**An-Najah National University**

**Faculty of Graduate Studies**

# Artificial groundwater recharge in Faria catchment
# A hydrogeological study

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## Dedication

***To my parents, my beloved wife, and my brothers for their efforts***

## Acknowledgements

Praise be to the Merciful Allah for enabling me to accomplish this hectic course in a sound health.

I would like to express my gratitude to the Ministry of Foreign Affairs of The Netherlands for funding this research in the frame of the EXACT project. My appreciation goes to Drs. J. Nonner and Dr. P.J.M. de Laat for the assistance I have received from them.

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Yahya Saleh

# الإقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

## Artificial groundwater recharge in Faria catchment A hydrogeological study

أقر بأن ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، و إن هذه الرسالة ككل، أو أي جزء منها لم يقدم من قبل لنيل أي درجة علمية أو بحث 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:** الاسم:

**Signature:** التوقيع:

**Date:** التاريخ:

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## Abstract

Faria catchment is classified as arid to semi-arid region without perennial water resources. Wells and springs are the main sources of water, yet these wells and springs do not withstand the entire dry season. So, it was important to find feasible solutions to utilize the surplus storm and spring water which flows to the Jordan Valley. One of the identified feasible solutions might be to artificially recharge the groundwater with the surplus water.

Therefore this study is to assist in the establishment of the effect of recharge by floodwater on the groundwater system made up of alluvial and consolidated sediments and karstic limestone in the Faria catchment.

The methodology of the work started with collecting and analyzing the data which are needed for establishing the water balances or to define proper locations for artificial recharge. Groundwater and surface water balances were established and the probable volume of artificial recharge was calculated. Moreover the best sites for artificial recharge were located and verified.

The use of artificial recharge will make changes in the quantity and quality of the groundwater system. In order to assess these changes, the

hydrological and hydro geological properties of the area under study were identified.

Within the light of this understanding, the groundwater and surface water balances were established using available data in the area. This was all done in order to establish the reference conditions that can be utilized in quantifying the impacts of artificial recharge on the groundwater resources of the study area. The results were that about 36 MCM is the natural recharge in the upper parts of the catchment against a total catchment recharge of 60.3 MCM. The man made artificial recharge in the upper catchment can contribute about 3.2 MCM.

Since the main wadi courses convey the disposal of wastewater and to avoid the negative effects of mixing the wastewater with recharge water, a separation method was proposed to separate the wastewater and to improve the current situation for the groundwater.

The Weighted Index Overlay Method (WIOA) was used to determine the most proper locations for artificial recharge structures based on infiltration capacity, slope, and type of aquifer to be recharged and the existence of fractures. The results show that 14% of the total area is very suitable for artificial groundwater recharge. These results were verified by field observations and previous studies and each of them supports the obtained results.

# Chapter One: Introduction

## 1.1 Background

Groundwater is the subsurface water that occurs beneath the water table in the soils and geologic formations that are fully saturated (Freeze, 1979). Safe groundwater abstraction and proper groundwater management is important for the sustainability of this resource (Fetter, 2001).Water management can be defined as comprehensive planning for beneficial use plus operation for optimum economic and social benefits of total water resources (UN, 1975).

The increase in demand for water in the West Bank should lead to the implementation of high intensive water management measures to achieve efficient utilization of the limited available water supplies. The artificial groundwater recharge will be one of the proposed management options.

The natural replenishment of groundwater occurs very slowly. If groundwater is exploited at a rate greater than that of its natural replenishment, it will cause declining of groundwater levels. In the long term, this causes depletion of groundwater resources. To increase natural replenishment of groundwater reserves, artificial recharge of groundwater has become increasingly important (Jemal A.M., 2006).

Artificial recharge is the process by which excess surface water moves through man-made systems from the surface of the earth to underground water-bearing strata where it may be stored for future use. Artificial recharge is sometimes called planned recharge (NRC, 1994).

This research studies the hydrogeology pertaining to the artificial recharge with surface water in the Faria catchment. This research is funded by the

Ministry of Foreign Affairs of The Netherlands in the frame work of the EXACT project. The EXACT project includes three phases, measuring parameters (two years), construction of the infiltration works (one year), and monitoring the performance of the infiltration site (two years). This study serves as a preparation for phase two.

This thesis is sponsored by the EXACT project and is implemented through WESI (Water and Environmental Studies Institute) . It is one of the two MSc thesis agreed between EXACT and WESI to focus on the evaluation and requirements of recharging the groundwater aquifer and wells in the Faria catchment with surface water and storm water flowing in the upper sub-catchments of the Faria catchment.

## 1.2 Problem statement

Palestine is known for its scarcity of renewable water resources that led to a low per capita water consumption of 55 l/c/d, which is 55% of the WHO minimum standard of 100 l/c/d (Abu Zahra, 2001).

The same conditions can be said about Faria catchment that is located in an arid to semi-arid region where the conservation of water resources in the catchment is very crucial. Groundwater is a major source of water supply in the area. Use of surface runoff as a source to artificially recharge the groundwater aquifer can be considered as an important way of water conservation.

## 1.3 Importance of the study

The following summarizes the importance of the study:

- The Faria catchment is characterized by the generation of flash floods that entail huge quantities of runoff water in a short period of time. Such quantities are generally lost and thus ought to be collected for later use after being artificially recharged into aquifers. The storing of water surplus will indeed enable the use of this water in times of water shortage to meet future water demands;
- The groundwater is the main source of water in this region. It is preferred over surface water for drinking and other purposes and thus the augmentation of groundwater quality is essential;
- Artificial recharge is an effective process to improve the quality of the existing wastewater through soil filtering treatment;
- Artificial recharge is a world-wide recognized method for the preservation of runoff and the replenishment of groundwater resources.

## 1.4 Research objectives

The following are the research objectives:

- To determine the appropriate locations and methods to be used for artificial groundwater recharge in the Faria catchment depending on the slope, the existance of fractures, the type of aquifer to be recharged and the infiltration capacity.

- To study the effects of artificial groundwater recharge on the quantity and quality of groundwater in the study area.

## 1.5 Research questions

The following are the research questions:

- What are the current groundwater balance components for the Faria catchment before the implementation of the proposed artificial recharge scheme?
- What are the changes that may occur after implementing the artificial recharge on the groundwater balance components?
- Which artificial recharge systems can be used and where?
- What would be the impact of the artificial recharge on the quality of groundwater?

## 1.6 Research methodology

The research methodology covers the following major tasks:

1. Collection of data: these data were obtained from field visits, reports and previous studies. The collected data include the following:

- Geological map, topographical map.
- Geological cross-sections.
- Climatic data which include rainfall, runoff, and temperature.

- Wells and springs discharge amounts.
- Water quality characteristics.
- Infiltration capacity values.

2. Establishment of groundwater and surface water balance components for the upper Faria catchment. The main task is to complete the water balance analyses and to find out the quantities of water that can be utilized.
3. Establishment of changes in the groundwater balance components. The water balance analyses have been calculated to identify quantities of the available water to recharge the aquifer within the upper Faria catchment.
4. Assessment of groundwater and surface water quality via analyses of water samples from different locations and sources, and comparing the water quality with international standards.
5. Preparing maps by using GIS to determine the proper locations for artificial recharge structures based on the following criteria:
    - Infiltration capacity
    - Slope
    - Type of aquifer
    - The fractures in the study area
    - Land use

# Chapter Two: Literature Review and General Background

## 2.1 Artificial groundwater

Recharge Artificial groundwater recharge systems are engineered systems where surface water is put on or in the ground for infiltration and subsequent movement to aquifers to augment groundwater resources. Other objectives of artificial recharge are to reduce land subsidence, to store water, to improve the quality of the water through soil-aquifer treatment or geo-purification, and to use the aquifer as water conveyance systems (Bouwer , 2002).

Artificial recharge can be used for a number of reasons: integrated water management, seasonal storage and recovery of water, long-term storage or water banking, emergency storage or strategic water reserve, short term storage, enhancement of well field production, restoration of groundwater levels, compensation for over-draft, reduction of pumping cost, stoppage or reduction of the rate of land surface subsidence, and improvement of groundwater quality to agricultural or municipal standards (Raju, et al., 1994).

The recharge objectives are important to select and prioritize these so that they are applicable to the area under study.

## 2.2 Methods of artificial recharge

In general, there are two methods of artificial recharge: Direct and Indirect methods. A combination of the Direct and Indirect methods, the Combination system, is also possible.

### 2.2.1 Direct methods

Direct methods can be divided into surface recharge techniques and subsurface recharge techniques (ASCE, 2001). In surface recharge, water moves from the land surface to the aquifer by means of infiltration through the soil. The surface is usually excavated and water is added to spreading basins, ditches, pits, and shafts and thus is allowed to infiltrate. Surface infiltration consists of in-channel and off-channel facilities (Bouwer , 2002).

#### 2.2.1.1 Surface techniques

*In-channel systems* consist of dams and weirs, canals, finger dikes, terrace or other structures in the stream bed or flood plain to impound and spread the water over as large a wetted area as possible, increasing the infiltration volume.

*Off-channel systems* consist of recharge basins, pits, ponds and ditches specially constructed by excavation, construction of berms (or both) or by using of old gravel pits, borrow areas, or similar excavations. This method involves surface spreading of water in excavated basins. The amount of water entering the aquifer depends on three factors (Bouwer , 2002): the infiltration rate, the percolation rate, and the aquifer’s capacity for horizontal water movement. These systems are depicted in Figure (2.1).

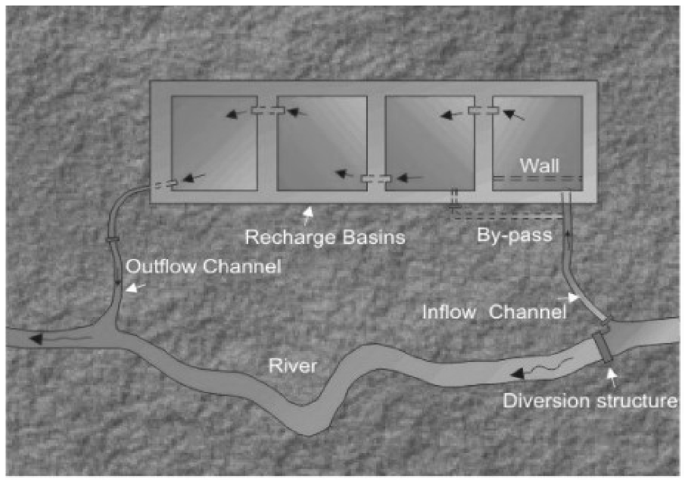


**Figure (2.1): Infiltration basins (Jemal, 2006)**

### 2.2.1.2 Subsurface techniques (Injection wells)

Injection techniques are used as an alternative to surface spreading operations when a zone with low permeability, within the unsaturated zone, impedes the recharge of the water to a designed aquifer, Figure (2.2) clarifies the gravity injection wells or bores.

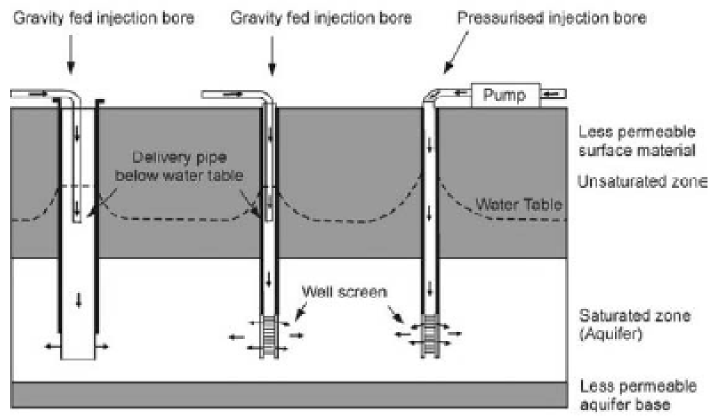


**Figure ( 2.2): Gravity injection wells or bore (Jemal, 2006)**

### 2.2.2 Indirect methods

Indirect methods include installing groundwater pumping facilities near connected surface water bodies to lower groundwater levels and induce infiltration elsewhere in the drainage basin. Indirect methods include modifying aquifers to enhance groundwater reserves.

### 2.2.3 Combination systems

This mixed recharge system is the combination of an infiltration basin and recharge wells. Figure (2.3) shows this system. The advantage of this system is that the water has been pre-filtered through the soil and the perched groundwater zone so that its clogging potential is significantly reduced. In this way the risk of aquifer obstruction is reduced (Raju, et al., 1994).

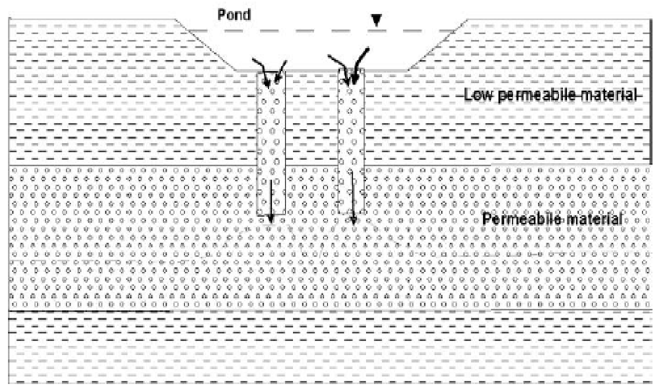


**Figure (2.3): Combination of injection well and basin (Jemal, 2006)**

Table (2.1) lists the advantages, disadvantages and conditions of use for a selection of methods for artificial groundwater recharge.

**Table (2.1) : Properties of artificial groundwater recharge (AGR) methods**

| Method of AGR | Advantage | Disadvantage | Condition of use |
| --- | --- | --- | --- |
| Dam | • Suitable for relatively low permeable soil | • Evaporation losses.<br>• Sediment accumulation.<br>• Potential structure failure | • Suitable geomorphology |
| Spreading | • Low construction and maintenance cost | • Clogging of the surface material by suspended sediment | • In areas with abundant land availability<br>• High permeability of the soil<br>• Shallow unconfined aquifer |
| Wells | • Relatively inexpensive | • Clogging up at infiltrating surface | • Suitable in areas where a thick impervious layer exists between the surface of the soil and the aquifer |

## 2.3 Factors determining the proper location of artificial

Recharge Factors like topography, geology, geomorphology, pedology, surface and sub-surface hydrology, vegetation cover, social and economic conditions, and environmental impacts of the projects should be considered when selecting an area for flood spreading and artificial recharge (Jafar, et al., 2004)

## 2.4 Water quality effects on an artificial recharge system

Water used for in- and off-channel recharge systems should be of adequate quality to prevent undue clogging of the infiltrating surface by deposition and accumulation of suspended solids (sediment, algae, and sludge), by formation of bio-films and biomass on and in the soil, by precipitation of calcium carbonate or other salts on and in the soil, and by formation of gases that stay entrapped in the soil. All these processes block the pores and reduce the hydraulic conductivity. Gases sometimes also accumulate under the clogging layer, where they form a vapor barrier to downward flow. One source of these gases is dissolved air in the infiltrated water (Bouwer , 2002).

## 2.5 Pre-treatment of sewage effluent used in artificial recharge

If the recharge is via basins or other surface infiltration facilities, any sewage effluent is typically first given primary and secondary treatment and disinfection with chlorine (National Research Council NRC, 1994). Primary effluent can also be used (Bouwer and Rice, 1984). Some projects use tertiary effluent, where the sewage after secondary treatment is filtered through sand or another granular medium and then chlorinated or otherwise disinfected. Primary treatment is a mechanical process that removes everything that floats or sinks. Secondary treatment is a biological process where bacteria degrade organic compounds in aerated tanks (activated sludge process) or trickling filters. Tertiary treatment consists of sand filtration and disinfection; and advanced treatment refers to all other treatment steps, such as lime precipitation; nitrification-de-nitrification; activated carbon filtration; and membrane filtration such as reverse osmosis. Often, water-quality improvement is the main objective of recharge with sewage effluent. For this reason, systems are usually no longer called recharge systems but instead they are called soil-aquifer-treatment systems or geo-purification systems (Bouwer, et al., 1984)

## 2.6 The implementation of artificial groundwater recharge worldwide

A global overview was made of areas suitable for artificial groundwater recharge techniques. The idea to identify areas on a global scale developed from the realization that digital global maps with sufficient detail are now available. The identification was executed for areas of South and Central America, Africa and Asia, using digital maps of geology, soils, climate, population and economic development, and by making overlays of the related spatial themes. The availability and quality of such digital maps has improved markedly in recent years. It should be realized that the areas identified only give a preliminary indication on a global scale of the suitability for artificial recharge. The analysis of local conditions remains necessary to determine actual suitable areas (Gale, et al., 2002).

**2.7 Artificial recharge in the developing countries**

The introduction of artificial recharge in Jordan is only of a very recent nature. Feasibility studies have been carried out around the year 1996 to find out whether conditions in Jordan are suitable to introduce artificial recharge schemes using surface runoff (rain) water. One of those studies was carried out by the Ministry of Water and Irrigation in cooperation with USAID (Chehata, 1997). The study focused on the Wadi Madoneh and the Wadi Butum areas, located northeast of Amman. Upon completion of the study, the conclusion was drawn that Wadi Madoneh offered the best scope for the implementation of artificial recharge.

The artificial recharge scheme at Wadi Madoneh has been implemented. First studies were done to assess the available amounts of storm water for infiltration, to assess water balances and to determine locations for the artificial recharge infrastructure (Al Qaisi, 2008). In 2007, the actual infrastructure consisting of four infiltration dams was built in the Madoneh area.

Other examples for applying the artificial recharge technology were in Saudi Arabia in the late-1950's and early 1960's, and in the United Arab Emiraates and Oman in the early 1980's. Dams were constructed in river valleys to retain water for the purpose of artificial recharge of groundwater aquifers by facilitating infiltration of the water into the soil, rather than having it flow to the sea or be evaporated in desert regions. It is estimated, for example, that about 120 MCM of water is lost to the sea or is evaporated in Oman, which is a very significant water loss in the dry environmental conditions existing in the country. Large projects have been implemented in Qatar, involving the injection of stored surface water to recharge the groundwater aquifers. Several experiments to test the efficiency and feasibility of the groundwater recharge technology for the prevailing environmental conditions are underway in Syria and Lebanon (UNEP, 2009).

## 2.8 Basic requirement for successful artificial recharge systems

The basic requirements for artificial groundwater recharge are (Central groundwater board/Ministry of water resources, 2000):

- Identification of suitable hydrogelogical environment and sites for creating subsurface storage through cost effective artificial recharge techniques.
- The quality of used water should be improved before mixing with native groundwater, otherwise, it should be separated away and protect the groundwater to be mixed with unaccepted water quality.

## 2.9 Previous Studies in the Faria catchment

Two studies from the literature were cited that are related to artificial groundwater in the Faria catchment.

1. Jamil (2006) made an attempt to relate the runoff coefficient to rainfall intensity in order to estimate runoff volumes for extreme rainfall events using the Nash model. Analyzing the efficiency of constructing the retention dams for different return periods, the study concluded that

about 90% of the storm water runoff could be used for artificial recharge for a return period of 2 years.

2. Abu Safat (1990) investigated the possibility of constructing an earth fill dam at Faria catchment for agricultural purposes. The study delineated the suitable location of the dam based on the morphometric characteristics together with the storage capacity and the size of the lake behind the dam for different heights of the dam. Such agricultural dams are used to store runoff water to be used later in irrigating cultivated lands downstream. The morphological characteristics is another criteria applied for selecting the location of infiltration structures.

# Chapter Three: Description of the Study Area

## 3.1 Physiography

### 3.1.1 Location

Faria catchment is located in the northeastern part of the West Bank (Figure 3.1) and extends from the ridges of Nablus Mountains to the Jordan River. Faria catchment overlies three districts of the West Bank; Nablus, Tubas and Jericho. It has an area of approximately 320 $km^2$ (Shadeed, 2005) which accounts for about 6% of the total area of the West Bank.

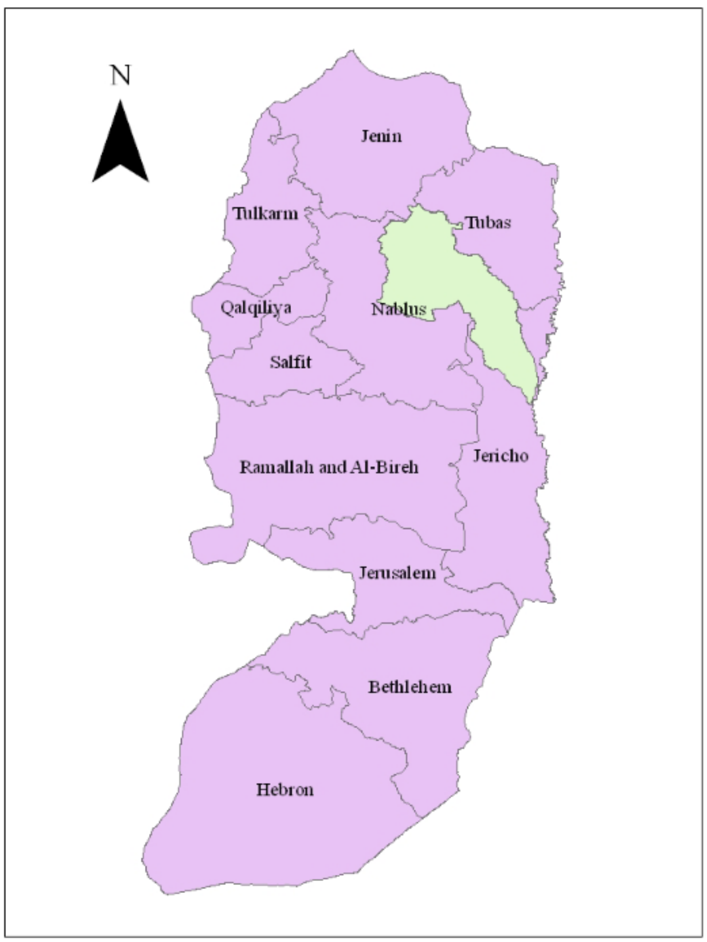


**Figure (3.1): Location of the Faria catchment in the West Bank (EQA, 2004)**

### 3.1.2 Climatology

Climate in the Faria catchment can be characterized as hot and dry during summer and cool and wet during winter. The average annual precipitation ranges between 450 to 500 mm in the mountainous areas. Precipitation decreases from west to east and from high to low altitudes. The rainy season is in winter, occurring from October to May with maximum rainfall in January. The annual average relative humidity is about 52 percent. Evapotranspiration is high in the summer when there is always a water deficit. The climate of the Faria catchment is classified as arid to semi-arid from the eastern parts to the western parts.

### 3.1.3 Geomorphology and topography

The study area is dominated by hills. The eastern and northern flanks of the mountains have a steep descent toward the rift valley. The southern part of the Faria catchment has a series of steps that descend toward the valley floor while the northern part of the study area has a homoclinal descent parallel to the dip of the strata that passes into a narrow, synclinal, hilly area, which drops steeply toward the Jordan Valley. The synclinal areas are built mainly of soft limestones and chalks. In the dry summer months, the soils and unconsolidated material loosen and usually cause mass wasting processes upon the first rainfall (Calvin College and Birzeit University, 2002). Figure (3.2) shows an example of erosion in the study area.

**Figure (3.2): Erosion in the study area (Calvin College and Birzeit University, 2002)**

Topographic relief in the Faria catchment changes significantly throughout the area. In less than 35 kilometer, there is a 1.3 kilometer change in elevation. In this short, but extreme topographic area, over 47,320 Palestinian people live in about 30 communities and villages while 120,000 people can be included from Nablus city (and its refugee camps). The highest point in the study area is 920 meter above mean sea level and the lowest point is 381 meters below mean sea level as shown in Figure (3.3).

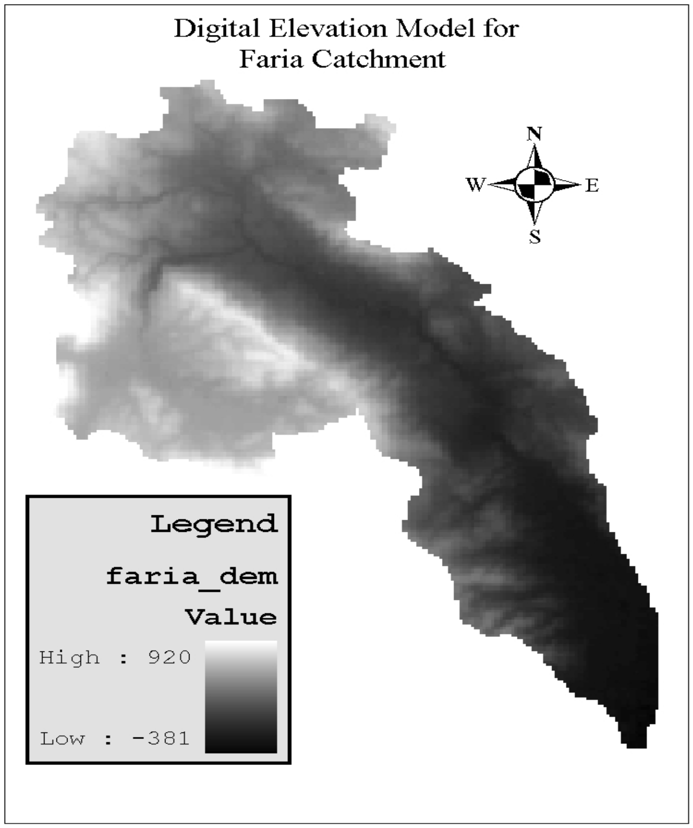


**Figure (3.3): A digital elevation model for Faria Catchment**

### 3.1.4 Drainage network

Wadi Faria extends from the upper part of the catchment to the Jordan River. Wadi Faria and Wadi Badan are the two main upstream branches contributing to the main wadi channel downstream which is also referred to as Wadi Faria. The upstream wadis meet at Al-Malaqi Bridge located 10 km east of Nablus (see Figure 3.4). Wadi Faria is the major drain in the catchment for storm water, but may also act as a water supply channel. Springs are located around the wadi stream channel and discharge water into the wadi. Part of the spring water is conveyed to irrigation ditches and pipelines that distribute irrigation water to the farms along both sides of the wadi.

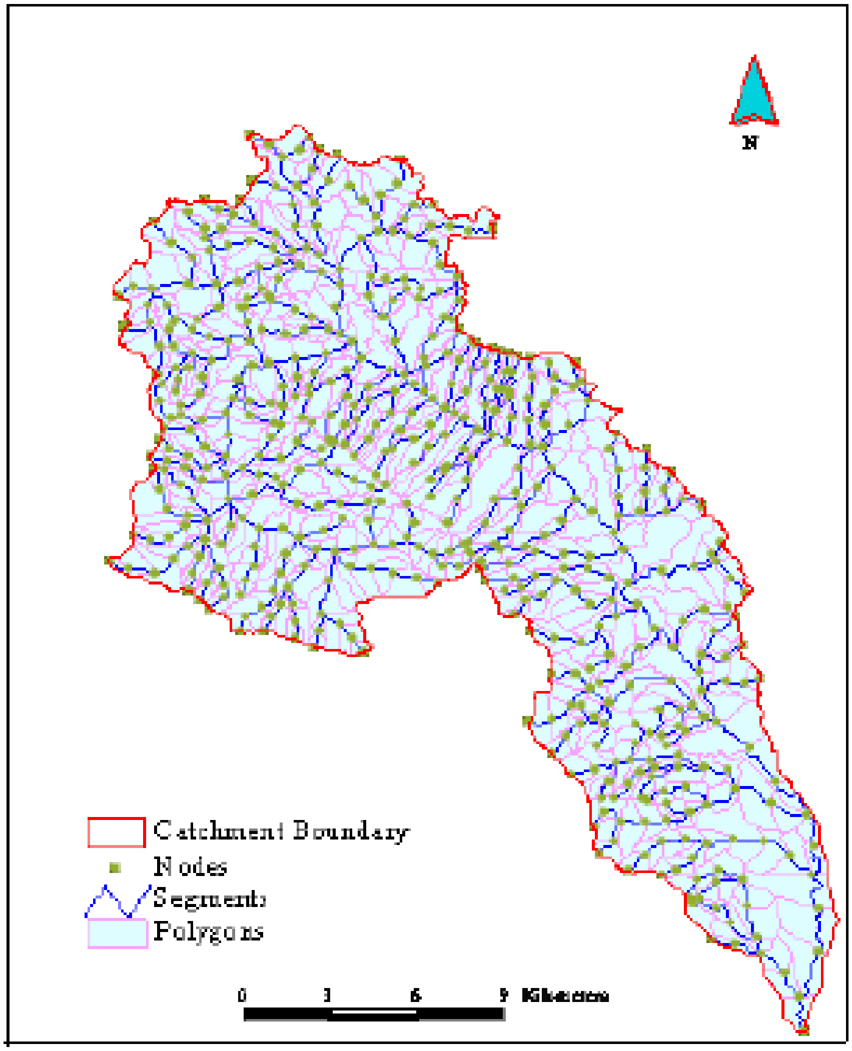


**Figure (3.4): Drainage network in Faria catchment**

## 3.15 Soils

Different soil types exist in the Faria catchment (EQA, 2004). Figure (3.5) shows the major soil classifications in Faria catchment. These are:

1. Loessial Seozems: This type of soil is found in the plateau and moderate slope areas in the lower parts of the catchment
2. Brown litholsols and loessial arid brown soils: This soil type is concentrated on the hilltops and foot slopes of the lower catchment areas.
3. Brown Rendzianas and pale Rendzinas: This soil type is concentrated in the mountainous areas mainly in the central parts of the catchment.
4. Grumusols: Parent materials for these soils are alluvial and/or aeolian deposits in the upper areas of the catchment around Wadi Faria.
5. Regosols: The parent materials for this soil type include sand, clay, loess and Lisan marl.
6. Terra Rossas, Brown Rendzinas and pale Rendzinas: This type of soil is common in the highland areas of the catchment.

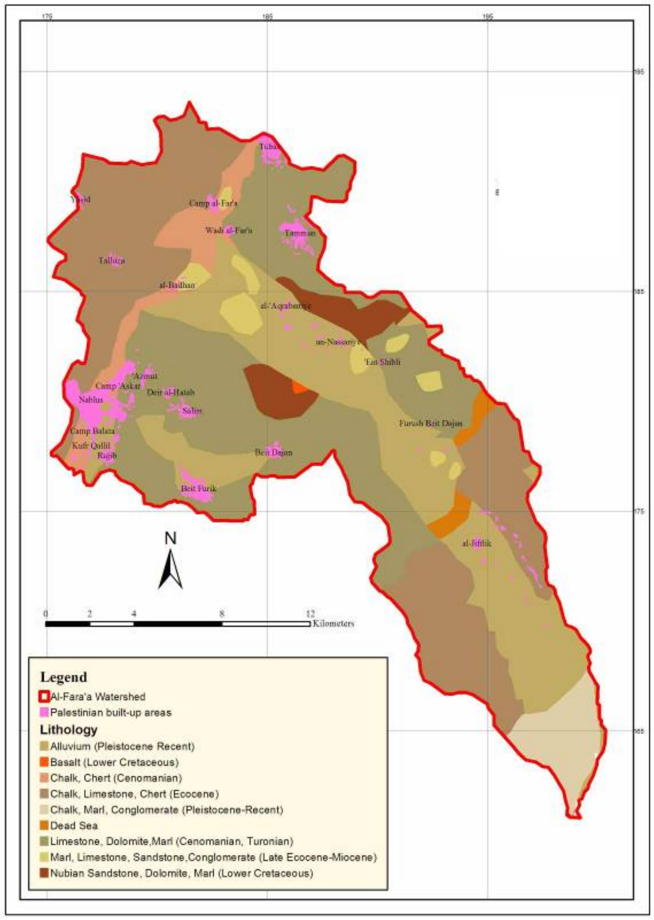


**Figure (3.5): Map of soil types of Faria catchment (EQA, 2004)**

### 3.1.6 Land use

Considering land use, the catchment includes Faria Valley which is one of the most important agricultural areas in the West Bank. The land use map of the Faria catchment shows four classes. These classes are artificial surfaces, agricultural areas, forests and semi natural areas, and water bodies. Table (3.1) presents these classes and the sub-categories, the area of each class, and the classes as a percentage of the whole catchment (EQA, 2004).

## Table (3.1): Land use classes (EQA, 2004)

| Land cover | Area (Dunum) | Area (%) |
|---|---|---|
| **Artificiel Surfaces** | | |
| Refuge camps | 900 | 0.3 |
| Discontinuous urban fabrics | 10488 | 3.2 |
| Israeli colonies | 2885 | 0.9 |
| Military camps | 649 | 0.2 |
| Construction sites | 817 | 0.2 |
| **Total** | **15739** | **4.8** |
| Agricultural Areas | | |
| Non-irrigated arable land | 27521 | 8.3 |
| Drip-irrigated arable land | 13847 | 4.2 |
| Vineyards | 71 | <0.1 |
| Drip irrigated vineyards | 16 | <0.1 |
| Olive groves | 25465 | 7.7 |
| Palm groves | 347 | 0.1 |
| Citrus plantations | 4722 | 1.4 |
| Others | 594 | 0.2 |
| Non-irrigated complex cultivation pattern | 4568 | 1.4 |
| Irrigated complex cultivation pattern | 15388 | 4.6 |
| Land principally occupied by agriculture | 32251 | 9.7 |
| **Total** | **124790** | **37.7** |
| **Forests and Semi Natural Vegetation** | | |
| Broad leave forests | 118 | <0.1 |
| Coniferous forests | 2569 | 0.8 |
| Natural grassland | 105398 | 31.8 |
| Sclerophyllous vegetation | 124 | <0.1 |
| Transitional wood land | 415 | 0.1 |
| Bare rock | 12937 | 3.9 |
| Sparsely vegetated area | 66353 | 20.0 |
| Halophytes | 1773 | 0.5 |
| **Total** | **189687** | **57.2** |
| **Wet Lands/** Inland Marshes | **54** | **<0.1** |
| **Water Bodies/** Artificial Surfaces | **886** | **0.3** |

Table (3.1) displays the total land use cover of the Faria catchment. From the table, it is clear that the non-agricultural area is dominant and it can be added that it is also above the average of the non-agricultural area in the West Bank. The land use map is shown in Figure (3.6).

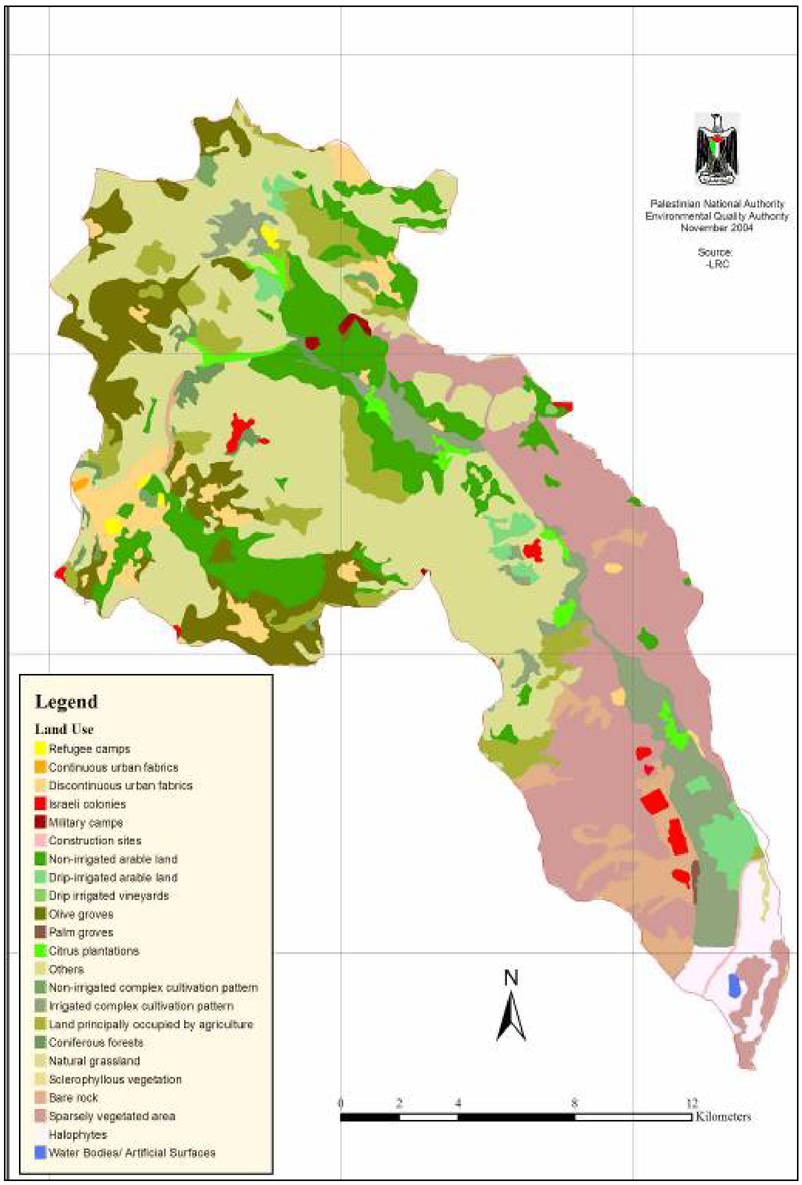


**Figure (3.6): Land use map in Faria Catchment (EQA, 2004)**

## 3.2 Geology

### 3.2.1 Regional setting

The geology of aquifers may be considered under the general headings of lithology and structure. Lithology is concerned with rock types, their formation and characteristics. Important hydraulic characteristics are permeability and porosity. The structure of an aquifer refers to the deformations in the strata caused by folding, faulting, uplift and other tectonic events.

Palestine is located in the northwestern part of the Arabian shield. During its geologic history, this shield separated from the great Afro-Arabian shield along the Red Sea line. A branch of this breakage extended along the line of Aqaba, Wadi Araba, the Dead Sea, and the Jordan Valley, and continued northwards to Lebanon, Syria, and Turkey. The West Bank occupies an area west of this branch known as the Jordan Rift Valley (Ghanem. 1999).

The Arabian shield consists of a complex of crystalline plutonic and metamorphic rocks. The western and northern parts of the shield received large amounts of erosion products. These sediments known as the shelf deposits lay with unconformity over the basement rocks. Within the shield deposits, two sedimentary mantles dominate, one is Terrestrial and the other is Marine. An inter-fingering of nitrite and lateral deposits characterizes the Terrestrial mantle. The Marine mantle dominates in the West Bank and consists in particular of carbonate deposits from the Mesozoic-Cenozoic age (Ghanem. 1999).

### 3.2.2 Stratigraphy and lithology of the West Bank

Presently, the majority of the exposed rocks in the West Bank are Marine sediments particularly made of carbonate rocks such as limestone and dolomite.

Chert is present as well. These rocks extend by age from lower Cretaceous to Quaternary. Jurassic rocks have limited exposures in the West Bank (Rofe and Raffety 1965). The geological column of the West Bank is presented in Table (3.2) and gives a clear picture of its stratigraphy and lithology (EQA, 2004).

## Table (3.2): Geological column for the West Bank (EQA, 2004)

| Period | | **Age** | Typical Lithology | Palestinian Terminology | | | **Israeli Terminology** | **Jordanian Terminolog y** | **Typical Thickness (m)** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Group | Formation | Symbol | | | |
| Quaternary | | Holocene | Alluvium, gravels, fan deposits, and surface crust (Nari). | | Alluvium | All | Alluvium | Alluvium | 0-100 |
| | | Pleistocene | Thinly laminated marl with gypsum bands, and poorly sorted gravel and pebbles. | | Lisan | Lis | Lisan/ Kurkar Group | Lisan | Unknown |
| Tertiary | | Pliocene-Miocene | Conglomerate, marl, chalk, clay, and limestone. | | Beida | Bei | Saqiya Group | Dana | ± 200 |
| | | Eocene | Numulitic limestone, reef limestone, bedded limestone, limestone with chalk, chalk with limestone (undifferentiated). | | Jenin | Jen | Avedat Group | Rijam & Shallala | 300-600 |
| | | Paleocene | Marl, clay, and chalk. | Gerzim | Khan Al Ahmar | KhA | Taqiya | | 150 |
| Cretaceous | Lower Upper | Maastrichtian | Chalk, marl, metamorphic rocks. | | | | Ghareb | Muwaqar | 55 |
| | | Campanian | Phosphate, and chert | | Al Qilt | Qil | Mishash | Amman & Hisa | 50-75 |
| | | Coniacian-Campanian | White chalk, Chalky limestone, chert, and phosphate | | Abu Dis | ADi | Minuha | Ghudran | 50-175 |
| | | Turonian | Karstified limestone, and dolomite. | Ramall ah | Jerusalem | Jer | Bina | Wadi Sir | 40-120 |

**Table (3.2) Continue : Geological column for the West Bank (EQA, 2004)**

| Period | Age | Typical Lithology | Palestinian Terminology | | | Israeli Terminology | Jordanian Terminology | Typical Thickness (m) |
|---|---|---|---|---|---|---|---|---|
| | | | Group | Formation | Symbol | | | |
| | Cenomanian | Limestone, dolomite, and marly limestone (karstic). | | Upper Bethlehem | Ube | Weradim | Wadi Shueib | 5-30 |
| | | Limestone, marly limestone, chalky limestone, and dolomitic limestone. | | Lower Bethlehem | Lbe | Kefar Sha'ul | | 30-115 |
| | | Karstic limestone, and dolomite. | | Hebron | Heb | Amminadav | Hummar | 105-260 |
| | | Marl, clay, and marly limestone. | | Upper Yatta | UYa | Moza | Fuhais | 50-150 |
| | | Limestone, chalky limestone, and dolomitic limestone. | | Lower Yatta | LYa | Beit Meir | | |
| | Albian | Reefal limestone interbedded with marl. | | Upper Beit Kahil 1 | UBK 1 | Kesalon | Na'uor | 10-40 |
| | | Dolomite interbedded with marl. | | Upper Beit Kahil 2 | UBK 2 | Beit Soreq | | 50-150 |
| | | Limestone, and dolomitic limestone. | | Lower Beit Kahil 1 | LBK 1 | Giv'at Ye'arim | | 10-50 |
| | | Limestone, dolomitic and marly limestone. | | Lower Beit Kahil 2 | LBK 2 | Kefira | | 100-160 |
| | | Marl, and clay. | | Qatana | Qat | Qatana | | 40-60 |
| | | Marl, and marly limestone. | | Ein Qinya | EQi | Ein Qinya | | 70-100 |
| | Aptian | Clay, and marl. | | Tammun | Tam | Tammun | | 50-90 |
| | Neocomian | Multicoloured sandstone. | | Ramali | Ram | Hathira Kurnub | Kurnub | 50-250 |
| Jurassic | Callovian-Bajocian | Marl interbedded with chalky limestone. | | Upper Malih | UMa | Zohar, Sherif, Mahmal | Ramlah, Hamam, Mughaneieh | 100-200 |
| | | Karstified and jointed dolomitic limestone. | | Lower Malih | LMa | | | 50-100 |

### 3.2.3 Stratigraphy and lithology of the Faria catchment

Rocky outcrops in Faria catchment range in age from Cretaceous to Quaternary. Partly due to cross faulting Jurassic limestone's and Kurnub sandstones (Ramali Formation), the oldest rocks in the area, are exposed in the core of Faria anticline (EQA, 2004). Below are the main lithological units of Faria catchment arranged by age from oldest to youngest.

1. Cretaceous rocks: These rocks have the following exposure in Faria catchment:

- Ramali Formation: The outcrops of the Ramali Formation in the Faria catchment are composed mainly of sandstones and exposed to the northeast of the middle zone of the catchment at the core of the Faria anticline.
- Lower Beit Kahil Formation: The main outcrops of this formation are exposed in the north of the Faria anticline axes. The lower part of the formation consists mainly of thick, massive iron-stained limestone. The formation passes up through sandy marls and shale's into thin-bedded pocellanous limestone.
- Upper Beit Kahil Formation: This formation may be part of the Albian or the lower Cenomanian. This formation has a small outcrop area because of its steep dips. The main outcrops of this formation are exposed on the deeply eroded flanks of the Faria anticline. It consists of dolomitic and sometimes chalky and marly limestone.
- Yatta Formation: It forms the lower part of the middle Cenomanian, and consists mainly of marl, chalky limestone, clay and thin inter-bedded

dolomitic limestone. This formation has outcrops at small localities in the middle and upper part of the catchment.

- Hebron Formation: This formation is regarded as equivalent to the upper part of the middle Cenomanian. It consists mainly of blue-green limestone and dolomitic limestone. The lower part of its outcrop is massive while the upper part is well bedded. The Hebron Formation rocks have karst caves and joints; therefore it is an excellent aquifer. It is exposed at the western parts of the Faria anticline.
- Bethlehem Formation: It is approximately equivalent to the upper Cenomanian and is exposed at different localities in the middle and upper basin, while it has wide exposures in the upper part of the catchment and has limited exposures in the middle zone of the Faria catchment. The upper part of the formation consists of limestone, dolomite, and marly limestone (karstic) while the lower part consists of limestone, marly limestone, chalky limestone and dolomitic limestone.
- Jerusalem Formation: This formation has wide exposures at the upper zone of the catchment and limited exposures in the middle zone of Wadi Faria. The rock consists mainly of massive limestone, dolomite and chalk in places.

The above formations have been depicted clearly in two cross-sections across the Faria catchment. These sections are shown in Figures (3.7) and (3.8) (PWA, 2006).

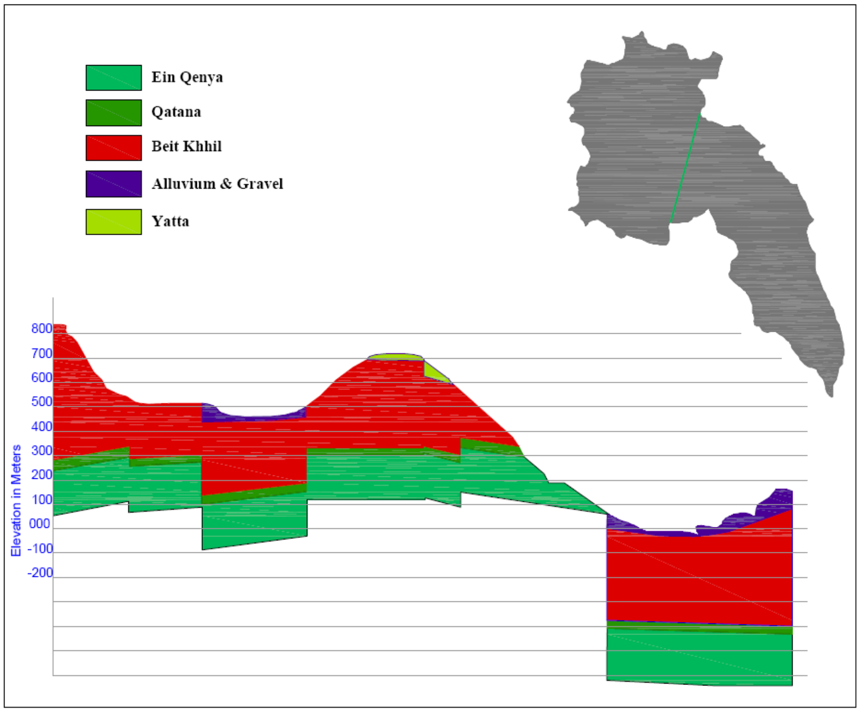


**Figure (3.7): Cross Section 1 in Faria Catchment**

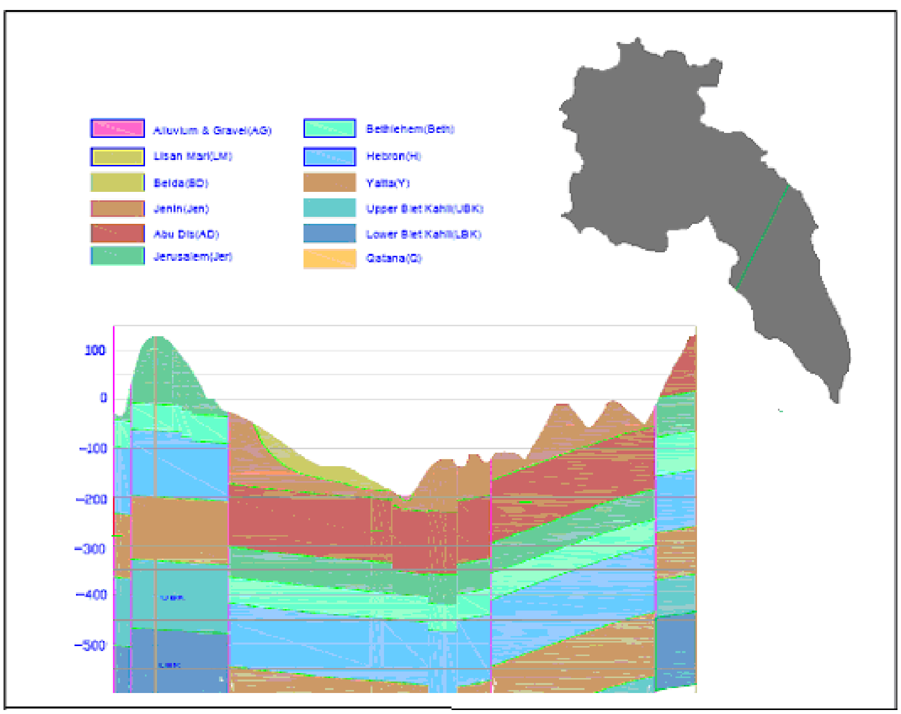


**Figure (3.8): Cross Section 2 in Faria Catchment**

2. Rocks of the Cretaceous-Tertiary transition: These rocks consist mostly of chalk with chert. The chalk formation has wide exposures at the lower zone of the Faria catchment while the chert formation has only a limited extent.

3. Tertiary rocks: These rocks consist of the following formations in the Faria catchment:

- Chalk with nummulitic limestone: This rock is exposed at different localities in the lower zone of the catchment.
- Nummulitic limestone with chalk: This rock is also exposed at different localities in the lower zone but it has more exposure areas than Chalk with nummulitic limestone exposures.
- Nummulitic bedded limestone: This limestone has exposures in the lower zone of the catchment.

4. Quaternary rocks: They have the following exposures in the Wadi Faria catchment:

- At small isolated localities of gravels and fans.
- Wide spreads of alluvial deposits are exposed along the basin and at both sides parallel to the wadi channels. They form a local unconfined aquifer in the basin, thus they are considered as a main source of water within the catchment.

Figure (3.9) presents a geological map for Faria catchment. The map shows the geologic formations prevailing in Faria catchment.

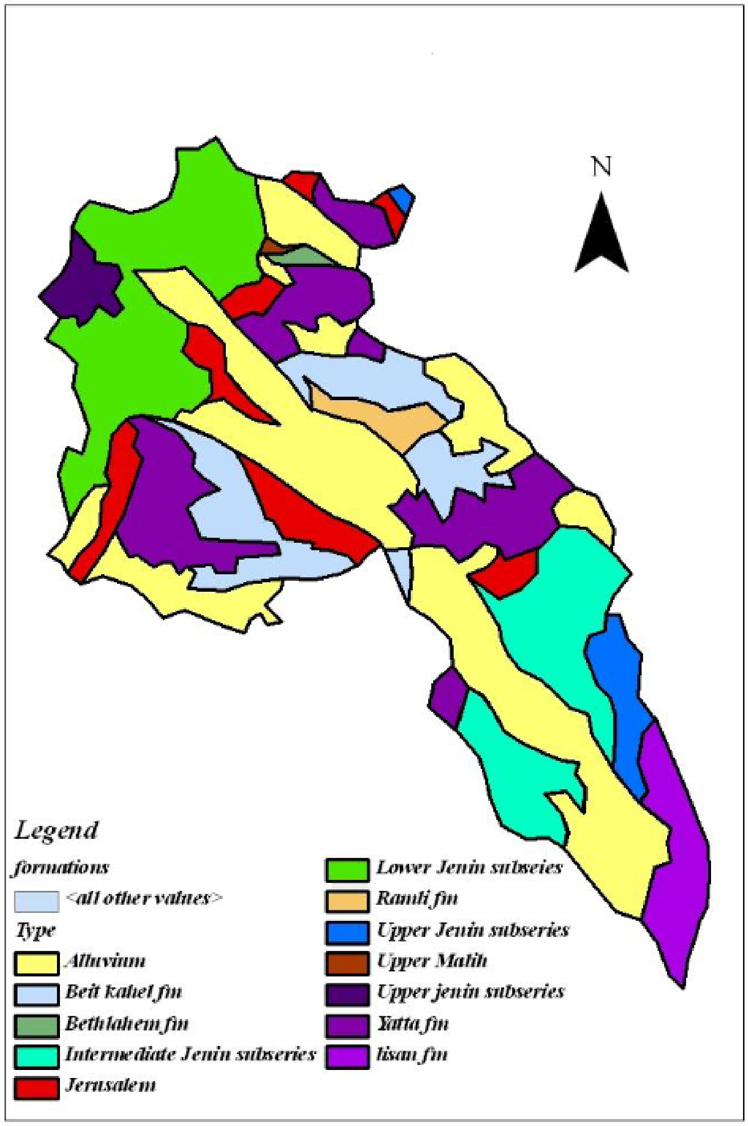


**Figure (3.9): Geologic Map Showing the Geologic Formations Prevailing in Faria catchment (Wadi Faria project, published report, 2002)**

To better understand the stratigraphy and lithology of the Faria catchment, the lithology of two wells; namely an Al-Jiftlic well ID 19-17/056 (x = 194.600, y = 174.100) and a Nassariyya well ID 18-18/031 (coordinates x = 186.410, y = 183.12) are illustrated in Tables (3.3) and (3.4) respectively.

These coordinates are based on local Palestine grid. The An-Nassariya well is located in the middle zone of the catchment, while the Al-Jiftlik well is in the lower zone of the Faria catchment (EQA, 2004). These geological formations and lithologies were used to judge the infiltration capacity and served as one of the criteria for the selection of the location of the infiltration structure.

**Table (3.3): Lithology of well ID 18-18/031 at An-Nassariyya**

| ID for the strata | Depth of the strata (m) | Description of the Lithology |
|---|---|---|
| 1 | 6 | Top Soil, Light Brown with Limestone Gravel, Sub rounded – Rounded |
| 2 | 18 | Gravel, Limestone and Flint, (Medium - Small Size Clean) |
| 3 | 21 | Clay Brown With Gravel (Small Size) |
| 4 | 24 | Gravel, Limestone (Medium Size) |
| 5 | 28.5 | Clay, Brown |
| 6 | 30 | Clay, Reddish Brown With Gravel (Small Size) |
| 7 | 33 | Clay, Reddish Brown |
| 8 | 42 | Gravel With Light Brown Clay (medium Size) |
| 9 | 45 | Gravel With Light Brown Clay (Small Size) |
| 10 | 54 | Clay, Reddish Brown With Gravel (Small Size) |
| 11 | 60 | Gravel, Limestone and Flint (Medium - Small Size) with Brown Clay |
| 12 | 70 | Gravel, (Small Size) with Reddish Brown Clay |
| **Total depth** | **431.5** | |

**Table (3.4): Lithology of well ID 19-17/056 at Al-Jiftlik area**

| ID for the strata | Depth of the Strata (m) | Description of the Lithology |
|---|---|---|
| 1 | 7 | Top Soil, Brown, Calcareous, variable |
| 2 | 10 | Gravel, Limestone, Sub rounded-Angular |
| 3 | 15 | Marl, Grey – Brown |
| 4 | 29 | Gravel, Limestone and Flint, Sub rounded – angular |
| 5 | 36 | Marl, Light Brown |
| 6 | 46 | Limestone, Beige-White, With Red Stains, Crystalline |
| 7 | 53 | Limestone, White, Crystalline |
| 8 | 58 | Limestone, Chalky, White |
| 9 | 75 | Limestone, Chalky, Pure White |
| 10 | 79 | Limestone, Beige with red Stains, Fine - Coarse Crystalline, With Fine Cavities Backfilled with Crystals (Crushed Coarse) |
| 11 | 90 | Limestone, Beige with red Stains, Fine - Coarse Crystalline, Fine Cavities (Crushed Coarse) |
| 12 | 106 | Limestone, Beige-Pinkish Light Brown, Fine Crystalline (Crushed Coarse) |
| 13 | 110 | Limestone, Pinkish Red, Cavernous, (Crushed Coarse) |
| **Total** | **714** | |

It would be good to study to the wells the well just 500 m upstream Malaqi Bridge, beside the road to Faria Camp (Well ID 18-18/038). This well is close to the place where the retention structure will be built. Table (3.5) illustrates the cross section of the well.

**Table (3.5): Cross section for well ID (18-18/038)**

| Formation | Thickness (m) |
|---|---|
| Abu Dees formation | 0-52 |
| Jerusalem formation | 52-190 |
| Bethlehem formation | 190-260 |
| Hebron formation | 260-395 |
| Yatta formation | Base formation |

### 3.2.4 Structural geology

A number of major folds and faults exist parallel to the Jordan Rift Valley as a result of previous tectonic activity. The dominant trends of the faults are from east to west with several secondary fractures being present throughout the region. The tectonic activity was associated with the splitting of the Arabian and Great African plates known as the Red Sea Rift Zone. The Dead Sea and Jordan Valley are the result of a left lateral fault caused by secondary tectonic movement in the rift zone (Calvin College and Birzeit University, 2002).

The Wadi Faria catchment itself is a structurally complex system within the Faria Anticline, trending northeast to southwest, acting as the primary controlling feature. Additionally, a series of smaller faults and joints perpendicular to this anticline have a significant effect on the surface water drainage system of the area (EQA, 2004).

# Chapter Four: Hydro-meteorological characteristics

## 4.1 Background

The availability of water sources is the basic requirement for the success of any artificial recharge project. The source of water for artificial recharge could be surplus surface water such as streams, groundwater from another aquifer and non potable water such as wastewater treatment plants effluent, storm runoff, irrigation return flow, and surface (canal) supplies from large reservoirs (Pyne, 1995). The source of water in the Faria catchment is limited to the surplus from storm runoff and springs flow. The wastewater is available in the streams but it is not recommended to be used as it is untreated and has negative impacts on groundwater quality.

Because of the variation of hydrological properties in the Faria catchment it was divided into three sub-catchments: Badan, Faria and Almalaqi sub-catchments (see Figure 4.1). Our research study will be focused on analyzing the hydrological properties for the upper two sub-catchments for two reasons. First, the required data to estimate the water balance are available, especially the runoff records and runoff coefficient which are not available for Almalaqi sub-catchment. The other reason is that the most effective way to restore the groundwater system is to implement the artificial recharge structure at the mouth of the upper sub-catchments.

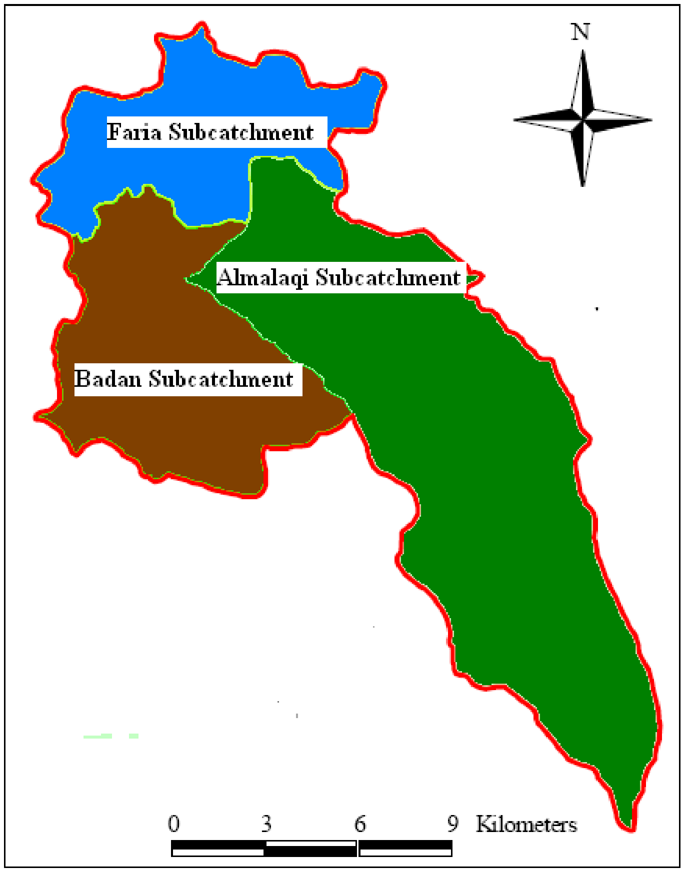


**Figure (4.1): The Three Sub-catchments of the Faria Catchment**

## 4.2 Rainfall

Rainfall data is necessary to estimate the generated runoff over the catchment area. The Faria catchment is gauged by six rainfall stations that recorded rainfall. These stations are: Nablus, Taluza, Tammon, Tubas, Beit Dajan and Al- Faria stations. Before 1994, the Israeli Authorities controlled these stations. After the establishment of the Palestinian Authority, the stations except Al-Faria station became under the control of the Palestinian Water Authority. The Nablus station is a regular weather station in which most climatic data are measured. Monthly and annual precipitation for this station is available for more than 55 years. For specific years continuous daily records are available as well.

The Faria station is located in Al-Jiftlik village in the lower part of the catchment and is still under Israeli control. The Jordanian government established this station as an agricultural experimental station. The station was taken over by the Israeli Occupation Authorities in 1967. The Israeli Authorities neglected the station and therefore its role in serving the Palestinian farmers became insignificant. In 1994, when the Palestinian Authority was established, the Israeli Authorities refused to hand it over to the Palestinians.

The other four rainfall stations are located at the schools of Taluza, Tubas, Tammon and Beit Dajan. These stations are simple rain gauges that measure daily precipitation. Data from these stations cover also monthly and annual precipitation for 30 to 40 years. No rainfall intensity charts are available in the catchment except from Nablus station where a few years are covered and are available. This is due to the lack of the placement of long-term continuous measuring instruments for precipitation or other weather data. Figure (4.2) shows the locations of these rainfall stations within the Faria catchment.

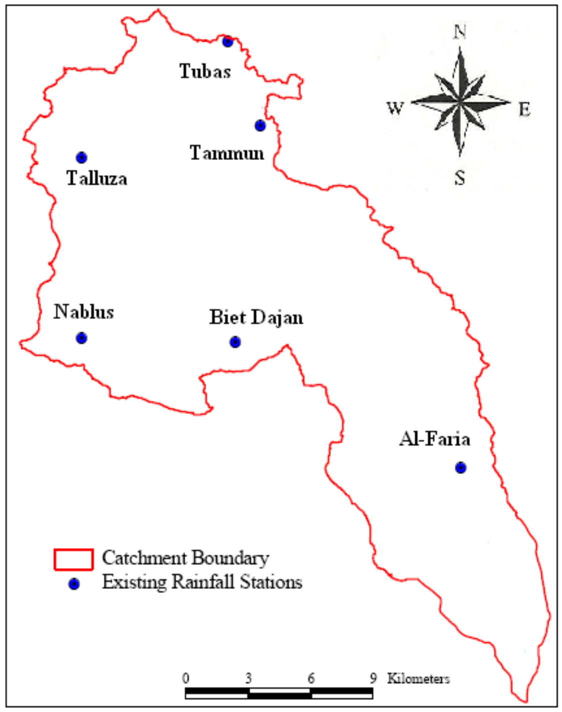


**Figure (4.2): Rainfall stations within the Faria catchment**

Since 2004 and within the context of the EXACT project, four tipping bucket rain gauges were installed at the schools of Taluza, Tammon and Salim, and at the municipality of Tubas. UNESCO-IHE has processed the data of these gauges allowing one to obtain an idea on rainfall intensities. All data were used to get the average monthly rainfall depths for the upper Faria sub-catchments for the period 2005 to 2007 such that Talluza, Tammon and Tubas stations will represent the average monthly depths for the Faria sub-catchment. The same average for the Selim station will represent the average monthly depths for the Badan sub-catchment as shown in Table (4.1)

**Table (4.1): Average Monthly Rainfall (mm)**

| Sub-catchment | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Badan** | 109.6 | 162.6 | 42.4 | 42.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 23.6 | 68.7 | 80.3 |
| **Faria** | 124.9 | 182.0 | 43.5 | 42.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 23.4 | 77.6 | 85.0 |

## 4.3 Evapotranspiration

The climate of Faria catchment is classified as arid in the eastern parts while it is moderately humid in the western parts. The Mediterranean climate (hot and dry in the summer, mild and wet in the winter) has 6-7 months of dryness in the year. Winter months, where moisture is available from rain, have low evapotranspiration rates, while summer months with high potential evapotranspiration (PET) rates have no rain and thus actual evapotranspiration (AET) is limited by the availability of water.

Evaporation rates in Faria catchment are measured using the US Class A-pan at Nablus and Faria stations. Evapotranspiration is usually smaller than pan evaporation. Evaporation rates should be multiplied by a pan coefficient (less than 1) to estimate evapotranspiration rates.

The actual evapotranspiration (AET) for Faria catchments depends on the precipitation and the initial soil moisture. If the total of these two quantities is more than the PET then the AET will equal the PET. This is the case for the rainy months (Nov-April). Otherwise the total of precipitation and initial soil storage will be the AET, which is the case for the months May to October. Average monthly potential and actual evapotranspiration for Faria catchment have been calculated also taking into account surface runoff and groundwater recharge. The results are presented in Table (4.2).

**Table (4.2): Potential and Actual Evapotranspiration for Faria catchment (mm)**

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pan ET in for Faria | 36 | 36 | 55 | 82 | 106 | 112 | 117 | 112 | 105 | 103 | 72 | 36.0 |
| Actual ET (Badan) | 36 | 36 | 55 | 82 | 38.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 72 | 36.0 |
| Actual ET (Faria) | 36 | 36 | 55 | 82 | 51.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 72 | 36.0 |

Several equations have been developed to estimate evapotranspiration using climatic data. The FAO modified Penman-Monteith method, using CROPWAT 4 Windows version 4.2 (FAO, 1989), was used to estimate the maximum potential rate of evapotranspiration at 1540 mm/yr in Al-Jiftlik and at 1380 mm/year in Nablus (Shadeed, 2005).

Although the temperature variability between Nablus and Al-Jiftlik might indicate a larger difference in evapotranspiration, this difference was reduced as a result of the higher wind velocities in the dry summer months in Nablus. In the upper areas of the catchment near Nablus, precipitation exceeds potential evapotranspiration in four to five months of the year (November through March). However, in the lower areas such as Al-Jiftlik, precipitation exceeds potential evapotranspiration in only one or two months of the year only (December and January).

## 4.4 Runoff

The stream flow of Faria catchment is a mix of:

1. Winter storm runoff water. This includes rural runoff and urban runoff mainly from the eastern side of the city of Nablus and other built up areas in the catchment.
2. Untreated wastewater from the eastern part of Nablus and Faria refugee camp.
3. Fresh water from springs which provides a base flow for the wadi and irrigation canals preventing the area from drying up in summer.

Runoff data were obtained from the Parshall Flumes at Malaqi Bridge in the upper part of the catchment to measure runoff rates from both Wadi Badan and the upper Wadi Faria. These Parshall Flumes were established in August 2003 by An-Najah National University in coordination with the GLOWA-JR project. Divers to measure water levels and flows were installed by UNESCO-IHE in 2004 and since then a complete series of runoff data is available. Part of this surface runoff of the streams recharges the shallow unconfined aquifer in Wadi Faria. Farmers use part of this water for irrigation while the rest is discharged into the lower Jordan valley or lost through evaporation (EQA, 2004).

Despite the fact that runoff coefficients for Badan and Faria sub-catchments were estimated in previous studies, they couldn't be used to estimate the runoff volume, because the smaller rainfall events do not generate floods and the estimates would be too high.

The volume of direct runoff, spring flow and wastewater in the streams was recorded between 2005 and 2007 for the 5 months from November to March (rainy months) for both Badan and Faria streams (Shadeed, 2008). The components of runoff in the other months are wastewater and springs flow. Although the values are questionable and need to be further verified, Table (4.3) illustrates the total runoff volume in the two streams.

**Table (4.3): Total Runoff volume in Faria sub-catchments**

| Sub-catchment | Runoff Volume (MCM) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **J** | **F** | **M** | **A** | **M** | **J** | **J** | **A** | **S** | **O** | **N** | **D** | **Total** |
| Badan | 0.74 | 0.90 | 0.82 | 0.84 | 0.72 | 0.64 | 0.60 | 0.53 | 0.46 | 0.47 | 0.53 | 0.59 | 7.82 |
| Faria | 0.42 | 0.48 | 0.53 | 0.48 | 0.47 | 0.37 | 0.36 | 0.32 | 0.26 | 0.30 | 0.27 | 0.34 | 4.60 |

# Chapter Five: Hydrogeology Conditions

## 5.1 Background

Hydrogeology is the study of the interrelationships between geologic materials and groundwater. A hydrogeological study plays a critical role in determining the suitability of a site for artificial groundwater recharge. Detailed hydrogeological features of Faria area were assessed for adequately selecting the site and the type of recharge structure (Jemal, 2006).

## 5.2 Hydro-geological settings

### 5.2.1 Classification of Faria aquifer units

In the West Bank, there are three major groundwater basins commonly referred to as the Northeastern, Eastern, and Western aquifer systems (Schwarz, 1982). The Faria catchment is almost completely contained within the Eastern aquifer system with the upper reaches located in the Northeastern basin as shown in Figure (5.1). Several phreatic-zone aquifers have been identified in the Lower-Tertiary and younger geologic units. The alluvium on the bank of the flood plain in Faria catchment acts as a key recharge location for the phreatic aquifer while thick clays and muds in the lower reaches of the valleys act as lower boundary surfaces. Lower aquifers, located in the Late Cretaceous era vary only slightly in lithological content.

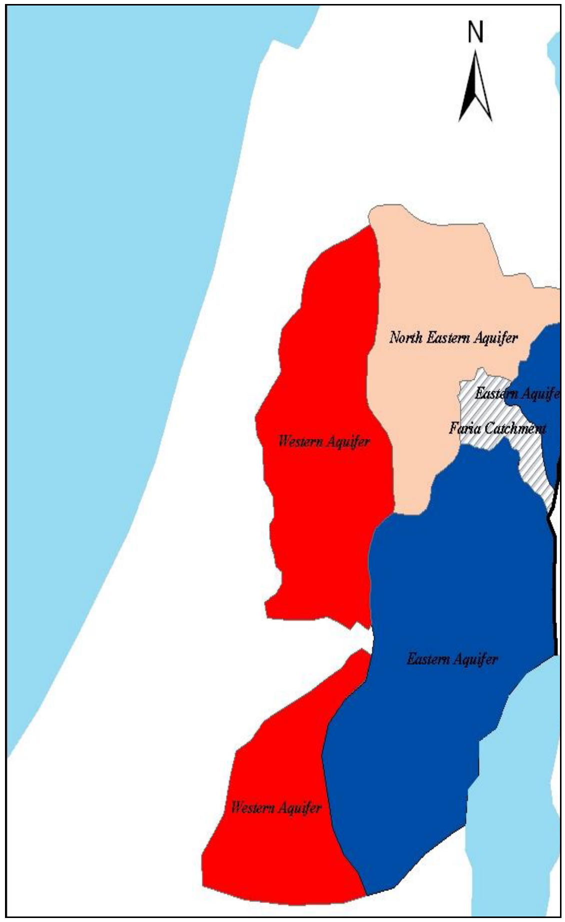


**Figure (5.1): Location of the Faria catchment within the aquifer systems in the West Bank**

The aquifer system characteristics were studied based on the existing geological map, well records, pumping test results and geophysical survey interpretations. The groundwater levels of the study area were encountered at depths between 4.5 m in well (18-18/31) and 301 m in well (19-17/59) below the surface.

The aquifer system is complex due to the fact that sedimentation took place concurrently with tectonic activity. Nevertheless, it is possible to separate the system into three distinctive units named the phreatic (upper) aquifer and the (two) confined (lower) aquifers. The phreatic aquifer consists of unconsolidated sand, gravel, cobbles and boulders in the alluvial Pleistocene sub-aquifer, well-cemented conglomerates in the Neogene sub-aquifer, and numulitic limestone with chalks, which are alternated with less permeable chert bands and marls, in the Eocene sub-aquifer (see Table 3.2). The phreatic aquifers in Faria catchment can be inspected in Figure (5.2).

The confined aquifers are mainly composed of limestone. They are referred to as confined aquifers since their exposed areas in Faria catchment are only of very limited extent and they are overlain by semi-permeable or impermeable layers. The upper confined aquifer consists of dolomitic limestone, chert and some marls of the Upper Cenomanian and the Turonian. The lower confined aquifer is mainly made up of inter-bedded limestones, chalks with marls and shales of the Lower Cenomanian (Albian). Some of the small outcrop areas of the confined aquifers can be observed in Figure (5.2).

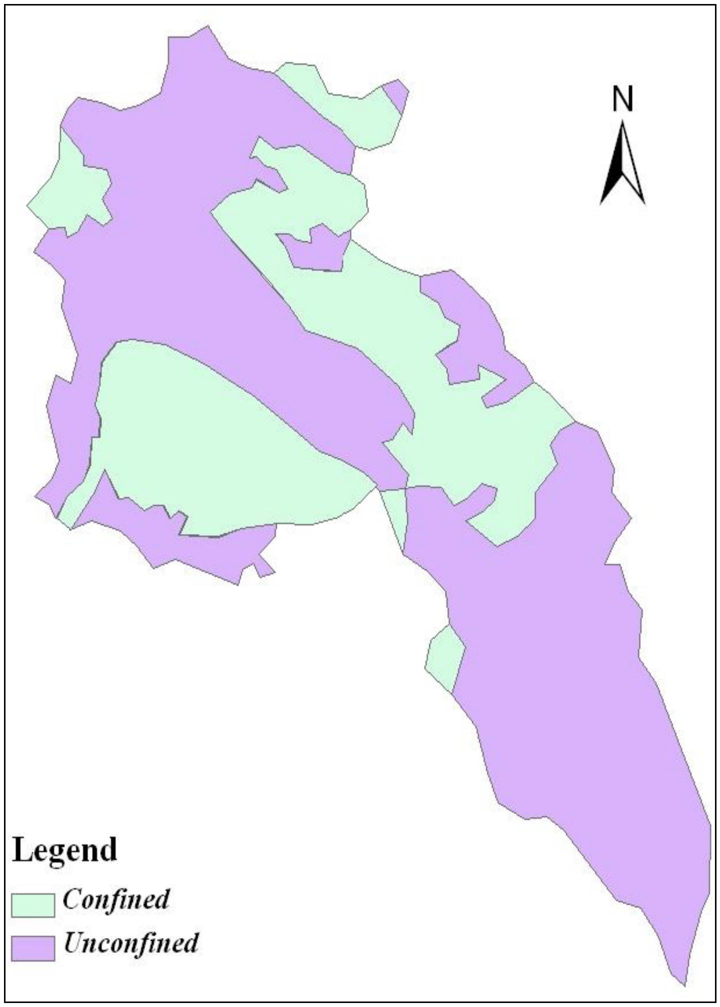


**Figure (5.2): Phreatic and confined aquifers in Faria basin**

### 5.2.2 Aquifer hydraulic parameters

The analysis of pumping test data is closely connected with having an understanding of the geologic setting and knowledge of well completion details (Weight and Sonderegger, 2001). In addition it can be mentioned that the most common methods to obtain the hydraulic parameters of an aquifer are the execution of pumping tests.

Four pumping tests at constant rates were conducted by Ghanem (1999) during his field work for wells 18-18/23, 19-17/1, 19-17/44 and 19-17/2.

The data for the groundwater levels and corresponding drawdown were taken from the pumped wells themselves since there is an absence of suitable observation wells in the area. Annex (1.2) summarizes the pumping test set up and data for these wells.

The pumping test data were interpreted and yielded transmissivity values in the range from 80 to 9600 $m^2$/day. Lithological descriptions and groundwater level information indicated that the saturated thickness ranges from 40 to 50 m at wells in the phreatic aquifer and from 29 to 350 m at wells in confined aquifers. This enabled the computation of hydraulic conductivity values in the range of 0.3 to 200 m/day. The results were tabulated in Annex (1.3).

General remarks of the previous table is that the transmissivity of the northern part is larger than the southern part for the two types of aquifer and the transmissivity in the confined aquifer is larger than for the phreatic aquifer.

## 5.3 Geo-hydrology

### 5.3.1 Groundwater level fluctuations

Fluctuations in the potentiometric surface in the study area are indicative of the changes in the amount of groundwater storage. Increases in storage are a result of recharge, for example from the winter rains, and the decreases are caused by outflows at springs, abstractions at wells and other subsurface outflows.

The decline in the water level in the Faria catchment may especially be related to the increased withdrawals from wells that are used for irrigation purposes and the increase in the water level are very much related to the recharge volume which is originating of the rainfall. The average monthly fluctuations of groundwater levels and depth of rainfall within the same period for two wells are presented in the Figure (5.3) and (5.4).

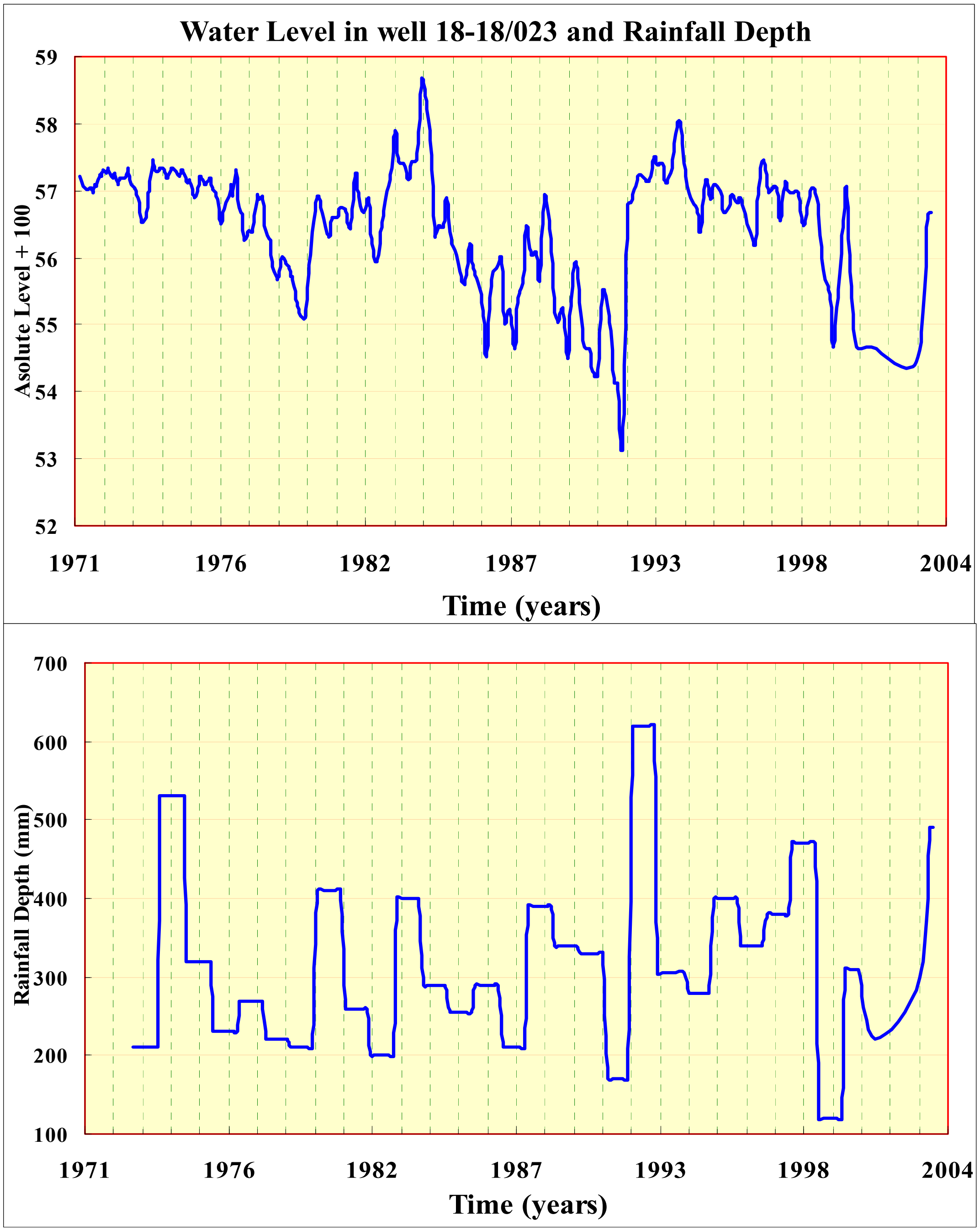


**Figure (5.3): Effect of rainfall depth on groundwater levels at a well in the phreatic aquifer**

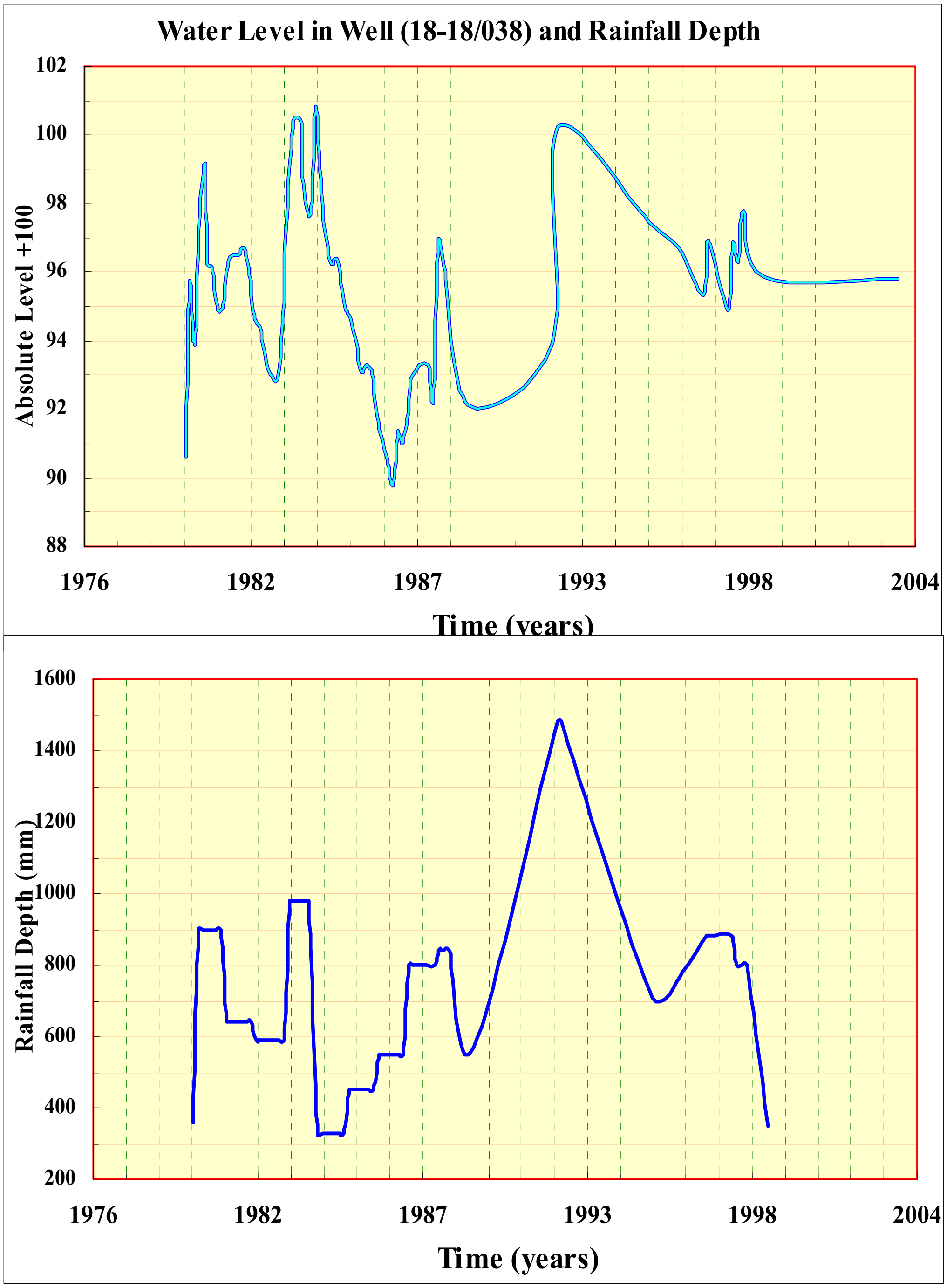


**Figure (5.4): Effect of rainfall depth on groundwater levels at a well in the confined aquifer**

### 5.3.2 Groundwater flow

In the eastern part of the West Bank, groundwater generally flows from west to east towards the Jordan Valley. The groundwater flow is affected by the geological formations and the structure of the area, the transmissivity, and the recharge and discharge areas in the catchment, in particular the areas where springs and abstraction wells are located.

The general direction of groundwater flow in the Faria catchment is parallel to the Faria Graben and has northwest to southeast trends, but is also heavily influenced by the locations of springs and abstraction wells. In the western part of Faria catchment, groundwater flows through the phreatic aquifers into the upper Cenomanian confined aquifer and is then descending into the lower Cenomanian confined aquifer. The differences in groundwater levels between the phreatic aquifer and the upper confined aquifer in the western part of the basin is not large and with a reasonable resistance between the systems, the downward flow from the phreatic aquifer is expected not to be that large or even be non-existent (Ghanem. 1999).

Following the downward flow, the groundwater then moves in an easterly and southeasterly direction and partly emerges at springs or is pumped at wells. Where the Faria Graben joints the Jordan Rift Valley, the remaining flow is again towards the upper Cenomanian aquifer with part of the groundwater flowing riftward through the Quaternary and Pleistocene aquifers.

## 5.4 Water quality

The quality of the water sources in the Faria catchment vary in their quality according to source and location (EQA, 2004). The quality of water is affected by the climatic conditions which may prevail for a certain period of time and may cause fluctuations in the discharge or quality of the source. Another reason that affects the water quality is the wastewater composition that flows continuously in the area.

The quality of water for domestic purposes is also highly affected by the existence and count of pathogenic microorganisms in the water resources and the concentration of certain chemicals that affect the health or preferences of users such as the concentration of nitrates or water salinity (EQA, 2004).

Winter runoff includes significant runoff amounts from urban areas and paved roads as it is usually contaminated from the traffic and other urban activities. This raises the possibility of adding heavy metals and other elements which might be hazardous to the stream habitat. A visual observation of the flowing water in Faria catchment and the wastewater flowing from the eastern part of Nablus city and Faria Refugee Camp gives an indication of the high deterioration of the surface water.

The current recharged water is runoff generated from precipitation in the rainy seasons in addition to the wastewater generated in the Badan sub-catchment. The wastewater is mixed with rain water and spring water. The rain water is free of pollutants that are found in the groundwater samples. However, the wastewater contains chemical contamination and suspended sediments from soil erosion which affect the surface water and groundwater in Faria catchment.

The chemical compatibility of the recharged water and the groundwater is important in artificial recharge studies. If the native water in an aquifer reacts with the recharge water, it can either degrade or improve (Jemal, 2006).

Therefore, chemical sampling and analyses of the water in the Faria catchment was undertaken. The objective is to analyze the water quality of the recharged water and groundwater. Samples were collected in the area and lab analyses were done by the Palestinian Water Authority (PWA) and Water and Environment Studies Institute (WESI). The samples were taken mainly from surface water and at springs to come to conclusions regarding the effects of artificial recharge on the quality of groundwater.

Annex (1.1) lists the analyses of surface and groundwater samples, whereas Figure in Annex (2.1) shows the locations where these samples were taken. The table indicates the type of the samples in the sense that it is surface runoff from the wadi stream or water collected from the springs. The samples designated by 'ww' indicate that these runoff samples may contain flowing wastewater.

With regard to surface water quality, the following can be concluded from the table and map.

- The analyses of the surface water samples show that the concentrations of pollutants vary spatially. The highest concentrations were encountered at the main wastewater outlets in Wadi Faria and Badan.

Here, we have potential mixing points of wastewater flowing from Nablus and the Faria Refugee Camp with rain water runoff. Further downstream the concentrations decrease as a result of additional runoff and spring water contributing to the surface water in the catchment.

- In the mixing places the concentrations of nitrate exceeded the internationally allowable limit of 50 mg/l.

With regard to groundwater quality, the following points can be raised:

- The quality of the spring water in the Faria catchment is considered fair in terms of the chemical quality of water. The water in the upper and middle area of the catchment, where most of the springs exist, has low concentrations of total dissolved solids and nitrates. The quality of water may be considered suitable for all sorts of purposes including the domestic uses.
- In all cases the high nitrate concentrations were recorded for springs adjacent to populated areas.
- Pollution by wastewater from cesspits or from agricultural return flows into the aquifer after heavy rainfall, cause the high nitrate concentrations in spring water.

EQA (2004) performed analysis of water samples taken from abstraction wells. The quality of the water taken from wells differs from one location to another. The contamination of well water with pollution sources in the upper area is clear in terms of increased nitrate concentrations in the tested well. On the other hand, other quality criteria such as salinity levels are considered acceptable.

In case of the downstream end of Faria catchment, the aquifer system is facing huge salinity problems while the nitrate pollution is less dominant. Values for the electrical conductivity higher than 5000 μS/cm are common in the downstream parts of the catchment (EQA, 2004).

## 5.5 Water balances

### 5.5.1 The balance without artificial recharge

This groundwater report concentrates on groundwater balances. One of the most important groundwater balance components is the natural recharge which can be determined with a soil water balance. The soil water balance method is often used to estimate hydrologic fluxes on different scales. The soil water balance method estimates recharge as the residual of all the other fluxes such as precipitation, runoff, evapotranspiration, and change in storage. The principle is that other fluxes can be measured or estimated more easily than recharge.

The soil water balance applied to the root zone of an area can generally be defined as:

$$PERC = P - E - R - STO_{Root} \quad ............(5.1)$$

Where PERC is recharge, P is precipitation, E is evapotranspiration, R is runoff, and $STO_{Root}$ is the change in volumetric water content in the root zone. All terms vary with the time (t).

In addition to components from other water balances, Figure (5.5) shows the components of the soil water balance.

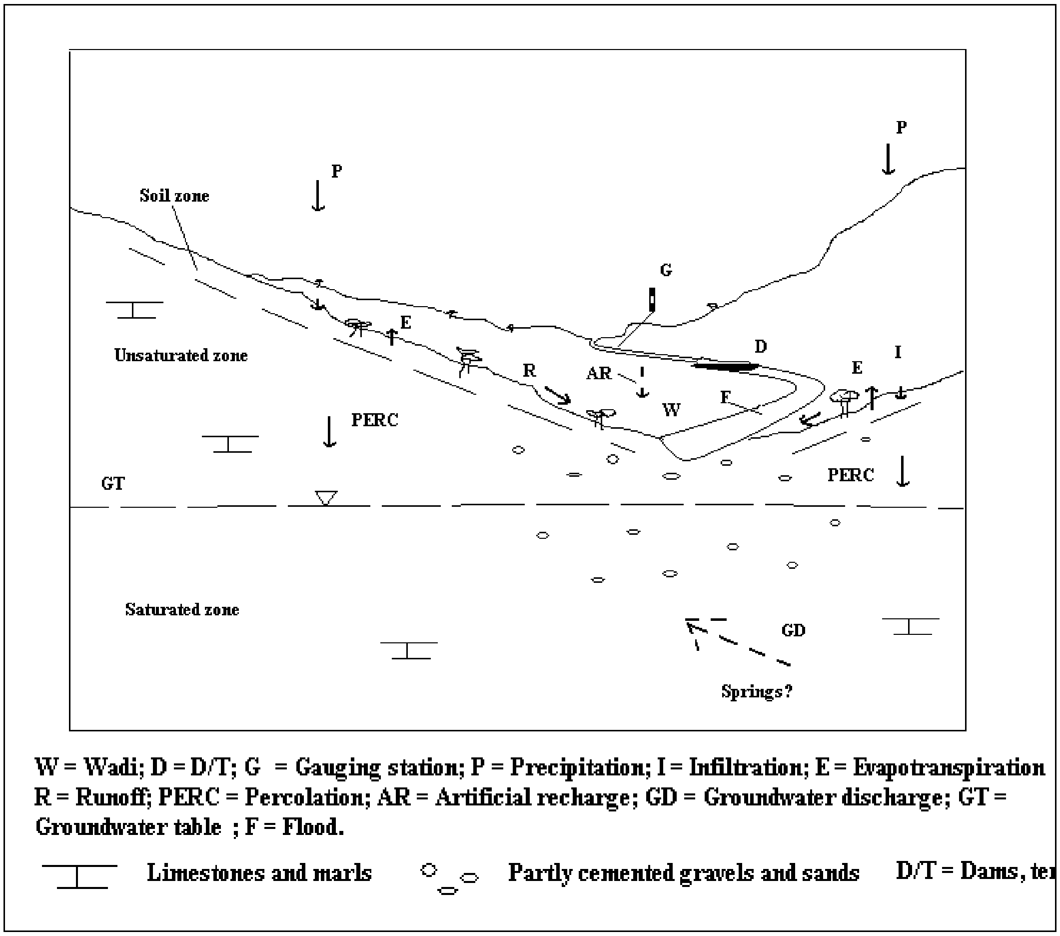


**Figure (5.5): The components of water balances (Nonner, 2007)**

To make recharge assessments using the soil water balance, a root zone model was prepared in the Excel spreadsheet. To carry out the computations, the upper part of the study area was divided into the Faria, Badan, and Al Malaqi sub-catchments. Each sub-catchment was modeled separately with its own specific parameters. The recharge or percolation quantities for these sub-catchments have been summed over the area and used as an input into the groundwater balance for the saturated zone. Although the use of daily data would have been better, the following monthly data were used for the computations with the root zone model:

- Climatic data. These data for this study were collected from personal communications with persons, governmental and non governmental agencies and from previous studies in the study area. Climatic data include average monthly values of pan evaporation and mean monthly rainfall for Nablus and Al-Faria stations for a selected period between 1960 and 2000.
- Soil max (soil moisture at field capacity minus soil moisture at wilting point in mm) was assumed to be equal to 100 mm. This value is also the initial value for the storage for the 1st of January for the study area (middle of the rainy season).
- The surface areas of the Badan and Faria sub-catchments are 86 and 64
- $km^2$, respectively.

In Equation (1) it should be understood that the E is the actual evapotranspiration which is based on the potential evaporation determined by pan evaporation methods. The actual value is computed with the root zone model. The change in volumetric water content in the root zone $STO_{Root}$ is also computed with the model. The runoff R is the direct runoff over land surface and has been assessed from the measurement of floods at the gauging stations at Malaqi Bridge. Finally, a rock factor has been applied to the root zone model. The model in fact has been developed for a porous soil and permeable underlying rock where a piston type of flow takes place. Not everywhere in the study area this is the case and therefore a rock factor, usually smaller than 1 has been applied.

The soil water balances for the two sub-catchments were calculated based on the available data for rainfall and runoff volumes. The Excel calculation sheets have as input average annual precipitation rates of 660 mm for both Badan and Faria catchment, and 471 mm for the Al Malaqi catchment. The figures are for a long period within the time frame from 1960 to 2000. With a denser rain gauge network, the average rainfall for 2005 to 2007 for Badan and Faria were calculated at respectively 529 and 578 mm. The more recent values for rainfall are therefore 15 to 20% lower.

For the longer period within 1960 to 2000, the soil water balance model computed for the actual evapotranspiration average annual values of 385, 387 and 337 mm for respectively, the Badan, Faria, and Al Malaqi catchments. The direct runoff (during floods) to the main wadis computed with maximum runoff coefficients which are based on the actual flood measurements in the period 2005 to 2007 gave values of 42.2, 4.8 and 0.5 mm for the same order of catchments. Runoff coefficients were 0.064, 0.0072, and 0.001 for the Badan, Faria and Al Malaqi sub-catchments (Moshe, 2008). Taking into account realistic rock factors, the annual average recharge into the sub catchments was respectively 203, 290 and 130 mm for Badan, Faria and AlMalaqi. The high recharge in the Faria catchment can be explained by the higher permeability of the Neogene and Eocene rocks. Evidence of the high recharge is also indicated by well known springs emerging from this area. The calculation sheets are partly summarized in Annex (1.4) and Annex (1.5).

It is not easy to estimate the natural recharge falling on land surface accurately because it may occur immediately after precipitation or after running as overland flow and then infiltrating in depressed areas through the fractures of the rock. Where the rock is permeable because fractures or coarse material is present like in the Faria sub-catchment the rock factor has been set at 1. On the other hand in places where less fractures are known to be present as in Badan catchment and an additional amount of water will evaporate from pools or soils, the rock factor has been set at 0.8. For these areas, the actual evapotranspiration as computed by the soil water balance model is also somewhat higher in reality.

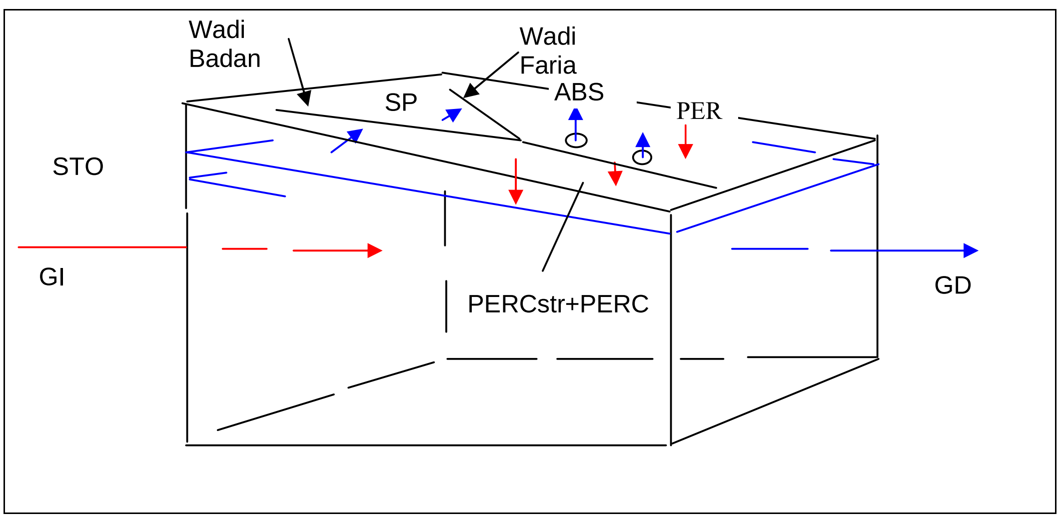


**Figure (5.6): Groundwater Parameters Without Artificial Recharge**

The natural recharge or percolation from precipitation at land surface (PERC) is the most important inflow term for the groundwater balance. The other terms can be formulated as depicted in Figure (5.6). All terms are:

| | |
|---|---|
| PERC: | Recharge or percolation from precipitation |
| PERCstr: | Recharge or percolation from wadi floods |
| PERCww: | Recharge or percolation from wadi wastewater |
| GI: | Subsurface groundwater inflow |
| SPR: | Net spring flow |
| GD: | Subsurface groundwater outflow |
| ABS: | Abstraction by pumping |
| STO: | Change in groundwater storage (variation) |

The groundwater balance terms can be further quantified and one and other has been worked out on a monthly basis in an Excel spreadsheet. Considerations and results are as follows:

- Recharge or percolation from wadi floods (PERCstr): Monitoring near Beit Hasan in the Al Malaqi sub-catchment indicated that floods could recharge the groundwater system. Nevertheless most of the floods pass through and recharge quantities are thought to be sufficiently small to have a large effect on the groundwater balance.
- Recharge from waste water (PERCww): The possibility for waste water infiltration originates from the Badan sub-catchment where an annually reported waste water flow of Nablus of 25 mm (2005-2007) has been estimated. The generation of waste water is much less in the other catchments. Since waste water flows are also used for irrigation and the (small) flows do not have the tendency to infiltrate into the wadi

sediments (cemented in many places), recharge to the groundwater system is thought to be small.

- Groundwater inflow and outflow (GI and GD): These are the subsurface groundwater inflow and outflow into the catchments. In case we consider the combined Faria catchment then a subsurface inflow across the catchment boundary could possibly be expected through the Eocene aquifer upstream of Faria Camp. On the other hand subsurface outflows could be anticipated across eastern catchment boundaries towards the Jordan Valley or adjoining limestone catchments. The terms may be small, but cannot be ignored in the groundwater balance.
- Net spring outflow (SPR): This term describes the flow emerging at springs minus that part of this spring flow that enters the groundwater system again when the spring water is flowing through wadi's or cracked canals. Flow data at springs were obtained from the PWA database for the years 1966-2000 (See Table 5.1). The combined total spring flow is 14.2 MCM. Considering the catchment area of 333 $km^2$, an average annual unit area spring flow of 43 mm can then be computed which is considerably less than the estimated recharge from precipitation. Since most of the spring flow is used for irrigation, the portion of this water entering the groundwater system again is thought to be small.

**Table (5.1): Average monthly Spring outflow in the Faria catchment in MCM, (PWA)**

| Group | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Badan | 0.37 | 0.43 | 0.59 | 0.62 | 0.57 | 0.49 | 0.46 | 0.38 | 0.31 | 0.28 | 0.25 | 0.28 |
| Faria | 0.56 | 0.61 | 0.70 | 0.65 | 0.65 | 0.55 | 0.54 | 0.50 | 0.45 | 0.47 | 0.43 | 0.50 |
| Miskah | 0.22 | 0.20 | 0.23 | 0.22 | 0.21 | 0.20 | 0.20 | 0.19 | 0.17 | 0.17 | 0.18 | 0.20 |
| Total | 1.13 | 1.22 | 1.51 | 1.49 | 1.43 | 1.27 | 1.22 | 1.10 | 0.96 | 0.95 | 0.90 | 0.98 |

- Pumping rate or abstractions (ABS). These data were calculated from the available pumping records for the wells in the catchment. The records indicated for the combined catchment total annual abstractions in the order of 33 MCM for a longer period within the 1960 to 2000 time frame. Average annual abstractions could be re-computed as 101 mm taking into account the catchment surface area (see above). This amount is a sizable portion of the natural recharge from precipitation into the catchment.
- Change in storage (STO): These data were calculated from the available records for groundwater level observations stored at the PWA for a longer period within the period 1960 to 2000. Within the period a net annual decrease in groundwater levels was computed in the order of 0.2 to 0.7 m. However, groundwater level records also suggest that these decreases are over-estimated (Beit Hasan wells available at PWA). Considering the combined catchment again and assuming storativities for the aquifer system in the order of 0.01 to 0.02 for different rock

types, an annual decrease in storage of about 14.0 MCM could be computed which equates to a surface area unit value of about 42 mm. The quoted values should be considered with extreme caution in view of the uncertainties in groundwater level behavior and the difficulty in estimating storativities.

Considering all the terms as defined above, the groundwater balance equation can be formulated as follows:

$$(PERC + GI) - (SPR + GD + ABS) = STO \text{..........}(5.2)$$

The balance can be quantified either in annual mm for a unit area or in MCM for the whole catchment. Table (5.2) shows the parameter values for units in MCM. Recharge (PERC) has been re-computed from mm into MCM. Theoretically one is able to compute the difference between the subsurface groundwater inflow and outflow (GD - GI) at 22.8 MCM, but this figure should be considered with caution in particular in view of the difficulty in determining the storage (STO) term.

**Table (5.2): Groundwater balance without artificial recharge**

| Balance terms | Annual Flow (MCM) |
| --- | --- |
| | Badan, Faria and Al Malaqi combined |
| **INFLOWS (MCM)** | |
| PERC | 60.3 |
| GI | (not known) |
| **OUTFLOWS (MCM)** | |
| SPR | 14.2 |
| ABS | 33.0 |
| GD | (not known) |
| **STO** | -14.0 |

### 5.5.2 The water balance with artificial recharge

To study the effects of artificial recharge on the groundwater balance, the following conditions were assumed:

1. The suitability of the area for artificial recharge will be categorized to three zones; suitable, moderate and not suitable (see Chapter 6). Locations of artificial recharge structures will be assumed to be in the suitable zone.
2. Type of artificial recharge structure: Two types of artificial recharge structures were proposed to be used in Chapter 6. They are the terraces and/or dams. Each of them has a groundwater recharging capacity as a percentage of the available water.
3. Area to be used for artificial recharge: The surface area of a terrace or the exposure of surface water behind the dam controls the quantity of

artificially recharged water. Since the infiltration capacity into the soil in any location will decrease gradually, large infiltration areas will have to be selected to increase the quantity of recharged water. On the opposite side, increasing the area will increase the exposure surface and this will increase the evaporation and decrease the recharge.

Water that will be used for artificial groundwater recharge should be free from flowing wastewater since this wastewater could affect the quality of groundwater. Water quality is based on the results of the analysis of water samples taken at surface and groundwater sources. These analyses are discussed in section 5.4.

To overcome the problem of wastewater infiltration, this water can be forced to flow separately through a trunk line or pipe from the upstream side of the recharge side to a point downstream the location of the terrace or dam that will be used to recharge the storm water. In this case, the groundwater will not be affected by wastewater components. Furthermore, the application of this technique is feasible and essential to prevent the groundwater system from pollution whether the artificial recharge method will be applied or not.

It can be concluded from a previous study (Moshe, 2008) that during the main storm events in the period 2004 to 2007 (three rainy seasons), 3.15 and 19.6 mm of storm water had been registered in respectively the Faria and Badan catchments. These amounts equate to annual amounts of 0.055 and 0.42 MCM for the respective catchments. For the water balance years covering a period within 1960 to 2000 when 10% higher rainfall amounts were measured the amounts would have been somewhat higher, but assuming that not all storm water can be trapped with the artificial recharge infrastructure (spill way losses), the quoted AR amounts seem to be reasonable. Storm runoff has been considered as an input value in Table 5.3 which has been compiled to assess the actual amounts of water available for artificial recharge also taking into account spring flow amounts and losses due to evaporation from water logged terraces and dam reservoirs.

**Table (5.3): Available water for artificial groundwater recharge in the upper sub-catchments**

| | Volume (MCM) | |
|---|---|---|
| | Badan | Faria |
| **INFLOWS (MCM)** | | |
| Storm runoff | 0.42 | 0.055 |
| Spring | 5.09 | 6.70 |
| **OUTFLOWS (MCM)** | | |
| Diversion for agricultural purposes | 3.82 | 5.02 |
| Evaporation | 0.13 | 0.11 |
| AR | 1.56 | 1.62 |

Table 5.3 also shows a breakdown of the spring flow for the Badan and Faria catchments. Most of the spring flow is used for irrigation or other purposes especially in the seasons without rain. Spring flow would be available in the rainy season covering the period from half December to half March. Then there is excess flow which could be available for artificial recharge. Taking into account a somewhat higher spring flow, but on the other hand winter claims on spring flow an estimated 25% of the flow may be available for artificial recharge. Diversions for agricultural purposes (75%) have therefore been set at amounts of 3.82 and 5.02 MCM for respectively Badan and Faria catchment.

What are the losses from evaporation from terraces and reservoirs? For example $E_{terrace}$ and $E_{dam}$. Assuming that also the evaporation losses from terraces cannot be prevented, the volumes for $E_{terrace}$ and $E_{dam}$ are a function of the area at and behind the terrace or dam. The open water evaporation for the upper catchments being 0.97 m/year then leads to the following formula:

$$E = 0.97 \times F \times A$$

The F is a factor since not all year around there will be water in the terrace or reservoir and A is the average surface area of the water in the terrace or reservoir. Maximum areas A of the area of the reservoir behind a dam located at the outlets of Badan and Faria sub-catchments will be about 0.27 and 0.23 $km^2$ respectively (Abu Safat, 1990). Taking an F of 0.5 then the maximum open water evaporation would be in the order of 0.11 to 0.13 MCM. Similar amounts could be expected for the terraces. In the analyses one should not forget that here we are dealing with maximum values assuming that nearly all water will be trapped, large reservoirs will be created and infiltration will be relatively slow. In reality the evaporation losses may be much lower.

Table 5.3 shows that the available amounts for AR are in the order of 1.6 MCM from each sub catchment. The majority of the water originates from spring flow, but in the Badan catchment the storm runoff also makes a contribution that cannot be ignored. Nevertheless, the actual availability of water also depends on additional factors that have not been considered. For example, an increase in irrigated agriculture based on abstraction by wells may leave the springs dry and therefore the water would not be available for artificial recharge.

When artificial recharge is applied it is expected that subsurface groundwater inflow, subsurface groundwater outflow, spring flow and the storage term change (see Figure 5.7). When it is assumed that there is hardly any change in natural recharge (PERC) and no change in abstraction, the new groundwater balance equation (5.3) in symbols is:

$$(PERC + PERC_{ar} + GI_{ar}) - (SPR_{ar} + GD_{ar} + ABS) = STO_{ar} \quad ...(5.3)$$

Such that:

$PERC_{ar}$: artificial recharge

$GI_{ar}$: new groundwater inflow

$SPR_{ar}$: new spring flow

$GD_{ar}$: new groundwater outflow

$STO_{ar}$: new storage term

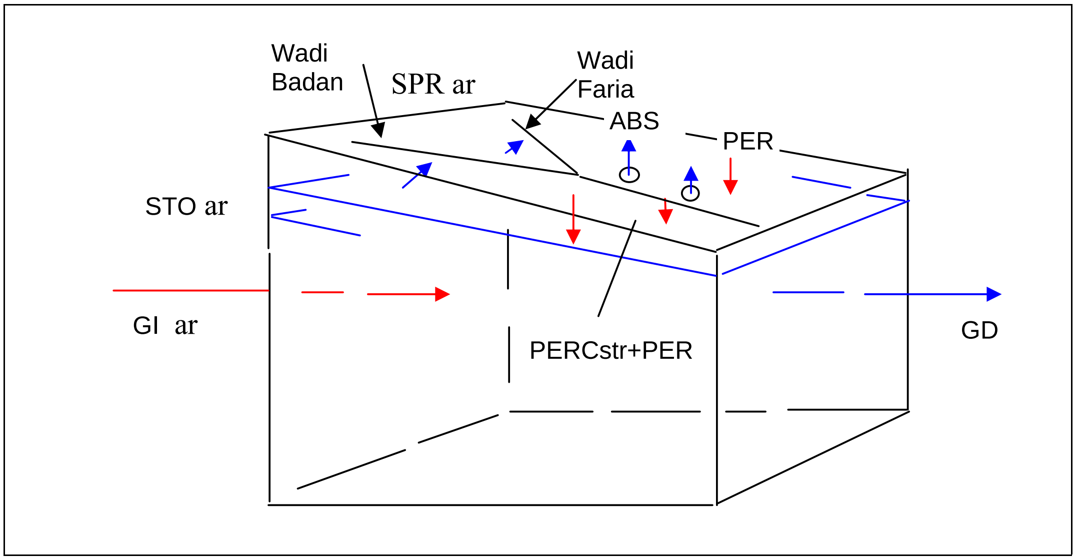


**Figure (5.7): Groundwater parameters for artificial recharge**

Table 5.4 presents the groundwater balance with artificial recharge in place. Since most of the storm water runoff is in the upper Wadi Badan and Wadi Faria catchments, any artificial recharge from the Al Malaqi catchment has not been considered.

The table indicates that an increase in recharge by an AR scheme should increase the spring flow ($SPR_{ar}$), the subsurface groundwater outflow ($GD_{ar}$) and the storage ($STO_{ar}$), whereas the subsurface groundwater inflow would be reduced. The net increase of these terms is equal to the amount of 3.18 MCM for artificial recharge, see groundwater balance sheets in annex (1.6) .

Without any field data being available after the implementation of the scheme, it is impossible to quantify these different terms separately. In case such a differentiation between the new groundwater balance terms has to be predicted, a groundwater model can be prepared. The existing groundwater model prepared by Marwan (1999) could possibly serve for this purpose.

**Table 5.4: Groundwater balance with artificial recharge included**

| **Balance terms** | **Annual Flow (MCM)** |
|---|---|
| | Badan, Faria and Al Malaqi combined |
| **INFLOWS (MCM)** | |
| PERC | 60.3 |
| $PERC_{ar}$ | 3.18 |
| $GI_{ar}$ | (not known) |
| **OUTFLOWS (MCM)** | |
| $SPR_{ar}$ | (not known) |
| ABS | 33.0 |
| $GD_{ar}$ | (not known) |
| **$STO_{ar}$** | (not known) |

# Chapter Six: Artificial Recharge Infrastructure

## 6.1 Site Selection Criteria

Within the framework of the artificial recharge project in the upper Faria catchment, a number of sites for artificial recharge have to be selected. The structures to be built at these sites enhance the infiltration of flood water from rain storms into the underlying sediments and (mostly) limestone rocks. The structure that one could think of would fall in the category of water spreading methods, since the other two major forms of artificial recharge, recharge well methods and induction methods, are not feasible in the area (Unesco-IHE, 2007)

In view of the geological complexity of the area and the permanent presence of a poor water quality of the base flow in parts of the area (wastewater in Wadi Badan and to some extent in Wadi Faria), proper sitting of the infrastructure is not easy. Nevertheless, five main criteria, to be described in the next sections, have been set for the identification of the suitability of the sites where infiltration could take place:

1) Infiltration capacities of the sediments.

2) Type of the aquifer.

3) The fractures along study area.

4) Slope.

5) Land use.

## 6.2 Weighted Index Overlay Method for Artificial Recharge

Weighted Index Overlay Analysis (WIOA) is a simple and straightforward method for a combined analysis of multi-class maps. The efficiency of this method lies in that the human judgment can be incorporated in the analysis. A weight represents the relative importance of a parameter vis-a-vis the objective.

The method is used world-wide in many regions to select artificial recharge sites, for examples it was used for this purpose in the Silai watershed in India and in Meimeh Basin in Iran.

The WIOA method takes into consideration the relative importance of the parameters and the classes belonging to each parameter. There is no standard scale for a simple weighted overlay method. For this purpose, criteria for the analysis are defined and each parameter is assigned importance (Saraf and Choudhury, 1997 and Saraf and Choudhury, 1998).

Determination of the weight of each class is the most crucial in integrated analysis, as the output is largely dependent on the assignment of the appropriate weight. Consideration of relative importance leads to a better representation of the actual ground situation (Choudhury, 1999).

Arc GIS software was used to process and analyse the databases for the mentioned criteria using classes depicting the suitability for artificial recharge. The areas for a certain class were converted to raster maps and combined with values (weigth factors) indicating the suitability for artificial recharge. One and other is shown in Table (6.1)

**Table (6.1): Values of parameters**

| NO | Criteria | Class | Values For Artificial Recharge |
|---|---|---|---|
| **1** | Infiltration Capacity | Low infiltration (Jerusalem, Yatta, Bethlahem, Biet Kahel geological formations) | 1 |
| | | Meduim Infiltration (Alluvium formation) | 2 |
| | | High Infiltration (Jenien subseies formations) | 3 |
| **2** | Hydro geology | Unconfined Aquifer | 2 |
| | | Confined Aquifer | 1 |
| **3** | Fractures | Close to Fracture | 1 |
| | | Other | 0 |
| **4** | Slope | High Slope (steep) | 1 |
| | | Gentle Slope | 2 |

Following the above described procedures, a set of rules has been designed to delineate the most suitable zones for artificial recharge. The actual location of the artificial recherge site within a zone then has to be determined in second instance.

#### 6.2.1 Infiltration capacities

For effective recharge the following conditions should be met (Jafar, 2004): materials in the sediments must have a high vertical permeability and the aquifer must sufficiently be transmissive for transport of water away from the spreading area, for estimating the infiltration rate, the relationship between formation or soil texture and infiltration rate are considered.

The spatial distribution of infiltration capacities along the study area is shown in Figure (6.1). This raster map was prepared based on the geological map, each cell has a value according to its infiltration capacity, and the same was done for the other maps in the next.

In terms of infiltration capacities, the Mesozoic to Tertiary rocks are believed to have low to medium capacities. Massive limestone and marls would have low capacities, whereas chalks and fractured or karstic limestone may have low to medium infiltration capacities. This would imply that the Cenomanian limestones of the Yatta, and Beit Kahil Formations as seen in Figure (3.9), mainly consisting of limestone, dolostone and marls have low infiltration capacities; at least where these rocks are not extensively fractured or karstified. The Turonian Jeruzalem Formation also consisting of karstic limestones has a higher infiltration capacity, but since its limited extent has been combined with the Cenomanian formations. The Eocene limestone and chalk is expected to have a high infiltration capacity. This includes the Jenin Formations, where the higher infiltration capacity is also proven by the presence of large springs emerging from this formation. Finally, the recent Alluvium has medium infiltration capacities on the average, but capacities are high where the materials are coarser and not cemented.

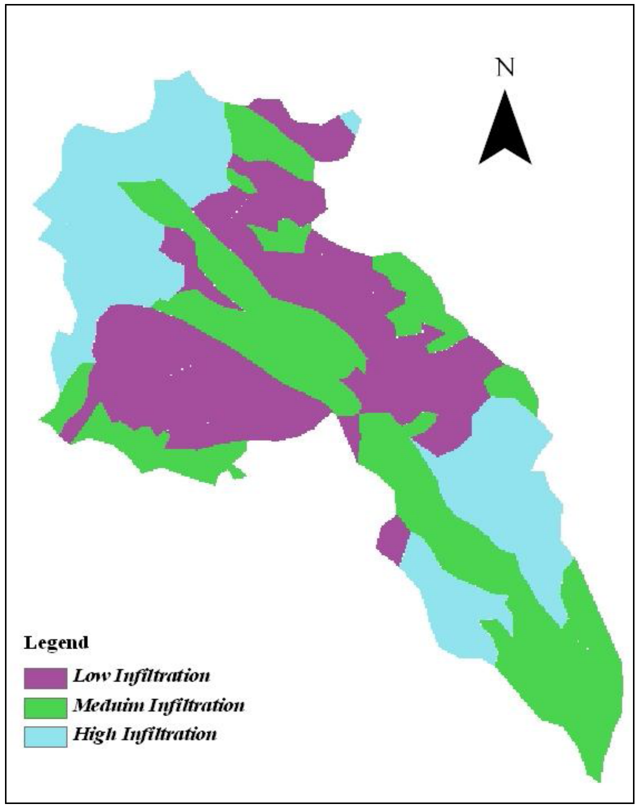


**Figure (6.1):Infiltration capacity classes**

### 6.2.2 Type of aquifer

This hydro-geological criterion was considered to distinguish between confined and unconfined aquifers that will be artificially recharged. Since the tendancy to accept recharge for unconfined aquifers is larger than for confined aquifers, the weight value for unconfined aquifers will be higher than the value for confined aquifers. The regional distribution of unconfined and confined aquifers is shown in Figure (6.2)

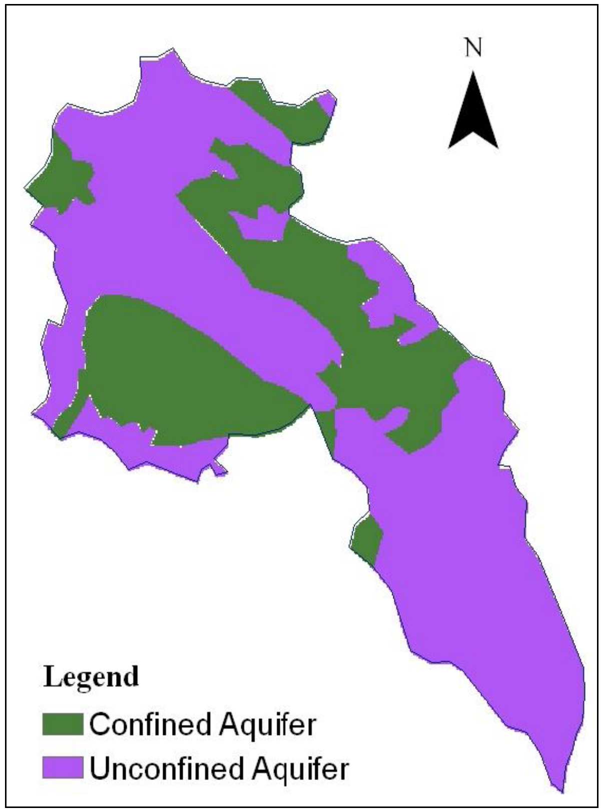


**Figure (6.2): Type of aquifer**

### 6.2.3 Fractures

Water enters the aquifer (recharges) by means of solution features controlled by faults and fractures exposed at the Earth's surface. Flow through the aquifer is accommodated by faults, fractures, and solution conduits below the surface. So there is a strong linkage between geologic structure and rapid pathways for groundwater recharge and flow in the aquifers (David, 2002)

The location of the fractures and faults can be concluded from structural and geological maps. These fractures are also located at the contacts between different formations. The regions close to fractures and faults will be given higher weights because the hydraulic conductivity will be higher for these regions. See Figure (6.3) for the distribution of the fractures (Prepared from geological map shown in Figure (3.9).

### 6.2.4 Slope

Slope is one of the main factors used in the selection of flood spreading areas. Water velocity is directly related to land slope and its depth. On steep slopes, runoff is more erosive. The objective is to spread water over a large area, forming a thin film that flows slowly downhill without disturbing the soil (Jafar, 2004).

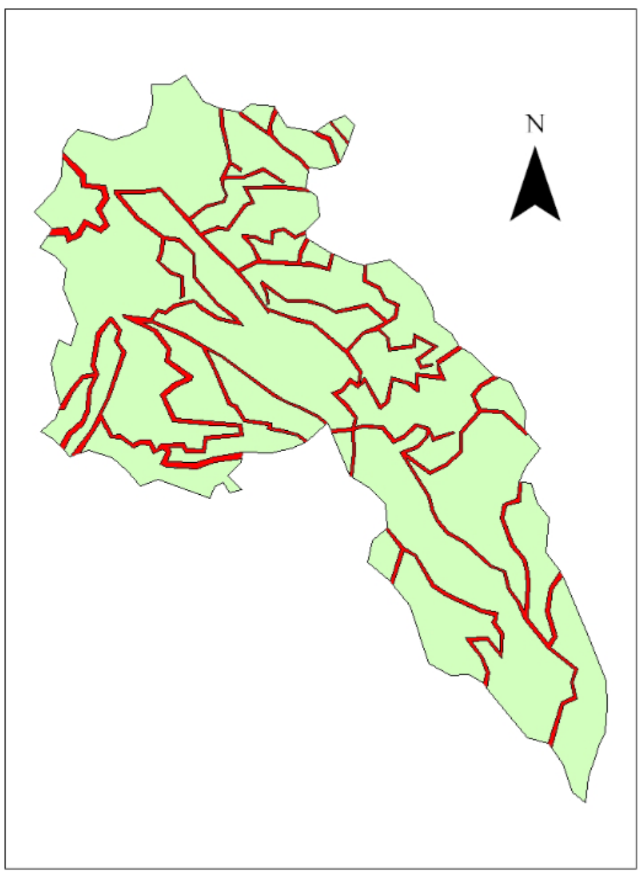


**Figure (6.3): Location of the main fractures and faults in the Faria catchments**

The slope classes map (Figure 6.4) was derived from the Digital Elevation Model (DEM). Gentle slopes are more suitable for artificial recharge because the trapped water by the artificial recharge structures will be larger than the infiltrations at structures in steep areas.

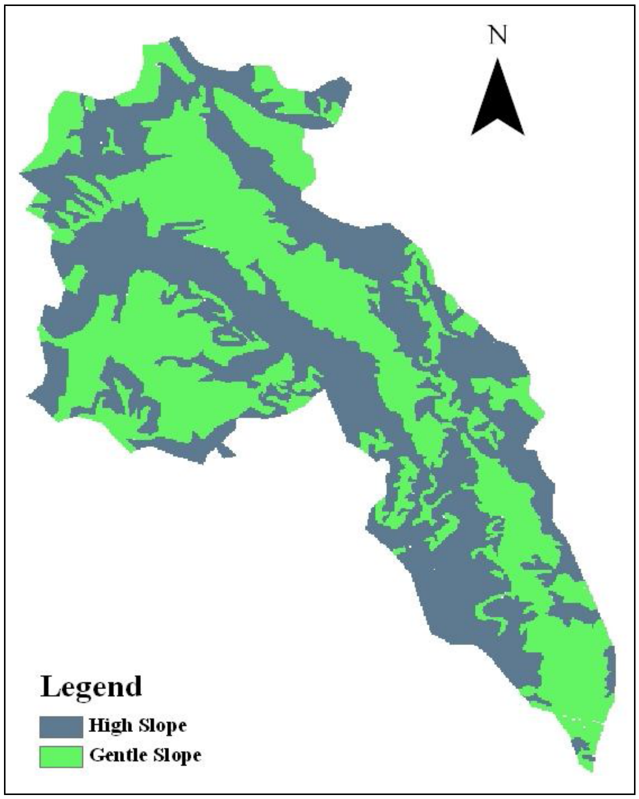


**Figure (6.4): Slope Classes in Faria catchment**

### 6.2.5 Land use distribution and administrative rules

Most of the area consists of hard mountainous rocks with only sparse vegetation. These areas are rather away from the flood generating wadi's and also in view of their generally steep slopes they do not qualify easily for the location of artificial recharge schemes. In terms of location, the areas at or in the vicinity of Wadi Badan, Wadi Faria and their main tributaries are then the remaining locations for artificial recharge.

Unfortunately, these areas, including the alluvial terraces are heavily used by farmers and the production of crops is practiced on a large scale. It may be difficult to reserve cultivated land for artificial recharge sites unless the farmers spot the direct benefits of such an operation. Administrative rules may also make the setting of a recharge scheme more difficult or on the contrary easier, for example, when land falls under regulations making it easy to be allocated for public use.

The land use criteria will not be represented as parameters in the weighted indexing (WIOA) method. Only the the first four criteria will be checked and on this basis the suitable zones for artificial recharge will be determined. However, in second instance it will be checked whether there are not conflicts with land use and administrative criteria.

In the WIOA, the individual thematic layers and also their classes are assigned weights as has been shown in (Table 6.1). In the present study, the results of the weighted indexing method to delineate the suitability zones for artificial recharge sites are shown in Figure (6.5). The zones with the higher values indicate the most favorable areas for artificial recharge structures.

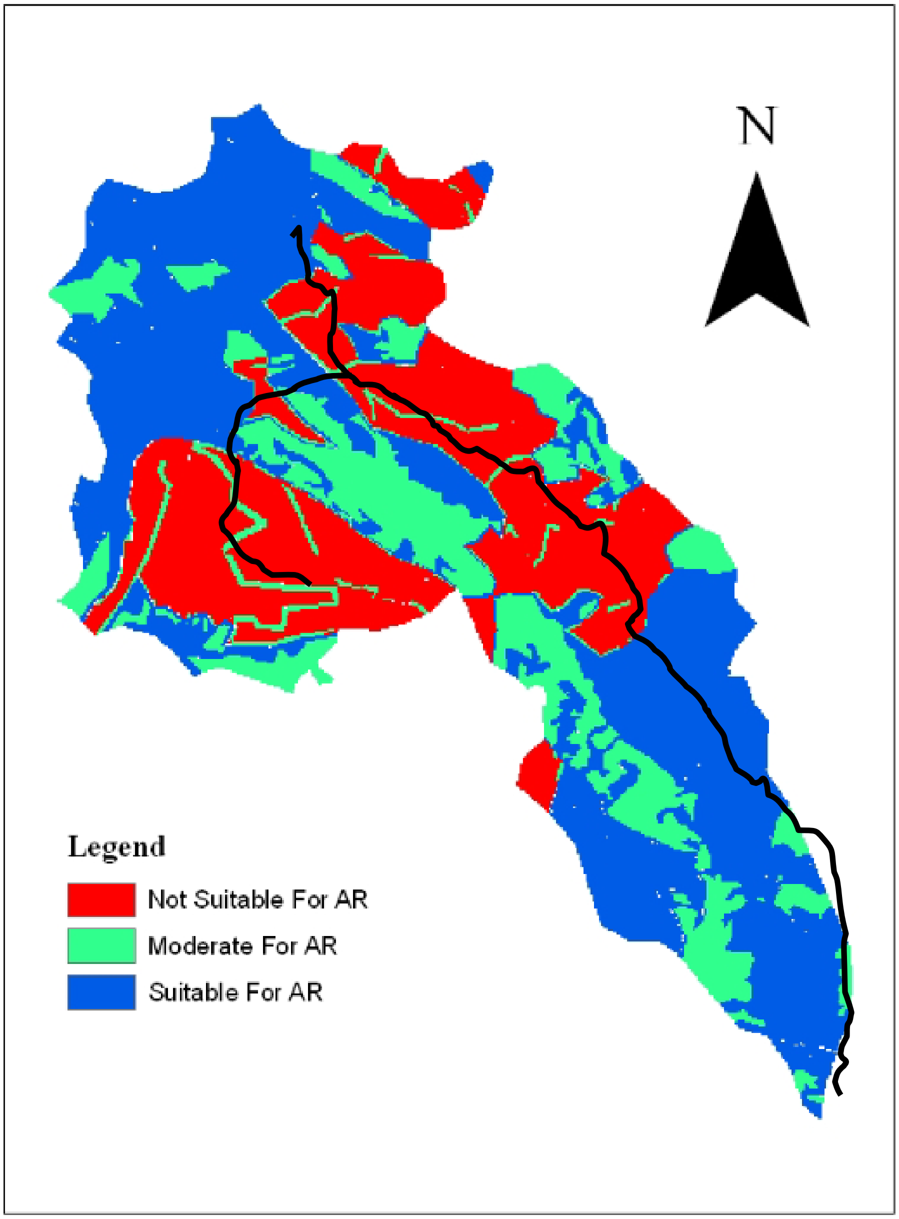


**Figure (6.5): The suitability zones for artificial recharge sites**

The obtained map shows that 14% of the study area is classified as suitable for artificial recharge, 56% is classified as moderately suitable and 30% as not suitable. Suitable locations are apparent in the upper part of the catchment and in the alluvials and rocks close to stream beds of the Wadi Fara.

Not suitable locations are mostly located at the steep mountains and the areas with a low infiltration capacity of the specific rock type. These locations cannot be used for artificial recharge.

Moderate locations were categorized based on the weakness of one or more optimizing criteria. To determine this weakness, specific locations can be checked on the maps presented in Figures 6.1, 6.2, 6.3 and 6.4.

### 6.3 Selected recharge method

The selection of one or more so called water spreading methods seems to be the obvious choice for the upper Faria catchment. Since they require advanced technical control and due to the sediment load in the flood water recharge well methods are not advocated. Due to the absence of permanent surface water bodies with a good water quality, the application of induction methods is also out of the question.

Water spreading methods include basin, ditch and furrow, flooding, stream channel, and pit methods. The basin method with sediment retention basins could be an option, but one would get less enthusiastic when realizing that most topographically suitable land near the wadi's is already cultivated and the soils may consist of loamy and clayey materials where infiltration rates may be relatively low. The ditch and furrow method may be an option, taking less space than the basin method, but it requires a high infiltration capacity, although this capacity does not necessarily have to be present at the upper part of the soil section. Also, such schemes require the installation of sediment retention basins, since otherwise the bottoms of the ditches or furrows will be rapidly clogged. Flooding enhanced by diversion weirs would cause the flood water to flow over the fields. The idea is similar to the flooding events that must have originally taken place in the area. Flood water submerged the alluvial plains and deposited sediments while water also infiltrated in the soil to recharge the groundwater. It is highly questionable whether, even in a controlled way, a flooding approach will work in the Faria catchment in view of the presence of cultivated land with orchards and other crops, stone walls, roads and populated settlements.

A more promising approach may be the application of stream channel methods. Artificial terracing could be applied in the stream channels of wadis that lead to wadi Badan and Faria, or in the upstream parts of these wadi's themselves. The terraces could be extended sideways onto the mountain slopes. Due to the low infiltration capacity of the soils forming the terraces (loam, clays, and perhaps some coarser material), infiltration rates may be low, but as a total could still be considerable in view of the large surface areas involved. The practice has already been implemented by farmers in the upstream areas of wadi Faria (Nonner**,** 2007), see Figure (6.6).

**Figure(6.6): Artificial Recharge using terracing method**

Another option is the installation of dams across the stream channels in the lower reaches of wadi Badan and wadi Faria. These could be simple check dams made up of so called gabions (graded local rock material held together by iron wiring), see Figure (6.7) or more sophisticated structeres.

**Figure(6.7): Artificial Recharge using gabions**

The idea is that the gabions retard the flow and set up the flood water levels, thereby enhancing infiltration. Since it carries less sediment and its (base flow) water quality is good, Wadi Faria seems to qualify better for the installation of gabions, but the placement of these structures in Wadi Badan should not be ruled out. Nevertheless, all methods enhancing infiltration into the beds of these wadi's cause an increase of infiltration of polluted base flow and this could be a major problem. Water quality considerations will decide whether the construction is feasible in this part of the catchment.

More sophisticated dams may also be constructed and a similar reasoning as above holds for the construction of these types of dams. Construction in Wadi Faria seems to be the better option, because of the lower sediment load of the flood water and the better water quality properties of the base flow. However, flood discharges in Wadi Faria are considerably lower than in Wadi Badan which would raise the costs of such a scheme when a construction cost price per cubic meter of infiltrated water is being calculated.

**6.4 Proposed recharge sites and methods.**

An attempt has been made to prepare a map showing the best sites for artificial recharge structures. The locations of the proposed structures are of a preliminary nature and further evaluations need to be done to take final decisions. Not all sites need to be realized. The infiltrating water at the proposed sites will benefit the local aquifer systems and may (partly) restore the natural characteristics of the system including groundwater levels and groundwater quality (Nonner, 2007).

Artificial terracing across wadi channels and extensions may be feasible in upstream areas as shown in Figure (6.8):

1) *Taluza – Tubas area* in the northeastern part of the Faria catchment. This is a relatively flat area that seems to be well suited for such schemes.

2) The *West of Faria area* in the northwestern part of the Faria catchment. This area is more sloping and terracing is already practiced by local farmers.

3) The *Central area* in the central part of the Faria catchment. The terraces are to be built across tributaries of the Wadi Faria downstream of Malaqi Bridge.

4) The *East of Nablus* area in the upper reaches of Wadi Badan. This is a relatively wide and flat area where the construction of terraces could be a possibility.

Gabions or possibly a more solid dam could be considered in a number of sub-areas. These are the following:

1) The *North of Malaqi Bridge* area. A possibly, suitable site for gabions or a dam was identified just north of the Malaqi Bridge in the Wadi Faria.

2) The *Malaqi Bridge* area. In Wadi Badan and downstream the confluence at Malaqi Bridge the construction of gabions could be considered.

3) The *Beit Hasan area*. In this agricultural area further downstream from Malaqi Bridge the placement of gabions across the wadi channel could be an option.

Fortunately, these proposed sites are located within suitable or moderately suitable regions according to the classification of the sites. Thus there is a good match between field observations and common sense, and the results of desktop analysis.

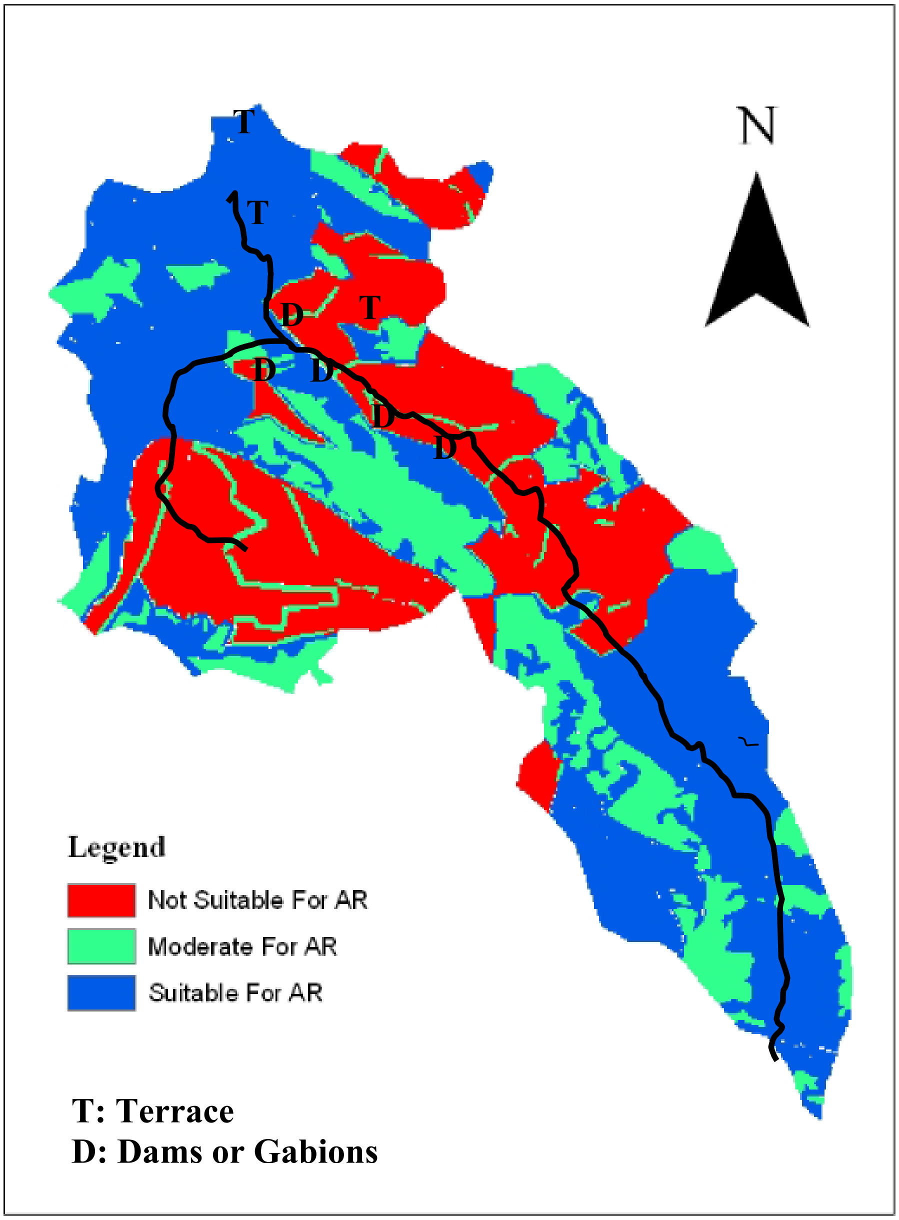


**Figure (6.8): Proposed sites and methods for artificial recharge structure**

In addition to these locations, suitable locations for dams had been selected by Abu Safat (1990). These dams were proposed to store the water in order to be used for irrigation purposes. The locations had been selected based on surface criteria without subsurface characteristics considerations. The locations of these dams can be investigated in the suitability zones for artificial recharge map in order to satisfy the storage for irrigation and to trap the water to be artificially recharged. These locations are shown in Figure (6.9).

Three of these proposed locations for the dams are located within suitable to moderate zones, so these locations will have the priority to be selected.

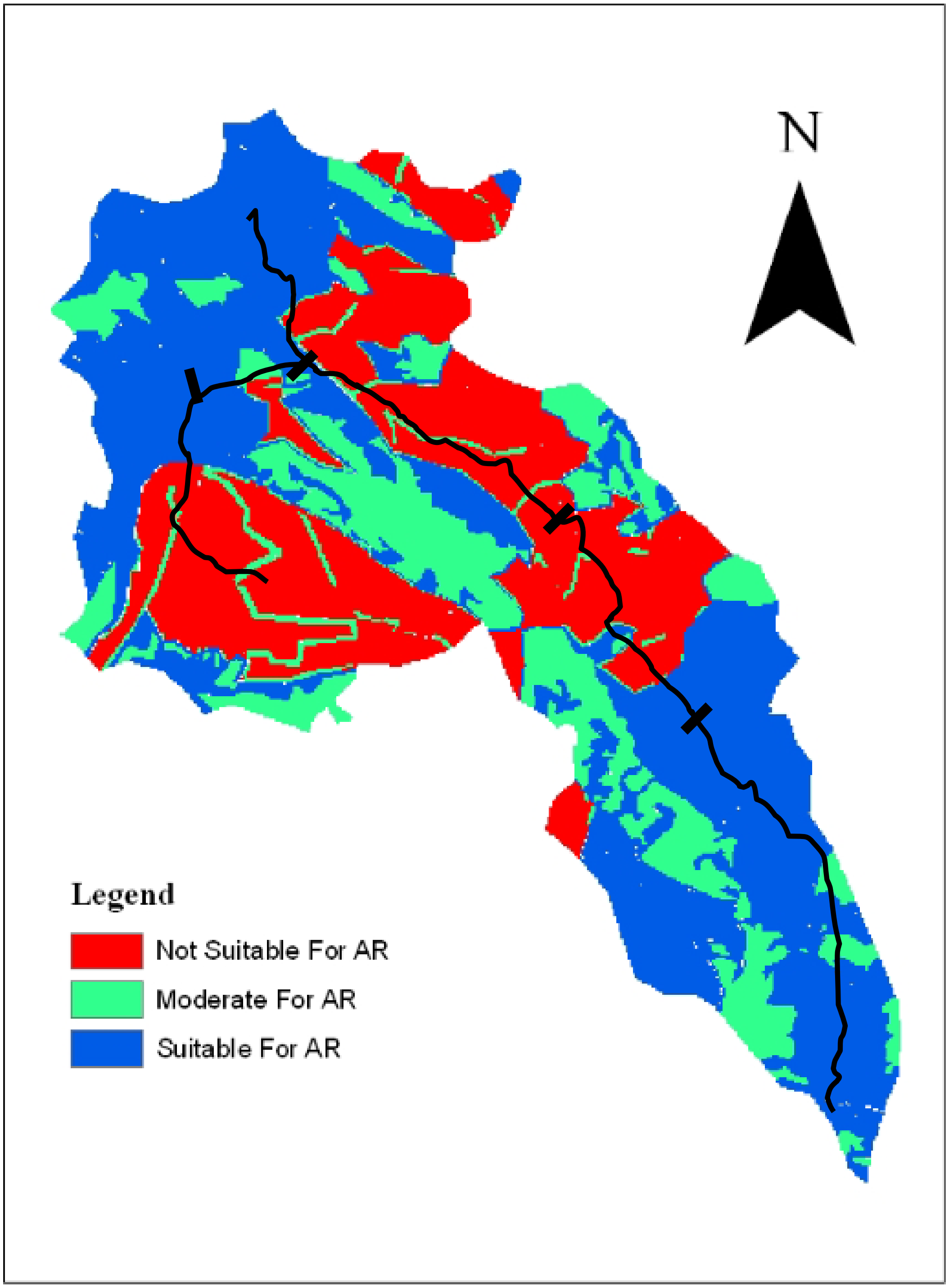


**Figure (6.9): The suitability zones for artificial recharge sites**

# Chapter Seven: Effects of Artificial Recharge

### 7.1 Effects on the soil

Near the surface at the artificial recharge sites, the interstices of the soil may be filled up and a layer of mud may be deposited on the surface. On the other hand suspended particles may penetrate deeper into the soil and accumulate there. These particles and mud decrease gradually the infiltration capacity for the soil. More accumulation of these particles form an impermeable layer so the artificial recharge will not be feasible anymore in these areas and scraping of the soil will have to be undertaken. Also, a green vegetation cover may increase in the zone of benefit and also along the structures due to the additional availability of soil moisture.

### 7.2 Effects on the aquifer

A rise in groundwater levels due to additional recharge to groundwater is expected to occur. In places where a continuous decline of groundwater levels is taking place, the intensity of the decline subsequently reduces. The energy consumption for lifting the water also reduces.

### 7.3 Water balance effects

The surface water and groundwater balances will be affected when the artificial recharge structure is in place. Changes include:

- The recharge volume from streambeds will increase and also this depends on the artificial recharge method and area of surface water behind artificial recharge structure.

- The groundwater outflow in many parts of the study area may be substantially raised, resulting in an increase in springflow and subsurface outflow.

# Chapter Eight: Conclusions and Recommendations

## 8.1 Conclusions

Based on the analysis and the obtained results, the following conclusions are reached:

1. The natural recharge quantities are about 17.5, 18.5, and 24.3 MCM in Badan, Faria and Al Malaqi sub-catchments respectively which accumulates to a total of 60.3 MCM.
2. The maximum water quantity that can be artificially recharged in excess of natural recharge in the upper Badan and Faria sub-catchments is about 3.2 MCM.
3. The results of the analysis for the site selection criteria appear that 14% of the study area classified as suitable for artificial recharge, 56% classified as moderate and 30% as not suitable.
4. Four locations for dams were proposed in a previous study (Abu Safat, 1990) to store the water for irrigation purposes. The proposed locations for the dams are located within suitable to moderate zones, so these locations will have priority to be selected.
5. Terracing is a proper method to be used as a structure for artificial groundwater recharge in the upstream parts of wadi Badan and Faria. The terraces could be extended sideways onto the mountain slopes. Due to the low infiltration capacity of the soils forming the terraces, infiltration rates may be low, but as a total could still be considerable in view of the large surface areas involved. Other AR methods which can be used at the outlet of the upper Faria catchment are dams and gabions.

## 8.2 Recommendations

- This study introduces a simple idea about artificial groundwater recharge so a pilot project is very important before full implementation of artificial recharge projects can be considered. A pilot study enables the collection of temporal data for water quality, studying the compatibility and mixing of recharge and groundwater in terms of predicting the effects on water quality improvement and clogging potential. Besides the quantity of the recharged water and the overall long term performance of recharging facilities can be evaluated.
- The proposed pipe or trunk line for wastewater should proceed when applying artificial groundwater recharge, in order to ensure a perfect quality of the recharged water. The outlet for the trunk line should be beyond the artificial recharge structure, and it may be developed to provide influent for a wastewater treatment plant. In this case the effluent of the treatment plant can be reused and recharged.
- To analyze the effects of artificial recharge on the regional groundwater it is important to have monitoring wells during the test program. The duration of the test should be long enough to observe and know aquifer performance.

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# Annexes

**Annex (1.1): Geological Column for the West Bank**

| Period | | **Age** | Typical Lithology | Palestinian Terminology | | | **Israeli Terminology** | **Jordanian Terminology** | **Typical Thickness (m)** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Group | Formation | Symbol | | | |
| Quaternary | | Halocene | Alluvium, gravels, fan deposits, and surface crust (Nari). | | Alluvium | All | Alluvium | Alluvium | 0-100 |
| | | Plestocene | Thinly laminated marl with gypsum bands, and poorly sorted gravel and pebbles. | | Lisan | Lis | Lisan/ Kurkar Group | Lisan | Unknown |
| Tertiary | | Pliocene-Miocene | Conglomerate, marl, chalk, clay, and limestone. | | Beida | Bei | Saqiya Group | Dana | ± 200 |
| | | Eocene | Numulitic limestone, reef limestone, bedded limestone, limestone with chalk, chalk with limestone (undifferentiated). | | Jenin | Jen | Avedat Group | Rijam & Shallala | 300-600 |
| | | Paleocene | Marl, clay, and chalk. | Gerzim | Khan Al Ahmar | KhA | Taqiya | | 150 |
| Cretaceous | Lower Upper | Mastrichtian | Chalk, marl, metamorphic rocks. | | | | Ghareb | Muwaqar | 55 |
| | | Campanian | Phosphate, and chert | | Al Qilt | Qil | Mishash | Amman & Hisa | 50-75 |
| | | Coniacian-Campanian | White chalk, Chalky limestone, chert, and phosphate | | Abu Dis | ADi | Minuha | Ghudran | 50-175 |
| | | Turonian | Karstified limestone, and dolomite. | Ramallah | Jerusalem | Jer | Bina | Wadi Sir | 40-120 |
| | | Cenomanian | Limestone, dolomite, and marly limestone (karstic). | | Upper Bethlehem | Ube | Weradim | Wadi Shueib | 5-30 |
| | | | Limestone, marly limestone, chalky limestone, and dolomitic limestone. | | Lower Bethlehem | Lbe | Kefar Sha'ul | | 30-115 |
| | | | Karstic limestone, and dolomite. | | Hebron | Heb | Amminadav | Hummar | 105-260 |
| | | | Marl, clay, and marly limestone. | | Upper Yatta | UYa | Moza | Fuhais | 50-150 |
| | | | Limestone, chalky limestone, and dolomitic limestone. | | Lower Yatta | LYa | Beit Meir | | |
| | | Albian | Reefal limestone interbedded with marl. | | Upper Beit Kahil 1 | UBK 1 | Kesalon | Na'uor | 10-40 |
| | | | Dolomite interbedded with marl. | | Upper Beit Kahil 2 | UBK 2 | Beit Soreq | | 50-150 |
| | | | Limestone, and dolomitic limestone. | | Lower Beit Kahil 1 | LBK 1 | Giv'at Ye'arim | | 10-50 |
| | | | Limestone, dolomitic and marly limestone. | | Lower Beit Kahil 2 | LBK 2 | Kefira | | 100-160 |
| | | | Marl, and clay. | | Qatana | Qat | Qatana | | 40-60 |
| | | | Marl, and marly limestone. | | Ein Qinya | EQi | Ein Qinya | | 70-100 |
| | | Aptian | Clay, and marl. | | Tammun | Tam | Tammun | | 50-90 |
| | | Neocomian | Multicoloured sandstone. | | Ramali | Ram | Hathira Kurnub | Kurnub | 50-250 |
| Jurassic | | Callovian-Bajocian | Marl interbedded with chalky limestone. | | Upper Malih | UMa | Zohar, Sherif, Mahmal | Ramlah, Hamam, Mughaneieh | 100-200 |
| | | | Karstified and jointed dolomitic limestone. | | Lower Malih | LMa | | | 50-100 |

## Annex(1.2): Pumping tests results of selected Faria wells by Ghanem M. (1999)

| Well No. | Depth (m) | S.W.L (m) | Pumping Rate ($m^3$/hr) | Saturated Thickness (m) | Aquifer | Transmissivity $m^2$/day | Storativity | Hydraulic Conductivity m/day |
|---|---|---|---|---|---|---|---|---|
| 18-18/17 | 79 | 35 | 67 | 45.4 | Eocene | 1781.1 | - | 39.2 |
| 18-18/23 | 50 | 15.1 | 90 | 40 | Neogene | 1137.5 | - | 28.4 |
| 18-18/37 | 413 | 90.53 | 222 | 320 | L&U.Ce | 9599.4 | - | 201.2 |
| 19-17/1 | 77 | 29.3 | 120 | 47.7 | Eocene | 81.1 | $9.6 \times 10^{-4}$ | 0.3 |
| 19-17/44 | 105 | 97.3 | 87 | 7.7 | L&U.Ce | 197.8 | $2.3 \times 10^{-5}$ | 25.7 |
| 19-17/2 | 60 | 31.3 | 70 | 28.7 | L&U.Ce | 5600 | $8.6 \times 10^{-5}$ | 195.1 |
| 19-17/52 | 75 | 30.8 | 162 | 49.2 | Pleistocene | 391.9 | - | 8 |
| Atara 1 | 520 | 100.1 | 447 | 350 | L&U.Ce | 9610.9 | $1.1 \times 10^{-3}$ | 27.5 |
| Maasua 1 | 600 | 90.02 | 550 | 255 | L&U.Ce | 116.4 | $7.6 \times 10^{-3}$ | 0.5 |

## Annex (1.3): Chemical analysis of the surface and groundwater samples in the Faria catchment (WESI, 2000)

| `Name | | | ms/cm | Mg/l | | | | | | | | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sample No. | pH | EC | TDS | Cl | $HCO_3$ | $NH_4$ | $NO_3$ | $SO_4$ | Ca | Mg | |
| Al Bathan | WW 42 | * | 1748 | 921 | 304 | 382 | 1.5 | 65 | 6.4 | 92 | 24 | Runoff water |
| Al Malaqi Bridge | WW 41 | * | 1852 | 678 | 336 | 305 | 0.8 | 69 | 4.5 | 98 | 21 | Runoff water |
| Faria | WW 40 | * | 3100 | 1641 | 560 | 667 | 1.7 | 26 | 7.7 | 93 | 36 | Runoff water |
| Ein Beda "Fares & El-Bas" | 117 | 7.28 | 538 | 281 | 31 | 200 | 0.3 | 15 | 2 | 82 | 11 | spring |
| Ein Beda "Fares & El-Bas" | 125 | 7.21 | 548 | 274 | 32 | 203 | * | 13 | 2.3 | 80 | 15 | spring |
| Jifftlik Canal | 131 | 7.48 | 2400 | 1200 | 529 | 273 | * | 22 | 3.6 | 115 | 100 | Runoff water |
| Main Faria Spring | 114 | 7.13 | 637 | 334 | 43 | 231 | 0.5 | 13 | 3 | 96 | 19 | spring |
| Main Faria Spring | 123 | 7.15 | 645 | 322 | 46 | 233 | * | 12 | 1 | 93 | 22 | spring |
| Miska Spring "Mazoz Masri" | 119 | 7.56 | 783 | 415 | 84 | 248 | 0.6 | 20 | 6.1 | 81 | 32 | spring |
| Miska Spring "Mazoz Masri" | 127A | 7.62 | 775 | 385 | 78 | 247 | * | 17 | 2.8 | 71 | 36 | spring |
| Miska Spring "Mazoz Masri" | 127B | 8.1 | 665 | 330 | 69 | 225 | * | 14 | 3 | 58 | 37 | spring |
| Shibli Spring | 120 | 7.3 | 701 | 370 | 61 | 232 | 0.5 | 16 | 5.3 | 68 | 39 | spring |
| Shibli Spring | 128 | 7.7 | 725 | 360 | 65 | 233 | * | 15 | 3.1 | 61 | 31 | spring |
| Subyan Spring | 116 | 7.37 | 560 | 394 | 31 | 205 | 0.4 | 15 | 3 | 91 | 12 | spring |
| Tabana Spring | 118 | 7.2 | 553 | 290 | 52 | 204 | 0.4 | 15 | 2 | 83 | 13 | spring |
| Wadi Befor Ein Shibli | 129 | 7.35 | 690 | 340 | 65 | 233 | * | 14 | 3 | 60 | 33 | Runoff water |
| Wadi Before Ein Shibli | 121 | 7.84 | 706 | 371 | 86 | 239 | 0.6 | 16 | 4.3 | 73 | 37 | Runoff water |
| Wadi Faia 100 m ahead | 115 | 7.58 | 722 | 382 | 43 | 235 | 0.4 | 16 | 21 | 108 | 15 | Runoff water |
| Wadi Faria 100 m ahead | 124 | 7.47 | 640 | 320 | 43 | 236 | * | 13 | 2.2 | 93 | 15 | Runoff water |
| Wahat Bathan | 126 | 7.72 | 1725 | 860 | 295 | 344 | 32 | 42 | 3.4 | 86 | 22 | Runoff water |
| Palestinian Guideline Value | | 6.5-8.5 | | 1000 | 250 | | | 45 | 200 | 100 | 50 | 0 |

# Annex (1.4): Root zone balance Faria Sub-catchment.

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Input Data** | | | | **Computed Values** | | | | | | | | |
| | | | | | **Badan Sub catchment** | | | | | | | | |
| | **Area =** | | | | **86.0** | **km$^2$** | ***Soilmax =*** | | | **100** | **mm** | | |
| | **Runoff coefficient =** | | | | **0.064** | | ***SoilreducedE =*** | | | **60** | **mm** | | |
| | **J** | **F** | **M** | **A** | **M** | **J** | **J** | **A** | **S** | **O** | **N** | **D** | **Year** |
| Precipitation (PPT in mm) | **141.1** | **146.9** | **104.0** | **20.2** | **7.8** | **0.0** | **0.0** | **0.0** | **1.8** | **20.7** | **77.1** | **140.5** | 660.1 |
| Temperature | **9.6** | **10.5** | **13** | **17.1** | **20.3** | **22.6** | **24.2** | **24.4** | **23.4** | **21** | **16.1** | **11.2** | |
| Waste water through wadi | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Runoff from precipitation (R in mm) | 9.0 | 9.4 | 6.7 | 1.3 | 0.5 | 0.0 | 0.0 | 0.0 | 0.1 | 1.3 | 4.9 | 9.0 | 42.2 |
| Pan (Pan ET in mm) or potential (PET) | 36.0 | 36.0 | 55.0 | 82.0 | 106.0 | 112.0 | 117.0 | 112.0 | 105.0 | 103.0 | 72.0 | 36.0 | 972.0 |
| Actual evapotranspiration (AET in mm) | 36.0 | 36.0 | 55.0 | 82.0 | 65.2 | 0.0 | 0.0 | 0.0 | 0.0 | 2.9 | 72.0 | 36.0 | 385.1 |
| Initial value and soil storage (SOIL in mm) | 100.0 | 100.0 | 100.0 | 36.9 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 18.2 | 18.3 | 100.0 | |
| Soil storage change (Delta SOIL in mm) | 0.0 | 0.0 | 0.0 | -63.1 | -36.9 | 0.0 | 0.0 | 0.0 | 1.7 | 16.5 | 0.2 | 81.7 | |
| Recharge from precipitation (PERC in mm) | 96.1 | 101.5 | 42.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 13.8 | 253.8 |
| Rock factor (porous media = 1; preferential flow >1; closed fractures <1) | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | |
| Recharge from precipitation including factor (PERC in mm) | 76.9 | 81.2 | 33.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 11.1 | 203.0 |
| Recharge from precipitation (PERC in MCM) | 6.6 | 7.0 | 2.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 17.5 |

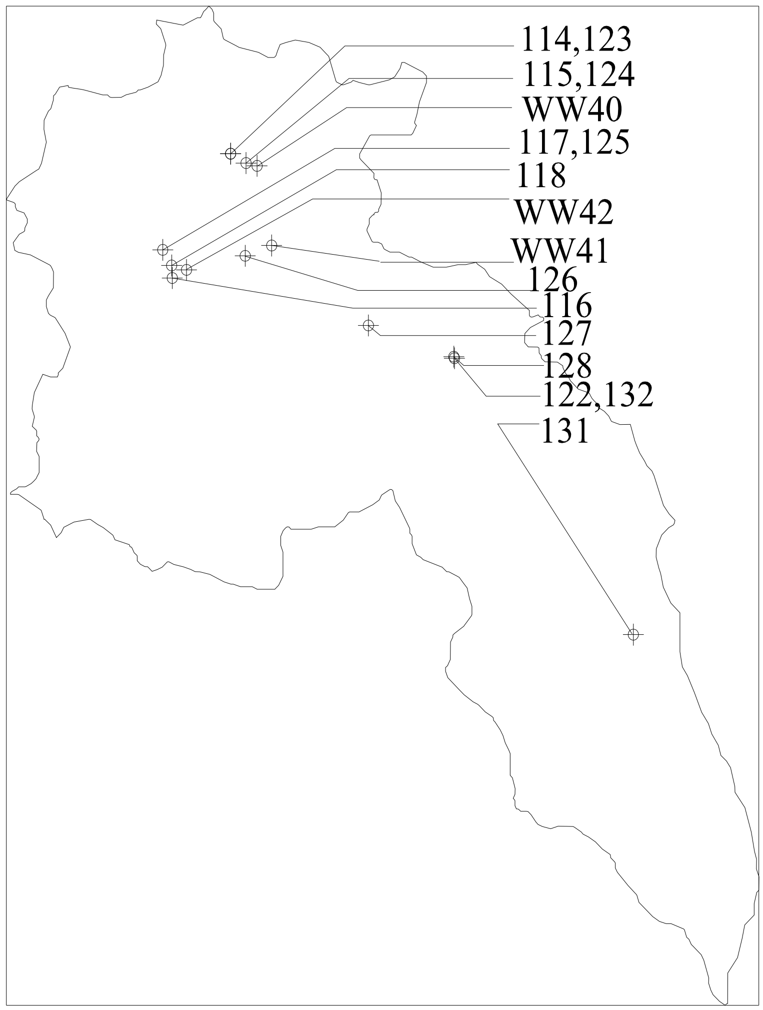
# Annex (1.5): Root zone balance Badan Sub-catchment.

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Input Data** | | | | **Computed Values** | | | | | | | | |
| **Faria Sub catchment** | | | | | | | | | | | | | |
| | **Area =** | | | | **64.0** | | **km²** | | ***Soilmax =*** | | | **100** | **mm** |
| | **Runoff coefficient =** | | | | **0.007** | | | | ***Soil reducedE =*** | | | **60** | **mm** |
| | **J** | **F** | **M** | **A** | **M** | **J** | **J** | **A** | **S** | **O** | **N** | **D** | **Year** |
| Precipitation (PPT in mm) | **141.1** | **146.9** | **104.0** | **20.2** | **7.8** | **0.0** | **0.0** | **0.0** | **1.8** | **20.7** | **77.1** | **140.5** | 660.1 |
| Temperature | **14.4** | **14.7** | **18.2** | **21.7** | **26.8** | **29.1** | **31.1** | **31.4** | **29.8** | **26.9** | **22.4** | **16.7** | |
| Waste water through wadi | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Runoff from precipitation (R in mm) | 1.0 | 1.1 | 0.7 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.6 | 1.0 | 4.8 |
| Pan (Pan ET in mm) or potential (PET) evapo(transpi)ration | 36.0 | 36.0 | 55.0 | 82.0 | 106.0 | 112.0 | 117.0 | 112.0 | 105.0 | 103.0 | 72.0 | 36.0 | 972.0 |
| Actual evapotranspiration (AET in mm) | 36.0 | 36.0 | 55.0 | 82.0 | 67.2 | 0.0 | 0.0 | 0.0 | 0.0 | 3.1 | 72.0 | 36.0 | 387.3 |
| Initial value and soil storage (SOIL in mm) | 100.0 | 100.0 | 100.0 | 38.1 | 0.0 | 0.0 | 0.0 | 0.0 | 1.8 | 19.3 | 23.8 | 100.0 | |
| Soil storage change (Delta SOIL in mm) | 0.0 | 0.0 | 0.0 | -61.9 | -38.1 | 0.0 | 0.0 | 0.0 | 1.8 | 17.5 | 4.5 | 76.2 | |
| Recharge from precipitation (PERC in mm) | 104.1 | 109.8 | 48.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 27.3 | 289.5 |
| Rock factor (porous media = 1; preferential flow >1; closed fractures <1) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | |
| Recharge from precipitation including factor (PERC in mm) | 104.1 | 109.8 | 48.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 27.3 | 289.5 |
| Recharge from precipitation (PERC in MCM) | 6.7 | 7.0 | 3.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 18.5 |

# Annex (1.6): Ground water Balance Calculation Sheet.

| INFLOWS | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Percolation from precipitation (PERC in MCM) | 25.62 | 22.97 | 8.99 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.70 | 60.29 |
| Percolation from wadi floods (PERCstr in MCM) | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | |
| Percolation from wadi waste water (PERCww in MCM) | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | **N.A** | |
| OUTFLOWS | | | | | | | | | | | | | |
| Spring (MCM)-BadanGroup | 0.36 | 0.44 | 0.59 | 0.61 | 0.57 | 0.50 | 0.45 | 0.39 | 0.32 | 0.30 | 0.27 | 0.29 | 5.09 |
| Spring (MCM)-Faria Group | 0.56 | 0.58 | 0.69 | 0.66 | 0.64 | 0.58 | 0.56 | 0.53 | 0.47 | 0.48 | 0.46 | 0.49 | 6.70 |
| Spring (MCM)-Miskah Group | 0.22 | 0.20 | 0.23 | 0.22 | 0.21 | 0.20 | 0.20 | 0.19 | 0.17 | 0.17 | 0.18 | 0.20 | 2.38 |
| Total springflow (SPR in MCM) | 1.13 | 1.22 | 1.51 | 1.49 | 1.43 | 1.27 | 1.22 | 1.10 | 0.96 | 0.95 | 0.90 | 0.98 | 14.16 |
| Subsurface groundwater outflow (GD in MCM) | | | | | | | | | | | | | |
| Total Pumping From Eocene Subaquifer | 0.06 | 0.06 | 0.09 | 0.14 | 0.18 | 0.17 | 0.17 | 0.18 | 0.18 | 0.17 | 0.13 | 0.07 | 1.59 |
| Total Pumping From Neogene Subaquifer | 0.02 | 0.03 | 0.05 | 10.20 | 10.93 | 0.83 | 0.14 | 0.14 | 0.14 | 0.12 | 0.08 | 0.04 | 22.72 |
| Total Pumping From Pleistocene Subaquifer | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total Pumping From Upper & Lower Cenomanian Subaquifer | 0.46 | 0.42 | 0.48 | 0.60 | 0.75 | 0.75 | 0.79 | 0.80 | 0.75 | 0.74 | 0.64 | 0.55 | 7.73 |
| Total Pumping From Alluvuim Subaquifer | 0.10 | 0.10 | 0.14 | 0.16 | 0.14 | 0.07 | 0.06 | 0.12 | 0.19 | 0.23 | 0.19 | 0.13 | 1.63 |
| Total pumping (ABS in MCM) | 0.64 | 0.60 | 0.76 | 11.09 | 12.00 | 1.82 | 1.16 | 1.25 | 1.26 | 1.26 | 1.04 | 0.79 | 33.66 |
| CHANGE IN GROUNDWATER STORAGE | | | | | | | | | | | | | |
| Eocene Subaquifer Fluctuation (MCM) | 2.13 | 1.36 | 1.14 | -0.17 | -0.46 | 0.05 | -0.68 | -0.84 | -1.11 | -1.60 | -0.91 | 0.47 | -0.62 |
| Neogene Subaquifer Fluctuation (MCM) | 2.41 | 1.76 | 0.78 | -1.36 | -2.06 | -1.83 | -1.76 | -0.93 | -0.79 | 0.53 | 0.86 | 1.88 | -0.50 |
| Pleistocene Subaquifer Fluctuation (MCM) | 0.08 | 0.04 | 0.03 | -0.01 | -0.03 | -0.04 | -0.07 | -0.09 | -0.07 | -0.08 | 0.08 | 0.10 | -0.05 |
| Alluivum Subaquifer Fluctuation (MCM) | 8.40 | -0.26 | 3.12 | 0.27 | 0.32 | 2.71 | 3.21 | -7.64 | -6.47 | -9.67 | -5.11 | -1.70 | -12.81 |
| Lower Cenomanian Sub aquifer Variation (MCM) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| Upper Cenomanian Subaquifer Variation (MCM) | 0.00 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| Total change in groundwater storage (STO in MCM) | 13.01 | 2.91 | 5.08 | -1.27 | -2.23 | 0.90 | 0.70 | -9.50 | -8.44 | -10.83 | -5.08 | 0.75 | -13.98 |
| GD-GI(MCM) | 10.83 | 18.24 | 1.64 | -11.31 | -11.21 | -3.99 | -3.07 | 7.15 | 6.23 | 8.62 | 3.14 | 0.18 | 26.44 |

# Annex (2): Figures




**Annex (2): Location of the taken samples in the study area**

# Annex (3):Invistigation Sites in the study area

| Location | Background geology | Alluvial | Soils | Base flow | Base flow changes river bed | Ground-water level | Infiltration capacity |
|---|---|---|---|---|---|---|---|
| BW | Massive lime-stone/ vertical fractures | Pebbles and sand; some loam | Loamy; on terraces | River bed and north canal – spring | No; or very small quantities | Not known | Low |
| BN1 | Massive lime-stone/locally intense open fracturing | Pebbles and sand; some loam and clay | Loamy; minor terraces | In river bed | No; or very small quantities | Not known | Low, or medium upslope |
| BN1 (dam site) | Same | Same | Same | Same | Same | Same | Same |
| BN2 | Limestone, fractured partly, and marl | Sandy, with loam? | Sandy and loamy; terraces | In river bed | No; or very small quantities | Not known | Low |
| BE1 | Limestone; varying fracturing; also sub horizontal | Pebbles, sand, but also loam and clay layers | Probably loamy/clay ey on terraces | River bed and north canal – spring | No; or very small quantities | Not known | Low, or medium up slope? |
| BE2 | Limestone; varying fracturing; in places karstic | Pebbles, sand, but also loam. Sandier downstream | Probably loamy/clay ey on terraces | River bed and north canal – spring | No; or very small quantities | Not known | Low, or medium up slope? |
| BE3 | Limestone; varying verti-cal fracturing; gently sloping west | Pebbles and unsorted material | Probably loamy/clay ey on terraces | River bed and north canal – spring; mixing of bed and canal water | No; or very small quantities | Not known | Low |
| BE4 | Limestone; varying verti-cal fracturing; gently sloping west. Valley widens | Pebbles and unsorted material | Probably loamy/clay ey on terraces | Dam in river and part of its water to south canal; north canal con-tinues, but also delivers water to south canal | Except the transfers to canals, no or only small quantities into or from river bed | Not known | Low |
| BE5 | Limestone at edges of widened valley | River bed: Pebbles and loam (cement) | Probably loamy and clayey on terraces | In river bed and both canals | No; or very small quantities | At Agricul-tural well 27 about 5 m below river bed | Low, or medium upslope |

BW, BN1, BN2, BE1, BE2: 21 September 2005; BN1: Dam site: 29 March 2007: dimensions of cross section; BE3, BE4 and BE5 29 March 2007.

# Annex(4):Wells drawdown

## Pleistocene Sub aquifer

| 18-<br>18/001 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 211 | 211 | 211 | 211 | 211 | 211 | 211 | 210 | 210 | 210 | 210 | 209 |
| 1971 | 209 | 208 | 208 | 209 | 208 | 206 | 207 | 207 | 207 | 207 | 207 | 206 |
| 1972 | 207 | 208 | 210 | 212 | 211 | 211 | 211 | 211 | 209 | 209 | 209 | 209 |
| 1973 | 209 | 208 | 208 | 208 | 207 | 206 | 206 | 205 | 205 | 204 | 204 | 205 |
| 1974 | 205 | 212 | 214 | 215 | 214 | 213 | 212 | 212 | 211 | 210 | 210 | 210 |
| 1975 | 210 | 210 | 210 | 209 | 209 | 208 | 208 | 208 | 207 | 207 | 207 | 207 |
| 1976 | 207 | 206 | 207 | 207 | 207 | 206 | 206 | 206 | 205 | 205 | 204 | 205 |
| 1977 | 205 | 205 | 206 | 206 | 206 | 205 | 205 | 205 | 205 | 204 | 204 | 205 |
| 1978 | 205 | 205 | 204 | 203 | 202 | 202 | 201 | 201 | 200 | 200 | 200 | 202 |
| 1979 | 202 | 201 | 200 | 200 | 199 | 199 | 199 | 199 | 198 | 198 | 198 | 202 |
| 1980 | 206 | 206 | 209 | 212 | 212 | 211 | 210 | 209 | 209 | 208 | 208 | 208 |
| 1981 | 208 | 209 | 209 | 209 | 209 | 210 | 209 | 208 | 208 | 208 | 207 | 207 |
| 1982 | 207 | 207 | 206 | 206 | 205 | 204 | 204 | 203 | 203 | 203 | 204 | 204 |
| 1983 | 206 | 208 | 209 | 216 | 215 | 214 | 213 | 212 | 212 | 211 | 211 | 211 |
| 1984 | 211 | 210 | 210 | 209 | 209 | 209 | 206 | 203 | 203 | 202 | 202 | 203 |
| 1985 | 204 | 205 | 205 | 205 | 205 | 205 | 204 | 203 | 203 | 202 | 202 | 203 |
| 1986 | 203 | 203 | 202 | 201 | 201 | 201 | 199 | 198 | 198 | 198 | 200 | 202 |
| 1987 | 205 | 207 | 207 | 207 | 207 | 207 | 206 | 205 | 204 | 204 | 205 | 206 |
| 1988 | 206 | 207 | 209 | 211 | 211 | 211 | 210 | 209 | 208 | 208 | 208 | 208 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1989 | 209 | 209 | 207 | 206 | 206 | 206 | 205 | 204 | 203 | 202 | 204 | 206 |
| 1990 | 206 | 207 | 206 | 206 | 206 | 205 | 204 | 203 | 203 | 202 | 203 | 203 |
| 1991 | 204 | 204 | 204 | 203 | 201 | 200 | 200 | 199 | 198 | 198 | 198 | 206 |
| 1992 | 214 | 217 | 220 | 220 | 220 | 219 | 218 | 217 | 216 | 215 | 215 | 216 |
| 1993 | 218 | 218 | 217 | 216 | 215 | 215 | 214 | 213 | 213 | 122 | 213 | 213 |
| 1994 | 213 | 213 | 212 | 210 | 209 | 208 | 208 | 207 | 206 | 207 | 207 | 207 |
| 1995 | 207 | 207 | 206 | 208 | 209 | 209 | 208 | 207 | 207 | 207 | 208 | 208 |
| 1996 | 208 | 208 | 208 | 207 | 206 | 205 | 204 | 203 | 202 | 203 | 203 | 204 |
| 1997 | 206 | 208 | 211 | 211 | 211 | 210 | 209 | 209 | 207 | 208 | 208 | 209 |
| 1998 | 209 | 209 | 209 | 210 | 211 | 211 | 210 | 209 | 207 | 208 | 208 | 208 |
| 1999 | 208 | 207 | 206 | 204 | 202 | 201 | 201 | 200 | 199 | 199 | 199 | 201 |

| 18-<br>18/027 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | | | | | | | | -23 | -24 | -24 | -24 | -23 |
| 1971 | -23 | -23 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 |
| 1972 | -24 | -24 | -24 | -23 | -23 | -23 | -23 | -24 | -24 | -24 | -24 | -24 |
| 1973 | -23 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | | -24 | -24 |
| 1974 | -24 | -24 | -24 | -23 | -23 | -23 | -23 | -23 | -23 | -23 | -23 | -23 |
| 1975 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 |
| 1976 | -23 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 | -24 |
| 1977 | -24 | -24 | -24 | -27 | -24 | -24 | -24 | -25 | -25 | -25 | -25 | -24 |
| 1978 | -24 | -24 | -24 | -25 | -25 | -24 | -25 | -25 | -26 | -26 | -26 | -26 |
| 1979 | -26 | -26 | -26 | -26 | -26 | -26 | -26 | -26 | -26 | -27 | -27 | -27 |

| 18-<br>18/014 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | | | | | | | | -37 | -37 | -37 | -37 | -37 |
| 1971 | -37 | -37 | -37 | -37 | -37 | -37 | -38 | -38 | -38 | -38 | -38 | -38 |
| 1972 | -38 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 |
| 1973 | -37 | -37 | -37 | -37 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -37 |
| 1974 | -38 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 |
| 1975 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -38 | -38 | -38 | -38 | -38 |
| 1976 | -38 | -37 | -37 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 |
| 1977 | -38 | -38 | -37 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 |
| 1978 | -38 | -38 | -38 | -38 | -38 | -38 | -39 | -39 | -38 | -39 | -39 | -39 |
| 1979 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -40 | -40 | -40 | -40 | -39 |
| 1980 | -39 | -39 | -39 | -39 | -39 | -38 | -38 | -38 | -39 | -39 | -39 | -38 |
| 1981 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -39 | -38 | -38 | -38 |
| 1982 | -38 | -38 | -38 | -38 | -39 | -38 | -38 | -38 | -39 | -38 | -38 | -39 |
| 1983 | -38 | -38 | -37 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 |
| 1984 | -38 | -37 | -37 | -37 | -37 | -37 | -38 | -38 | -38 | -38 | -38 | -38 |
| 1985 | -39 | -38 | -38 | -38 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -39 |
| 1986 | -38 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -40 | -39 | -39 | -39 |
| 1987 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -39 |
| 1988 | -39 | -39 | -38 | -38 | -39 | -39 | -39 | -39 | -39 | -39 | -38 | -38 |
| 1989 | -38 | -38 | -38 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -39 | -39 |
| 1990 | -39 | -39 | -39 | -39 | -40 | -40 | -39 | -40 | -40 | -40 | -40 | -39 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1991 | -39 | -39 | -39 | -39 | -40 | -40 | -40 | -40 | -40 | -40 | -40 | -39 |
| 1992 | -38 | -38 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 |
| 1993 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 |
| 1994 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -38 | -38 | -37 | -37 |
| 1995 | -37 | -37 | -37 | -37 | -37 | -37 | -37 | -38 | -38 | -38 | -38 | -38 |
| 1996 | -37 | -37 | -37 | -37 | -37 | -38 | -38 | -38 | -38 | -38 | -38 | -38 |
| 1997 | -38 | -38 | -38 | -38 | -38 | -37 | -37 | -37 | -37 | -38 | -38 | -38 |
| 1998 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 | -38 |
| 1999 | -38 | -38 | -37 | -38 | -38 | -38 | -39 | -39 | -39 | -39 | -39 | -39 |

## Eocene Sub aquifer

| 19-<br>17/023 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | -274 |
| 1970 | -273 | -272 | -271 | -271 | -272 | -273 | -273 | -273 | -275 | -275 | -275 | -275 |
| 1971 | -275 | -275 | -274 | -275 | -274 | -275 | -276 | -276 | -277 | -276 | -278 | -278 |
| 1972 | -277 | -276 | -275 | -275 | -275 | -275 | -275 | -275 | -277 | -277 | -277 | -277 |
| 1973 | -277 | -277 | -276 | -276 | -277 | -277 | -278 | -278 | -279 | -278 | -280 | -280 |
| 1974 | -279 | -276 | -275 | -274 | -274 | -274 | -275 | -275 | -276 | -276 | -277 | -276 |
| 1975 | -276 | -275 | -274 | -274 | -275 | -276 | -276 | -277 | -277 | -278 | -278 | -279 |
| 1976 | -278 | -278 | -277 | -277 | -278 | -278 | -279 | -279 | -279 | -280 | -280 | -280 |
| 1977 | -280 | -280 | -280 | -280 | -280 | -281 | -281 | -281 | -281 | -282 | -282 | -282 |
| 1981 | -282 | -281 | -281 | -281 | -281 | -281 | -281 | -281 | -282 | -282 | -283 | -283 |
| 1982 | -283 | -282 | -282 | -282 | -282 | -282 | -282 | -283 | -283 | -283 | -283 | -283 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1983 | -282 | -282 | -281 | -281 | -280 | -280 | -280 | -280 | -280 | -281 | -281 | -281 |
| 1984 | -281 | -281 | -280 | -280 | -280 | -280 | -281 | -281 | -281 | -282 | -282 | -282 |
| 1985 | -283 | -283 | -282 | -283 | -283 | -284 | -284 | -284 | -284 | -285 | -285 | -285 |
| 1986 | -286 | -286 | -286 | -286 | -286 | -286 | -286 | -288 | -289 | -289 | -289 | -288 |
| 1987 | -287 | -286 | -285 | -286 | -286 | -287 | -287 | -288 | -289 | -288 | -288 | -287 |
| 1988 | -287 | -286 | -284 | -285 | -285 | -286 | -287 | -287 | -288 | -288 | -289 | -288 |
| 1989 | -287 | -286 | -285 | -286 | -287 | -285 | -287 | -288 | -288 | -289 | -289 | -289 |
| 1990 | -288 | -287 | -286 | -287 | -287 | -285 | -288 | -289 | -290 | -290 | -291 | -291 |
| 1991 | -291 | -292 | -291 | -290 | -291 | -291 | -291 | -291 | -279 | -292 | -292 | -291 |
| 1992 | -274 | -276 | -279 | -281 | -280 | -279 | -278 | -277 | -279 | -277 | -276 | -276 |
| 1993 | -275 | -274 | -274 | -274 | -273 | -273 | -274 | -274 | -279 | -275 | -274 | -276 |

| 19-<br>17/007 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | -277 |
| 1970 | -277 | -277 | -276 | -276 | -276 | -276 | -277 | -277 | -277 | -277 | -278 | -278 |
| 1971 | -278 | -278 | -278 | -278 | -278 | -278 | -278 | -278 | -278 | -279 | -280 | -280 |
| 1972 | -279 | -279 | -278 | -278 | -278 | -278 | -278 | -278 | -278 | -279 | -280 | -280 |
| 1973 | -280 | -279 | -279 | -280 | -280 | -280 | -280 | -280 | -281 | -280 | -282 | -282 |
| 1974 | -281 | -280 | -279 | -278 | -278 | -278 | -278 | -278 | -279 | -279 | -280 | -279 |
| 1975 | -279 | -280 | -278 | -278 | -279 | -279 | -279 | -279 | -280 | -281 | -281 | -281 |
| 1976 | -281 | -281 | -280 | -281 | -281 | -281 | -281 | -281 | -281 | -282 | -282 | -282 |
| 1977 | -282 | -282 | -282 | -283 | -283 | -283 | -282 | -283 | -283 | -283 | -284 | -284 |
| 1978 | -284 | -283 | -284 | -284 | -284 | -283 | -283 | -284 | -284 | -284 | -284 | -284 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1979 | -284 | -285 | -285 | -285 | -285 | -284 | -284 | -285 | -285 | -285 | -286 | -285 |
| 1980 | -284 | -284 | -283 | -283 | -284 | -283 | -283 | -283 | -284 | -284 | -285 | -284 |
| 1981 | -284 | -284 | -283 | -283 | -283 | -283 | -283 | -283 | -283 | -284 | -285 | -285 |
| 1982 | -285 | -284 | -283 | -283 | -283 | -283 | -284 | -283 | -283 | -284 | -284 | -284 |
| 1983 | -284 | -284 | -283 | -283 | -283 | -282 | -282 | -282 | -282 | -283 | -284 | -283 |
| 1984 | -283 | -281 | -279 | -279 | -278 | -278 | -278 | -280 | -283 | -283 | -284 | -284 |
| 1985 | -285 | -285 | -285 | -285 | -285 | -285 | -285 | -285 | -285 | -286 | -287 | -287 |
| 1986 | -287 | -287 | -288 | -288 | -288 | -287 | -287 | -288 | -288 | -288 | -289 | -288 |
| 1987 | -287 | -287 | -287 | -287 | -288 | -288 | -287 | -288 | -289 | -289 | -290 | -289 |
| 1988 | -288 | -288 | -287 | -287 | -287 | -287 | -287 | -288 | -289 | -289 | -290 | -289 |
| 1989 | -288 | -288 | -288 | -288 | -289 | -289 | -288 | -289 | -290 | -290 | -291 | -290 |
| 1990 | -290 | -289 | -288 | -289 | -289 | -290 | -290 | -291 | -292 | -292 | -292 | -291 |
| 1991 | -291 | -292 | -292 | -292 | -292 | -292 | -292 | -292 | -293 | -293 | -292 | -292 |
| 1992 | -291 | -290 | -288 | -285 | -284 | -283 | -282 | -281 | -281 | -280 | -280 | -279 |
| 1993 | -278 | -278 | -277 | -277 | -277 | -277 | -276 | -276 | -277 | -278 | -278 | -278 |
| 1994 | -277 | -277 | -277 | -277 | -277 | -277 | -278 | -278 | -279 | -280 | -279 | -279 |
| 1995 | -278 | -278 | -278 | -278 | -278 | -278 | -278 | -279 | -280 | -281 | -280 | -280 |
| 1996 | -280 | -279 | -279 | -279 | -280 | -280 | -280 | -281 | -282 | -283 | -283 | -283 |
| 1997 | -282 | -281 | -280 | -280 | -280 | -280 | -281 | -281 | -281 | -282 | -280 | -279 |
| 1998 | -279 | -279 | -278 | -278 | -278 | -278 | -279 | -279 | -280 | -282 | -282 | -281 |
| 1999 | -281 | -281 | -283 | -284 | -284 | -283 | -284 | -285 | -285 | -286 | -286 | -287 |

Neogen Sub aquifer

| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | | | | | | | | | | | | |
| 1971 | | | | | | | | | | | | -270 |
| 1972 | -268 | -264 | -261 | -261 | -266 | -269 | -271 | -272 | -272 | -273 | -272 | -268 |
| 1973 | -264 | -259 | -258 | -259 | -266 | -269 | -271 | -274 | -275 | -275 | -275 | -274 |
| 1974 | -270 | -262 | -262 | -262 | -264 | -266 | -269 | -270 | -272 | -269 | -269 | -266 |
| 1975 | -260 | -259 | -260 | -264 | -267 | -270 | -273 | -272 | -274 | -274 | -273 | -269 |
| 1976 | -267 | -266 | -265 | -267 | -270 | -271 | -273 | -276 | -276 | -275 | -275 | -273 |
| 1977 | -270 | -269 | -267 | -270 | -273 | -275 | -276 | -276 | -276 | -276 | -274 | -273 |
| 1978 | -270 | -272 | -272 | -273 | -275 | -277 | -277 | -278 | -278 | -277 | -275 | -274 |
| 1979 | -273 | -271 | -274 | -276 | -277 | -277 | -278 | -278 | -278 | -276 | -275 | -274 |
| 1980 | -273 | -272 | -271 | -271 | -271 | -273 | -276 | -276 | -277 | -277 | -276 | -274 |
| 1981 | -272 | -272 | -272 | -273 | -273 | -275 | -276 | -277 | -278 | -276 | -275 | -274 |
| 1982 | -273 | -271 | -269 | -271 | -274 | -275 | -276 | -277 | -278 | -276 | -274 | -273 |
| 1983 | -272 | -271 | -269 | -269 | -269 | -270 | -272 | -274 | -276 | -274 | -272 | -271 |
| 1984 | -270 | -271 | -271 | -271 | -271 | -274 | -277 | -277 | -277 | -277 | -276 | -276 |
| 1985 | -275 | -274 | -273 | -275 | -277 | -277 | -278 | -279 | -280 | -281 | -283 | -280 |
| 1986 | -278 | -277 | -276 | -276 | -276 | -279 | -282 | -283 | -284 | -283 | -281 | -278 |
| 1987 | -275 | -275 | -274 | -276 | -278 | -280 | -281 | -282 | -283 | -284 | -284 | -280 |
| 1988 | -275 | -273 | -270 | -273 | -275 | -276 | -277 | -277 | -277 | -277 | -276 | -274 |
| 1989 | -272 | -272 | -271 | -273 | -275 | -276 | -278 | -278 | -279 | -277 | -276 | -275 |
| 1990 | -274 | -272 | -271 | -273 | -275 | -277 | -278 | -279 | -281 | -281 | -280 | -282 |
| 1991 | -279 | -276 | -276 | -276 | -277 | -279 | -280 | -280 | -281 | -282 | -281 | -280 |

Alluvuim Sub aquifer

| 19- 17/024 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1969 | | | | | | | | | | | | -277 |
| 1970 | -277 | -276 | -276 | -276 | -276 | -276 | -276 | -277 | -277 | -277 | -278 | -278 |
| 1971 | -278 | -278 | -277 | -278 | -278 | -278 | -278 | -278 | -278 | -279 | -280 | -280 |
| 1972 | -279 | -279 | -278 | -278 | -278 | -278 | -278 | -278 | -276 | -276 | -276 | -278 |
| 1973 | -277 | -279 | -279 | -279 | -279 | -280 | -275 | -277 | -276 | -276 | -276 | -282 |
| 1974 | -281 | -280 | -279 | -275 | -274 | -275 | -273 | -273 | -273 | -272 | -273 | -273 |
| 1975 | -272 | -274 | -273 | -272 | -272 | -272 | -279 | -279 | -280 | -281 | -281 | -281 |
| 1976 | -281 | -281 | -280 | -281 | -281 | -281 | -281 | -281 | -282 | -282 | -282 | -282 |
| 1977 | -282 | -283 | -283 | -283 | -283 | -283 | -283 | -283 | -283 | -284 | -284 | -284 |
| 1978 | -283 | -284 | -284 | -284 | -284 | -283 | -283 | -284 | -284 | -285 | -285 | -284 |
| 1979 | -284 | -285 | -285 | -285 | -285 | -284 | -284 | -284 | -284 | -284 | -285 | -285 |

| 19- 17/009 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1973 | -280 | -279 | -280 | -281 | -281 | -282 | -281 | -281 | -282 | -282 | -283 | -282 |
| 1974 | -282 | -280 | -280 | -279 | -280 | -280 | -279 | -279 | -280 | -281 | -281 | -280 |
| 1975 | -279 | -279 | -278 | -279 | -280 | -280 | -280 | -280 | -281 | -282 | -281 | -281 |
| 1976 | -281 | -281 | -281 | -282 | -281 | -281 | -281 | -282 | -282 | -283 | -283 | -283 |
| 1977 | -282 | -283 | -283 | -284 | -284 | -283 | -283 | -283 | -284 | -284 | -284 | -285 |
| 1978 | -284 | -284 | -285 | -285 | -285 | -284 | -284 | -284 | -284 | -286 | -285 | -285 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1979 | -286 | -286 | -285 | -285 | -285 | -285 | -285 | -285 | -285 | -286 | -287 | -286 |
| 1980 | -283 | -281 | -282 | -283 | -285 | -284 | -284 | -285 | -285 | -285 | -285 | -285 |
| 1981 | -284 | -284 | -284 | -284 | -284 | -283 | -283 | -283 | -284 | -284 | -285 | -285 |
| 1982 | -285 | -285 | -284 | -284 | -284 | -284 | -283 | -284 | -284 | -284 | -285 | -284 |
| 1983 | -284 | -283 | -283 | -283 | -283 | -283 | -282 | -283 | -283 | -284 | -284 | -284 |
| 1984 | -284 | -282 | -281 | -281 | -280 | -280 | -280 | -282 | -283 | -284 | -285 | -285 |
| 1985 | -285 | -285 | -285 | -285 | -285 | -285 | -284 | -285 | -285 | -286 | -287 | -287 |
| 1986 | -287 | -288 | -288 | -288 | -287 | -287 | -287 | -287 | -288 | -288 | -289 | -288 |
| 1987 | -287 | -288 | -288 | -288 | -288 | -287 | -287 | -288 | -289 | -290 | -291 | -289 |
| 1988 | -288 | -288 | -287 | -288 | -288 | -287 | -287 | -288 | -290 | -290 | -291 | -289 |
| 1989 | -288 | -289 | -289 | -289 | -289 | -288 | -288 | -289 | -290 | -290 | -291 | -290 |

جامعة النجاح الوطنية
كلية الدراسات العليا

# تغذية المياه الجوفية في حوض وادي الفارعة
## (دراسة هيدروجيولوجية)

إعداد
يحيى فتحي كامل صالح

إشراف
د. محمد المصري
د. حافظ شاهين

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

2009

**تغذية المياه الجوفية في حوض وادي الفارعة (دراسة هيدروجيولوجية)**

**إعداد**
**يحيى فتحي كامل صالح**
**إشراف**
**د. محمد المصري**
**د. حافظ شاهين**

## الملخص

يصنف حوض وادي الفارعة على أنه منطقة شبه جافة لا يوجد بها مصادر مياه دائمة ، وتعتبر مياه الأمطار و الينابيع هي المصادر الرئيسية في المنطقة و التي يعتمد تزويدها للمياه على وفرة مياه الأمطار في موسم الشتاء، و كثير من هذه الآبار والينابيع لا يمكنها الاستمرار في التزويد في مواسم الجفاف، لذلك كان لا بد من الوصول إلى حل مجدي يمكن من خلاله الاستفادة من مياه الأمطار والينابيع التي تجري إلى نهر الأردن.

الحل الممكن يتمثل بترشيح هذه المياه عبر طبقات الأرض المتشكلة من الرواسب و التجاويف الجيرية إلى المياه الجوفية.

و تتلخص آلية عمل الدراسة بجمع وتحليل المعلومات التي تلزم لتكوين الميزان المائي و كذلك لتحديد المواقع التي يمكن استخدامها لهذه التقنية ، حيث أنه من خلال نتائج التحليل تم تكوين الميزان المائي للمياه السطحية و الجوفية و تحديد الكمية التي يمكن ترشيحها اعتمادا على مساحة سطح المياه التي يتم جمعها بهدف ترشيحها، كذلك تم التوصل من خلال نتائج تحليل المعلومات المتوفرة إلى تحديد أفضل الأماكن التي يمكن استخدامها لهذا الغرض.

تطبيق هذه التقنية سيكون له تأثير كمي ونوعي على المياه الجوفية و لقياس هذا التأثير فإنه لابد من التعرف على الخصائص الهيدرولوجية والهيدورجيولوجية لطبقات الأرض في منطقة الدراسة لفهم المتغيرات الموجودة.

و على ضوء هذا الفهم فقد تم تكوين الموازنة المائية للمياه السطحية والجوفية باستخدام البيانات المتوفرة لتحديد مركبات هذه الموازنة ليتم استخدامها كمرجع يمكن من خلاله تكوين الموازنة المائية بعد تطبيق تقنية الترشيح و معرفة تأثير تطبيقه على الميزان المائي.حيث كانت النتيجة أن36 مليون متر مكعب ترشح إلى المياه الجوفية بشكل طبيعي في الأجزاء العلوية من الحوض من

أصل 60.3 مليون متر مكعب ترشح من حوض الفارعة بشكل طبيعي، و في حال استخدام تقنية الترشيح فإن كمية المياه التي يمكن أن تساهم بها هذه التقنية قدرت بحوالي 3.2مليون متر مكعب في الجزء العلوي لحوض الفارعة.

ولتفادي الآثار السلبية لاختلاط المياه العادمة بالمياه التي يمكن استخدامها لترشيح المياه الجوفية تم اقتراح وسيلة لعزل المياه العادمة في منطقة تنفيذ مشروع الترشيح، و لتحسين نوعية المياه الجوفية الحالية من نتائج تسرب هذه المياه و اختلاطها بها.

كما خلصت الدراسة إلى تحديد أفضل الأماكن والأساليب التي يمكن استخدامها لتطبيق هذا المشروع تبعا لأربعة معايير هي: القدرة على الترشيح و انحدار المنطقة ونوع الأحواض التي سيتم ترشيحها بالإضافة إلى تحديد إمكانية وجود تصدعات في طبقات الأرض، حيث يتم ذلك باستخدام طريقة المعيار الوزني لهذه المعايير ليتم تصنيف حوض الفارعة إلى مناطق صالحة للترشيح و مناطق غير صالحة حيث أظهرت النتائج أن 14% من المساحة الكلية لحوض الفارعة مناسبة لتطبيق تقنية الترشيح، وتم مقارنة نتائج التصنيف مع مقترحات ميدانية و كذلك مع دراسة أخرى دعمت النتائج التي تم التوصل إليها.