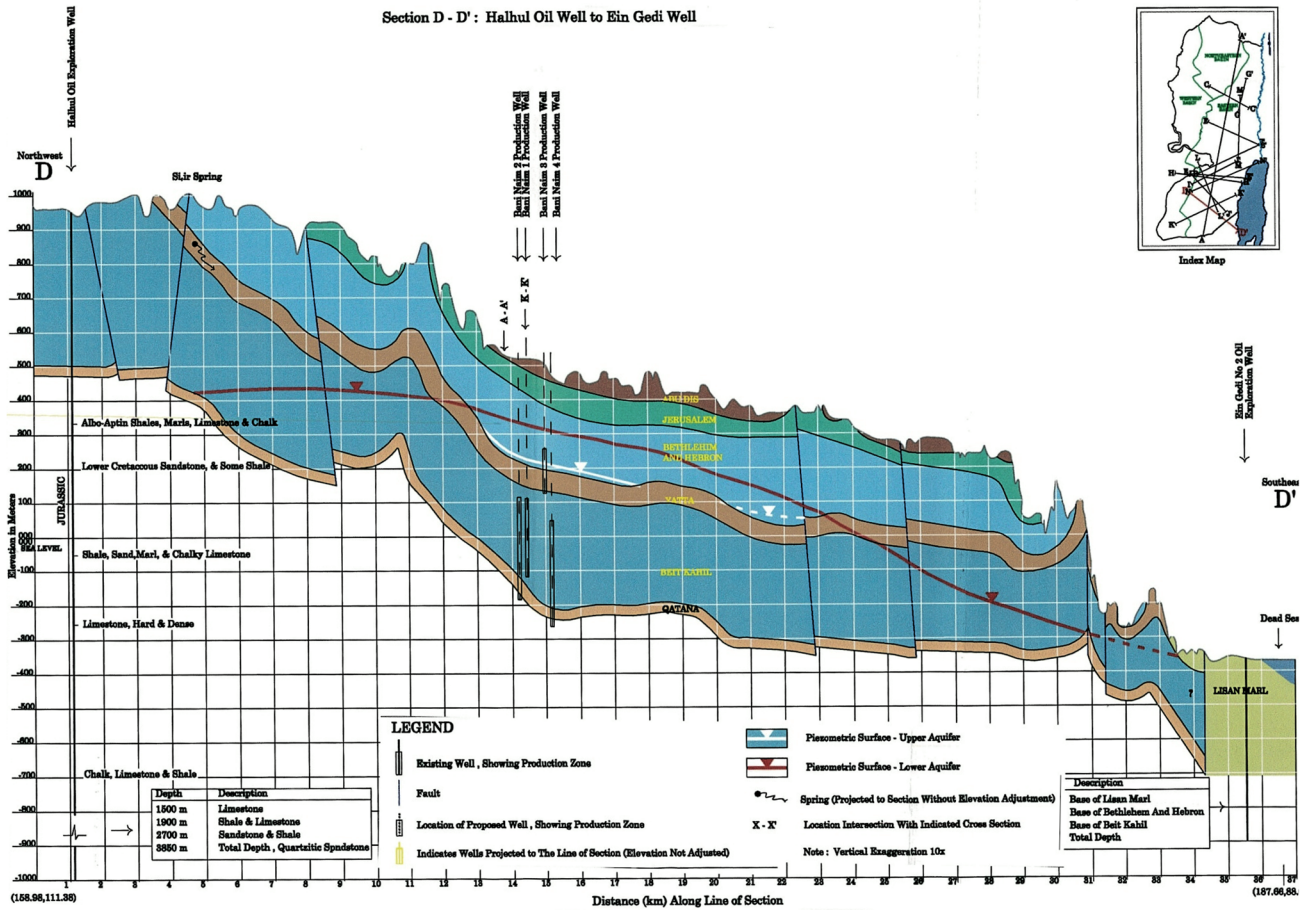
Previous studies (Rosenthal et al. 1981; Kronfeld et al. 1990; Rosenthal et al. 1990; Guttman and Zuckerman 1995), have shown that the groundwater system in the study area is composed of (i) an upper sub-aquifer of Turonian to Upper Cenomanian age (Jerusalem-Bethlehem-Hebron formation) and (ii) a lower sub-aquifer of Albian age (upper and lower Bet Kahel). Separation between the upper and lower sub-aquifers occurs within the Yatta Formations of Lower Cenomanian age (Guttman and Zuckerman 1995; Flexer et al. 2003). The confined condition of the lower sub aquifer system makes the water levels in the lower aquifer higher than those in the upper aquifer in some locations of the area.

The aquifer is fed solely by rainwater falling during the winter season. An average recharge of 21 million cubic meters (MCM)/year for the study area was calculated by the authors using GIS tool at Al-Quds University. The natural aquifer discharge is through springs along the Dead Sea shore line and in the form of subsurface leakage into the Dead Sea group aquifer while crossing the rift faults.

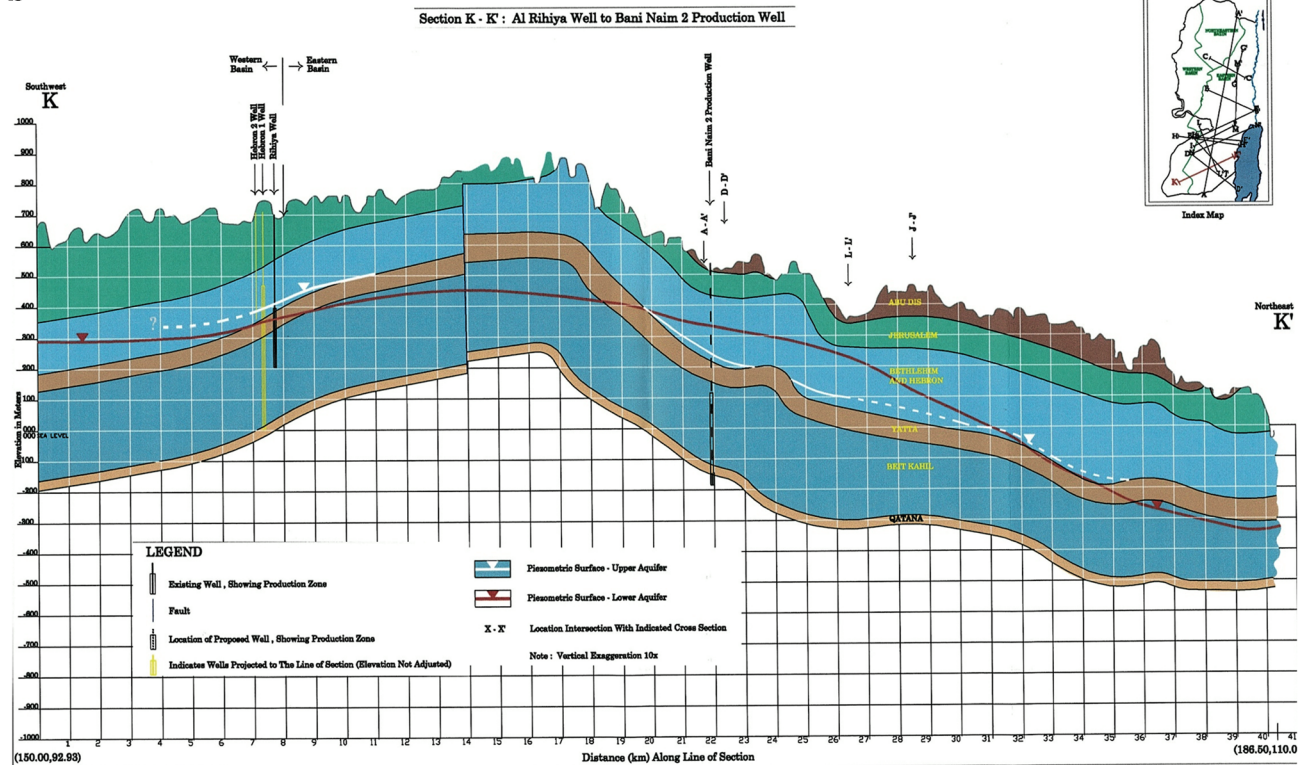
The total number of springs within the Dead Sea catchment area is about 200 (Gvirtzman 2006). These springs are of two types, the thermal springs that discharge their waters to surface from the deep seated aquifers and the fresh springs that occur at wadi beds from the upper carbonate aquifers generating the base flow of the wadis (Gvirtzman 2006). The major springs that are discharged from the upper and lower aquifers systems are Feshkha, Ein Gedi, and Ein Qalia. The total discharge volume from the Dead Sea springs was calculated as 83.8 MCM/year from which Kalia discharged around 5–6 MCM/year (Ben-Itzhak and Gvirtzman, 2005b).

The springs are a mixture of meteoric fresh water with a relatively small amount of ascending deep brine (Stanislavsky and Gvirtzman 1999). There is not much more information about the groundwater flow regime from the upper to the lower aquifer and the relation between the major sub-aquifers and the Dead Sea springs (Gräbe et al. 2013). The geological cross-sections *D–D'* shown in Fig. 2a are very significant in developing an overview of the hydro-stratigraphy related to the study area (MEG 1999, unpublished). Figure 2a

a



b



◀ **Fig. 2** **a** *D–D'* geologic cross-section in the eastern aquifer section 1, from the Halhul oil well to the Ein Gedi well (MEG 1999). **b** *K–K'* geologic cross-section in the eastern aquifer section 2, from the Al Rehiyeh well to the BN2 production well (MEG 1999, unpublished).

table from the lower aquifer to drop down fast and the mixing zone to shrink as well.

Methodology

Water isotope hydrology addresses the application of the isotopes that form water molecules. These are the oxygen (^{16}O , ^{17}O , $\delta^{18}\text{O}$) and the hydrogen isotopes (^1H , ^2H , ^3H). These isotopes (unlike other tracers of “water” such as Cl^- which are still widely used) are ideal tracers of water sources and movement because they are constituents of the water molecules (Gat et al. 1981). These elements (hydrogen, oxygen) undergo changes in the various phases of hydrologic environments—atmosphere, hydrosphere, and biosphere—and the upper part of the earth’s crust. These changes result in isotopic fractionation that give isotopic “fingerprints” due to different physicochemical, biochemical, kinetic, and thermodynamic effects (Clark and Fritz 1997).

The isotopic fractionation at any location is affected by the geology of the area, origin of the water, climate (evaporation, condensation, melting), and other local effects (simple mixing at or below the surface).

The correlation between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in atmospheric precipitation commonly called global meteoric water line is defined by the expression (Clark and Fritz 1997)

$$\delta^2\text{H} = 8\delta^{18}\text{O} + 10$$

For each area, there is a local meteoric water line that expressed the natural isotopic content in the rainwater as the recharge source. Any deviation from the meteoric water line with distinctive signature can give indication about the possible sources and mechanisms of recharge as well as mixing between water bodies. Tritium (^3H , half-life of 12.43 years (Unterweger, 1980) has provided an excellent tracer of young waters. Tritium input to groundwater has occurred in a series of spikes following periods of atmospheric testing of nuclear devices that began in 1952 and reached a maximum in 1963–1964. Concentrations of ^3H in precipitation have decreased since the mid-1960s bomb peak, except for some small increases from French and Chinese tests in the late 1970s.

Many working wells were selected from the upper and lower aquifers beside some of the Dead Sea springs, namely Qalia, Feshkha, and Ein Gedi. The first set of samples that was analyzed was taken from rainwater samples in the hydrological year 2015/2016, whereas rain gauges were distributed in representative location across the study area.

In addition, groundwater samples from wells and springs in the study area were also collected in the winter season, for chemicals, and isotope analysis of ^2H , $\delta^{18}\text{O}$, and ^3H . Samples for deuterium and $\delta^{18}\text{O}$ isotopes in rainwater and groundwater were collected with 25-ml bottles and sent to the Central Laboratory of Ministry of Water and Irrigation/Jordan for analysis. Samples were analyzed using laser spectroscopy for deuterium and $\delta^{18}\text{O}$ in per mill, where it was the ratio of international V-SMOW (Vienna Standard Mean Ocean Water) standard; the precision of $\delta^{18}\text{O}$ measurements is $\pm 0.1\%$; the precision of δD values is $\pm 2\%$. The method used for determination of the tritium content consists in the measurement in an ultra-low-level liquid scintillation spectrometer of the water. However, some samples show TU below detection limit using this method. Therefore, tritium enrichment by electrolysis technique was used to indicate the absence or the presence of tritium traces in water samples (Florkowski 1981; Plastino et al. 2007).

Divers’ readings were taken from those divers installed by the Helmholtz Centre for Environmental Research in Halle, Germany. The readings were used to measure the groundwater level in the Bet Fajjar well that is in the upper aquifer, Ras Elwad in the lower aquifer, and the last one was installed in the Qalia spring directly near the Dead Sea shore. The set of isotopes, hydrochemistry, and hydraulic data were used integrally to have a conceptual model about the possible relations between different sub-aquifer systems in the study area. Such integrated tools can give more information about the mode and potential sources of recharge to different sinks and explain the problem of groundwater drought especially in the upper aquifer layers.

Results and discussion

Table 2 shows the isotopes and some hydro-chemical values for the groundwater collected from wells around the study area.

The piper diagram differentiates the groundwater samples in groups with more Ca^{+2} content in the groundwater from the lower aquifer and relatively higher Mg^{+2} from the upper aquifer whereas the springs exhibited more Na^+ and Cl^- due to the mixing with brine water (Fig. 3). The diagram can differentiate different water bodies that get specific hydrochemical characters according to recharge and flow mechanism.

In general, the hydrochemical values for the groundwater from the upper aquifer show higher Ca^+ values for all samples. The high Ca^+ rate is also indicated even in those wells which are suspected to perch its water from the lower aquifer. This can be reflective of the effect of the upper calcareous layers, where more Ca^+ input overshadows the presence of other cations.

The Mg show relatively high values in the groundwater samples from the lower aquifer. This is mainly due to the

Table 2 Measured hydrochemical and isotopes values from the sampled wells and springs in the study area

Station ID	Aquifer	$\delta^{18}O\text{‰}$ (SMOW)	2H	TU	Cl (mg/L)	HCO ₃ (mg/L)	SO ₄ (mg/L)	NO ₃ (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)
Al Rehea	Upper	- 5.90	- 23.80	1.80	46	319	11	22	14	2.0	36	58
Al Samoua	Upper	- 5.60	- 23.50	3.45	84	321	28	42	34	2.30	34	51
Al Fawar (1)	Upper	- 5.90	- 24.00	3.60	110	342	38	55	42	2.50	38	58
Herodion (1)	Upper	- 5.90	- 26.60	0.25	22	317	9	6	19	1.80	37	50
BN1 - PW	Upper	- 5.55	- 23.40	0.84	36	257	4	7	11	1.30	35	51
Bet Fajar PW	Upper	- 5.80	- 26.90	0.67	32	318	9	13	25	1.60	38	55
PWA3	Upper	- 5.70	- 22.90	0.40	24	267	8	9	7	1.10	30	48
Bet Fajjar	Upper	- 6.00	- 26.20	0.69	32	300	7	11	23	1.50	38	52
BN2	Lower	- 5.90	- 27.70	0.02	25	314	12	6	16	2.00	23	57
Rashadya	Lower	- 5.80	- 28.20	0.02	99	184	14	7	18	2.50	30	61
Herodion (2)	Lower	- 6.20	- 26.60	0.34	28	154	15	6	19	1.90	27	63
Herodion (4)	Lower	- 6.10	- 26.70	0.30	21	300	10	4	18	1.60	30	56
Herodion (3)	Lower	- 6.20	- 26.00	0.28	36	257	18	7	15	1.80	19	48
PWA 1	Lower	- 6.20	- 25.90	0.37	24	315	11	6	13	2.00	25	65
PWA 11	Lower	- 6.10	- 26.90	0.50	27	296	9	7	21	2.10	18	47
Izzariya (1)	Lower	- 5.90	- 26.60	0.03	23	311	11	4	19	2.20	16	32
Izzariya (2)	Lower	- 6.20	- 26.60	0.06	56	269	20	17	24	1.80	27	55
Izzariya (3)	Lower	- 5.80	- 24.10	0.04	43	190	13	6	17	2.40	16	45
Hundaza	Lower	- 6.10	- 29.00	0.02	23	332	12	8	16	2.30	28	53
JWC 4	Lower	- 6.20	- 26.70	0.03	23	336	13	5	20	2.00	29	69
Ein Gedi	Spring	- 5.20	- 22.00	1.00	82	211	35	29	48	5.00	29	56
Feshha 7	Spring	- 5.30	- 22.60	0.15	6469	238	176	6.34	2407	344	542	318
Feshha S.	Spring	- 5.45	- 22.50	0.89	1588	195	70	27	463	60	248	193
Qalia	Spring	- 4.94	- 21.30	0.75	6700	283	860	11	1890	340	1130	660

mineralogical composition of the Upper Beit Kahel formation which consists of dense limestone and dolomite and can be also indicated as high K inputs which are related to cation exchange through long contact with marly Yatta formation of Lower Cenomanian age.

The $\delta^{18}O$ content in rain water ranges between - 7‰ in the upper mountain and - 3.6‰ in Bani Naim area down in the eastern slope. The local meteoric water line was found as $Y = 7.02X + 19.5$ (Fig. 4), with a slope that is relatively deviated from the LMWL in other studies in

Fig. 3 Piper diagram showing the major water types for groundwater samples from the upper, lower, and Dead Sea sub-aquifer systems

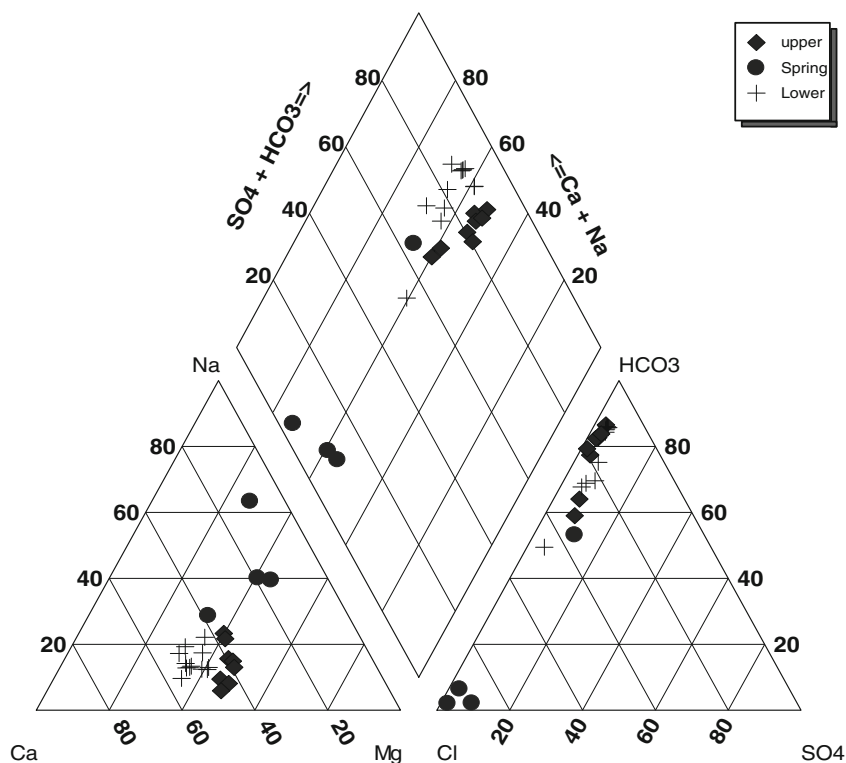
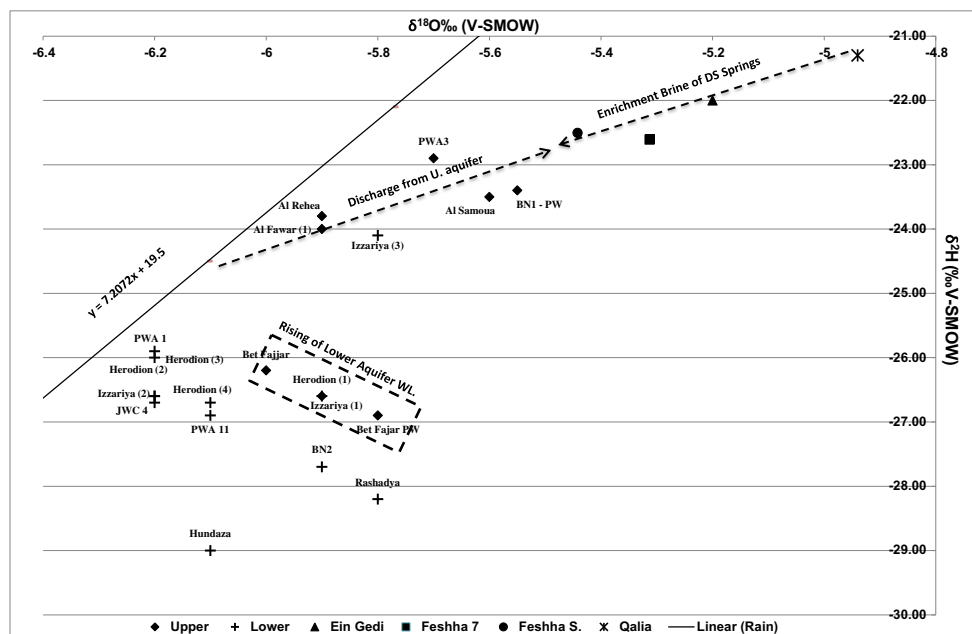


Fig. 4 $2D$ and $\delta^{18}O$ ‰ (SMOW), for the groundwater samples from different sub-aquifer systems



Jericho and eastern slope of Ramallah (Khayat et al., 2006; Lange et al. 2008).

In general, most of the groundwater has more or less the signature of rainwater and is located near local meteoric water line.

Figure 4 shows the relation between $2D$ and $\delta^{18}O$ ‰ (SMOW). The $\delta^{18}O$ signatures for the groundwater range between -5.2 and 6.2 ‰. The isotopic signatures from the upper aquifer have relatively enriched $\delta^{18}O$ and deuterium signatures due to the quick discharge from surface water runoff which promotes more evaporation (Fig. 4).

The isotopic signature for the Dead Sea springs lies also within those signatures of the upper aquifer groundwater with further enrichments due to mixing with brine water from the Dead Sea. In general, most of the groundwater has more or less meteoric signatures and is located near local meteoric water line. However, it seems that the recharge area or mechanism is different between the upper and lower aquifers with different deuterium values.

The sensitive recharge zones for the study areas are distributed as follows: Albian to Lower Cenomanian that is exposed to the surrounding Surif anticline and Lower Cenomanian Turonian that extended from the east of Surif Anticline to the Bet Fajjar Bet Sahur syncline to the east of Esh Shekh Khalifa anticline where the beginning of Senonian exposure is (Fig. 1).

Cross-sections (Fig. 2a, b) show that many of the wells within the study area obtained water from the raised lower aquifer water which occurs by the end of winter season. Moreover, the direct recharge area for the upper aquifer is relatively small in the upper mountain area (Fig. 2a, b). Therefore, the isotope signatures for the groundwater in some

wells from the upper aquifer come as mixing signatures between both aquifers.

The location of the sampled wells between the Surif anticline and the Esh Shekh Khalifa anticline, where most of them are distributed around the Bet Fajjar Bet Sahur syncline, facilitates the process of groundwater exchange between both aquifers (Fig. 1). Moreover, the Eljaqma syncline, Qarn Hajar anticline, and Jericho syncline which are located further to the east with a steep gradient slope to the Dead Sea area can also play a role in quick water seepage to the Dead Sea spring group.

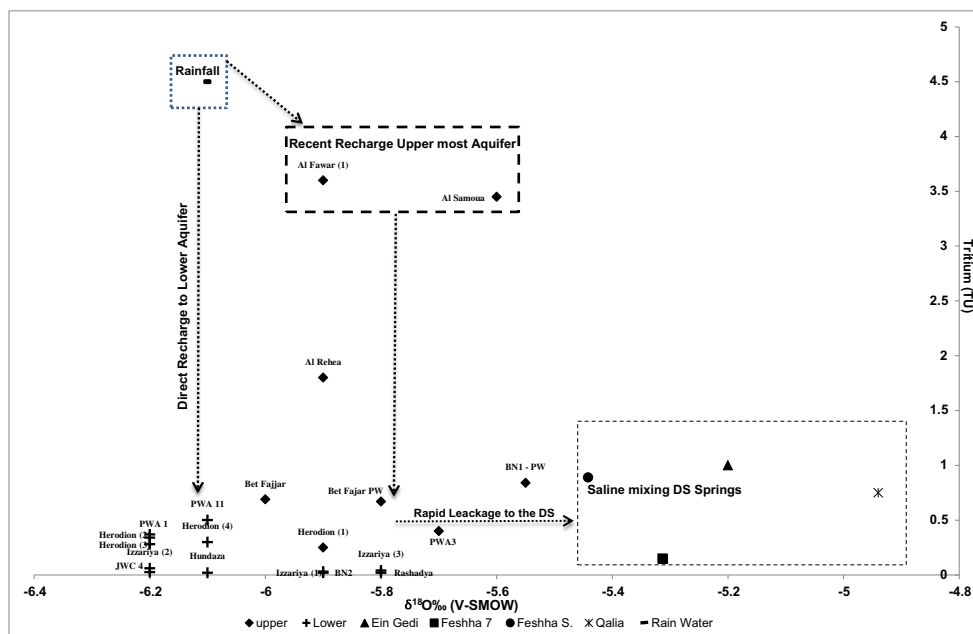
Figure 5 shows that all the lower aquifer tritium contents were below 0.8, while those for the upper aquifer range between 1 and 1.5 TU, those including also the Dead Sea springs. The rainfall tritium content has an average of 4.5 TU. Thus, the groundwater values between the Upper aquifer are considered a mix of modern- and sub-modern-age water. This also can illustrate the slight mixing between the Upper (modern water) and Lower aquifers (sub-modern water).

The isotope data shows that the groundwater from the study area has three possible recharge mechanisms which are discussed below for each aquifer.

Isotope signatures from the lower aquifer

The isotope signatures from the lower aquifer show values near the meteoric line, which reflects a direct infiltration from rain through the exposed Bet Kahil formation of Albian age which is exposed about 4 km^2 to the east of the Surif monocline (GIS calculation) (Fig. 2a). However, the relatively

Fig. 5 $\delta^{18}O_{\text{‰}}$ (SMOW) vs. tritium showing the principle of suggested conceptual model for the sub-aquifer relations



depleted deuterium in some of the lower aquifer wells, like Bani Naim 2, Hundaza, and Rashaydeh, can indicate the possibility of a longer process of recharge with slow infiltration of groundwater between the upper and lower aquifers through geological structures. These structures are, namely, the Surif anticline, Esh Sheikh Khalifa anticline, Bet Fajar-Bet Sahour syncline, Aljakma syncline, and Qarn Hagar anticline, respectively (Fig. 1). As mentioned in the “Geology and hydrogeology” section, the water table of the lower aquifer upraised under high hydraulic conditions, and then, the groundwater declined and re-infiltrated the lower aquifer in an opposite movement. For example, Hundaza and Rashayda show relatively depleted deuterium signatures. Hundaza is located directly with the syncline area but closer to the Surif anticline. Hundaza wells show the most depleted deuterium signature which may reflect a direct recharge from the exposed lower Cenomanian-Albian parts in the Surif anticline area, while the Rashayda well is located at the high slope gradient further to the east of the Esh Shekh Khalifa anticline. The geological outcrop between both anticlines is mainly Upper Cenomanian-Turonian. The recharged water from the exposed Upper Cenomanian-Turonian can be infiltrated through the geological structures and feed the Rashayda well.

The depletion in the isotope signatures beside the low tritium units for the water from the lower aquifer can emphasize this assumption. The deuterium isotopes show depletion for the groundwater from the lower aquifer, which is mainly due to the long residence time with aquifer material that causes, in role, ultra-fractionation caused by cation exchange with hydrogen (Hoefs 2008). Such depletion suggests that the slow infiltration or re-infiltration from the upper aquifer through

different geological structures has the most contribution to the lower aquifer water budget, more than the direct infiltration through the exposed area east of the Surif monocline.

On the contrary, many of the mentioned geological structures act sometimes as barriers that intersect the groundwater flow and lead finally to upward slow movement of water to the upper aquifer layers. However, such upward movement is assumed to occur seasonally mainly by the end of the wet period where the hydraulic pressure of the lower aquifer is getting high. Most of the wells in the upper aquifer were sampled by the end of the wet season. Some of these wells show the same signatures for the groundwater from the lower aquifer which will be described in the next section. In the dry period from July to September, the water level of the lower aquifer moves downward and allows the water to infiltrate back slowly through the fault system causing more depleted deuterium signatures (Fig. 4). It has been noticed that many of the wells in the upper aquifer become out of operation due to the quick lowering of water by the end of the summer season (personal measurements). The measured tritium units for the lower aquifer can also give an indication about such hydrological situation, where the TU for most of the lower aquifer groundwater samples shows low values between 0 and 0.5 TU, which reflect long travel and storage time of recharge (Fig. 5). The assumption of seasonal groundwater exchange between the upper and lower aquifers through geological structure is the most reasonable factor that is reflected through the isotope signatures for the lower aquifer in the study area.

The low tritium signatures for the lower aquifer indicate a slow infiltration process through fault system, apparently from the area which lies in the southwest where the upper and lower cretaceous is widely exposed. However, in the winter season,

further limited replenishment comes through the small outcrop of the upper aquifer in the upper mountain mixing within the upper cretaceous with the water table from the upper aquifer that rose up with heavy abstraction through fault system.

The excessive abstraction from wells is consuming from the aquifer much more than its replenishment rate. The over abstraction is causing a severe drawdown in the water table of the upper aquifer due to small catchment area. Therefore, depending on the isotopes results, it seems that the groundwater exhibits long recharge travel time whereas the exposed direct recharge area for the lower aquifer extends away to the southwest. Moreover, the additional replenishment that infiltrates from the upper aquifer through fault system during dry period occurs slowly with time. This is clearly the most important reason for the lowering of piezometric head for the lower aquifer in the last two decades (Flexer et al., 2003).

The increase of Mg in the groundwater from the lower aquifer is mainly due to the mineralogical composition of the Upper Beit Kahel formation which consists of dense limestone and dolomite. This can be also the reason for the high K input which is related to cation exchange through long contact with the marly Yatta formation of Lower Cenomanian age (Fig. 6).

Isotope signatures from the upper aquifer

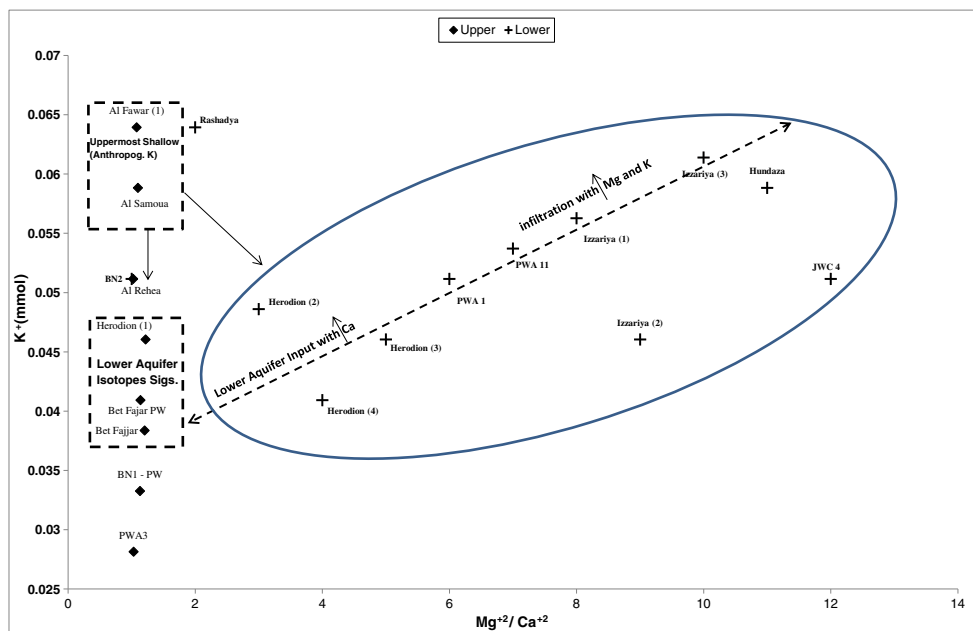
As has been mentioned in the “Geology and hydrogeology” section, the upper aquifer layers can be divided into two major aquifers, the topmost exposed layer of Turonian age (Jerusalem Formation). The upper most sub-aquifer is local, partially perched, with few pumping wells. These wells are also characterized by high sensitivity to anthropogenic pollutants (Fig. 6). The other upper

sub-aquifer is of Upper Cenomanian age (Hebron-Bethlahim formation). The uppermost aquifer layer fed solely from the direct rainwater with tritium units of 3.5 TU (Fig. 5). The area from which the Upper aquifer is fed covers around 10 km² where Bethlehem, Hebron, and Jerusalem formations are cropped out (GIS calculations).

Some of the water from the uppermost aquifer seeps down quickly to feed partially the upper aquifer layers (Fig. 5). In general, the groundwater from the upper and the uppermost aquifer wells shows a meteoric water signature; however, some of those wells are located in the area near the folded anticlinorium and synclinal systems where the groundwater level from the lower aquifer is upraised through faults. For example, Herodion 1 and Bet Fajar wells are located directly close to the west of the Bet Fajar Bet Sahour syncline. Those wells show relatively the same isotope signatures of the groundwater from the lower aquifer, specifically the deuterium signatures. However, the presences of tritium units reflect a kind of mixing process between recent and relatively old ascending lower aquifer water. The hydrochemical values for the groundwater from the upper aquifer show higher Ca⁺ values for all of the samples. The high Ca⁺ rate is also indicated even in those wells which are suspected to perch its water from the lower aquifer (Fig. 6). This can reflect the effect of the upper calcareous layers, where more Ca⁺ input overshadows the presence of other cations.

During the decrease of hydraulic head of the lower aquifer, the structure of the extensively folded anticlinorium forces groundwater to flow through synclinal axes in the

Fig. 6 Potassium in micromoles per liter vs. Mg/Ca molar ratio expressed the cation behaviors in response to groundwater mixing between the upper and lower aquifers



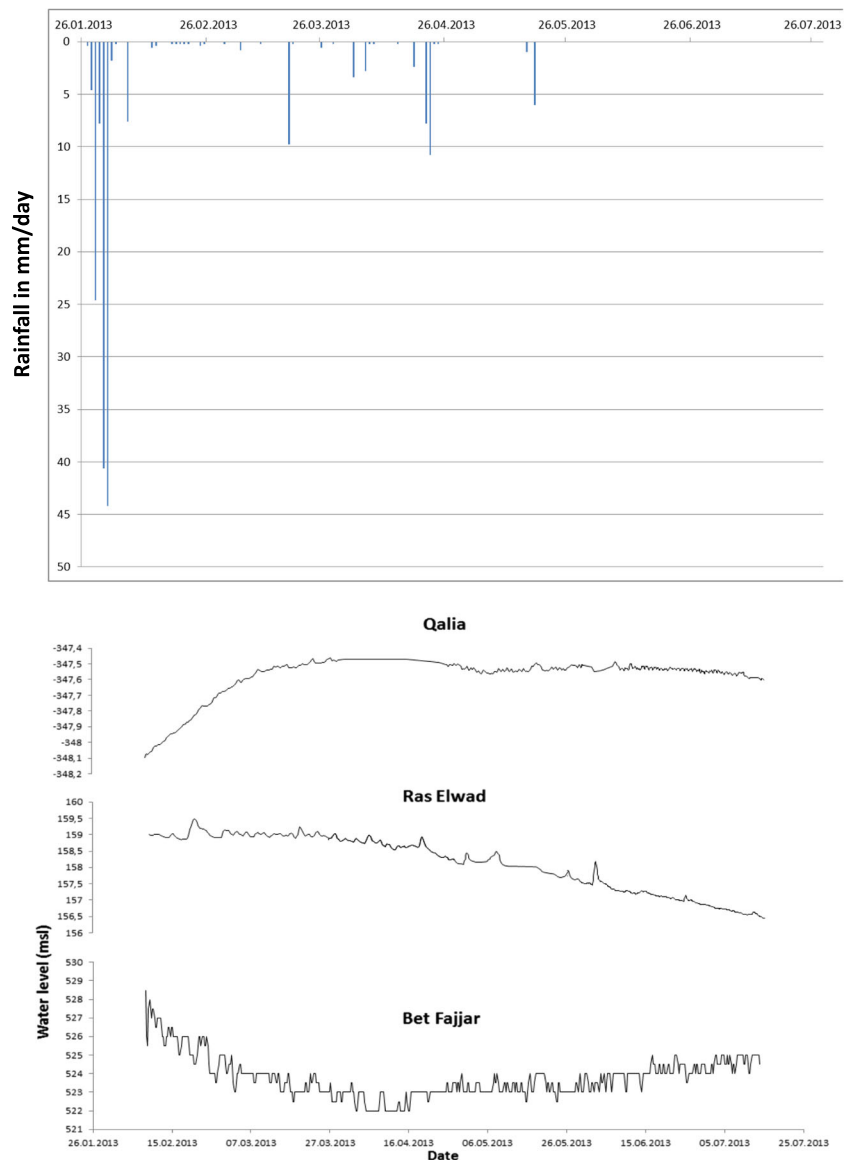
upper aquifer and in certain places, it overflows from one syncline to an adjacent one (Ben-Itzhak and Gvirtzman, 2005a). This process traps the groundwater for a longer time within the folded structure in a manner that allows both the movement of infiltration and water exchange between both the upper and lower aquifers. However, the direction of groundwater movement between both aquifers is highly dependent on the hydraulic presser in wet and dry seasons. The other hydraulic process controlling this aquifer is quick flow of the groundwater due to steep hydraulic gradient by the end of the wet season. This results in a high discharge through the springs along the Dead Sea shore and as subsurface leakage into the Dead Sea group aquifer while crossing the rift faults (Ben-Itzhak and Gvirtzman, 2005b). The relation between this aquifer and the Dead Sea springs is described in the next section.

Isotope signatures from the Dead Sea spring group

The isotopic signature for the Dead Sea springs lie also within those signatures of upper aquifer groundwater. However, mixing of Dead Sea brackish water for Qalia and Feshkha springs causes further enrichment in $\delta^{18}\text{O}$ signatures which reach 4.9‰ in Qalia. En Gedi shows relatively freshwater input with the closest $\delta^{18}\text{O}$ signature to the upper aquifer 1 (Fig. 4). The cations and anions in the groundwater from the springs show the highest values as a result of mixing with Dead Sea brine. The springs show tritium units that are varied from 0.15 to 1 TU depending on the mixing rate between fresh upper water and brackish Dead Sea water (Fig. 5).

Moreover, the presence of the Eljaqma syncline, Qarn Hajar anticline, and Jericho syncline, with the steep gradient

Fig. 7 The diver reading between the period from 26 January 2015 to 25 July 2013 in Qalia (Dead Sea spring), Ras Elwad (lower aquifer), and Bet Fajjar (upper aquifer)



slope to the Dead Sea, facilitates the quick leakage of water from the upper aquifer to the Dead Sea springs (Fig. 1).

The rate of discharge from the upper aquifer to those spring groups varied seasonally, where it reached its maximal level by the end of the winter season in March–April and then the discharge rate is lowering (Fig. 7). The divers' reading taken from Qalia as an example on the Dead Sea spring group, Ras Elwad as lower aquifer wells, and Bet Fajjar as upper aquifer well reflects such seasonal relation that can be clear between the spring and the upper aquifer well (Fig. 7). The main huge rainfall events in the study area normally occur by the end of January to March. Reasonable height for both aquifers is normally noticed a short time after the rainfall event. However, the groundwater levels for the upper aquifer show a significant fast response which is quickly reflected as a high discharge from the Qalia spring in the Dead Sea. It is important to mention that the recharge area for the Qalia spring could be wider and extend to the Jerusalem Ramallah mountain area; however, such measurement can reflect the direct connectivity between the upper aquifer and the Dead Sea marine and sub-marine springs. This quick discharge can also explain the reason of the drying of many of the wells that has dogged the upper aquifer layers in the past decade.

Conclusion

This study used stable isotope hydrochemistry and hydraulic data to describe the relation between different aquifer systems in the eastern slope of Bethlehem Hebron to the Dead Sea.

The results indicate different recharge processes that occur within different aquifer layers and through geological structures. The isotopes emphasize the previous finding about the role of the structure, mainly, the extensively folded anticlinorium that forces groundwater to flow through synclinal axes up- and downward, with different recharge mechanisms. While the lower aquifer received a limited direct recharge from the exposed Bet Kahil formation in the upper mountain, some of the upper aquifer groundwater seeping down through structural axes and faults fed the lower aquifer with additional amount of water. This process is attributed to the lowering of hydraulic status of the aquifer that varied seasonally. On the other hand, the direct recharge for the upper aquifer can be enough unless a huge amount of water from the upper aquifer seeps down due to steep hydraulic gradient to the Dead Sea springs. This process is apparently responsible for the quick draw down of the groundwater level besides the drying of some wells drilled recently in the upper aquifer layers.

As has been described before, the study area is suffering from an acute water shortage especially in the summer time. In

the last decade, many wells have been drilled in the study area to meet the increased population and water shortage demand. However, the safe yield for those wells decreased in the mean of time and many of those wells, mainly those drilled in the Upper aquifer, dried 3 years after operation. Nowadays, some of the functional wells that were drilled in the upper aquifer show rapid decrease in the water level in summer time, and then, it is completely dried by the end of the summer period (personal measurements). Moreover, other wells that were dug in different places within the study area have been stopped after less than 3 years of operation due to limited recharge especially to the upper aquifer layer.

Delineating the relations between different aquifer systems within the study area can give further explanation and help the stakeholders to manage the water shortage problem, taking into account the main finding about aquifer relations in the future plans.

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References

- Barbieri M et al (2005) Stable isotope (^2H , ^{18}O and $^{87}\text{Sr}/^{86}\text{Sr}$) and hydrochemistry monitoring for groundwater hydrodynamics analysis in a karst aquifer (Gran Sasso, Central Italy). *Appl Geochem* 20: 2063–2081
- Barbieri M et al (2017) Groundwater mixing in the discharge area of San Vittorino Plain (Central Italy): geochemical characterization and implication for drinking uses. *Environ Earth Sci* 76(11):393
- Ben-Itzhak LL, Gvirtzman H (2005a) Groundwater flow along and across structural folding: an example from the Judean Desert, Israel. *J Hydrol* 312(1):51–69
- Ben-Itzhak LL, Gvirtzman H (2005b) Groundwater flow along and across structural folding: an example from the Judean Desert, Israel. *J Hydrol* 312(1–4):51–69
- Clark I, Fritz P (1997) Environmental isotopes in hydrogeology. CRC Lewis Publishers, Inc., New York
- Flexer A et al (2003) A 3D hydrogeological model of the Marsaba Feshchah region. Final report. Project no. WT004, Tel-Aviv, Israel
- Florkozski T (1981) Low-level tritium assay in water samples by electrolytic enrichment and liquidscintillation counting in the IAEA laboratory. In: Proceedings of the International Symposium on Methods of Low-Level Counting and Spectrometry. IAEA, Vienna, p 558
- Gat JR et al (1981) Stable isotope hydrology :deuterium and oxygen-18 in the water cycle : a monograph prepared under the aegis of the IAEA/UNESCO Working Group on Nuclear Techniques in Hydrology of the International Hydro-logical Programme / scientific editors: J.R, Gat, R. Gonfiantini. Vienna, International Atomic Energy Agency
- Gräbe A et al (2013) Numerical analysis of the groundwater regime in the western Dead Sea escarpment, Israel + West Bank. *Environ Earth Sci* 69(2):571–585

- Guttman J, Zuckerman H (1995) Flow model in the eastern basin of the Judea and Samaria hills. Tel-Aviv: Tahal Consulting Engineers Ltd 1(95):66
- Gvirtzman H (2006) Groundwater hydrology and paleohydrology of the Dead Sea rift valley. *Geol Soc Am Spec Pap* 401:95–111
- Hoefs, J. (2008) *Stable Isotope Geochemistry*, 6th Edn. Springer-Verlag, Berlin Heidelberg
- Khayat S et al (2006) Hydrochemical investigation of water from the Pleistocene wells and springs, Jericho area, Palestine. *Hydrogeol J* 14(1–2):192–202
- Kronfeld J et al (1990) Natural isotopes and water stratification in the JUDEA group aquifer (JUDEAN DESERT). *Isr J Earth Sci* 39(2–4): 71–76
- Lange T, Hammerschmidt K, Friedrichsen H, Marei A, Weise SM (2008) Groundwater in the shallow aquifer of the Jericho area, Jordan valley—noble gas evidence for different sources of salinization. *Climatic Changes and Water Resources in the Middle East and North Africa*. Springer, Berlin, Heidelberg, p 469–495
- Nazer DW et al (2008) Water footprint of the Palestinians in the West Bank1. *JAWRA J Am Water Res Assoc* 44(2):449–458
- Palestinian Water Authority (PWA) (2012) Water supply report for the year 2010. West Bank, Palestinian Territories, Ramallah
- Petitta M et al (2010) Hydrodynamic and isotopic investigations for evaluating the mechanisms and amount of groundwater seepage through a rockslide dam. *Hydrol Process* 24(24):3510–3520
- Plastino W et al (2007) Tritium in water electrolytic enrichment and liquid scintillation counting. *Radiat Meas* 42(1):68–73
- Rosenthal E et al (1990) Definition of groundwater flow patterns by environmental tracers in the multiple aquifer system of southern Arava Valley, Israel. *J Hydrol* 117(1–4):339–368
- Rosenthal E et al (1981) Hydrogeological interrelationship between the Judea Group and the Nubian Sandstone Aquifers in Sinai and the Negev. *Isr J Earth Sci* 30(4):145–153
- Shalev E, Yechieli Y (2007) The effect of Dead Sea level fluctuations on the discharge of thermal springs. *Isr J Earth Sci* 56:19–27
- Stanislavsky E, Gvirtzman H (1999) Basin-scale migration of continental-rift brines: paleohydrologic modeling of the Dead Sea basin. *Geology* 27(9):791–794
- Unterweger M (1980) Preparation and calibration of the 1978 National Bureau of Standards tritiated-water standards. *Int J Appl Rad Isot* 31(10):611–614