Environ Earth Sci
DOI 10.1007/s12665-014-3944-8

ORIGINAL ARTICLE

A preliminary investigation of wadi–aquifer interaction in the semi-arid watershed of Faria, Palestine using tracer-based methodology

Atta M. E. Abboushi · Mohammad N. Almasri · Sameer M. Shadeed

Received: 15 March 2014 / Accepted: 5 December 2014

Abstract This paper aims to investigate the potential existence of wadi–aquifer interaction in the 320 km^2 semi-arid Faria catchment using a tracer-based methodology. Faria catchment is located in the northeastern part of the West Bank and accounts for 6 % of the total West Bank's area. Surface runoff in the catchment consists mainly from springs discharge, runoff generated from winter storms, untreated wastewater effluent from the eastern part of Nablus City and Al-Faria refugee camp, and the return flow from the adjacent agricultural areas. As such, wadi–aquifer interaction may pose serious pressures on groundwater quality which is the only water source for the agricultural and domestic uses in the area. In this study, and in order to investigate the potential existence of wadi–aquifer interaction in the Faria catchment, a tracer-based experiment was conducted. The experiment was carried out using Uranine as a conservative tracer material. A representative reach of 600 m was chosen and was divided into four equal distances. A concentration curve was plotted at each section (monitoring point) with the help of OTIS (solute transport model for streams and rivers) which was used to calibrate the measured concentration curves. Accordingly, the flow rates were estimated at the different monitoring points. The obtained results proved that transmission losses took place in the wadi bed sediments of the selected reach and with different ratios. The percent loss in the flow rates' values in the different sections ranged from 4.8 to 68.3 %. It was found that the largest transmission losses took place in the section between the first and the second monitoring points. In conclusion, tracer-based methodology is considered as a modern and innovative technique that was used via this research to understand the nature of the wadi–aquifer interaction in Faria catchment and to quantify it as well.

Keywords Faria catchment · Wadi–aquifer interaction · Semi-arid · Tracer-based methodology · OTIS · Palestine

Introduction, terminology, and literature review

Arid and semi-arid areas account for one–third of the earth's surface area (Huang et al. 2010). Generally, groundwater is often the major water source available for domestic and agricultural uses in arid and semi-arid regions where there is no perennial surface water (Abdin 2006). However, the importance of this source is threatened when groundwater becomes contaminated and its quality is questioned. Groundwater quality in the West Bank is being deteriorated from the effluent of untreated wastewater that comes from cesspits and the leakage from the wastewater collection networks. In turn, the untreated wastewater from sewage networks in general flows freely in the nearby wadis and ultimately can pollute the groundwater (Jayyousi and Srouji 2009).

The wadis system in the arid and semi-arid areas refers to that dry and ephemeral riverbed that contains water only during times of heavy rain. Most of the wadis in the arid and semi-arid regions are losing wadis, since the water

A. M. E. Abboushi (✉) · S. M. Shadeed
Water and Environmental Studies Institute,
An-Najah National University, Nablus, Palestine
e-mail: maher-aboushi@hotmail.com

S. M. Shadeed
e-mail: sshadeed@najah.edu

M. N. Almasri
Department of Civil Engineering, College of Engineering,
An-Najah National University, Nablus, Palestine
e-mail: mnmasri@najah.edu

level of the wadi is higher than the potentiometric head of the underlying aquifer, and so the wadi recharges the aquifer. There are two types of losing wadis: contagious losing wadis where there is a hydraulic connection between the wadi and the aquifer, and perched losing wadis where the hydraulic connection does not exist and in this case the wadi recharges the aquifer through vertical flow (Alley et al. 1999). This later type is the supposed case which exists in Faria catchment. The aquifer system in the region includes both the confined and the unconfined aquifers. This research concentrated on the study of the interaction that might occur from the wadi to the upper unconfined aquifer. The reasons behind this are that the unconfined aquifers are more susceptible to pollution than the confined aquifers. In addition, most of the wells in the study area are agricultural wells which tap this kind of aquifers and are shallow wells.

Effective management of the limited water resources requires a realistic quantification and understanding of the interaction between surface water and groundwater through conjunctive management (Winter et al. 1998).

Faria catchment is one of the most important catchments in the West Bank due to the intense agricultural activities. The agriculture is divided into two main types in Faria catchment; the rainfed agriculture which predominates in the upper part of the catchment such as olive trees and almonds, and the irrigated agriculture which predominates in the middle and lower parts of the catchment such as citrus trees and the most kinds of vegetables. However, the catchment is under water pollution threats and quantity stresses (Shadeed et al. 2011).

Sampling and analyzing water quality for different water resources in the catchment revealed that most of these resources are polluted and contaminated with different levels of potential environmental risks due to the different surrounding pollution sources (Shadeed et al. 2011).

The wadi flow in the catchment consists mainly from springs discharge which flows to the wadi from upstream area (Al-Badan area near Nablus; see Fig. 1), runoff generated from winter storms, the untreated wastewater effluent from the eastern part of Nablus City and Al-Faria Refugee Camp, and the return flow from the adjacent agricultural areas. The polluted wadi flow is of high potential to pollute groundwater bodies in the catchment as a result of considerable transmission losses, which take place in the wadi bed (Shadeed 2008). In essence, this can be attributed to wadi–aquifer interaction where pollutants can migrate freely due to the hydraulic connection between wadi bed and aquifer formation. This situation has compelled the motivation to conduct a preliminary investigation to understand the wadi–aquifer interaction in Faria catchment.

To investigate the wadi–aquifer interaction in Faria catchment, tracer-based experiment was conducted. It was chosen since it is considered as an innovative tool and one of the most modern techniques that is used to understand the flow pathways from the surface water systems to the groundwater aquifer systems (Leibundgut et al. 2009).

There are many studies all over the world which used tracing techniques to address issues like surface water–groundwater interactions. Winter (2006) used a combination of environmental and artificial tracers to investigate stream–aquifer interaction processes in Nahal Oren in Mount Carmel, Palestine. Lange et al. (1997) used tracer techniques to study infiltration losses into a dry wadi bed in a small arid stream channel, NahalShahmon, Palestine. Nikanorov and Trunov (1993) evaluated a new type of fluorescent tracer for studying mass transport in surface water and groundwater in the city of Gorlovka, Ukraine.

Generally, most of the previous studies in the Faria catchment concentrated on studying the hydrologic characteristics of rainfall and runoff in the region (Salahat 2008; Shadeed 2005). Few researches focused on studying the hydrological conditions and infiltration systems and processes in the catchment (Saleh 2009; Shadeed 2008; Ghanem 1999). In another study, Abboushi (2013) proved the existence of wadi–aquifer interaction in Faria catchment through developing quantitative and qualitative relationships of rainfall depths, wadi flows, change in water table levels and groundwater quality data. Those relationships gave evidence that the hydrogeology of the region enhances the interaction to take place between the wadi and the aquifer and proved the existence of a potential recharge to the upper groundwater aquifer.

This research is the first attempt of its kind in the Faria catchment to study the probability of the occurrence of wadi–aquifer interaction through conducting a tracer-based experiment in the catchment.

OTIS is a mathematical simulation model developed by Runkel (1998) that can be utilized to characterize the fate and transport of water-borne solutes in streams and rivers, and it was used in this research to calibrate the measured concentration curves. The use of OTIS model typically involves a trial-and-error approach wherein parameter estimates are adjusted to obtain an acceptable match between simulated and observed tracer concentrations.

There are many studies that used OTIS model to make simulations with observed data to smooth the shape of the observed concentration curves, and to predict the complete shape of the concentration curves based on the input data to the model, so as to conduct the required calculations in a proper way and to quantify the hydrodynamic characteristics of a certain stream or river. Bencala and Walters (1983) described an instream experiment in which chloride was used as a conservative tracer in Uvas Creek; a small pool-and-riffle stream in northern California, and where OTIS model was used to simulate the experimental data to

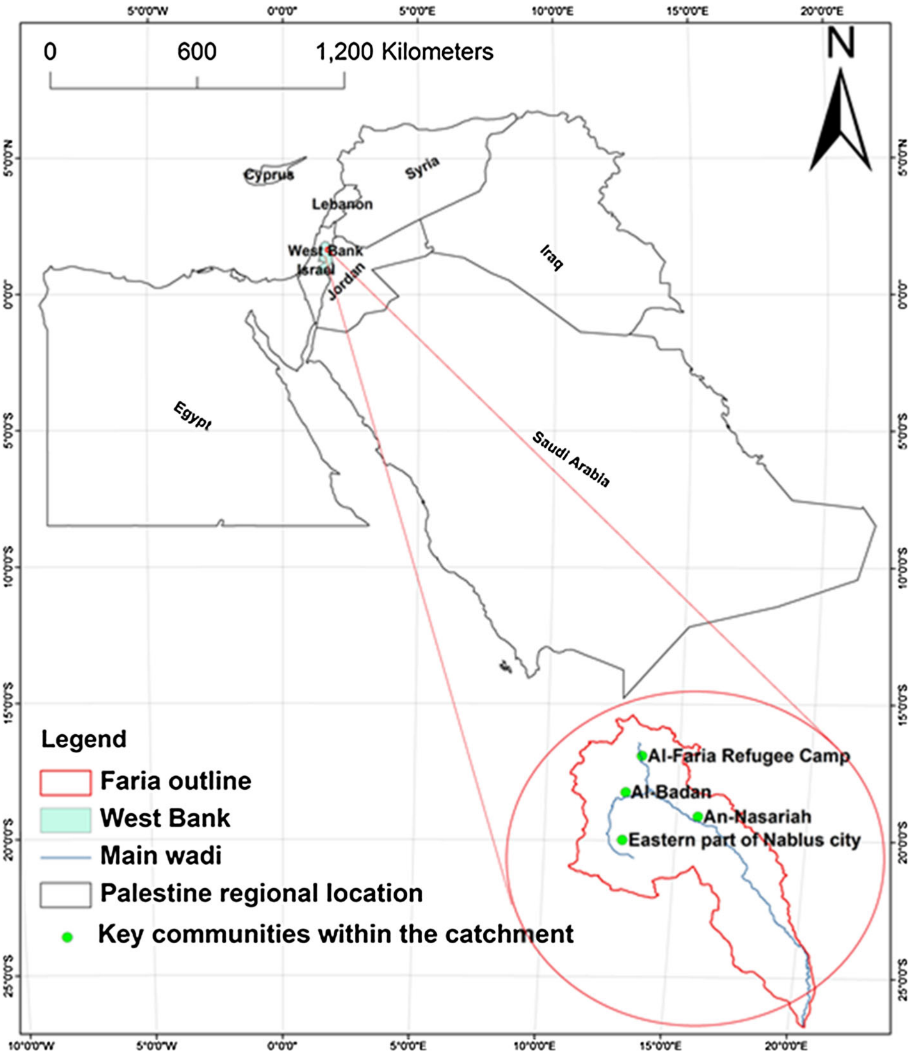


Fig. 1 Regional location map of Faria catchment and the local locations of the key communities within the catchment

quantify some hydrologic characteristics of Uvas Creek. Another solute transport experiment was conducted by McKnight and Andrews (1993) in Huey Creek, a glacial meltwater stream in the McMurdo Dry Valleys of Antarctica, where also OTIS model was used.

Study area

Faria catchment is a 320-km^2 catchment that drains into the northeastern slopes of the West Bank from Nablus City in the west to the Jordan River in the east (see Fig. 1). Topography is a unique feature of the catchment which starts at an elevation of about 920 m above mean sea level in the western edge of the catchment in Nablus Mountains and descends drastically to about 385 m below mean sea level in the east at the confluence of the Jordan River over a horizontal distance of 35 km (see Fig. 2). Faria catchment lies almost completely over the eastern aquifer basin in the West Bank. There are more than seventy wells in the catchment; most of them are agricultural, some are domestic, and the remaining are Israeli-controlled wells. Also, there are 13 fresh water springs in the catchment. Most of the agricultural and domestic wells in the catchment were drilled in the vicinity of the main wadi (see Fig. 3).

Note that the two springs located near the selected reach were dried several years ago, and the only springs which flow to the wadi are from Al-Badan upstream area.

To show the wadi–aquifer interaction in Faria catchment through conducting a tracer field experiment, a representative reach was selected at An-Nasariah area where the depth to water table is relatively low (around 25 m). Also, there are many wells surrounding the selected reach as depicted in Fig. 3. The effect of the wadi–aquifer interaction on some of these wells was studied (see Abboushi 2013 for more details).

The hydrogeology plays a key role in the occurrence of wadi–aquifer interaction, since it controls the movement of

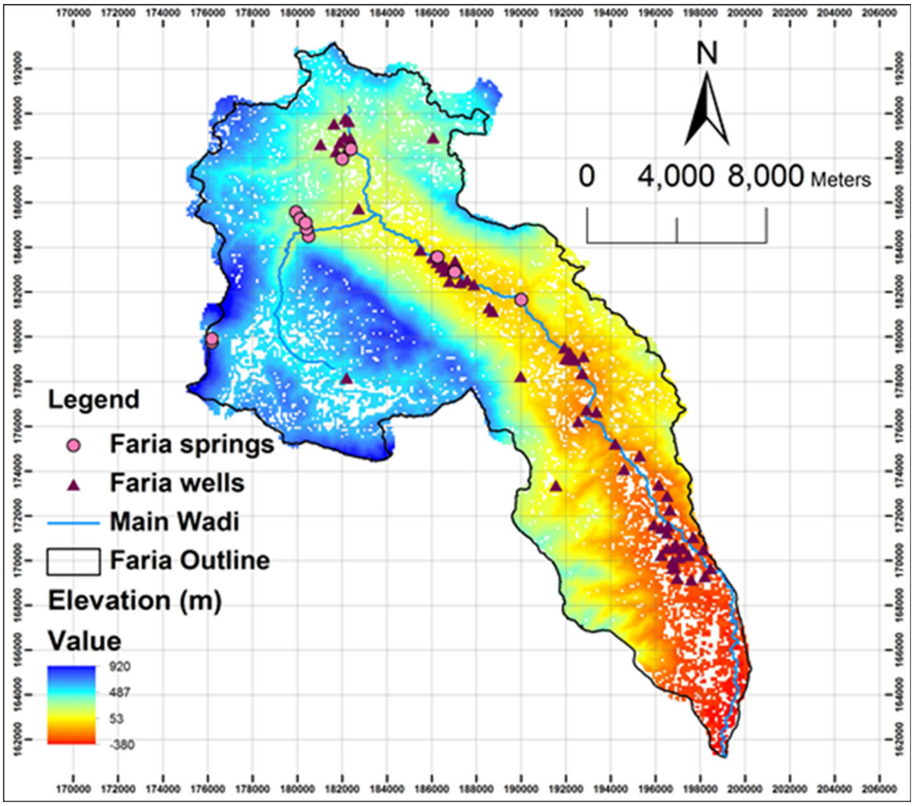


Fig. 2 Topography of Faria catchment

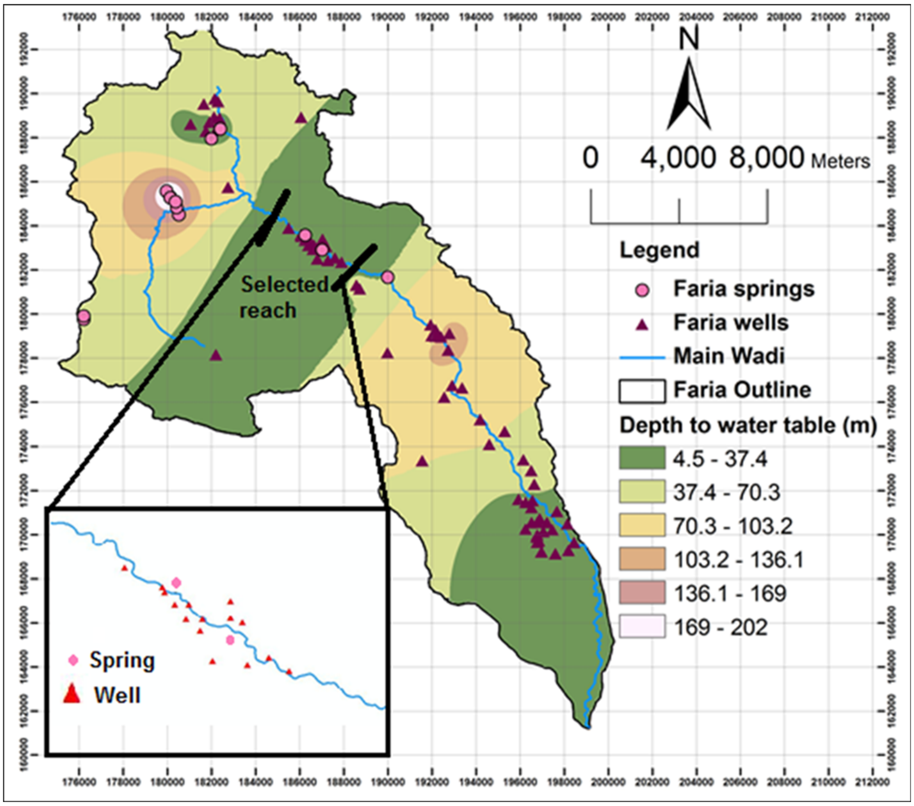


Fig. 3 The distribution of wells and springs along the main wadi in Faria catchment and the selected reach for the tracer-based experiment

the flow from the surface and its probability to reach the groundwater through the different soil lithological formations. To consolidate the potential existence of wadi–aquifer interaction in Faria catchment, the hydrogeology of the region should be studied and realized.

The main geologic formation along the main wadi is the quaternary formation (see Fig. 4). The main typical lithology of this formation includes gravels and alluvium. Gravels and alluvium in turn allow water to infiltrate easily to the aquifer. In other words, they enhance the interaction to take place between the wadi and the aquifer.

To understand the movement of the flow from the wadi to the aquifer, the geological formations existed above the saturated zone should be well understood. Some of the geologic formations that exist above the saturated zone are summarized in Table 1.

Note that all the layers which are located above the groundwater table have high to moderate hydraulic conductivities (see Table 2), so they allow the flow to infiltrate quickly and easily from the surface to the aquifer, except Yatta formation which is considered as an aquitard. At the same time, this formation outcrops at small localities in the middle and upper parts of the catchment and does not extend completely above the water table which ranges from 5 to 38 m from the ground surface at An-Nasariah area (see Fig. 5).

The major soil types in Faria catchment are Terra Rossas Brown Rendzinas soil and Loessial Seozems. These two types comprise up to 70 % of the total catchment's area (Shadeed 2008). The texture of these soils mainly includes karastic formations, such as alluvium, dolomite, and limestone. These formations by their nature allow water to infiltrate easily and this in turn enhances the wadi–aquifer interaction to take place in the catchment.

Through several field visits, many variations in the wadi's flow rates were noticed under different weather circumstances; in summer, apparently there is no flow in the wadi as shown in Fig. 6 except for wastewater and low spring flow that are discharged from upstream area, and most of it is used by the farmers and the recreational areas. While in winter there is often a considerable flow in the wadi as shown in Fig. 7 due to mixing of wastewater and spring flow with rainfall water. Values of wadi's flows measured at Al-Badan flume for the period from 2004 to 2007 ranged from 0.1 to 24 m^3/s according to the different weather conditions (Shadeed 2008).

Methodology

Using a tracer-based experiment as the adopted methodology in this research has many benefits. Tracer

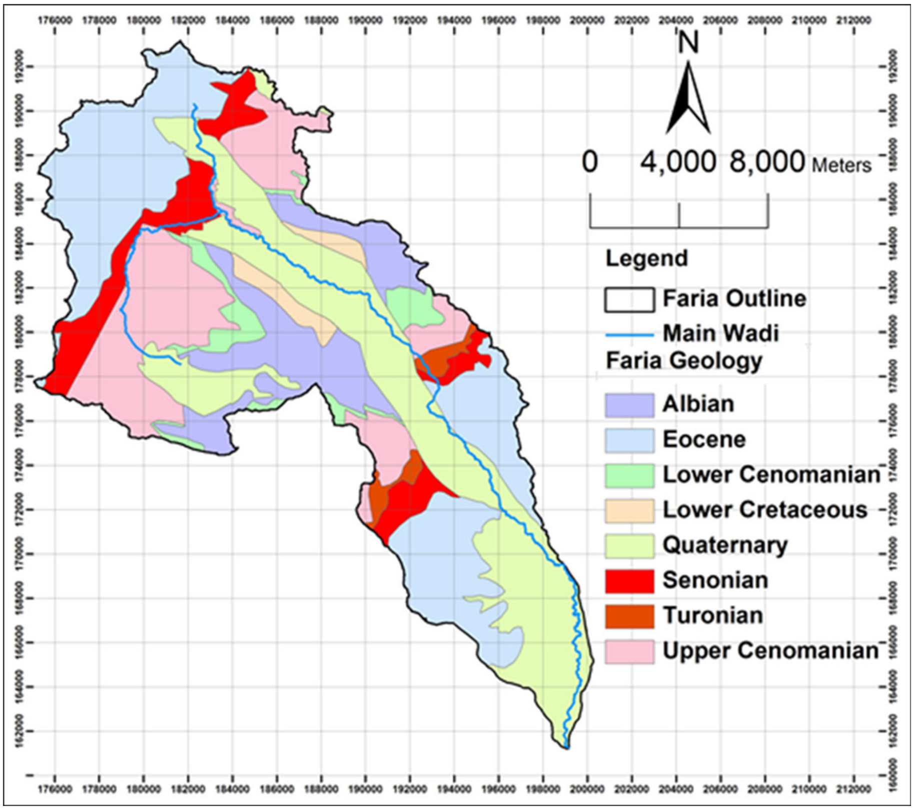


Fig. 4 Geologic map of Faria catchment (MOPIC 1998)

Table 1 The geologic formations existed above the saturated zone in Faria catchment (EQA 2004; Saleh 2009)

Geologic age	Formation (Palestinian terminology)	Depths ranges	Typical lithology
Albian	Upper and lower Beit Kahil	Upper Beit Kahil: (10–40) m Lower Beit Kahil: (10–50) m	Limestone interbedded with marls, and dolomite This formation forms the lower aquifer
Eocene	Jenin	Up to 200 m	Limestone, limestone with chalks
Lower Cenomenian	Upper and lower Bethlehem, and Hebron	Upper and lower Bethlehem: (5–115) m Hebron: (105–260) m	Karastic limestone, and dolomite Hebron forms the formation of the upper aquifer
Upper Cenomenian	Upper and middle Yatta	Upper Yatta: (5–15) m Middle Yatta: (40–50) m	Marls This formation has outcrops at small localities in the middle and upper part of the catchment
Lower Cretaceous	Ramli	(50–250) m	Sandi stone and Basalt rocks
Quaternary	Alluvium	Up to 100 m	Gravels, crust, and alluvium
Senonian	Abu Deis	(50–175) m	White chalk, chalky limestone, chert, and phosphate
Turonian	Jerusalem	(40–120) m	Karstified limestone, and dolomite

Table 2 Typical features of various conductance categories for wadi–aquifer systems (Lewis et al. 2006)

Features	High conductance	Moderate conductance	Low conductance
Typical lithologies	Gravels, coarse sands, karst	Fine sands, silts, fractured rocks, basalt	Clay, shale, fresh unfractured rocks
Typical hydraulic conductivities (K) (m/d)	>10	0.01–10	<0.01
Typical seepage flux (m^3/d/km)	>1,000	10–1,000	<10
Ratio of seepage to total flow	>0.5	0.1–0.5	<0.1

experiments are innovative tools and among the modern techniques that are used to address issues like surface water–groundwater interaction, especially in the arid and semi-arid regions. Most of the classical methodologies that were used to study this interaction focused on developing mathematical models to describe the mechanism of the wadi–aquifer interaction presented in the study area. This research is one of the first attempts in this field in Palestine which used the tracer techniques to quantify and study the probability of the occurrence of the wadi–aquifer interaction. Using tracer field experiments provides compelling practical evidence to the occurrence of the wadi–aquifer interaction in the study area, and this is why it was used.

The tracer-based experiment was conducted on the 21st of January, 2013 after a considerable rainfall storm event. The reason of conducting the experiment in winter is to have a considerable flow in the wadi and to have a negligible evaporation effect (i.e., no evaporation diversions).

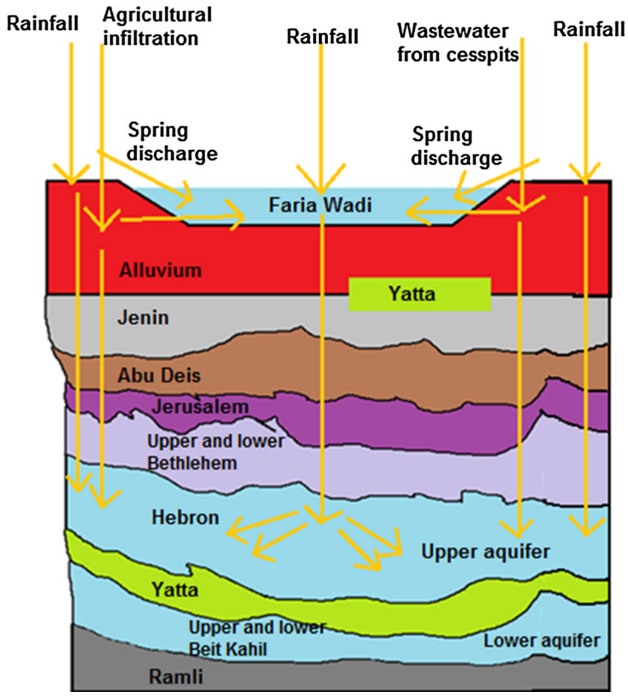


Fig. 5 A general hydrolithological sketch that shows the different pollutants that may reach the upper aquifer through the wadi–aquifer interaction in Faria catchment

The tracer experiment was preceded by determining a specific reach along the main wadi, determining a tracer type, and a tracer dose mass.

Field work

The first activity that was conducted in the field work was the selection of the reach. A representative 600-m reach along the main wadi at An-Nasariah area in Faria

Fig. 6 A section in the main wadi of Faria at An-Nasariah area in summer

Fig. 7 A segment in the main wadi of Faria at An-Nasariah area in winter

catchment was selected. One injection point and four monitoring points were identified at 150 m apart from each other on the selected reach.

In general, there are no criteria set for the selection of the reach for the tracer field experiment. However, a chosen reach is better to be more uniform (straightness) as possible, accessible and easy to take measurements on it, less slope reaches are preferable than steep ones, and the chosen reach is better to be surrounded by a group of wells, so as to study the effects of this interaction on these wells.

The selected reach for this research (at An-Nasariah) does not have that desired uniformity to conduct a tracer experiment although it is one of the most uniform reaches in the area. It is relatively accessible and has relatively low slopes compared to other reaches in the region.

The second step was determining the type of the tracer to be used in the field experiment. In order to select the appropriate tracer type to be used, several criteria were considered. Since there is no ideal tracer, the choice must be based on the comprehensive understanding of all limiting factors (Kass and Schneider 1998). Artificial tracers were preferred to be used in this research and for the purpose of this study, Uranine as a fluorescent tracer dye (one of the most famous types of artificial tracers) was specifically selected, since it is considered as a conservative and a non-toxic tracer (Leibundgut et al. 2009).

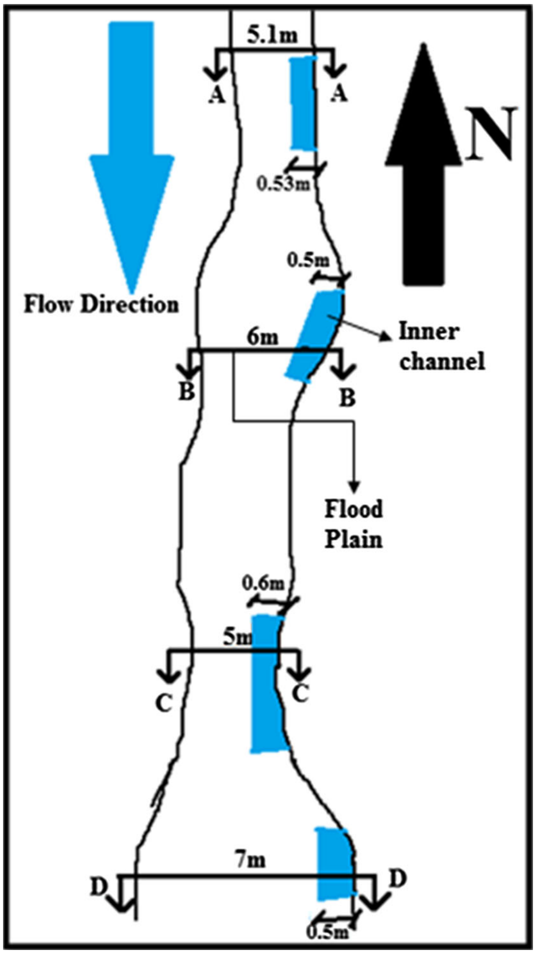


Fig. 8 A longitudinal plan of the selected reach at An-Nasariah area

The third step that preceded the conduction of the experiment was determining the tracer dose mass. In this experiment, the tracer injection mass of Uranine was taken as 5 g and was dissolved in a sufficient amount of water (the amount of water here is just to ensure dissolving the tracer, and is not of that importance since the tracer solution was spilled instantaneously into the wadi; i.e., slug injection). The amount of the tracer was determined based on an initial tracer experiment conducted in April 2012. Generally, the amount of tracer should not be too high, since it will scare the local people in the area due to dyeing the wadi by its green color and not too small, fearing that it is less than the detection limit of the measuring device.

Additional important step before the conduction of the experiment was determining the channel's longitudinal profile and the cross-sections for the different monitoring points. As depicted in the longitudinal profile (see Fig. 8), the selected reach is nearly straight and this in turn made the conduction of the tracer experiment easier. Also, it is very important to note that when the experiment was conducted, the flow did not cover the whole channel's cross-section but it took a strip on one edge of the channel.

The channel's cross-section area ranges from 0.8 to 3.3 m^2 as depicted in Fig. 9. The depth from the bed to the channel's banks ranges from 27 to 93 cm on average. It is also noted that the depth is varying at the same cross-section and this is another reason why the tracer experiment was selected specifically in the study area to show the interaction over other methods.

Thirty samples were taken at each monitoring point with a sampling frequency of 1.5 min. These observed data were used then to plot the measured concentration curves.

Laboratory and desk works

After doing the sampling process, all the samples were analyzed using a field fluorometer (AquaFluor device, model No: 8000-010). For each monitoring point, the sets of observed time and concentration data were plotted and calibrated using a solute transport software model called OTIS (Runkel 1998). After that, each concentration curve was transformed to an average flow rate by dividing the injected tracer mass by the area under the concentration curve at each monitoring point. Finally, each of the two successive flow rates were subtracted to quantify the wadi–aquifer interaction (If the difference between the upward flow rate and the downward flow rate is positive; this means that transmission losses are taking place). Figure 10 presents a simple sketch that illustrates the procedure of the conducted field experiment. OTIS was used in particular, since it was found that most of the relevant studies and researches used it to simulate and calibrate the observed data, which resulted from tracer-based experiments.

The average flow rate can be obtained from the tracer concentration curve using the following formula (Leibundgut et al. 2009):

$$Q = \frac{M}{\int_0^\infty C(t)\,dt} = \frac{M}{F} \tag{1}$$

where M is the mass of tracer injected (at $x = 0$; at the beginning of the first section) and F is the area under the tracer concentration curve, which can be calculated using the trapezoidal method of integration (Leibundgut et al. 2009):

$$F = \frac{1}{2}\sum_{i=1}^{N}(C_{i-1} + C_i) \times (t_i - t_{i-1}) \tag{2}$$

where N is the number of points measured. (t_i, C_i) are the ordered pairs of time and corresponding tracer concentration. Note that the tracer dose mass (M) was chosen to be 5 g.

Results and discussion

Observed data were taken directly from the tracer field experiment. However, simulated data results were taken from the OTIS model. The injection time of the tracer material (Uranine) was at 11:26 a.m.

The observed concentration curve for the first monitoring point is depicted in Fig. 11a which was used as an

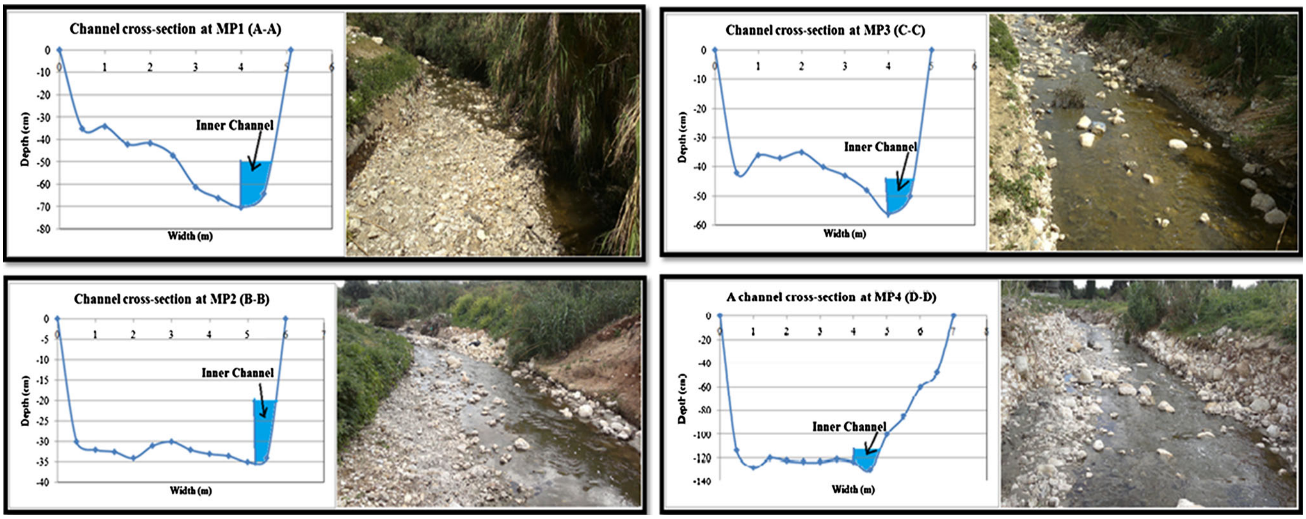
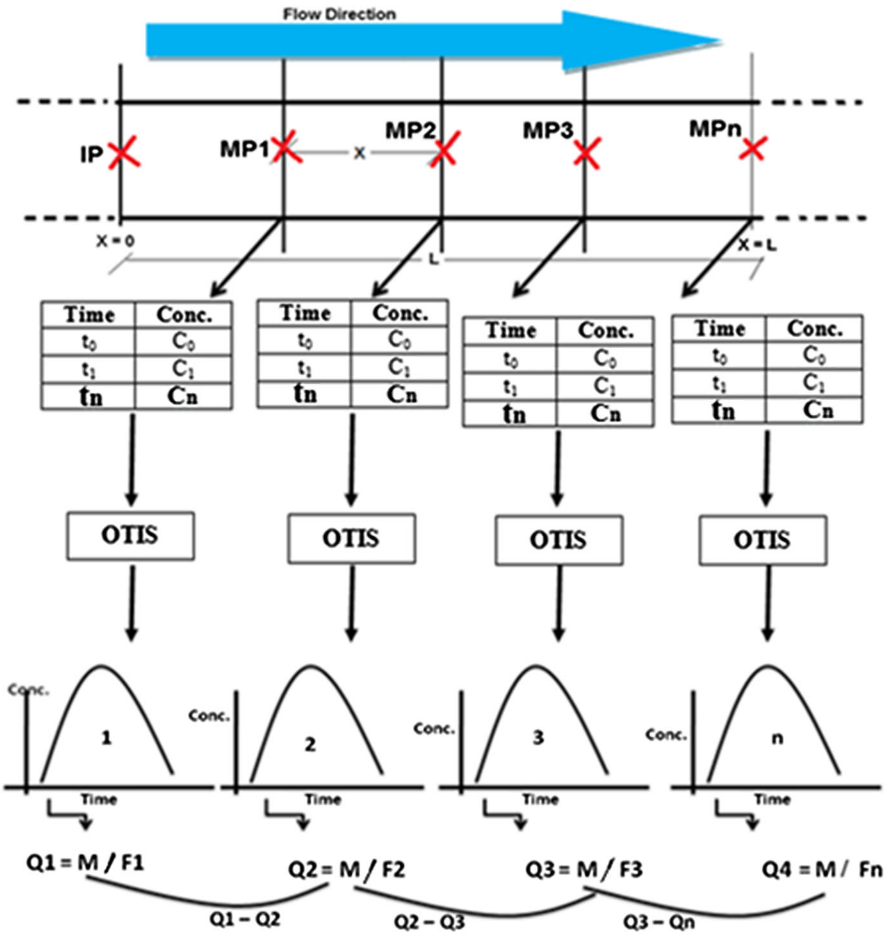


Fig. 9 The different monitoring points cross-sections along the selected reach

Fig. 10 General scheme of the tracer field experiment (Abboushi 2013)



Time	Conc.
t_0	C_0
t_1	C_1
tn	Cn

Time	Conc.
t_0	C_0
t_1	C_1
tn	Cn

Time	Conc.
t_0	C_0
t_1	C_1
tn	Cn

Time	Conc.
t_0	C_0
t_1	C_1
tn	Cn

Figure Key Notations:

IP: Injection point
MP: Monitoring point
t: Time since injection
c: Tracer concentration
F: The area under the tracer concentration curve
Q: Average flowrate in the section
M: Mass of tracer injected
OTIS: One-Dimensional Transport with Inflow and Storage

upper boundary condition in the OTIS model, whereas the observed and simulated concentration curves for the second, third, and fourth monitoring points are depicted in Fig. 11b–d.

It is noticed that the flow was not rapid enough to complete the shape of the observed concentration curves for the second, third, and fourth monitoring points with a total number of 30 samples and an interval time sampling period of 1.5 min.

In the second and third monitoring points, the observed concentration curves reached their peak values. On the contrary, the observed concentration curve for the fourth monitoring point is increasing progressively, and it is not clear whether it reached the peak value or not.

To have correct and complete concentration curves so as the required calculations can be applied, OTIS model was used.

It is very important to mention that the correlation coefficients between the observed and the simulated concentration curves ranged from 0.86 to 0.98 which means that the results are in a good agreement, so we can assume that the OTIS model can be applied to the Faria catchment and the calibration process was proper. To have a clearer picture about the transmission losses effect, the first observed curve and the other simulated ones are plotted in a single graph as shown in Fig. 12. From the figure, it is clear that the attenuation of the peak concentration and the widening of the curves bases are noticed as the flow moves

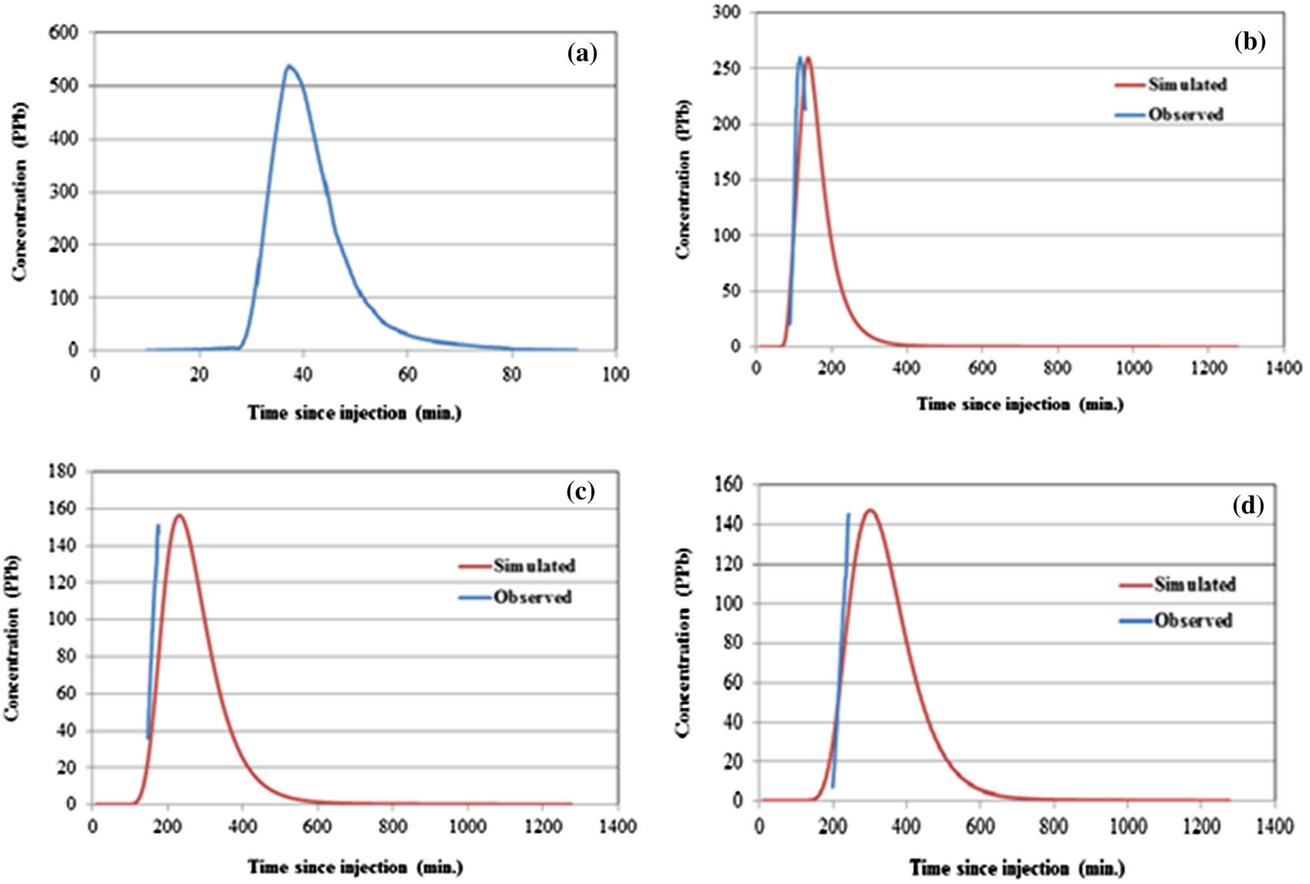


Fig. 11 The observed and simulated concentration curves for the different monitoring points

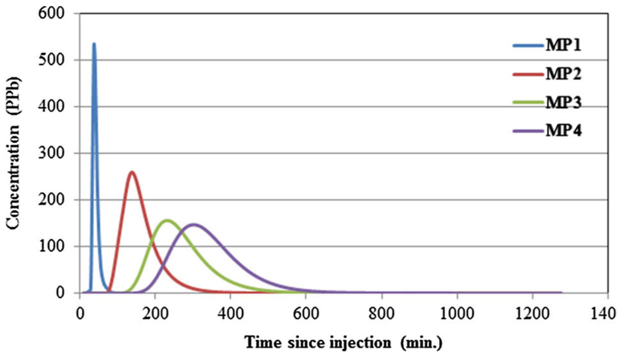


Fig. 12 All concentration curves at the different monitoring points

downward from the injection point. Also, the relation between the mass of the tracer remained at each monitoring point and the time since injection was plotted in Fig. 13 to show the tracer mass losses with the wadi flow through the wadi bed sediments.

All relevant information, data, and calculations for each monitoring point at each section are summarized in Table 3.

The sampling frequency was estimated in the field depending on the visual view of the flow velocity in the wadi. The depths, widths, and areas that are indicated in the table refer to the portion of the cross-section that most of the flow passed through and where the sampling processes took place. The flow in the reach has relatively slow velocity that ranges from 0.041 to 0.089 m/s. The mass of tracer remained at each monitoring point is calculated by multiplying the average concentration by the volume of

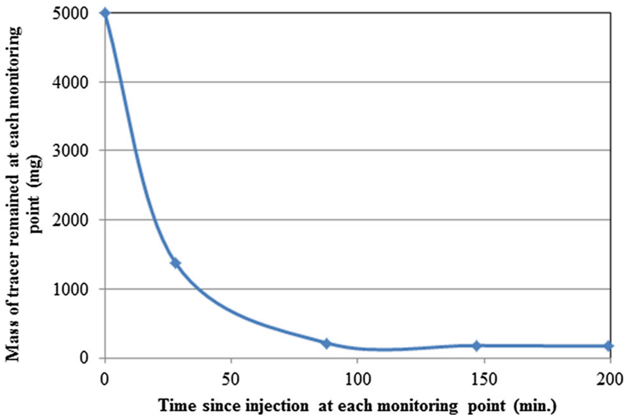


Fig. 13 Tracer mass losses in each section through the wadi bed sediments

Table 3 Experiment-relevant information, data, and calculations for each monitoring point at each section

Monitoring point$^{\#}$	Distance from the IP (m)	Section length (m)	Starting sampling time since injection (min)	Sampling frequency (#/min)
1	150	150	28	Sample/ 1.5
2	300	150	88	Sample/ 1.5
3	450	150	147	Sample/ 1.5
4	600	150	199	Sample/ 1.5

Monitoring point$^{\#}$	Depth of the inner channel at each section (m)	Width of the inner channel at each section (m)	Cross-section area of the inner channel at each section (m^2)	Volume of water at the section (m^3)
1	0.19	0.53	0.100	15
2	0.15	0.5	0.075	11.25
3	0.1	0.6	0.06	9
4	0.1	0.5	0.05	7.5

Monitoring point$^{\#}$	Travel time within each section (s)	Velocity in the section (m/s)	Avg. concentration (PPb)	Mass of tracer remained in each section at the monitoring point (mg)
1	1,680	0.089	91.98	1379.7
2	3,600	0.041	19.24	216.45
3	3,540	0.042	20.21	181.89
4	3,120	0.048	23.29	174.68

Monitoring point$^{\#}$	Area under the tracer solute curve (*F*) (mg min/m^3)	Peak concentration (PPb)	Flow rate (*Q*) (l/s)	% loss in (peak concentration, flow rate), respectively
1	7725.83	534	10.79	(51.4, 68.3)
2	24384.79	259.69	3.42	(39.8, 4.8)
3	25613.32	156.43	3.25	(5.8, 13.2)
4	29518.15	147.34	2.82	

Table 4 The slope of the sections in the selected reach

The section	Slope
Between MP1 and MP2	0.008
Between MP2 and MP3	0.015
Between MP3 and MP4	0.024

water in each section at the monitoring point. The mass of tracer decreases as the distance becomes farther from the injection point due to the infiltration of the material through the wadi bed sediments only, since Uranine has neither decay nor adsorption impacts (this is an evidence of wadi–aquifer interaction that occurs in the area). Commonly, if there is no lateral flow between the monitoring points, the average flow rate becomes smaller as the distance moves away from the injection point due to transmission losses that took place in the wadi (this is also an evidence of wadi–aquifer interaction that occurs in the area). If the wadi flow covers the whole channel's cross-section and with a higher depth, the transmission losses will be assumed to be higher and so, the interaction will appear more clearly. The largest peak concentration loss is occurred in the section between the first and the second monitoring points and it is equal to 51.4 %. The hot spot area is the one which has the largest percent loss in the flow rate (largest transmission losses), and it is in the section between the first and second monitoring points (the percent loss is 68.3 %). The peak concentrations of the tracer solute curves are decreasing as the distance moves downward from the injection point; this is due to dispersion effects of the flow on the tracer as well as the infiltration of some of the tracer material through the wadi bed sediment (this is again an evidence of wadi–aquifer interaction that occurs in the area). The fact that the first section of the reach (between the first and the second monitoring points) is determined as the hot spot area was expected, since this section has the least slope upon other sections in the selected reach (see Table 4) and so, the flow in this section has the largest residence time; this in turn increases the chance of the interaction to take place between the wadi and the aquifer, as well as the nature of the wadi bed sediment in this section was dominated by sandy and gravelly soil structures. On the contrary, the nature of the wadi bed sediments in the other sections was dominated by silty and clayey soil structures, which also in turn enhances the wadi–aquifer interaction to take place within the first section more than in the other ones (for more details, see the hydrological description in the study area section).

From the final results, it can be concluded that the conducted tracer experiment is valid, and it has a good agreement with the hydrolithological and hydrodynamic evidence which has been described in the study area section in this paper. With more clarification, through the hydrolithological analysis of the study area, it was expected that the wadi–aquifer interaction has a strong probability to occur, and this is what the tracer experiment verified through the transmission losses which took place in the wadi bed between the monitoring points.

Conclusions

This paper is a preliminary attempt to investigate the occurrence of wadi–aquifer interaction in the semi-arid area of Faria catchment through conducting a tracer-based experiment. The tracer-based experiment showed that transmission losses took place in all sections of the selected reach with different ratios and became a potential recharge to groundwater. The transmission losses were the highest in the first section, which is located between the first and the second monitoring points. This result is reasonable and expected because this section has the lowest slope compared with other sections, and the nature of the wadi bed sediments in this section was dominated by gravelly and sandy soil, in contrast to the other sections which were dominated by silty and clayey soil structures. The correlation coefficients between the observed and the simulated concentration curves ranged from 0.86 to 0.98 which means that the results are in a good agreement, so we can assume that the OTIS model can be applied to the Faria catchment and the calibration process for the model was proper.

Based on the findings of this research, a thorough analysis is required to better assess the hydrologic characteristics of the wadi bed in Faria catchment. Such characteristics include mainly the infiltration capacity and hydraulic conductivity. Also, additional work should be directed toward the employment of more specialized software for the modeling of stream–aquifer interaction.

Acknowledgments This research was financially supported by UNESCO-IHE Partnership Research Fund (UPaRF), the Netherlands under the UWIRA project. This financial support is gratefully acknowledged.

References

Abboushi A (2013) A preliminary investigation of wadi–aquifer interaction in semi-arid regions: the case of Faria catchment, Palestine. Thesis (Msc), An-Najah National University

Abdin S (2006) Qantas a unique groundwater management tool in arid regions, the case of Bam Region in Iran. International symposium on groundwater sustainability, 4–5 May 2011 Nablus, Palestine. Nablus: Faculty of Gradute Studies, An-Najah National University, 38–51

Alley W, Reilly T, Franke O (1999) Sustainability of groundwater resources. US Geol Surv Circ 1186:30–31

Bencala KE, Walters RA (1983) Simulation of solute transport in a mountain pool-and-riffle stream-A transient storage model. Water Resour Res 19:718–724

Environmental Quality Authority (EQA) (2004) Faria and Jerash integrated watershed management project-Faria baseline report. Unpublished Report, Palestine

Ghanem M (1999) Hydrogeology and hydrochemistry of the Faria drainage basin/West Bank. Thesis (PhD), Freiberg University

Huang J, Minnis P, Yan H, Yi Y, Chen B, Zhang L, Ayers JK (2010) Dust aerosol effect on semi-arid climate over Northwest China detected from A-Train satellite measurements. Published by Copernicus publications on behalf of the European Geosciences Union. 10:6863–6872

Jayyousi A, Srouji F (2009) Future water needs in Palestine. Palestine Economic Policy Research Institute, Jerusalem

Kass W, Schneider K (1998) Tracing technique in geohydrology. A ABalkema Publishers, Netherlands

Lange J, Leibundgut C, Grodek T, Lekach J, Schick A (1997) Using artificial tracers to study water losses of ephemeral floods in small arid streams. Karst hydrology (Proceedings of Workshop W2 held at Rabat, Morocco, April May 1997). IAHS Publ. 247: 31–40

Leibundgut C, Maloszewski P, Külls C (2009) Tracers in hydrology. John Wiley & Sons, Chichester, UK

Lewis M, Cheney C, Ódochartaigh B (2006) Guide to Permeability Indices. Published by British Geological Survey, Open report, CR/06/160N, pp 29

McKnight DM, Andrews ED (1993) Hydrologic and geochemical processes at the stream-lake interface in a permanently ice-covered lake in the McMurdo Dry Valleys, Antarctica. Verhandlungen der Internationalen Vereinigung fuer Limnologie 25:957–959

Ministry of Planning and International Cooperation (MOPIC) (1998) Valuable agricultural land in the West Bank governorate emergency natural resources protection plan. Directorate for Urban and Rural Planning, Palestine

Nikanorov A, Trunov N (1993) Using a new-type of fluorescent tracers to study the dynamic processes in surface and groundwater. Tracers in hydrology (Proceedings of the Yokohama Symposium, July 1993). Gorlovka city, Ukraine. IAHS Publ. 215:249–251

Runkel R (1998) One-Dimensional transport with inflow and storage (OTIS). Published by US geological survey, Denver, Colorado, USA. Water-resources investigations report 98–4018

Salahat B (2008) Natural runoff and development of infiltration system in Faria catchment. Thesis (Msc), An-Najah National University

Saleh Y (2009) Artificial groundwater recharge in Faria catchment: a hydrogeological study. Thesis (Msc), An-Najah National University

Shadeed S (2005) GIS-based hydrological modelling of semi-arid catchments, the case of Faria catchment. Thesis (Msc), An-Najah National University

Shadeed S (2008) Up to date hydrological modeling in arid and semi-arid catchment, the case of Faria catchment, West Bank, Palestine. Thesis (PhD), Freiberg University

Shadeed S, Swalha M, Abu Jaish A, Haddad M, Alawneh A, Abboushi A, Doraidi D, Homeidan M (2011) Overview of quantity and quality of water resources in the Faria catchment, Palestine. Internationa graduate conference on science, humanities, and engineering, 4–5 May 2011 Nablus, Palestine. Nablus: Faculty of Gradute Studies, An-Najah National University, 38–51

Winter F (2006) Using tracer techniques to investigate groundwater recharge in the Mount Carmel Aquifer, historical Palestine. Thesis (PhD), Freiberg University

Winter T, Harvey J, Franke O, Alley W (1998) Groundwater and surface water: a single source. US Geol Surv Circ 1139:79