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DEVELOPING QUANTITATIVE AND QUALITATIVE RELATIONSHIPS OF WADI-AQUIFER INTERACTION IN THE SEMI-ARID WATERSHED OF FARIA, PALESTINE

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ABSTRACT

This paper aims to investigate the potential existence of wadi-aquifer interaction (i.e. transmission losses that are taking place in the wadi bed and their potential recharge to the aquifer) in the semi-arid region of Faria catchment. Faria catchment, 320 km^2, located in the northeastern part of the West Bank. Surface runoff in the catchment consists mainly form springs discharge, runoff generated from winter storms, and untreated wastewater effluent from the eastern part of Nablus city and Al-Faria refugee camp. As such, wadi-aquifer interaction may exert serious pressures on groundwater quality and jeopardize further development in the catchment. Evidence of wadi-aquifer interaction is presented through quantitative analysis of rainfall records, wadi flows, and change in the water table levels in addition to quality analysis of groundwater wells. Quantitative analyses show that the water table level in a selected groundwater well next to the main wadi is significantly changed and spiked as a result of increasing rainfall and corresponding runoff in the wadi. This in turn provides good evidence that the hydrogeology allows wadi-aquifer interaction to take place in the catchment. Many quantitative measures are determined such as: travel time, hydraulic conductivity, and well's capture zone. In general, these measures showed that the soil layers in the region next to the main wadi have high flow conductance, and so there is a high probability for the flow to transmit from the wadi to the aquifer. Also, the well's capture zone was found to have a total width of 26.64 m which is considered to be relatively large enough to receive the pollutants infiltrated from the wadi bed. On the other hand, quality analyses show that some chemical and microbial pollutants were found in the sampled well. This can be attributed to untreated wastewater flows in the wadi which provide another evidence of wadi-aquifer interaction in the catchment. Those concentrations were found to have higher trends in summer than in winter due to the lack of diluting rainfall water in the dry season.

Keywords: *Faria catchment; Semi-arid, Wadi-aquifer interaction; Untreated wastewater effluent; and Hydrogeology.*

1 INTRODUCTION

Approximately one third of the world's land area can be classified as arid to semi-arid regions [1]. Generally, groundwater is often the major water source available for domestic and agricultural use in arid and semi-arid regions where there is no perennial surface water [2]. However, the importance of this source is threatened when groundwater becomes contaminated. Groundwater quality in the West Bank is being deteriorated from the effluent of untreated wastewater that comes from cesspits and sewerage systems. In turn, the wastewater from sewerage systems in general flows freely in the nearby wadis and ultimately can pollute the groundwater.

Faria catchment is one of the most important catchments in the West Bank due to the intense agricultural activities. However, the catchment is under water pollution threats and quantity stress. Wadi flow in the catchment consists mainly from springs discharge, runoff generated from winter storms and the untreated wastewater effluent from the eastern part of Nablus City and Al-Faria Refugee Camp. 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 [3]. In essence, this can be attributed to wadi-aquifer interaction where pollutants can migrate freely due to the hydraulic connectivity of the formations. This situation has compelled the motivation to conduct a preliminary investigation to understand the wadi-aquifer interaction in the catchment.

This paper aims to provide evidence for wadi-aquifer interaction in the Faria catchment through quantitative and quality analysis of rainfall depths, wadi flows, change in water table levels and groundwater quality data. This in turn will improve the sustainable development of the vulnerable groundwater resources in the catchment by proposing some mitigation measures to protect groundwater aquifers in the catchment.

2 STUDY AREA

Faria catchment is a 320 km^2 draining into the northeastern slopes of the West Bank from Nablus to the Jordan River (See **Figure 1**). Topography is a unique feature of the catchment which starts at an elevation of about 920 meters above mean sea level in the western edge of the catchment in Nablus Mountains and descends drastically to about 385 meters below mean sea level in the east at the confluence of the Jordan River over a distance of about 35 km.

Faria catchment lies almost completely over the eastern aquifer basin in the West Bank (See **Figure 2**). 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 thirteen fresh water springs in the catchment.

Moreover, most of the agricultural and domestic wells in the catchment were drilled in the vicinity of the main wadi, (See **Figure 3**). So, this compelled the dire need to investigate the wadi-aquifer interaction, which is assumed to be the key factor for groundwater contamination in the catchment.

The major soil structures in the main wadi of Faria are rocks and gravels. These formations by their nature allow water to infiltrate easily and this in turn helps the wadi-aquifer interaction to take place in the catchment.

In this study and in trying to prove the wadi-aquifer interaction in the Faria catchment, the focus was to identify a reach in the main wadi where the depth to groundwater is relatively short. Thus, wadi reach which is located at An-Nasariah area was selected to carry out the analyses. The selected reach is surrounded by agricultural area where agricultural wells located. Different pollution sources in the selected segment can be conceptually described as illustrated in **Figure 4**.

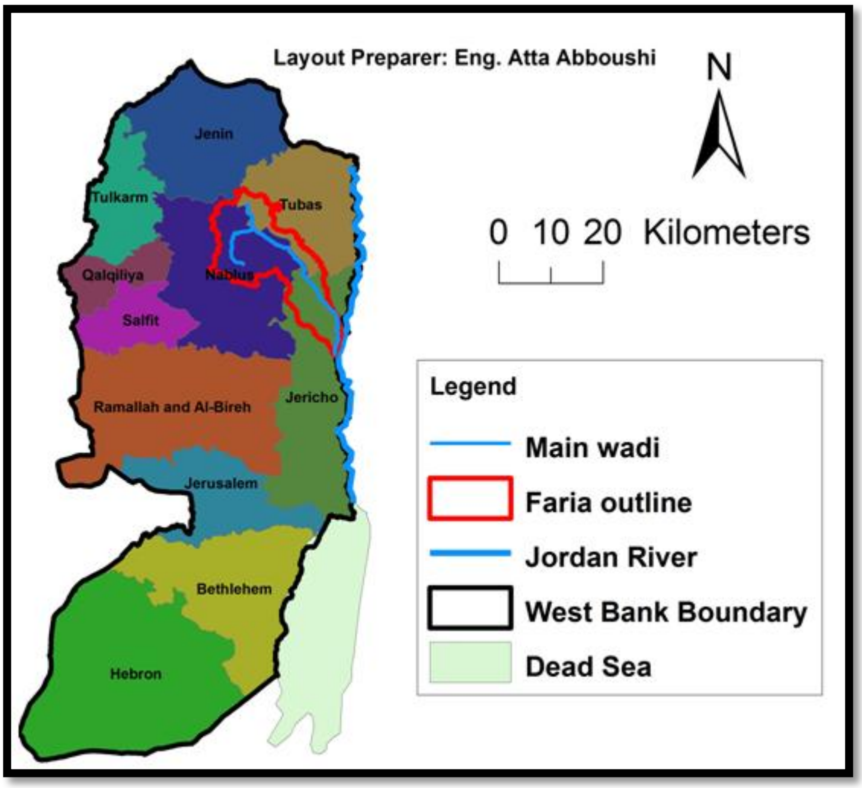

Figure 1: Location map of Faria catchment

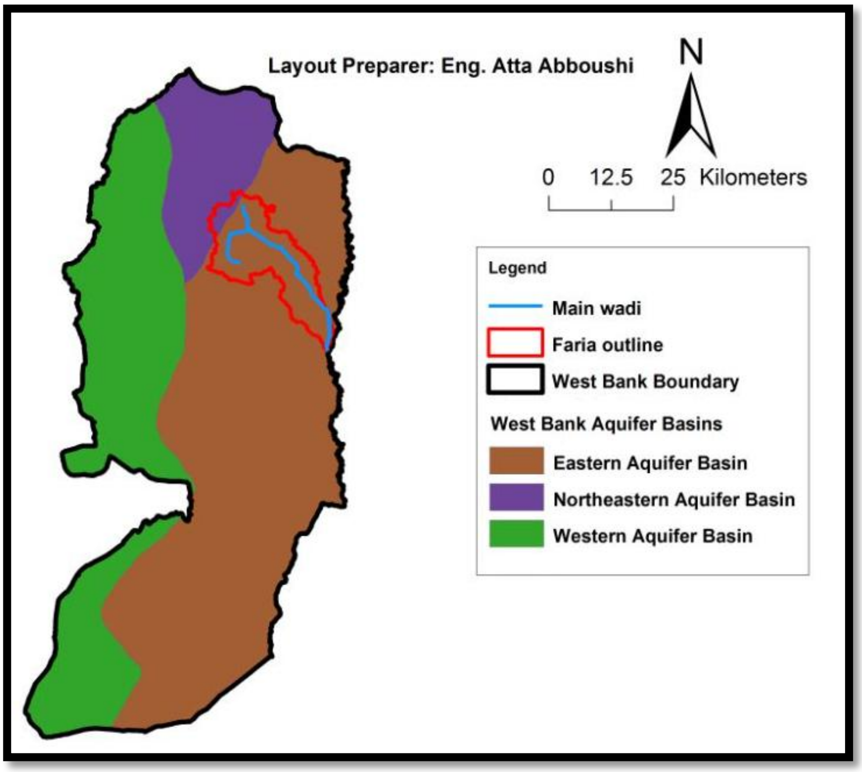

Figure 2: Location of Faria catchment within the eastern aquifer basin

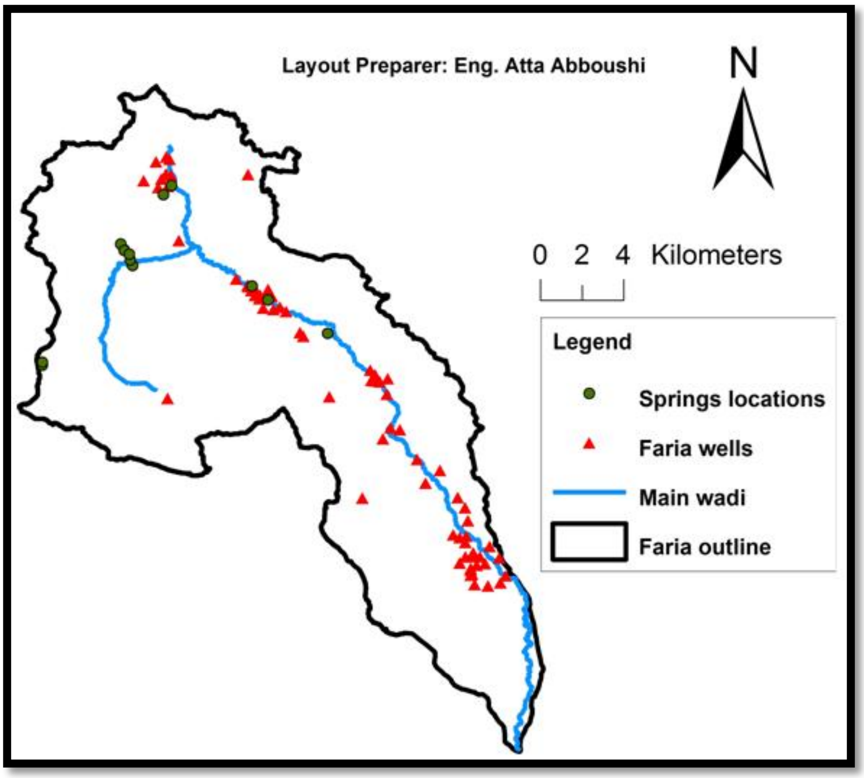

Figure 3: The distribution of wells and springs along the main wadi in Faria catchment

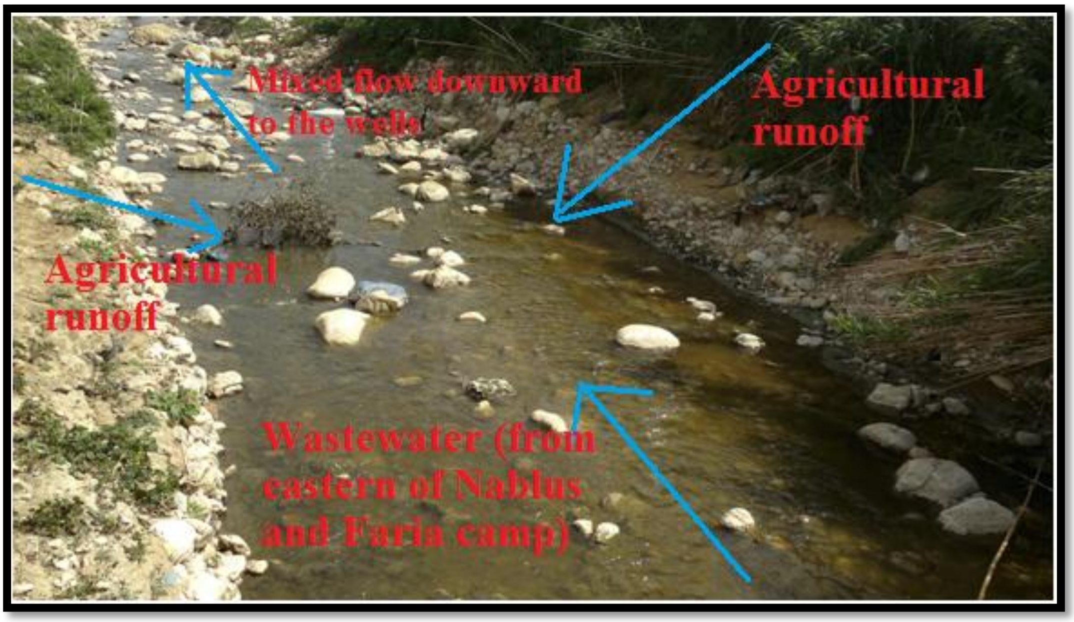

Figure 4: The wadi segment at An-Nasariah area that describes the pollutants contributing to the wadi upstream the agricultural wells in the region

The hydrogeology plays a key role in the occurrence of wadi-aquifer interaction, since it controls the movement of 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. The main typical lithology of this formation includes gravels and alluvium. Gravels and alluvium in turn allow water to infiltrate easily from the wadi to the aquifer. In other words, they enhance the interaction to take place between the wadi and the aquifer (See **Figure 5**).

In order to understand the movement of the flow from the wadi to the aquifer, the geological layers above the water table should be well understood (**Refer to Figure 18, Page 14**).Some of the geologic formations that exist above the water table are summarized in **Table 1**.

Table 1: The layers detected above the water table in Faria catchment [4]

Geologic Formation	Lithology
Jenin Formation	Reef limestone, bedded limestone, limestone with chalk
Jerusalem Formation	Thinly bedded limestone and dolomite
Hebron Formation	Hard dolomistic limestone and chert rocks
Bethlehem Formation	Limestone, dolomite with chalk, and marl massively bedded with a well – developed karst
Upper BeitKahil Formation	Dolomite and dolomistic limestone
Yatta Formation (Aquitard)	Marly limestone interbedded with dolomistic limestone or dolomite. This formation has outcrops at small localities in the middle and upper part of the catchment

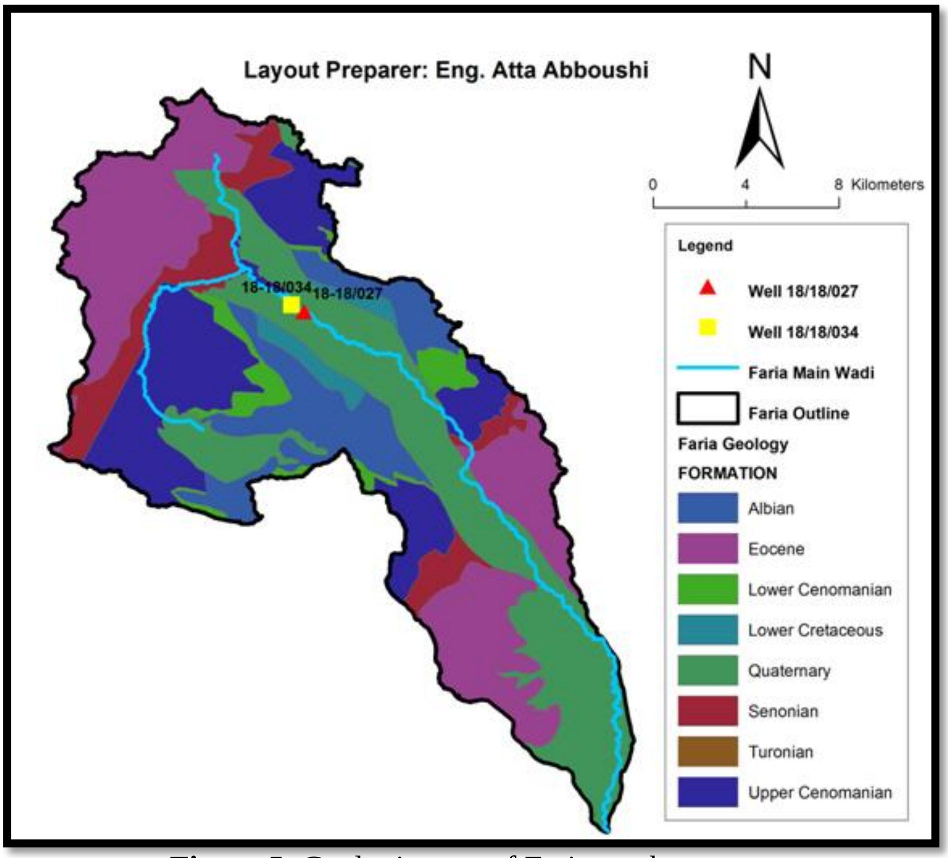

Figure 5: Geologic map of Faria catchment

Note that all the layers which are located above the groundwater table have high to moderate hydraulic conductivities (**Refer to Table 4, Page 10**), so they allow the flow to infiltrate quickly from the surface to the aquifer, except Yatta formation which is considered as an aquitard, but at the same time this formation outcrops at small localities in the middle and upper part of the catchment and doesn't extend completely above the water table which ranges from 25 to 27 m from the ground surface at An-Nasariah area.

3 METHODS AND DATA ANALYSIS

3.1 Data Collection and Methods

In order to prove the wadi-aquifer interaction in Faria catchment, quantity and quality analyses were conducted. Quantitative analyses combine various variables such as wadi flows, rainfall depths, and variability of the change in the groundwater table to conclude some relations (rainfall and wadi flows vs. change in groundwater table depths) in order to note if there is any influence of rainfall and wadi flow on groundwater level so as to prove the wadi-aquifer interaction from a quantity point of view.

Average rainfall data of February for the year 2006 was used in rainfall-water table relationships. These data were collected from four rainfall gauges in Faria catchment. These gauges are: Salim, Taluza, Tamun, and Tubas. Wadi flow readings were recorded and collected from Al-Badan flume which is about three kilometres from well 18/18/027 for February, 2006. Al-Badan Venturi flume was established in 2003 at Jiser Al-Malagi in the upper part of the lower Faria catchment to measure the runoff rates of Al-Badan wadi (See **Figure 6**). The Flume of Al-Badan wadi was designed to measure 25 m^3/s and 0.23 m^3/s of maximum and minimum flows respectively [3]. In addition, the changes in the water table levels of well 18/18/027 were recorded by using well loggers [5]. The year 2006 was chosen to conduct the quality analyses since it was considered as a heavy rainfall season, especially in the month of February. And so, this will give us a clearer picture of the interaction between the wadi and the aquifer in the catchment.

While, quality analyses try to combine various microbial and chemical pollutants concentrations with time throughout the year to get different relations to give another evidence of wadi-aquifer interaction from a quality point of view.

Three pollutants were chosen to conduct the qualitative analyses; one is microbiological (Fecal coliform bacteria), and the others are chemicals [Nitrate (NO_3^-) and Chloride (I^-)]. These pollutants are chosen intentionally since they are considered as primary pollutants in wastewater, and so the presence of these pollutants in groundwater gives other evidence that there is an interaction between the polluted wadi and the aquifer.

The groundwater samples for the qualitative analyses were taken regularly on monthly basis and the microbiological and chemical tests were conducted in the laboratories of WESI at An-Najah National University.

Wells (18/18/027) and (18/18/034) at An-Nasariah area were chosen to conduct the quantitative and qualitative analyses respectively since these wells are located next to the main wadi and loggers have been set up to well 18/18/027 to read the change in the water table depths. Major information relevant to the wells under consideration is summarized in **Table 2**.

Table 2: General characteristics of the wells under study

Well's serial number	Location	X (m)	Y (m)	Usage	Abstraction (m^3/d)	Aquifer	Basin	Depth to water table (m)
18/18/27	Faria catchment/An-Nasariah	186060	183610	Agricultural	2880	UC-T*	N-E**	25
18/18/34	Faria catchment/An-Nasariah	185500	183900	Agricultural	3360	PL***	N-E	27

* UC-T: Upper Cretaceous – Tertiary

****** N-E: North Eastern
******* PL: Quaternary – Pleistocene

It is clear from the above table that the groundwater table is not relatively deep from the surface and this increases the chances of interaction to take place during a short period of time. **Figure 7** shows the locations of the wells under study.

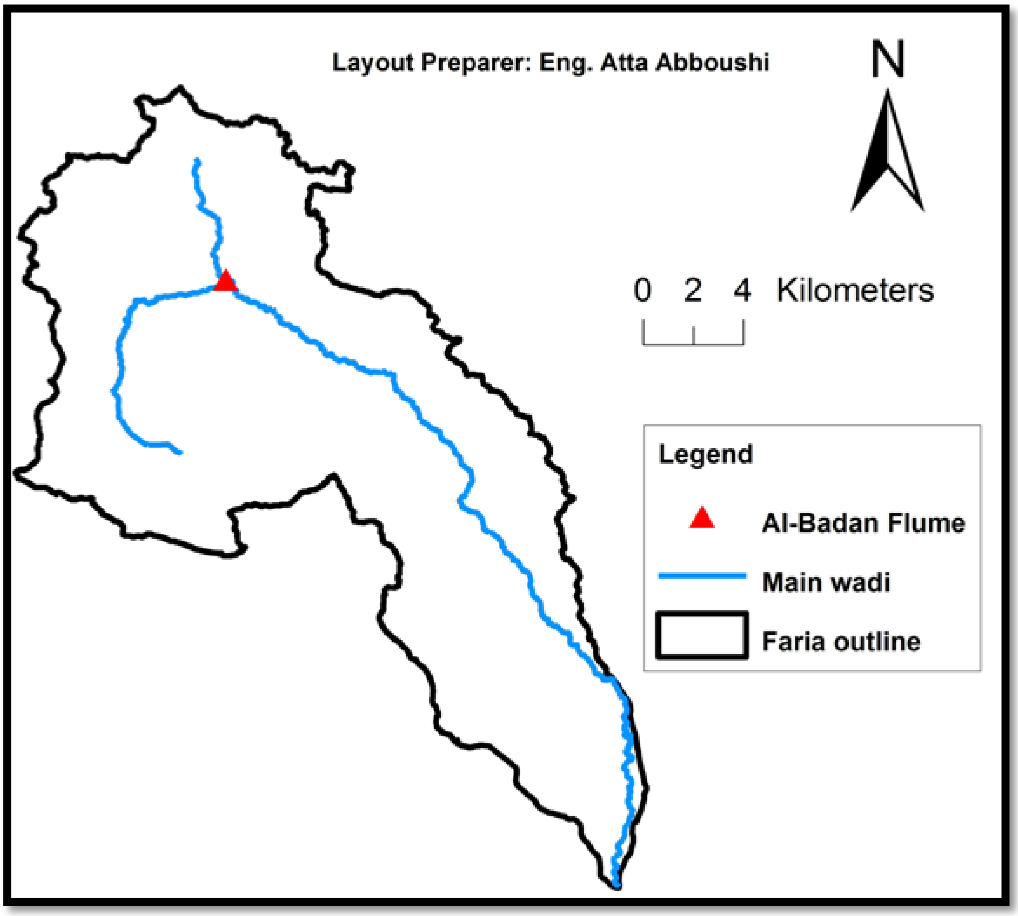

Figure 6: The location of Al-Badan flume at Jiser Al-Malaqi

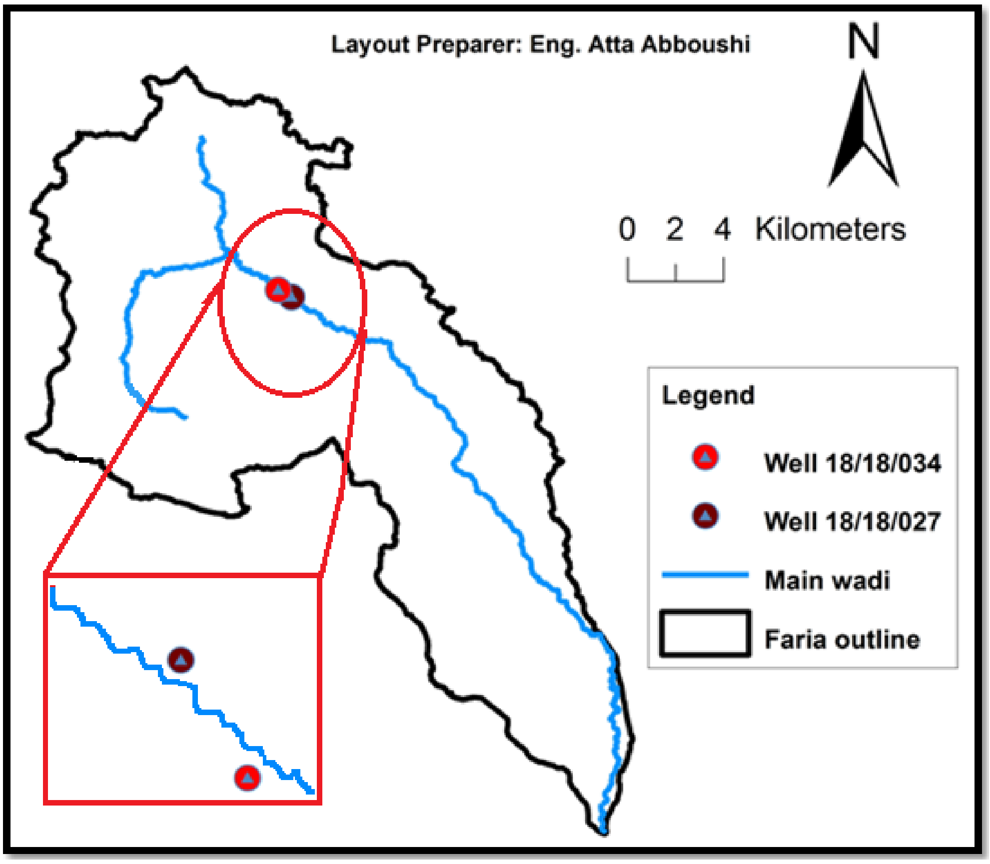

Figure 7: The locations of the wells under consideration

3.2 Quantitative Analysis

3.2.1 Groundwater Table and Rainfall

The first quantitative relations were developed between groundwater table variability of well 18/18/027 and rainfall as shown in **Figure 8**.

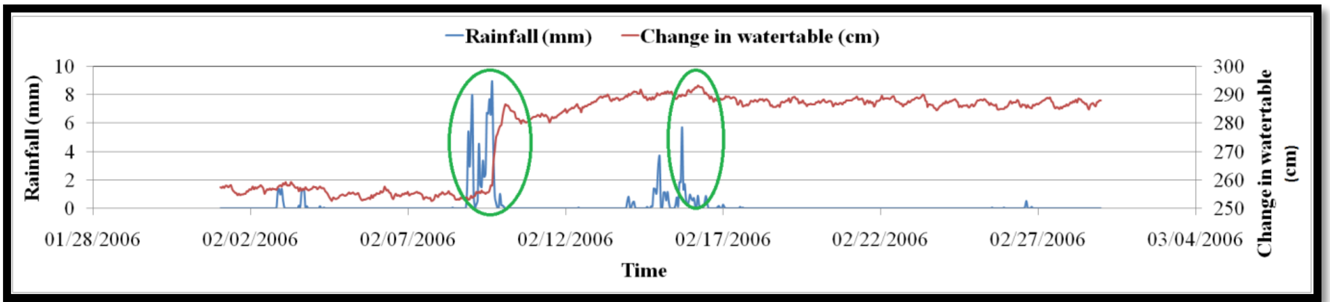

Figure 8: Change in water table – rainfall relationship of well 18/18/027 (February, 2006)

As seen above, at the beginning of the month when there are almost no rainfall events, the change in the well's water table is not significantly altered and it fluctuates about a certain value of 255 cm (this change was measured from the reference level of sensor) given that the depth to water table is less than 25 m. But when a considerable rainfall event took place on the 9th of February, the change in the water table level spiked to a value of 287 cm. Another rainfall event took place on the 15th of February and this was also reflected in the change of the water table level where it was locally higher after the storm than other adjacent readings. In general, the rise in the water table levels significantly after considerable rainfall storms is evidence that the hydrogeology of the region helps the interaction to take place between the wadi and the aquifer and proves the existence of a potential recharge to the groundwater aquifer.

Now, an important and influencing factor that can be concluded from rainfall – water table levels relationships is the delay time. The delay time is the time when the response of the groundwater table took place after a significant occurrence of rainfall events or considerable change in the surface flow [6]. In order to estimate a reasonable value of a delay time in the area, another three rainfall-water table relationships were developed for the months of December (2005), January, and March of the year 2006 (See **Figures 9, 10,** and **11**).

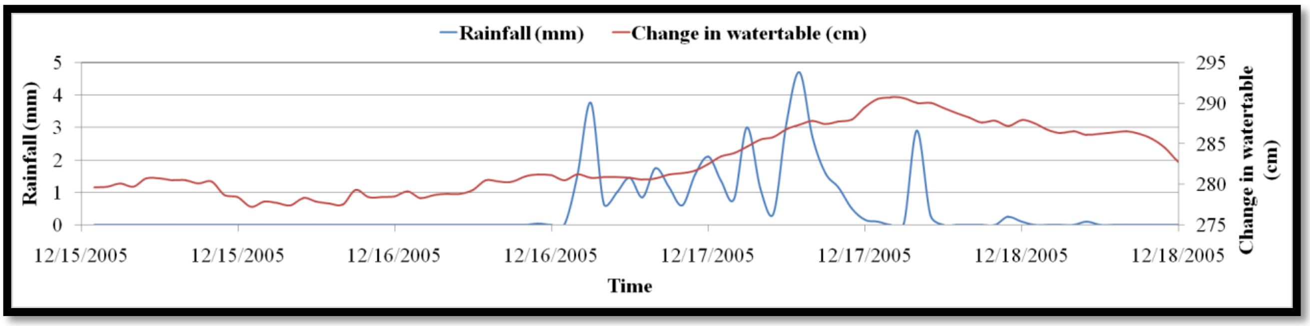

Figure 9: Change in water table – rainfall relationship of well 18/18/027 (December, 2005)

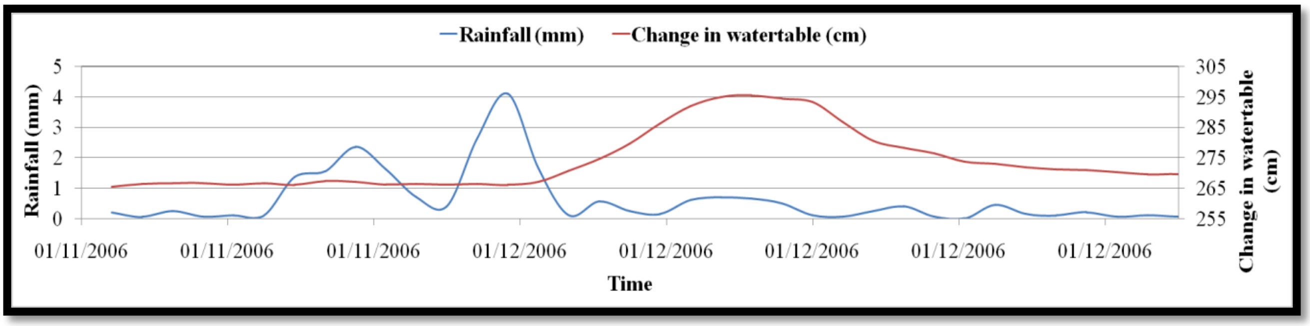

Figure 10: Change in water table – rainfall relationship of well 18/18/027 (January, 2006)

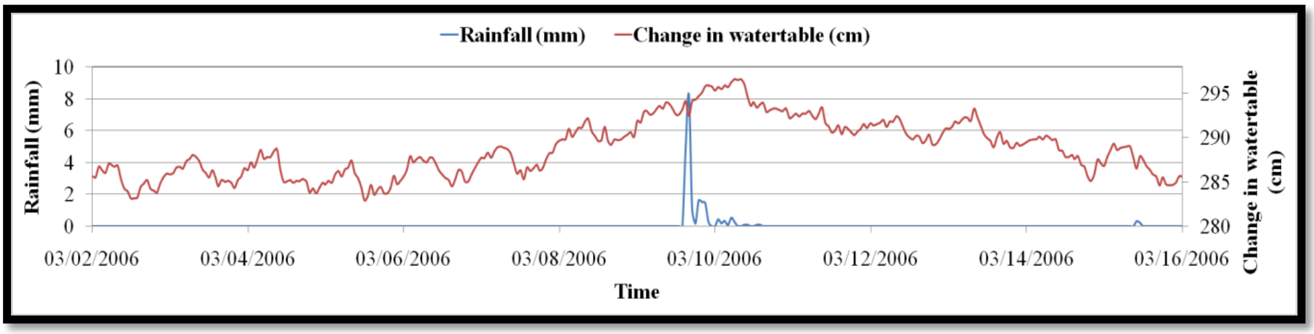

Figure 11: Change in water table – rainfall relationship of well 18/18/027 (March, 2006)

Generally, it is noted from the figures that the increase in the water table level begins after a storm event took place and reaches to its maximum value after a specific delay time depending on the soil's antecedent saturation conditions. This change in the water table levels in parallel with the change in the rainfall variability is evidence of wadi-aquifer interaction in the Faria catchment.

From the quantitative relations above, the difference between the rainfall peak time and the change in the water table peak time was estimated and stated as the delay time for well 18/18/027 (See **Table 3**).

Table 3: Different delay times estimated between the rainfall peak time and the change in the water table peak time for the well 18/18/027

Month/year	Rainfall peak time	Water table peak time	Delay time (Hour)
December/2005	17/12, 7 am	17/12, 3 pm	8
January/2006	12/1, 2 am	12/1, 10 am	8
February/2006	9/2, 4 pm	10/2, 2 am	10
March/2006	9/3, 4 pm	10/3, 6 am	14
Average delay time	-	-	**10**

The calculated delay time which is relatively short is evidence that the nature of the hydrogeological conditions in the area promotes the transmission of water from the surface to the aquifer quickly and easily, and therefore this confirms a high possibility for the wadi-aquifer interaction to take place in the catchment.

The hydraulic conductivity (**K**), which measures the ability of the medium to transmit water, can be estimated using the value of the average delay time determined above. The hydraulic conductivity determines the ability of the soil fluid to flow through the soil matrix system under a specified hydraulic gradient [7].

The hydraulic conductivity is classified into three main categories depending on soil lithologies as described in **Table 4**. As hydraulic conductivity increases, the chance of wadi-aquifer interaction to take place is also increases since the soil's ability to transmit water through the different layers heightens until it reaches to groundwater table.

The hydraulic conductivity in the unconfined aquifer in Faria catchment ranges from 2 to 200 m/d [8]. To estimate a reasonable value of a hydraulic conductivity at the vicinity of well 18/18/027 depending on the average delay time determined above, Darcy flux equation is used. The hydraulic gradient (**i**) and the effective porosity ($\mathbf{n_e}$) are taken approximately as 0.027 and 0.05 respectively [8]. The distance between the well 18/18/027 and the main wadi (**L**) is nearly 20 m.

Table 4: Typical features of various conductance categories for wadi-aquifer systems [9]

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)	> 10 m/d	0.01 – 10 m/d	< 0.01 m/d
Typical seepage flux	> 1000 m^3/d/km	10 – 1000 m^3/d/km	< 10 m^3/d/km
Ratio of seepage to total flow	> 0.5	0.1 – 0.5	< 0.1

After doing the required calculations, the following outcomes resulted:

The velocity (V) needed for the flow to reach the well 18/18/027 from the main wadi = L/ delay time = **48 m/d** (1)

Darcy flux (q) = $V.n_e$ = **2.4 m/d** (2)

Then, the hydraulic conductivity (K) = q/i = **89 m/d**. (3)

The estimated value of K is reasonably acceptable since it lies within the range of (2~200) m/d for the unconfined aquifer and referring to **table 4**, the soil in the region has high conductance since K > 10 m/d and so there is a high probability for the wadi-aquifer interaction to take place in the area.

Finally in this section, the well capture zone will be determined to assign the area that contributes flow to the well. The parameters that are used in determining the well's capture zone are summarized in **Table 5**.

Table 5: Parameters used in determining the capture zone of well 18/18/027

Parameter	Value	Unit	Reference
K (Hydraulic conductivity) =	89	m/d	Calculated
B (Aquifer thickness) =	45	m	[8]
i (Hydraulic gradient) =	0.027	_	[8]
Q (Well pumping rate) =	2880	m^3/d	Known from field visits
q (Darcy flux) =	2.4	m/d	Calculated

Firstly, the location of the stagnation point ($\mathbf{X_L}$) and the maximum width ($\mathbf{y_L}$) are determined by substituting in the following equations.

$X_L = (-Q/2\pi Bq) =$ **- 4.24 m** (4)

$y_L = \pm (Q/2Bq) =$ **13.32 m** (5)

Width of capture zone = 2 y_L = **26.64 m** (6)

If the transmission losses from the nearby wadi infiltrate and reach the capture zone of this well, the well will be contaminated (See **Figure 12**).

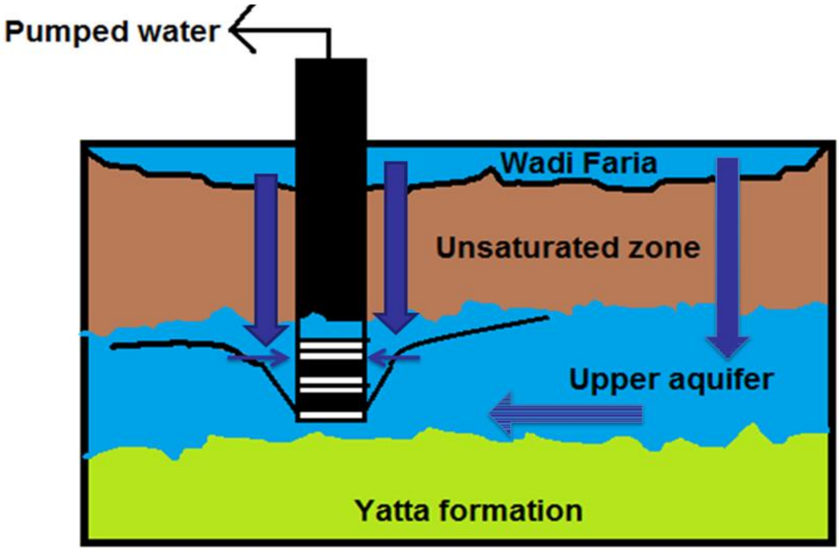

Figure 12: A pictorial sketch of the interaction processes between the wadi and the upper aquifer and the arrival of contaminants to the well's capture zone

3.2.2 Groundwater Table and Wadi Flow

Other quantitative relations were developed between groundwater table variability of well 18/18/027 and wadi flows as shown in **Figure 13**.

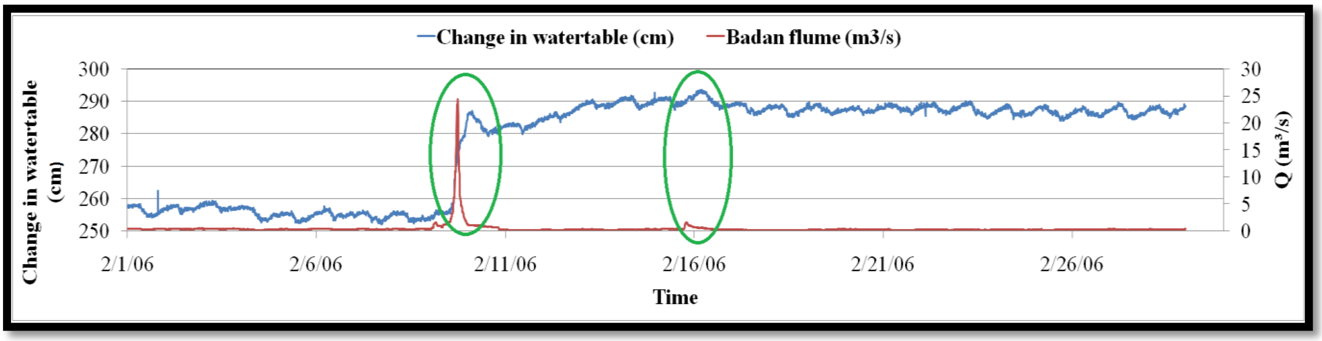

Figure 13: Change in wadi flow – water table relationship of well 18/18/027 (February, 2006)

From the figure, it is clear that at the beginning of the month where baseflow is dominant, the change in the well's water table is not significantly different. But when a considerable increase in surface runoff took place on the 9th of February, the change in the water table level spiked to a value of 287 cm (this change was measured from the reference level of sensor) given that the depth to water table is less than 25 m. Another small increase in the surface runoff of the wadi took place on the 15th of February and this was also reflected in the change of the water table level where it was locally higher after this increase than other adjacent readings. In general, the rise in the water table levels significantly after considerable increase in the wadi surface runoff is evidence that the hydrogeology of the region helps the interaction to take place between the wadi and the aquifer and also proves the existence of a potential recharge to the groundwater aquifer.

3.3 Quality Analysis

3.3.1 Chemical and Microbiological Analyses

The variations in the fecal coliform bacteria, nitrate, and chloride concentrations that found in groundwater from well 18/18/034 with time are depicted in **Figures14**, **15**, and **16** respectively.

It is clear from the figures that the pollutants have higher concentrations in summer than in winter, although the wadi is dry next to the well in the summer period; this result makes sense, because there is a high probability for the flow in the wadi upstream the well to infiltrate and move with the regional groundwater flow until it reaches the well's capture zone and because there is no rainfall in summer, the pollutants are very concentrated.

Also, it is important to mention that most of landuse and practices around the main wadi of Faria is categorized as agriculture. The local farmers use the natural organic fertilizers (manure) in addition to artificial agrochemicals such as ammonia and sulphur fertilizers. As well as most of the houses adjacent to the main wadi have no local sewage systems, they mainly use cesspits. So, in addition to the pollution that comes from the wadi, the agricultural and domestic wastewaters may infiltrate and percolate directly to the upper groundwater aquifer and later intersects with the capture zone of the well (See **Figure 17**). At the same time, because the use of organic fertilizers is relatively few in the area and a large portion of wastewater is evacuated from cesspits and poured directly into the main wadi in Faria catchment, the pollution from the wadi has a greater influence on the aquifer than the pollution resulted from the surface infiltration.

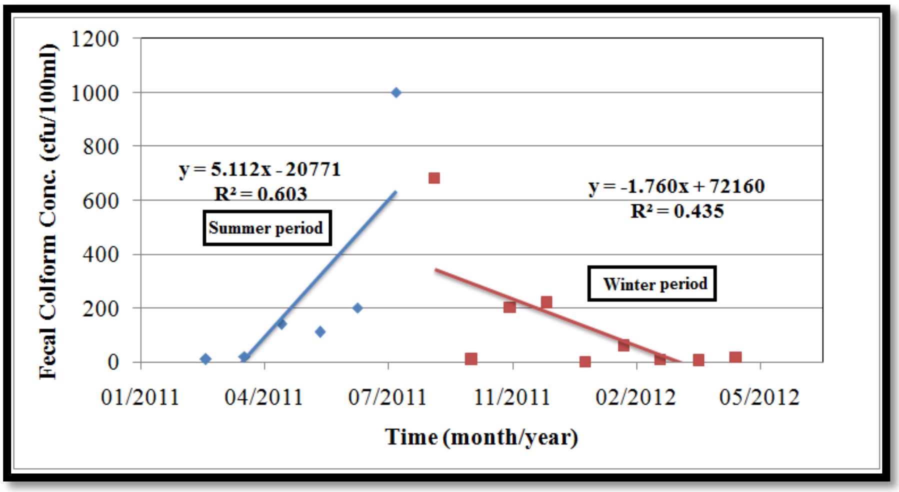

Figure 14: Variation in the fecal coliform concentration found in groundwater from well 18/18/034 with time and the trend of contamination

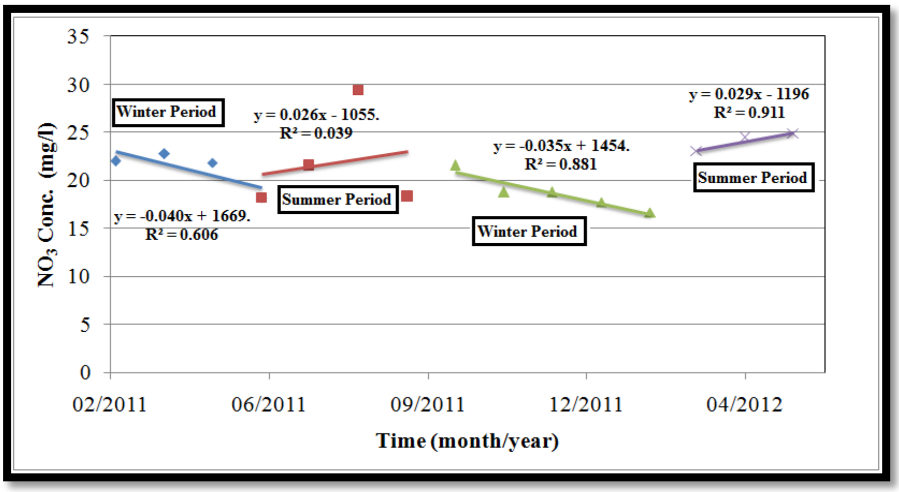

Figure 15: Variation in the nitrate concentration found in groundwater from well 18/18/034 with time and the trend of contamination

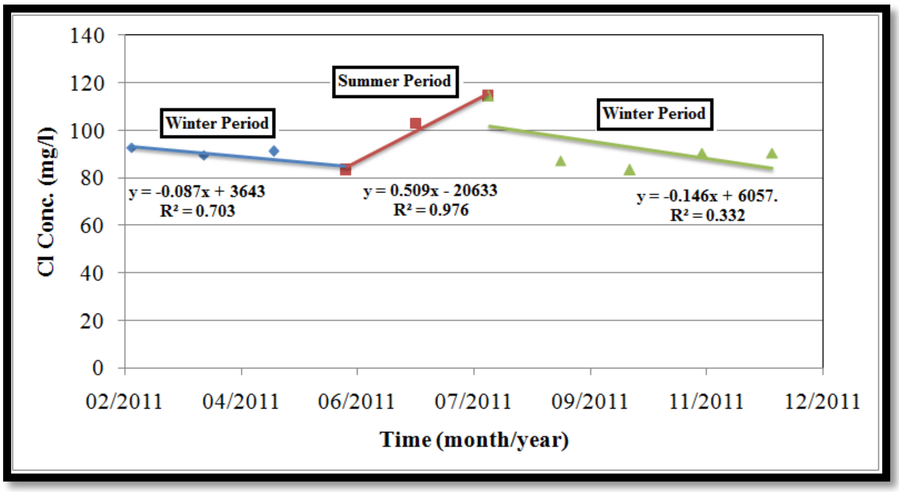

Figure 16: Variation in the chloride concentration found in groundwater from well 18/18/034 with time and the trend of contamination

Note that in all summer periods, the chemical and microbiological contaminations have increasing contamination trends while this is the opposite in all winter periods where the chemical and microbiological contaminations have decreasing contamination trends.

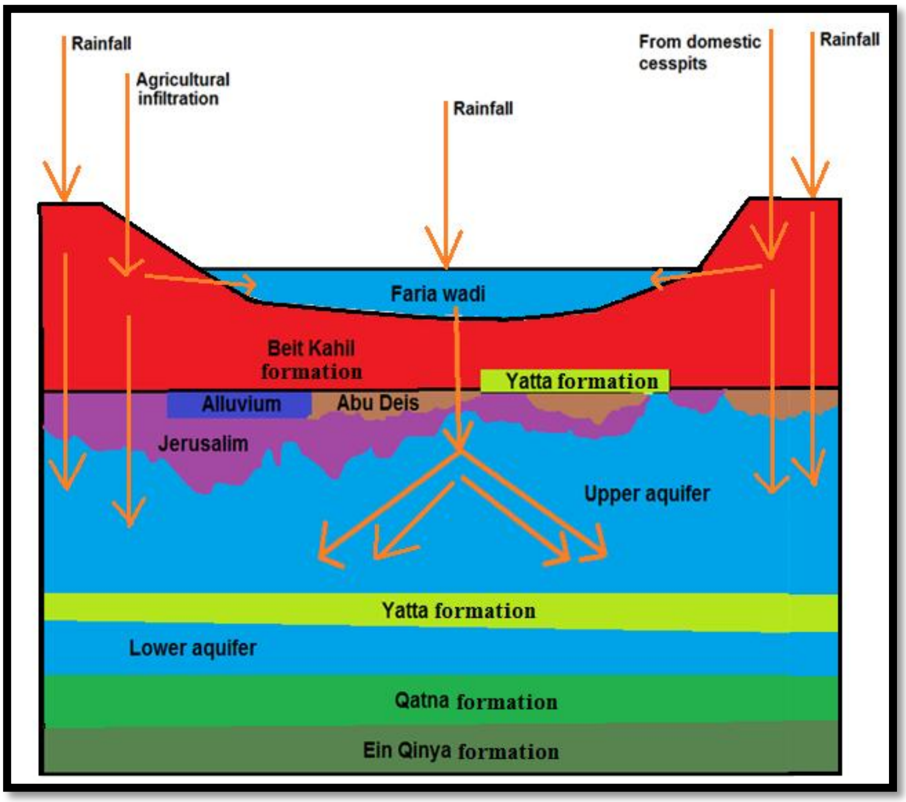

Figure 17: A simple sketch that shows the different pollutants that may reach the upper aquifer

4 CONCLUSION

This paper preliminarily investigated the occurrence of wadi-aquifer interaction in the semi-arid region of Faria and specifically at An-Nasariah area in the middle part of the catchment. The results indicate that the hydrogeological conditions of the area enhance the wadi- aquifer interaction in Faria catchment. The flow infiltrates the wadi bed, passing through the different lithological formations (which they have moderate to high values of hydraulic conductivity) until reaching the saturated zone. This was revealed when the quantitative relations of wadi flow readings, rainfall depths, and change in the groundwater table records were developed. These relationships showed that any slight variations in rainfall and wadi flow will reflect in the change of the water table level.

Also, this paper proved the potential existence of wadi-aquifer interaction from a quality point of view through developing relations that describe the variations in the concentrations of different microbial and chemical pollutants found in groundwater from a well that is located next to the polluted wadi. These relationships showed that the pollutants concentrations had higher trends in summer while they lowered in winter and this can be attributed to the lack of mixing with rainfall water that dilutes them in the wet season. Finally, a thorough analysis is required to better assess the hydrologic characteristics of wadi bed in Faria catchment; such characteristics include mainly the infiltration capacity and hydraulic conductivity.

5 ACKNOWLEDGEMENT

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