An-Najah National University

Faculty of Graduate Studies

A Preliminary Investigation of Wadi-Aquifer Interaction in Semi-Arid Regions: the Case of Faria Catchment, Palestine

By

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Dedication

My father's soul (mercy upon him), my mother (Deena) and my cousins (Momen and Mamoun)

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Firstly, praise be to Allah for completing this research. I would like to express my thanks and appreciation to my supervisors Dr. Mohammad N. Almasri and Dr. Sameer M. Shadeed for their supervision, ongoing support and advising. Special thanks presented to the defense committee members for the scientific reviewing of my thesis.

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My mother... whatever I spoke about you, I cannot give you your right. You have given me (and still) everything I needed despite the hard and difficult circumstances that we have lived together under. Thank you for your moral support, encouragement and patience.

I would like to express my sincere gratitude to our close neighbor, Mrs. Im-Nemir Touqan for her great encouragement.

Finally, I would also like to thank everyone who unnamed here and has presented me his/her support and contributed in the accomplishment of this thesis.

الإقرار

أنا الموقع أدناه مقدم الرسالةالتي تحمل العنوان:

A Preliminary Investigation of Wadi-Aquifer Interaction in Semi-Arid Regions: the Case of Faria Catchment, Palestine

أقر بأن ما اشتملت عليه هذه الرسالة إنما هي نتاج جهدي الخاص، باستثناء ما تم الإشارة إليه حيثما ورد، وأن هذه الرسالة ككل، أو أي جزء منها لم يقدم لنيل أي درجة أو لقب علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى.

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name:	**اسم الطالب:**
Signature:	**التوقيع:**
Date:	**التاريخ:**

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List of Abbreviations

Symbol	The meaning
OTIS	One-Dimensional Transport with Inflow and Storage
WESI	Water and Environmental Studies Institute
UNESCO-IHE	Institute for Water Education/ Netherlands
UWIRA	Impact of Untreated Wastewater on Natural Water Bodies: Integrated Risk Assessment
UPaRF	UNESCO-IHE Partnership Research Fund
PWA	Palestinian Water Authority
MCM	Million cubic meters
P	Average annual precipitation
PET	Average annual potential evapotranspiration
K_L	Longitudinal dispersion coefficient
V	Stream velocity
S_m	Mass flux per unit volume
EXACT	Executive Action Team
K	Typical hydraulic conductivity
i	Hydraulic gradient
n_e	Effective porosity
L	Distance between the wadi and the well under study
q	Darcy flux
B	Aquifer thickness
Q	Well pumping rate
X_L	The location of stagnation point
Y_L	Maximum width of well's capture zone
UC-T	Upper Cretaceous – Tertiary
N-E	North – Eastern
PL	Quaternary – Pleistocene
NO_3^-	Nitrate
Cl^-	Chloride
MCL	Maximum contamination level
M	Mass of tracer injected
F	The area under the tracer concentration curve
MP	Monitoring point
IP	Injection point
c	Tracer concentration
I	Integer
C	Character
D	Double precision
Conc.	Concentration
Min.	Minute
PPb	Part per billion

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Abstract

This thesis aims to investigate the potential existence of wadi-aquifer interaction in the semi-arid Faria catchment. Faria catchment, located in the northeastern part of the West Bank is considered as one of the most important catchments in the region due to the intense agricultural activities. Surface runoff in the catchment consists mainly from springs, 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 land. The groundwater in the catchment is the only water source for the agricultural and domestic uses. As such, wadi-aquifer interaction would be an important issue to investigate when considering the importance of groundwater in the catchment.

Many analysis methods were considered to highlight the potential existence of wadi-aquifer interaction. Analysis of the variability of water table elevation with both the variability of rainfall and wadi flows was carried out. In addition, the quality of groundwater was assessed through chemical and microbiological tests.Also,a tracer field experiment was implemented to quantify the proposed interaction.

The analyses show that the water table level in a selected groundwater well next to the main wadi significantly changed and spiked as a result of increasing rainfall and corresponding runoff in the wadi. This in turn provides a good evidence that the hydrogeology allows wadi-aquifer interaction to take place in the catchment. Also, the quantitative analyses revealed that the delay time in the area was relatively small and was estimated at 10 hours. This value of delay time also reflected in the value of the horizontal hydraulic conductivity of the formations at the vicinity of the well under consideration, which was calculated as 89 m/d using Darcy flux equation. And so, these formations have high conductance to transmit the water from the wadi to the aquifer.

Whereas, the quality analyses show that some chemical and microbial pollutants were found in the sampled well. This can be mainly attributed to untreated wastewater flows in the wadi, which provide another potential evidence of wadi-aquifer interaction in the catchment. As well as the trends of contaminations in the different seasons were plotted. They showed that the pollutants concentrations had higher trends in summer than in winter.

The tracer field experiment was conducted at An-Nasariah area in the middle part of Faria catchment using Uranine as a conservative tracer material. A representative reach of 600 m was chosen, and divided into four equally long distances. A concentration curve was plotted at each section (monitoring point) with the help of OTIS, a solute transport model for streams and rivers. Then, each concentration curve was converted to an average value of flowrate in the section. Finally, each two successive flowrates were subtracted to quantify the interaction.

The tracer field experiment proved that transmission losses took place and infiltrated through the wadi bed (they became a potential recharge to groundwater). The percent loss in the flowrates values in the different sections ranged from 4.8% to 68.3%. As well as the hot spot area along the selected reach was located by determining the section, which has the largest loss in the flowrates between its monitoring points.

Chapter One
Introduction

1.1 General Background

Approximately one third of the world's land area can be classified as arid to semi-arid regions (Rogers, 1981). Extreme climatic variability and subsequent hydrological fluctuations are typical in these regions. The climatic variability occurs seasonally, inter-annually, and on longer time frames. Consequently, arid to semi-arid areas are subjected to frequent and severe droughts and infrequent but significant floods (I.D. and Rassam, 2009).

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 (Abdin, 2006). Groundwater resources support agriculture by providing significant quantities of water for irrigation, especially in regions where the climate is dry and crop production without enhanced irrigation is not feasible. Therefore, groundwater is considered as the most important source of fresh water in arid and semi-arid regions (Janchivdorj, 2008).Nowadays, the groundwater and springs provide essentially all of the consumed water in Palestine. So, groundwater is considered as the most important source for domestic and agricultural uses in the West Bank.

However, the importance of this source is threatened by contamination. Groundwater pollution is caused by substances originating from many different activities. Many of them originate from man's direct use of water and others from indirect contamination through the soil zone (Janchivdorj, 2008).

Groundwater pollution occurs when man-made products such as gasoline, oil, and chemicals get into the groundwater and cause it to become unsafe and unfit for a certain specific use. Some of the major sources of these products, called contaminants, are storage tanks, cesspits, hazardous waste sites, landfills, fertilizers, pesticides, herbicides along with other chemicals[1].

The upper groundwater aquifer system of the Faria catchment is usually utilized through springs and agricultural wells which are used also for domestic uses. During wet years, when the spring's discharges are high abstraction from wells reduces, while pumping increases in dry years (Shadeed et al., 2011).

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 (Jayyousi and Srouji, 2009).

Faria catchment is one of the most important catchments in the West Bank since it is considered as the food basket of Palestine due to the intense agricultural activities. However, the catchment is under water pollution threats and quantity stress.

Sampling and analyzing water quality for different water resources in the catchment revealed that most of these resources are polluted and

[1] **http://www.groundwater.org/gi/sourcesofgwcontam.html (last viewed on 16/4/2013)**

contaminated with different levels of potential environmental risks due to the different surrounding pollution sources. (Shadeed et al., 2011).

Wadi flow in the catchment consists mainly from the spring discharge of Badan and Faria areas (located in the catchment), 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 land. This mix of water and wastewater meets at Al-Malaqi Bridge and continues flowing downstream through the agricultural areas.

The polluted wadi flow is of high potential to pollute groundwater aquifers 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 connectivity of the formations. This situation has compelled the motivation to conduct a preliminary investigation to understand the wadi-aquifer interaction 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 1).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.

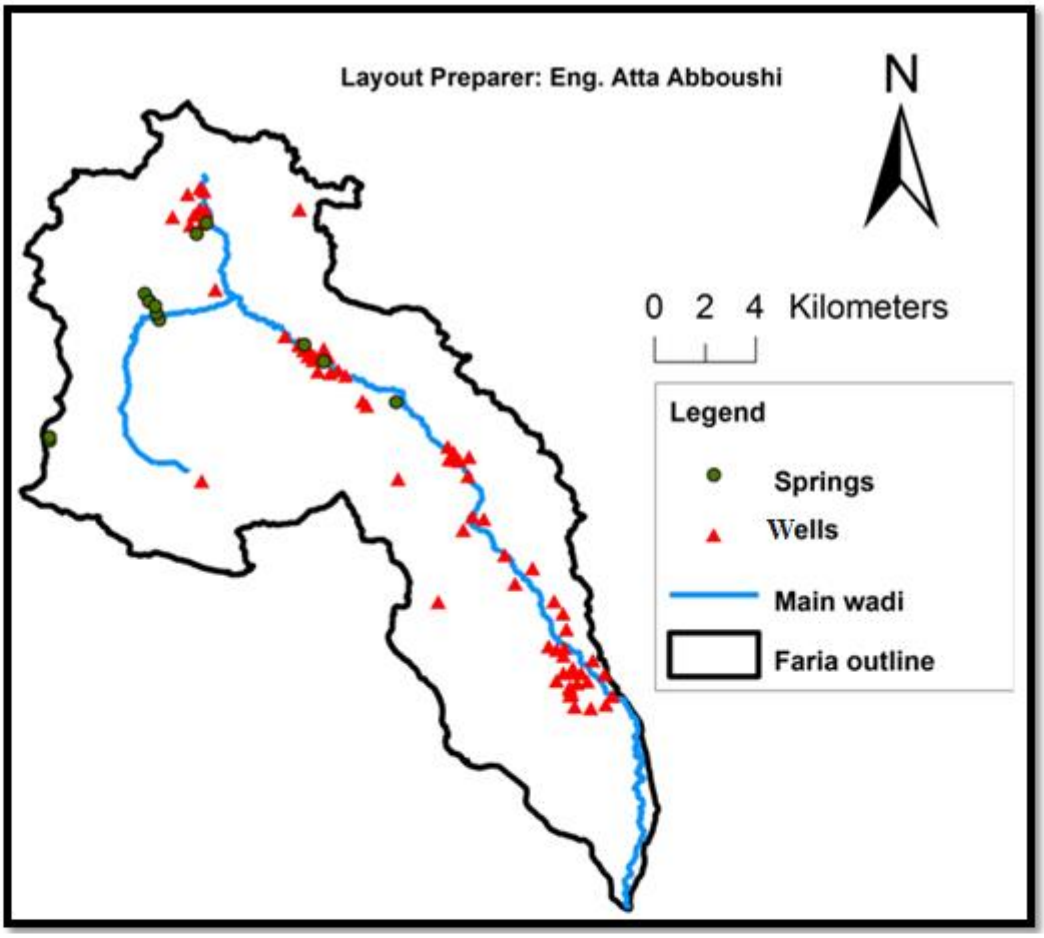

Figure 1: The distribution of the wells and springs along the main wadi in the Faria catchment

This thesis aims to provide evidence for wadi-aquifer interaction in the Faria catchment through quantity and quality analysis of rainfall variability, subsequent wadi flows, and the change in water table levels as well as groundwater quality data. In addition to that, a tracer field experiment was conducted to investigate the proposed interaction. 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 by controlling the existence and location of pollution sources.

1.2 Research Objectives

The following are the main objectives of this research:

1. To comprehend the specificity of wadi-aquifer interaction process in semi-arid areas.
2. To investigate the potential existence of wadi-aquifer interaction in the Faria catchment quantitatively and qualitatively.

1.3 Research Hypothesis

The main source of contamination to the upper groundwater aquifer is the wadi-aquifer interaction in the Faria catchment.

1.4 Research Questions

This research will answer the following two main questions:

1. Do transmission losses occur along the main wadi channel of Faria catchment and contribute to aquifer's contamination?
2. Does the hydrogeology enhance the wadi-aquifer interaction to take place in the catchment?

1.5Research Methodology

The overall research methodology is depicted in Figure 2.

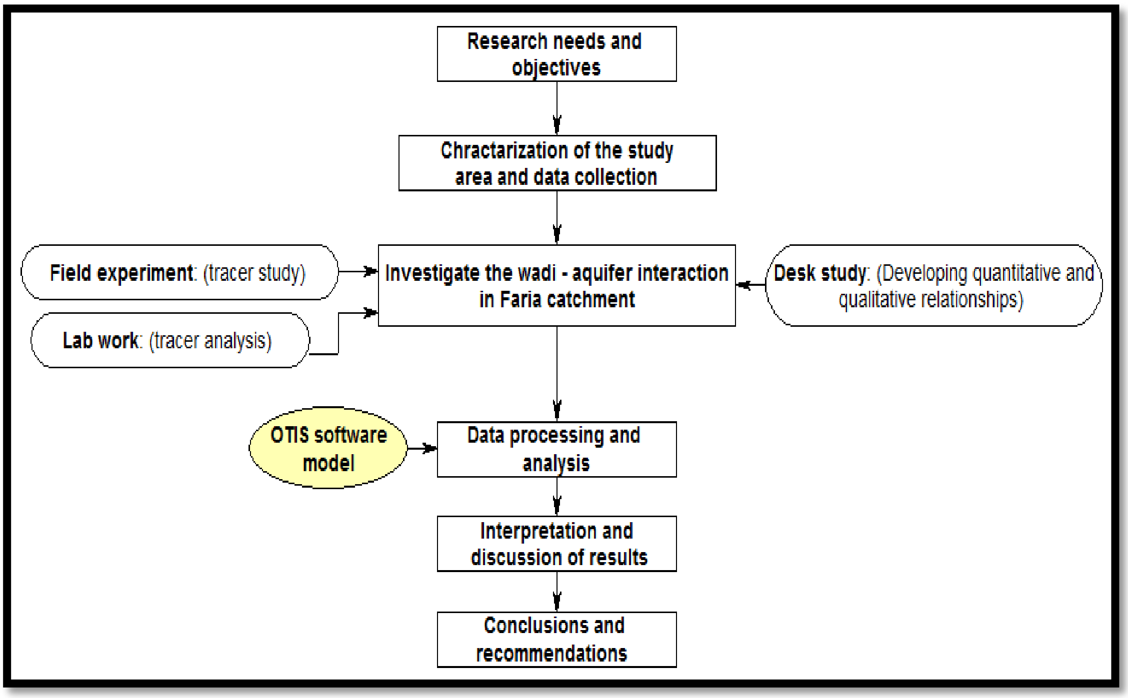

Figure 2: Research methodology

To achieve the research objectives, firstly the study area is characterized, and then all relevant data (hydrologic, hydrogeologic, geologic, geographic, topographic, and hydrochemical data) are collected from different sources (e.g. books, reports, published papers, interviews, meetings, and field investigations and experiments).

These data will be used in comprehending the mechanism of the wadi-aquifer interaction. The main research objective is to prove and explore the potential existence of this interaction in the Faria catchment.

Tracer-based field experiment was conducted to prove the wadi-aquifer interaction in the catchment. The tracer-based field experiment is 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. The proposed tracer experiment was preceded by determining a specific reach along the main wadi, determining a tracer type, and a tracer dose mass.

Also, a One-Dimensional Transport with Inflow and Storage (OTIS) model to simulate the observed data concentrations taken from the tracer field experiment was used.

Desk studies were conducted through developing quantitative analysis of rainfall records, wadi flows, and water table levels as well as qualitative analysis of groundwater wells.

A representative 600 m reach along the main wadi at An-Nasariah area was selected and divided into four equally sized distances each of 150 m. After doing the required measurements, one injection point and four monitoring points were determined. After doing the sampling process, all the samples were analyzed using a field fluorometer. For each monitoring point, the observed concentrations were drawn and when needed, they were simulated using the OTIS model. Then, each concentration curve was transformed to an average flowrate by dividing the mass of tracer that will be injected at the injection point by the area under the concentration curve at each monitoring point. Finally, each two successive flowrates were subtracted to quantify the interaction.

Data obtained from field experiments, laboratory analysis, and desk studies were processed and analyzed by MS Excel. Accordingly, the obtained results were interpreted and discussed to gain a deeper understanding of the wadi-aquifer interaction in Faria catchment. Finally, conclusions and recommendations were presented.

1.6 Thesis Organization

This thesis is organized as follows: Chapter one provides a brief introduction about the research, the main objectives, research hypothesis, research questions, the methodology, and description of the study area. Chapter two provides brief gatherings from the literature include some research terminology, brief understanding about wadi-aquifer interaction, fate and transport of contaminants, and different related case studies. Chapter three presents the quantitative and qualitative analyses of wadi-aquifer interaction in Faria catchment. The field experiment of the tracer study is described in chapter four. Chapter five presents the conclusions and recommendations.

1.7 Description of Faria Catchment

1.7.1 Geography and Topography

Faria catchment is a 320 km^2area that drains into the north eastern slopes of the West Bank from Nablus to the Jordan River (See Figure 3).Topography is a unique feature of Faria catchment since it 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 (See Figure 4).

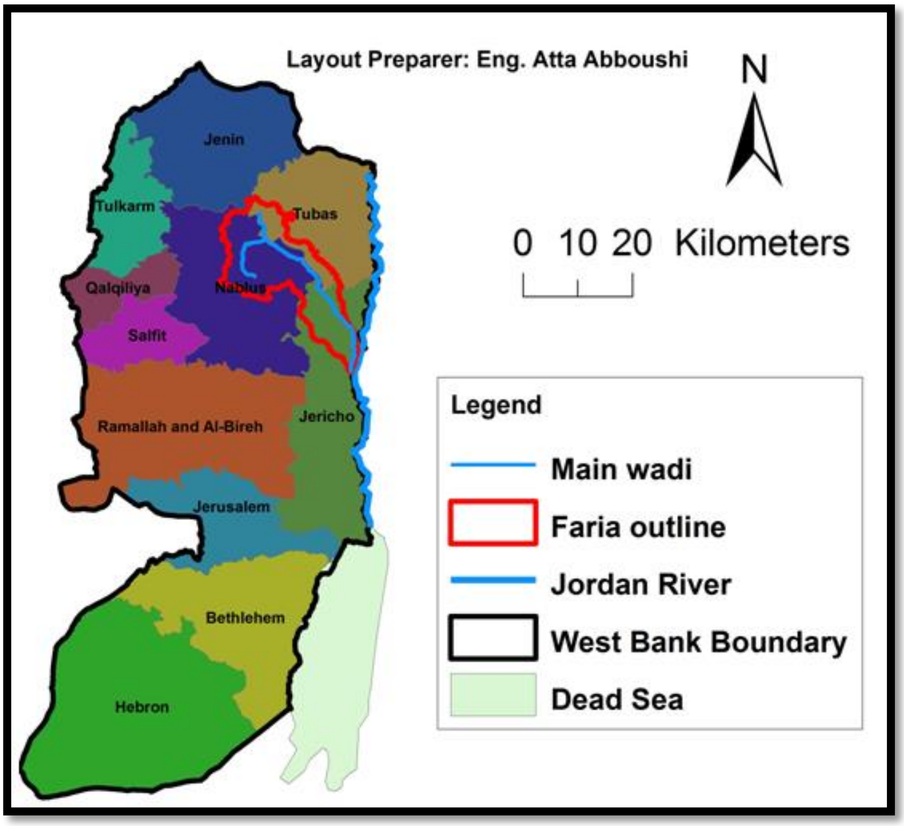

Figure 3: Location map of Faria catchment

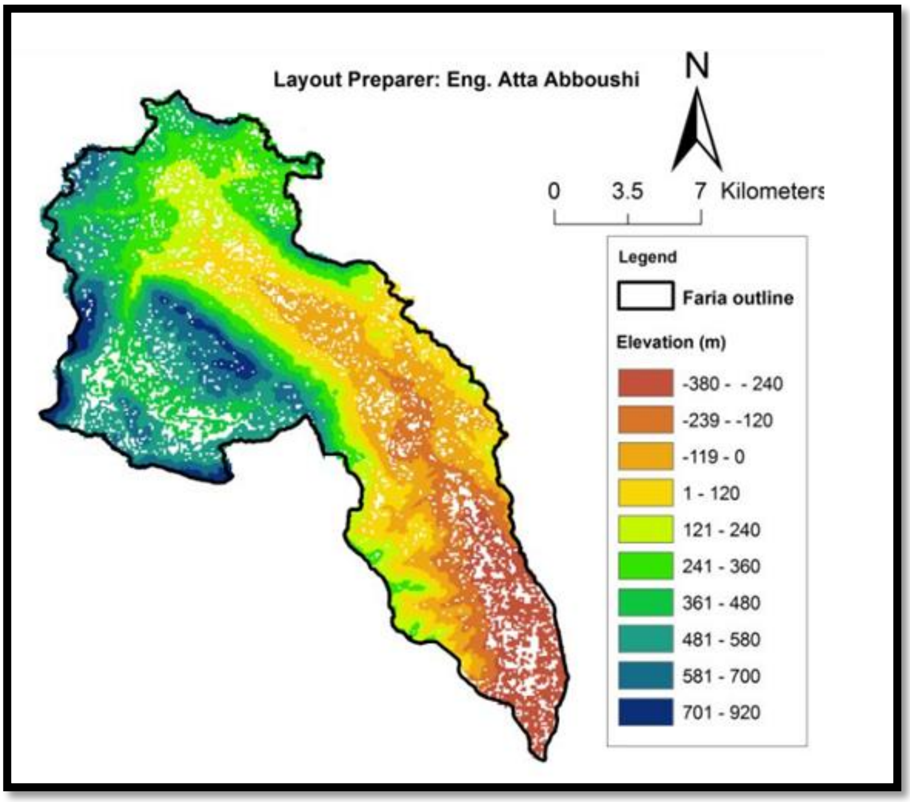

Figure 4: Topography of Faria catchment

1.7.2Water Resources

In Faria catchment, water resources are either surface water or groundwater. Faria catchment lies almost completely over the eastern aquifer basin in the West Bank (See Figure 5). There are about seventy wells in the catchment; of which sixty one are agricultural, four are domestic, and five wells are totally utilized by the Israelis. Based on the available data from the Palestinian Water Authority (PWA), the total average utilization of the Palestinian wells ranges from 4.4 to 11.5 MCM/year. Also, there are thirteen fresh water springs in the catchment. Based on the available data, the annual discharge from springs varies from about 4.1 to 37.8 MCM/year with an average amount of 14.3 MCM/year (Shadeed et al., 2011). Figure 6 depicts the distribution of the springs and wells in the catchment. The surface waterflow in the catchment is a mixture of:

1. Groundwater from springs.
2. Runoff generated from winter storms.
3. Untreated wastewater from the eastern part of Nablus City and untreated wastewater from Al- Faria Refugee Camp.
4. Return flow from the adjacent agricultural land (Agricultural runoff).

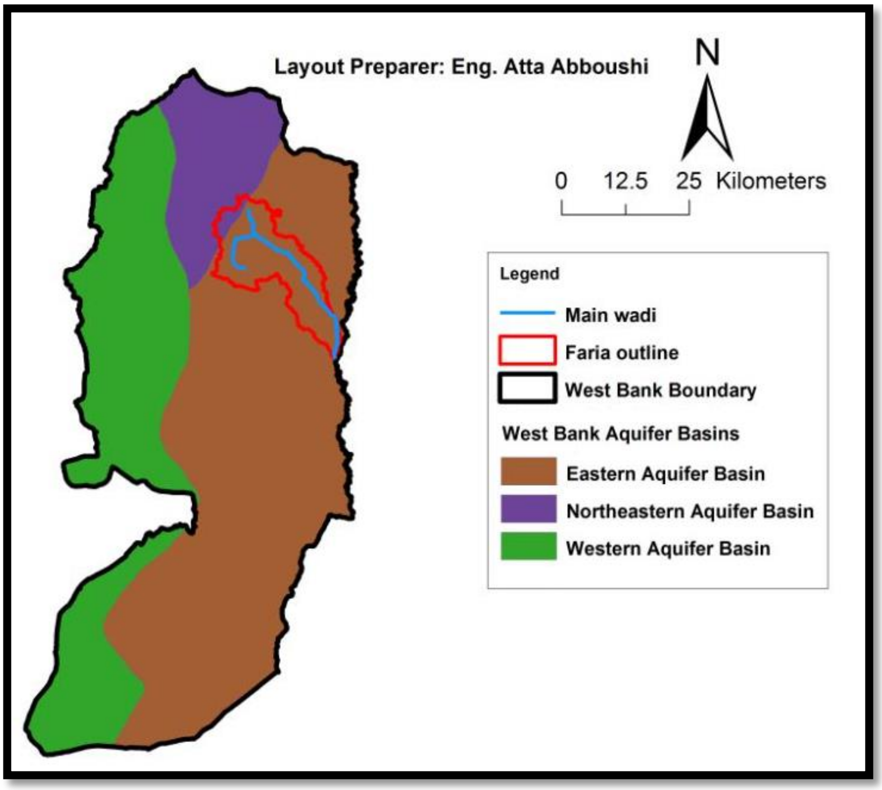

Figure 5: Location of Faria catchment with reference to the eastern aquifer basin

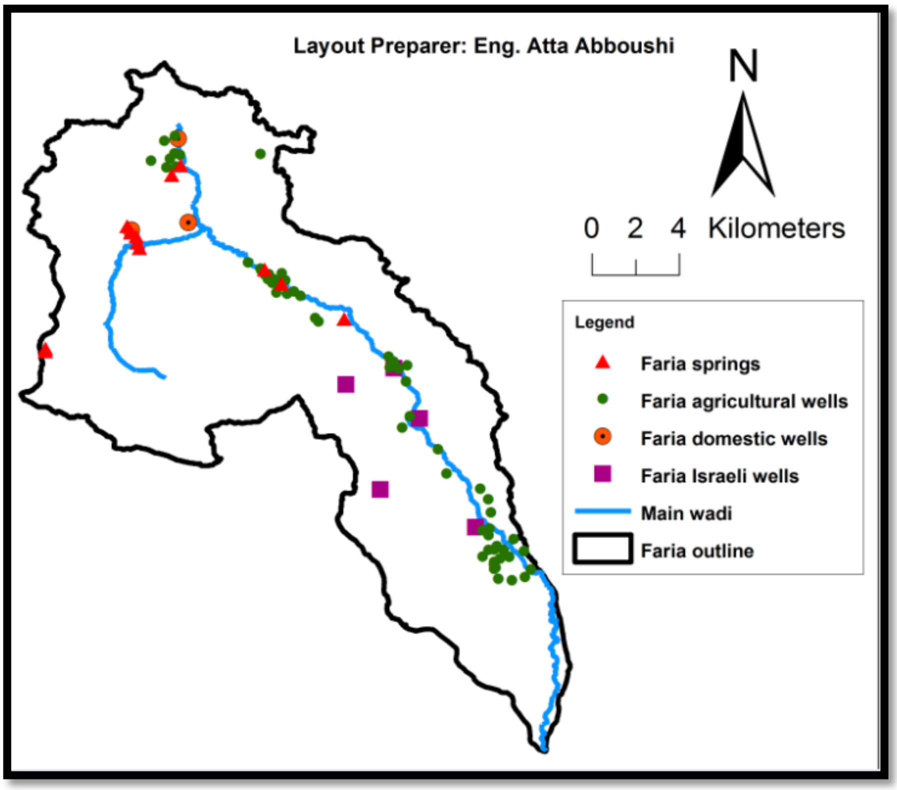

Figure 6: Water resources in Faria catchment

1.7.3 Soil and Landuse

1.7.3.1 Soil

The major soil types in Faria catchment are Terra Rossas Brown Rendzinas soil and Loessial Seozems. These two types are taking 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.

1.7.3.2 Landuse

Since Faria catchment is one of the most important agricultural areas in the West Bank, the main economic activity in the area is agriculture (See Figure 7). The percentages represented by landuse classes are shown in Figure 8. While, the landuse map is shown in Figure 9.

Figure 7: The agricultural land surrounding the main wadi of Faria catchment at An-Nasariah area upstream the agricultural wells in the region

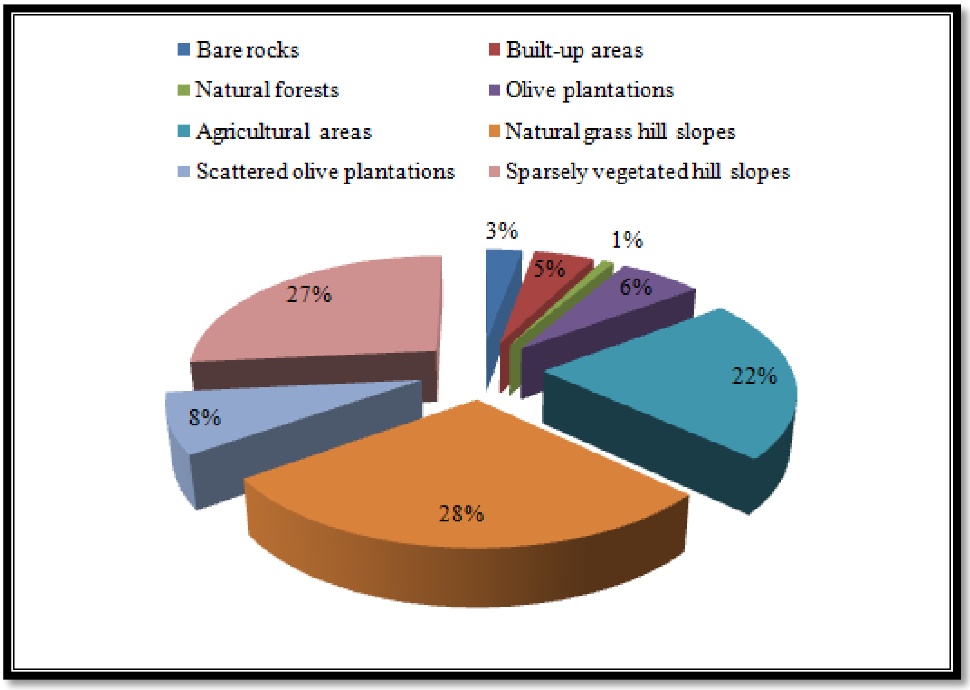

Figure 8: Percentages of landuse classes in Faria catchment

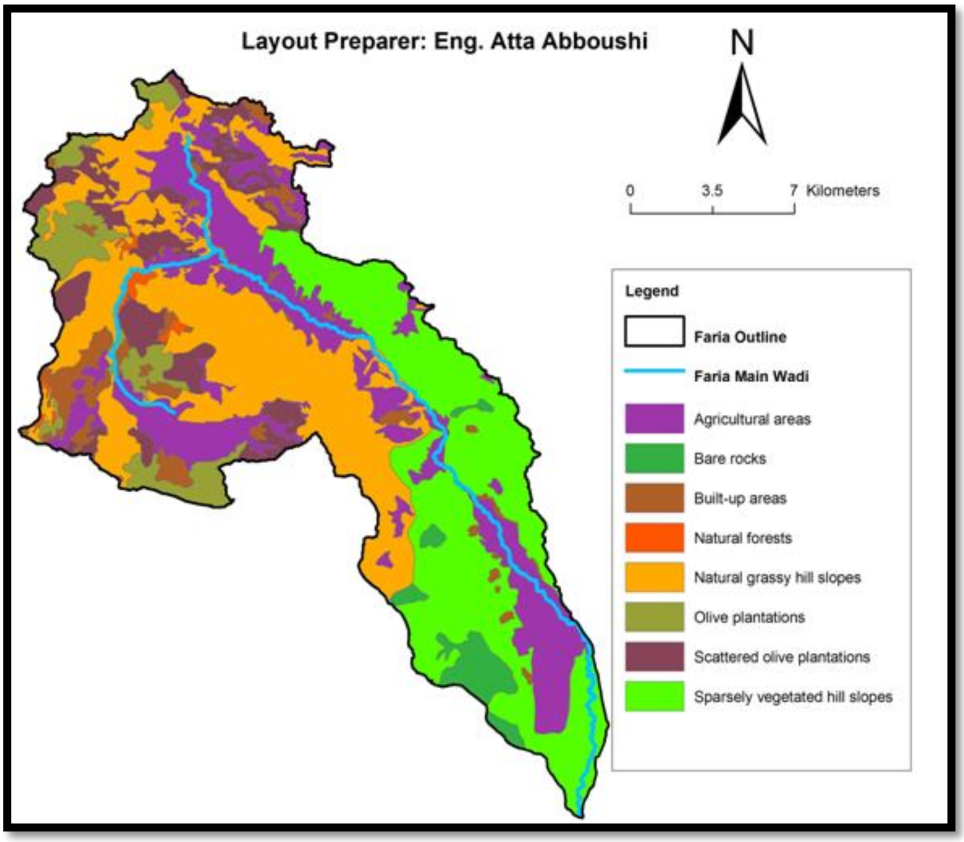

Figure 9: Landuse map in Faria catchment

As shown in Figure 9, the main wadi of Faria is flowing through the agricultural areas in the catchment. The agricultural areas form more than 40% of the total area of the catchment. Most agricultural crops in the catchment are: citrus, olives, and various types of vegetables. Some of these crops are irrigated, others are rainfed, and the rest are irrigated at the beginning of their life cycle and later they depend on rainwater. So, the uncontrolled agricultural activities in the catchment will affect the water quality of the wadi through the return flow from the surrounding agricultural land, and later on the quality of the groundwater aquifer.

1.7.4 The Hydrologic Classification of Faria Catchment Climatic Zones

According to the classification of UNESCO (1984)an area can be considered as arid and semi-arid when ($0.05 \leq P/PET < 0.20$) and ($0.20 \leq P/PET < 0.50$), respectively, where P is the average annual precipitation in (mm) and PET is the average annual potential evapotranspiration in (mm).Potential evapotranspiration is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming no control on water supply[2].

In Faria catchment, there are two weather stations. The first is located in Nablus and the second is in Al-Jiftlik. From the available data, the hydrological classification of Faria catchment was obtained and summarized in Table 1.

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[2]**http://www.physicalgeography.net/fundamentals/8j.html (Last viewed on 20/6/2013)**

Table 1: The hydrological classification of Faria catchment (Shadeed, 2008)

Station	P (mm)	PET (mm)	P/PET	The classification
Nablus	650	1400	0.46	Semi-arid
Al-Jiftlik	200	1540	0.13	Arid

1.7.5 Pollution Sources Contributing to the Wadi's Contamination in Faria Catchment:

A. Solid waste: Lack of sanitary landfills in the catchment results in throwing the solid waste randomly along the main wadi of Faria. Hence, leachate from solid waste will potentially contaminate the wadi in the catchment.

B. Liquid waste: This kind of waste is divided into three main types:

1. **Untreated wastewater discharge** from the eastern part of Nablus City and from Al-Faria Refugee Camp.
2. **Agricultural runoff** (draining into the main wadi) due to excess irrigation from the adjacent agricultural land which commonly use sprinklers and furrows as dominant irrigation methods. Agricultural runoff contains complex pollutants due to uncontrolled agricultural activities resulted from the use of natural organic fertilizers (manure), in addition to artificial agrochemicals such as ammonia and sulfur fertilizers, pesticides, and herbicides.
3. **Raw wastewater** that is generated in the catchment may infiltrate directly to the upper unconfined aquifer through cesspits or poured directly into the main wadi (from evacuated wastewater from

cesspits) due to lack of local sewage networks and thus it may threaten the groundwater quality.

Figure 10 (a) shows a plan view of a section that is taken at An-Nasariah area, where the surrounding agricultural land and two agricultural wells appear (these two wells were used for conducting quantity and quality analyses as described in Chapter 3). The arrows in Figure 10 (a) represent the various types of pollutants that contribute to wadi's contamination.

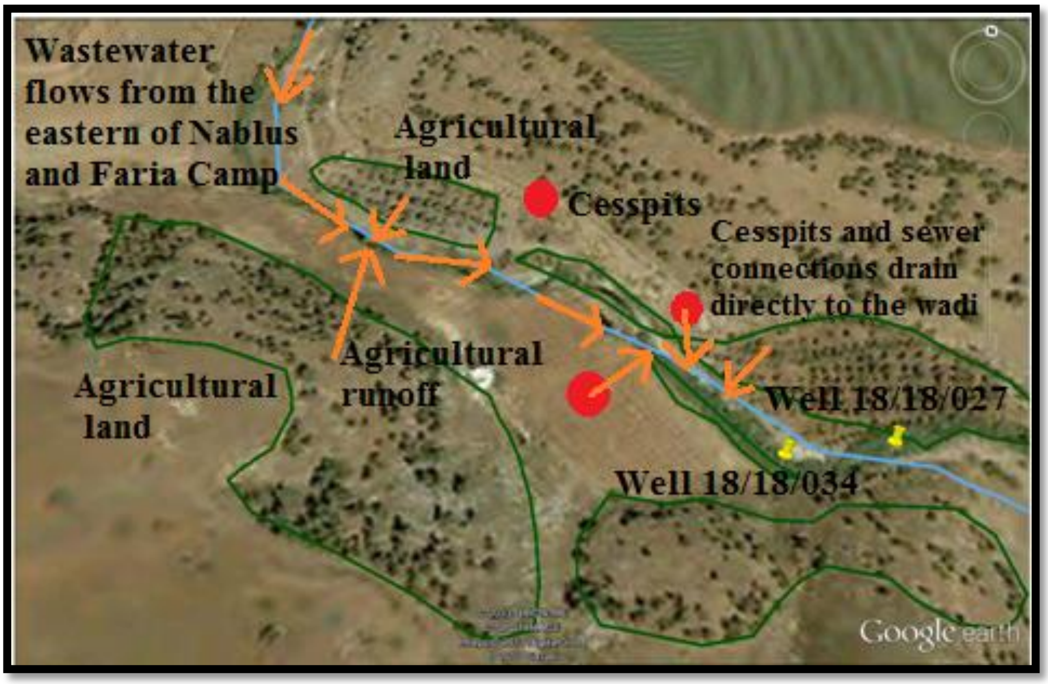

Figure 10 (a): All potential pollution sources to a selected reach located at An-Nasariyah area in Faria catchment (Source: Google earth)

Figure 10 (b) is a picture for a section at An-Nasariah area that depicts how the different pollutants are contributing to the wadi's contamination upstream the agricultural wells in the area.

Figure 10 (b): The wadi segment at An-Nasariah area that describes the pollutants contributing to the wadi upstream the agricultural wells in the region

1.7.6 Seasonal Variations of Wadi's Flow

Through several field visits, many variations in the wadi's flow were noticed in different weather circumstances; in summer apparently there is no flow in the wadi as shown in Figure 11 except for wastewater and spring flow. While, on contrary in winter where there is often a considerable flow in the wadi as shown in Figure 12 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 m^3/s to 24 m^3/s according to the different weather conditions (Shadeed, 2008).

Figure 11: A section in the main wadi of Faria at An-Nasariah area in summer

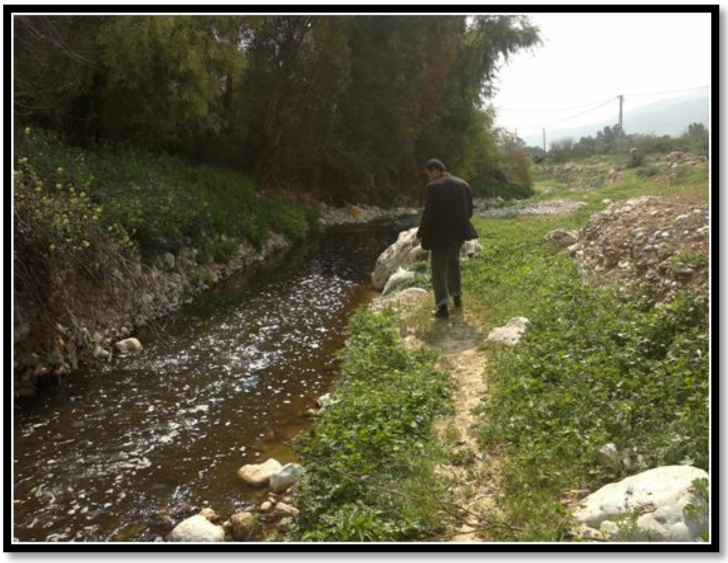

Figure 12: A segment in the main wadi of Faria at An-Nasariah area in winter

1.7.7 The Hydrogeology of Faria Catchment

The hydrogeology plays a key role in the occurrence of wadi-aquifer interaction, since it controls the movement of the flow and to 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 Figure 13). 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.

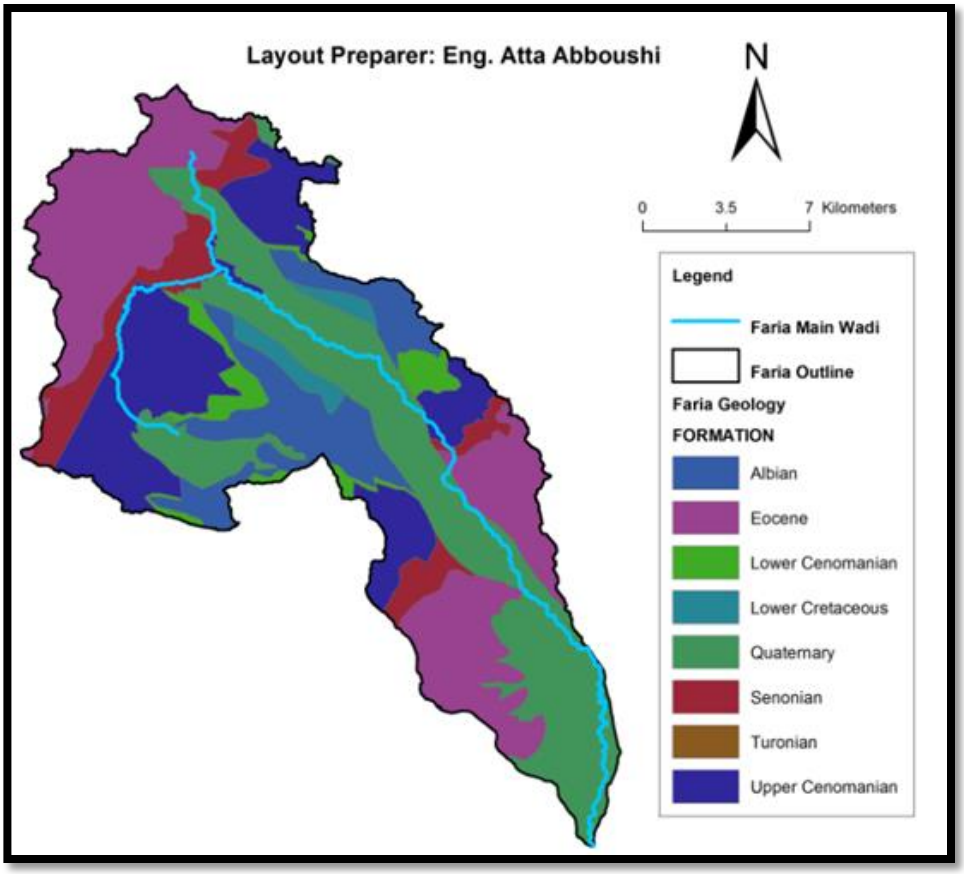

Figure 13: Geologic map of Faria catchment

In order to understand the movement of the flow from the wadi to the aquifer, the geological layers existed above the saturated zone should be well understood. Some of the geologic formations that exist above the saturated zo

ne are summarized in Table 2.

Table 2: The layers existed above the saturated zone in Faria catchment (EQA, 2004 and Saleh, 2009)

Geologic Formation	Depths Ranges	Lithology
Jenin Formation	Up to 200 m	Reef limestone, bedded limestone, limestone with chalk
Jerusalem Formation	(50-120) m	Thinly bedded limestone and dolomite
Hebron Formation	(105-260) m	Hard dolomistic limestone and chert rocks
Bethlehem Formation	(40-110) m	Limestone, dolomite with chalk, and marl massively bedded with a well-developed karst
Upper Beit Kahil Formation	(10-50) m	Dolomite and dolomistic limestone
Yatta Formation (Aquitard)	Upper Yatta: (5-15) m Middle Yatta: (40-50) m	Marly limestone interbedded with dolomistic limestone or dolomite. This formation has outcrops at small localities in the middle and upper part of the catchment

Note that all the layers which are located above the groundwater table have high to moderate hydraulic conductivities (See Table 5), 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 part of the catchment and does not extend completely above the water table which ranges from 25 to 27 m from the ground surface at An-Nasariah area.

Chapter Two

General Definitions and Literature Review

2.1 Terminology

2.1.1 Wadi System

It is the term that refers to a dry (ephemeral) riverbed that contains water only during times of heavy rain or simply an intermittent stream[3]. Most of the wadis in the arid and semi-arid regions are losing wadis, since the water 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 (Figure 14 A) where there is a hydraulic connection between the wadi and the aquifer and perched losing wadis (Figure 14 B) where the hydraulic connection does not exist and in this case the wadi recharges the aquifer through vertical flow. Note that in most cases, streams are called rivers when they become seventh order streams or higher.

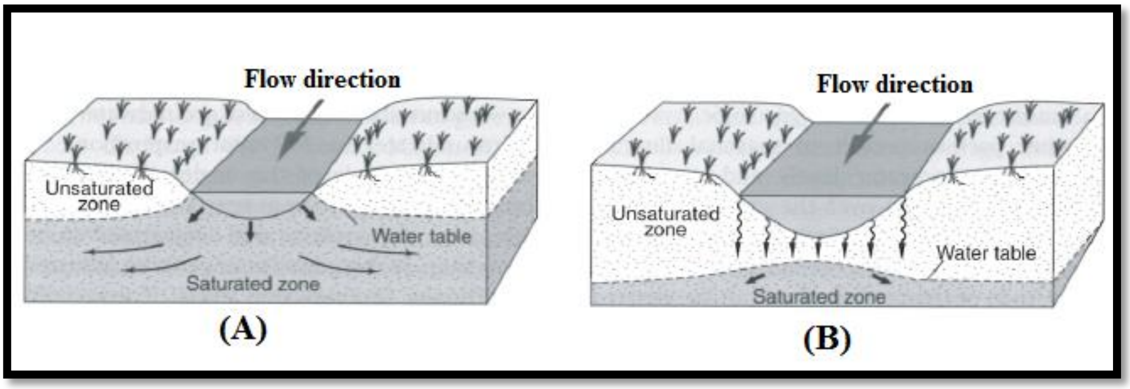

Figure 14: A) Contagious losing wadi, B) Perched losing wadi[4]

2.1.2 Aquifer System

Groundwater is the water that occurs in the tiny spaces(called pores or voids) between the underground soil particles or in the fractured rocks. The

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[3]http://en.wikipedia.org/wiki/Wadi (last viewed on 16/4/2013)
[4]http://www.rgc.ca/moe/04.php (last viewed on 3/1/2013)

substantial quantities of groundwater are found in aquifers, these aquifers are the source of water for wells and springs (Kasenow, 2001).

Aquifer is a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs, this in turn implies an ability to store and transmit water. Aquifers are bounded by confining covers which are relatively impermeable; there are three main types of confining covers (Kasenow, 2001):

1. Aquiclude: is a saturated but relatively impermeable formation that does not yield appreciable quantities of water to wells, such as clay.
2. Aquifuge: is a formation that does not contain or transmit water, such as granite.
3. Aquitard: is a saturated but poorly permeable formation that does not yield water freely to wells but may transmit appreciable water to or from adjacent aquifers, such as sandy clay.

There are two main types of aquifers; the confined aquifers, and the unconfined aquifers (See Figure 15).

Confined aquifers: they form when groundwater is confined under pressure by overlying a relatively impermeable formation. In a well penetrating such an aquifer, the water level will rise above the bottom of the confining bed and this defines the elevation of the piezometric surface at that point. Water enters a confined aquifer in an area where the confining bed ends (called recharge area) or by leakage through the confining bed (Kasenow, 2001).

Unconfined aquifers: they do not have a confining layer (cover) above them and so the aquifer can be directly recharged by rainfall or irrigation return flow (Kasenow, 2001). Accordingly, these types of aquifers are more susceptible to pollution than the confined aquifers. In the unconfined aquifers, the water table is the elevation in wells that tap these aquifers.

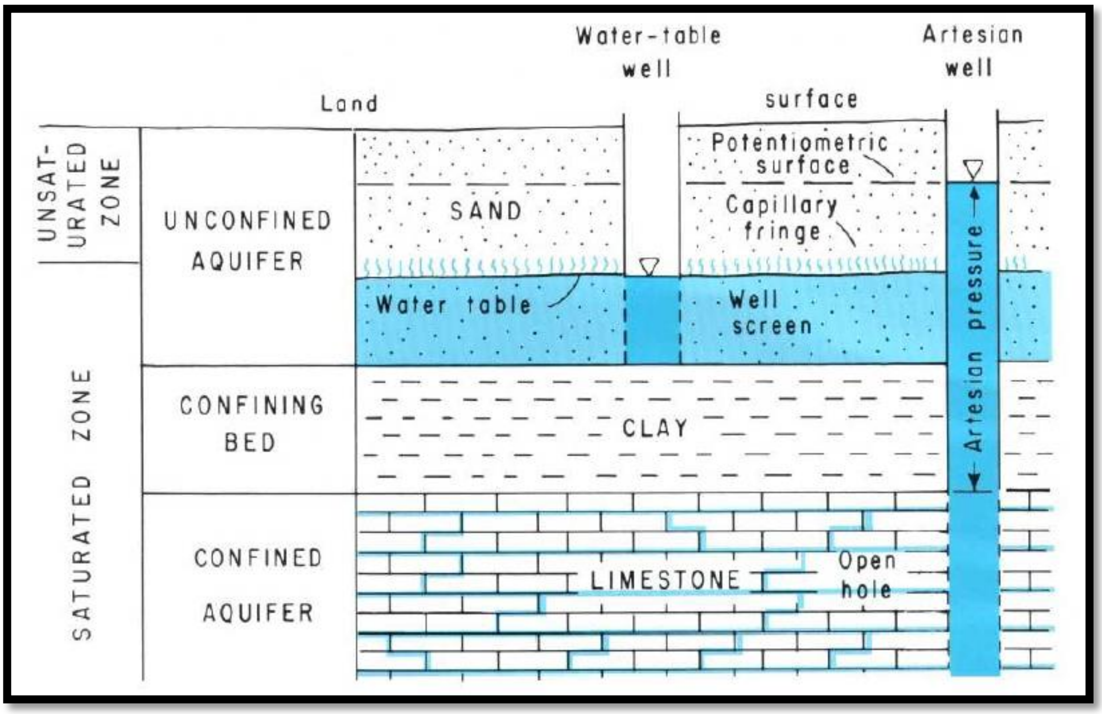

Figure 15: Types of aquifers and confining beds

2.1.3 The Interaction Zone

In arid and semi-arid areas, the interaction zone can be defined as the zone that links surface water and groundwater together (from wadis to aquifers). In the semi-arid regions, when wadis are polluted this zone helps in the transmission of the pollutants from the wadis to the groundwater aquifers. So, this zone plays a key role in groundwater's quantity and quality (Lerner, 1997).

2.2 Forms of Surface water – Groundwater Interactions

The interaction between surface water and groundwater has many forms as summarized in the following:

A) Groundwater exfiltration into rivers and lakes: this form of interaction is dominant in humid regions where the water table elevation is greater than the water level in streams and river. And so, the aquifer discharges the stream[5]. (Figure 16 A)

B) Submarine groundwater discharge in lakes and coastal sea: this form is dominant in the coastal areas. Sea water intrusion is the main problem here due to this interaction (Qahman and Zhou, 2001). (Figure 16 B)

C) Surface water infiltration into unsaturated zone and groundwater: this form of interaction is dominant in arid and semi-arid regions where the water table is disconnected from the earth's surface by an unsaturated zone. And so, the wadi recharges the aquifer[6]. (Figure 16 C)

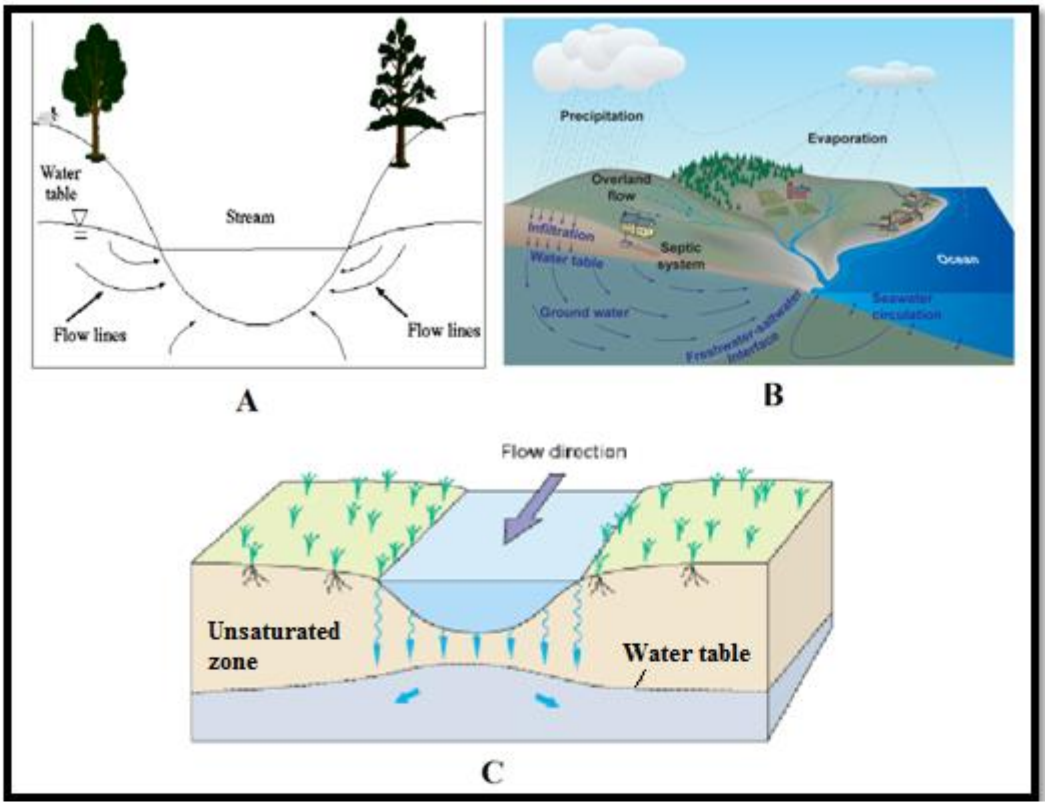

Figure 16: Forms of interactions between surface water and groundwater[7]

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[5]**www2.nau.edu/~doetqp-p/courses/env302/lec5/LEC5.html (last viewed on 16/4/2013)**

[6]**www.kgs.ku.edu/General/Geology/Sherman/05_gw.html (last viewed on 16/4/2013)**

[7]**http://www.whoi.edu/oceanus/viewArticle.do?id=2485 (last viewed on 16/4/2013) and http://water.usgs.gov/ogw/gwrp/stratdir/issues.html (last viewed on 16/4/2013)**

2.3 Basic Understanding of the Wadi-Aquifer Interaction

Traditionally, management of water resources has focused on surface water or groundwater as if they were separate entities. As development of land and water resources increases, it is apparent that development of either of these resources affects the quantity and quality of the other. 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).

Aquifers and wadis are in direct hydraulic connection in some places, particularly where the aquifers in the stream valleys consist of unconsolidated deposits or under unconfined conditions (See Figure 17). Water can move either from the aquifer to the wadi (gaining wadi) or from the wadi to the aquifer (losing wadi), depending on the level of the water level in the wadi and the aquifer and on the alluvial bed of the wadi[8].

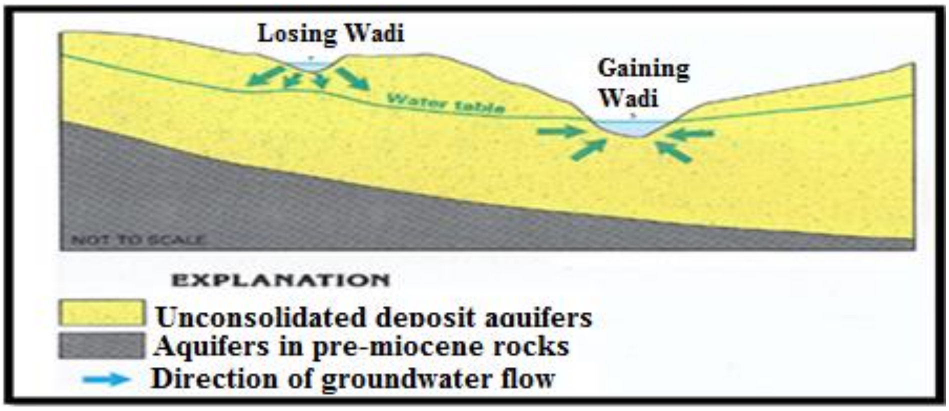

Figure 17: Wadi-aquifer interactions in the two directions[9]

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[8]**www.usgs.gov (last viewed on 16/4/2013)**
[9] **http://pubs.usgs.gov/ha/ha730/ch_h/jpeg/H013.jpeg (Last viewed on 20/6/2013)**

Groundwater is often recharged by ephemeral streams in arid and semi-arid regions, where ephemeral or intermittent streams flow only after rainfalls events[10], as shown in Figure 18.

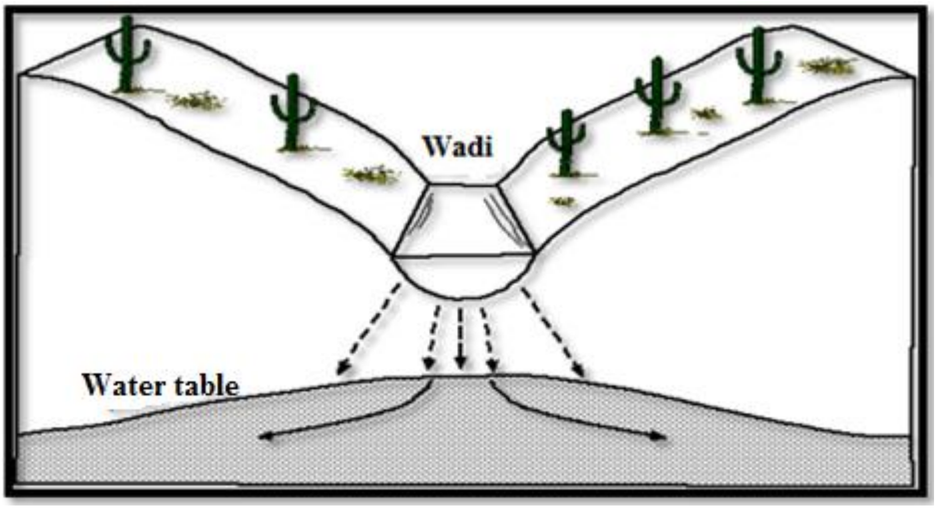

Figure 18: Wadi-aquifer interaction in arid and semi-arid regions[11]

A standard method for identifying recharging regions in arid and semi- arid areas has been used to monitor levels of both groundwater in shallow observation wells and nearby surface water. Recharge is expected to occur when the surface water level is higher than groundwater head. Seasonal effects can alter the type of connection between groundwater and surface water systems, with wadis gaining in summer months and losing in winter in some regions and vice-versa in other regions[11].

2.4 Transport and Fate of Contaminants in Wadi Systems

2.4.1 General Definition

Fate and transport refers to the way chemicals move through the environment to their ultimate destinations and how they arrive. Defining

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[10]www.kgs.ku.edu/General/Geology/Sherman/05_gw.html (last viewed on 16/4/2013)

[11]pubs.usgs.gov/circ/circ1293/circ1293.html (last viewed on 16/4/2013)

the fate and transport for any single contaminant is often complex. Fate and transport begins with a well-defined source point. A chemical's initial release into the environment and environmental conditions are important for determining its free moving lifespan and ultimate destination[12].

2.4.2 Tracer's Movement and Mixing in Streams

Diffusion and dispersion are the processes by which a tracer spreads within a fluid. Diffusion is the random advection of tracer molecules on scales smaller than some defined length scale. At small (microscopic) length scales, tracers diffuse primarily through Brownian motion of the tracer molecules, whereas at larger scales, tracers are diffused by random macroscopic variations in the fluid velocity. In cases where the random macroscopic variations in velocity are caused by turbulence, the diffusion process is called turbulent diffusion (See Figure 19). But where spatial variations in the macroscopic velocity are responsible for the mixing of a tracer, the process is called dispersion. It is a common practice to use the terms diffusion and dispersion interchangeably to describe the larger-scale mixing of contaminants in natural water bodies (Chin, 2006).

The Brownian motion is the random movement of microscopic particles suspended in a liquid or gas, caused by collisions between these particles and the molecules of the liquid or gas. This movement is named for its identifier, Scottish botanist Robert Brown[13]

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[12] **http://www.ehow.com/about_6583480_contaminant-fate-transport-definition.html (last viewed on 16/4/2013)**

[13] **http://science.yourdictionary.com/brownian-motion (last viewed on 20/6/2013)**

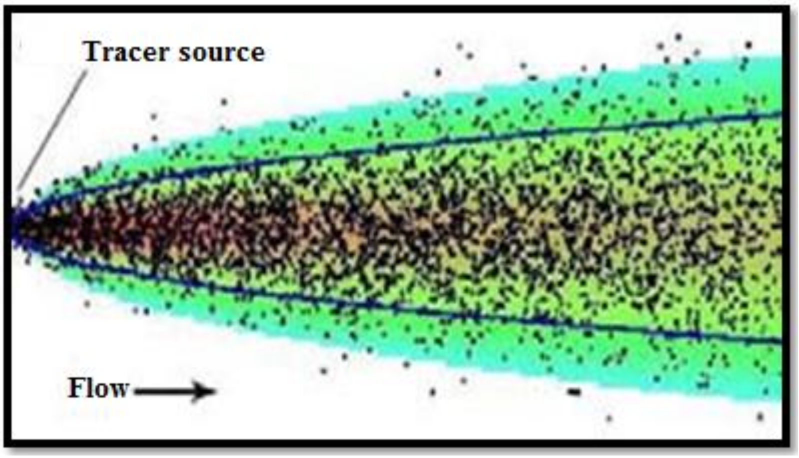

Figure 19: Turbulent diffusion of tracer particles in uniform flow (NOAA, 2005)

Longitudinal mixing in streams is caused primarily by shear dispersion, which results from the "stretching effect" of both vertical and transverse variations in the longitudinal component of the stream velocity (V) which differs due to different factors including the physical characteristics of the stream channel. The longitudinal dispersion coefficient (K_L) is used to parameterize the longitudinal mixing of a tracer that is well mixed across a stream, in which case the advection and dispersion of the tracer is described by the one-dimensional advection-dispersion equation (Chin, 2006):

$$\frac{\partial c}{\partial t} + V\frac{\partial c}{\partial x} = \frac{\partial}{\partial x}\left(K_L\frac{\partial c}{\partial x}\right) + S_m$$

Where:

C: Tracer concentration

V: Water flow velocity

t: Time

x: distance

In cases where the tracer mass is neither created nor destroyed, as in chemical and biochemical reactions, the contaminant is called conservative and so the mass flux per unit volume (S_m) = 0.

2.5 Wadi-Aquifer Interactions: Different Case Studies

This section is intended to provide a summary of the available related studies that addressed surface water-aquifer interactions.

Wang et al. (2010) studied the behavior of groundwater in response to leakage of surface water in the middle reaches area of Heihe River Basin in China. A nonlinear leakage model was developed to calculate the monthly leakage of Heihe River in considering changes of streamflow, river stage and agricultural water utilization. They found that the groundwater regime is a result of two recharge events due to leakage of Heihe River and irrigation water with different delay-time.

Xie and Yuan (2010) used a statistical-dynamical approach to predict the water table elevation near a Yingsu section in the lower reaches of the Tarim River in an arid region of China. That was achieved by a numerical model, a fitted stage-discharge function, and an automatic parameter calibration method. The rise or decline of the water table results in salinization or desertification respectively, and these damages the vegetation growth.

Andersen and Acworth (2009) used many techniques to investigate the interaction between surface water streams and groundwater in the Maules Creek catchment of northern New South Wales, Australia. One of the methods is measuring the hydraulic gradient. Zones where surface water appears to be recharging the aquifer were investigated by measuring the vertical head gradient between the stream and adjacent bores and by estimates of the decreasing surface flow. Inspection of the geological data revealed that the locations of high downward gradients correlated with a highly permeable palaeochannel and so, at these points the stream recharges the aquifer.

Zume and Tarhule (2007) developed a numerical groundwater flow model that was used to evaluate the impacts of groundwater exploitation on stream flow depletion in the alluvium and terrace aquifer of the Beaver-North Canadian River (BNCR) in the semi-arid northwestern Oklahoma, USA. The model provides a framework for isolating and quantifying impacts of aquifer pumping on stream's function in semi-arid alluvial environments.

Schmidt et al. (2006) developed a heat transport model to determine the regions of interactions between the stream and the aquifer along a 220 m - long reach of the Schachtgraben near the town of Wolfen, Germany. Based on the observed temperatures, the vertical water fluxes were estimated by applying a one-dimensional analytical solution of the heat-advection diffusion-equation. As temperature can be easily measured, hundreds of measurements can be taken to draw a high resolution picture of groundwater-stream water interactions on the scale of stream reaches. The study focused on the temperature of the interaction zone, if it has a range close to air temperature then the water is transferred from the wadi to the aquifer and vice versa.

Werner et al. (2006) constructed a fully coupled stream-aquifer model using the code MODHMS. It was calibrated to near-stream observations of water table behavior and multiple components of gauged stream flow. They used this model in planning and management of water resources in the Pioneer Valley, north-eastern Australia, for assessing the impact of groundwater and stream abstractions on water supply reliabilities and environmental flows in Sandy Creek.

Winter (2006) used a combination of environmental and artificial tracers to investigate stream-aquifer interaction processes in Nahal Oren in Mount Carmel, historical Palestine, with emphasis on the localized recharge following ephemeral floods in the river system. Winter found that transmission losses may be contributing to groundwater recharge, but in a larger time-scale than expected due to longer flow paths.

Rodr´ıguez et al. (2005) developed a groundwater-surface water interaction model using MODFLOW for the shallow alluvial aquifer of the Choele Choel Island in Patagonia, Argentina. They noticed that during the irrigation season, seepage losses through unlined distribution canals in irrigated fields contribute to elevated groundwater levels. Moreover, high stream stages during the irrigation season interfere with groundwater drainage. The model helped to provide a better understanding of the coupled system to elucidate some of the causes of a rising water table in the island.

Lamontagne et al. (2005) studied groundwater–surface water interactions over a 2-year period in the riparian area of a large floodplain (Hattah-Kulkyne, Victoria) using a combination of piezometric surface monitoring and environmental tracers. The findings of this study suggest that understanding the spatial variability in the hydraulic connection with the river channel and in vertical recharge following inundations will be critical to designing such floodplain remediation programs.

Wurster et al. (2003) used hydrologic data and stable isotope analyses to understand the interaction between Sand Creek and the unconfined aquifer in the area where wetlands occurred in Great Sand Dunes National Monument, Colorado. When the intermittent Sand Creek flows, seepage through its bed creates a large groundwater mound under the creek. The seasonal development and dispersion of this mound propagates pressure waves through the aquifer that influence ground water levels up to 2 km from Sand Creek.

Urbano et al. (2000) developed a free-surface paleohydrologic model along a cross-section across the Murray Basin in South-Eastern Australia to study the effects of groundwater flow on paleoclimate records in semi-arid environments over millennial time scales. This interaction can have a significant influence on the interpretation of paleoclimatic records since lake–groundwater interactions are crucial to the formation of limnologic paleoclimatic indicators in arid environments.

Lange et al. (1997) used tracer techniques to study infiltration losses into a dry wadi bed in a small arid stream channel, Nahal Shahmon, historical Palestine. They found that transmission losses are the main contributors of groundwater recharge in the catchment and so for the arid and semi-arid regions.

Hadlock et al. (1996) studied the stream-aquifer interactions in the San Luis Valley of Colorado, USA. They proposed that groundwater withdrawals in the San Luis Valley of Colorado may lower the water table in Great Sand Dunes National Monument. In response, the National Park Service initiated a study that has produced a generalized conceptual model of the hydrologic system in order to assess whether a lowering of the water table might decrease the surface flow of lower Medano Creek.

Nikanorov and Trunov (1993) evaluated a new type of fluorescent tracer for studying mass transport in surface water and groundwater. These investigations were conducted in the area of the city of Gorlovka, Ukraine. Results of field experiments indicated the area where pollutant, in case of an accident, might easily reach the underground horizons. The travel times of maximum concentrations and minimum times required for the first arrival of pollutants to specific horizons and various parts of the mines were estimated. Pollutant pathways, including the identification of fractures and accompanying zones of intensely jointed rock, from each of the potentially dangerous industrial sources were detected.

2.6 Previous Work in the Study Area

Generally, most of the previous studies in the Faria catchment concentrated on studying the hydrologic characteristics of rainfall and runoff in the region, such studies are: (Salahat, 2008) and (Shadeed, 2005). As well as few researches focused on studying the hydrogeological conditions and infiltration systems and processes in the catchment, such studies are: (Saleh, 2009) and (Ghanem, 1999).

From all the previous work in the catchment, the most relevant study to this thesis is the search conducted by (Shadeed, 2008) in his PhD dissertation. Shadeed studied the hydrological modeling in Faria catchment under limited hydro-meteorological and spatial data, and proved the occurrence of the channel transmission losses through using the Muskingum-Cunge flow routing technique in which the Green - Ampt infiltration model was integrated to simulate the transmission losses.

The parameters used in the channel routing method were measured directly in the field (infiltration capacity and channel geometry) in addition to some estimated values taken from the literature review.

In a conclusion, all the previous studies focused on either developing mathematical models to describe the system and the mechanism of wadi-aquifer interaction or using tracers to quantify this interaction. This research has been the first attempt of its kind in the Faria catchment to study the probability of the occurrence of wadi-aquifer interaction in the catchment. In this study, the interaction is proved in Faria catchment through developing quantitative and qualitative relationships in addition to conducting a tracer field experiment at An-Nasariah area to investigate and quantify this interaction.

Chapter Three

Developing Quantitative and Qualitative Relationships of Wadi-Aquifer Interaction in the Semi-Arid Area of Faria Catchment

3.1 Introduction

This chapter is trying to develop quantitative and qualitative relations to prove the existence of wadi-aquifer interaction in Faria catchment.

Quantitative analyses combine various variables such as wadi flows, rainfall depths, and variability in the groundwater table to conclude some relations (rainfall and wadi flows vs. change in groundwater table elevations) 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.

On the other hand, 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.

3.2 Data Collection and Methods

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 (GLOWA, 2003). Al-Badan Venturi flume was installed in 2003 at Jiser Al-Malagi in the upper part of the lower Faria catchment to measure the runoff rates of Al-Badan wadi. 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 (Shadeed, 2008). In addition, the changes in the water table levels of well 18/18/027 were recorded by using well loggers (EXACT, 2004).

The year 2006 was chosen to conduct the quality analyses since it was considered as a year of a heavy rainfall season, especially in the month of February (See Figure 20). This gives us a clearer picture of the interaction between the wadi and the aquifer in the catchment.

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 (Cl^-)]. These pollutants are chosen intentionally since they are considered as primary pollutants in wastewater, and so the presence of these pollutants in groundwater gives additional evidence that there is an interaction between the polluted wadi and the aquifer.

The groundwater samples for the quality analyses were taken regularly on monthly basis and the microbiological and chemical tests were conducted in the laboratories of Water and Environmental Studies Institute (WESI) at An-Najah National University.

Wells (18/18/027) and (18/18/034) located at An-Nasariah area were chosen to conduct the quantity and quality analyses, respectively, since they are located next to the main wadi and loggers have been only set up to well 18/18/027 to read the change in the water table elevations. Also, well 18/18/034 was chosen as a candidate well to conduct the groundwater quality analyses during the UWIRA project in the Faria catchment based on desk studies and field investigations.

General information relevant to the wells under consideration is summarized in Table 3.

Table 3: General characteristics of the wells under study

Well's ID number	Locati-on	X (m)	Y (m)	Usage	Abstr-action (m^3/d)	Aquif-er	Basin	Depth to water table (m)
18/18/27	Faria catchment/ An-Nasari-ah	186060	183610	Agricu-ltural	2880	UC-T*	N-E**	25
18/18/34	Faria catchment/ An-Nasari-ah	185500	183900	Agricu-ltural	3360	PL***	N-E	27

***** UC-T: Upper Cretaceous – Tertiary

****** N-E: North Eastern

******* PL: Quaternary – Pleistocene

It is clear from the 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 21 shows the locations of the wells under study and Al-Badan flume.

Figure 20: Al-Badan flood on the 9th of February 2006 (Shadeed, 2008)

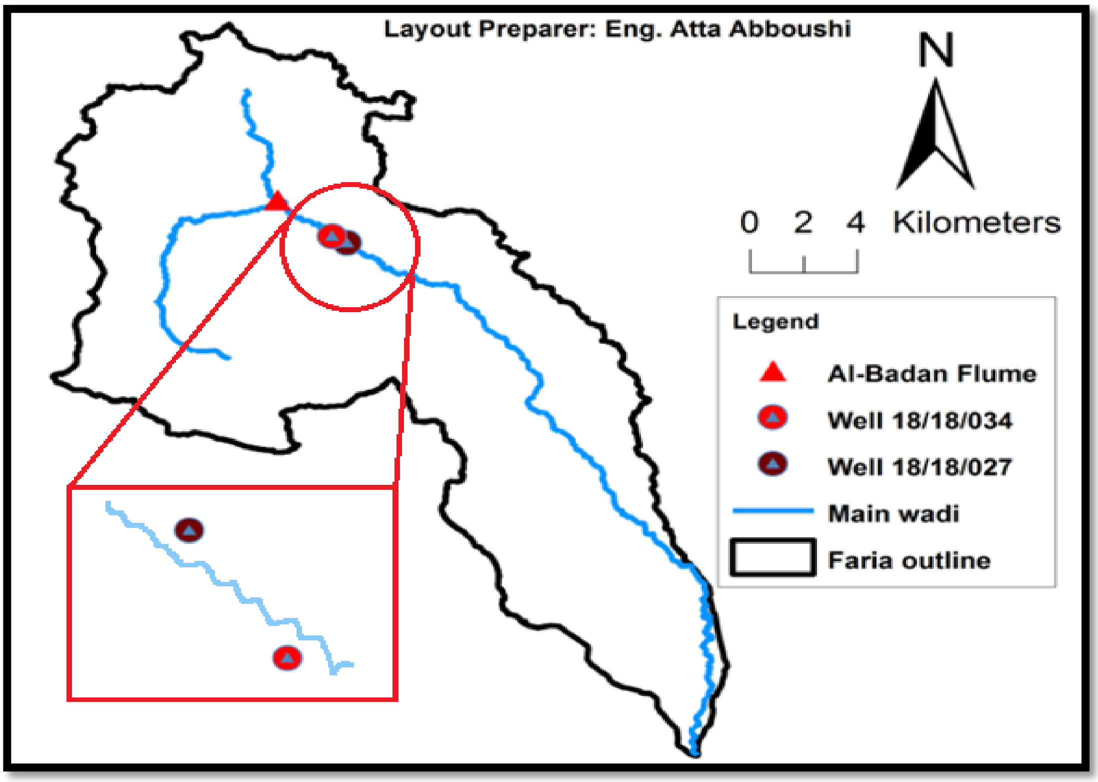

Figure 21: The locations of the wells under consideration and Al-Badan flume at Jiser Al-Malaqi

3.3 Quantitative Analysis

3.3.1 Groundwater Table and Rainfall

The first quantitative relations were developed between groundwater table variability of well 18/18/027 and average rainfall as shown in Figure 22.

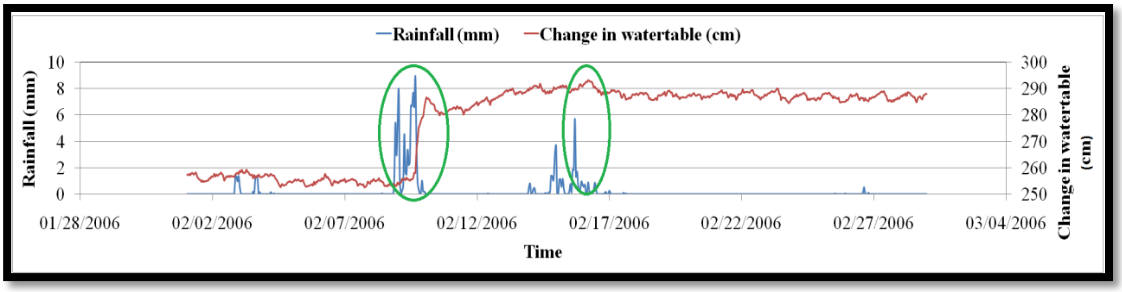

Figure 22: Change in water table-rainfall relationship of well 18/18/027 (February, 2006)

As can be seen from Figure 22, at the beginning of the month when there were almost no rainfall events, the change in the well's water table level 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 enhances the interaction to take place between the wadi and the aquifer and proves the existence of a potential recharge to the upper groundwater aquifer.

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 (Lee et al., 2005).

In order to estimate a reasonable value of the delay time in the area, another three rainfall-water table relationships were graphed for the months of December (2005), January, and March of the year 2006 (See Figures 23, 24, and 25).

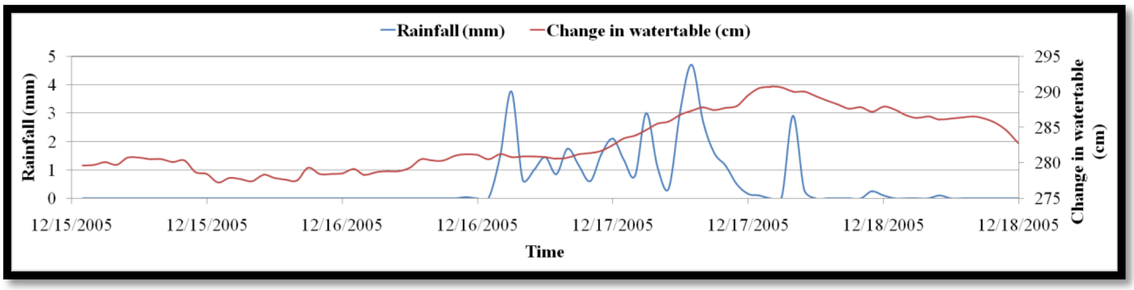

Figure 23: Change in water table-rainfall relationship of well 18/18/027 (December, 2005)

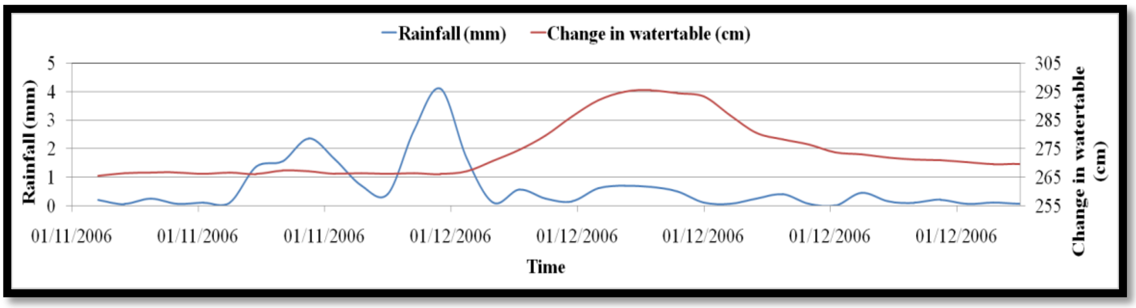

Figure 24: Change in water table rainfall relationship of well 18/18/027 (January, 2006)

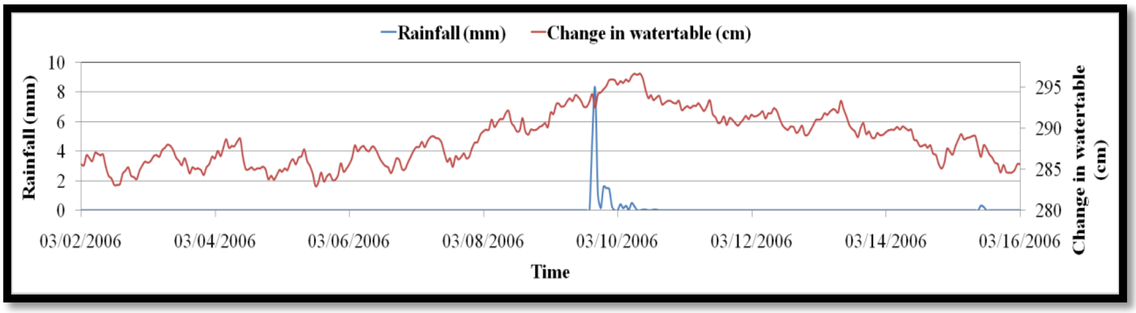

Figure 25: Change in water table-rainfall relationship of well 18/18/027 (March, 2006)

Generally, it is noted from the figures that the increase in the water table level begins after a storm event took place and reaches 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 with this relatively small delay time 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 4).

Table 4: 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 date and time	The change in the water table peak date and 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 an 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.[14]

The hydraulic conductivity is classified into three main categories depending on soil lithologies as described in Table 5. As hydraulic conductivity increases, the chance of wadi-aquifer interaction to take place also increases since the soil's ability to transmit water through the different layers heightens until it reaches the groundwater table.

Table 5: Typical features of various conductance categories for wadi-aquifer systems[15]

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

[14] **http://web.ead.anl.gov/resrad/datacoll/conuct.htm (last viewed on 16/4/2013)**

[15] **www.connectedwater.gov.au/processes/connectivity_cat.html (last viewed on 8/4/2011)**

The hydraulic conductivity in the unconfined aquifer in Faria catchment ranges from 2 to 200 m/d (Ghanem, 1999).

To estimate a reasonable value of the horizontal 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 (**n_e**) are taken approximately as 0.027 and 0.05 respectively (Ghanem, 1999). The distance between the well 18/18/027 and the main wadi (**L**) is nearly 20 m.

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**

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

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

The estimated value of K is reasonably acceptable since it lies within the range of (2~200) m/d for the unconfined aquifer (Ghanem, 1999). Referring to Table 5, the soil in the area has a 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 was 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 6.

Table 6: Parameters used in determining of the capture zone of well 18/18/027

Parameter	Value	Unit	Reference
K (Horizontal hydraulic conductivity) =	89	m/d	Calculated
B (Aquifer thickness) =	45	m	Ghanem, 1999
i (Hydraulic gradient) =	0.027	–	Ghanem, 1999
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:

$\mathbf{X_L} = (-Q/2\pi Bq) = \mathbf{-\ 4.24\ m}$

$\mathbf{y_L} = \pm\ (Q/2Bq) = \mathbf{13.32\ m}$

Width of capture zone = $\mathbf{2\ y_L = 26.64\ m}$

If the transmission losses from the nearby wadi infiltrate and reach the capture zone of this well, the well will be contaminated (See Figure 26).

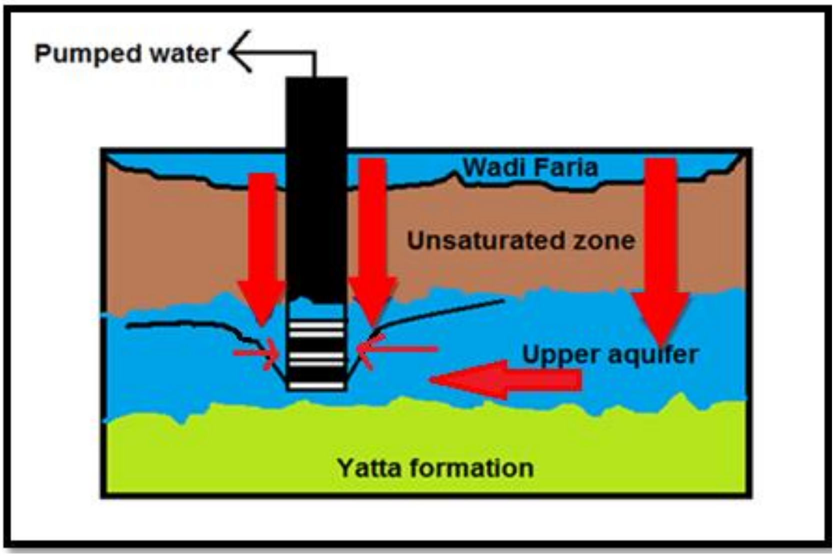

Figure 26: A pictorial sketch of the interaction processes between the wadi and the upper aquifer and the arrival of contaminants to the well's capture zone

3.3.2 Groundwater Table and Wadi Flow

Other quantitative relations were developed between groundwater table variability of well 18/18/027 and wadi flows (Q) as shown in Figure 27.

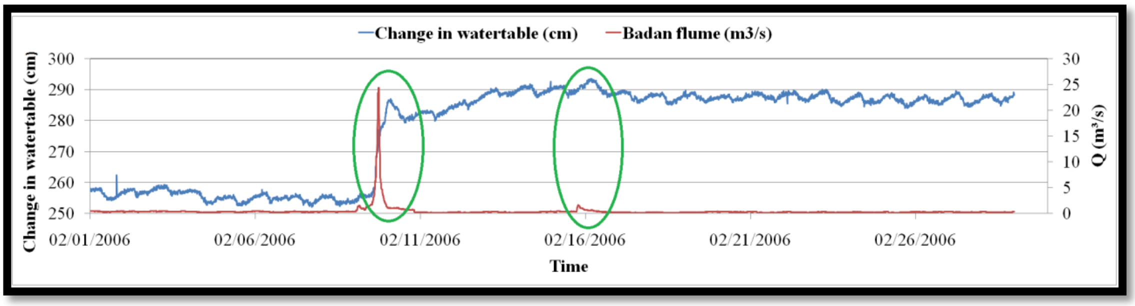

Figure 27: Change in wadi flow-water table relationship of well 18/18/027 (February, 2006)

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.

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 and the depth of sediment is around 1 m from the ground surface in the region under study as depicted in Figure 28.

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 significant rise in the water table levels 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.

The distinctive thing in this relationship is the relative small value of the delay time as in the previous water table-rainfall relationships, and this in turn also enhances the wadi-aquifer interaction to take place very quickly and easily.

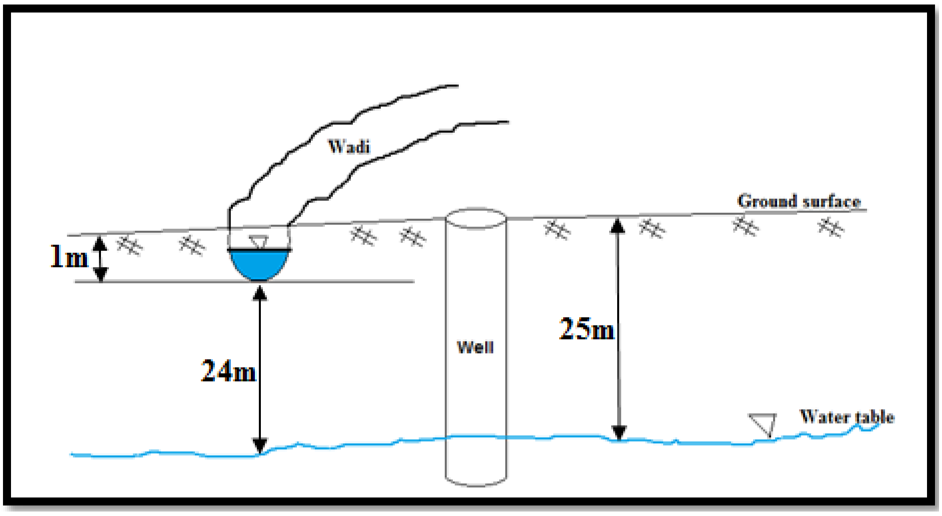

Figure 28: The depth to water table for well 18/18/027 and the depth of sediment in the reach under study

From the figure, it is clear that the distance between the wadi bed sediment and the water table is less than 24 m, so the transmission losses that took place in the wadi bed have high probability to become a potential recharge to groundwater. Another important thing to be mentioned is that most of the storm events that occurred in semi-arid regions in general and in Faria catchment in particular, have high intensity and taking place within a short period of time. This in turn reduces the chances of rainfall to infiltrate and so flash floods generate and run towards the main wadi where transmission losses are taking place.

3.4 Quality Analysis

3.4.1 Chemical and Microbiological Analyses

In this section, the variations in the fecal coliform bacteria, nitrate, and chloride concentrations that were found in groundwater from well 18/18/034 with time are depicted in Figures 29, 30, and 31, respectively.

It is clear from the figures that the pollutants have higher concentrations in the summer than in the winter, although the wadi is dry next to the well in the summer period. This result makes sense since there is a high probability for the flow in the wadi in the upstream area of 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 then, the pollutants are very concentrated.

Also, it is important to mention that most of land use and practices around the main wadi of Faria as mentioned earlier are categorized as agriculture. 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 32). And so, the nitrate and fecal coliform bacteria that found in the groundwater samples from the well 18/18/034 have the probability to come from the adjacent agricultural land as another source of contamination and pollution in addition to the wadi.

At the same time, because the use of organic fertilizers is relatively low in the area and a large portion of wastewater is evacuated from cesspits and poured directly into the main wadi in Faria catchment, the chemical contamination and the microbiological pollution from the wadi has a greater influence on the aquifer than of that resulted from the surface infiltration from the surrounding agricultural land.

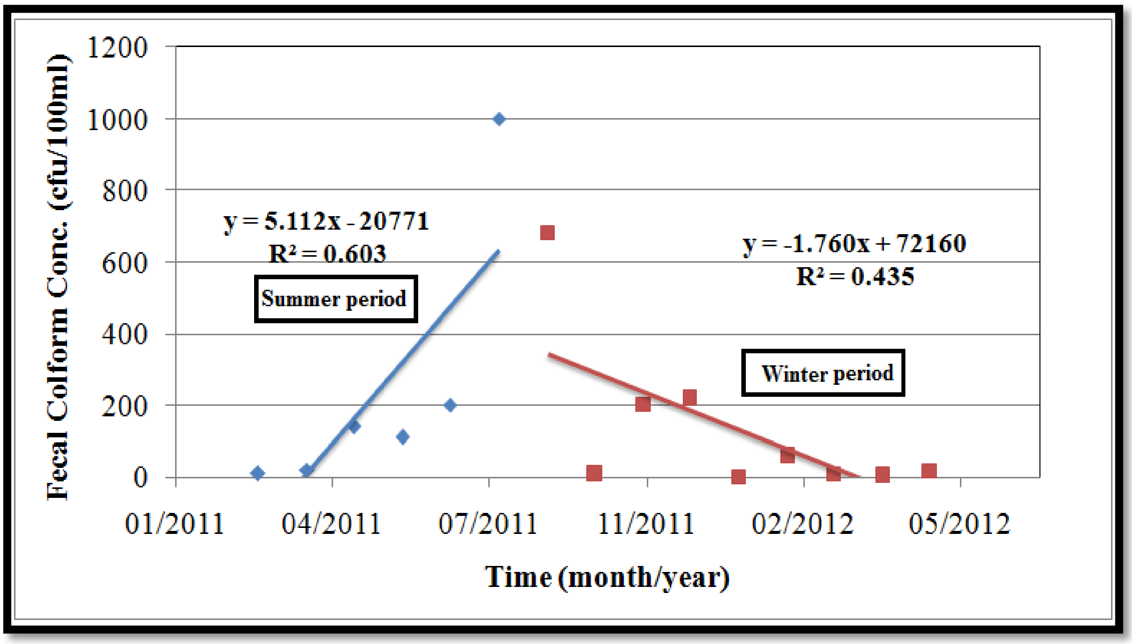

Figure 29: Variation in the fecal coliform bacteria concentration found in groundwater from well 18/18/034 with time and the trend of pollution

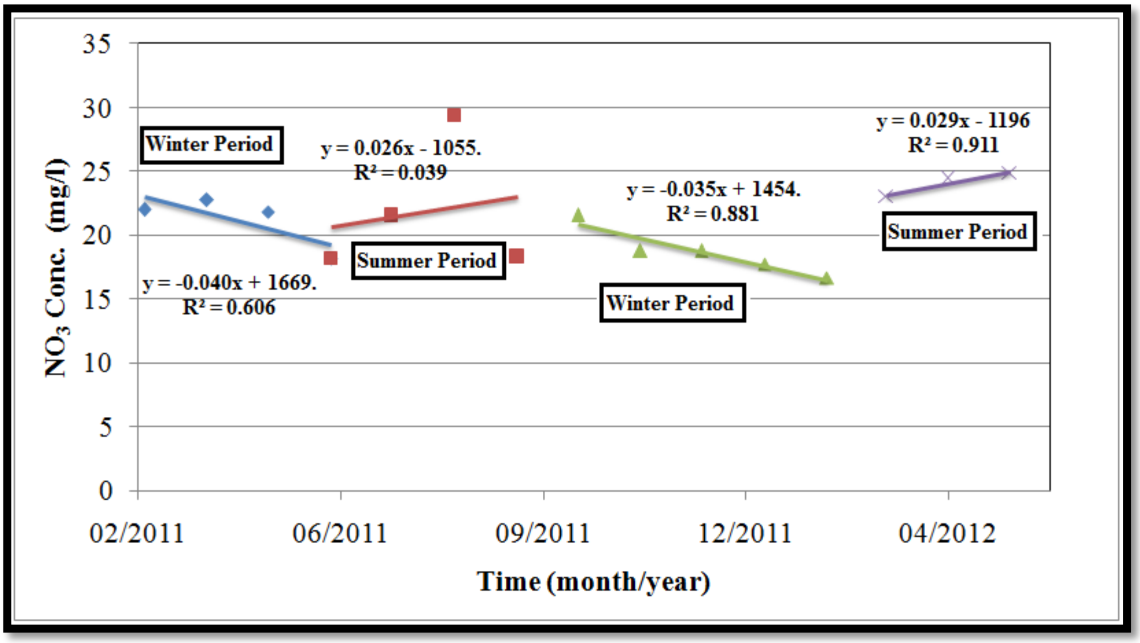

Figure 30: Variation in the nitrate concentration found in groundwater from well 18/18/034 with time and the trend of contamination

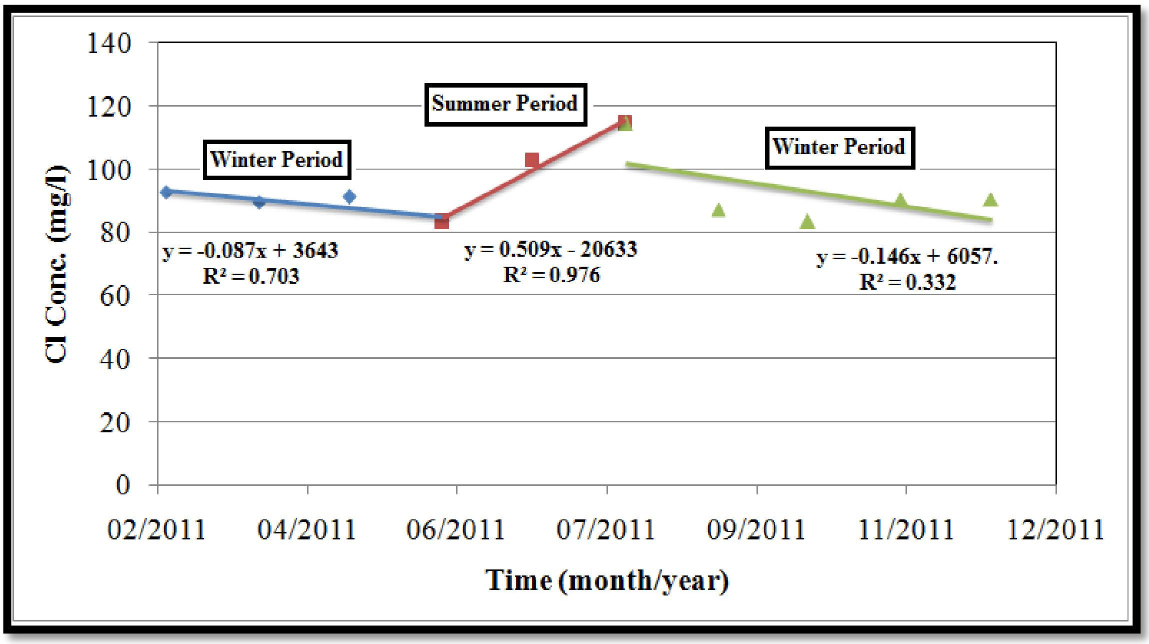

Figure 31: Variation in the chloride concentration found in groundwater from well 18/18/034 with time and the trend of contamination

Note that in all summer periods, the chemical and microbiological contaminations have increasing contamination and pollution trends, respectively, while there is an opposite trend in all winter periods where the chemical contamination and microbiological pollution have decreasing trends.

Finally in this section, the Maximum Contamination Levels (MCL) for the different chemical and microbiological indicators were considered to determine whether a contamination or a pollution exists in the area. When the indicators values are less than the MCL, this means that there is contamination, but no pollution exists, in other words, no harmful effects will be on humans and on the environment. But, if the indicators values exceed the MCL, the pollution will exist and so there will be serious consequences on human health and the environment.

According to the Palestinian Drinking Water Standards, the MCLs for the fecal coliform bacteria, nitrate, and chloride are: 0, 50, and 250 mg/l respectively (EQA, 2010). From the figures, it is very clear that the fecal coliform bacteria concentrations are beyond the MCL, but the nitrate and chloride concentrations are within the acceptable limits. So, we can say that there are microbiological pollution and chemical contamination in the groundwater in the area. Note that the agricultural wells in the area are used also for drinking purposes.

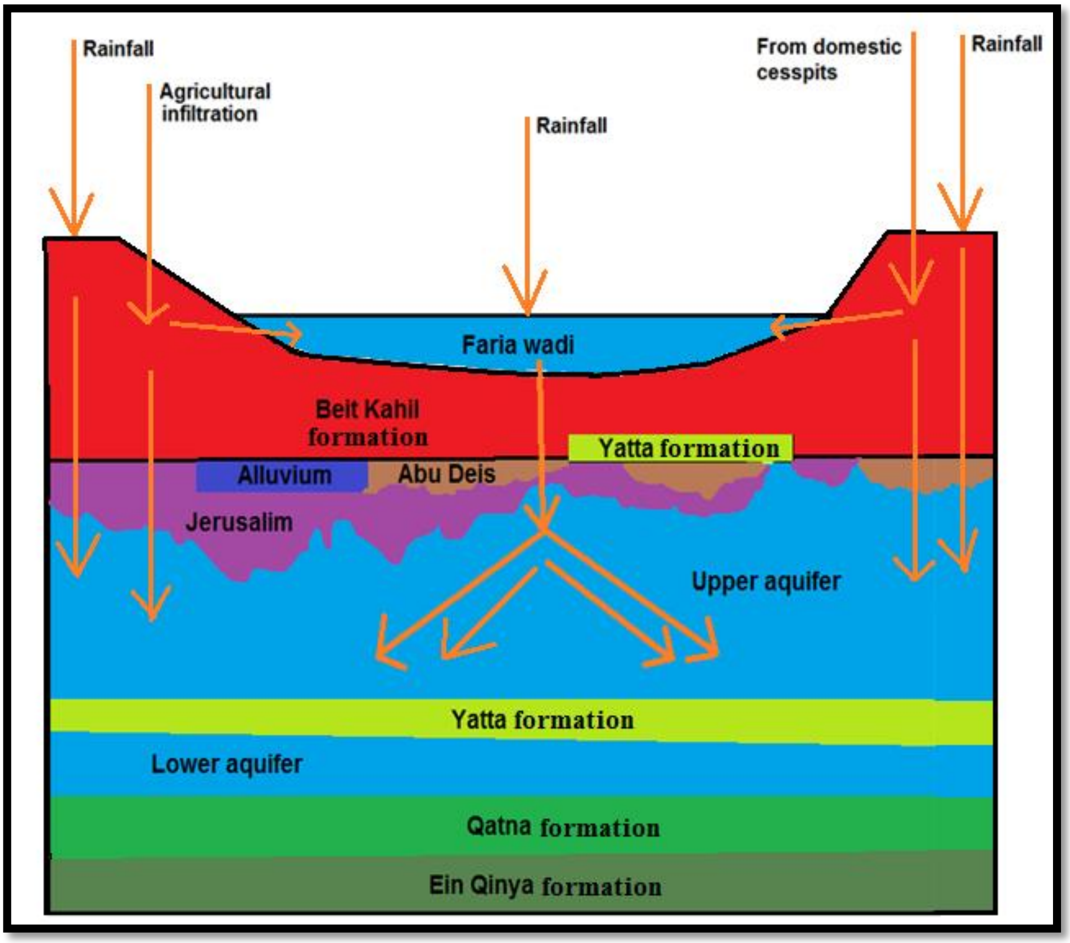

Figure 32: A simple sketch that shows the different pollutants that may reach the upper aquifer

Chapter Four

Wadi-Aquifer Interaction in Faria Catchment Using Tracer-Based Methodology

4.1 Tracer Based Approach

4.1.1 Introduction and General Description

This section introduces the main part of this chapter; the field experiment that was conducted in at An-Nasariah area in order to prove the existence of wadi-aquifer interaction in the semi-arid areas of Faria catchment.

As discussed in the research methodology; it was decided to conduct a tracer field experiment in the study area, since the field experiment enables us to:

1. Determine if the wadi-aquifer interaction exists along a specific reach or not.
2. Quantify this interaction by determining the percent of loss or gain of the flow for each reach segment.
3. Locate the hot spot areas (areas in which transmission losses are taking place more than others) along the chosen reach.

The tracer field experiment was conducted on the 21st of January, 2013 after a heavy rain 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 (No evaporation diversions).

A representative 600 m reach along the main wadi at An-Nasariah area in Faria catchment was selected. It was divided into four equally long distances each of which is 150 m. After doing all the required measurements, one injection point and four monitoring points were identified (See Section 4.1.3). Thirty samples were suggested to be taken at each monitoring point with a sampling frequency time of 1.5 minutes for the first, second, and fourth monitoring points, and 1 minute for the third monitoring point. After doing the sampling process, all the samples were analyzed using a field fluorometer (AquaFluor device) as shown in Figure 33. For each monitoring point, the sets of observed time and concentration data were plotted and when needed, they will be simulated using a solute transport software model called OTIS. After that, each concentration curve was transformed to an average flowrate by dividing the injected tracer mass by the area under the concentration curve at each monitoring point. Finally, each two successive flowrates were subtracted to quantify the wadi-aquifer interaction (If the difference between the upward flowrate and the downward flowrate is positive; this means that transmission losses will take place).

Figure 33: The fluorometer device and analyzing the samples

Figure 34 presents a simple sketch that illustrates the procedure of the conducted field experiment.

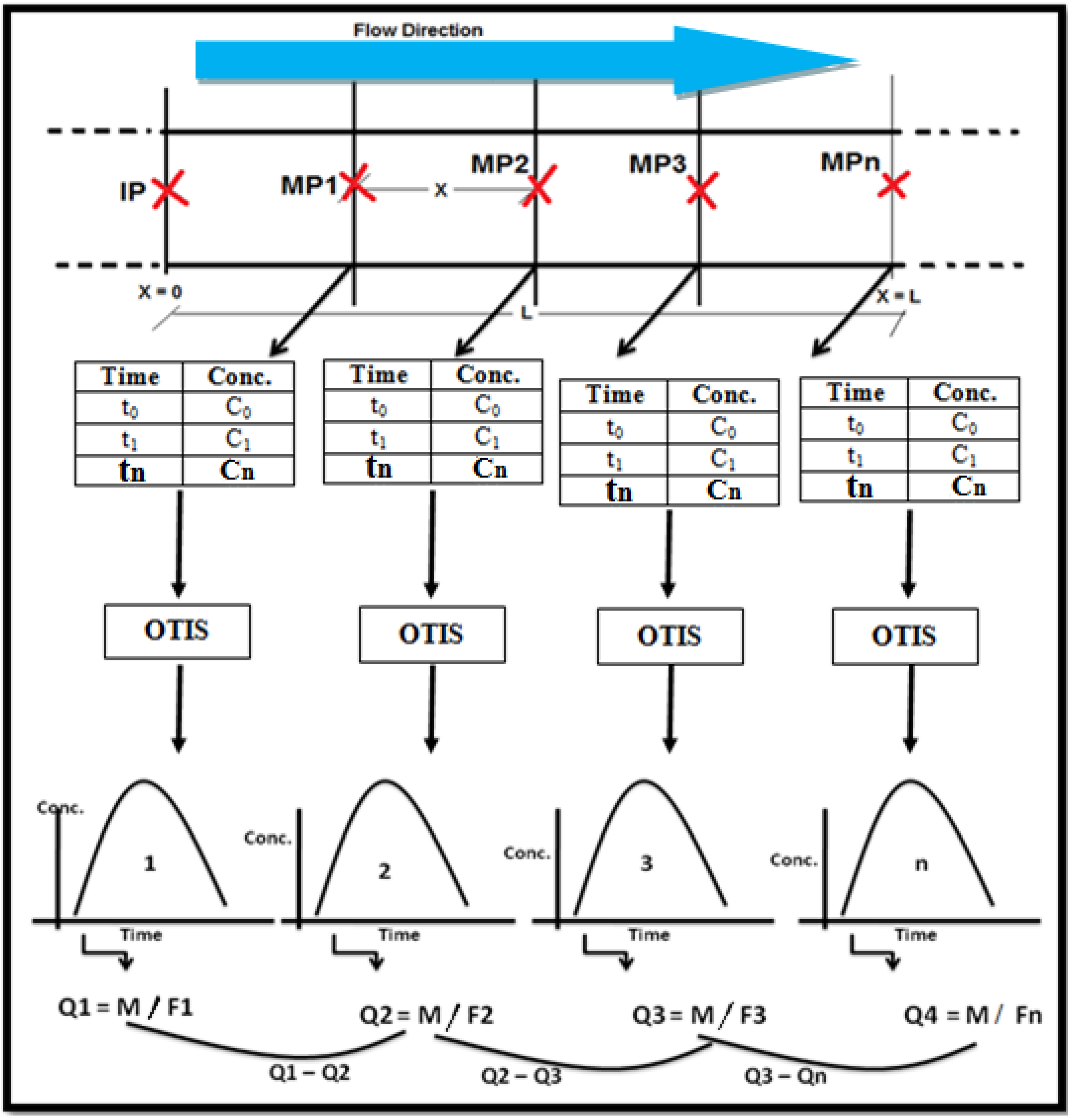

Figure 34: General scheme of the tracer field experiment

4.1.2 Reach Selection

In general, there are no set criteria for the selection of the reach for the tracer field experiment. However, a chosen reach is better to be:

1. More uniform (straightness) as possible.
2. Accessible and easy to take measurements on it.

3. Less slope reaches are preferable than steep ones.
4. 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) is not having 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 (See Figures 35 and 36). Also, the study wells used to conduct the quantitative and qualitative analyses in chapter 3 are located in the vicinity of the chosen reach.

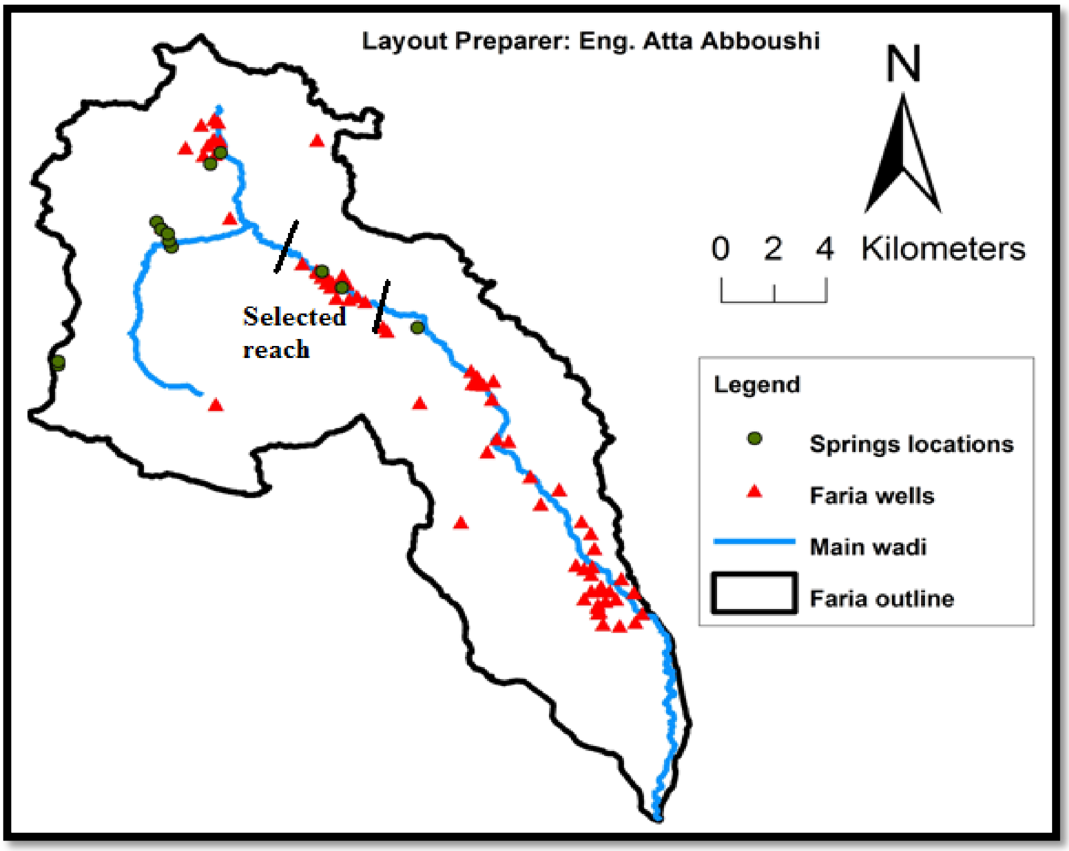

Figure 35: The selected reach along the main wadi at An-Nasariah area in Faria catchment to conduct a tracer field experiment

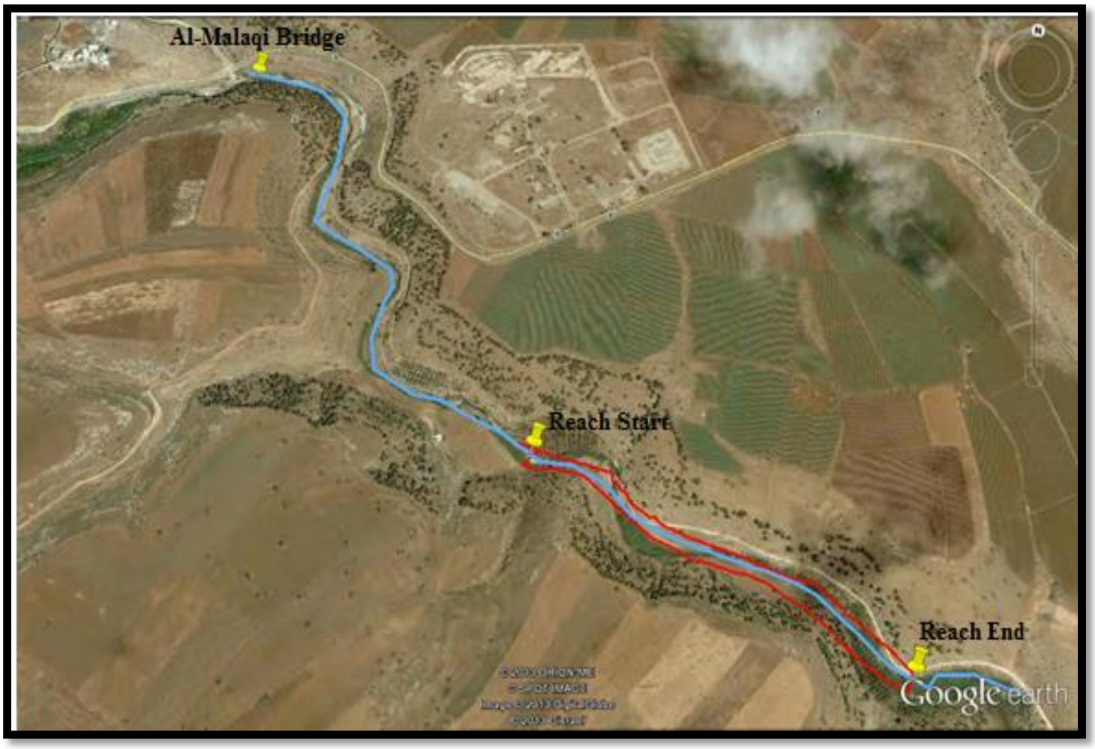

Figure 36: A satellite image that shows the selected reach (Source: Google earth)

4.1.3 Channel's Longitudinal Profile and Cross-Sections

After many field visits, the approximate shape of the wadi at An-Nasariah area was laid out through drawing the channel's longitudinal profile and the cross-sections at the different monitoring points. Also, a photo of each monitoring point is accompanied with each cross-section. Note that the cross-sections were drawn from right to left direction with respect to the longitudinal profile's north direction.

As depicted in the longitudinal profile (See Figure 37), 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.

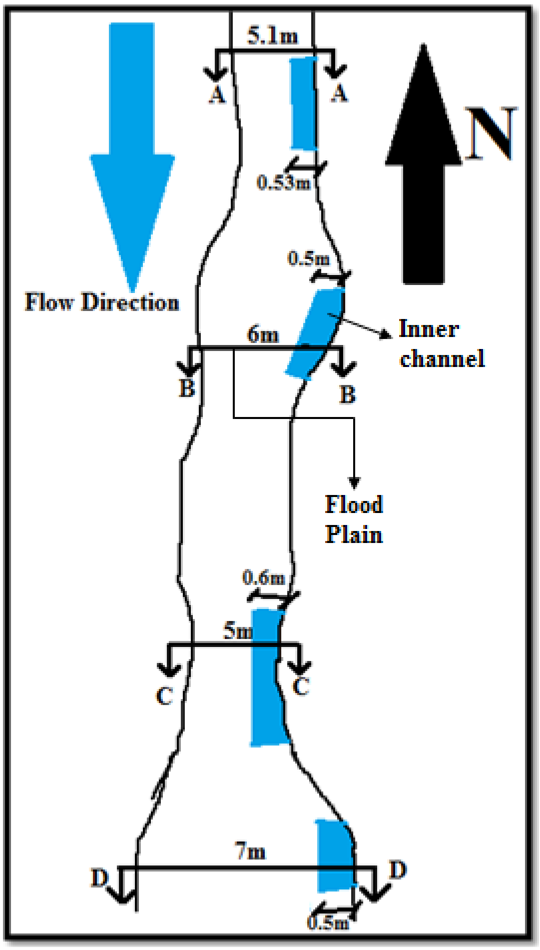

Figure 37: A longitudinal profile of the selected reach of the main wadi at An-Nasariah area in Faria catchment

The channel's cross-section area ranges from 0.8 m^2 to 3.3 m^2 as depicted in Figures 38 through 41. The depth from the bed to the channel's banks ranges from 27 cm to 93 cm on average. It is also noted that the depth is varying at the same cross-section.

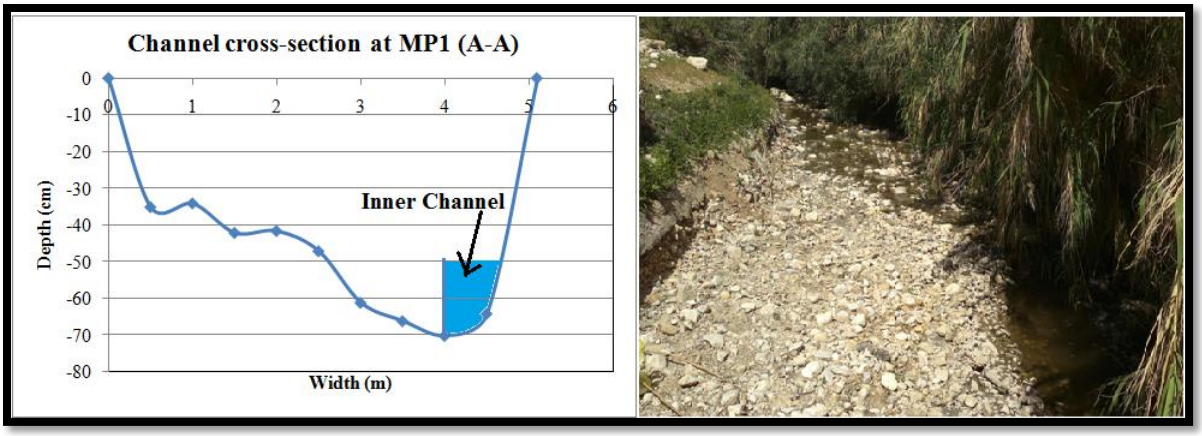

Figure 38: A-A cross-section and a photo of the first monitoring point

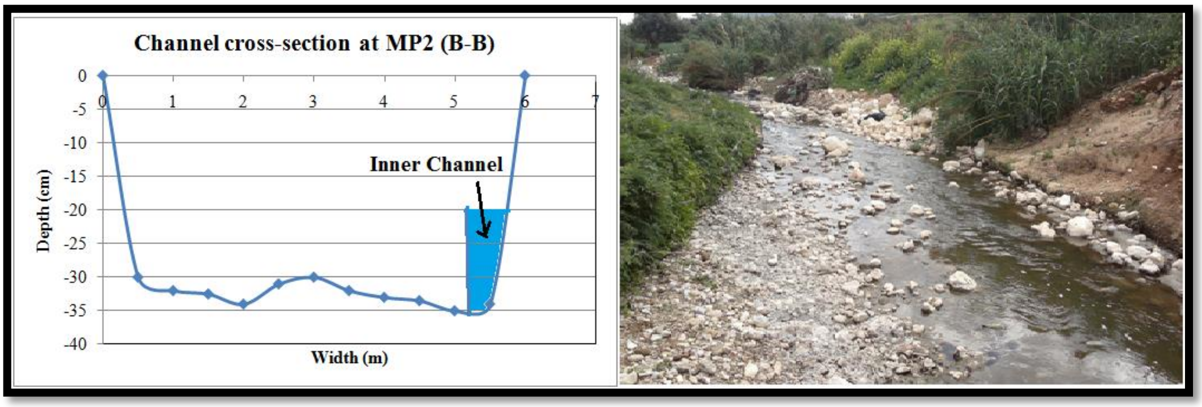

Figure 39: B-B cross-section and a photo of the second monitoring point

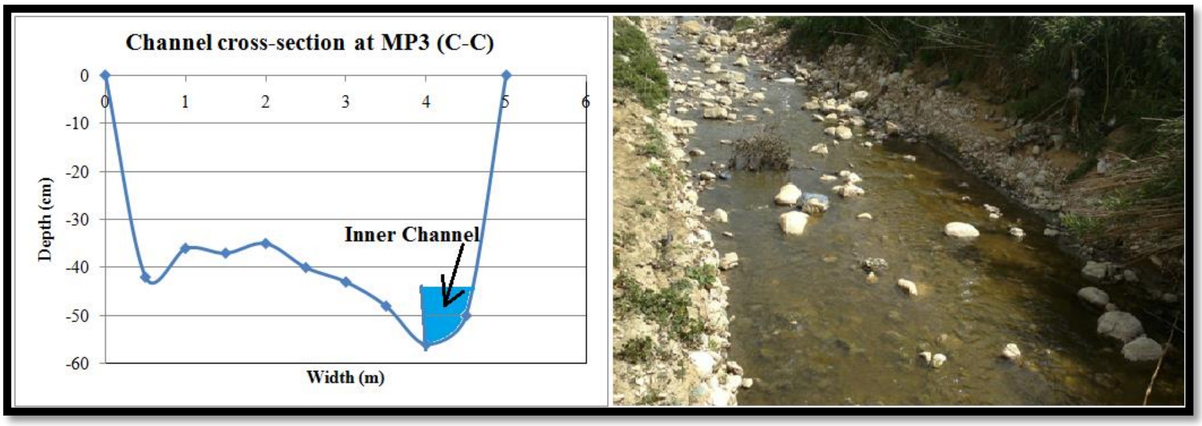

Figure 40: C-C cross-section and a photo of the third monitoring point

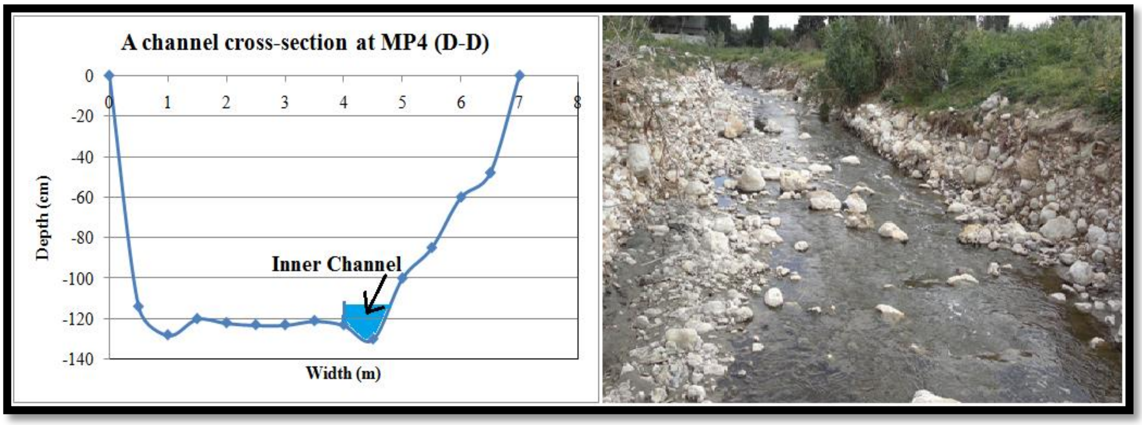

Figure 41: D-D cross-section and a photo of the fourth monitoring point

4.2. Tracers

4.2.1 Definition

Tracers are inert chemicals used in hydrogeology to quantify selected hydraulic or hydrochemical parameters. They are dissolved, suspended, or floating substances according to their purpose and the field of application. Tracing of water provides unique methods for a direct insight into the dynamics of surface and subsurface water bodies (Leibundgut et al., 2009).

4.2.2 Objectives from Tracers Tests

1. Tracer approaches are commonly used to address issues like surface water–groundwater interactions (This is the objective of the tracer field experiment in this research).
2. Tracer techniques are useful tools in understanding the transport processes and quantifying their parameters.
3. Tracers help to identify and quantify the phase changes (evaporation, condensation, sublimation), shed light on the origin of pollution, and assist in the respective remediation processes.

4. Tracer methods are also a major tool for calibration and validation of strategies in modeling catchment hydrology and hydrological models of groundwater systems.

4.2.3 Tracers Types

1. **Environmental tracers**: They are inherent components of the water cycle, such as (CFCs, Krypton).
2. **Artificial tracers**: are substances that offer additional information of value in the investigation of hydrological systems and subsystems. They are defined by their active injection into the hydrologic experiment such as fluorescent tracers. Artificial tracer types are summarized in Table 7.

Table 7: Artificial tracer types (Leibundgut et al., 2009)

Artificial Tracer Type	Examples
Fluorescent tracers	Pyranine, Uranine, Eosine, and Rhodamines
Non-fluorescent tracer dyes	Brilliant Blue which used in food industry
Salt tracers	Sodium/potassium chloride, Lithium chloride, and Potassium iodide

4.2.4 Tracer Selection

In order to select the appropriate tracer to be used, several criteria should be considered. Since there is no one ideal tracer, the choice must be based on the comprehensive understanding of all limiting factors (Kass and Schneider, 1998). Table 8 shows the main pros and cons of the two major tracer types.

Table 8: The pros and cons of the environmental and artificial tracers (Leibundgut et al., 2009) and (Kass and Schneider, 1998)

Tracers Types	Environmental Tracers	Artificial Tracers
Advantages	1. The injection of tracers into the hydrologic system is provided by nature. 2. They are harmless.	1. Seemingly simple analysis. 2. Low detection limit. 3. Small quantity of tracer needed in field experiment. 4. Their toxicities are very low (some of them are non toxic. 5. Very common to be used to address issues like surface water-groundwater interactions.
Disadvantages	The application of them is limited by the availability of analytical techniques.	1. Some of them are toxic. 2. Some of them are high affected by photolytic decay, adsorption, and organic degradation. 3. Considered as relative expensive material.

Based on the comparison above, artificial tracers were preferred to be used in this research.

For the purpose of this study, Uranine as a fluorescent tracer dye (one of the most famous types of artificial tracers) was selected depending on the following reasons:

1. It is a harmless and non-toxic tracer.
2. It has high solubility in water (Leibundgut et al., 2009).

3. Uranine has the least sorptivity in neutral and alkaline media (Kass and Schneider, 1998). In our case, the average pH of the stream flow is 7.5, so sorptivity effect is negligible. Sorptivity is the effect of capillarity on liquid movement in the unsaturated zone, where the minerals and soil particles with a large surface area adsorb molecules and ions onto their surfaces (Leibundgut et al., 2009).
4. Uranine was the only dye unaffected by the presence of animal manure (Flury and Wai, 2003). So, the organic effects are also negligible (It has no degradation effects during the time frame of interest).

One of the most important limitations in using Uranine is its relative high light sensitivity (Leibundgut et al., 2009). So, to eliminate the effect of photolytic decay, dark brown sampling bottles were used.

4.2.5 Tracer Dose Mass

There are many equations used to calculate the dose mass of tracers, depending on the nature of the experiment. The target concentration should be as low as possible, due to environmental considerations, but high enough to provide a distinct signal beyond the range of uncertainty (Leibundgut and Wernli, 1982). In this experiment, the tracer injection mass of Uranine was taken as 5 grams and was dissolved in a sufficient amount of water. 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 large, since it will scare the local people in the area due to dyeing the wadi by its green color. On the other hand, the amount should not be too small, fearing that it is less than the detection limit of the device.

Some Photos Taken from the field for the Tracer Experiment

The processes of dissolving and mixing of Uranine solution, pouring it into the wadi, and the sampling processes are depicted in Figures 42 through 44.Figures 45 and 46show how the wadi looks like before and after the injection process, respectively.

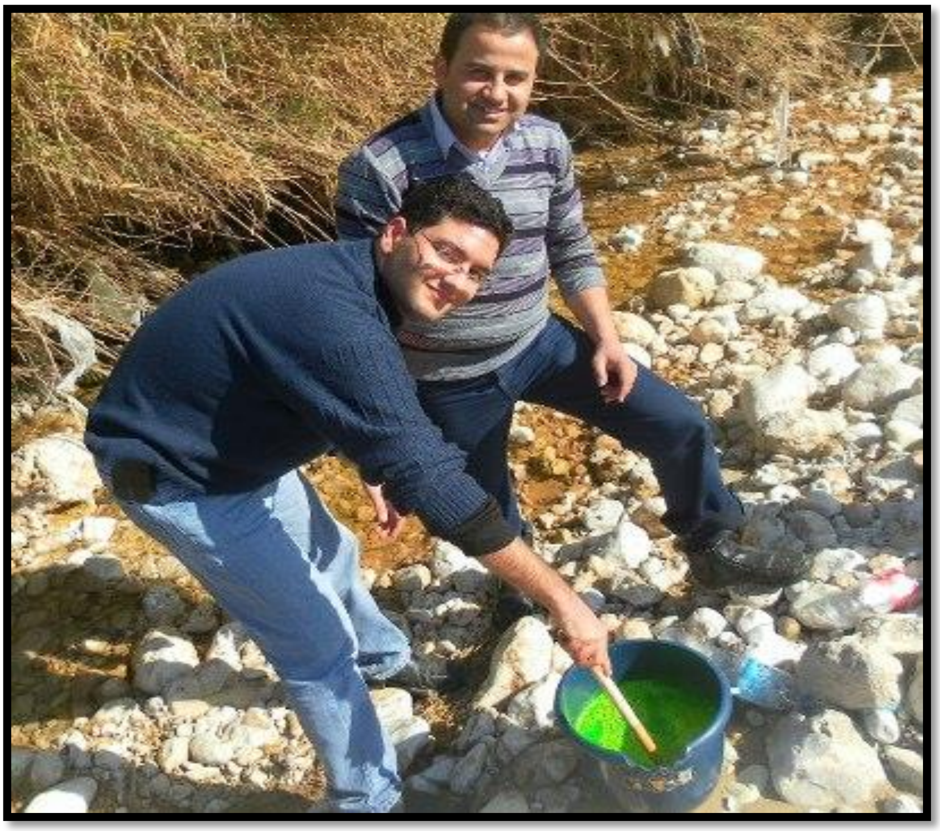

Figure 42: Dissolving and mixing of Uranine solution

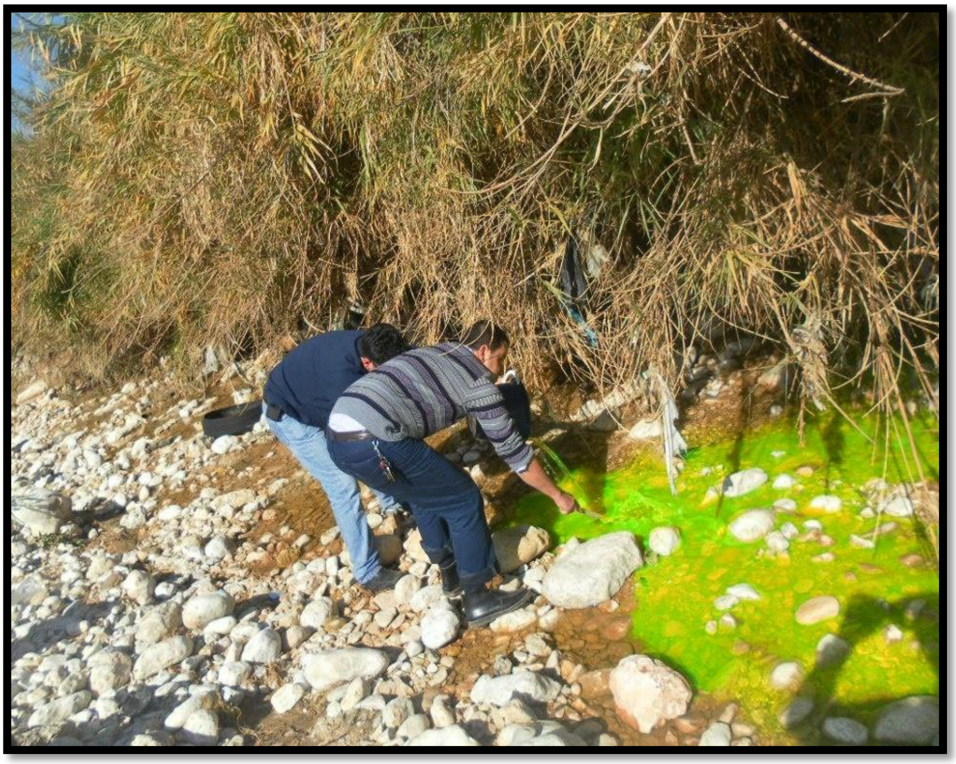

Figure 43: Pouring of Uranine solution into the wadi

Figure 44: Sampling process at section 4 (600 m from the injection point)

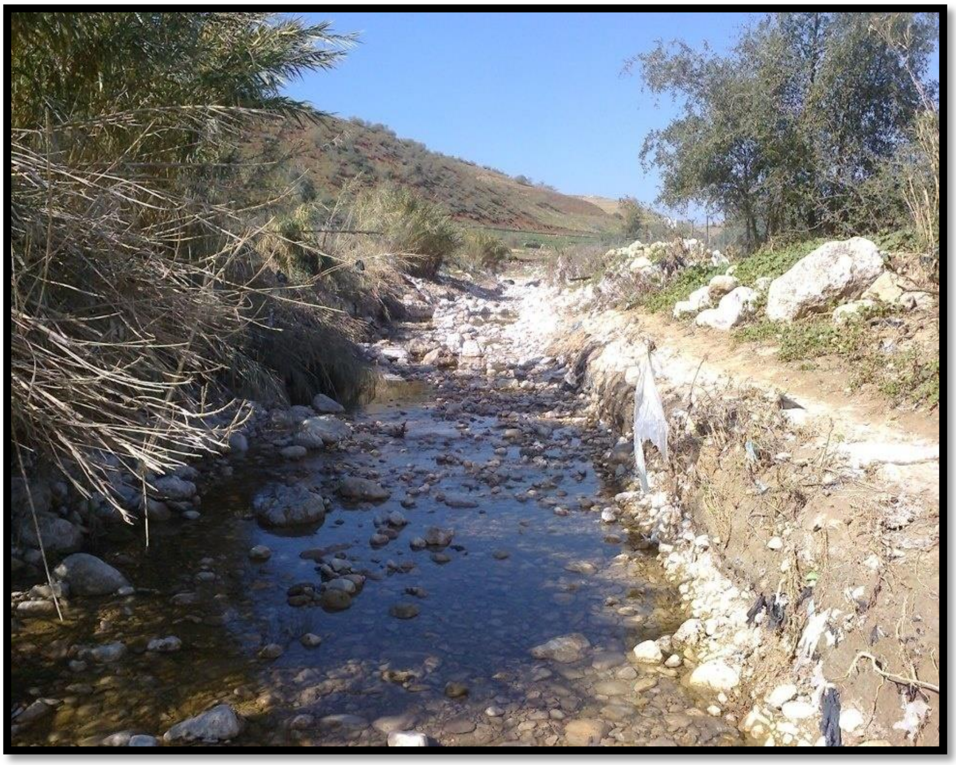

Figure 45: The wadi outlook before the injection process

Figure 46: The wadi outlook after the injection process

4.3 One-Dimensional Transport with Inflow and Storage (OTIS): A Solute Transport Model for Streams and Rivers

4.3.1 Introduction

OTIS, a mathematical simulation model developed by Runkel (1998), is used to characterize the fate and transport of water-borne solutes in streams and rivers. The governing equation underlying the model is the advection-dispersion equation with additional terms to account for transient storage, lateral inflow, first-order decay, and sorption.

OTIS may be used in conjunction with data from field-scale tracer experiments to quantify the hydrologic parameters affecting solute transport. This application typically involves a trial-and-error approach wherein parameter estimates are adjusted to obtain an acceptable match between simulated and observed tracer concentrations. Additional applications include analyses of non-conservative solutes that are subject to sorption processes or first-order decay (Runkel, 1998).

Given a description of watershed loading, OTIS determines the solute concentrations that result from hydrologic transport and chemical transformation. The primary assumption used within the model is that solute concentration varies only in the longitudinal direction; solute concentration does not vary with width or depth (Runkel, 1998).

4.3.2 Model Application on the Case Study

A description of the model features that are illustrated in the application of this research in addition to a brief description of the OTIS input and output files structure will be presented in this section, the parameters used within the input files will be shown in Annexes L and M and the final simulated results will be presented in the next section.

4.3.2.1 General Description of Model Application Features

Model application features are summarized in Table 9.

Table 9: Model application features of case study

Tracer type	Uranine
Conservative/Non-conservative tracer	Conservative: No decay and adsorption
Simulation type	Time-variable
Injection type	Slug injection*****
# of downstream monitoring locations	4 (150m,300m,450m,600m)
Flow type	Uniform, and steady state
Physical transport mechanisms modeled	Dispersion
Lateral inflow concentration, and storage zones	Lateral inflow concentration :Not considered Storage zones: Considered

***** Slug injection means that the tracer mass is added in bulk into the system or spilled instantaneously into the system.

From the above table, it is clear that the main assumptions that were made in the model are as the following:

1. Adsorption, degradation, and photolytic decay are not considered, since conservative tracer was used.
2. Assume the flow type is uniform (it doesn’t vary with space at any instant of time) and steady state (it doesn’t vary with time at the same cross-section).
3. The physical transport mechanism that was only considered in the model is the dispersion. The dispersion can be defined as the spatial

variations in the macroscopic velocity which are responsible for the mixing of a tracer (Chin, 2006).

4. No lateral inflow concentration of Uranine exists.
5. The storage zones were considered in the model. Storage zones can be defined as the portion of the stream that contributes to transient storage; that is, stagnant pools of water and porous areas of the streambed. Water in the storage zone is considered immobile relative to water in the stream channel (Runkel, 1998).
6. Evaporation effects were not considered. Since, the experiment was conducted in winter.

4.3.2.2 OTIS Input/Output Files Structure

OTIS consists mainly of three input files; the first input file, the **control file**, is used to specify the filenames of the input and output files. Unlike the other input files, the filename for the control file is set to **control.inp** within the software and its name cannot be changed. A second input file, the **parameter file**, sets simulation options, boundary conditions, and model parameters that remain constant throughout the run. The final input file, the **flow file**, contains model parameters that can potentially vary during the simulation (for example, volumetric flow rate and main channel cross-sectional area).

Upon completion of a model run, OTIS creates two output files; the first output file, **echo.out**, contains an “echo” of the user-specified simulation options and model parameters. This file also contains any error messages generated during model execution. In addition to the echo file, the model creates one **solute output file** for each solute. If sorption is being modeled, one sorption output file is also created for each solute. The filenames for the solute and sorption output files are specified by the user in **control.inp** file (Runkel, 1998).

4.4 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 am**.

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

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

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

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

Where **N** is the number of points measured.

The tracer dose mass (M) was chosen to be five grams.

- **First Monitoring Point**

The observed concentration curve for the **first** monitoring point (at x = 150 m from the injection point) is depicted in Figure 47.

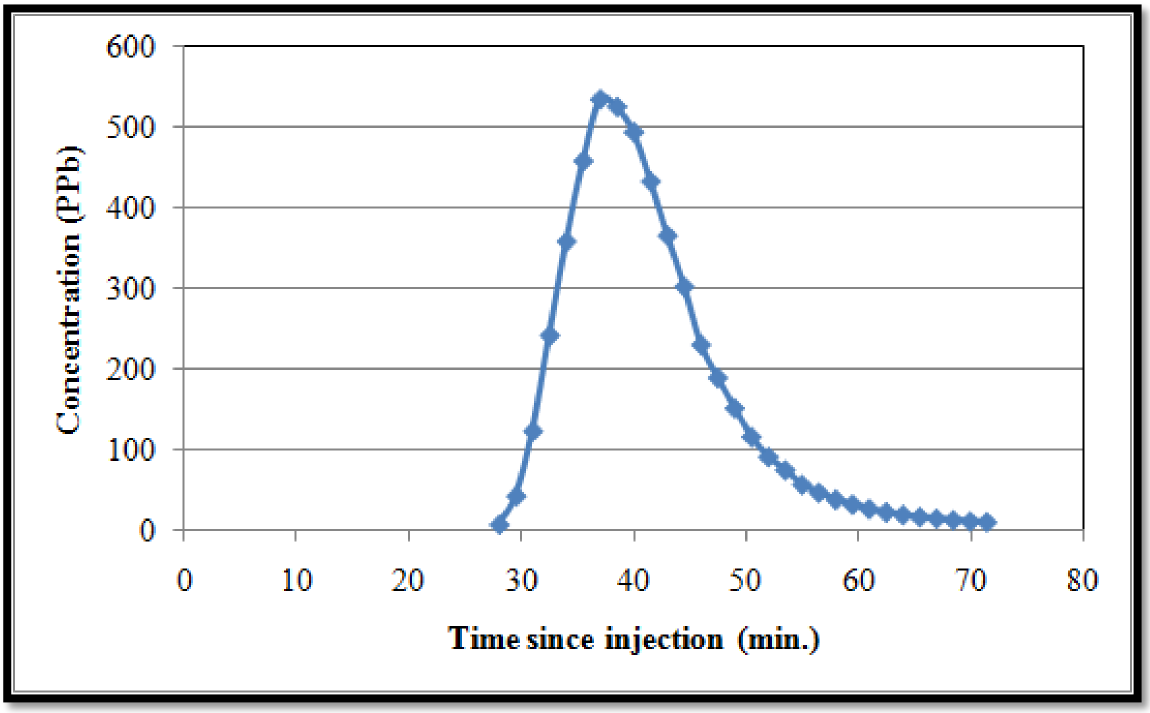

Figure 47: The observed concentration curve for the first monitoring point

Since the above concentration curve approximately has its common and complete shape, it is not needed to simulate it using the OTIS software model. The first monitoring point observed data were used as an upper boundary condition in the OTIS software model. But before using them directly, the concentration curve was extended manually (to scale) to have a complete one (See Figure 48), so as it could be used in the model accurately.

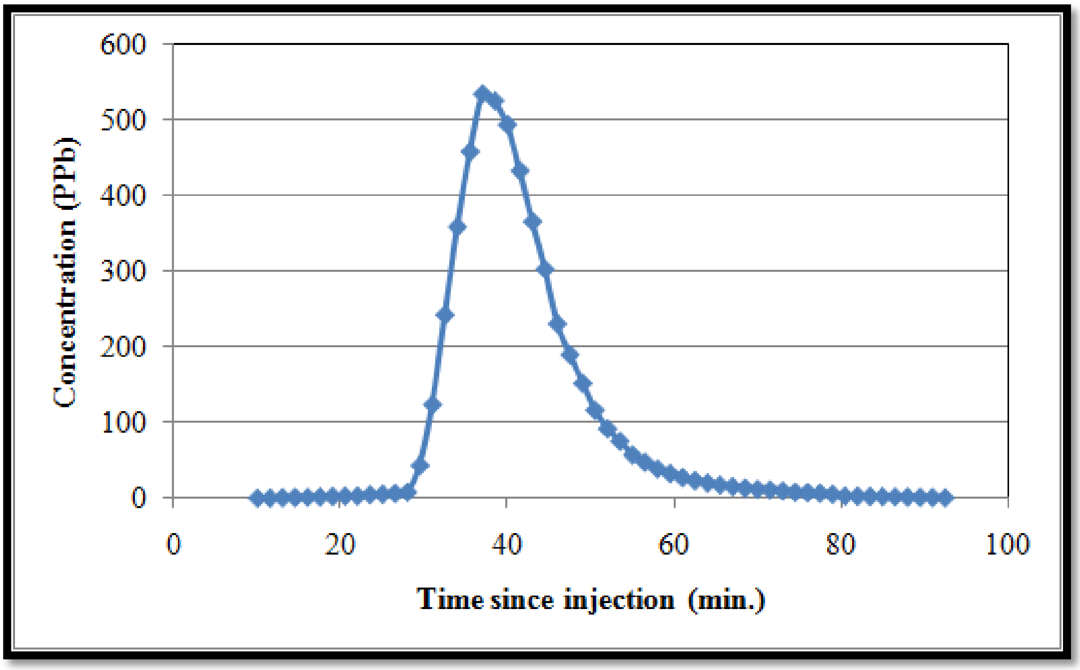

Figure 48: The observed concentration curve for the first monitoring point after the manual extension

- **Second Monitoring Point**

The observed concentration curve for the **second** monitoring point (at x = 300 m from the injection point) is depicted in Figure 49.

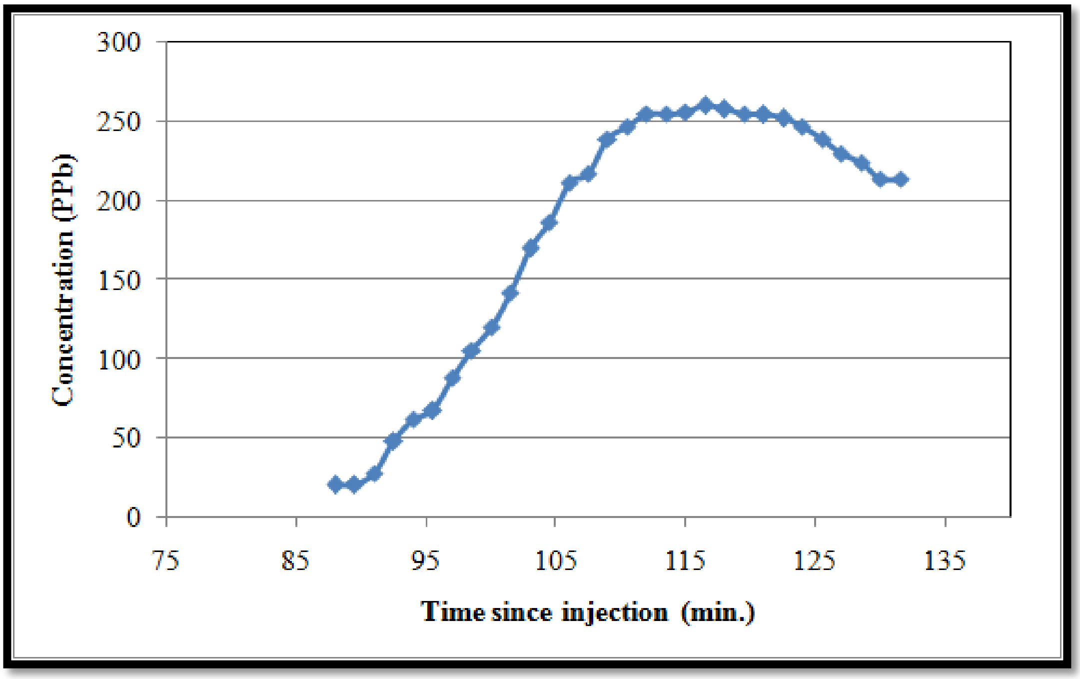

Figure 49: The observed concentration curve for the second monitoring point

It is noticed that the flow was not rapid enough in order to complete the shape of the concentration curve above with a total number of thirty samples and an interval time sampling period of 1.5 minutes. To complete the curve, OTIS model was used as depicted in Figure 50.

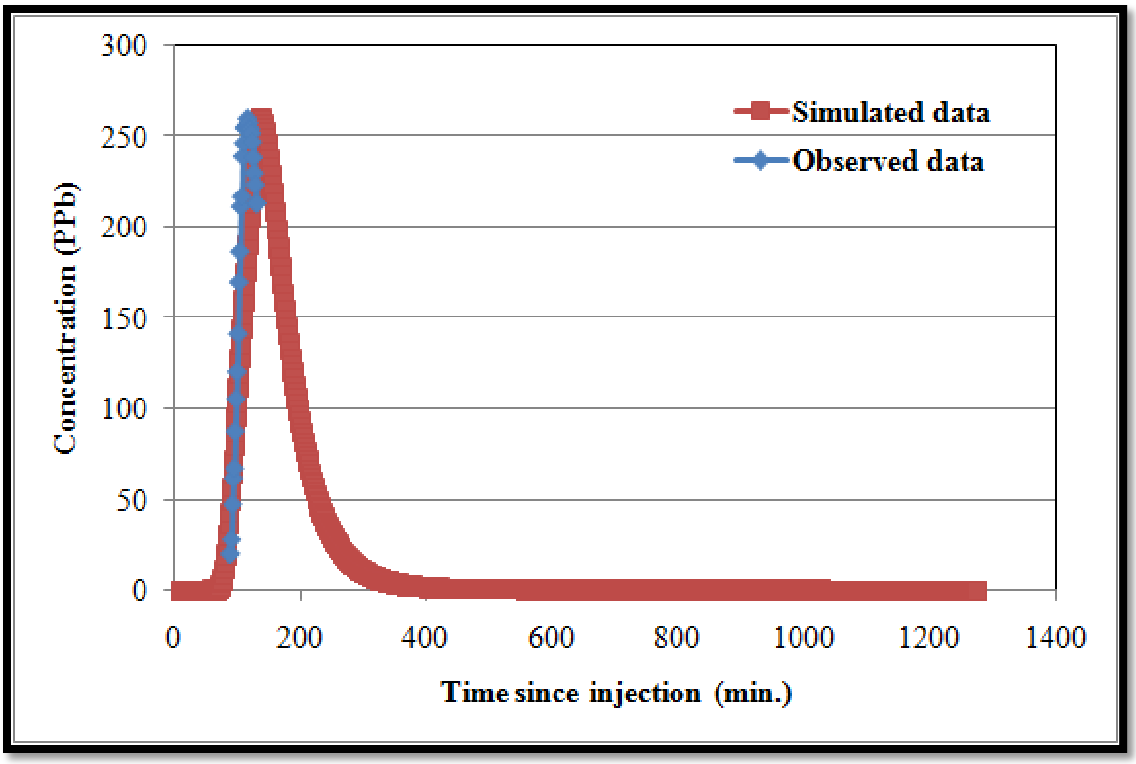

Figure 50: The observed and simulated concentration curves for the second monitoring point

Now, after the completion of the curve, it is ready to conduct the required calculations on it.

- **<u>Third Monitoring Point</u>**

The observed concentration curve for the **<u>third</u>** monitoring point (at x = 450 m from the injection point) is depicted in Figure 51.

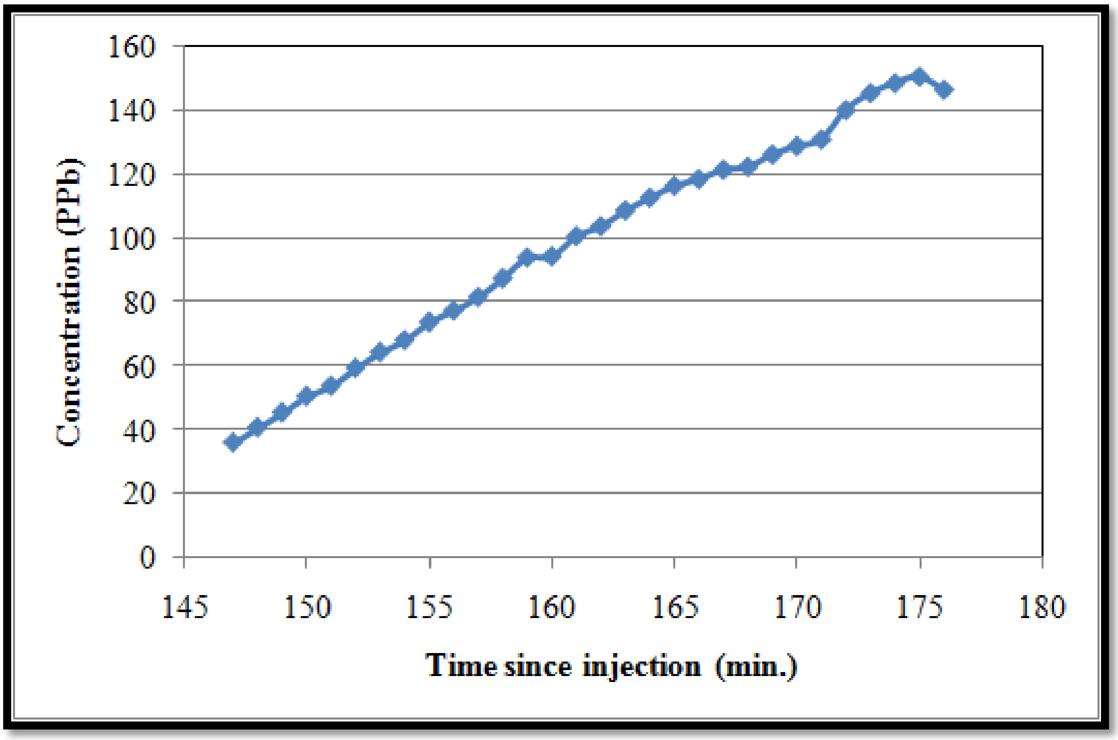

Figure 51: The observed concentration curve for the third monitoring point

It is clear from the figure that the curve reached to the peak value and one point lower, and then stopped. The sampling frequency at this location was taken as one sample per minute. The interval time sampling period is very small with respect to the relative slow flow in the channel which led to the non-completion of the curve. So, as in the second case and in order to conduct the required calculations, the curve was completed using the OTIS model as depicted in Figure 52.

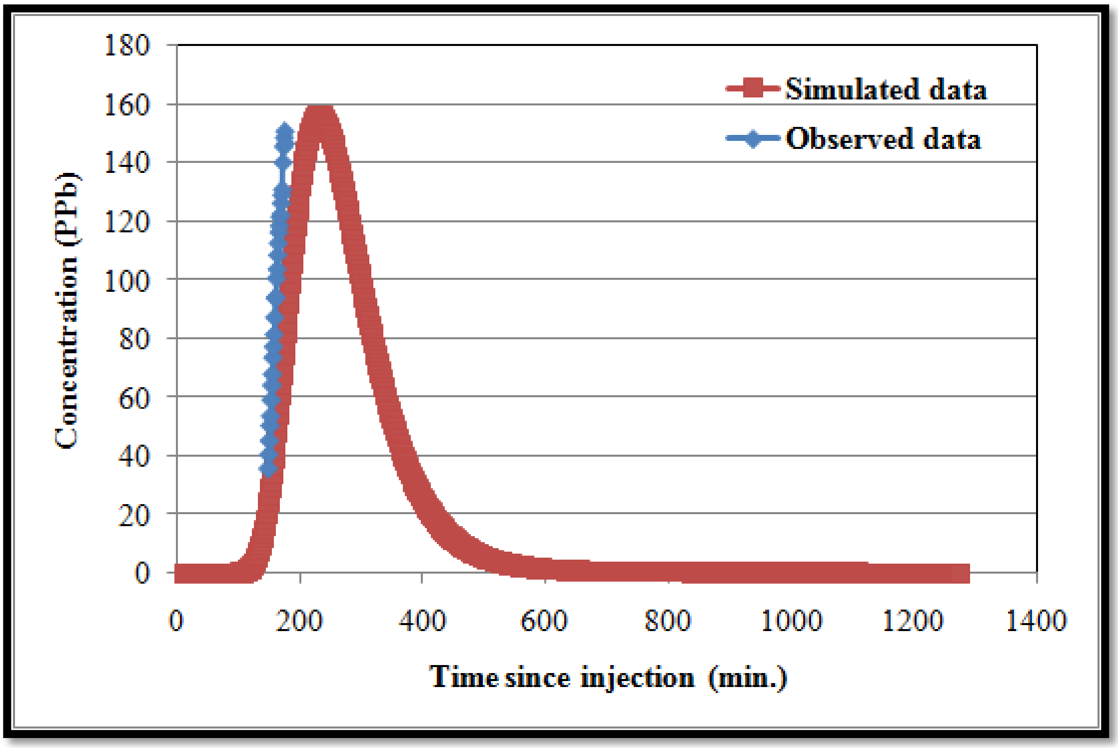

Figure 52: The observed and simulated concentration curves for the third monitoring point

- **<u>Fourth Monitoring Point</u>**

The observed concentration curve for the **<u>fourth</u>** monitoring point (at x = 600 m from the injection point) is depicted in Figure 53.

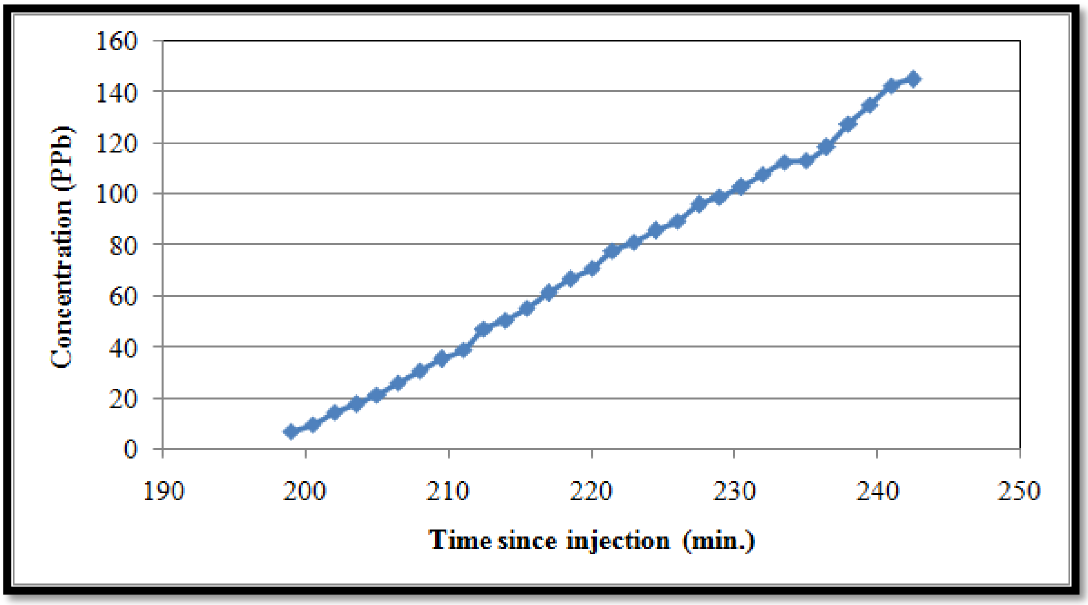

Figure 53: The observed concentration curve for the fourth monitoring point

It is shown from the above figure that the curve is increasing progressively and it is not clear whether it reached to the peak value or not. So again, it was simulated using the OTIS model in order to have the correct and complete concentration curve as depicted in Figure 54.

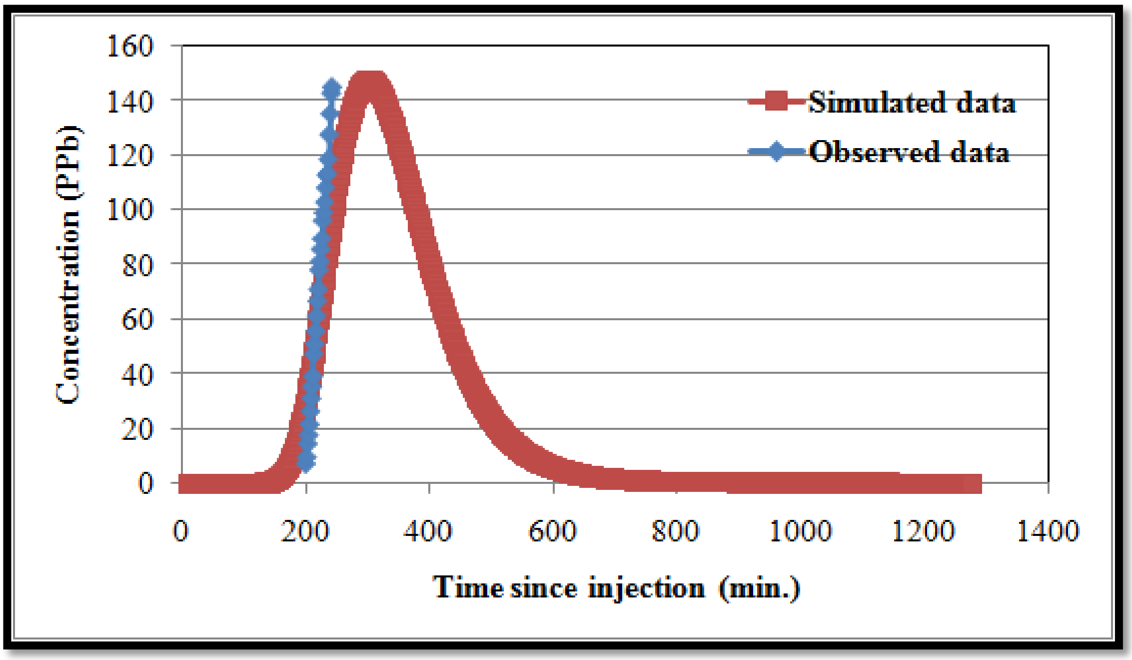

Figure 54: The observed and simulated concentration curves for the fourth monitoring point

It is very important to mention that the correlation coefficients between the observed and the simulated concentration curves range from 0.86 to 0.98 which means that the results are in a good agreement, so as we can assume that the OTIS model can be applied to the Faria catchment and the calibration process was made very properly.

To have a clear picture about the transmission losses effect, the first observed curve and the other simulated ones are plotted in a single graph as shown in Figure 55.

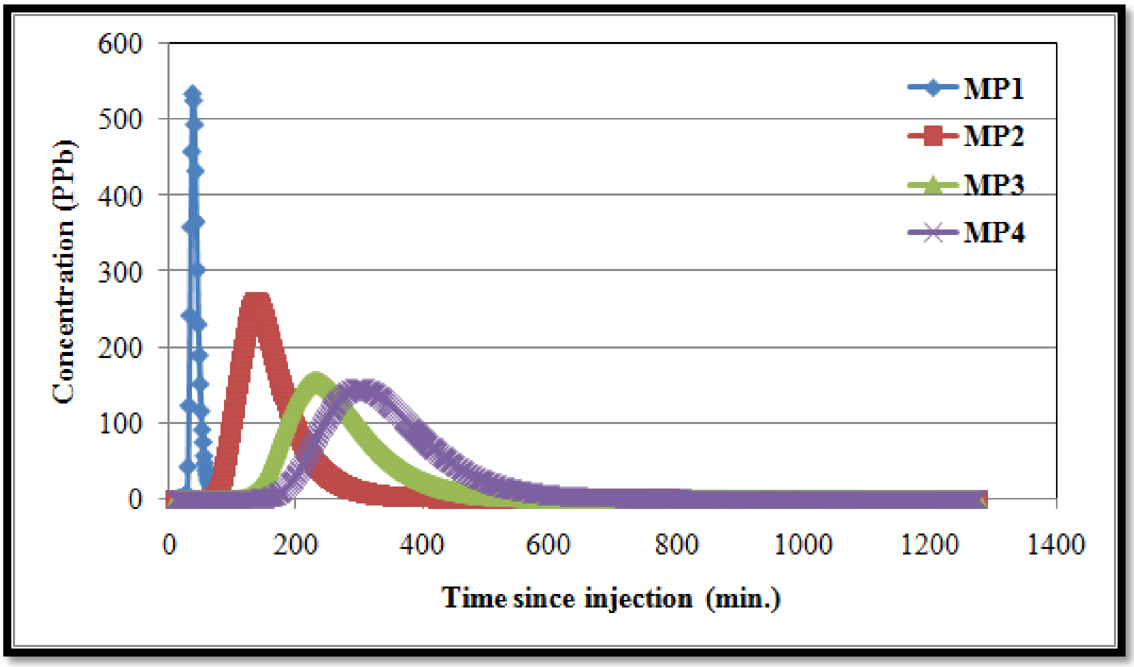

Figure 55: All concentration curves at the different monitoring points

From the above figure it is clear that attenuation of peak concentration and the widening of the curves bases as the flow moves downward from the injection point are noticed.

All relevant information, data, and calculations for each monitoring point at each section are summarized in Table 10.

Table 10: 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
1	150	150	28	Sample/1.5 min.
2	300	150	88	Sample/1.5 min.
3	450	150	147	Sample/1 min.
4	600	150	199	Sample/1.5 min.
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 (sec.)**	**Velocity in the section (m/s)**	**Avg. Concentrati-on (PPb)**	**Mass of tracer remained in each section at the monitoring point (mg)**
1	1680	0.089	91.98	**1379.7**
2	3600	0.041	19.24	**216.45**
3	3540	0.042	20.21	**181.89**
4	3120	0.048	23.29	**174.68**
Monitoring point #	**Area under the tracer solute curve (F) ($mg.min/m^3$)**	**Peak concentrate-on (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**	

Notes about the above table:

- 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 water in each section at the monitoring point.
- The mass of tracer decreases as the distance becomes farther from the injection point due to infiltration of the material through the wadi bed sediments only, since Uranine has neither decay nor adsorption (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 this case (this is also an evidence of wadi-aquifer interaction that occurs in the region).
- If the wadi flow covers the whole channel's cross-section and with a higher depth. Then, 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 second monitoring points and it is equal to 51.4%.
- The hot spot area is 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 region).
- The fact that the first section of the reach is determined as the hot spot area was expected, since this section has the least slope upon other sections in the selected reach and so, the flow in this section will have the largest residence time, this in turn increases the chance of interaction between the wadi and the aquifer. As well as, the nature of the wadi bed sediment in the first section was dominated by the sandy and gravelly soil structures. On the contrary, the nature of the wadi bed sediments in the other sections was dominated by the silty and clayey soil structures, which also in turn enhances the wadi-aquifer interaction to take place more than in other sections.

Also, the slopes of the sections in the selected reach (See Table 11) were found using an approximate estimation depending on the contour lines in the study area.

Table 11: The slope of each section in the selected reach

Section #	Slope
1 (0-150) m	0.005
2 (150-300) m	0.008
3 (300-450) m	0.015
4 (450-600) m	0.024

It is clear from the above table that as the distance moves away from the injection point, the slope increases. But in general, the above slopes values are considered to be relatively small and this in turn enhances the chance of wadi-aquifer interaction to take place since the steep reaches accelerate the arrival flow time to the outlet of the wadi, and thus reduce the chance of interaction.

Now, after the transmission losses took place and proved (potential recharge to groundwater) in the field experiment, the most important question that should be asked is: Will these transmission losses reach to groundwater? In order to be able to answer this question, the hydrogeology of the region should be studied and realized. The region's hydrogeological conditions allow the wadi-aquifer interaction to take place as discussed in Section 1.7.7 in Chapter 1.

Chapter Five

Conclusions and Recommendations

5.1 Conclusions

Faria catchment which is located in the northeastern part of West Bank suffers from both quantity and quality water related problems.

Most of the domestic and agricultural wells were drilled in the vicinity of the main wadi in Faria catchment, and this in turn affects the quality of groundwater due to wadi-aquifer interaction which is found to be one of the most important contamination sources in the catchment.

The wadi-aquifer interaction in the semi-arid regions of Faria catchment was mainly proved through developing quantity and quality analyses, and conducting a tracer field experiment at An-Nasariah area in the middle part of Faria catchment.

The following are the key conclusions of the research:

1. 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 have moderate to high values of hydraulic conductivity and calculated as 89 m/d) until reaching the saturated zone.
2. The quality analyses showed that the microbial and chemical pollutants concentrations, which were detected in groundwater samples from a well that is located next to the main wadi had higher trends in summer than in winter. The presence of those pollutants in groundwater is another evidence of wadi-aquifer interaction in the area.

3. The quality tests for nitrate, chloride, and fecal coliform bacteria revealed that there are chemical contamination and microbiological pollution in the groundwater in the area according to the Palestinian MCL for drinking water.
4. 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 as we can assume that the OTIS model can be applied to the Faria catchment and the calibration process was made very properly.
5. The tracer field experiment showed that transmission losses took place in all sections and they were the highest in the first section, which is 150 m from the injection point. This result makes sense because the first 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 rest sections which were dominated by silty and clayey soil structures.
6. Generally, the uncertainty in tracer field experiments is often high. In our case, many mitigation measures were followed to reduce this uncertainty. Such of these measures are: the selection of the reach; it was one of the most uniform (straight) reaches in the area. The selection of the tracer material; since Uranine is considered as a conservative tracer. The tracer dose mass was suitable with respect to the flow in the wadi. This in turn, helped to avoid the misinterpretations in the results. There was no evaporation diversion, since the experiment was conducted in winter. No lateral inflows and outflows were noticed. And

finally, the samples were analyzed within 24 hours of the time of the experiment to avoid any unexpected changes in them.

5.2 Recommendations

Based on the findings of this research, the following points are recommended:

- 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.
- The water table head in the vicinity of the wadi is better to be well observed via the development of a network of observation wells in order to gain a better understanding of groundwater dynamics corresponding to wadi flow.
- Additional work should be directed toward the employment of more specialized software for the modeling of stream-aquifer interaction.

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Annexes

Annex A:Hourly average rainfall depths for different Faria catchment stations and the hourly average change in the water table depths of well 18/18/27 from (1^{st} to 21^{st}/2005) of December.

Annex B: Hourly average rainfall depths for different Faria catchment stations and the hourly average change in the water table depths of well 18/18/27 from (11^{th} to 13^{th}/2006) of January.

Annex C: Hourly average rainfall depths for different Faria catchment stations and the hourly average change in the water table depths of well 18/18/27 from (1^{st} to 28^{th}/2006) of February.

Annex D: Hourly average rainfall depths for different Faria catchment stations and the hourly average change in the water table depths of well 18/18/27 from (1^{st} to 16^{th}/2006) of March.

Annex E: 10 minutes average in the change of the water table depths of well 18/18/27 and the 10 minutes average wadi flow records (taken from Al-Badan flume) from (1^{st} to 28^{th}/2006) of February.

Annex F: Records of fecal coliform bacteria, nitrate, and chloride concentrations found in groundwater from well 18/18/034.

Annex G: Observed data at the first monitoring point before the manual extension.

Annex H: Observed data at the first monitoring point after the manual extension.

Annex I: Observed data at the second monitoring point.

Annex J: Observed data at the third monitoring point.

Annex K: Observed data at the fourth monitoring point.

Annex L: Research case study’s parameter input file (Params.inp) in OTIS model.

Annex M: Research case study’s flow input file (q.inp) in OTIS model.

Annex A: Hourly average rainfall depths for different Faria catchment stations and the hourly average water table depths of well 18/18/27 from (**1st to 21st/2005**) of **December**

Date	Rainfall (mm)	Water table (cm)
1/12/2005	0	295
2/12/2005	0	294
3/12/2005	0	293
4/12/2005	0	293
5/12/2005	0	294
6/12/2005	0	294
7/12/2005	0	292
8/12/2005	0	289
9/12/2005	0	288
10/12/2005	0	289
11/12/2005	0	287
12/12/2005	0	286
13/12/2005	0	285
14/12/2005	0	281
15/12/2005	0	279
16/12/2005	0.68	280
17/12/2005	1.01	288
18/12/2005	0.004	284
19/12/2005	0	282
20/12/2005	0.05	282
21/12/2005	0	283

Annex B: Hourly average rainfall depths for different Faria catchment stations and the hourly average water table depths of well 18/18/27 from (**11th to 13th/2006**) of **January**

Date	Rainfall (mm)	Water table (cm)
11/1/2006	0.868	266
12/1/2006	0.577	278
13/1/2006	0.117	266

Annex C: Hourly average rainfall depths for different Faria catchment stations and the hourly average water table depths of well 18/18/27 from (**1st to 28th/2006**) of **February**

Date	Rainfall (mm)	Water table (cm)
1/2/2006	0	256
2/2/2006	0.204	257
3/2/2006	0.2	257
4/2/2006	0.008	255
5/2/2006	0	254
6/2/2006	0	255
7/2/2006	0	254
8/2/2006	0.637	254
9/2/2006	2.86	262
10/2/2006	0.008	283
11/2/2006	0	283
12/2/2006	0.002	286
13/2/2006	0.054	289
14/2/2006	0.552	290
15/2/2006	0.869	290
16/2/2006	0.202	290
17/2/2006	0.01	288
18/2/2006	0	287
19/2/2006	0	287
20/2/2006	0	287
21/2/2006	0	288
22/2/2006	0	288
23/2/2006	0	287
24/2/2006	0	287
25/2/2006	0.004	287
26/2/2006	0.031	287
27/2/2006	0	287
28/2/2006	0	287

Annex D: Hourly average rainfall depths for different Faria catchment stations and the hourly average water table depths of well 18/18/27 from (**1st to 16th/2006**) of **March**

Date	Rainfall (mm)	Water table (cm)
1/3/2006	0	287
2/3/2006	0	285
3/3/2006	0	286
4/3/2006	0	286
5/3/2006	0	285
6/3/2006	0	287
7/3/2006	0	288
8/3/2006	0	290
9/3/2006	0.794	294

Date	Rainfall (mm)	Water table (cm)
10/3/2006	0.077	294
11/3/2006	0	292
12/3/2006	0	291
13/3/2006	0	291
14/3/2006	0	288
15/3/2006	0.021	287
16/3/2006	0	285

Annex E: 10 minutes average water table depths of well 18/18/27 and the 10 minutes average wadi flow records (taken from Al-Badan flume) from (**1st to 28th/2006**) of **February**

Date	Water table (cm)	Wadi flow (m^3/s)
1/2/2006	256	0.353
2/2/2006	257	0.357
3/2/2006	257	0.369
4/2/2006	255	0.239
5/2/2006	254	0.305
6/2/2006	255	0.302
7/2/2006	254	0.305
8/2/2006	254	0.332
9/2/2006	263	3.84
10/2/2006	282	0.753
11/2/2006	283	0.149
12/2/2006	286	0.201
13/2/2006	289	0.224
14/2/2006	290	0.259
15/2/2006	290	0.519
16/2/2006	290	0.377
17/2/2006	288	0.174
18/2/2006	287	0.147
19/2/2006	287	0.249
20/2/2006	287	0.279
21/2/2006	288	0.190
22/2/2006	288	0.227
23/2/2006	287	0.220
24/2/2006	287	0.224
25/2/2006	286	0.243
26/2/2006	286	0.271
27/2/2006	287	0.254
28/2/2006	287	0.248

Annex F: Records of fecal coliform bacteria, nitrate, and chloride concentrations found in groundwater from well 18/18/034

month/year	Fecal coliform (cfu/100ml)	NO_3^{-1} (mg/l)	Cl^{-1} (mg/l)
03/2011	10	22	92.8
04/2011	20	22.7	89.4
05/2011	140	21.9	91.1
06/2011	110	18.2	83.3
07/2011	200	21.6	102.8
08/2011	1000	29.4	114.4
09/2011	680	18.3	87.2
10/2011	10	21.6	83.3
11/2011	200	18.8	90.5
12/2011	220	18.8	90.5
01/2012	0	17.7	83.9
02/2012	60	16.7	115
03/2012	7	23.2	105.8
04/2012	6	22.5	103.3
05/2012	16	23	91.1

Annex G: Observed data at the first monitoring point **before** the manual extension

Sample #	Time since injection (min.)	Conc. (PPb)
1	28	8.2
2	29.5	43.5
3	31	123.9
4	32.5	242.3
5	34	358.5
6	35.5	458
7	37	534
8	38.5	525
9	40	493.4
10	41.5	432.6
11	43	365.6
12	44.5	302.5
13	46	230.5

Sample #	Time since injection (min.)	Conc. (PPb)
14	47.5	189.7
15	49	152
16	50.5	116.6
17	52	92
18	53.5	75.6
19	55	57.6
20	56.5	47.6
21	58	39.1
22	59.5	33
23	61	27.5
24	62.5	23.4
25	64	20.3
26	65.5	17.7
27	67	15.7
28	68.5	13.8
29	70	12.2
30	71.5	11.3

Annex H: Observed data at the first monitoring point **after** the manual extension

Sample #	Time since injection (min.)	Conc. (PPb)
1	10	0.2
2	11.5	0.5
3	13	1
4	14.5	1.2
5	16	1.5
6	17.5	1.9
7	19	2.6
8	20.5	3
9	22	3.1
10	23.5	4.8
11	25	5.4
12	26.5	6.5
13	28	8.2
14	29.5	43.5
15	31	123.9
16	32.5	242.3
17	34	358.5
18	35.5	458

Sample #	**Time since injection (min.)**	**Conc. (PPb)**
19	37	534
20	38.5	525
21	40	493.4
22	41.5	432.6
23	43	365.6
24	44.5	302.5
25	46	230.5
26	47.5	189.7
27	49	152
28	50.5	116.6
29	52	92
30	53.5	75.6
31	55	57.6
32	56.5	47.6
33	58	39.1
34	59.5	3
35	61	27.5
36	62.5	23.4
37	64	20.3
38	65.5	17.7
39	67	15.7
40	68.5	13.8
41	70	12.2
42	71.5	11.3
43	73	9.9
44	74.5	8.2
45	76	7.7
46	77.5	6.9
47	79	5.5
48	80.5	3.1
49	82	2.9
50	83.5	2.5
51	85	2.3
52	86.5	2.1
53	88	1.8
54	89.5	1.4
55	91	1.2
56	92.5	0.8

Annex I: Observed data at the second monitoring point

Sample #	Time since injection (min.)	Conc. (PPb)
1	88	20.6
2	89.5	20.7
3	91	28.4
4	92.5	47.9
5	94	62.4
6	95.5	67.6
7	97	88.2
8	98.5	105.8
9	100	120.8
10	101.5	141.8
11	103	170
12	104.5	186.9
13	106	211.9
14	107.5	217.3
15	109	239.3
16	110.5	246.8
17	112	255.1
18	113.5	255.3
19	115	256.3
20	116.5	260.1
21	118	257.7
22	119.5	254.9
23	121	254.2
24	122.5	252.1
25	124	247.4
26	125.5	238.7
27	127	230.1
28	128.5	223.9
29	130	213.8
30	131.5	213.6

Annex J: Observed data at the third monitoring point

Sample #	Time since injection (min.)	Conc. (PPb)
1	147	36
2	148	40.8
3	149	45.5
4	150	50.6
5	151	53.8
6	152	59.5
7	153	64.5
8	154	68.2
9	155	73.9
10	156	77.5
11	157	81.7
12	158	87.6
13	159	94.1
14	160	94.5
15	161	100.9
16	162	104
17	163	108.9
18	164	112.9
19	165	116.6
20	166	118.8
21	167	121.7
22	168	122.7
23	169	126.5
24	170	129.2
25	171	131.2
26	172	140.5
27	173	145.8
28	174	148.9
29	175	151
30	176	146.9

Annex K: Observed data at the fourth monitoring point

Sample #	**Time since injection (min.)**	**Conc. (PPb)**
1	199	7.4
2	200.5	9.8
3	202	14.6
4	203.5	17.8
5	205	21.7
6	206.5	26.5
7	208	31.1
8	209.5	35.4
9	211	39.1
10	212.5	47.3
11	214	51
12	215.5	55.6
13	217	61.4
14	218.5	66.8
15	220	71.1
16	221.5	78.2
17	223	81.3
18	224.5	85.7
19	226	89.6
20	227.5	96.1
21	229	99.1
22	230.5	102.9
23	232	108.2
24	233.5	112.7
25	235	113.4
26	236.5	118.5
27	238	127.5
28	239.5	135.3
29	241	142.8
30	242.5	145

Annex L: Research case study's parameter input file (Params.inp)

Input variable	Format	Units	Description	Case study's value
PRTOPT	C	---	Print option	1*
PSTEP	D	hours	Print step: time interval at which results are printed	0.015
TSTEP	D	hours	Integration time step: Δt within the time-variable numerical solution	0.015
TSTART	D	hour	Simulation starting time	11.36
TFINAL	D	hour	Simulation ending time	24.0
XSTART	D	m	Distance at the upstream boundary	0.0
DSBOUND	D	m/sec	Downstream boundary condition	0.0
NREACH	I	---	Number of reaches	4
NSEG	I	---	Number of segments in reach	150/150/150/180
RCHLEN	D	m	Reach Length	150.0/150.0/150.0/180.0
DISP	D	m^2/sec	Dispersion coefficient	0.0/7.5/4.0/10.0
AREA2	D	m^2	Storage zone cross-sectional area	0.0000015**/0.1/0.25/0.20
ALPHA	D	/second	Storage zone exchange coefficient	0.0/0.5/0.5/0.2
NSOLUTE	I	---	Number of solutes	1
IDECAY	I	---	Decay option	0
ISORB	I	---	Sorption option	0
NPRINT	I	---	Number of print locations	4
IOPT	I	---	Interpolation option	0
PRTLOC	D	m	Print location	150.0/300.0/450.0/600.0
NBOUND	I	---	Number of boundary conditions	57
Input	**Format**	**Units**	**Description**	**Case study's value**

variable				
IBOUND	I	---	Boundary condition option	3***
USTIME	D	hour	Time boundary condition begins	Time readings taken from reach 1 (x= 150m)
USBC	D	mg/m^3 = PPb	Upstream boundary value	observation readings taken from reach 1 (x= 150m)

I: Integer

C: Character

D: Double precision

* If the print option is set to 1, solute concentrations are output for the main channel only (not also for the storage zone).

** AREA2 must be set to a non-zero value.

*** IBOUND is set to 3 since the type of injection is slug.

Annex M: Research case study's flow input file (q.inp)

Input variable	Format	Units	Description	Case study's value
QSTEP	D	hour	Change in flow indicator	0.0
QSTART	D	m^3/sec	Flowrate at the upstream boundary	0.013
QLATIN	D	m^3/sec-m	Lateral inflow rate	0.0/0.0/0.0/0.0
QLATOUT	D	m^3/sec-m	Lateral outflow rate	0.0/0.0/0.0/0.0
AREA	D	m^2	Main channel area	0.10/0.075/0.06/0.05
CLATIN	D	mg/m^3 = PPb	Lateral inflow solute concentration	0.0/0.0/0.0/0.0

D: Double precision

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قدمت هذه الأطروحة استكمالا لمتطلبات درجة الماجستير في هندسة المياه و البيئة بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين.
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الملخص

تهدف هذه الرسالة الى استكشاف احتمالية وجود تداخل بين الوادي الرئيسي (المياه السطحية) و المياه الجوفية في المناطق شبه الجافة من حوض الفارعة. تبلغ مساحة حوض الفارعة حوالي 320 كم^2 و يقع في الجزء الشمالي الشرقي من الضفة الغربية، و يعتبر واحدا من أكثر الأحواض أهمية في المنطقة، نظرا لأن الزراعة تشكل النشاط الإقتصادي الرئيسي فيه، حيث أنه يوصف بسلة فلسطين الغذائية.

الجريان السطحي في الحوض يتألف من مياه الينابيع، و الجريان الذي يتكون بفعل مياه الأمطار، و المياه العادمة الغير معالجة و التي تتدفق من الجزء الشرقي من مدينة نابلس و من مخيم الفارعة، بالإضافة الى المياه العائدة من الجريان الزراعي من الأراضي الزراعية المجاورة. تعتبر المياه الجوفية في الحوض هي المصدر الوحيد للإستخدامات المنزلية و الزراعية، و بالتالي فإن تداخل مياه الوادي الى المياه الجوفية سيكون له آثارا كبيرة على جودة المياه الجوفية، و سيعيق أي تنمية مستقبلية في الحوض.

الدلائل على تداخل مياه الوادي الى المياه الجوفية تعرض في هذه الرسالة من خلال تطوير علاقات كمية تشمل سجلات مياه الأمطار، و الجريان السطحي للوادي الرئيسي، و التغير في مستويات المياه الجوفية في حوض الفارعة، و كذلك تطوير علاقات نوعية لمياه الآبار المياه الجوفية في المنطقة، و أخيرا تم تنفيذ تجربة حقلية باستخدام المتتبعات الصناعية (Artificial tracers) من أجل إثبات و تكميم (quantify) عملية التداخل.

تظهر التحليلات الكمية أن مستوى المياه الجوفية في أحد الآبار المختارة بجانب الوادي الرئيسي يتغير بشكل ملحوظ مع أي تغير يرافق مياه الأمطار و الجريان السطحي في الوادي، و هذا بدوره

يقدم دليلاجيدا على أن هيدروجيولوجية المنطقة تسمح و تساعد في حدوث هذا التداخل، و بالتالي وصول التسربات من المياه السطحية المتمثلة بالوادي الى خزانات المياه الجوفية. كما تكشف التحليلات الكمية أيضا أن الزمن اللازم لوصول المياه من الوادي الى الخزانات الجوفية العليا قصير نسبيا و تم تقديره بحوالي 10 ساعات، وهذا بدوره انعكس أيضا على قيمة الموصلية المائية المحسوبة في المنطقة و التي قدرت ب 89 m/d و تبعا لهذه القيمة فإن طبقات التربة في المنطقة تصنف على أنها ذات موصلية مائية عالية.

بينما تظهر تحليلات نوعية المياه أن هناك بعض الملوثات الكيميائية و الميكروبيولوجية ظهرت في عينات استخرجت من بئر آخر يقع أيضا بجانب الوادي الملوث. و عزت الدراسة بشكل رئيسي هذا الأمر الى المياه العادمة الغير معالجة التي تنساب في الوادي و تتسرب الى المياه الجوفية، و هذا دليل آخر على حدوث تداخل بين الوادي و الخزانات الجوفية. أيضا تم رسم نزعات و مؤشرات التلوث التي أظهرت زيادة في فصل الصيف و نقصانا في فصل الشتاء.

التجربة الحقلية باستخدام المتتبعات الصناعية (Artificial tracers) أجريت في منطقة النصارية في الجزء الأوسط من حوض الفارعة (منطقة شبه جافة) باستخدام مادة اليوراناين (Uranine) وهي متتبع صناعي مقاوم لأي تغير يحدث في خواصه.

تم اختيار جزء ممثل من الوادي الرئيسي بطول 600 م و تم تقسيمه الى أربعة مقاطع متساوية في الطول، و كذلك تم رسم منحنى التركيز عند كل مقطع (نقطة مراقبة) بمساعدة برنامج (OTIS) وهو برنامج يستخدم لنمذجة انتقال الملوثات في الجداول و الأنهار، و من ثم فإن كل منحنى تركيز تم تحويله الى قيمة متوسطة للتدفق في كل مقطع، و أخيرا تم طرح كل قيمتين متتاليتين من قيم التدفق المحسوبة في المقاطع المختلفة من أجل إثبات و تكميم عملية التداخل.

أثبتت تجربة المتتبعات الصناعية الحقلية أن هناك ضياعا في التدفق المائي أثناء جريانه في الوادي، و أن المياه الملوثة تتسرب من الوادي الى المياه الجوفية و بالتالي يصبح الجريان الضائع بمثابة تغذية محتملة لخزانات المياه الجوفية. و تراوحت نسبة الفاقد في معدلات التدفق السطحي في المقاطع المختلفة بين 4.8% و 68.3%. و في النهاية تم تحديد المنطقة (المقطع) الأكثر مساهمة في حدوث تسربات من السطح الى خزانات المياه الجوفية من خلال أخذ المقطع الذي كان فيه أكبر فرق في معدل التدفق بين نقطتي المراقبة فيه.