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Chapter

Mapping the Stable Isotopes to Understand the Geo-Structural Control of Groundwater Recharge and Flow Mechanisms (Case Study From the Northeastern Basin of the West Bank)

Saed Khayat, Amer Marei and Zaher Barghouthi

Abstract

Conventional stable isotopic technique was used to differentiate between the potential recharge sources and mixing and flow mechanisms in the Northeastern basin of the West Bank. The isotopic signatures from deep wells show two main fingerprints with respect to recharge sources and mechanisms. These are wells located in the upper part of the Faria fault system and along the Rujeib Moncline which are fed by triggered water in-line the fault system in the south and deep wells surrounded by the Anabta anticline to the west which are fed by the exposed Jerusalem-Hebron formations. This suggests a mixing process with freshwater sources that mainly flow to the system from southern mountains. The isotopic signatures from the shallow well in Marj Sanoor wells and Nassariyeh in the upper Faria well suggest a kind of partial recharge from the Marj Sanoor Lake leaking to the upper Faria Graben area and participating in the recharge process of these wells. The whole finding out of this project might be used for tuning and revision of the groundwater model that has been built by the Palestinian Water Authority.

Keywords: isotope hydrology, Palestine, Northeastern aquifer, recharge mechanism, groundwater salinity

1. Introduction

Providing the Palestinian people with their water needs is the main concern for the Palestinian Water Authority, Ministry of Agriculture, as well as for water service providers. During the last 20 years, the annual average water consumption from the Northeastern aquifer reached 25 MCM [1]; this is due to improvement of water infrastructure including drilling new domestic deep wells, improvement of water institutions, and increase in the public awareness.

Tapping of groundwater, using spring water, purchase of water from Mekerot Israeli Company, and collection of rainwater are the sources for domestic and agricultural water in the West Bank. In this context, groundwater is the main one which

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covers about 70% of the total water supply which is about 100–145 MCM/a from the three water basins in the West Bank, namely, Eastern, Western, and Northeastern (the study area) [1]. During the last two decades, many domestic deep wells were drilled in the Mountain Aquifer in order to improve domestic water supply, where hundreds of illegal groundwater boreholes are drilled in the shallow aquifer systems mainly in Jenin and Jericho districts.

The Mountain Aquifer system with its three groundwater basins, namely, Western, Eastern, and Northeastern basins, covers most of the West Bank area (**Figure 1a**). The Western and Eastern basins cover the western and eastern parts of the West Bank and extend from Hebron in the south to Jerusalem and Ramallah in the north, while the Northeastern locates in the northern part of the West Bank, within the boundary of Nablus-Beit Qad syncline. About 410,000 Palestinians are living in three main districts (Nablus, Jenin, and Tubas), within the surface catchment area of this basin. These districts include large cities such as Nablus, Jenin, Tubas, and Tammon, beside many small municipalities, villages, and refugee camps [2].

Due to the fact that groundwater is the main source of water in the West Bank, management of this source is a high priority by line ministries, so solid and advance scientific knowledge is essential for sustainable management of the water resources [4]. Identification of recharge-discharge zones, groundwater flow regimes, connection between sub-basins, as well as shallow and deep aquifer systems are vectors for better management process. Applying environmental stable isotopic is a method in hydrogeology that is used to help in identification of these vectors, so we use $O^{18}_{[SMOW]}$ ‰ and D in the Northeastern Basin (NE Basin). We also combined the isotope analysis method, with the geological and hydrogeological setting of the sub-catchment areas [5]. High attention is given to the role of the main structural features of the groundwater flow regimes.

Recharge mechanisms, flow direction, and groundwater resident time are generally quite difficult to measure directly. Measurement of recharge flow can be exacerbated by preferential flow (i.e., macropore flow) in the unsaturated zone, although preferential flow paths are of greatest concern as potential conduits for rapid contamination of aquifers. The above factors, in addition to

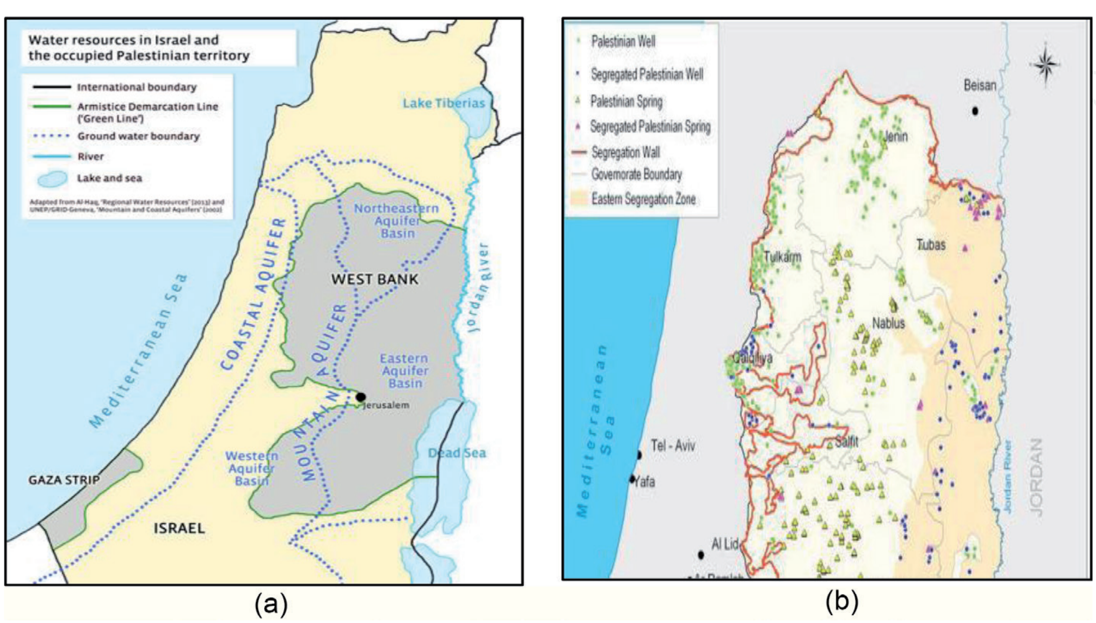

Figure 1.
(a) Location of the Northeastern Basin and (b) urban zones in the NE basin catchment area [3].

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temporal and spatial variability, greatly complicate the estimation of basin-wide recharge rates and flow mechanisms. Estimation methods include use of water budgets, tracers, geophysics, and simulation models. Because of the inherent uncertainties in any method, it is often advisable to apply multiple techniques for any study.

Isotopes as tracer's isotopes for mapping the groundwater recharge and flow mechanisms are important tools in groundwater research and in sustainable management of groundwater resources. Important applications in shallow and deep groundwater include estimation of groundwater recharge and evaluation of the fate of contaminants, because meaningful groundwater deviation from the local meteoric water line LMWL gives the possibility to determine the residence time of groundwater and the dissolved contaminants [6–8].

2. Hydrogeological settings in NE Basin of the West Bank

Sedimentary rocks of the Upper Cretaceous to Quaternary ages cover most of the surface areas of the West Bank. Old rock formation exposed deep eroded area at the top of the anticlines or in deep wades and along some structural features (**Figure 2a**). The development of the structural features took place during the Late Upper Cretaceous-Tartary ages, where many structural features are still active. In the study area, two anticlines and one syncline in addition to the Faria Graben are main structural features. The Anabta anticline with northwest direction, parallel to the Faria anticline with northeast axis direction, borders the study area from the west and east, respectively, where the lines at the top of booths consider as surface/sub-surface water divide. Nablus-Beit Qad syncline with northeast axis direction locates between the two anticlines [9]. Due to the erosion process, the top of the anticlines is eroded, where rock formation of Cenomanian age crops out at the top of Faria and Anabta anticline, where carbonate rock of Eocene to Quaternary ages covers the central part of Nablus-Beit Qad syncline (**Figure 2b**).

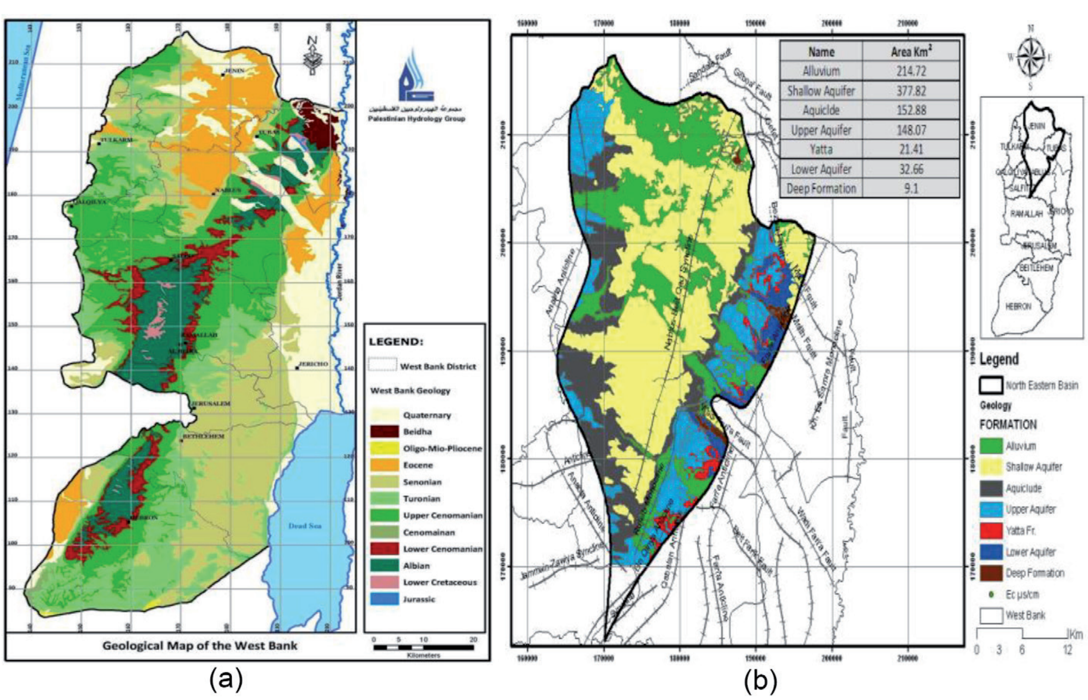

Figure 2.
(a and b) Geological map of the West Bank and NE Basin.

2.1 Stratigraphy

The stratigraphy sequences of the sedimentary rocks are the following from youngest to the oldest (**Figure 1b**) [10]:

2.1.1 Alluvial deposits (Quaternary to recent age)

It consists of alluvial deposits, mainly sand and gravel in flat and depression areas within the syncline. Brown earth Rendzina is the dominant soil type. The alluvial deposits cover an area of about 215 km^2 and normally overlay the Jenin subseries formation (**Figure 2b**).

2.1.2 Jenin subseries (Eocene age)

It consists of six members: relief limestone, nummulitic limestone, karstified limestone, limestone, and chalky limestone. The thickness of this subseries varies from one site to another depending on the location within the syncline but generally range between 100 and 300 m. The series is considered as a local shallow aquifer system that is used mostly in the agricultural sector. The majority of the springs in the NE Basin drain water from this aquifer; in addition to that, most of the groundwater boreholes (up to 350 m depth) in Jenin governorate are tapping water from this system. This rock formation covers an area of about 378 km^2 (**Figure 2b**). This formation overlays the Abu Dis formation in the central part of the syncline, where the Jerzim Group crop outs in the southern part of Nablus city.

2.1.3 Jerzim group (Maastrichtian age)

This group crops out in Jerzim Mountain 832 m above sea level within the southern part of the syncline to the south of Nablus city. It consists of chert nodules, chalk, and chalky limestone. The thickness is about 400 m. This group is considered as a local aquifer, where many springs in Nablus city drain water from this formation along the contact line between this layer and the underlying Abu Dis chalk unit.

2.1.4 Abu Dis unit (Senonian age)

It is composed of a massive thick hard chalk unit, interbedded with two bands of highly fractured cherty layers with a distance of 2–5 m between the two bands; the material of the upper part of unit l becomes soft and unclear in bedding. The unit exposes to the surface over the anticline flanks (**Figure 2b**) with a thickness range between 100 m at the edges and 500 m in the middle of the syncline. This unit is considered as an impermeable layer that separates the shallow Eocene aquifer from the underlying Jerusalem formation that is considered as the upper part of the Upper Mountain Aquifer system. The chalky units cover an area of about 153 km^2.

2.1.5 Jerusalem formation (Turonian age)

This formation consists of thin-bedded highly fractured limestone and dolomitic limestone. The lower part consists mainly of rosy limestone, where oyster fossil could be found at the top of this formation with variable thickness range between 70 and 150 m thick. This formation is cropped out mainly over the anticline and considered as recharge zone, where below the central part of the syncline consider as good aquifer. This formation overlays the Bethlehem formation (**Figure 2b**, Upper Aquifer).

2.1.6 Bethlehem formations (Upper Cenomanian age)

This formation consists of 50–120 m of thin-bedded limestone and marly limestone which is highly karstified. Large caves and voids are common phenomena within this formation. This formation outcrop also covers the anticline flanks, and considers as the Jerusalem formation as good aquifer in the central and western part of the basin (**Figure 2b**, Upper Aquifer).

2.1.7 Hebron formations (Upper Cenomanian age)

It consists of 105–250 m of thick bedded limestone and dolomite; it is highly fractured and karstified. This formation is cropped out also over the anticlines flanks and in deep eroded Wadis like Wadi Al Faria (**Figure 2b**), in these sites; it considers are recharge zone, where within the syncline consider as a target layer for groundwater subtraction.

2.1.8 Yatta formation (Lower Cenomanian age)

It is composed mainly of marl and marly limestone; this formation is considered as an aquiclude in the southern part of the West Bank and separates the Upper from the Lower Aquifer system, but in the study area, this formation is more of limestone than marl and crops out at the flank of the anticline and is considered as part of the Upper Aquifer system.

The catchment area of the Upper Aquifer system (Jerusalem, Bethlehem, and Hebron formation) is about 148 km^2, where the area of Yatta formation is about 21 km^2. Together, Jerusalem, Bethlehem, and Hebron formation build up the Upper Aquifer system of the Mountain Aquifer system and are separated from the Lower Aquifer system through impermeable marl layer of Yatta formation of Lower Cenomanian age. Older formations such as Upper and Lower Beit Kahel do not out crop in the study area.

2.1.9 Upper Bet Kahel formation (Albian)

It consists of a 160–190-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 calcite massive limestone near the base.

2.1.10 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.

Both formations are considered as Lower Aquifer system of the Mountain Aquifer in the southern part of the West Bank, but in the northern part of the Upper and Lower Aquifer system, they are considered as one hydrological system. The outcrop area of the deep aquifer system is about 33 km^2. The two formations crop out also in deep eroded streams within the Faria anticline as well as within the Faria Graben.

2.2 Hydrology

Rainy months extend from October to May, where 70% of the rainfall takes place between December and February. **Figure 3** shows the rain fall distribution during

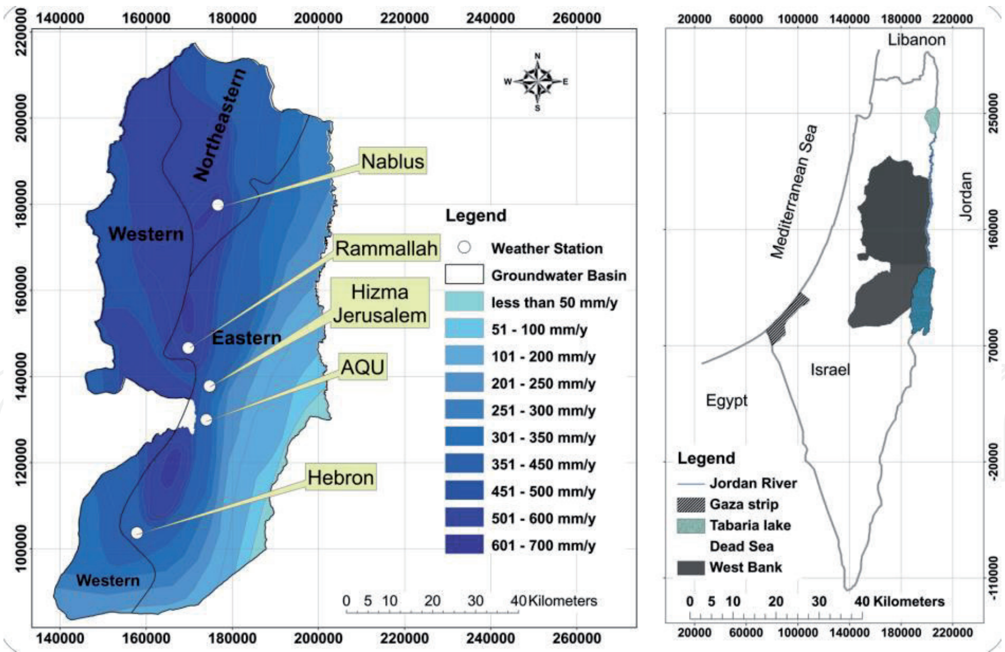

Figure 3.
Actual average rainfall in the West Bank in the hydrological year 2010/2011.

the hydrological year 2015/2016, where three high rainfall zones are identified namely within the boundary of the basin, these are north of Nablus, Selet al Thaher with 600 and 800 mm/a respectively [11]. It's also noticed that rainfall decreases in the eastward direction of the Faria Graben which locates more within the rainfall shadow site (**Figure 3**). The average monthly temperature during December, January, and February is 11, 14, 17°C. respectively; this indicate that the losses of water through evapotranspiration is relatively low during these months which improve the groundwater recharge rate [12].

2.3 Groundwater aquifer systems

The Northeastern Basin covers 959 km^2 of surface area (**Figure 1b**), depending on surface water shed divide; within the basin, two aquifer systems are identified; Mountain Aquifer with rock layers related to the Upper Cretaceous age, and shallow aquifer with rock layers related to the Tertiary-Quaternary eras (Eocene-Miocene age). Both systems are hydraulically separated from each other in most of the basin especially in the central part but seems to be connected where deep structural features strike the rock layers of both systems, such as in Al Faria Graben [13].

Recharge process for both aquifer systems takes place wherever the rock formation is outcropped and exposed directly to the rainfall or underlying thin soil layers. Marei et al. estimate the groundwater recharge rate, by using chloride mass balance method for the study area, of about 95.2 and 269.7 mm/year, with a total average recharge volume of 138.5 MCM/year (**Figure 4**) [14], while the total calculated recharge rate by the previous study of the authors is 107.1 MCM/a [14]. Recharge rate can be higher than estimated when karstic and high fractured rock layers are cropped out at the surface such as the formation of the Upper and Lower Mountain aquifer system at the two anticline flanks in the west and in the east, in the other hand ground recharge decrease to about zero from Abu Dis formation "Chalky Unit". The formation of shallow aquifer system is exposed mainly in the central part of the basin, and water body responds quickly to rainfall.

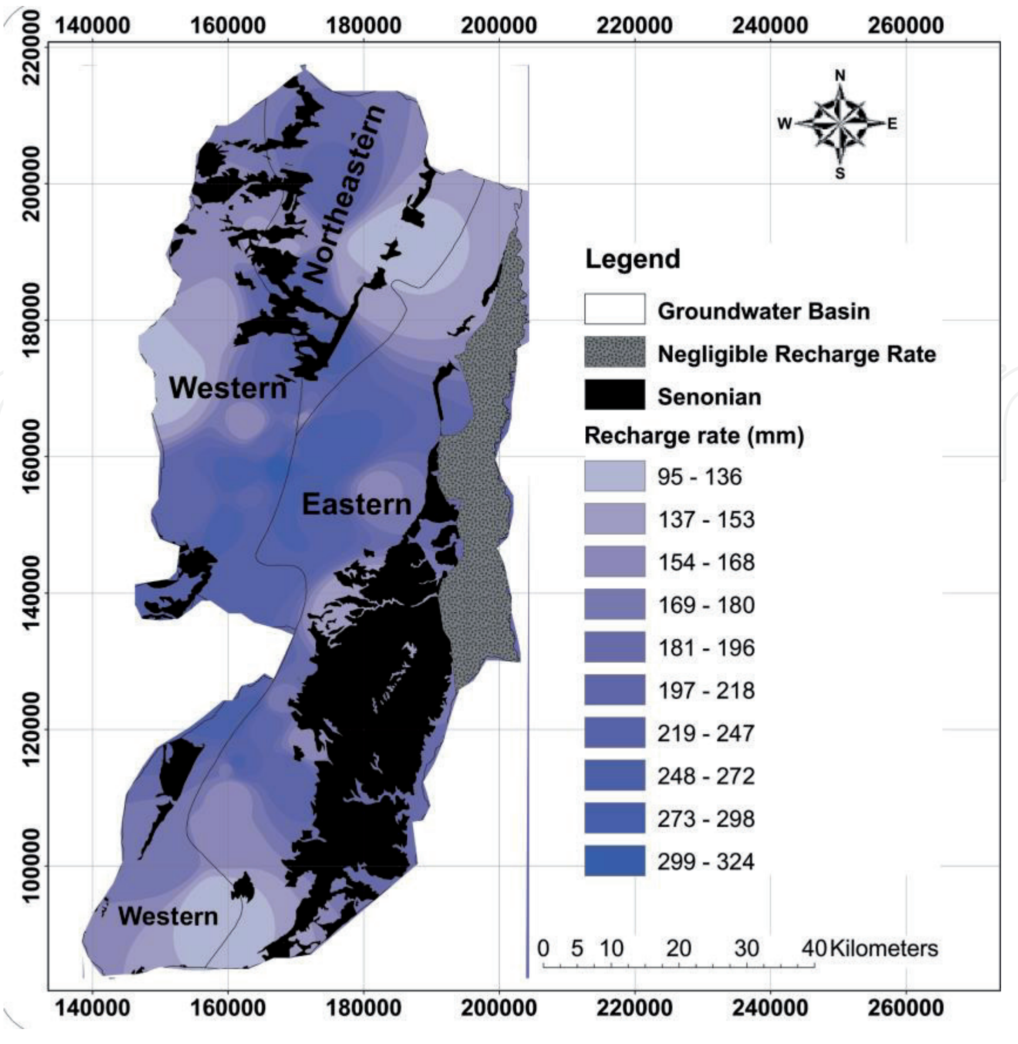

Figure 4.
Recharge rate over the West Bank including the NE Basin (Marei et al., 2011).

	Mountain Aquifer "Cretaceous age"		Shallow Aquifer "Eocene"
	Eastern flank of "Anabta anticline"	Western flank of "Al Faria anticline"	Nablus-Beit Qad "syncline"
Outcrop area with km^2	60	95	378
Recharge rate	210 mm/year	210 mm/year	200 mm/year
Recharge volume	12.6 MCM	19.9 MCM	75.6 MCM
Total recharge in MCM/a	32.5 MCM		75.6 MCM

Table 1.
Recharge volume of NE Basin.

Table 1 summarized the recharge volume of the deep and shallow aquifer systems depending on the chloride mass balance method [14].

2.4 Groundwater flow regimes

Two main groundwater flow regimes are assumed to present in the study area. These are as follows: a SW-NE main groundwater flow direction parallel to

Nablus-Beit Qad syncline axis with historical discharge site in Hiteen and Ein Jaloot spring and a flow direction from both anticline flanks (Anabtaa, and Al Faria) to the center of the syncline which joins the NE flow direction; these flow directions take place within the Mountain Aquifer system [15, 16]. Addition flow direction to the southeast is governed through Al Faria fault system "Graben" that diverted groundwater to flow in this direction [17].

3. Methodology

Integrated isotopic tools were used to investigate the effect of complex geologic structure on the groundwater residence times and respective potential sources, mixing, and recharge mechanisms [18]. In order to achieve the abovementioned objectives, 82 groundwater samples were obtained from different areas in the Northeastern basins. The samples represent 8 springs, 20 wells from shallow Eocene aquifer in the plain zone of the study area, 7 wells in Sanoor swamp area, 10 shallow wells in Nassariyeh area in the upper part of Wadi Faria stream, 20 wells from the lower part of Faria stream, and 17 deep aquifer wells within and near the flanks of the NE basin (**Figure 5**). All samples were taken in the hydrological year 2017/2018. Several rainwater samples were obtained from rain gauges' stations that were constructed on the roofs of some schools all over the study area.

Groundwater samples for deuterium and $\delta^{18}O$ isotopes have been taken from the mentioned wells and spring. Samples for deuterium and $\delta^{18}O$ isotopes were collected with 25 ml bottles and sent to the Al-Quds University research lab for analysis. Samples were analyzed using laser spectroscopy for deuterium and $\delta^{18}O$ in ‰ in respect to Vienna Standard Mean Ocean Water (V-SMOW) standard; the precision of $\delta^{18}O_{[SMOW]}$ ‰ measurements is ±0.1‰; the precision of δD values is ±2‰ [19].

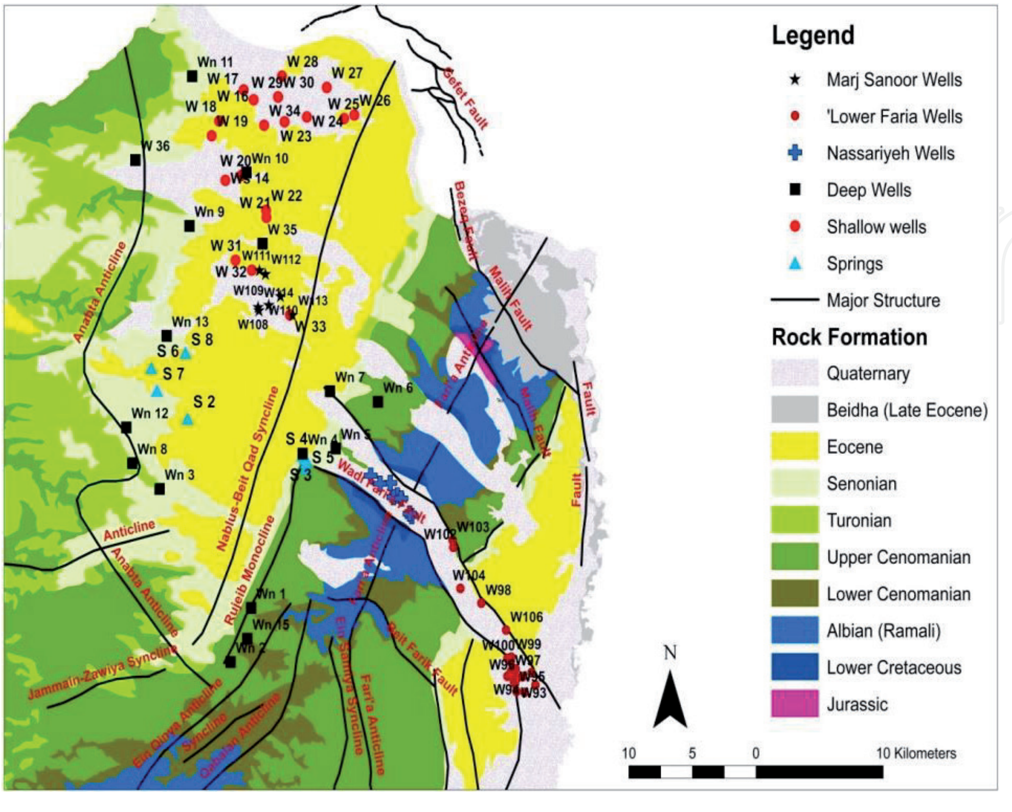

Figure 5.
The study area including all the sampled wells and springs, including rock formations and structure.

4. Results and discussion

4.1 Results overview

The local meteoric water line shows the same slope for the Mediterranean Meteoric Water Line but with more enriched deuterium excess. This might refer to the formation of a large swamp lake in Sanoor area which resulted from the inundation from the runoff drained to the area from the surrounded mountains causing high humid conditions in the area (**Figure 6**).

The data show a wide range of isotopic signatures, which reflects wide variations with respect to recharge mechanisms and groundwater flow directions.

Figure 5 shows the distribution of sampled wells and different geological structures that control the hydrology of the region. As it is mentioned above, the structural geology is highly controlling the hydrological flow system in the region. The main structure that might play an important role in this regard is the Faria fault system which might control the groundwater flow regime in the eastern part of the NE Basin.

Spring systems in both locations (Bathan in the east and Nablus in the north west) show closed signatures to the local meteorological line, which indicate rapid freshwater input; the other end member of shallow wells within the middle of the syncline shows the most enriched signatures (**Figure 6**).

Other wells, which show signatures in between, have different recharge mechanisms which need to be separated in details with respect to isotopic signature from each group.

The following sections illustrate the relations between different aquifers as well as the recharge mechanism for each system.

4.2 Deep wells

The isotopic signatures from deep wells show two main fingerprints with respect to recharge sources and mechanisms.

First, the deep wells that are located within the area of the Faria fault system, southern part of the syncline and upper part of Faria fault system, show depleted signatures that are more or less closed to springs and LMWL, while other deep wells reflect high variation in isotopic enrichment with respect to its depth and location

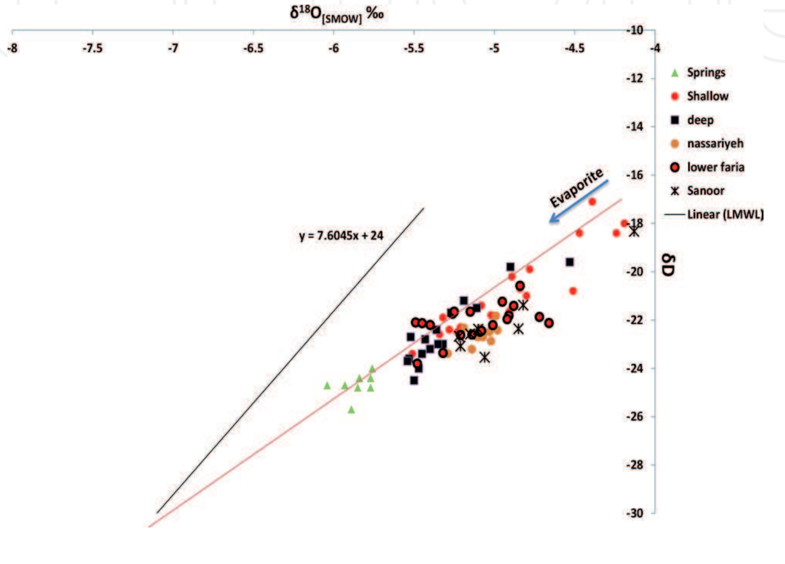

Figure 6.
Deuterium vs. $\delta^{18}O_{[SMOW]}$ ‰ for the whole wells and springs in the study area.

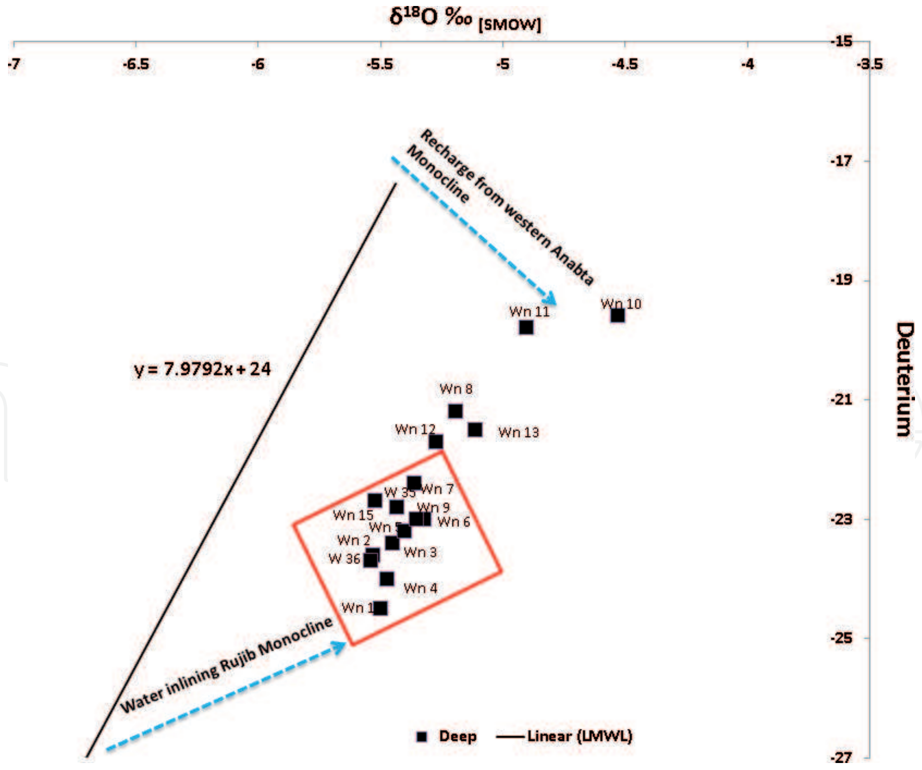

Figure 7.
Relation between $\delta^{18}O_{[SMOW]}$ ‰ and deuterium for the groundwater from deep aquifer shows different recharge mechanisms for each cluster.

(**Figures 6** and 7). Some of the deep wells show obvious close relation to the recharge that feeds the aquifer layers through the exposed Jerusalem-Hebron formations on Anabta anticline (**Figure 7**), where the wells within this area show more enriched $\delta^{18}O$ signatures than those near the upper Faria fault system (**Figure 7**).

The isotopic signatures of deuterium show clear differences between each deep well cluster with an average shifting of 4‰. These differences are more or less related to the recharge locations with different altitudes [20].

The deep wells in the south and upper part of Faria show relatively more depleted deuterium than those deep wells that receive direct recharge from the western Anabta anticline outcrops. The elevation of Anabta anticline in the western part of the basin has an average altitude of 300 m above sea level, while the southern elevation over the mountains in Nablus and Salfit areas to the south, from where the recharge for deep Faria well cluster is expected, reaches an average of 500 m above sea level.

However, the $\delta^{18}O_{[SMOW]}$ ‰ signatures show slight shifting between both clusters, with more slight enrichment for the wells near to the western Anabta anticline that reach around −1‰. This also reflect different recharge mechanisms and different hydrological flow conditions from each source [21].

Figure 8 shows the suggested recharge zones and flow mechanisms for each of deep well cluster.

4.3 Shallow wells

This group of wells can be divided into three major categories according to its locations: shallow Eocene wells that are distributed in the plain area of syncline, Sanoor wells which are belonging to the same previous area but located directly within the area of surface water swamp, and upper Faria (Bathan) shallow wells in Nassariyeh area and lower Faria shallow wells to the southeast.

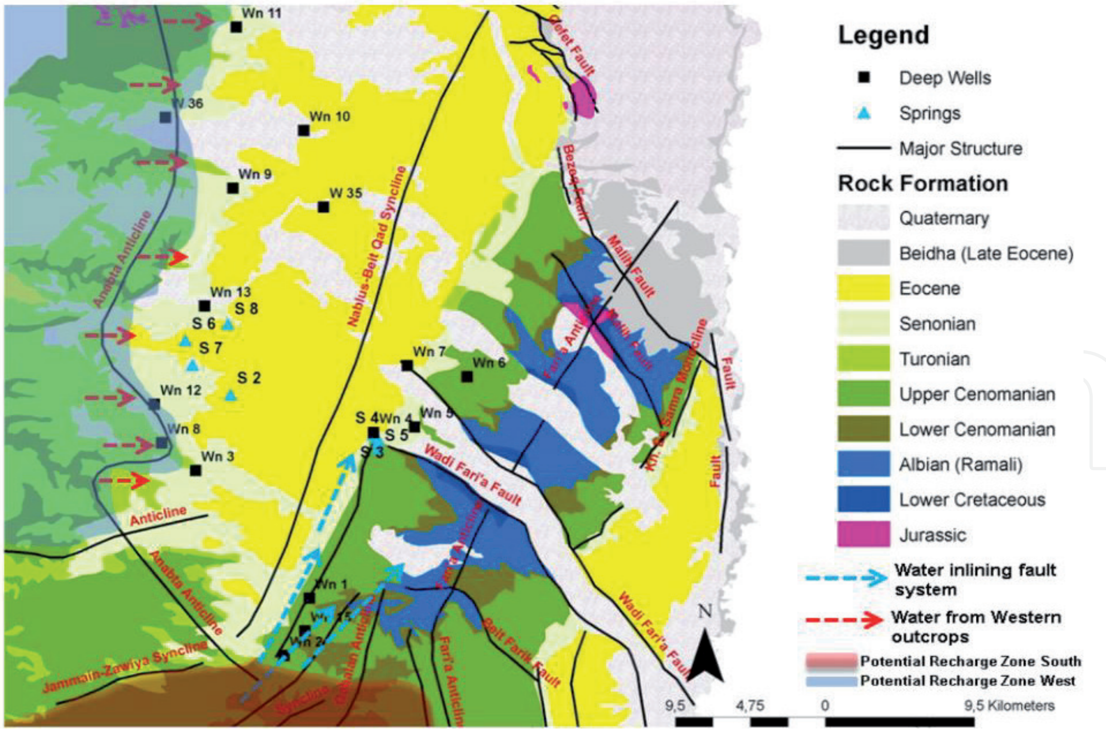

Figure 8.
Suggested recharge zones and flow mechanisms for each of deep well cluster.

According to isotopic signatures from these shallow wells, different recharge mechanisms for each group can be indicated. Also the isotope data reflect some hydrological connections between some groups. The hydrological relations as well as recharge mechanisms can be described with respect to each group.

4.3.1 Shallow wells within the Eocene plain area

This includes the shallow wells that are dug in the Eocene and Quaternary alluvial areas in the northwest of Nablus-Bet Qad syncline (**Figure 5**). Those wells show high evaporation inputs with relatively high TDS content. The $\delta^{18}O_{[SMOW]}$ ‰ and deuterium values for the shallow wells in the Al Jalameh (north) indicate relatively enrichment deviation from the LMWL due to fractionation with the thick soil layer during slow infiltration. For these wells, the $\delta^{18}O_{[SMOW]}$ ‰ values reach −3.5‰ (**Figure 6**). The deviation from LMWL with the slope of 4 indicates an evaporation trend that increases toward the north of the study area where those wells tapped their water from (**Figure 6**).

In general, the problem of water deterioration in this group seems to be connected with the heavy abstraction rate from these wells. The slow replenishment, with such heavy abstraction, increases the evaporite salinity problem [22].

In general, Marj Sanoor wells show relatively enriched $\delta^{18}O$ signatures but less than the rest of shallow wells in the north (**Figure 6**). This might be due to the fact that the aquifer is located beneath the water swamp that is collected in the winter time and infiltrated slowly to the aquifer layers. The integration of the results with the results of other locations shows a connection between the infiltrated surface water from this group with some wells to the southeast as it will be described below.

4.3.2 Shallow wells in Nassariyeh

The shallow wells in Nassariyeh that are located at the beginning of Faria structural faults show the same stable isotopic signatures as Marj Sanoor wells. This

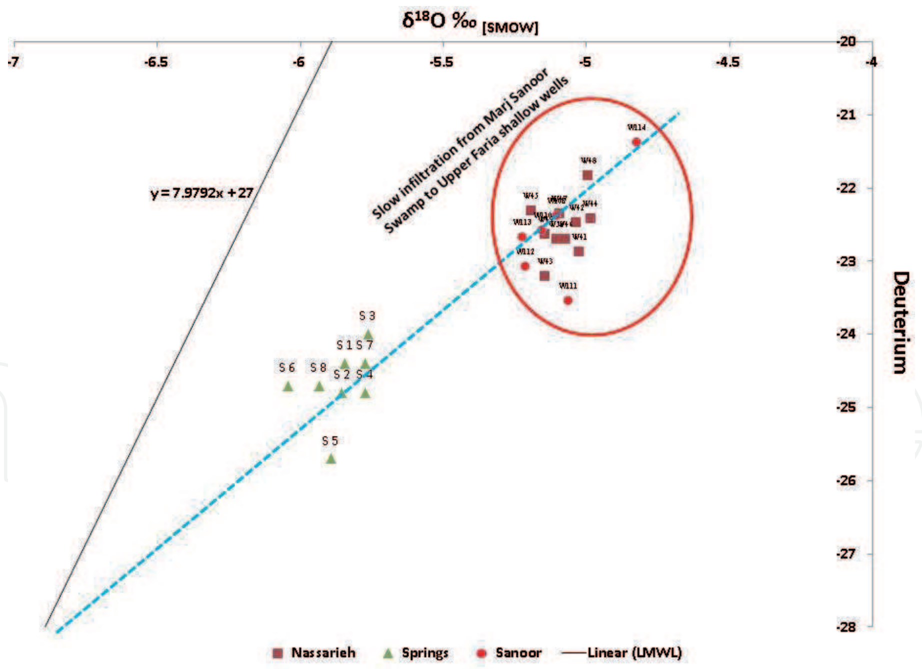

Figure 9.
Relation between $\delta^{18}O_{[SMOW]}$ ‰ and deuterium for the groundwater from Nassariyeh and Sanoor shallow wells.

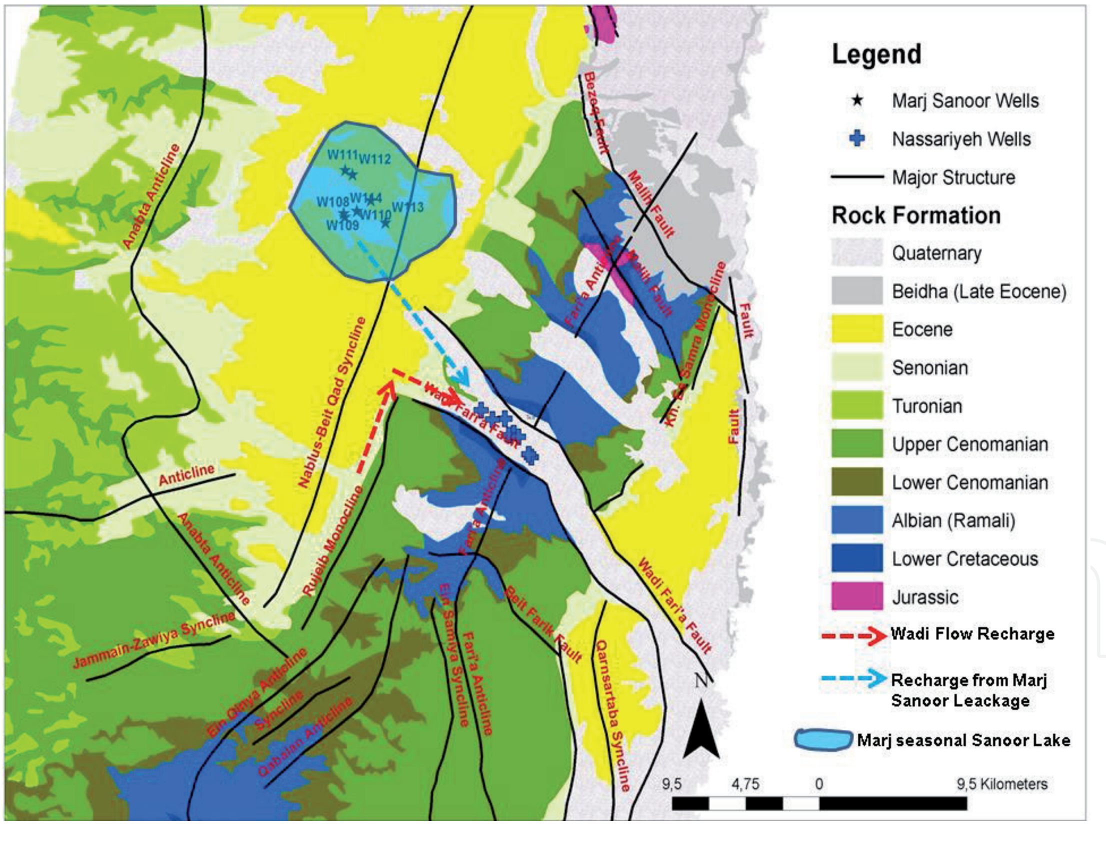

Figure 10.
Suggested groundwater model for the water leakage from Marj Sanoor Lake to the Nassaria and upper Faria wells.

strongly suggests a connection between seeping water from the seasonal Marj Sanoor Lake, which forms by the collected runoff from surrounding mountains in the late winter season to the wells that are located within the upper Faria and Bathan area (**Figure 9**).

The isotopes signatures suggest that the recharge mechanism for these wells is a mixing between water seepage from Marj Sanoor surface water and fresh water that

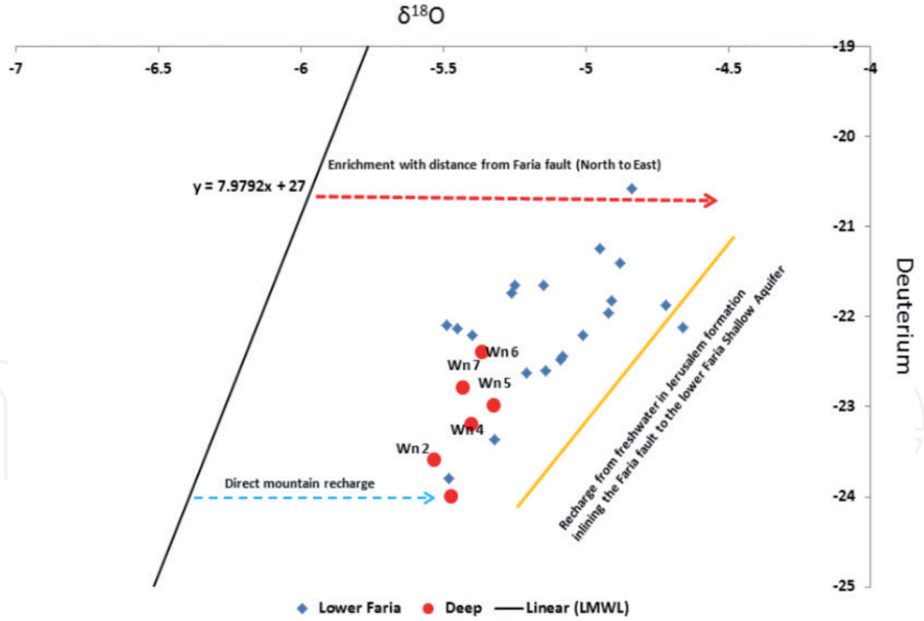

Figure 11.
Relation between $\delta^{18}O_{[SMOW]}$ ‰ and deuterium for the groundwater from deep wells and lower Faria shallow wells.

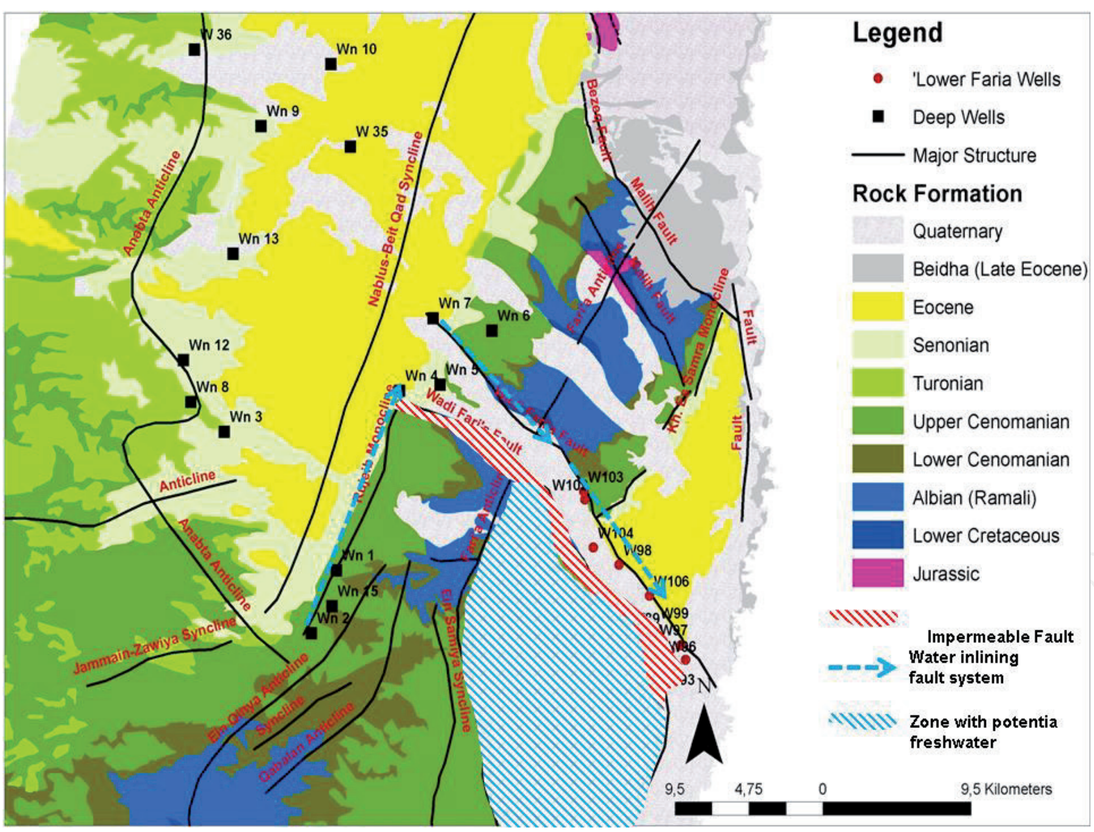

Figure 12.
Model of groundwater recharge and flow mechanisms for the lower Faria wells from different sources.

inline the Faria Fault that triggered from deeper Jerusalem formation, and seeping along the area of Faria Graben (**Figure 10**).

This finding can be used to efficiently utilize the surface water in the syncline area to artificially feed the wells further to the east, keeping the groundwater level in good standing all over the summer season. On the other hand, heavy abstraction from the shallow and deep wells within the syncline area might affect the productivity of Bathan and upper Faria wells.

4.3.3 Lower Faria shallow wells

The isotopic signatures from lower Faria shallow wells suggest strong correlation with the recharge of the deep well in the upper Faria part. Most of the shallow lower Faria wells show the same δ^{18}O and deuterium signatures for the deep wells of Bathan, Faria, Tubas, and Tammoun. This similarity emphasizes the unity of recharge mechanism for both locations which mainly come from Jerusalem formation of Turonian age, that triggered along the northern Faria fault and seeping to the wells drilled within lower Faria plain (**Figures 11** and **12**).

However, the isotopic signatures show enrichment trend with respect to distance from the fault to the middle and the south of the Wadi (**Figure 13**). This emphasizes that the main recharge source for the wells in the lower Faria is coming mainly from the northwest, in-line the Fault system (**Figure 12**).

This also can be an indicator about the limitation of the water recharge from the southern part of the Fault, which suggests in role that most of the recharge in the southern area is drain surfacely and sub-surfacely to the area constrains between the southern Faria Fault and Bet Forik Fault, where the mentioned area must be a good potential for freshwater production with sufficiently high amount.

5. Conclusion and recommendations

The isotopic signatures from deep wells show two main fingerprints with respect to recharge sources and mechanisms. Those are wells located in the upper part of Faria fault system and along the Rujeib Moncline which are fed by triggered water in-line the Fault system in the south and deep wells surrounded by Anabta anticline to the West which are fed by the exposed Jerusalem-Hebron formations. This suggests a mixing process with freshwater sources that mainly flow to the system from southern mountains. However, the impermeability of the southern part of Faria fault system makes this water diverted to the area constrain between the southern

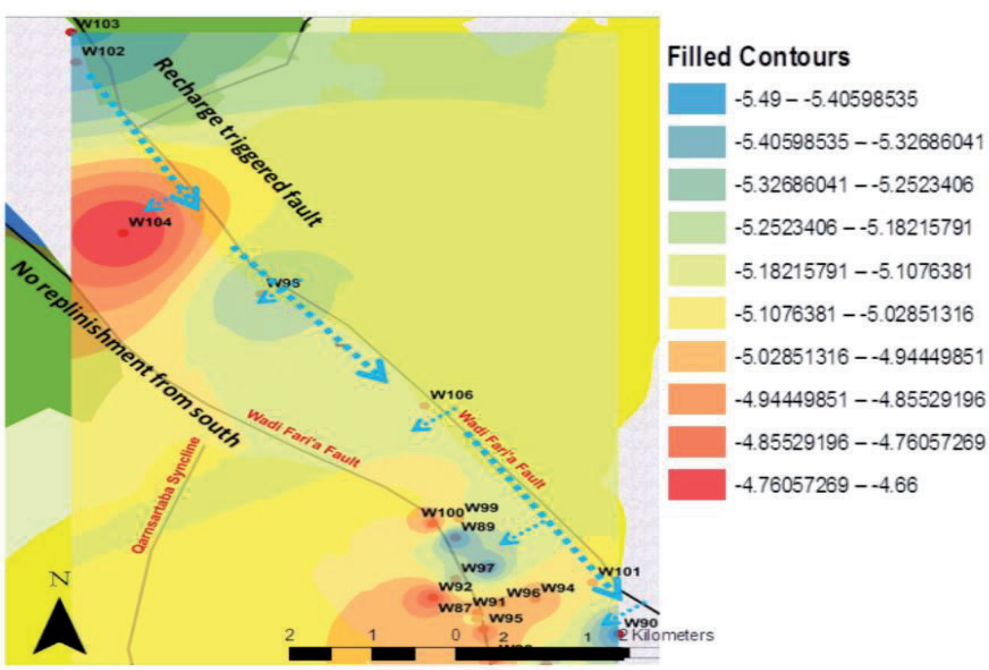

Figure 13.
Spatial distribution of $\delta^{18}O_{[SMOW]}$ ‰ for the shallow wells in lower Faria shows relatively depleted signatures along the fault and more enriched to the center of the Graben.

Faria fault and Bet Forik faults, where the mentioned area must be a good potential for freshwater production with sufficiently high amount (**Figure 13**).

The isotopic signatures from the shallow well in Marj Sanoor wells and Nassariyeh in the upper Faria well suggest a kind of partial recharge from the Marj Sanoor Lake that leaks to the upper Faria Graben area and participates in the recharge process of these wells. This finding can be used to efficiently utilize the surface water in the syncline area to artificially feed the wells further to the east, keeping the groundwater level in good standing all over the summer season. On the other hand, heavy abstraction from the shallow and deep wells within the syncline area might affect the productivity of Bathan and upper Faria wells.

The northern part of the Faria Graben fault which shows a good ability for freshwater transmission from different sources is extended further to the north-west, reaching the syncline area. The area of fault extension can be a good potential source for drilling new wells in the future.

The whole finding of this project might be used for tuning and revision of the groundwater model that has been built by the Palestinian Water Authority. The suggested new flow mechanisms and potential recharge zones can help the Palestinian stakeholders in good planning for the whole Northeastern aquifer system.

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