ARTIFICIAL RECHARGE ASSESSMENT OF GROUNDWATER

THROUGH MEKHTAN DAM BANI HUSHEISH , SANA'A BASIN – YEMEN

AND WAYS TO IMPROVE IT OUT OF THE PERSPECTIVE OF IWRM

By

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This Thesis was Submitted in Partial Fulfillment of the Requirements for the Master's Degree in IWRM

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أعوذ بالله من الشيطان الرجيم

بسم الله الرحمن الرحيم

قال الله عز وجل في القرآن الكريم: (فقُلْتُ اسْتَغْفِرُوا رَبَّكُمْ إِنَّهُ كَانَ غَفَّاراً ،يُرْسِلِ السَّمَاء عَلَيْكُم مِّدْرَاراً وَيُمْدِدْكُمْ بِأَمْوَالٍ وَبَنِينَ وَيَجْعَل لَّكُمْ جَنَّاتٍ وَيَجْعَل لَّكُمْ أَنْهَاراً) سورة نوح آية 10، 11 ،12

[10] "I said (to them): 'Ask forgiveness from your Lord, verily, He is Oft-Forgiving; [11] 'He will send rain to you in abundance, 'And give you increase in wealth and children, and bestow on you gardens and bestow on you rivers.' "

COMMITTEE DECISION

This Thesis/Dissertation (Artificial Recharge Assessment of Groundwater through Mekhtan Dam Bani Husheish, Sana'a Basin – Yemen And Ways To Improve It Out Of The Perspective Of IWRM) was Successfully Defended and Approved on 29.01.2009

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DEDICATION

To My Parents

Whom supported me and lights up my life since my birth to this date

To My Uncle Abdulraqeeb

To My Brothers

Mobarak, Mogeeb and Shaker

To My Sisters

To My Wife

&

My Sons Abdullah and Abdurrahman

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Thank you for a.3ll Kindly friends, Natheer, Abdulghanee, Shams, and all who helped me during of this work.

I wish happiness to all of them

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LIST OF ABBREVIATIONS

GDI	General Directorate of Irrigation
GIS	Geographic Information System
GPS	Global Position System
GSMRB	Geological Survey and Minerals Resources Board
IWRM	Integrated Water Resources
JICA	Japan International cooperation Agency
MCM	Million Cubic Meter
MWE	Ministry of water and Environment
NWRA	National Eater Resources Authority
NWSA	National Water Supply and Sanitation Authority
NWSSIP	National Water Sector Strategy and Investment Program
SBWMP	Sana'a Basin Water Management Project
SCS	Soil Conservation Service
TNO-DGV	Institute of Applied Geoscince- Delft, The Netherlands
VES	Vertical Electric Sounding
YOMINCO	Yemen Oil and Mineral Resources Corporation
WEC	Water and Environment center

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ARTIFICIAL RECHARGE ASSESSMENT OF GROUNDWATER

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ABSTRACT

Dams are considered as important water harvesting techniques which are increasingly utilized in Sana'a basin for artificial groundwater recharge. Some of these dams are being used in the absence of systematic management and without implementing effective strategies for water releasing.

For the purpose of this study, Mekhtan dam was selected during the year 2008 as a major goal, Musaibeeh dam have to be mentioned which was not suitable for doing complete study, as it has leakage and water was discharge for maintenance purpose at the time of the study. These dams are located in Wadi Mekhtan within Sa’wan basin (one of Sana’a sub-basins). Significantly, this sub-basin is highly dense with a huge number of wells per square kilometre. With regard to that, this study aims to (1) assess the artificial groundwater recharged by Mekhtan dam. (2) explore the satisfaction of residents, i.e. resided near these two dams, regarding the performance and pros and cons arising from the utilization of these dams. (3) suggest suitable measurements to improve the role of dams and to investigate the community acceptance for these measurements .

Geo-electric method was adopted using vertical electric sounding (VES), hydrological, hydro-geological study (i.e. dams and wells water level monitoring, coefficient of permeability test, and sieve analysis for the sediments in the reservoir's dams). Then, people were interviewed using a questionnaire to evaluate the social aspect in the study.

From the results of this study, it was found that the average amount of infiltrating water from Mekhtan dam was about 37,512 m3/year, representing 42% of the amount of water lost (i.e. evaporation + infiltration) and the average amount of evaporation was about 46,620 m^3/year which represents 58% of the daily water lost from Mekhtan dam. The amount of water infiltrated reduced significantly at the low water level in the dam while the evaporation is prevailing and approximately constant (i.e it changes a little during the periods of computation which was selected in this study). Moreover, the sediments accumulated in the dams reservoir constituting a very fine sediment silt and clay, with low coefficient of permeability. The results obtained from people's interviews revealed that residents who are residing near and at a middle distance from the dams, are satisfied with the current performance of the dams. Conversely, people who are residing at distance more than 1.8 km from the dams are unsatisfied.

The suggested improvement accepted by the majority of people was water discharge from the dams in an equitable manner in order to be used for irrigation purposes. The removal of sediments accumulated in the reservoirs was also recommended. Regarding dams construction in future, subsurface and cascade dams are more suitable for arid and semi arid regions.

CHAPTER ONE

INTRODUCTION

1. Introduction

1.2 General background

Yemen is one of the ten poorest countries in water resources in the world. The annual per capita water share is about 125m^3 (MWE, 2005). This has various reasons: Yemen's location in the south-western part of the Arabian peninsula and within the northern extension of the arid tropical climate, where the amount of evapotranspiration exceeds the rainfall in most situations, but also its high population growth, especially in the north-western highlands, where high population density coincides with increasing urbanisation, expansion of agricultural land use and now also growing industrial and commercial sectors as well as increasing tourism activity. All of these factors lead to overexploitation of groundwater resources, "the yearly total water consumption in the country is 3.4 BCM, renewable resources is 2.5 BCM of it, the annual deficit then is 0.9 BCM" (JICA, 2007).

Sana'a is the capital of Yemen located in the highlands of the central part of Yemen. The population rose from around 1.00 million in 1994 to an estimated 2.14 million in 2008 (based on the 2004 Census under a moderate growth rate of 4.95) and is expected to grow to around 3.44 million by 2020 (JICA 2007). The total area of Sana'a city is about 13,550 km^2 (WEC, 2001). The city faces a critical problem in water resources where "the annual water demand in 2005 reached 269.3 MCM, of which 50.7 MCM is from renewable sources; with the annual deficit being about 218.6 MCM. The water demand is expected to reach to 349.6 MCM by the year 2020" (JICA 2007). In addition, Sana'a faces annual groundwater table drawdown where the total observation wells (wells& springs) recorded is about 13,425 (WEC, 2001) as well as problems associated with wastewater and sanitation. This alarming situation has led to an increased awareness among a large part of the population and across various sectors, creating a desire to implement water management and planning strategies.

Water scarcity in Sana’a for the above-mentioned reasons has led to increase the number of drilled wells and a high reliance on non-renewable groundwater sources, creating a huge gap between abstraction and recharge. "The annual water demand exceeds approximately six times the annual recharge potential" (JICA, 2007).

The government is taking many measures to mitigate water problems and provide fresh drinking water for urban and rural areas with health sanitation. For example, Sana'a Basin together with four other areas has been designated as a protected water area by the Council of Ministers law number 33 in 2002. The establishment of the Ministry of Water and Environment (MWE) in 2003 is also one of the efforts to give the water issue more concern, attention and importance. Other authorities that focus on the water sector include the National Water Resources Authority (NWRA), the Rural Water Supply Authority and the National Water Supply and Sanitation Authority (NWSA). Working in a number of governorates and implementing decentralization policies in order to facilitate their work. The accomplishment of National Water Sector Strategy and Investment Program (NWSSIP) 2005-2009 by the MWE is an important step and serves as an action plan to clearly define the proposed policies to be implemented in order to develop and improve the water sector according to the given priorities.

There are also other measures like concentrating on water harvesting techniques by building many dams for that purpose and for artificial groundwater recharge, to reduce the gap between abstraction and recharge. However, the performance of some of these dams does not meet expectations due to various reasons such as location, maintenance, high evaporation rates etc. Beside that, the absence of good management in some of these dams leads sometimes to conflicts between people living upstream and downstream of the dams. To understand the effects of these dams on groundwater and on the local social and economic situation, various studies and investigations are required to determine hydrology, hydrogeology and social satisfaction. Results of such studies can suggest proper water resources management strategies to improve the role of the dams and other water harvesting techniques in the respective areas.

This study will follow such an approach and evaluate the performance of one dam constructed for the purpose of artificial groundwater recharge and suggest solutions to enhance the management, by researching the social dimension of the dam to find ways of avoid conflicts, realization the benefits of artificial groundwater recharge and suggest appropriate groundwater recharge methods that hope to be taken by decision-makers in future planning.

1.2 Problem statement:

- The high gap between abstraction and recharge will cause water resource depletion in the coming years, while the current solutions have high costs and are not easily implemented (e.g. desalinating water from the Red Sea, at a distance of 150 km to Sana'a and an elevation difference of about 2500 m).
- From the total of 13,425 observation wells (wells and springs) recorded in Sana’a basin, up to 97 wells per square kilometre were recorded in the study area “Wadi Sa'wan” as shown in the map Figure 1.1A (WEC, 2001).
- Many dams are constructed in Sana’a basin for the purpose of artificial groundwater recharge (Figure 1.1B shows all dams in the Sana’a basin). The efficiency of some of these dams is low for the following reasons:
    - Some dams lack previous geological and geophysical studies.
    - The high distance from the dam to the water table.
    - High evaporation rates always exceed the rainfall.
    - No maintenance for the accumulation of clay and silt in the dam reservoirs, decreasing permeability and water infiltration.
    - The bad location of some of these dams: small catchment area or side-seepage of the water, which easily evaporates.
- Absence of other artificial groundwater recharge techniques like subsurface dams, recharge shafts, injection wells, etc.
- Some dams led to conflicts between residents in the upstream catchment areas and those downstream of the dams, reflecting the absence of management and an awareness of the importance of artificial groundwater recharge.

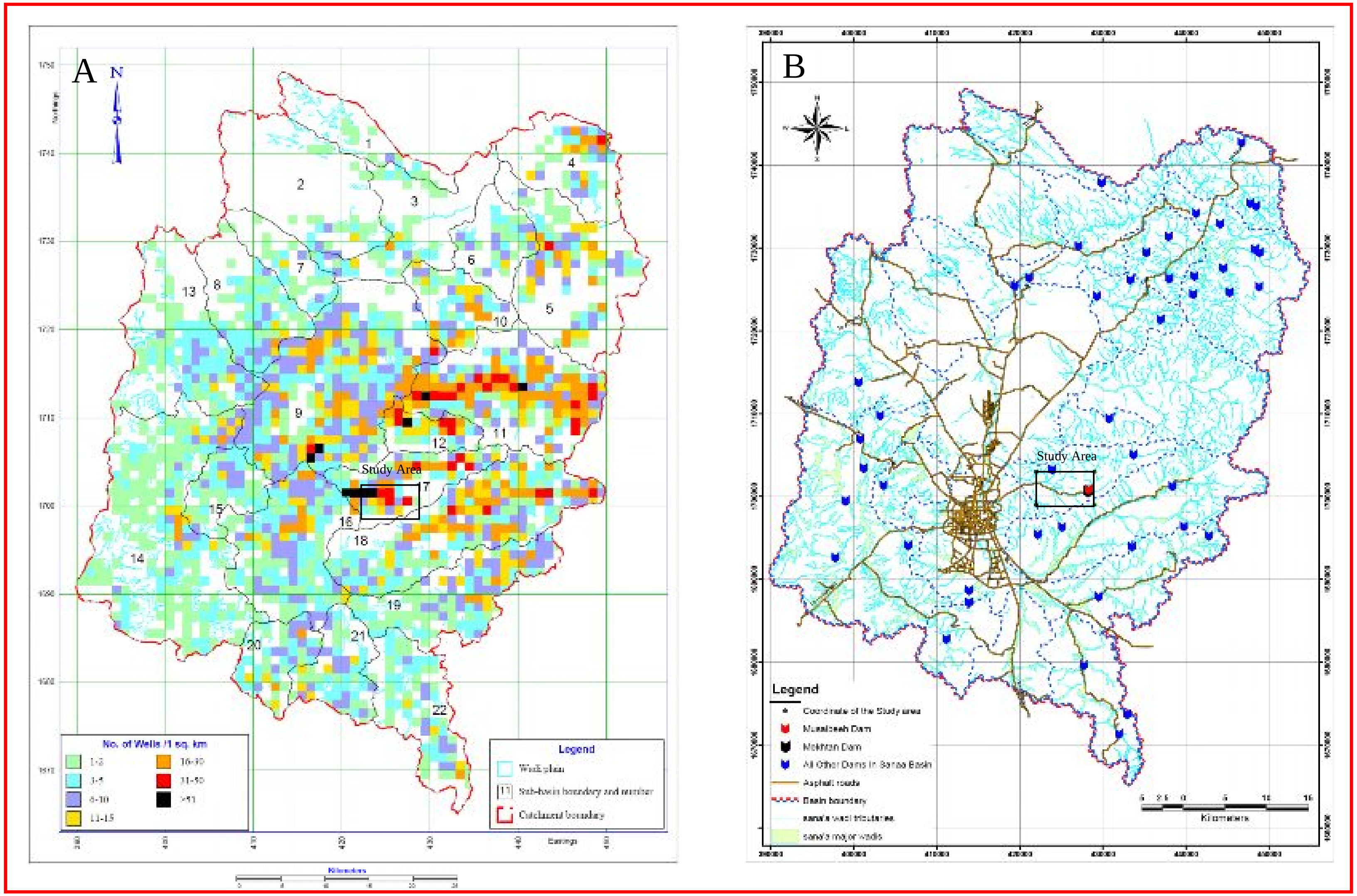


Figure 1.1 (A) Number of wells per km^2 (WEC, 2001), (B) Location of the existing dams in Sana’a basin (SBWMP, 2008)

1.3 Connecting to Integrated Water Resources Management (IWRM)

This study tries to concentrate on the three aspects of IWRM as seen in Figure 1.2. IWRM is most commonly defined as "a process, which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital eco-systems" (Global Water Partnership, 2000).

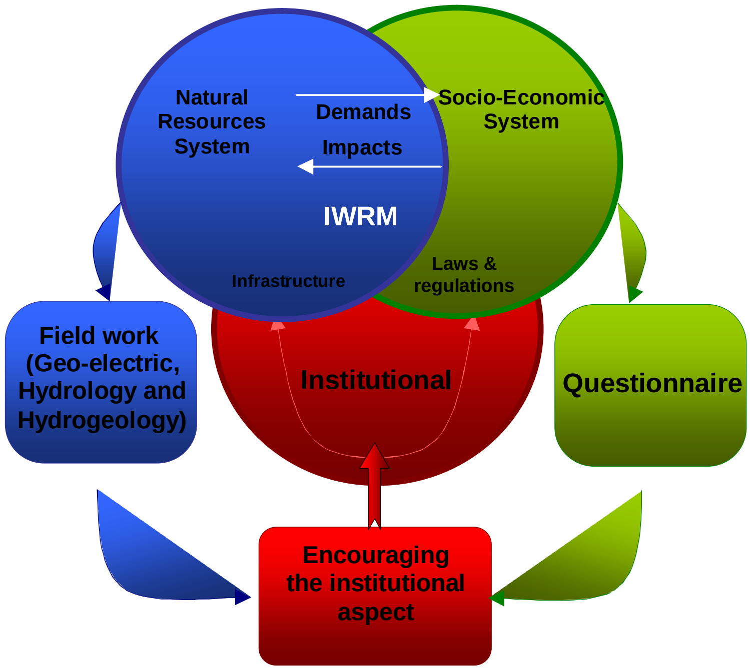


Figure 1.2 Relating this study to the concept of IWRM (Modified after Global Water Partnership, 2000)

This will be achieved by studying the aspects of sustainable water resources and evaluating the role of dams established for the purpose of groundwater recharge (which, if successful, is a way of contributing to the sustainability of water resources by balancing the amount of water extracted with the amount recharged to the aquifer) and by studying the possibility of using other methods of water harvesting, their effectiveness and ways of improving their performance to the maximum efficiency.

The importance of artificial groundwater recharge is also to achieve the principles of IWRM and avoid compromising the sustainability of vital eco-systems. With regard to aspects of tectonic structure, for example, the decline of earth layers and the collapse of rock masses can occur as a result of overexploitation of water without maintaining the balance between extraction and recharge, which leads to resource depletion and increased risk of landslides in the affected areas, which in turn can result in the destruction of buildings and vital infrastructure.

This study focused on both scientific and socio-economic aspects. In the scientific aspect, a geo-electrical field survey will be carried out to determine the nature of rock formations on which the dams were constructed and whether or not they allow infiltration to the aquifer. Hydrological and hydrogeological studies monitor water levels in the dams' reservoirs and in wells near the dams, comparing the amount of vaporized water with the amount that is supposed to infiltrate to recharge the aquifers.

The socioeconomic aspect of this study fills the gap between the knowledge of and the practical application on the ground of the principles of IWRM. Through interviewing people up- and downstream of dams with a questionnaire, the possibility and the acceptance of the application of those solutions are studied, as well as the social and economic impact. For example, dams for artificial recharge is one of the solutions implemented in the study area, but its efficiency on the ground in terms of scientific, economic and social aspects is largely unknown. The questionnaire was distributed to three groups of people: those directly downstream of the dams, those a middle distance away from dams and those far from the dams.

The results from the scientific field study and the socio-economic study will then be used to reach to the third link in IWRM (see Figure 1.2), which is the role of concerned institutions that can contribute to improving the situation through legislation by seeking to implement IWRM principles as well as by strengthening the infrastructure required in the region.

1.4 Study Area:

1.4.1 Location of the study area:

Sana'a basin has an area about 3250 km^2 with an elevation of 2200 m.a.s.l in the plane, surrounded by mountains from the west, south and east, with elevations between 3000 and 3700 m.a.s.l (Jabal Annabi Shu'ayb). The lowest altitude is about 1900 m.a.s.l in the north at Wadi Al Kharid. Hydrologically, the Sana'a Basin can be divided into two units, an upper (northern) unit and a lower (southern) one. These units are referred to as Wadi Al-Kharid Hydrological Unit and Musyareka Hydrological Unit respectively and on the basis of surface water drainage systems and topography, a total of 22 sub-basins have been identified as illustrated in Figure 1.3 B (WEC, 2001).

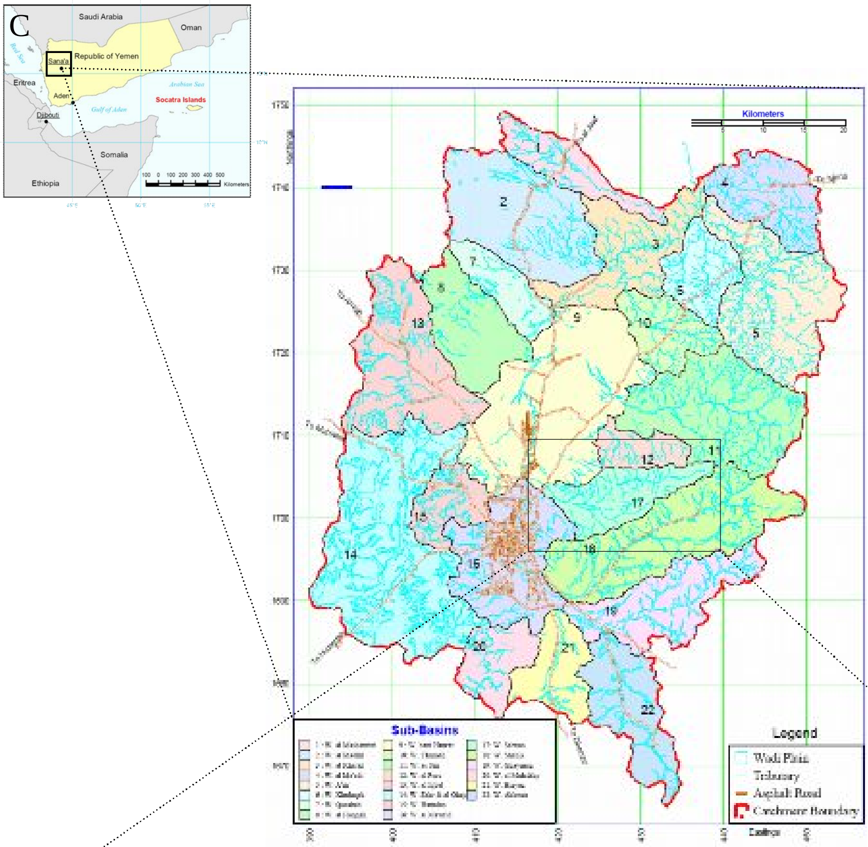
The study area is located in one of these sub-basins by the name of Wadi Sa'wan and includes the Mekhtan dam in Wadi Mekhtan and Musaibeeh dam (a small dam). The study area has coordinates between 1,699,000N to 1,703,000N and 422,000E to 429,000E.

The important villages in the area are Mekhtan and Al-Khiraba, within the Bani Hushaish district in the central part of Sana'a basin, toward the SE (15.6 km asphalt road from Sana'a city) as can be seen in Figure 1.3 A, B and C. The most important catchment areas are Wadi Mekhtan and Wadi Sa'awan.

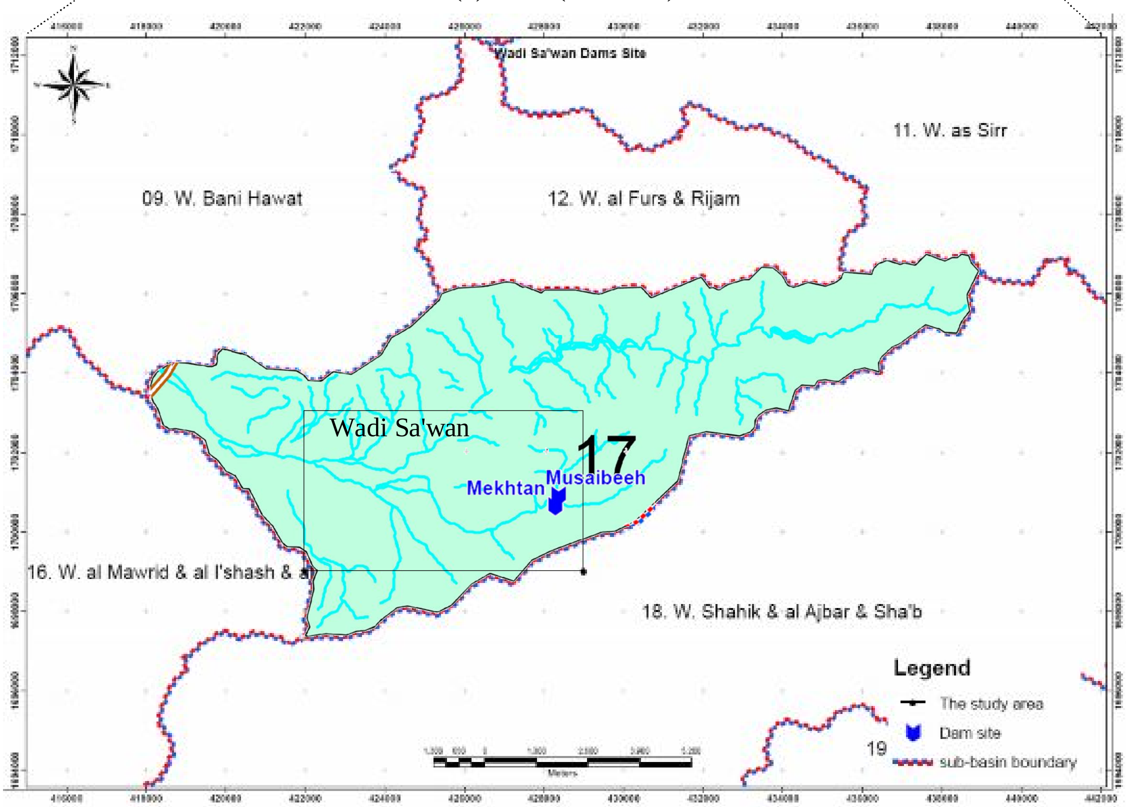
The population in the study area is about 100 capita in Mekhtan village (GDI, 2001) and about 3371 in Al-Khirbah village (Census, 2004). Table 2.3. shows more details about Al-Khirbah population.

Table 1.1 Demographic Situation of Al Khirbah Village - Census, 2004 (Alga'fari, 2007).

Recent Population			Households No.	Families No.	Av. No. Person/Family	Av. No. Person/Households
M	F	Total	471	471	7.2	7.2
1678	1693	3371				



(B) Source: (WEC, 2001)



(A) Source: SBWMP , 2008

Figure 1.3 Location of the study area

1.4.2 Topography of the study area:

The study area of Wadi Mekhtan is characterised by tough topography, especially at the top of the valley beside the dam, where the wadi is narrow near the dam and surrounded by high mountains with elevations reaching to 2800 m, which is about 400m higher than Mekhtan and Musiabeeh dams reservoirs. The highest elevations of these mountains are in the area, where Wadi Mekhtan runs toward the west into Wadi Sa'wan.

The topography further downstream the wadi becomes wider, consisting of alluvial plains toward Wadi Sa'wan, with decreasing elevations reaching to about 2260 m.a.s.l and increasing thickness of sediments.

1.4.3 Geology setting:

In general the geological setting of Sana’a basin and the stratigraphic column begins like most Yemeni stratigraphic units from **Precambrian Basement Rocks** which were “observed from subsurface data in the Arhab and Al-Hitarish wells, which represent the deepest wells drilled in Sana’a basin” (SAWAS, 1996), overlain by various younger rocks, **Phanerozoic rocks**, marine and continental sediments and volcanic rocks. Sana’a basin represents the following six geologic rock:

(1) Kohlan Group Sandstone, ranging in age “from lower to middle Jurassic” (Bydoun, 1982), observed from subsurface data such as in Arhab and Hatarish wells (SAWAS, 1996).

(2) Amarn Group Limestone, which consists mainly of limestone and gypsum with intercalated shales in some interval horizons, such as in Wadi Al-Ahjur. The map in Figure 2.1 shows this rocks exposed in the north part of Sana’a basin and some in the west. The thickness of this group ranges from 320 m in the northern part of the basin, decreasing southward to about 100 m near the basin boundary. This group’s age ranges from middle to upper Jurassic, was determined by Geukens, (1966) and Al-Anbaawy, (1984). (WEC, 2001).

(3) Al-Tawilah Group Sandstone, which is exposed in a large area around Sana'a city, ranges in age from late Cretaceous to Eocene, with a total thickness reaching more than 400 m. It has been divided into two formations, the Gharas formation for the lower part and the Medjzir formation for the upper part (WEC, 2001).

(4) Tertiary Volcanic Rocks, which form the Yemen Plateau, reach to more than 3660 m above sea level. It is from the Oligocene-Miocene age and has a thickness in excess of 2000 m in some places. The geological map in Figure 1.4 shows the exposure of this group, which dominant in the southern part and simple exposure in the north east of Sana'a basin.

(5) Quaternary Volcanic rocks occur widely around the Sana'a area and more commonly to the northern part, as seen in the geological map Figure 1.4. Their age has been determined at about 5 million years. Two types of eruptions can be recognized within these quaternary volcanic rock formations. The first eruption involves the cinder cones, which are found in the northern part of the Basin and further north. The second is the lava sheet rocks that occur along the Sana'a-Amran road.

(6) Quaternary Sedimentary Deposits shown in the geological map in Figure 1.4, consist of mainly alluvial materials and conglomerates, which reach a thickness of more than 30 m in middle of the Basin, such as in the Sana'a University campus (WEC, 2001). Some of these groups are exposed in parts of Sana'a basin and are also found at subsurface levels of varying depths from area to area. Figure 1.4 shows these rocks exposed at the surface.

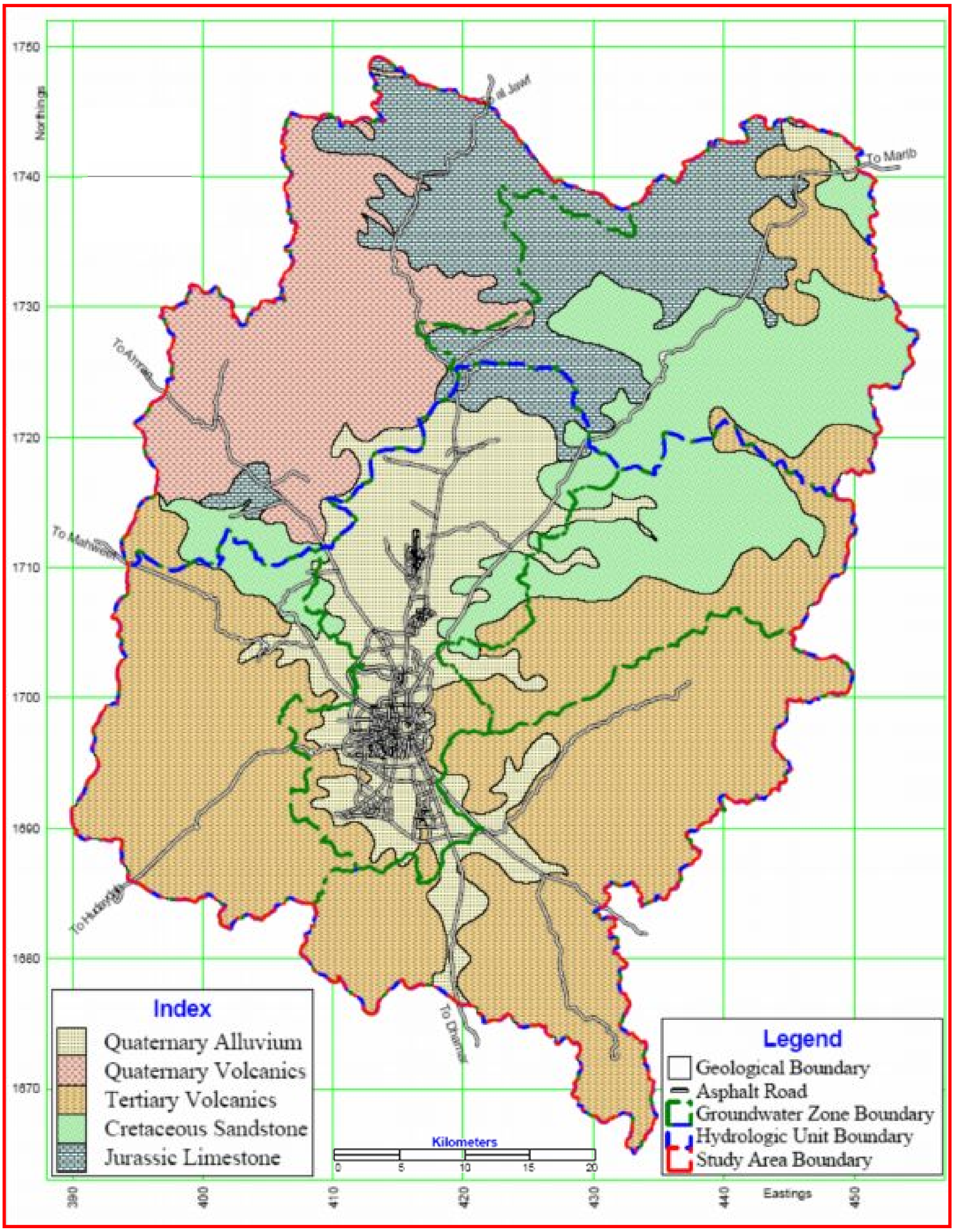


Figure 1.4 Geological map of Sana'a basin (SAWAS, 1996)

The geology of the study area located within Bani Hushaish district in the eastern part of Sana'a basin (as shown in the geology map in Figure 1.5) represents the following stratigraphic sequences from lower to upper**:**

1) Cretaceous Al-Tawilah Sandstone Group is not exposed on the surface in the study area. It is found at different depth below the earth surface. **Tawilah Sandstone** is only exposed in the northern part of Bani Hushaish, outside the study area.

2) Tertiary Volcanic rocks

According to new study of Sana’a basin done by SBWMP (2008), based on the previous study, the tertiary volcanics group in Sana'a Basin has been subdivided into five units from older to younger as below:

1- **Lower Basalt and Lahima Volcaniclastics**
2- **Lower Acidic Volcanics and Sediments**
3- **Middle Basic Volcanics**
4- **Upper Basic Volcanics and**
5- **Middle Acidic Volcanics**

The term Yemen volcanic group replaces the former name, Trap Series, as recommended by Geukens (1966). The geological map in Figure 1.5 shows the presence of Yemen volcanic group exposed and covering most of study area. It consists of basic and acidic volcanic rocks, rhyolite tuff and basalt rocks. The exposed units in the study area and around the study area from older to younger are: (1) Lower Acidic Volcanics and Sediments, which is dominant in all parts of the study area (2) Upper Basic Volcanics found in some parts east of the study area (3) the oldest unit found out of the study area in the north west direction is Lower Basalt and Lahima Volcaniclastics. This volcanic group is made up mainly of alternating lava flows (basalts, andesites, or trachyte porphyries), and different types of tuffs.

3) The Quaternary Alluvial Deposits:

The geological map in Figure 1.5 indicates the unconsolidated quaternary deposits in the central and western part of the study area, formed of Wadi Sa'wan beds, and some part in the north, formed of Wadi Al-Rawnah. It consists of silt, clay, silty sand, gravel and boulders of different thickness; the lowest thickness is near the dams, where the volcanic rocks are exposed on the surface. The thickness increased downstream the dam toward Al-Khirbah village and Wadi Sa'wan.

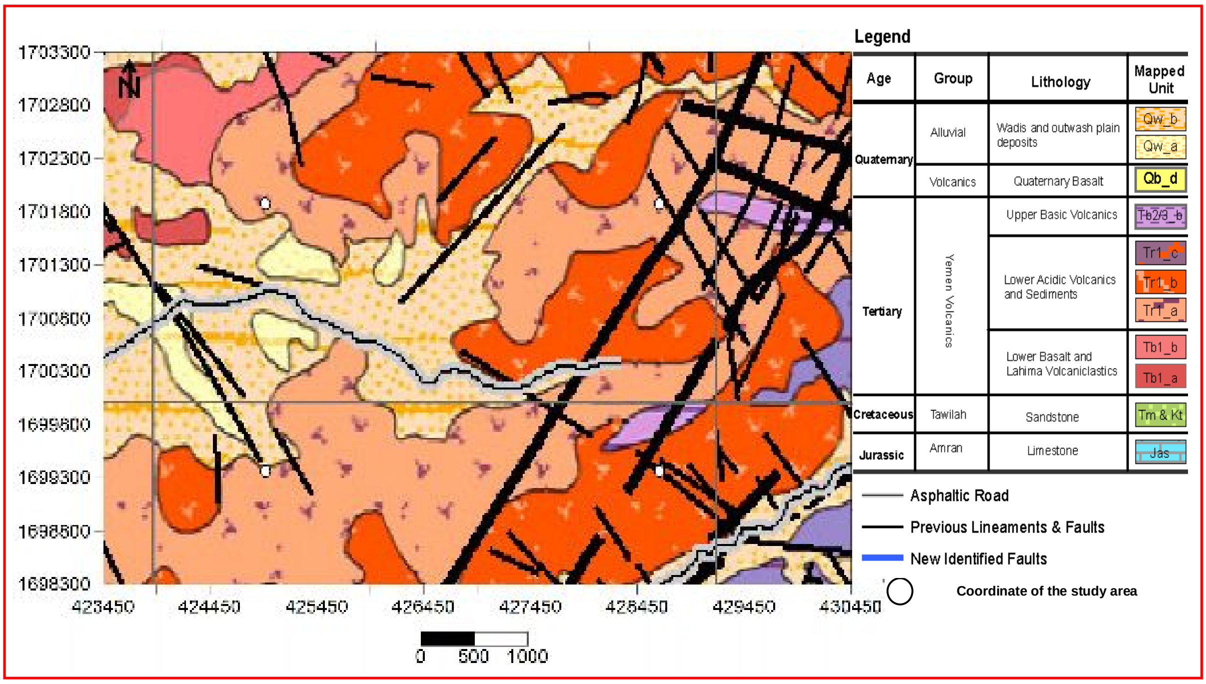


Figure 1.5 Geological map of the study area (SBWMP, 2008)

- Structure:

The tectonic movement associated with the opening of the Red Sea (Red Sea fault) and the tectonic uplift in the Mersozoic time, associated with volcanic activity, affected the area. The geological map in Figure 1.5 shows major faults in the eastern part of the study area, having a NE-SW direction and other small faults with trend approximately parallel to the Red Sea rift system. Wadi Mekhtan and Wadi Sa'wan are developed along these faults.

1.4.4 The dams in the study area:

In the study area there are two dams (Mekhtan and Musaibeeh), but the assessment of groundwater recharge was only done for Mekhtan dam (computation of the dam's water balance), because the other dam was unsuitable, as it has leakage and water was discharged for maintenance purpose at the time of the study. However, it is mention below, in order to give complete information about the study area.

- Mekhtan dam

The dam is located in Wadi Mekhtan at an altitude of 1,700,643N and longitude of 428,224E, with an elevation of 2421.5 m.a.s.l (at the bottom). The map in Figure 1.6 shows the dam location with its catchment area and the satellite image and some photos in Figure 1.7 show the shape of the dam. Constructed in 1999, the dam is of earth fill type, with a maximum height of 25 m and a top-length of 104m with capacity at full reservoir level of 550,000 m^3 and 700,000 m^3 at maximum reservoir level. The catchments area is 5.1 km^2. There are two steel pipes outlet with capacity 8$^{//}$ (8 inches) located in the wadi's centre. (GDI, 2001)

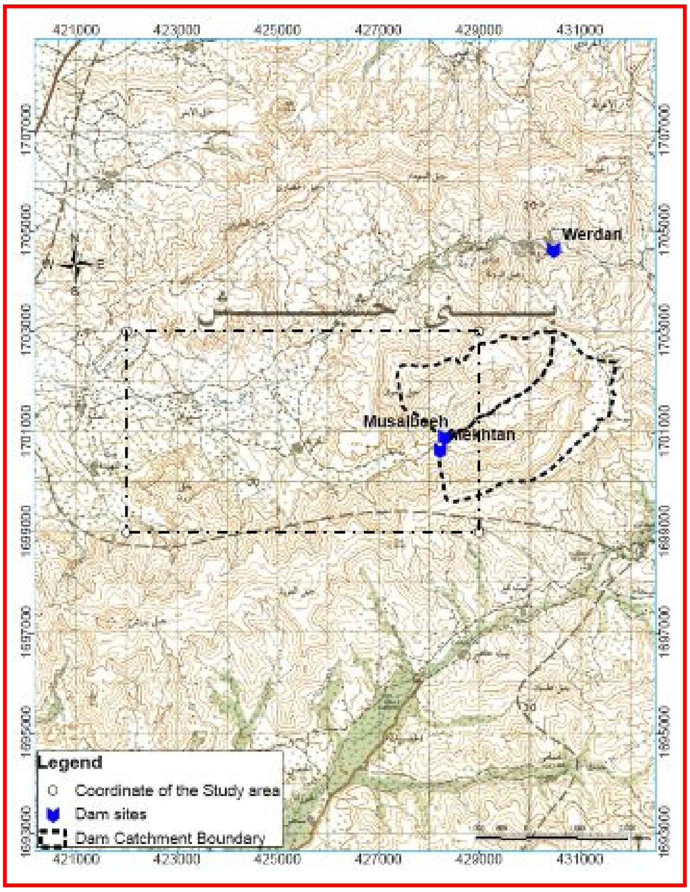


Figure 1.6 Mekhtan and Musaibeeh dams with their catchment areas. (SBWMP, 2008)

- Musaibeeh dam:

The dam is located in Wadi Mekhtan at an altitude of 1,700,913N and a longitude of 428,298E, with an elevation of 2422.5 m.a.s.l. The map in Figure 1.6 shows the dam location with its catchment area and the satellite image and some photos in Figure 1.7 show the shape of the dam. The dam was constructed in 2001 and is of concrete type with a maximum height of 16 m, while the length of the dam at the top is 70 m and the width at the top is 2 m. Capacity at full reservoir level is 156,000 m^3. There is a steel pipe outlet located in the wadi's centre. (GDI, 2001)

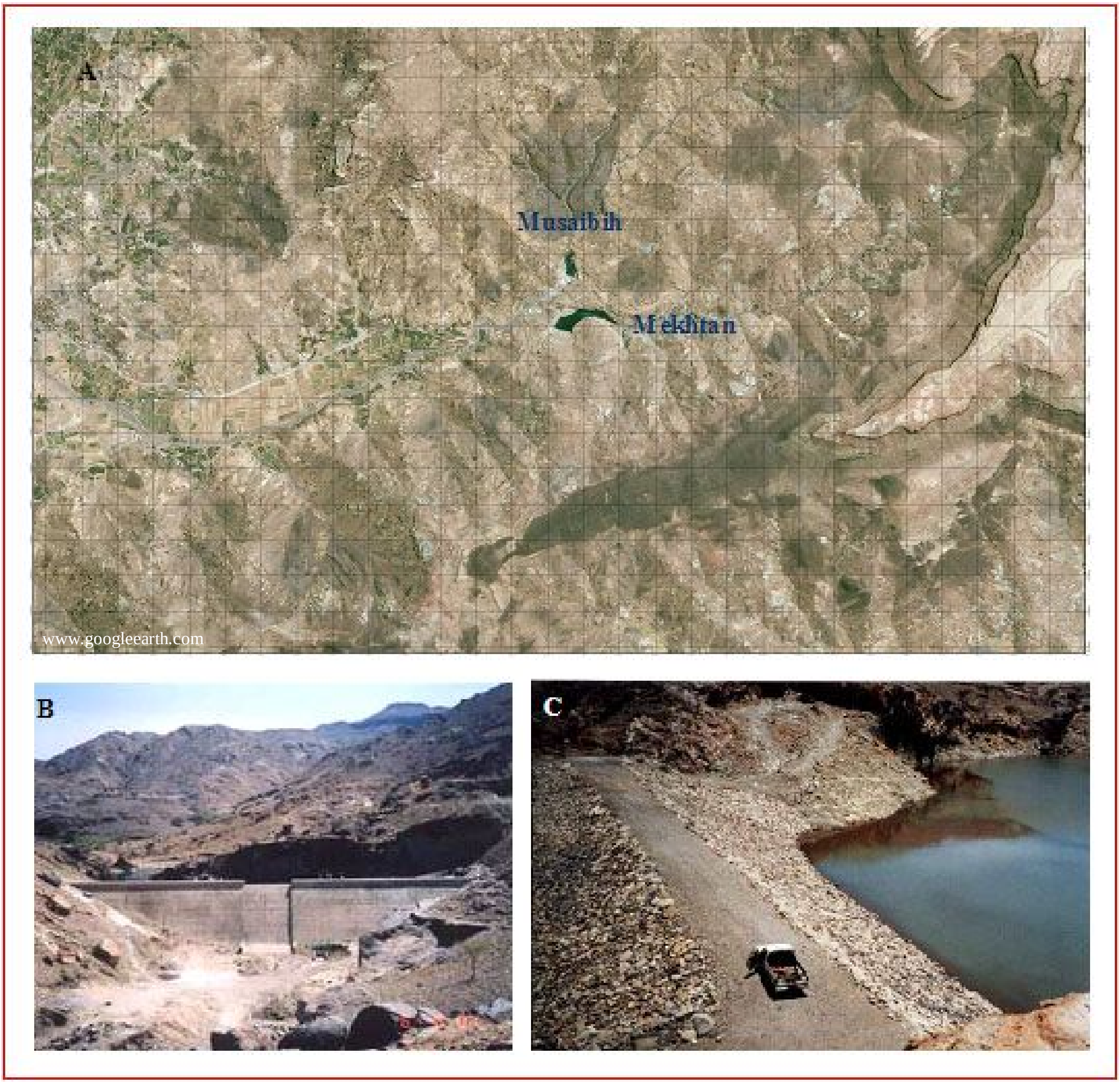


Figure 1.7 (A) Satellite image of Mekhtan and Musiabeeh dams, (B) Photo of Musiabeeh dam. (C) Photo of Mekhtan dam.

1.5 Objectives of this study:

- To evaluate the possibility of artificial groundwater recharge by the dam in the study area and to determine measures to enhance it.
- To study the ability to implement other techniques, such as injection wells, recharge shafts or others.
- To evaluate the extent of community acceptance of the idea of groundwater recharge through the dam and its advantages and disadvantages.
- To evaluate the possibility and acceptance of other artificial groundwater recharge methods, such as subsurface dams and injection wells or similar techniques.

1.6 Methodology

1.6.1 Geo-electrical study:

The aim of the geo-electrical field survey is to provide additional geological and hydrogeological information about the subsurface structures required for artificial groundwater recharge, such as the following:

1- The type of geological formations under the constructed dams and downstream of the dams. Is it suitable for groundwater artificial recharge and what are their properties (Granular, fissured, karstic or massive and compact rocks)?

2- The types of aquifers and their thickness.

3- The thickness of the unsaturated zone (top soil).

4- The depth to water table in shallow aquifers.

5- The subsurface structure.

6- The depth to the saturated zone and its thickness.

A total of 10 investigation si3tes were conducted by using vertical electrical sounding technique (VES). A Schlumberger array was chosen in the field procedure, with half

Table 1.2 Summarize of geo-electric survey (VES) in the study area

No.	Coordinates		Elevation m.a.s.l	AB/2 (m)
	UTM-E	UTM-N		
1	427875	1700666	2403	300
2	427036	1700394	2387	700
3	426899	1700435	2365	600
4	426668	1700233	2397	800
5	426042	1699996	2380	800
6	425460	1700903	2300	700
7	424358	1701015	2319	900
8	424340	1700458	2340	600
9	423695	1700932	2390	700
10	422943	1701863	2307	700

spacing between current electrodes ranging from 300 to 9000 m, Table 1.2 summarizes the geo-electric investigation in the study area.

The field measurements of the vertical electrical sounding were taken as follows:

1- The location and the direction of fixed central points of this survey were determined by using Global Positioning System (G.P.S).

2- The total lengths of the profiles were taken according to the required estimated depths and the nature of the area. The difficult topography as well as a lot of vegetation cover was an obstacle to increasing the length of investigation in some locations. The map in Figure 1.8 shows the locations of the geo-electric field survey and the topography of the study area.

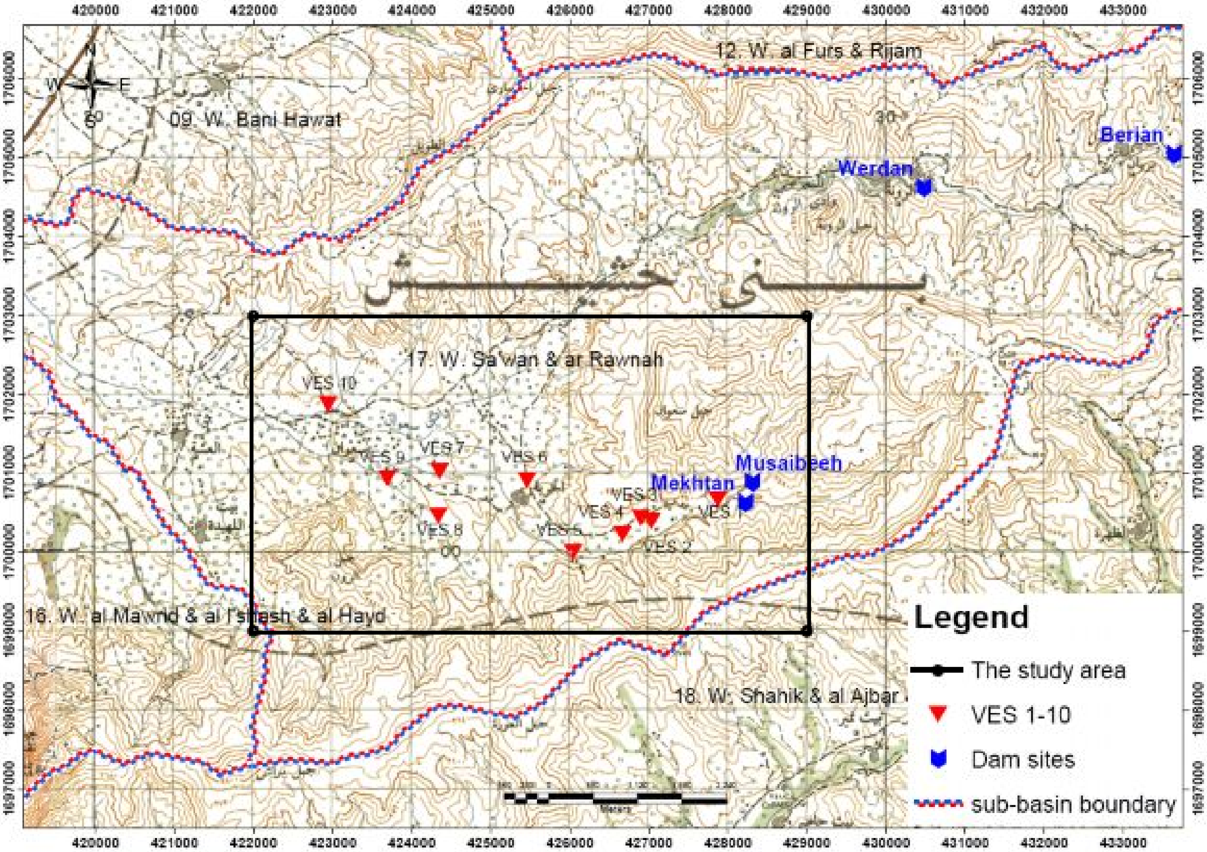


Figure 1.8 Locations of the geo-electric investigation sites (VES's) in the study area (SBWMP, 2008)

1.6.2 Hydrology and hydrogeology monitoring:

- Monitoring of water levels in the dams and wells

Calculating the quantification of the water infiltrated to the subsurface aquifers requires doing hydrologic modelling. However, the process of hydrologic modelling requires large amounts of hydrological and climatic data such as records of rainfall for long periods of time, runoff flows, temperature, wind speed, evaporation as well as other information regarding the form and topography of the study area and also the type and characteristics of the soil. Because not all of this information was available (for example, there is no runoff gauge to measure the runoff flows in the wadis and no evaporation pan), the water levels in the dams and two wells near the dams were measured for short periods. Combined results of this with previous monitoring data allowed for calculating the quantification of infiltrated water by using the dams water balance method in a specific way that reduces the required parameter that are missing.

- Coefficient of permeability and sieve analysis test of the accumulated sediments in the dams' reservoirs

Coefficient of permeability test of the accumulated sediments in the reservoirs (10 cm depth) of Mekhtan and Musaibeeh dams was done to estimate the effect of those sediments on artificial recharge (infiltration) and to compare the coefficient of permeability of wadi deposits with those sediments. A sieving analysis was also done in order to know the type and size of grains in the accumulated sediments for the same samples .

1.6.3 Questionnaire

Carrying out a study using a questionnaire to interview a relevant portion of the people living within the catchment area and close to the dam sites, evaluate the social and cultural acceptance of artificial recharge and generate ideas on how to increase the acceptance on district level and on the political level. The questionnaire extracted the following information:

- The social activity and environmental situation in the area around the dams.
- Activities directly or indirectly related to the dams, e.g. water tanker business, small farming irrigation with submersible pumps or suction pumps
- The social and economic impact of the dams and the impact of future activities like artificial recharge.

1.6.4 Analysis and interpretation

By using available computer software such as the Geo-electrical interpretation program, GIS 9.2, Surfer8, Graf4win and Excel, profiles and maps were drawn, e.g. groundwater level map, geology and geo-electric cross section etc.

This study contains five chapters as follows:

- Chapter 1: Introduction.
- Chapter 2: Literature Review.
- Chapter 3: Hydrology and Hydrogeology.
- Chapter 4: Geo-electric field survey.
- Chapter 5: Analysis and Results.
- Chapter 6: Conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEWS

2.1 Study area and Sana'a Basin

Though no studies were specifically done on the study area, many studies have been made on the whole Sana'a basin, of which the study area is an integral part, with almost the same hydrological and hydrogeological characteristics.

Many studies have been done about Sana’a basin since 1970. The first study that focused on water and geology of Sana’a basin was done by Italconsult in 1973, after which several studies followed. More recently, the Water and Environment Center (WEC) did a study in 2001, Japan International Cooperation Agency (JICA) in 2007 and in 2008, the Sana’a Basin Water Management Project (SBWMP) and carried out with Hydrosult Inc, conducted a detailed study on the Sana’a basin, using the results of previous studies and filling the information gaps to get a more complete picture of Sana’a basin.

The JICA (2007) study dealt with water resources management and rural water supply improvement, as part of the Water Resources Management Action Plan for Sana'a basin in 2007 and carried out by Japan Techno company, LTD (JICA). It focused on the current water consumption and forecast the future increase in water demand and suggested various scenarios to reduce water demand in order to avoid water depletion as a result of the gap between water abstraction and groundwater recharge. Figure 2.1 shows the water demand from year 2005 and the forecast until 2020 and the effect of each demand reduction scenario. The scenarios aim to reduce water losses through water transportation, increasing the agricultural irrigation efficiency and reducing water consumption to the greatest degree in the agricultural, industrial and tourism sector. Table 2.1 summarizes these scenarios.

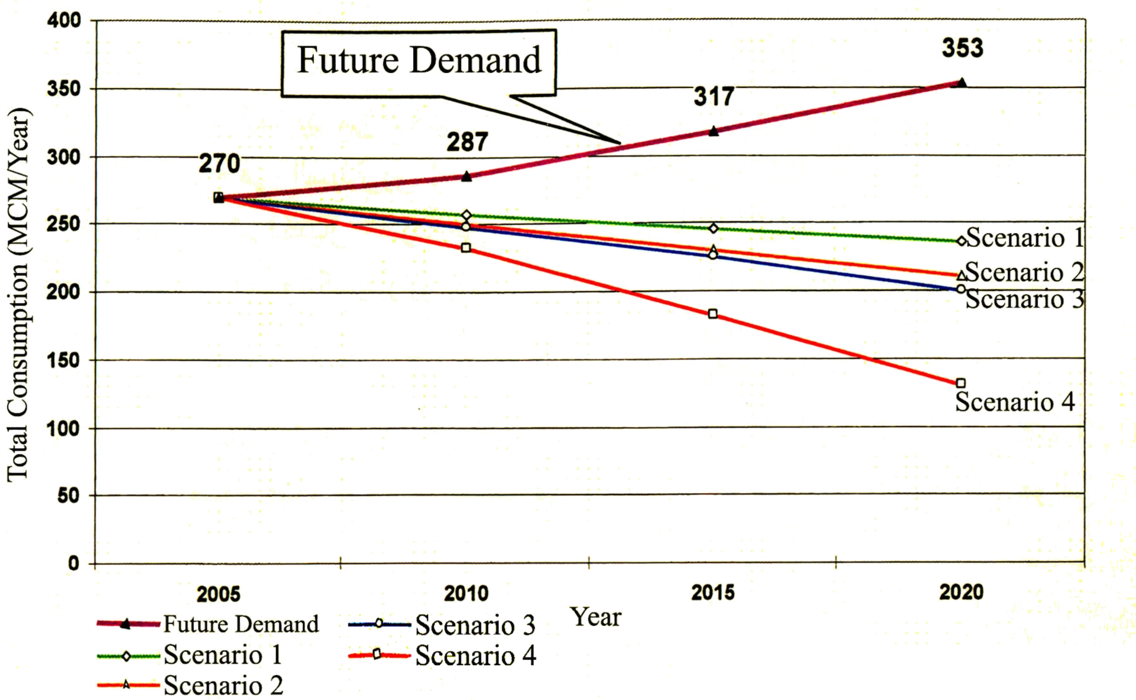


Figure 2.1 Scenarios for water demand 2005 – 2020 (JICA, 2007).

Table 2.1 Summarized scenarios of water demand (JICA, 2007).

	Urban Area Water Supply (Domestic and Institutional)	Domestic Use in Rural Area	Industrial Use	Touristic Use	Irrigation Use	Total[*8)] Consumption
Scenario 1	Population: 3,198,573 LPGR[*1)] Physical Loss: 14.6 MCM (20%)[*2)] Unit water consumption : 35 l/c/d[*3)]	Population: 437,532[*5)] Unit water consumption: 20 l/c/d[*5)]	Historical growth rate, DPPR[*6)]	Based on DPPR	No expansion of irrigated area since 2005 IE: 60%[*7)] Actual requirement: 83.68 MCM/year	*232.3*
MCM/year	**73**	**3.2**	**9.5**	**7.1**	**139.5**	
Scenario 2	Population: 3,198,573 LPGR Physical Loss: 10.3 MCM (15%)[*4)] Unit water consumption: 35 l/c/d	Population: 437,532 Unit water consumption: 20 l/c/d	Historical growth rate, DPPR	Based on DPPR	No expansion of irrigated area since 2005 IE: 70% Actual requirement: 83.68 MCM/year	*208*
MCM/year	**68.7**	**3.2**	**9.5**	**7.1**	**119.5**	
Scenario 3	Population: 3,198,573 LPGR Physical Loss: 10.3 MCM (15%) Unit water consumption: 35 l/c/d	Population: 437,532 Unit water consumption: 20 l/c/d	No growth in Industry inside the Basin since 2005	No growth in Tourism inside the Basin since 2005	No expansion of irrigated area since 2005 IE: 70% Actual requirement: 83.68 MCM/year	*196.6*
MCM/year	**68.7**	**3.2**	**4.8**	**0.4**	**119.5**	
Scenario 4	Population: 3,198,573 LPGR Physical Loss: 10.3 MCM (15%) Unit water consumption: 35 l/c/d	Population: 437,532 Unit water consumption: 20 l/c/d	No growth in Industry inside the Basin since 2005	No growth in Tourism inside the Basin since 2005	Reduce 11,111 ha of irrigated area out of 18,954 ha Install improved irrigation system for 7,843 ha	*127.1*
MCM/year	**68.7**	**3.2**	**4.8**	**0.4**	**50**	

*1) LPGR: Limited Population Growth Rate set in Sana'a Water Supply and Sanitation Project (SWSSP).
*2) Physical loss, 20% is set in SWSSP.
*3) Option 1 set in SWSSP, Minimum option, water is supplied of entire city population.
*4) Physical loss, 15% is set by the Study team.
*5) Population growth rate in rural area: 2.5% adopted by GARWSP and unit water consumption, 20 l/capita/day adopted by NWRA.
*6) Calculated value based on the Socio-economic development plan for poverty reduction (DPPR, 2006-2010)
*7) Irrigation efficiency.
*8) Total consumption includes loss of water supply and overuse in irrigation.

The Geological Survey and Minerals Resources Board under the Yemeni – German Thematic Mapping Project (2004), published the Geological Description of Sana'a Basin Dams, the main objectives of which were a geological description of the Sana’a basin dams and to determine the thickness of precipitates in some chosen dams. Results of this study have shown that some dams have accumulated considerable amounts of thick mud in their reservoirs, as a result of which the recharge of groundwater was reduced. Other dams showed damages in parts of the dam’s body, such as cracks leading to leakages, or the reservoir floor was found to be of solid rock, leading to much of the water evaporating and in some cases the selection of the dams’ locations did not comply with geographical, geological, geophysical, geotechnical and environmental studies .

Sufian *et al*. (2006), in their study (proposal study) “Water for Sana’a and Taiz’z from Solar Desalination”, proposed that of all the options for resolving Sana’a’s imminent water crisis that have been investigated “the only lasting solution we found to be seawater desalination using solar energy. There are 2 fundamentally different options: (1) the desalinated water is pumped to Sana’a (the “Saving Sana’a solution”) or (2) The vast majority of Sana’a’s population is relocated to the coasts (the “Sana’a relocation solution”)" (Sufian et al, 2006). Figure 2.2 shows the possible routes for a water pipe line from the red sea coast to Sana'a city and table 2.2 summarize the costs of the two options.

Table 2.2 The cost of suggested solutions for Sana’a water supply

Saving Sana’a option Pumping 1 BCM water for 2.1 Million people (or more) from Red Sea to Sana’a		**Sana’a Relocation option** Move 2.1 Million people (or more) from Sana’a to new settlements at the coasts	
Item	Cost (Billion $)	Item	Cost (Billion $)
Pipeline	3	Housing	12
Solar power plant for pumping	3	Community infrastructure	23
Total	6	Total	35

Source: (Sufian, *et al*, 2006)

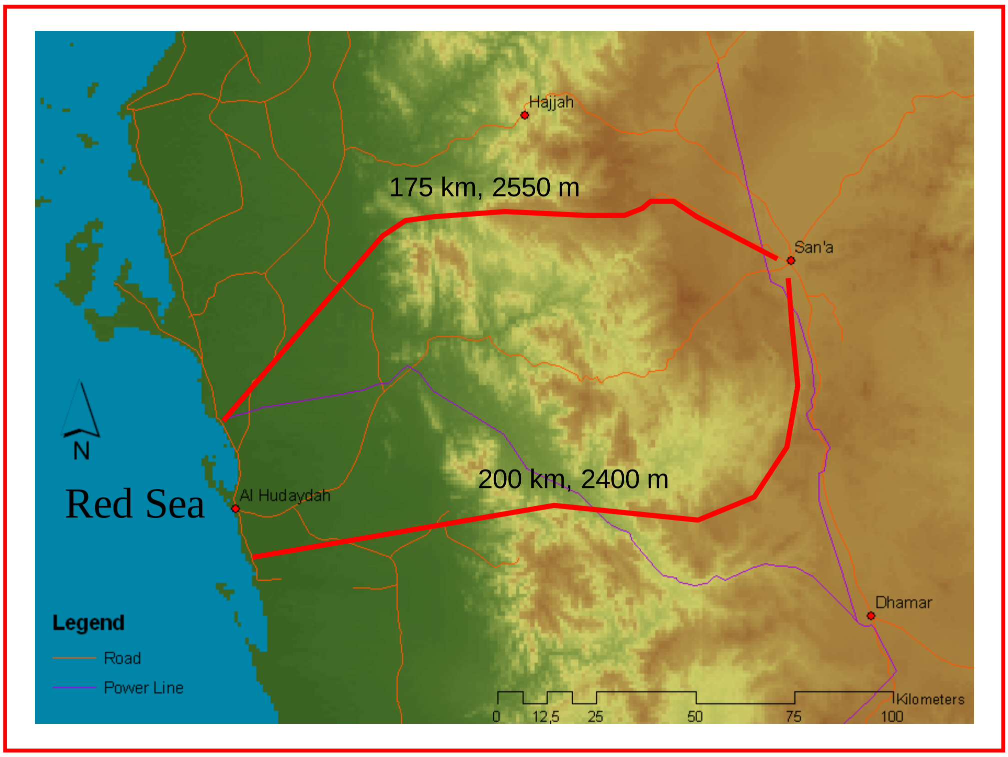


Figure 2.2 Sana'a city and the possible routes for a water pipe line. (Kern, 2005)

2.2 Groundwater recharge studies

The studies on groundwater recharge (artificial or natural) have takes many different approaches to estimate or evaluate the groundwater recharge. Some use hydrological and hydro-geological modelling, others measure soil moisture and subsurface temperature, while again others use geo-electric measurements to determine subsurface geological and hydro-geological structures required for artificial groundwater recharge and also to suggest the best locations for injection wells to enhance artificial groundwater recharge.

Alawneh (2003) studied groundwater recharge modelling using Wadi Bayer as case study. He addressed the natural recharge and the effectiveness of the currently constructed dike by using

(1) Hydrological analysis and models and collection of climatic data (daily, monthly, annual rainfall, temperature and evaporation). He used different techniques

and models, such as HEC-HMS, and the SCS method-curve number method for an evaluation of the collected data. In order to make runoff estimations, he studied soil type, other exposed rock formations and catchment characteristics.

(2) Hydrogeological conditions. Alawneh (2003) used a Processing Mod flow model in order to determine the suitability of aquifers for natural recharge and to quantify the infiltration rate. He also made permeability tests for 15 m top soil. Some of his results revealed that the permeability of the upper 2 meters, which form the floor of the reservoir, is 11.82×10^{-2} cm/sec and for other depths (5-15m) the permeability ranges between 1.805×10^{-3} and 7.331×10^{-6} cm/sec. From the ground water model it was found that the natural recharge in the area is due to the flood water runoff filling the reservoir. For a 30 day and 15 day retention period it was found that the groundwater table will rise in the range of 0.33 to 1.5 m and 0.11 to 0.90 m for the two retention periods respectively.

Zunic, et al. (2001) conducted infiltration tests to enhance the efficiency of groundwater recharge dams in the Batinah region of northern Oman by using field tests from downstream the Wadi Ahin dam. An artificial rectangular infiltration basin (11m x 3.5m) 4 km downstream of the dam was constructed and 11 bore holes were drilled with tensiometers and temperature probes installed at different depths reaching to 20 m, in order to measure the soil moisture. Another bore hole was drilled to 30 m depth to take soil samples and to install pizometers for measuring the groundwater level as shown in figure 2.3. During the infiltration test, it was found that 550 m^3 of water infiltrated within four days (137.5 m^3/day). The velocity of infiltration varied from 5 to 80 cm per hour. Note that the hydraulic permeability of the soil was determined in the range of 10^{-4} to 10^{-5} m/s, while the cemented gravel layer has a permeability of approximately 10^{-7} m/s and the groundwater level lay at a depth of about 23 m during the test period.

Another result of this study was that the efficiency of groundwater recharge increases with (1) the moisture content of soil, (2) the water level of the surface flow and (3) with time of infiltration.

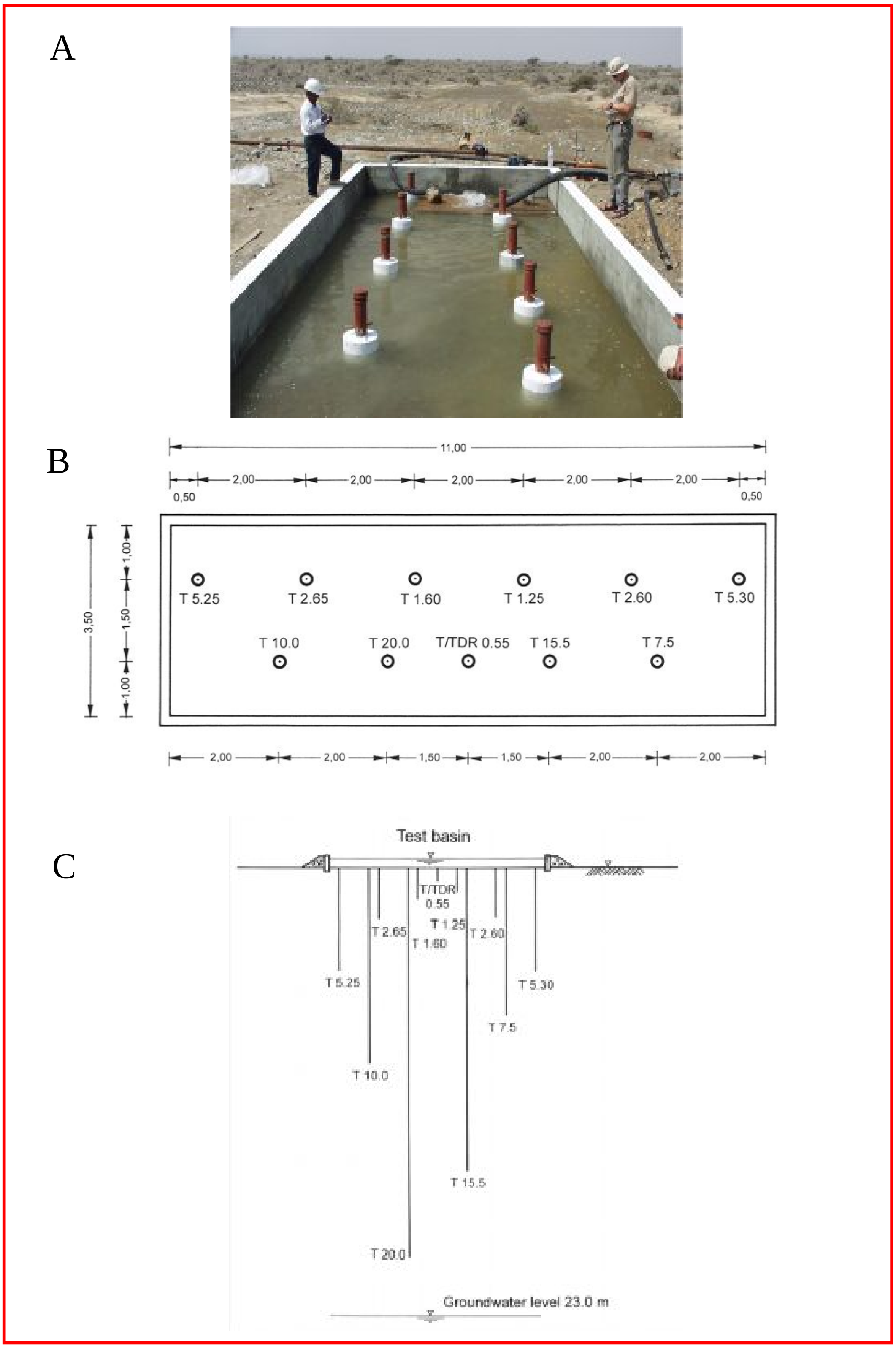


Figure 2.3 (A) Photo of test basin (B) Layout of the test basin (C) Vertical cross section of the test basin and subsoil. (Zunic, *et al*., 2001).

For the studies have focused on improving the groundwater recharge, the case study prepared by Kaledhonkar, *et al*. (2002), studied Artificial Groundwater Recharge through Recharge Tube Wells. A feasibility study on groundwater recharge was done through two recharge tube wells constructed in the bed of the old Sirsa branch canal (a branch of Western Yamuna canal – India). The canal flows on a seasonal basis and passes through North-East Haryana, an area of groundwater depletion. A site in the canal’s bed was selected as an experimental site to identify the most appropriate location for a potential groundwater recharge site. A geo-electrical resistivity survey was carried out, the results of which are shown in figure 2.4A (as geologic cross sections). The most appropriate locations for recharge tube wells were identified as points N4 and N5. Two recharge tube wells were installed (50 cm diameter to the depth of 45 m) at a distance of 50 m between points N4 and N5 in the canal’s bed to recharge groundwater artificially.

All design precautions for the wells were taken to prevent choking, avoid sedimentation and trapped air in the case of sudden entry of floodwater in the rainy season (see figure 2.4B). Observation wells were constructed to monitor the changes in water table as a result of the recharge wells, as shown in figure 2.4C. One separate row of three observation wells was installed upstream (at 320 m) to provide a comparison, as recharge was also taking place naturally, due to canal seepage and paddy fields. Data on drawdown from the different observation wells was collected regularly starting in June 1998. Fluctuations in the observation wells’ water table were studied to monitor the performance of the recharge tube wells. Chemical analysis of water samples for electrical conductivity and dissolved sodium concentration was also carried out. As the recharge tube wells were installed in the canal itself, their recharge was superimposed on the natural seepage from the canal.

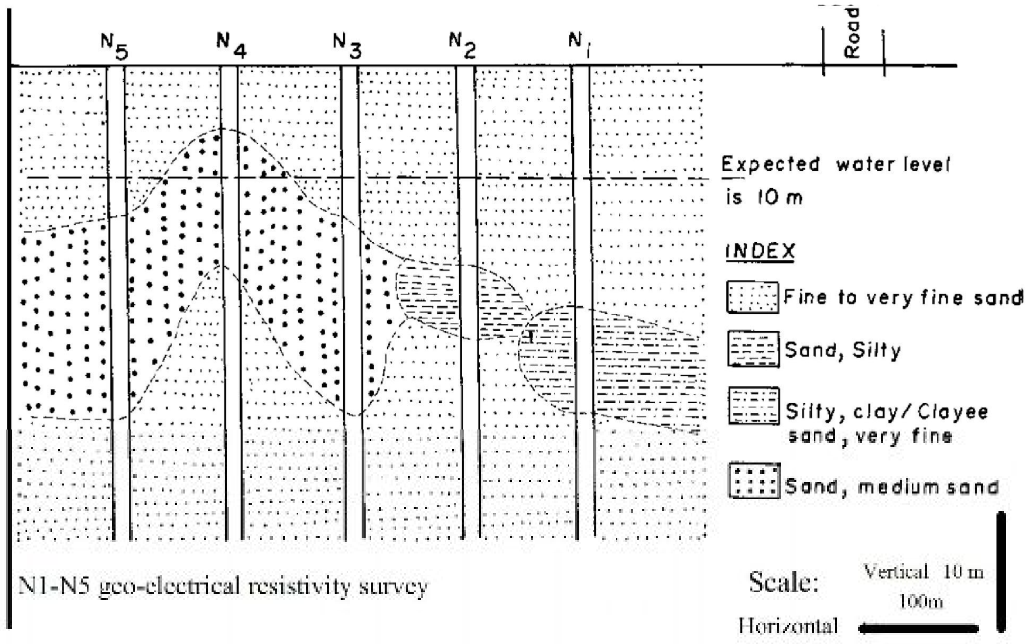


Figure 2.4 (A) Geological section based on geo-electrical resistivity survey. (Kaledhonkar, *et al*., 2002)

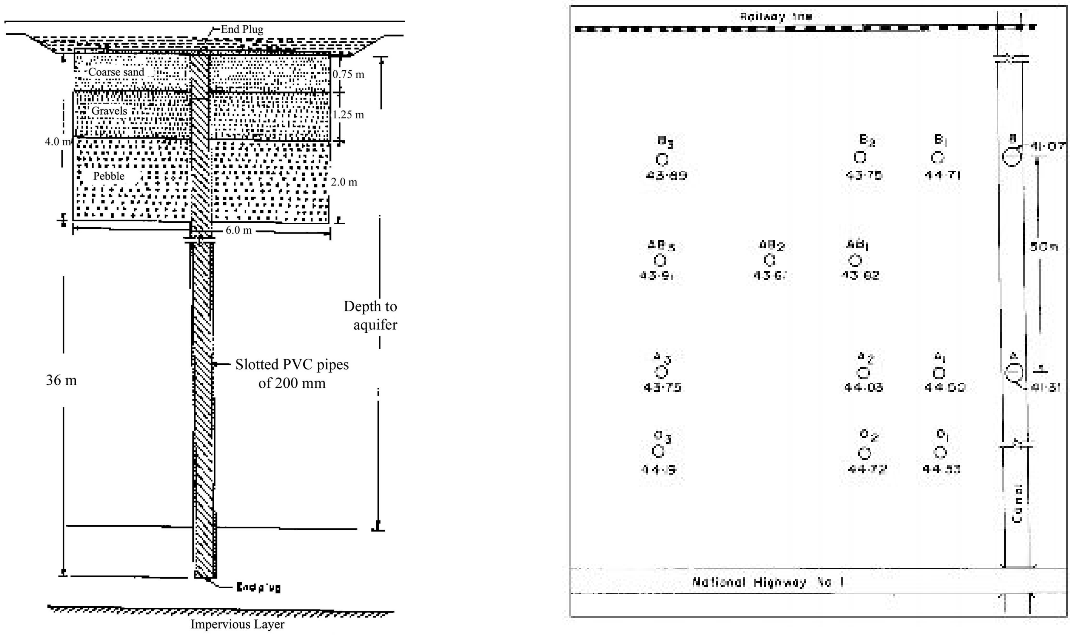
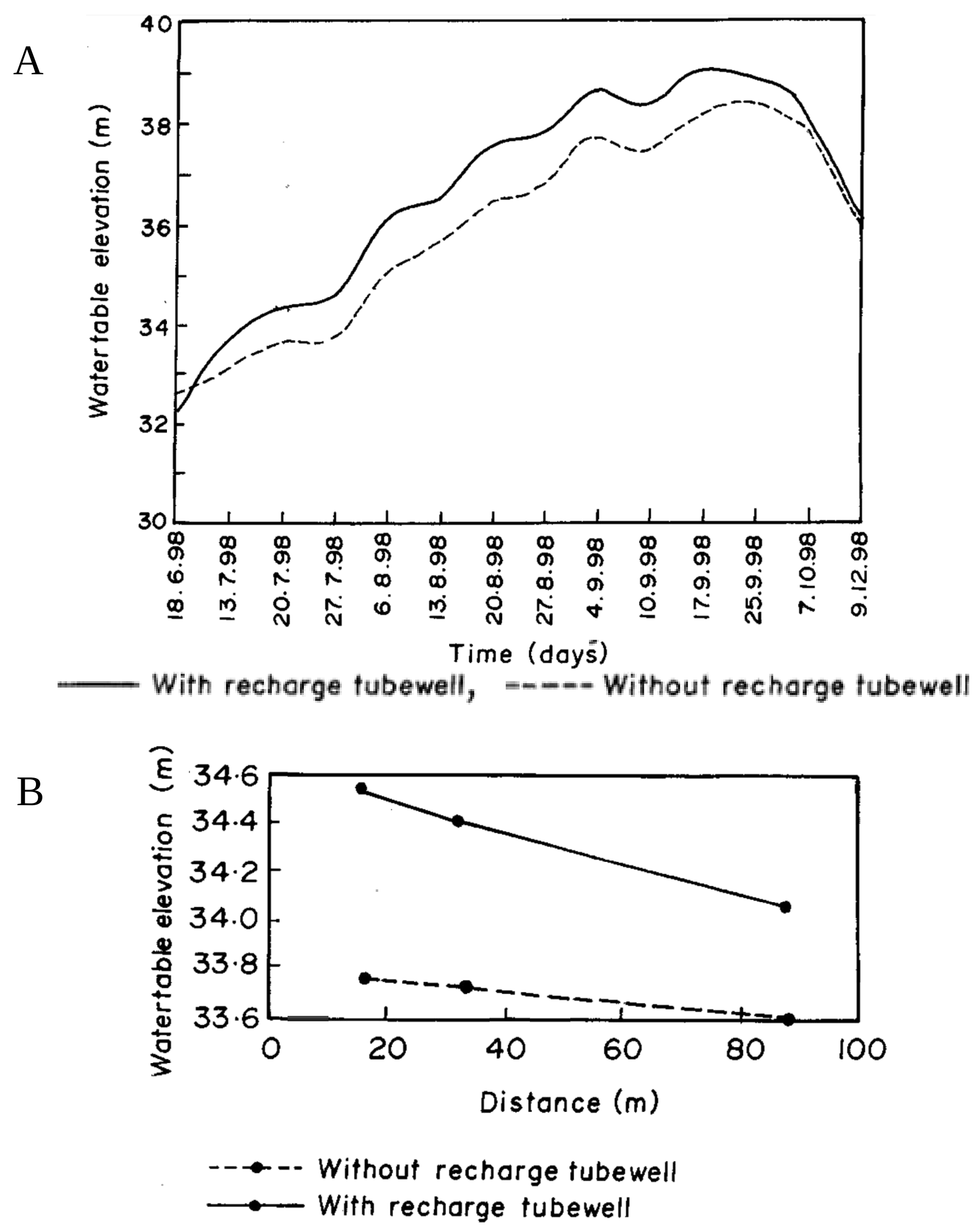


Figure 2.4 (B) Recharge tube well, (C) Layout of recharge tube wells and observation wells set-up with reduced levels. (Kaledhonkar, *et al*., 2002)

Therefore, seepage from the canal had to be separated from the total recharge to estimate the actual recharge resulting from the tube wells. For this purpose, net change in water table due to canal seepage for a particular time period was measured and deducted from total head (the combined head of canal seepage and recharge tube wells) observed at the end of the same time period. The study lead to a clearer understanding of the effectiveness of recharge tube wells by comparing water table fluctuations in observation well (A1), located downstream of recharge tube well (A), with water table fluctuations in the observation well (O1), located at the same distance (16 m) from recharge tube well (A), but upstream (see figure 2.4C). The water table elevations over time at observation wells (A1) and (O1) are shown in figure 2.5A. Higher water table elevations at observation well (A1) clearly indicated the enhancement of recharge due to recharge tube wells. Also, water table fluctuations at observation wells (A2) and (A3) were compared with water table fluctuations at observation wells (O2) and (O3), respectively. Similar results were observed as in the first case: there was a noticeable increase in recharge rate due to the recharge tube wells. Data on water table elevations at wells (A1), (A2) and (A3) were plotted against the same data from wells (O1), (O2) and (O3) in figure 2.5B. The figure indicates that water table elevations at the wells located downstream of the recharge tube wells were higher compared to those at observation wells upstream of the recharge tube wells (the bottom of the recharge tube wells was selected as datum elevation). It was also noticed that the radius of influence of the recharge tube wells was around 100 m. The conductivity and dissolved Na^+ concentration of water samples from observation wells (A1), (A2) and (A3) were lower compared to samples from (O1), (O2) and (O3). This was thought to be due to higher dilution of groundwater as a result of higher recharge rates at (A1), (A2) and (A3) compared to (O1), (O2) and (O3). It was concluded that using recharge tube wells is a viable option for artificial groundwater recharge in the depleting water table areas of the Indo-Gangetic plains. Estimations of availability of rechargeable water are very important before planning any groundwater recharge project. This study proved that geo-electrical resistivity surveys may be effectively used to identify suitable sites for recharge. The provision of a silt basin and a suitable filter can ensure long life for recharge tube wells. The average recharge rate of 10.5 l/s (907.2 m^3/day) was estimated for one recharge tube well, which showed reasonably good performance.



The bottom of the recharge tube well was selected as datum Elevation (at 45m)

Figure 2.5 (A) Water table fluctuations at 16 m from canal; and (B) Water table elevation with distance from the canal on July 27, 1998. (Kaledhonkar, *et al.*, 2002)

CHAPTER 3

HYDROLOGY AND HYDROGEOLOGY

3.1 Hydrology

3.1.1 Background

In general, Hydrology is that branch of physical science, which deals with the origin, distribution, and properties of water of the earth. It also deals with the transportation of water through the air, over the ground surface and through the earth strata. Hydrology may be defined as the science dealing with the depletion and replenishment of our water resources.

The importance of hydrology stems from Water as it is the most crucial component of life. In addition, it is considered as an important resource of any society as a part, and any country as a whole, since no life is possible without water. It occupies a unique position among other natural resources due to the impossibility of survival in the absence of this resource.

The importance of water is obvious, and can be more important depending on the availability of this resource, in addition to demands and uses. It could be much valuable, when this resource is scarce or when the available resources are not evenly distributed in time and space through out any country.

Sometimes the country can depend on the available groundwater to cater for the demand of water for the domestic and irrigation purposes. However, this resource should be renewable. In the case of over-pumping (i.e., the exploited water exceeds the recharge to the aquifer), the groundwater resource can face a general draw down which may cause a loss of the aquifer or at least increasing its salinity, which at the end result in an unusable water.

In order to stop the continuous increasing demand on water and decreasing the dependency on the groundwater as sole resource, we should get benefit of the surface waters, which are mostly wasted, either to sea or being lost by evaporation in mudflats in the desert. (GDI, 2006)

3.1.2 Climate:

Yemen is located in the tropical and sup tropical climate zones. Although Yemen has no major seasonal differences, it can be broadly divided into distinctive seasons: summer from April to October with high temperatures and a milder winter season from October to April.

There are two rainy periods in the country; the first from March to May and the second from July to September. In the highlands and mountain regions, where the Sana'a basin is located (i.e. the study area), the weather is moderate in summer and cold in winter during night time and early morning and moderate during day time (JICA, 2007).

3.1.3 Monitoring stations:

Monitoring hydrological and hydrogeological conditions is one of the most important factors for achieving an appropriate management of water resources in any area. With regard to this, the monitoring information shall be essential for long-term operational strategy for water resources (JICA, 2007).

In the area where the present study was conducted, new manual rainfall monitoring stations were found such as Sa'wan-Haial House located near Mekhtan and Musaibeeh dams with coordinates, 1700580N, 427744E and elevation 2393m. It started operating in 2008 under the SBWMP (2008) recent study.

3.1.4 Temperature

According to NWRA-A (i. e. a temperature recorded station located in the north edge of the urban area of Sana'a city with altitude of about 2250m), the average annual temperature ranges between 15ºC and 25ºC. The hottest season is from June to Augusts and the coldest season starts from January to February (JICA, 2007).

3.1.5 Humidity

The average monthly relative humidity varies from 40 % to 65 % while the mean annual duration of sunshine hours is 9 ha/day. The average wind speed is 2.7 to 3.5 m/sec in the winter and 2.9 to 4.8 m/sec in summer (SAWAS, 1995).

3.1.6 Precipitation

The average rainfall in Sana'a basin drastically differs from area to area and also from year to year. As shown Figure 3.1, the study that carried out by WEC (2001) shows that the south west of Sana'a basin characterized by high rainfall reach to 350 mm and this amount decreases in the north and north east. In the study area, the average annual rain fall was about 200 mm to 220 mm. The rainy periods as it was mentioned above are: one is in the spring season (from March to May) while the other one is in the summer (from July to September) but the latter is more in depth, reach to 90 mm in one rain.

In this study, the rainfall recorded in the year 2008 at Sa'wan-Haial House manual rainfall station fluctuated between 0 to 18.2 mm/day. Table 3.1 and Figure 3.2 list all rainfall records and shows that the summer rain in this year, 2008, continuous until November, 2008 (as abnormal rainfall time). This happens in this year, 2008 not only in Sana’a city but also in other provinces such as Hadramout which is suffering from destruction caused by devastating water floods.

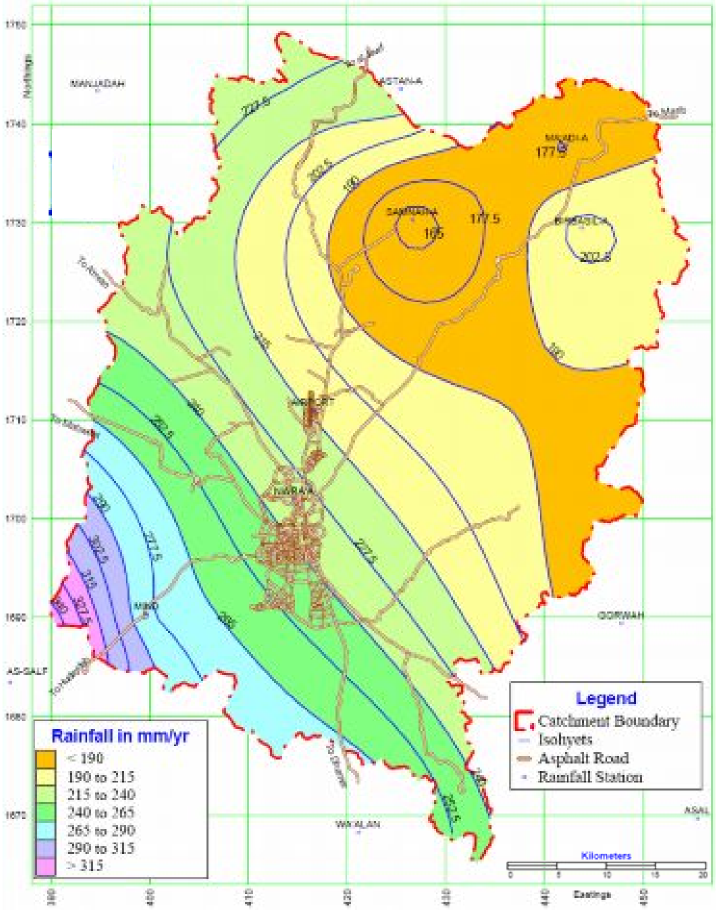


Figure 3.1 Isohyetal map showing mean annual rainfall of Sana'a Basin (WEC, 2001).

Table 3.1 Amount of rainfall in the study area (SBWMP, 2008)

Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)
09/04/2008	0.0	09/07/2008	0.4	30/08/2008	0.0
13/04/2008	0.0	15/07/2008	0.0	06/09/2008	0.0
16/04/2008	0.0	22/07/2008	0.0	10/09/2008	0.5
20/04/2008	0.0	29/07/2008	16.2	13/09/2008	0.0
23/04/2008	0.0	02/08/2008	1.8	20/09/2008	0.0
27/04/2008	0.0	05/08/2008	0.0	11/10/2008	0.0
30/04/2008	0.0	09/08/2008	5.7	25/10/2008	18.2
03/05/2008	1.0	12/08/2008	3.2	29/10/2008	0.0
04/05/2008	7.5	16/08/2008	0.0	01/11/2008	12.4
06/05/2008	13.9	19/08/2008	0.0	08/11/2008	0.0
10/05/2008	23.4	23/08/2008	3.4		
17/05/2008	1.6	26/08/2008	0.0		

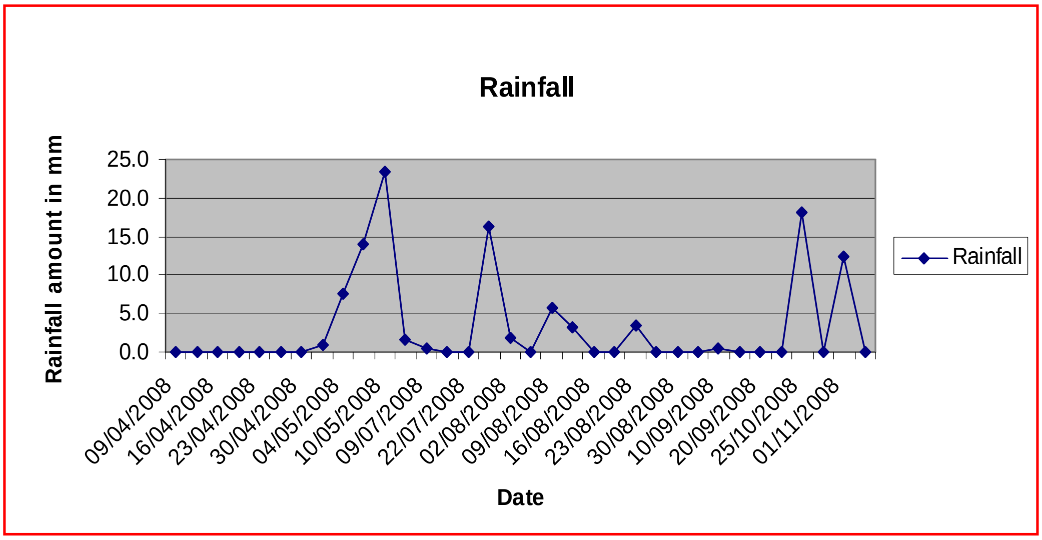


Figure 3.2 Amount of rainfall in the study area (SBWMP, 2008)

3.1.7 Runoff

According to the previous studies, methods that used to estimate runoff of wadies in Sana'a basin are of two types, by using runoff coefficient and by using Soil Conservation Service (SCS) (empirical model prepared by the U.S. soil conservation service). The first methods use runoff coefficient, or the ratio of runoff depth to the precipitation depth. "The average coefficient for the wadies in Yemen is 0.055 based on the observed flow volumes from primary watershed. The volume of runoff in Sana'a basin is estimated at about 40.9 MCM/year with the supposition of the 230 mm of annual rainfall, the 3,240 km^2 of the area of the Sana'a basin" (JICA, 2007).

In the study area runoff was estimated by using the first method. "The mean annual flow estimated at about 199,000 m^3 for the catchment area of Mekhtan dam (wadi Mekhtan), with runoff coefficient 0.2 (estimated according to the catchments characteristics)" (GDI, 2001).

Recalculated of runoff for Mekhtan and Musaibeeh dams is done in this study by using the map (see Figure 3.3) (SBWMP, 2008), using GIS to compute the catchment area by using the two runoff coefficient, 0.2 (GDI, 2001) and 0.055 (JICA, 2007). Formula below was used for calculation, the results are listed in Table 3.2.

Runoff = Catchment area × Annual rainfall × Runoff coefficient

Table 3.2 Runoff estimation of the dams

Dams	Area (m^2)	Runoff (m^3) *1	Runoff (m^3) *2	Average Runoff (m^3)
Mekhtan	5,683,888.5	227,355.5	62,522.8	144,939.2
Musaibeeh	3,660,162.7	146,406.5	40,261.8	93,334.2

* 1 by using Runoff Coefficient = 0.2 (GDI, 2001) and 0.2 m rainfall

* 2 by using Runoff Coefficient = 0.055 (JICA, 2007) and 0.2 m rainfall

3.1.8 Evaporation

The rate of actual lake evaporation is estimated in Sana'a basin which is about 3092.5 mm/year (SAWAS, 1995). It is excess of 10 to 15 times per year over the annual rainfall (in all Sana'a sub-basin) as the rainfall ranges between 200 to 300 mm per year. On such arid to semi arid dry condition, 95% of the rain which falls is re-evaporated and does not contribute to runoff.

"There is no evaporation pan in the Sana'a Basin. Sana'a Airport Meteorological station possesses meteorological observations. Estimation of evaporation in Sana'a Basin was based on evaluation of potential Evapotranspiration (Etp)." (SBWMP, 2006).

- Evaporation losses from reservoir:

Evaporation depth (Evaporation loss from the reservoir) was derived directly from the estimation of Evapotranspiration (Etp) using the following expression:

$$\mathbf{E_{(i)} = Etp_{(i)} \times Cc}$$

$E_{(i)}$ – Evaporation depth loss from reservoir in specific period (i), day, week, month…etc

$Etp_{(i)}$ - Evapotranspiration depth for (i), day, week, month…etc

Cc - Coefficient to transform the Etp into free surface lake evaporation.

Table 3.3 shows the results of evaporation depth obtained from the Airport meteorological station (CAMA) - the statistics means over the period 1983 – 1990 and computation of Etp by applying Penmann's equation for period (i) = month. The actual evaporation depth was computed by using the formula above with Cc equal to 1.25 (SAWAS, 1995). The volume of water lost by evaporation from the reservoir at specific period, using the results from the Table 3.3, is given by this formula:

$$\mathbf{Ed_{(i)} = E_{(i)} \times A_{(i)}}$$

$Ed_{(i)}$ – reservoir evaporation in specific period (i)

$E_{(i)}$ – actual evaporation in the area in specific period (i)

$A_{(i)}$ – Area of the reservoir

Table 3.3 The Meteorological Statistics for Calculation E(i)

Month	Temp (C)	Relative Humidity (%)	Sunshine Duration (hrs/day)	Wind Speed (m/s)	Etp (mm/month)	$E_{(i)}$ (mm/month)	E (mm/day)
JAN	12.9	64.3	10.4	2.8	150	187.50	6.25
FEB	16.8	49.9	4.6	2.7	134	167.50	5.58
MAR	19.1	49.4	4.2	3.2	174	217.50	7.25
APR	19.6	57.8	7.7	4.4	205	256.25	8.54
MAY	21.9	43.8	10.1	3.8	255	318.75	10.63
JUN	23.5	41	9.6	4.8	281	351.25	11.71
JUL	23.5	44.5	8.3	4.5	264	331.25	11.04
AUG	23.5	47.7	7.6	4.3	249	311.25	10.38
SEP	21.4	39.4	9.5	3.2	223	278.75	9.29
OCT	18.5	38.7	10.6	2.9	205	256.25	8.54
NOV	15.7	39.5	10.2	2.4	158	197.50	6.58
DEC	13.0	39.4	9.6	2.8	152	190.00	6.33
MEAN	19.1	46.3	8.5	3.5	2450 (mm/yr)	3063.75 (mmlyr)	Average 8.5/day

(SAWAS, 1995)

3.1.9 Water balance of the dams

To evaluate the recharge efficiency of a surface reservoir, first it is important to know how much the stored water infiltrates from the bottom of the reservoir. One way to quantify this is to apply a water balance approach (by measuring groundwater inflows and outflow).

In this study, in order to calculate the quantification of infiltration water (subsurface flow or deep percolation) from the dams reservoirs, short periods of monitoring of water levels in the dams was done with cooperation from SBWMP. The periods of measurements are from September 2008 to November 2008 and the previous data of monitoring and rainfall recorded is collected from on going study, the study which planed by Sana'a Basin Water Management Project (SBWMP) and carried out by hydrosoult Inc. (SBWMP, 2008).

The instrument which used for monitoring water levels in the dams is a staff gauges (rulers) installed in the dams (please refer to the photo in appendix 3). The Figure 3.3 shows the location of the rainfall stations and dams. Sa’wan-Haial House rainfall station is located near to the dams and Sa’wan-Brian Al-hosain School rainfall is located near to the catchment area of the two dams. Table 3.4 lists all of these data, Rainfall recorded and water level monitoring for both Mekhtan and Musaibeeh dams.

The formula that is used for calculation of water infiltration from the dams’ resirvoir is:

Infiltration = Change in the storage level + Inflows – Evaporation – outflow

The parameters of this formula are:

1 - Change in dam’s reservoir storage (water volume change) within the specific time period.

2 - Inflow to the dams reservoirs: even due to rainfall or due to runoff from the catchement area of the dam.

3 - Outflow from the dams reservoirs even for purpose of irrigation or any other purposes.

4 - Evaporation from dams reservoirs.

In order to reduce the parameters required for dam's water balance calculation, the computations is done in specific time periods when there was no rainfall, according to the results of manual rainfall station record as in Table 3.4., therefore runoff will be zero. This method is suitable for many reasons; 1) some of these parameters are missing, 2) to avoid the inaccuracy which may be resulted from calculating some of those parameters. Figure 3.4 shows the schematic diagram of the parameter that required for dams water balance calculation in this case.

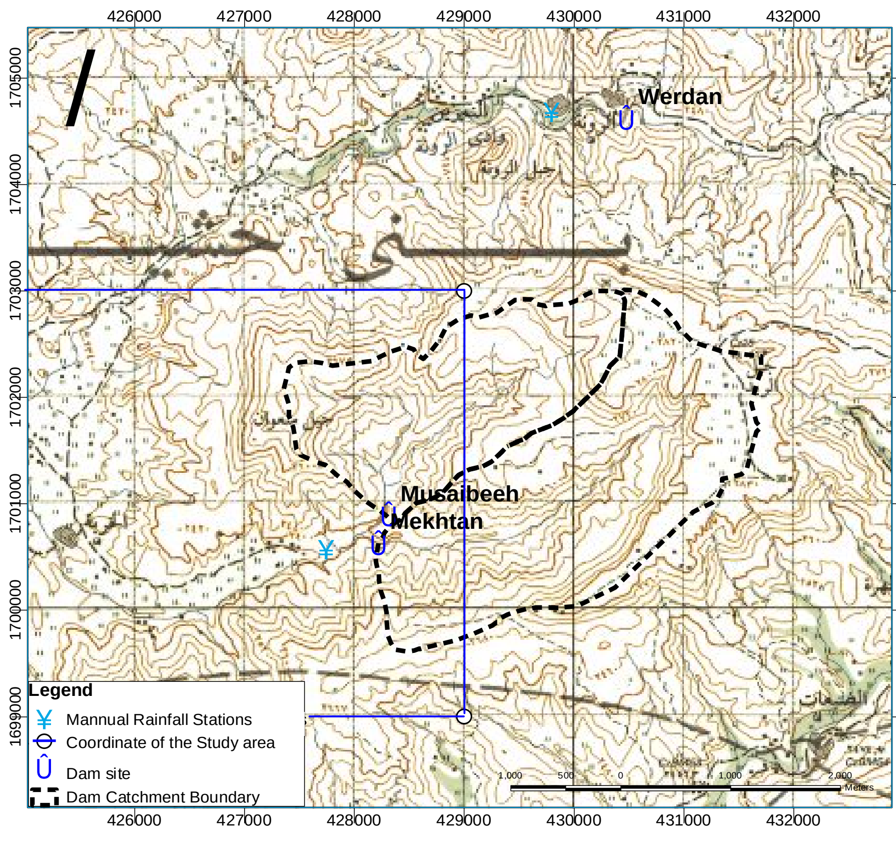


Figure 3.3 Location of manual rainfall stations (SBWMP, 2008)

Table 3.4 Rainfall stations recorded with dams water level monitoring (2008)

Date	Rain station Record (mm)		Mekhtan dam		Musaibeeh dam	
	Sa'awan-Haial House*[1]	S'awan-Brian Al-hosain School*[2]	Water level (m) A.B.R*[3]	Water volume (m^3)	Water level (m) A.B.R*[3]	Water Volume (m^3)
09/04/2008	0.0	0.0	1.48	12611.60	3.84	10984.11
13/04/2008	0.0	0.0	1.29	10363.93	3.80	10739.27
16/04/2008	0.0	0.0	1.22	9576.54	3.77	10557.61
20/04/2008	0.0	0.0	1.12	8491.15	3.72	10258.57
23/04/2008	0.0	0.0	1.06	7862.78	3.69	10081.39
27/04/2008	0.0	0.0	0.98	7052.40	3.65	9847.75
30/04/2008	0.0	0.0	0.90	6274.28	3.62	9674.48
04/05/2008	7.5	-	0.84	5712.49	3.61	9617.09
06/05/2008	13.9	-	0.82	5529.48	4.36	14442.30
10/05/2008	23.4	-	0.79	5259.01	4.45	15093.24
13/05/2008	-	-	0.73	4732.92	4.43	14947.24
17/05/2008	1.6	-	0.64	3982.01	4.40	14729.68
20/05/2008	-	-	0.59	3585.38	4.39	14657.55
09/07/2008	0.4	-	0.51	2982.64	3.76	10497.43
15/07/2008	0.0	-	0.38	2091.78	3.69	10081.39
22/07/2008	0.0	-	0.21	1110.24	3.61	9617.09
29/07/2008	16.2	-	2.52	27483.21	4.05	12318.91
02/08/2008	1.8	5.5	2.56	28134.44	4.01	12058.25
05/08/2008	0.0	-	2.41	25720.86	3.97	11800.61
09/08/2008	5.7	-	2.35	24777.44	3.93	11545.99
12/08/2008	3.2	5.0	2.4	25562.74	3.9	11357.01
16/08/2008	0.0	0.0	2.33	24465.79	1.23	980.56
19/08/2008	0.0	0.0	2.28	23692.93	0.68	292.53
23/08/2008	3.4	2.2	2.21	22626.02	0.67	284.01
26/08/2008	0.0	0.0	2.15	21725.71	0.65	267.38
30/08/2008	0.0	0.0	2.07	20545.93	0.61	235.75
06/09/2008	0.0	0.0	1.95	18821.24	0.55	192.33
10/09/2008	0.5	1.2	1.87	17702.01	0.53	178.92
13/09/2008	0.0	0.0	1.8	16743.13	0.50	159.79
20/09/2008	0.0	0.0	1.64	14624.73	0.45	130.49
11/10/2008	0.0	0.0	1.18	9136.74	0.26	47.73
22/10/2008	-	-	0.94	6659.24	0.18	25.76
25/10/2008	18.2	27.6	1.51	12980.85	0.18	25.76
29/10/2008	0.0	0.0	1.47	12489.38	0.17	23.53
01/11/2008	12.4	15.4	2.91	34062.64	1.18	899.61
08/11/2008	0.0	0.0	2.81	32327.38	1.06	720.68
Source: (SBWMP, 2008).						

* [1] Rainfall station near the dams with UTM Coordinate= **1700580 N, 427744 E and** elevation **2393 m**
* [2] Rainfall station near the catchment area of the dams with UTM Coordinate= **1704686 N, 429792 E and** elevation **2452 m**
* [3] Water height, above reservoir bottom

The green colors represent the periods that was chosen for dams water balance.

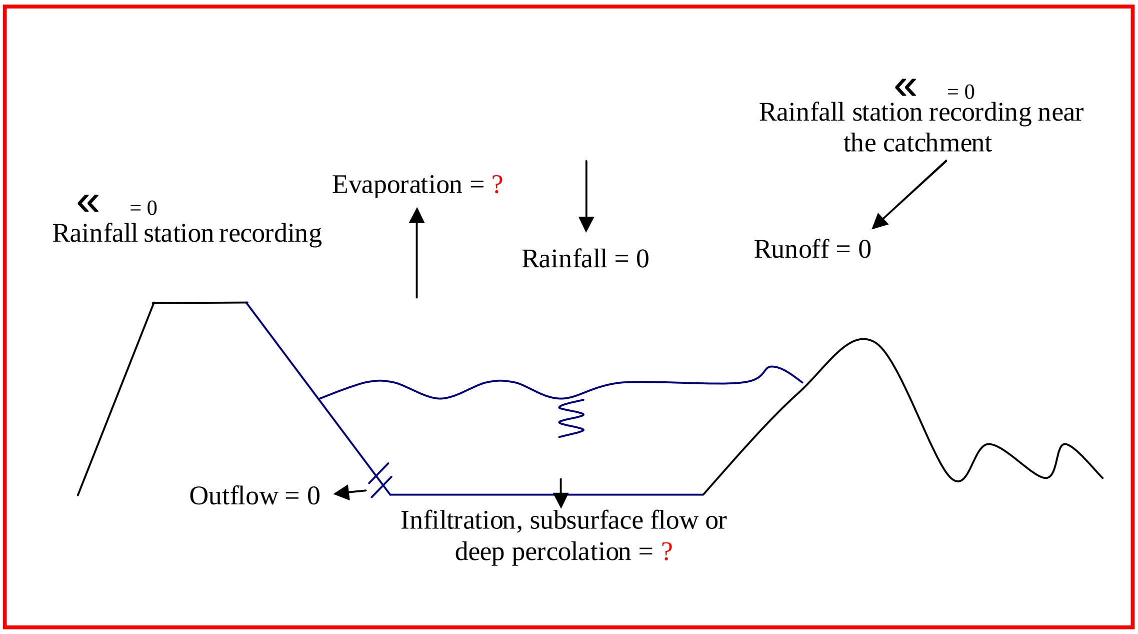


Figure 3.4 Schematic diagram shows the parameters that required for dams water balance calculation

- Calculation

- Reservoirs outflow and the periods that were chosen for the computation

The periods that were chosen for estimation recharge from the dams listed in the Table 3.4. They were chosen in consideration to these factors:

1. Time periods were selected when there was not any rainfall recorded as we mention above.
2. Time periods were selected to be also far from any previous rain storm (at least three days).
3. The computation of the selected periods were done in different time intervals (three days, four days, week and month), then the mean of the water evaporation and infiltration per day were computed.
4. According to the people interview (questionnaire), it has found that the water did not discharge form Mekhetan dam. It only discharged one or two time in a year when there was huge amount of water. For Musiabeeh dam there is a problem

which is leak from the body of the dam (It was noticed a little leakage during the fields measurements) and also as the residents said that they released the water from the dam for maintenance purposes. Because of that reason the computation will be done only for Mekhtan dam. The periods that were chosen for computations as the following:

- From 15-07-2008 to 30-04-2008.
- From 16-08-2008 to 19-08-2008.
- From 26-08-2008 to 06-09-2008.
- From 13-09-2008 to 11-10-2008.

- Change in the storage level of the dam: the measurement of water level change and water volume change are listed in Table 3.4

- Inflow (Rainfall and runoff): As it is mentioned above, the selected periods of measurements were chosen when rainfall equal zero, therefore there will be no runoff.

- Evaporation: By using free lake evaporation in m/day from the Table 3.3 (SAWAS, 1995) in the periods of the calculation which are July (0.01104 m/day), August (0.01038 m/day), August& September (0.00929 m/day), September (0.00929 m/day), and September& October (0.00892 m/day). Table 3.6 lists the results of computation of evaporation in (m^3) for Mekhtan reservoir in the selected periods according to water level fluctuation. (Changes in water areas in the reservoir)

Evaporation = Average daily evaporation × the area of the dam in that Level

- The area of the dam and water volume

The computation of the area and volume of the reservoir in different rural reading (staff gauge), contoured topographic map of the reservoir and volume curve is used, as shown in Fgure 3.5 A&B. This map is done by topographic survey by using total station method (SWMP, 2008). It was drowning with contour interval 0.5 m. Table 3.5 lists the results of calculations.

In this case the formula will be:

Infiltration = Change in the storage level – Evaporation

Table 3.6 is summarized all calculations and all results, which is infiltration and evaporation in every period with the percentage of each period. The average of water evaporation is 129.5m^3/day and the average of water infiltration is 104.2m^3/day.

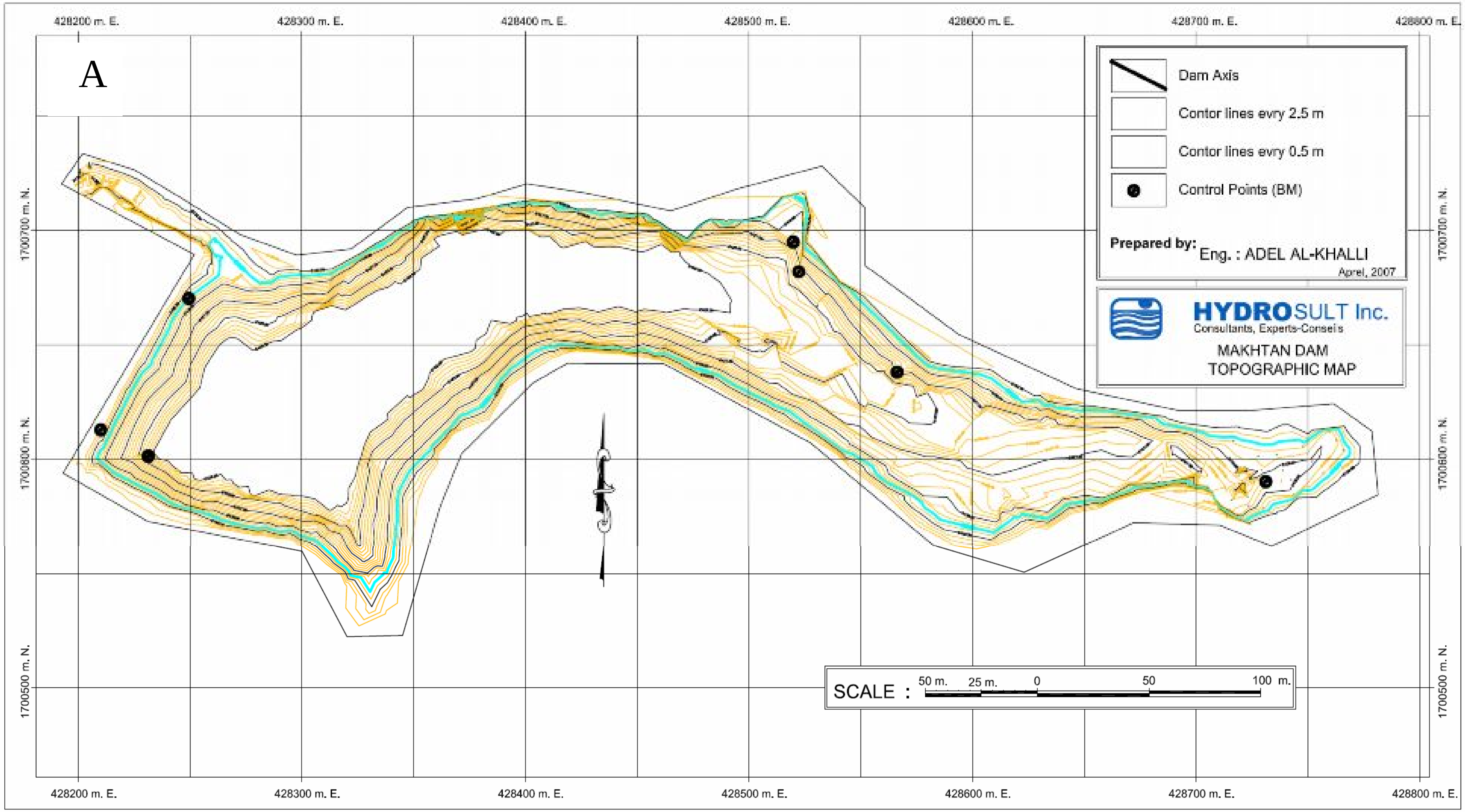


Figure 3.5 (A) Mehktan topographic map at bottom reservoir elevation is 2421.5 m.a.s.l (SBWMP, 2008)

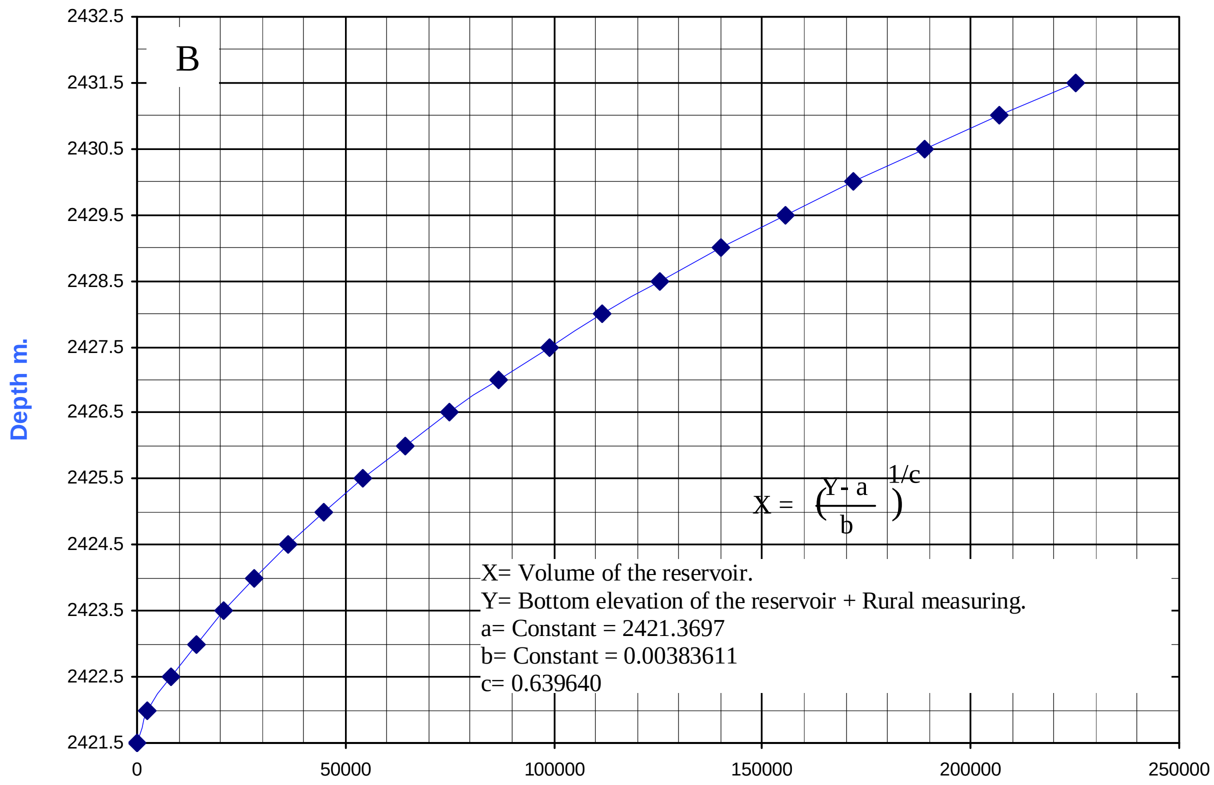


Figure 3.5 (B) Curve for calculation of reservoir's volumes (SBWMP, 2008)

Table 3.5 Results of calculation, reservoir's areas and volumes (SBWMP, 2008)

Elevation		Area	Volume
A.R.B*[1]	A.S.L*[2]		
10	2431.5	37771.29	225349.5
9.5	2431	36352.10	206818.6
9	2430.5	34907.54	189003.7
8.5	2430	33351.78	171938.9
8	2429.5	31785.00	155654.7
7.5	2429	30167.67	140166.5
7	2428.5	28415.82	125520.6
6.5	2428	26612.32	111763.6
6	2427.5	25216.14	98806.49
5.5	2427	23769.35	86560.11

*[1] Height above reservoir bottom of the dam

Elevation		Area	Volume
A.R.B*[1]	A.S.L*[2]		
5	2426.5	22247.92	75055.8
4.5	2426	20784.55	64297.68
4	2425.5	19372.16	54258.5
3.5	2425	17984.95	44919.22
3	2424.5	16638.01	36263.48
2.5	2424	15417.07	28249.71
2	2423.5	14093.46	20872.08
1.5	2423	12979.13	14103.93
1	2422.5	11565.81	7967.698
0.5	2422	10152.49	2538.123
0	2421.5	8739.17	0

*[2] Height above Sea level

Table 3.6 Estimation of water losses from Mekhtan Dam (Evaporation and Infiltration)

Date		Days in each period	W.L. change		W.V. change		Total Net Loss/period	Net Loss/day	E (m/d)	Average Area	Evaporation from the Reservoir		Infiltration from the Reservoir	
From	To		From	To	From	To					(m^3/day)	%	(m^3/day)	%
15/07/2008	22/07/2008	7.00	0.38	0.21	2091.78	1110.24	981.54	140.22	0.01104	9714.36	107.25	76.48%	32.97	23.52%
16/08/2008	19/08/2008	3.00	2.33	2.28	24465.79	23692.93	772.86	257.62	0.01038	14900.86	154.67	60.04%	102.95	39.96%
26/08/2008	30/08/2008	4.00	2.15	2.07	21725.71	20545.93	1179.78	294.95	0.01038	14384.65	149.31	50.62%	145.63	49.38%
30/08/2008	06/09/2008	7.00	2.07	1.95	20545.93	18821.24	1724.69	246.38	0.00929	14130.40	131.27	53.28%	115.11	46.72%
26/08/2008	06/09/2008	11.00	2.15	1.95	21725.71	18821.24	2904.47	264.04	0.00984	14170.10	139.43	52.81%	124.61	47.19%
13/09/2008	20/09/2008	7.00	1.80	1.64	16743.13	14624.73	2118.40	302.63	0.00929	13469.44	125.13	41.35%	177.50	58.65%
20/09/2008	11/10/2008	21.00	1.64	1.18	14624.73	9136.74	5487.99	261.33	0.00892	12682.87	113.13	43.29%	148.20	56.71%
13/09/2008	11/10/2008	28.00	1.80	1.18	16743.13	9136.74	7606.38	271.66	0.00892	12951.67	115.53	42.53%	156.13	57.47%
Average/day (for the durations in conqueror green color)								254.85			129.22	57.96%	104.17	42.04%

T. Days= Total days that used in the calculation in that periods, W. L. change= Water level change in the reservoir according to the field measurements, and then the W. V. change= the water volume change,

3.2 Hydrogeology:

3.2.1 Aquifers and the groundwater level:

Aquifers in this study area have been identified into three aquifers: Tawillah Sandstone, Tertiary Volcanic aquifer, and Alluvial Quaternary aquifer.

Cretaceous Tawilah sandstone formation is the main lower aquifer in the study area. Wells increased in the middle and west of area especially in the recent year because the productivity of wells in alluvial aquifer was decreased. The wells depth reached to more than 450 m in this aquifer.

Tertiary Volcanic rocks which are basalt flows mixed with rhyolite, overlying on sandstone aquifer. These rocks consider as Aquiclude formation except where fractured occurs in some top part of these sequence and contain perched aquifer which can be exploited by relatively dug wells and drilled wells. The water table ranges from 6 m to 30 m as the well inventory indicates (WEC, 2001).

Quaternary Alluvial aquifer (shallow aquifer), which is semi-to unconsolidated alluvial deposits represent an aquifer of variable permeability coefficient. This aquifer is heavily exploited by a lot of dug wells. The water tables differ from a few meters to reach more than 50 m in some places of the study area.

3.2.2 Aquifer properties:

- Hydraulic conductivity (Coefficient of permeability)

Hydraulic conductivity is the rate of flow through a unit cross section under a unit of hydraulic gradient, which is the coefficient of permeability of a layer (JICA, 2007). Alluvial aquifer have higher coefficient of permeability than other aquifers, Table 3.7 lists the range of permeability coefficient in the Sana’a basin which is “from

0.09 to 12.23 m/day for alluvial aquifer, from 0.0004 to 0.42 m/day for the Tertiary volcanic rocks and from 0.5 to 7.3 m/day for sandstone aquifer." (SBWMP, 2008)

- Transmissivity

Transmissivity- measure of the amount of water that can be transmitted horizontally through an aquifer unit by the full saturated thickness of the aquifer under a hydraulic gradient of one. The value of transmissivity indicates groundwater supply potential of the aquifer. Sandstone aquifer characterized by high Transmissivity than other aquifers. The values of hydraulic conductivity and transmissivity of the three aquifers in Sana'a basin which also represent the aquifers in the study area are listed in Table 3.7

Table 3.7 Aquifers properties

Aquifers	Aquifers Properties	
	Hydraulic Conductivity (K) (m/day)	Transmissivity (T) (m^2/day)
Alluvial	0.09 -12.23	9 - 3618
Volcanic	0.0004 – 0.42	0.34 - 200
Tawilah Sandstone	0.5 – 7.3	6 - 3770

(SBWMP, 2008)

- Coefficient of permeability test

In order to evaluate the effect of sidemen's that accumulate in the dams reservoir. Two samples from the reservoir of the two dams (from the top 10 cm) are taken for laboratory permeability test (Falling Head Test) and also for sieve analysis.

The results of analysis indicate very low permeability for both samples, which is in Mekhtan dam equal 4.9×10^{-7} cm/sec (0.00042336 m/day) and represent 88.98% fine sediment (silt) and 11.02% fine sand. The coefficient of permeability for the sediments in Musaibeeh dam equal 3.35×10^{-7} cm/sec (0.00028944 m/day) represents 94.34% silt and 5.66% fine sand. This indicates that the sediments in the two reservoirs have very poor drainage characteristic.

In order to correlate that permeability with the permeability of the alluvial rocks in the wadi. Data of coefficient permeability test for alluvial deposits is collected which done for Berian dam by (SBWMP, 2006). Berian dam locates north east of the study area on distance about 7 km. The permeability of alluvial ranges between 2.76×10^{-5} cm/sec (0.024 m/day) and the volcanic rocks have coefficient of permeability (K) 8.46×10^{-5} cm/sec (0.073 m/day) (Andesite rocks) {k equal 6.7×10^{-5} cm/sec (0.058 m/day) for fractured zone}.

3.2.3 Number of wells in the study area:

According to the well inventory (WEC, 2001) the total wells in the study area (7km × 4km) are about 495 wells (449 from it is dug wells) and if we extend the area to the end of wadi Sa'wan the number of wells will be 710 well. Wadi Sa'wan is considered as the high density of wells per square kilometer, up to 97 wells per square kilometer are rigisterd in this wadi "wadi Sa'wan" as shows in Figure3.6.

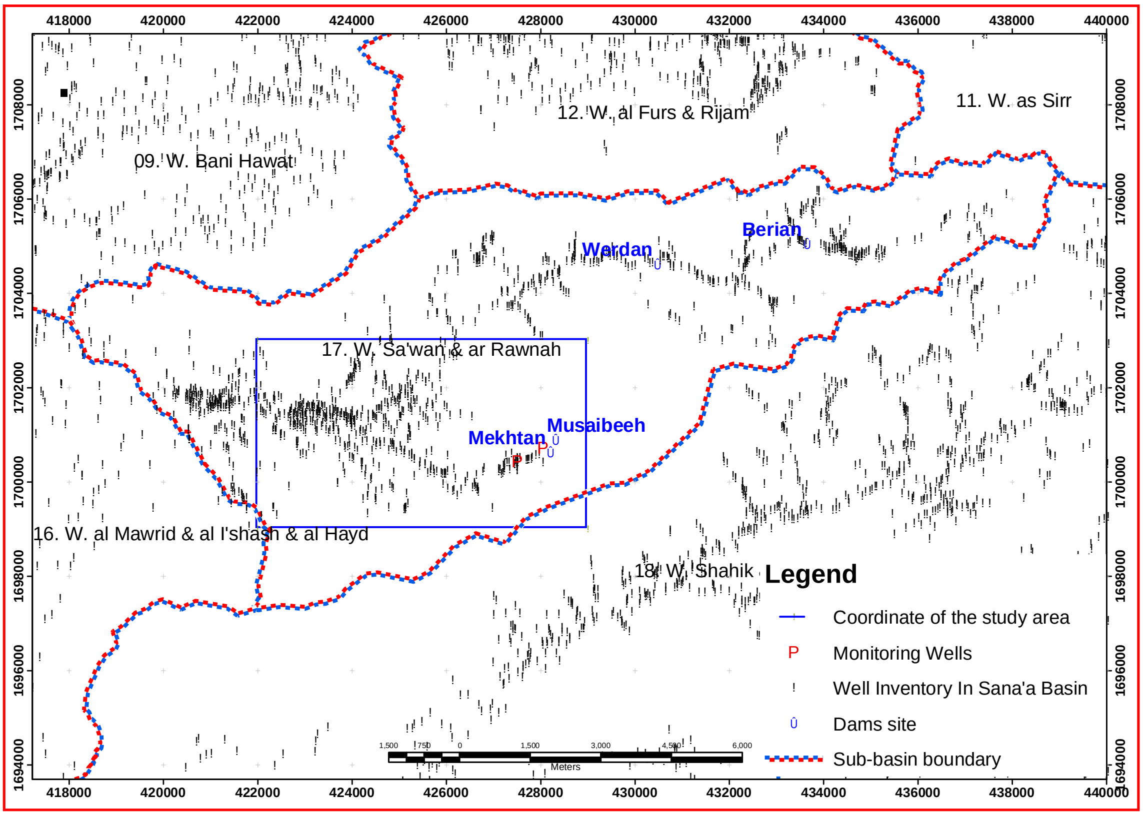


Figure 3.6 Number of wells in the study area according to well inventory (WEC, 2001)

-Well depth and yield and abstraction

According to the well inventory WEC, (2001) the depth of dug wells between few meters to 75 m and most of the wells characteristic by low yield, less than 4 l/sec. The depth of borehole ranges from 90 m to more than 500 m. The yield of most of these borehole wells is between 4- 6 l/sec.

-Water abstraction and electrical conductivity:

According to WEC well inventory, (2001), the total water abstraction in the study area are based on numbers of well, type, pumping hours, aquifer, and use is between 50,000 to 500,000 m^3 as in the map. The heavily water abstraction for mainly irrigation purposes by heavily concentration of wells per square kilometer in the study area leads to increased the salinity. Figure 3.10 shows the Electrical conductivity (EC) for the shallow water in the dug wells (water in alluvial aquifer). EC is between 500 µS/cm (0.2 Siemens/m) to 2000 µS/cm (0.05 Siemens/m) which equal 5 to 20 ohm.m respectively, by using the formula below for conversion from EC to resistivity (ρ).

$$\rho = 1/\sigma \qquad \text{where } \rho = \text{Resistivity in ohm.m}, \quad \sigma = \text{EC in Siemens/m}$$

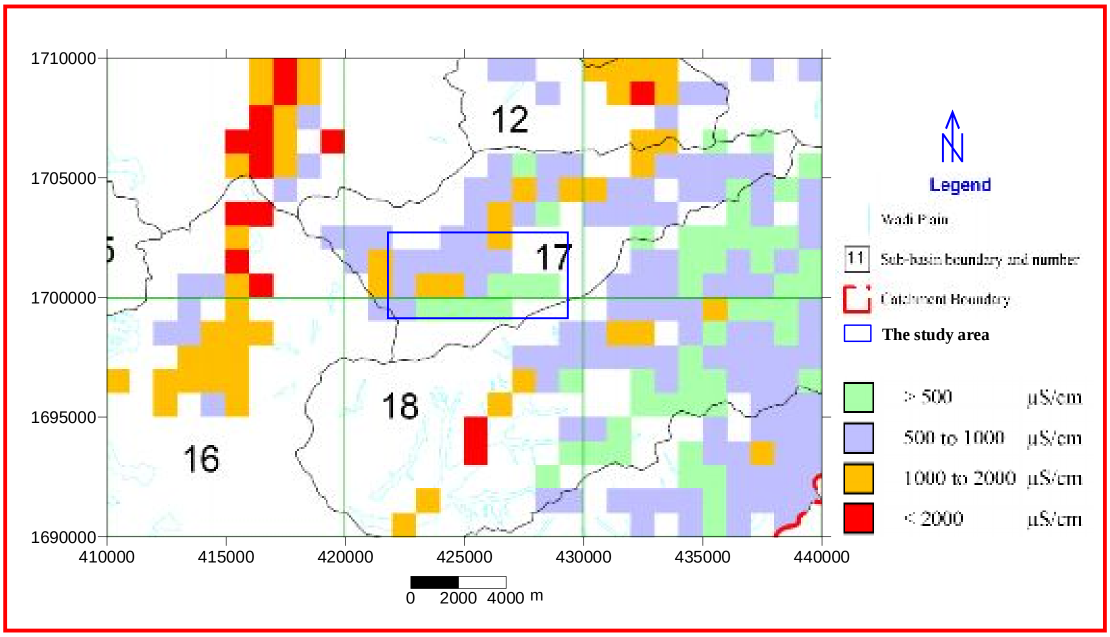


Figure 3.7 Electrical conductivity distribution per square kilometer in alluvial aquifer (Dug wells), (WEC, 2001)

3.2 4 Monitoring wells:

As in the Table 3.8 monitoring wells are done for two dug wells. The first one, well's number (HSS5). It has depth approximately 13 m locates near the dams, 200 m from Mekhtan dam and 300 m from Musaibeeh dam. The coordinate of this dug well 1700726 UTM-N and 428053 UTM-E with elevation of 2409 m. The second well, well's number (HS173). It has depth approximately 20 m, with location a little bit far from the dams. It is located at a distance about 730 m from Mekhtan dam and 915 m from Musaibeeh dam. The coordinate of this dug well is 1700453 UTM-N and 427512 UTM-E at elevation of 2398 m. Map in Figure 3.7 shows the locations of these monitoring wells. Monitoring of static water levels of the two wells are done for short period with cooperation from SBWMP. The periods of monitoring are from September to November 2008. Previous data were collected from the current ongoing study, the study which planed by (SBWMP) and carried out by hydrosoult Inc. (SBWMP, 2008).

The instrument which is used for monitoring the static water levels is Electric Sounder (Please refer to the photo in the appendix 3). Table 3.8 lists all these data, Static water level with also the water levels changes and water volume change in dam's reservoirs. This will be used in order to find the relationship between the static water level of the wells and reservoirs water levels fluctuation.

Table 3.8 Data of monitoring wells and dam's water levels

Date	Water Level		Rainfall station Record (mm)		Mekhtan dam		Musaibeeh dam	
	HSS5[*1]	HS173[*2]	Sa'awan -Haial House	S'awan- Brian Al-hosain School	Water level (m) A.B.R[*3]	Water volume (m^3)	Water level (m) A.B.R[*3]	Water volume (m^3)
09/04/2008	4.42	8.62	0.0	0.0	1.48	12611.60	3.84	10984.11
13/04/2008	4.40	9.66	0.0	0.0	1.29	10363.93	3.80	10739.27
16/04/2008	4.43	9.70	0.0	0.0	1.22	9576.54	3.77	10557.61
20/04/2008	4.44	9.74	0.0	0.0	1.12	8491.15	3.72	10258.57
23/04/2008	4.45	9.80	0.0	0.0	1.06	7862.78	3.69	10081.39
27/04/2008	4.47	11.23	0.0	0.0	0.98	7052.40	3.65	9847.75
30/04/2008	4.49	11.14	0.0	0.0	0.90	6274.28	3.62	9674.48
04/05/2008	4.52	11.02	7.5	-	0.84	5712.49	3.61	9617.09
06/05/2008	3.50	10.02	13.9	-	0.82	5529.48	4.36	14442.30
10/05/2008	4.32	10.88	23.4	-	0.79	5259.01	4.45	15093.24
13/05/2008	4.38	10.83	-	-	0.73	4732.92	4.43	14947.24
17/05/2008	4.37	10.77	1.6	-	0.64	3982.01	4.40	14729.68
20/05/2008	4.39	10.71	-	-	0.59	3585.38	4.39	14657.55
09/07/2008	4.49	10.33	0.4	-	0.51	2982.64	3.76	10497.43
15/07/2008	4.53	10.43	0.0	-	0.38	2091.78	3.69	10081.39
22/07/2008	4.52	10.33	0.0	-	0.21	1110.24	3.61	9617.09
29/07/2008	4.4[*4]	10.3	16.2	-	2.52	27483.21	4.05	12318.91
02/08/2008	4.29	10.29	1.8	5.5	2.56	28134.44	4.01	12058.25
05/08/2008	4.17	10.24	0.0	-	2.41	25720.86	3.97	11800.61
09/08/2008	4.17	10.17	5.7	-	2.35	24777.44	3.93	11545.99
12/08/2008	4.15	10.18	3.2	5.0	2.4	25562.74	3.9	11357.01
16/08/2008	3.48	8.24	0.0	0.0	2.33	24465.79	1.23	980.56
19/08/2008	3.71	7.1	0.0	0.0	2.28	23692.93	0.68	292.53
23/08/2008	5.92	7.48	3.4	2.2	2.21	22626.02	0.67	284.01
26/08/2008	4.42	7.61	0.0	0.0	2.15	21725.71	0.65	267.38
30/08/2008	4.49	7.73	0.0	0.0	2.07	20545.93	0.61	235.75
06/09/2008	4.45	7.83	0.0	0.0	1.95	18821.24	0.55	192.33
10/09/2008	4.71	7.88	0.5	1.2	1.87	17702.01	0.53	178.92
13/09/2008	4.84	11.24	0.0	0.0	1.8	16743.13	0.50	159.79
20/09/2008	4.59	11.59	0.0	0.0	1.64	14624.73	0.45	130.49
11/10/2008	7.00	11.34	0.0	0.0	1.18	9136.74	0.26	47.73
22/10/2008	4.55	9.54	-	-	0.94	6659.24	0.18	25.76
25/10/2008	4.53	9.72	18.2	27.6	1.51	12980.85	0.18	25.76
29/10/2008	4.52	9.41	0.0	0.0	1.47	12489.38	0.17	23.53
01/11/2008	4.50	9.36	12.4	15.4	2.91	34062.64	1.18	899.61
08/11/2008	4.37	9.38	0.0	0.0	2.81	32327.38	1.06	720.68

Source: (SBWMP, 2008).

*1 Dug well with UTM Coordinate UTM 1700726N, 428053E at elevation 2409 m.
*2 Dug well with UTM Coordinate UTM 1700453N, 427512E at elevation 2398 m.
*3 Water height above reservoir bottom.
*4 No data in this date (the average was taken).

CHAPTER FOUR

GEOELECTRIC SURVEY

Geoelectrical Survey

4.1 Introduction

Geophysical exploration methods are applied to obtain information of the subsurface which can't be obtained or can be obtained in high cost. The most widely used geophysical methods in groundwater studies are the geo-electrical methods. The direct current DC resistivity method is one of many geo-electrical methods like Self-Potential, Telluric-Current method, Inductive methods, and Electrical well Logging. (Nasher, 2004).

The objective of electrical sounding is to deduce the variation of electrical resistivity with depth below a given point on earth's surface, and to correlate it with geologic knowledge in order to infer the subsurface structure in greater detail (Zohdy et al., 1974).

The advantages of this method are: equipment is inexpensive, portable, easy to operate, and it is economical. Although it is probable that geo-electrical investigations will never replace drilling, they can provide information about the principal features of the underground structure. In addition, in such a way of investigation the number of drillings may be held to a minimum and the depths of the exploratory boreholes may be estimated before hand (Dobrin, 1952 and Brown *et al*, 1972).

In this study, the aim of geo-electrical investigation is to provide extra hydrogeological information about the subsurface that would help 1) to evaluate the recharge across the wadi through determine whether the aquifers contain water or not (Horizontal variation), 2) to determine the depth of water in the aquifers (Vertical variation) and 3) the relationship between aquifers water depth and it's distance from the dam. More specifically, the objectives are as follows:

1- Delineate the vertical distribution of geological formation within the 10 investigation sites, it's suitability for groundwater recharge and determines their properties (granular, fissured, karstic or massive and compact rocks).

2- The types of the aquifers and their thickness.

3- The thickness of unsaturated zone (Top soils).

4- The depth to water table in the alluvial aquifer.

5- Subsurface structure.

6- The depth to the saturated zone and its thickness

Many books describe the methods in detail such as, those by Zohdi (1974) and Richard (1992) in which they describe the details of this method and its application in groundwater studies. The main principles will be discussed below.

Geophysical exploration method is based on measuring the contrast in physical properties of subsurface. Thus, the electrical resistivity method is founded on contrast in the electrical resistivity values of the different lithological units or of formation with the different water salinity. The electrical properties of most rocks are primarily dependent upon the amount of water in the rock, the salinity of water and the distribution of the water in the rock. Saturated rocks have lower resistivity than unsaturated and dry rocks; the higher the porosity of the saturated rock, the lower its resistivity and also the higher the salinity of saturating fluids, the lower the resistivity of the formation. (YOMINCO, 1985). So, the effective parameters in the resistivity are the geometry of the units, porosity, water content, type of water content (saline or fresh), minerals, structures and …etc. The DC resistivity method relies on the application of Ohm's Law:

$$V = I \cdot R$$

Where:

V = Difference of potential between two points.

I = Current.

R = Resistance measured between the same two points as the difference of potential.

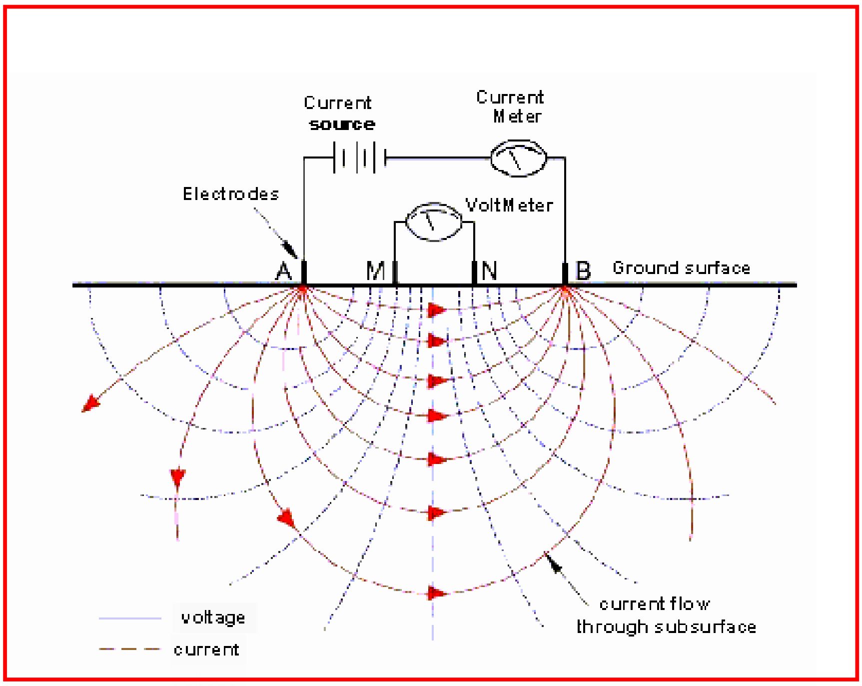


Figure 4.1 Basic principle of DC resistivity measurements. **A** and **B** are the current electrodes, **M** and **N** are potential electrodes.

The **R** is related to apparent resistivity ρ_a through both the path length ***L*** and the cross-sectional area ***A*** through which the current flows. The DC electrical resistivity of the earth can be studied by measuring the electrical potential distribution produced at the earth surface within two electrodes **M**& **N**) by an electrical current that is passed through the earth within two electrodes **A**& **B** Figure4.1.

The voltage difference between M and N and the corresponding apparent resistivity is given by:

$$\rho_a = \frac{2\pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}} \cdot \frac{\Delta V}{I}$$

Where AM, BM, AN, and BN are the distances between the corresponding electrodes.

4.2 Survey methods and electrode configuration

Resistivity surveys are conducted as either soundings or profiles. A sounding is used to determine changes in resistivity with depth. The electrode spacing is varied for each measurement, but the center point of the array is constant. A resistivity profile is used to detect lateral variations in resistivity. For this method the electrode spacing is fixed while the center of the array is varied.

There are various electrode configurations which can be used in resistivity surveying. The apparent resistivity ρ_a that is measured by the array depends on the geometry of the electrodes. The majority of resistivity surveys use two current electrodes and two potential electrodes. There are many electrical resistivity configuration array such as Schlumberger array, Winner array and Dipole Dipole array. In this study Schlumberger array set up in Figure 4.2, four electrodes are placed along straight line and symmetrical with its center.

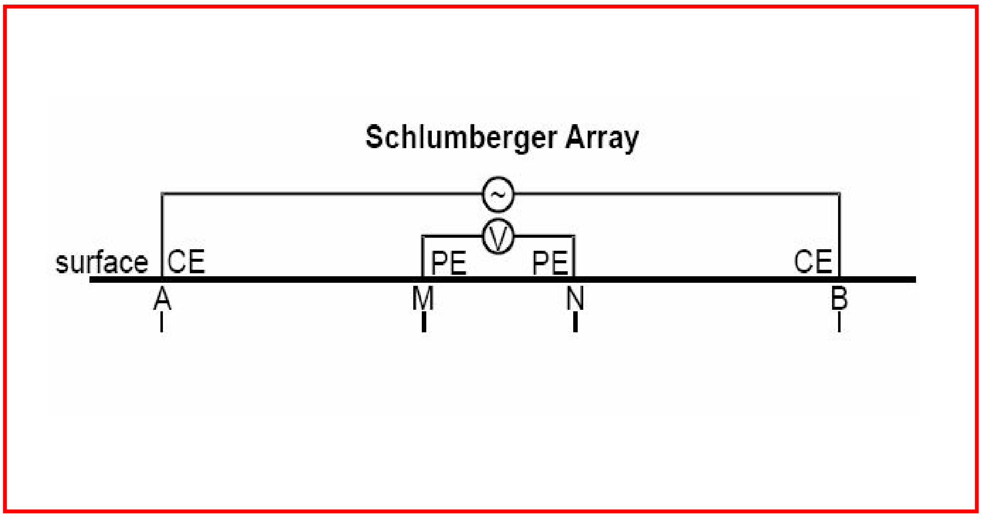


Figure 4.2 Schlumberger array, A and B are current electrodes, M and N are potential electrodes. The distance AB should be large compared to the distance MN

In the case of a homogeneous earth, the potential differences between the electrodes are:

$$\Delta V = \frac{\rho I}{\pi} \cdot \frac{MN}{(AB/2)^2 - (MN/2)^2}$$

Thus the resistivity ρ is:.

$$\rho = \pi \frac{(AB/2)^2 - (MN/2)^2}{MN} \cdot \frac{\Delta V}{I} \qquad \text{Ohm-m}$$

Where $$\pi \frac{(AB/2)^2 - (MN/2)^2}{MN} = K$$

K = called the geometric factor depend on the mutual electrode distance so:

$$\rho = K \cdot \frac{\Delta V}{I} \qquad \text{Ohm-m}$$

In the case of layered earth, build up out of a serious of strata or units with different resistivities, apparent resistivity values are measured.

$$\rho_a = K \cdot \frac{\Delta V}{I} \qquad \text{Ohm-m} \qquad \text{(YOMINCO, 1985)}$$

The apparent resistivity result of measuring resistivity over an inhomogeneous and or an isotropic. It depends on the electrode configuration and the geology of the area.

4.3 Field procedure and survey data

The geo-electrical field work has been carried out in September 2008. All measurements were made using IRIS instrument SYSCAL R2 resistivity meter of the Department of Geophysics at the Geological Survey and Mineral Resources Board

(GSMRB). It is a fully automatic equipment design for DC electrical survey applied to groundwater exploration, environmental studies, civil engineering, structural geology investigation and mineral exploration. It combines the transmitter and receiver in a single unit and the power source is external as in Figure 4.3

The survey is Vertical Resistivity Sounding (VES) type. All measurements were taken using Schlumberger array. The Schlumberger array has a number of advantages over other arrays. First, the potential electrodes are not moved, or at least are moved a minimum number of times during a given electrical sounding. This means a considerable saving in material and effort. Also, any local inhomogenities near the fixed potential electrodes including those caused by hammering in the probes are constant during the measurements. These results from the fact that the potential electrodes are not moved or at least moved a minimum number of times during a given electrical sounding.

This configuration is widely used to measure vertical changes in the resistivity of the subsurface rocks below the investigation site.

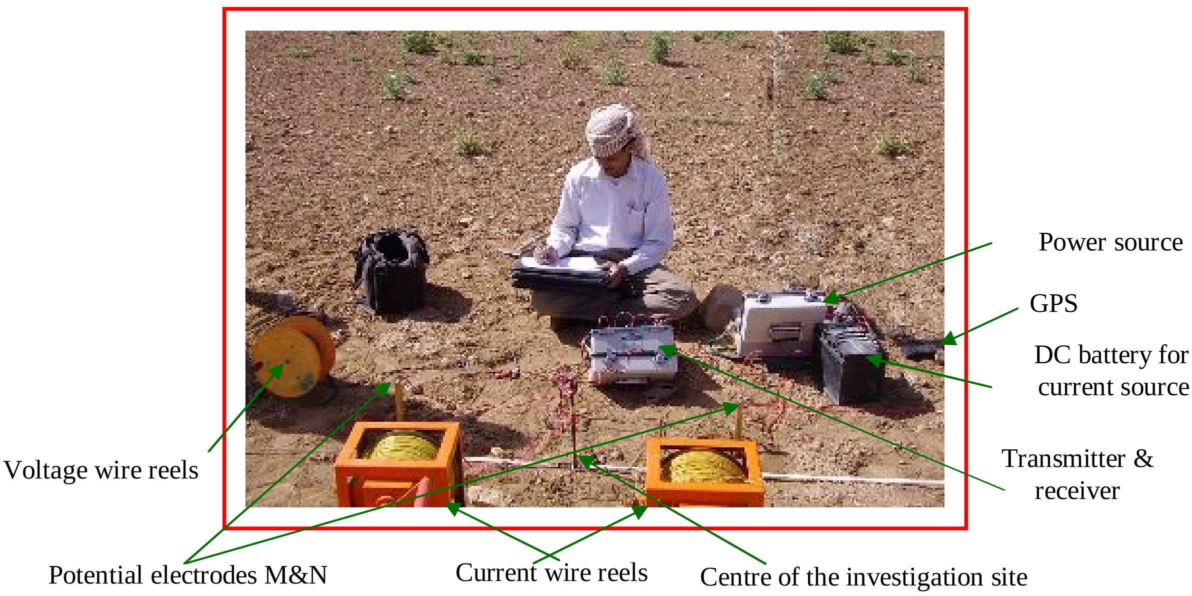


Figure 4.3 Field instruments, IRIS instrument SYSCAL R2 resistivity meter and the other tools.

The total number of vertical electric sounding investigation sites is 10 points summarized in Table 1.1 which shows the coordinates, elevation and half spacing of these VES sites. It is located across the wadi Mekhetan toward wadi Sa’wan with different distance from the dams sites as in the map in Figure 1.7.

During the survey, every precaution was taken to reduce and avoid errors in the resistivity measurements, as follows:

- The profiles were chosen far away from the noise sources such as power lines, pipe lines, and buildings.
- All sites of the VES have been chosen in flat areas to avoid topography effects.
- The utilized field layout start with a current electrode separation (AB/2) of from 1.5 to 40 m with potential electrodes separation (MN/2) of 0.5 m, (AB/2) from 30 m -200 m with potential electrodes separation (MN/2) of 10 and (AB/2) from 150 m – end of the investigation (300 or 900) m with potential electrodes separation (MN/2) of 50 m. Tables in the appendix 4 show all data measurements. The maximum separation of current electrodes was affected by the difficult topography and intensive agriculture areas.

The profile in Figure 4.4 and the three dimension elevation map in Figure 4.5 show the topographic of the earth surface where the geo-electric investigation points (VES) are set as well as their elevation above sea level. It shows that the high elevation is in the eastern part of the study area in the VES station 1 which locates near the dams and there is a gentile slope in the earth surface toward the middle part of the study area and forming small graben.

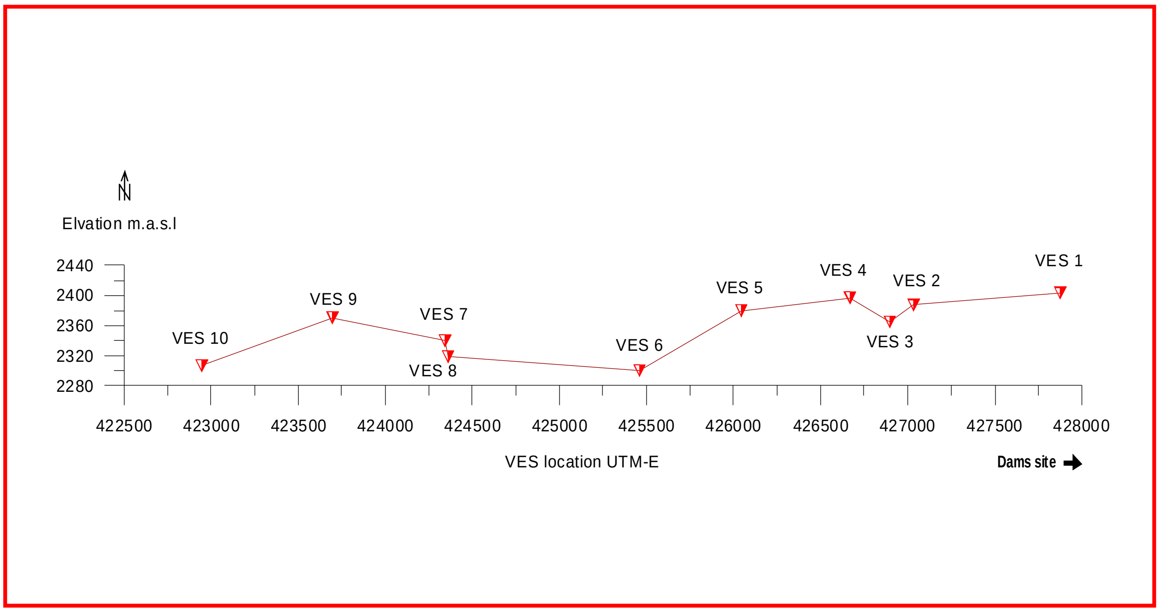


Figure 4.4 Cross section elevation profile with the locations of geo-electric investigation sites.

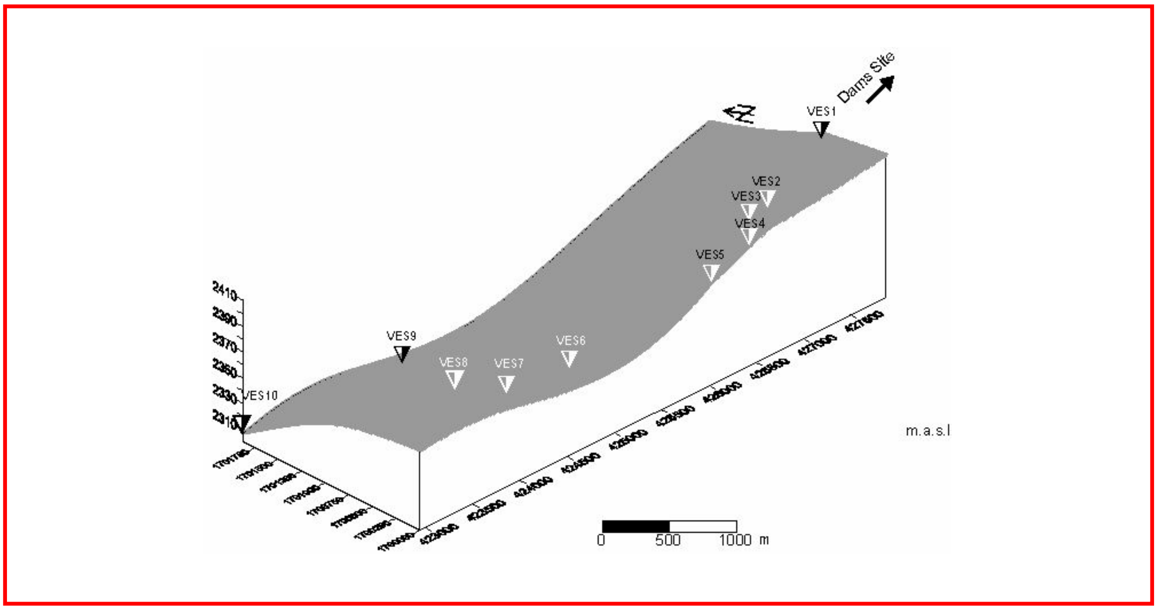


Figure 4.5 Three dimensions elevation map with the locations of geo-electric investigation sites

4.4 Data processing and interpretation:

The IRIS instrument SYSCAL R2 resistivity meter gives directly the apparent resistivities ρa (please refer to Appendix 4) with the potential and current reading.

4.4.1 Interpretation

There are two main methods used for interpreting the resistivity measurements. These are qualitative and quantitative methods.

4.4.2 Qualitative interpretation

To obtain a first, general impression of the study area, a qualitative interpretation is carried out by mapping the apparent resistivities of all investigation stations at fixed current electrode distance. These maps are useful for distinguishing a relatively high resistivity from the ones of relatively low resistivity at a certain AB/2 distance (not well define depth).

Iso- Resistivity contour maps

These maps are constructed according to the apparent resistivity (ρ_a) values measured at specific half current electrode spacing (AB/2) for every electrical sounding. The points of equal values are jointed together by iso-resistivity contours. These maps reflect and give a good picture about the lateral variations of the measured apparent resistivity values at different subsurface levels parallel to the ground surface.

In this study four iso-resistivity contour maps are constructed for the different electrode spacing (AB/2): 4, 10, 100, and 300. The Map in Figure 4.6, which constructed at half current electrode spacing (AB/2) = 4 m, shows that the eastern part of the study area near the dams locations especially at the site of VES 1 (300 m far from the dams) characterized by high resistivity values because of presence of alluvial deposits (sandy gravel and gravel) near the surface.

In the middle part of the study area especially at the site of VES 2, 3, 4, 6, 8 and 9, there is a decrease in the resistivity values due to presence of top wet soil (clay, sandy clay). The locations of the VES 5 and 7 represent dry soil.

The contour apparent resistivity map in Figure 4.7, at (AB/2) = 10 represents high values of resistivity in the location of VES 1 which is dry alluvial deposits (gravels and boulders). In most of the other VES locations in the map, the low resistivity occurs because of presence of alluvial deposits which is wet or saturated with water in most cases.

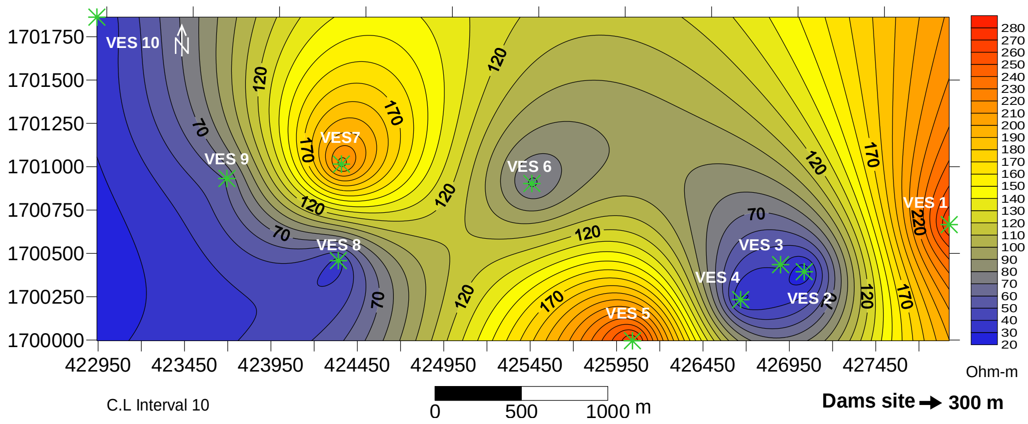


Figure 4.6 Iso-resistivity contour map in Ω.m at current electrode spacing (AB/2) = 4

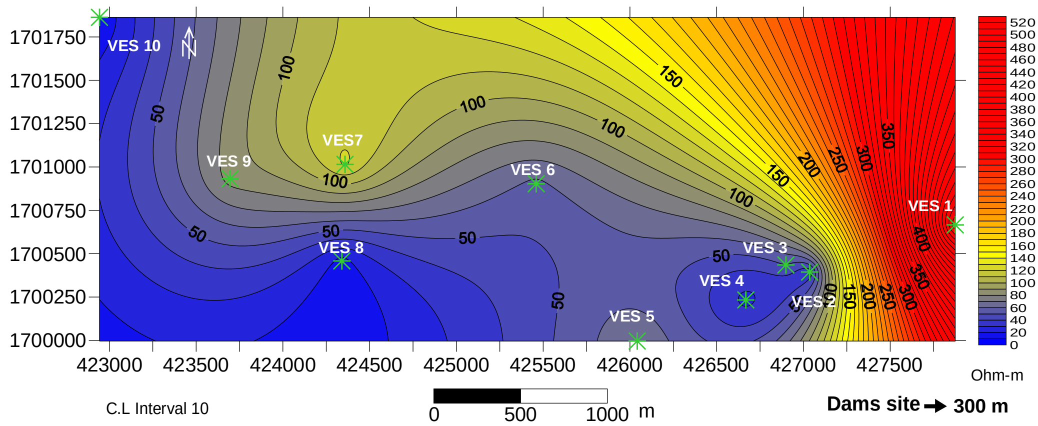


Figure 4.7 Iso-resistivity contour map in Ω.m at current electrode spacing (AB/2) = 10 m

The apparent resistivity contour map in Figure 4.8 reflects the presence of alluvial deposits (low resistivity) at the depth higher than the previous map. This layer appears in the middle of the study area especially on the location of VES 7, 8, 9 and 10, and disappears in the locations of VES 1. In the locations of VES 7 and 8 this layer has very low resistivity values reach 20 ohm.m because of the salinity increases in this area than other locations. The salinity increasing resulting from intensive water abstraction for agricultural irrigation activity in the middle of the study area are more than the eastern part of the study area.

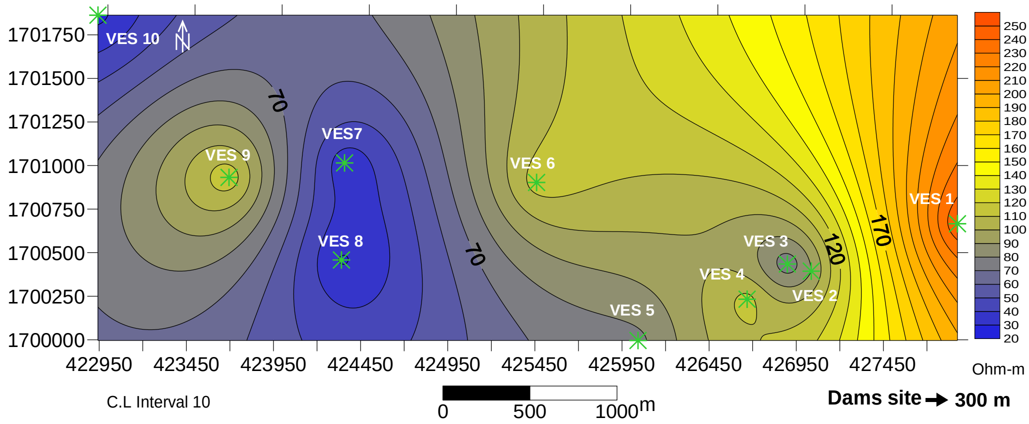


Figure 4.8 Iso-resistivity contour map in Ω.m at current electrode spacing (AB/2) = 100 m

Figure 4.9 represents low resistivity values in all the investigation sites that ranged from 50 ohm.m to 100 ohm.m. This low resistivity values reflects the presence of the main aquifer in the study area which is cretaceous Tawilah sandstone (saturated with water).

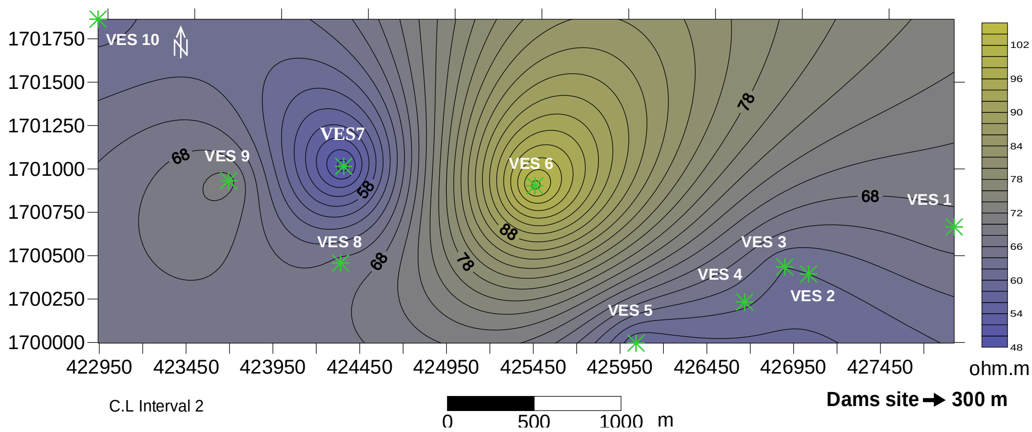


Figure 4.9 Iso-resistivity contour map in Ω.m at current electrode spacing (AB/2) = 300 m

4.4.3 Quantitative interpretation of resistivity data

The apparent resistivities ρ_a are different from the true resistivity ρ_t. The quantitative interpretation is concerned with calculations of the true resistivity and the thickness of the layers. This process depends on applying ρ_a and the half electrode spacing (AB/2). Consequently, the final resistivity structures of sounding data were determined applying the automatic interpretation method (Zohdy, 1989).

The main objective of the interpretation process of the measured VES-curves is to determine the different parameters of the subsurface geo-electrical section from the observed sounding curves. This is not an easy task regarding to the problems of 1)"Subsurface suppression which mean that layer with resistivity value in between the resistivities of the layers lying immediately above and below, may not be reflect in the curve. 2) Problem of equivalence, which mean that there is no unique solution for a certain curve, many models, composed of sequences of layer resistivity and thickness could produce the same apparent resistivity curve" (YOMINCO, 1985). The selection of the model which represent the best condition in the subsurface depend on the knowledge (pervious data) about the study area (Geology, hydrology, haydrogeology). In this study the geo-electric chapter comes after the chapters of geology, hydrology, and hydrogeology which contains additional information that would help in the interpretation process. In addition to the results of wells inventory which has been found by WEC (2001). Computer interpretation technique is used (VES, Version 4.20-S program, Fortran version, TNO, Institute of Applied Geoscience, Delft, The Netherlands) to compute the true resistivity curve (model) from the apparent resistivity curve after making the apparent resistivity curve matching.

Curve Matching

The Measured apparent resistivities are plotted against half electrode distance (AB/2) on log – log papers. Because of taking two apparent resistivities measurements in the same (AB/2) distance with different potential electrode distance, so that they will be small differences between the two apparent resistivities measurements. These differences depend on number of subsurface layers and its properties (Homogeneity or inhomogeneity). Figure 4.10 A (of VES 10) shows the two resistivities reading in each of the following case:

1- Distance AB/2 = 30 m with MN/2 distance 0.5 m and 10 m.

2- Distance AB/2 = 40 m with MN/2 distance 0.5 m and 10 m.

3- Distance AB/2 = 150 m with MN/2 distance 10 m and 50 m

4- Distance AB/2 = 200 m with MN/2 distance 10 m and 50 m.

Curve matching is prior step in order to complete the interpretation process. Mathematical formula below is used for shift calculations. When the calculated values (shift0 & shift1) was entered into the VES analysis program then curve will be matching as in Figure 4.10B.

$$\textbf{Shift (0)} = \left[\frac{\text{Log}\left(\frac{(\rho\ AB/2=30)_{MN=10}}{(\rho\ AB/2=30)_{MN=0.5}}\right) + \text{Log}\left(\frac{(\rho\ AB/2=40)_{MN=10}}{(\rho\ AB/2=40)_{MN=0.5}}\right)}{2} \right] \cdot 100$$

$$\textbf{Shift (2)} = \left[\frac{\text{Log}\left(\frac{(\rho\ AB/2=150)_{MN=50}}{(\rho\ AB/2=150)_{MN=10}}\right) + \text{Log}\left(\frac{(\rho\ AB/2=200)_{MN=50}}{(\rho\ AB/2=200)_{MN=10}}\right)}{2} \right] \cdot 100$$

Shift (1) = Shift (0) + Shift (2) (Quoted from my colleague, GSMRB)

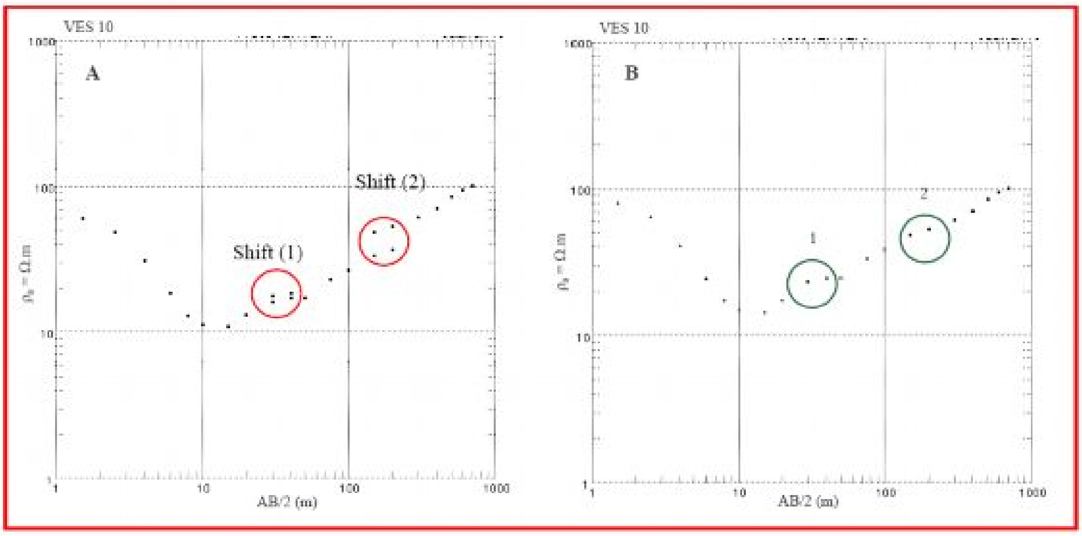


Figure 4.10A Shift occurs because of reading ρ with different potential electrode distance. B) After the correction by using mathematical formula.

- Representations of the Quantitative Interpretation

The results of computer interpretation, which is the model of true resistivites and depths of the layers obtained from the apparent resistivity curve for every VES, are given in Figure 4.11. (A, B, C, D, E, F, G, H, I and J).

The interpretation of these models can be summarized as the following: All VES's measured in E-W direction along the wadi with different AB distance depend on the topography and other obstacle. The interpretation of the curves and models is that the upper part of the subsurface in the study area formed by low to high resistivity layers ranging from 5 ohm.m to 400 ohm.m and reach to more than 2000 ohm.m in only the model of VES1 (characterized by big dry boulders). These layers consist of alluvial deposits clay, silt, sandy clay, gravels and boulders, have different thicknesses from 3-4 m in the site of VES1 (eastern part of the study area) and increasing toward the west, downstream the wadi to reach to about 55m, in the locations of VES 7 and 8. The surface water table in this zone found from 4 meter in the eastern part of the study area (location of VES 1). This depth increased toward the west to reach to 8 m in locations of VES 2, 3, 4 and at depth from 15 to 27 m in the middle and western part of the study area (in the locations of the other VES's).

The second zone beneath the alluvial deposits has high resistivity (130 to 600 ohm.m). This part represents the upper part of tertiary volcanic rocks group, presence in all the VES's investigation sites and conceder as massive volcanic rocks. It found in different depth from the earth surface as follows:

1- At depth from 5 to 6 m in the location of VES1.

2- At depth 12 to 23 m in the location of VES 2, 3, 4, 5 and 6.

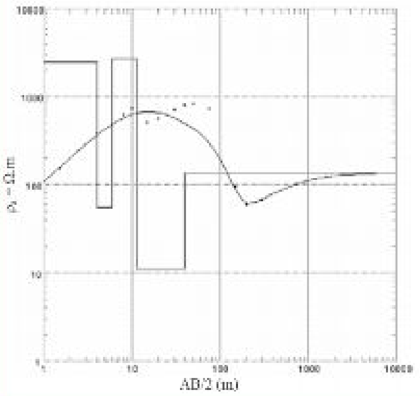
3- At depth from 56 to 45 m under the sites of VES 7 and 8.

4- At depth from 12 t0 30 m under the location of VES 9 and 10.

The lower part of this group is characterized by succession of low and high resistivity, under the most of the VES's investigation sites, represent the fractured and massive volcanic rocks.

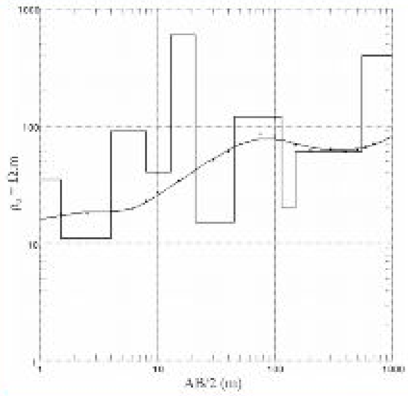
This group is considered as aquiclude aquifer except the fractured parts which consider as perched aquifer (contains water).

The last zone which is characterized with low resistivity in its upper part ranges from 20 to 120 ohm.m found at depth 135- 220 m from the ground surface. The upper part of this zone represents high porosity saturated sandstone rock. The lower part of this zone is characterized by high resistivity between 200 to 500 ohm.m which indicates low porosity and compact sandstone. The thickness of this zone reaches more than 500m.



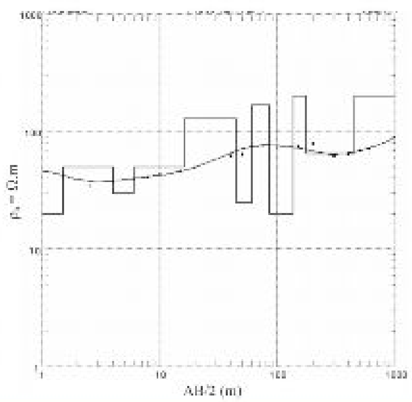
No. of Layers	Depth from sea level.		$\rho_i(\Omega.m)$
	From	To	
1	2403	2402.5	55
2	2402.5	2399	2500
3	2399	2397	55
4	2397	2391.5	2700
5	2391.5	2363	11
6	2363	-	135

Figure 4.11 (A) Interpretation of apparent resistivity data 0f VES 1 AB/2= 300 m



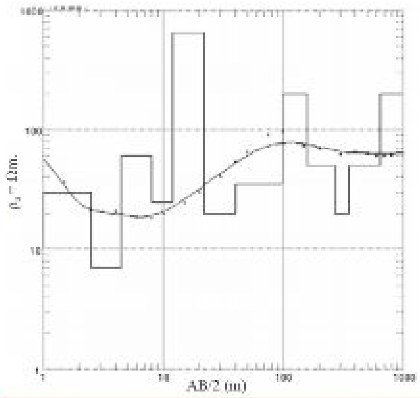
No. of Layers	Depth from sea level.		$\rho_i(\Omega.m)$
	From	To	
1	2387	2386.1	15
2	2386.1	2385.2	35
3	2385.2	2383	11
4	2383	2379	90
5	2379	2374	40
6	2374	2366	600
7	2366	2342	15
8	2342	2272	120
9	2272	2237	20
10	2237	1832	60
11	1832	>	400

Figure 4.11 (B) The interpretation of apparent resistivity data 0f VES 2 AB/2= 700 m



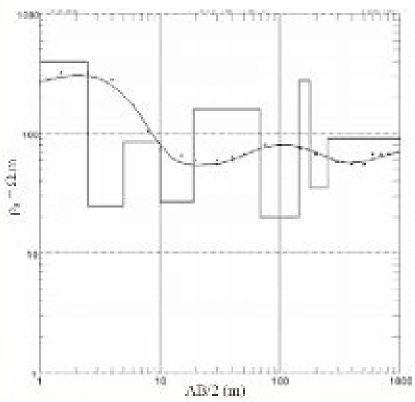
No. of Layers	Depth from sea level.		$\rho_i(\Omega.m)$
	From	To	
1	2365	2364.1	50
2	2364.1	2363.5	20
3	2363.5	2361	50
4	2361	2359	30
5	2359	2349	50
6	2349	2320	130
7	2320	2305	25
8	2305	2280	170
9	2280	2230	20
10	2190	2190	200
11	1915	1915	65
12	1915	-	200

Figure 4.11 (C) Interpretation of apparent resistivity data 0f VES 3 AB/2= 600 m



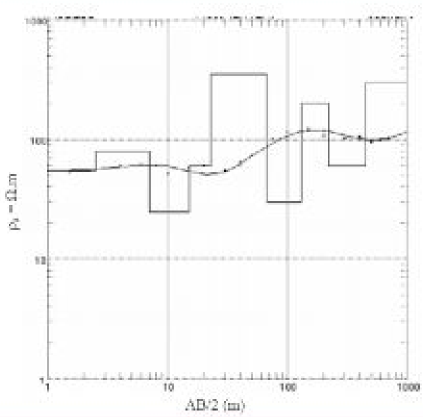
No. of Layers	Depth from sea level.		$\lvert\rho_i(\Omega.m)\rvert$
	From	To	
1	2397	2396.5	110
2	2396.5	2396	10
3	2396	2394.5	30
4	2394.5	2392.5	7
5	2392.5	2389	60
6	2389	2385	25
7	2385	2375	600
8	2375	2357	20
9	2357	2297	35
10	2297	2237	200
11	2237	2127	50
12	2127	2047	20
13	2047	1747	50
14	1747	-	200

Figure 4.11 (D) Interpretation of apparent resistivity data 0f VES 4 AB/2= 800 m



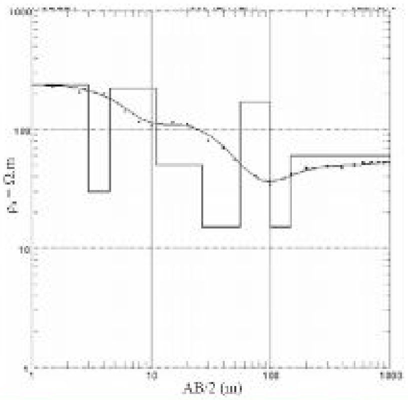
No. of Layers	Depth from sea level.		$\lvert\rho_i(\Omega.m)\rvert$
	From	To	
1	2380	2379.5	225
2	2379.5	2377.5	400
3	2377.5	2375	25
4	2375	2370	85
5	2370	2361	27
6	2361	2312	158
7	2312	2235	20
8	2235	2200	280
9	2200	2130	35
10	2130	>	90

Figure 4.11 (E) Interpretation of apparent resistivity data 0f VES 5 AB/2= 800 m



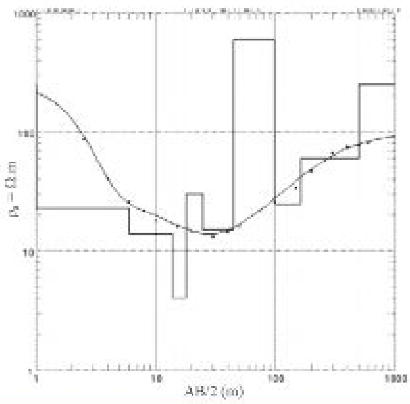
No. of Layers	Depth from sea level.		$\lvert\rho_i(\Omega.m)\rvert$
	From	To	
1	2300	2297.5	55
2	2297.5	2293	80
3	2293	2286	25*
4	2286	2277	60
5	2277	2233	350
6	2233	2170	30
7	2170	2080	200
8	2080	1850	60
9	1850	>	300

Figure 4.11 (F) Interpretation of apparent resistivity data 0f VES 6 AB/2= 700 m



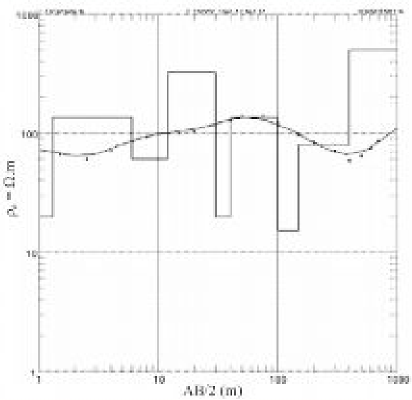
No. of Layers	Depth from sea level.		$\rho_i(\Omega.m)$
	From	To	
1	2319	2316	240
2	2316	2314.5	30
3	2314.5	2308	220
4	2308	2292	50
5	2292	2263	15
6	2263	2219	170
7	2219	2172	15
8	2172		60

Figure 4.11(G) Interpretation of apparent resistivity data 0f VES 7 AB/2= 900 m



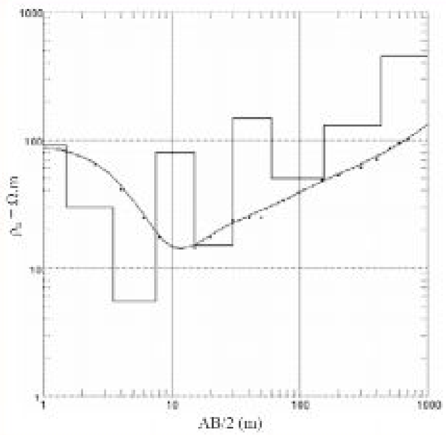
No. of Layers	Depth from sea level.		$\rho_i(\Omega.m)$
	From	To	
1	2340	2339	250
2	2339	2334	23
3	2334	2326	14
4	2326	2322	4
5	2322	2315	30
6	2315	2295	15
7	2295	2240	600
8	2240	2175	25
9	2175	1840	60
10	1840	>	250

Figure 4.11 (H) Interpretation of apparent resistivity data 0f VES 8 AB/2= 600 m



No. of Layers	Depth from sea level.		$\rho_i(\Omega.m)$
	From	To	
1	2370	2369.1	80
2	2369.1	2368.7	20
3	2368.7	2364	135
4	2364	2358	60
5	2340	2340	325
6	2340	2325	20
7	2325	2270	135
8	2270	2220	15
9	2220	1970	80
10	1970	>	500

Figure 4.11 (I) Interpretation of apparent resistivity data 0f VES 9 AB/2= 700 m



No. of Layers	Depth from sea level.		$[\rho_t(\Omega.m)]$
	From	To	
1	2307	2305.5	90
2	2305.5	2303.5	30
3	2303.5	2299.5	5.5
4	2299.5	2292	80
5	2292	2277	15
6	2277	2247	150
7	2247	2152	50
8	2152	1877	130
9	1877	>	450

Figure 4.11 (J) Interpretation of apparent resistivity data 0f VES 10 AB/2= 700 m

CHAPTER FIVE

ANALYSIS AND RESULTS

5.1 Geo-electric cross section

According to geo-electric survey result (Quantitative interpretation), the sequence and the properties of surface and subsurface layers are shown in Figure 5.1 which represent the geo-electric cross section EA, along the wadi which covers a horizontal distance about 5,200 m with a direction approximately EW. The dams are located in the east direction of this cross section on distance about 300 m. This cross section shows clearly the following:

1- Three aquifers with lithostratigraphic units from lower to upper as follows:

- **Cretaceous Tawilah sandstone**: consists of fine to coarse grain sandstone with small layers of silt. This formation represents the main confined aquifer in the study area. The thickness of this aquifer is more than 500 m. Water table depth in this aquifer is between 135 m to 220m.

- **Tertiary volcanic rocks** in which basalt flows mixed with rhyolite and ignimbrite overlying on sandstone aquifer. The thickness of these rocks is high in the middle of the study area which reaches 197 m and in the other places ranged between 90 m to 197 m. These rocks are considered as aquiclude formation except where fractured occurs in some part of this sequence and contain perched confined aquifer. Water exists in this formation at depths range from 6 m to 100 m.

- **Quaternary Alluvial aquifer** (unconfined aquifer): consists of layers of clay, sandy clay, sand, gravel and boulders. The thickness of this aquifer is four meters in the east to about 55 m in the middle of the study area. Table 5.1 summarizes these aquifers with its thickness and water depth.

2 – Presence high resistivity layer (massive volcanic rocks) directly under Alluvial deposits at depth between 6 m to 56 m from the earth surface. This layer prevents deep water percolation.

3- Presence two grabens: small one at distance 1,300 m from the dams site and the bigger one at distance 2,800 m in al-kherabah village.

4- Presence some surface and subsurface faults which most of them have direction NW-SE.

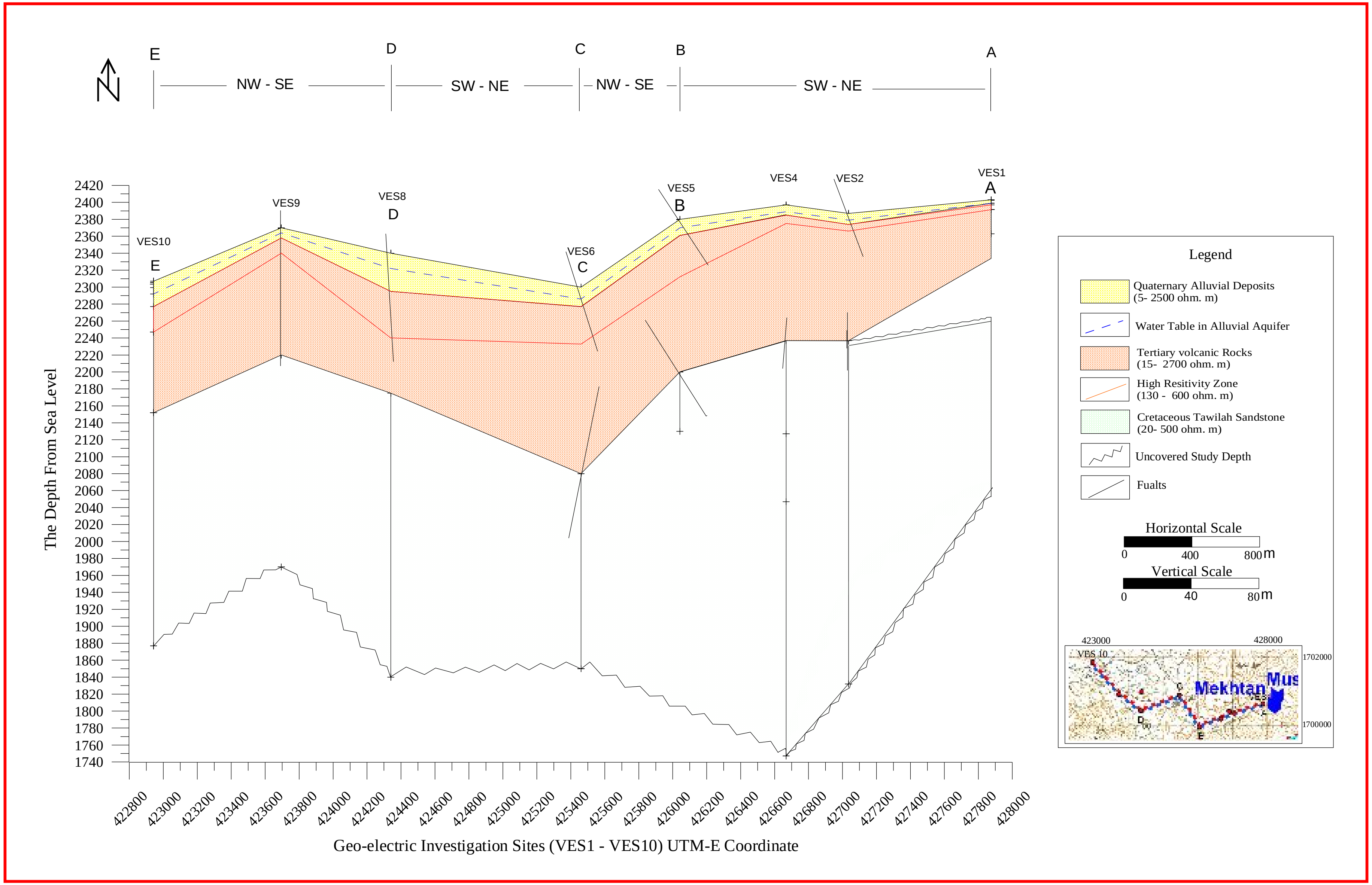


Figure 5.1 Geo-electric cross section E-A

Table 5.1 Aquifer types in the study area

Lithostratigrahic unit	Aquifers type	Thickness	Water table depth (Under earth surface)
Alluvial	aquifer / Unconfined	4 to 55	4 ~ 27 m
Basalt Aquifer	Aqiclude/ confined	90 to 197	6 ~ 100 m
Tawilah Sandstone	Aquifer/ confined	More than 500	135 ~ 220 m

5.2 Static water level in alluvial aquifer.

The maps in Figure 5.2 A, B and C show water table depth in alluvial aquifer above sea level and water table depth from earth surface with water flow direction. These maps were drawn from the results of quantities interpretation models of all VES (depth and layers). Maps in Figure 5.2A and B show that the depth of water increase from 6 m in the eastern part of the study area toward west which reaches to highest depth in the middle of the area. (In the second graben that appears in geo-electric cross section in Figure 5.1). Water flow direction is toward the first graben and then toward the second graben. Water level depth increased in the direction from east toward west except some areas in west where the water is a little shallow and takes two flow directions toward the east and west. This clearly appears in the map Figure 5.2C and also from the Figure 5.1, cross section with the topography.

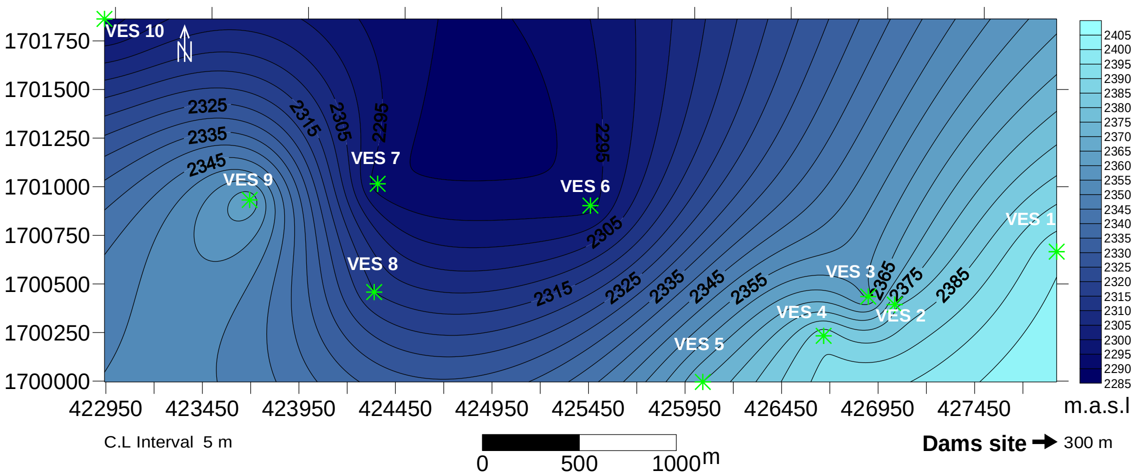


Figure 5.2 (A) Contour map of water table depth (m.a.s.l) of Alluvial aquifer in the study area

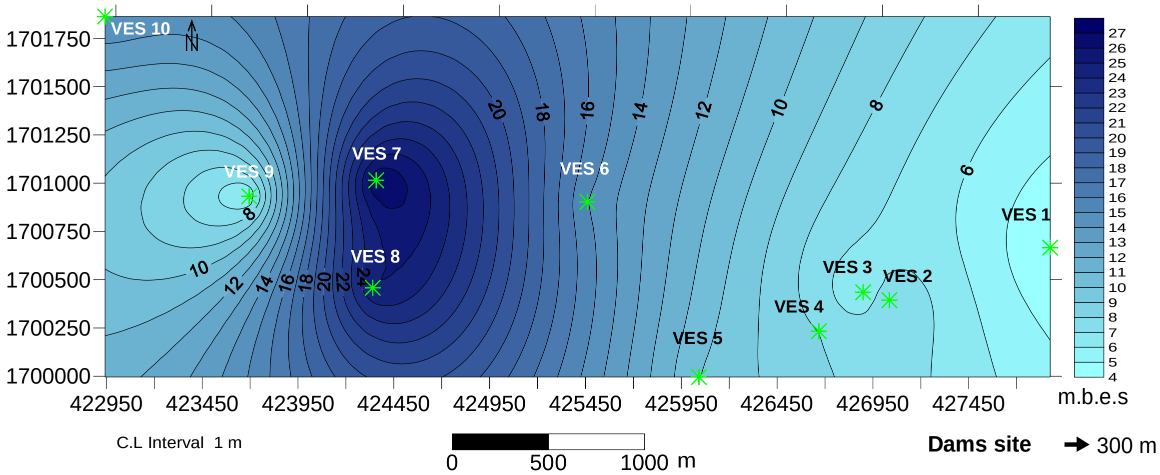


Figure 5.2 (B) Contour map of water table depth (from the earth surface) of Alluvial aquifer in the study area

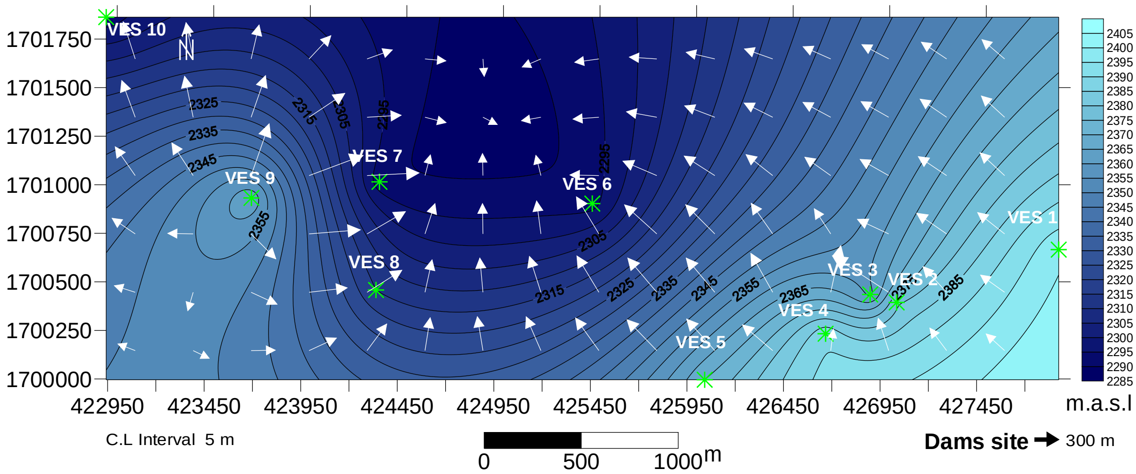


Figure 5.2 (C) Contour map of water table in alluvial aquifer with water flow directions.

5.3 Groundwater quality

Resistivity contour map of alluvial deposits at depth between 4-55m below the earth surface (containing surface water) as shown in Figure 5.3. This Figure shows a low resistivity value which reaches 20 ohm.m in the middle of the study area in location of VES 7 and 8 . This difference due to salinity concentration increase in this area than others locations. This is also clear and corresponding with the Figure 3.7 which represents the electrical conductivity in the study area. The high amount of EC encounter with the low resistivity as in the middle of the study area. The situation near the dams is different, the salinity is low. The reasons of the salinity increasing are because of the intensive water abstraction for irrigation purposes and high numbers of wells in this area.

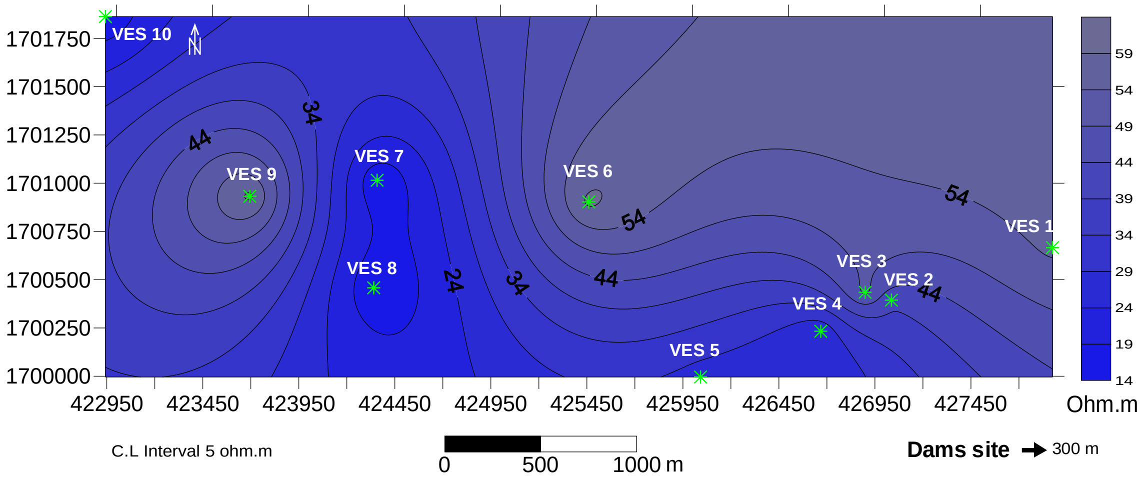


Figure 5.3 Resistivity contour map of alluvial layers

5.4 Groundwater artificial recharge evaluation

5.4.1 Water evaporation and infiltration from dam reservoir

As a result of hydrology study (dam water balance), the average amount of water infiltration is about 104.2 m^3/day (37512 m^3/year) from Mekhtan dam. This amount of recharge is sufficient amount but the evaporation losses are higher than the recharge. The average evaporation is about 129.5 m^3/day (46620 m^3/year). The amount of evaporation represents 58% from the total daily water lost from the dam reservoir in comparison to the amount of water infiltration which is 42 % in most months of the year. Table 5.2 summarizes the average result of dam water balance computation, evaporation and infiltration per day, month and year and the daily percentage from the total water lost from the dam.

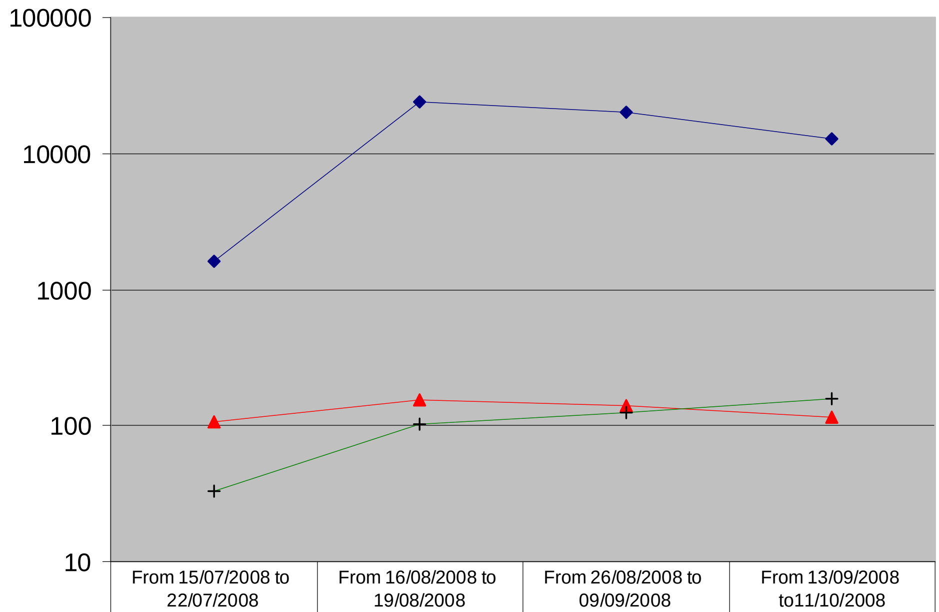
Table 5.2 Evaporation and infiltration from Mekhtan dam

Parameters	Per Day		Per Month (m^3)	Per Year (m^3)
	(m^3)	%		
Evaporation	129.5	58%	3885	46620
Infiltration	104.2	42 %	3126	37512

5.4.2 Relationship between evaporation, infiltration and water levels in the reservoir

The relationship between evaporation, infiltration and amount of water volume in Mekhtan reservoir is illustrated in Figure 5.4 A, B and C. It is clear from the Figures that the amount of infiltrate water depends on the water level and water volume in the dams. When the water level is very low then the amount of infiltration water is low too. The evaporation is approximately constant in all periods of computations with little change due to water surface area increasing (change water level in the reservoir) or weather change.

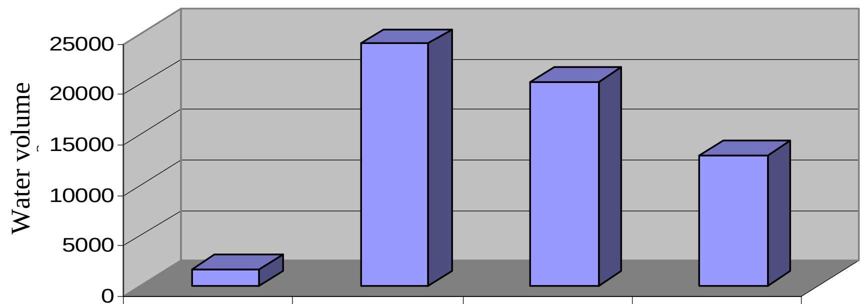
Figure 5.4A clearly shows the strongly relation between reservoir water level fluctuation and the amount of water infiltrate from the reservoir. It shows that in the period where water volume equal 1601 m^3, the evaporation equal 107.3 m^3/day. When the water volume (water level) in the dam increased to 20,273.5 m^3, the evaporation amount is a little bit changed, equal 139.4 m^3/day. On the other hand the amount of water infiltrate in the first period equal 33 m^3/day and in the second period it significantly increased (four times), equal 125 m^3.



	From 15/07/2008 to 22/07/2008	From 16/08/2008 to 19/08/2008	From 26/08/2008 to 09/09/2008	From 13/09/2008 to11/10/2008
Average Water Volume (m^3)	1601.01	24079.36	20273.475	12939.935
Evaporation (m^3) /day	107.25	154.67	139.43	115.53
Infiltration (m^3) /day	32.97	102.95	124.61	156.13

Figure 5.4 (A) Relationship between evaporation, infiltration and reservoir water volume in the periods of monitoring.

The previous results could be presented differently as in Figures 5.4B and 5.4C. The former Figure shows the average amount volume of water in dams reservoirs during the periods of measurements which is represent 7 days, 3 days, 11 days and 28 days. This amount is differing from period to period, from only 1601 m^3 to 20,273 m^3. Figure 5.4C, on the other hand, shows the relationship between that amount in the reservoir and the daily evaporation and infiltration which is daily net loss from that amount during those periods. It is clear, as mentioned before, that the evaporation amount is approximately constant even though the daily net loss increased or decreased. The water infiltration decreases significantly when the water levels is decreased in the dam reservoir.

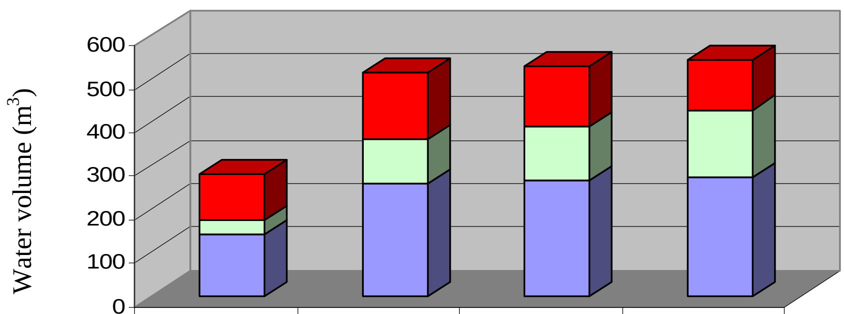


	1	2	3	4
Average Water Volume (m^3)	1601.01	24079.36	20273.475	12939.935

X axis: Periods of Measurements

1		2		3		4	
15/07/08	22/07/08	16/08/08	19/08/08	26/08/08	06/09/08	13/09/08	11/10/08

Figure 5.4 (B) Average amount of water in Mekhtan reservoir during the periods of measurements.



	1	2	3	4
Evaporation (m^3)	107.25	154.67	139.43	115.53
Infiltration (m^3)	32.97	102.95	124.61	156.13
Net Loss/day	140.22	257.62	264.04	271.66

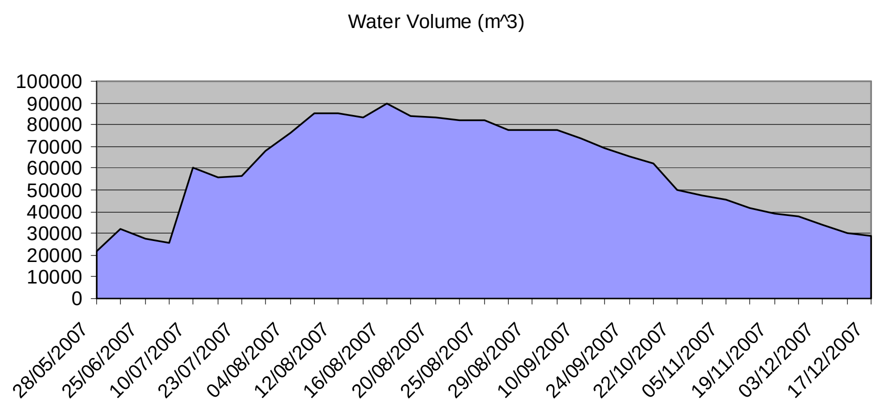
X axis: Periods of Measurements

1		2		3		4	
15/07/08	22/07/08	16/08/08	19/08/08	26/08/08	06/09/08	13/09/08	11/10/08

Figure 5.4 (C) Relationship between evaporation, infiltration and net water volume lost per day in the periods of monitoring

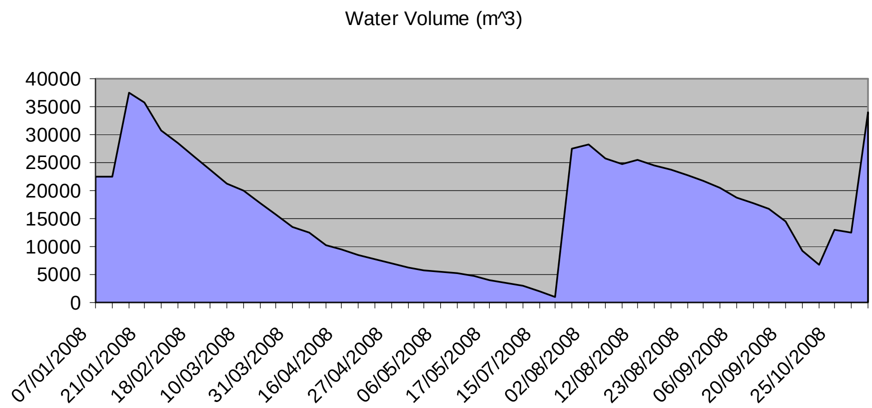
5.4.3 Relationship between reservoir capacity and yearly water volume stored

Even if the constructed capacity of the reservoir is high, the yearly water stored in the dams is low. Figures 5.5 A and B illustrate water fluctuation in the dam during the year 2007 and year 2008. The maximum amount of water which stored in year 2007 is equal to 88,508.4 m^3 whereas in 2008 is equal to 37020.2 m^3. However, these numbers represent small amounts of water compared to700,000 m^3 which is the full capacity of the dam at the maximum reservoir level.



Date		Water Level		Water Volume	
from	To	Min.	Max.	Min.	Max.
28/05/2007	08/11/2008	2.15	5.51	21477.74	88508.35

Figure 5.5 (A) Water's reservoir fluctuations (Max. and Min. volume in 2007)



Date		Water Level		Water Volume	
from	To	Min.	Max.	Min.	Max.
07/01/2008	08/11/2008	0.21	3.10	1097.74	37020.23

Figure 5.5 (B) Water's reservoir fluctuations (Max. and Min. volume 2008)

5.4.4 Relationship between water table depth of the two dug monitoring wells

As result of hydrogeology study, monitoring of dug wells number HS173 and number HSS5. The relationship between water table depths (Static water table) of the two dug monitoring wells is illustrated in Figure 5.6. The Figure shows that there is a clear match between the fluctuations of water levels in the two observation wells. This relationship indicates that these two wells were affected by the same source of effect.

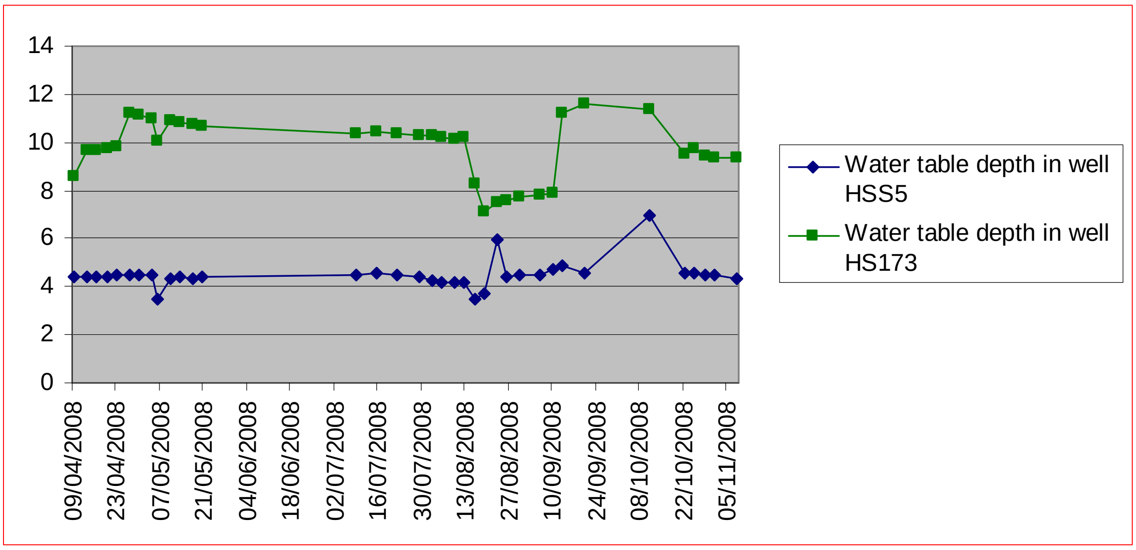


Figure 5.6 Relationship between static water table the two dug monitoring wells

5.4.5 Relationship between water table depths of monitoring wells and reservoir's water levels

The relationship between the static water level of the wells (measured from earth surface) with the water levels in Mekhtan and Musaibeeh dam during measurement periods is shown in Figure 5.7A, B. It can be noticed that there are reverse relationship between water table levels of wells and water levels in dams i.e. by increasing the water levels in dams, the water depth decreased in two opserved wells in most of the moniotoring periods which is very clear in Mekhtan dams. This indicates that the source which affects on wells and leads to increase the water table (groundwater recharge) is by the dams.

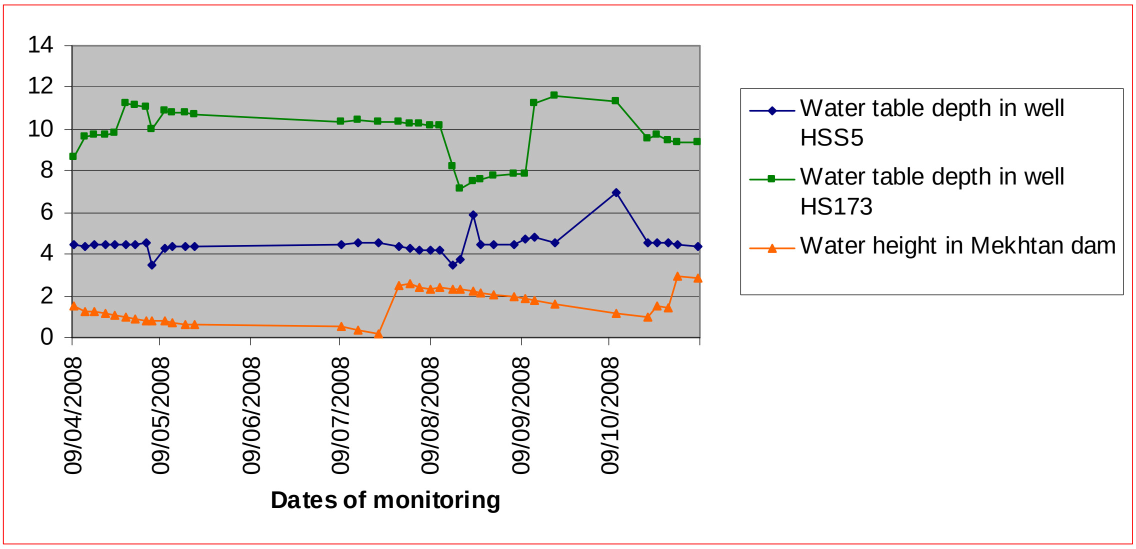


Figure 5.7 (A) Relationship between water table of two observation wells and Mekhtan's reservoir water levels

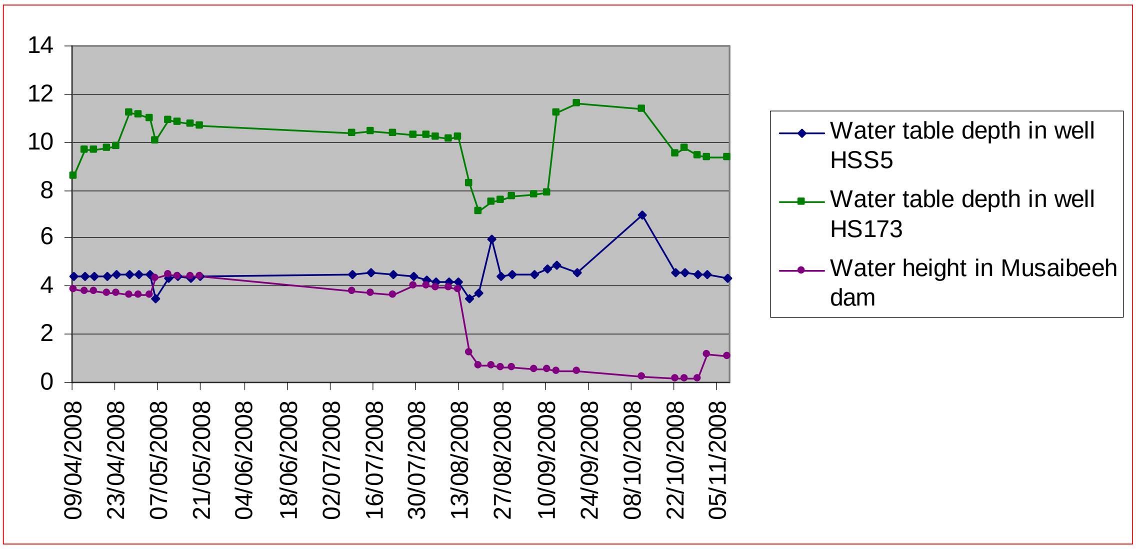


Figure 5.7 (B) Relationship between water table of two observation wells and Musaibeeh's reservoir water levels

5.4.6 Relationship between water table of monitoring wells and rainfall record

The relationship between water table depth of monitoring wells and rainfall record is a reverse one. The water table depth decreases with the duration of rainfall recorded. As in Figure 5.8, the relation is clear in well number HSS5 which is closer to the dams. The reasons of that are as follows:

1- The increase of water level in the dams.

2- The decrease of the water abstraction from well which used for irrigation.

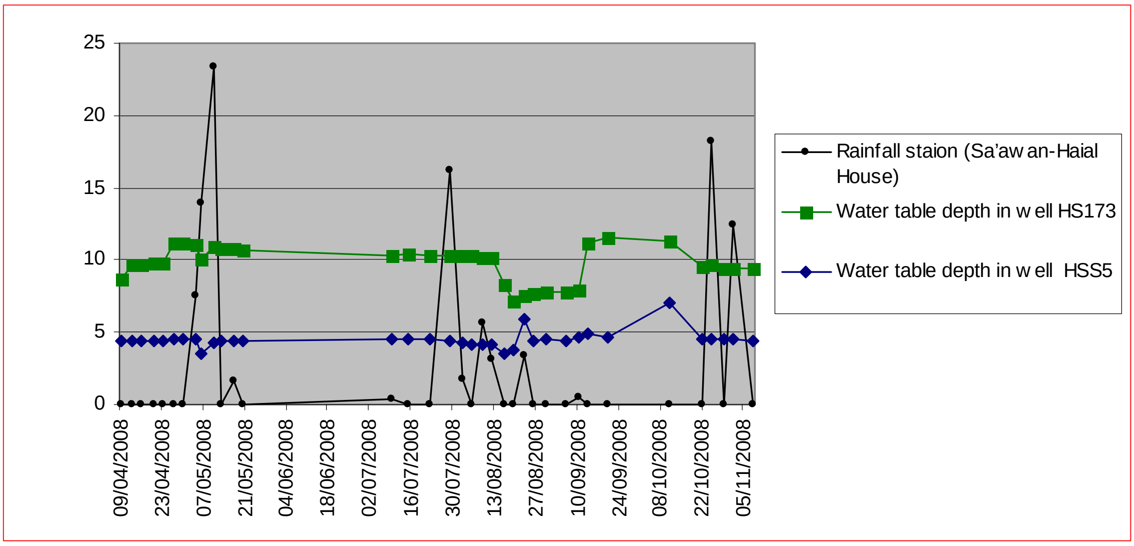


Figure 5.8 Relationship between water table of two observation wells and rainfall record

5.4.7 Community assessment of groundwater recharge through the dams

During the people interview (please refer to Appendix 5) in this study, the interviewees' vision about artificial groundwater recharge by the dams was obtained using many questions regarding the effect of dams on wells, dug and borehole wells. The sample for the interview was selected based on how far they are from the dams location. They are divided into three groups 1) those who are near to the dams and represent about 20.5% from the total sample of the interview, 2) those who are at the middle distance from the dams and represents around 38.6% and 3) those who are far away from dams and represent about 38.6%. In addition, few people from the sides of the wadi that represent 2.3%.

When asked about the effect of the existing dams on dug wells, people live near the dams 67% of them said that water level rises, 22% of them said that the water remain constant and 11% of them said that the water level drawdown as these percentages illustrated in Figure 5.8A. For the second group, half of them said that the water raised in the dug wells where 12% of them said that there was no effect on water level of the wells, 12% said the water in the wells is drawdown and about 29% of this group said that the wells was drought. The third groups, which they live far from the dams, most of them (76%) said the wells were drought and 24% said water level in the wells was dropdown. Figure 5.9A represents the percentages of all those groups.

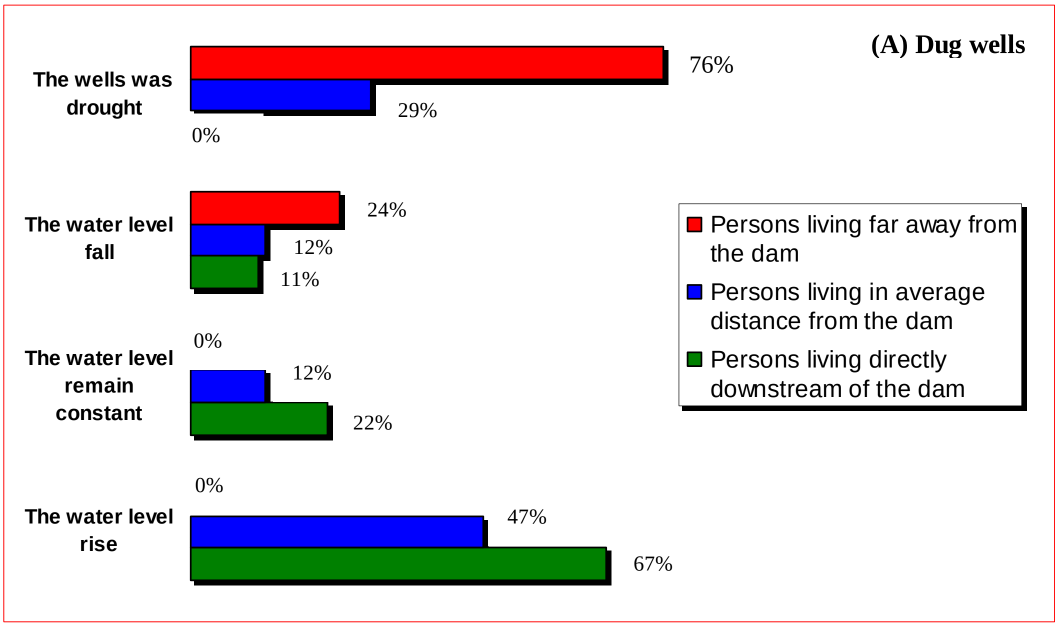


Figure 5.9 (A) people viewpoint about the effect of constructed dams on dug wells

For the deep wells, as in Figure 5.9B, about 33% from the first group said that water level raised, 44% were of the view that water remains constant and 22% said that the water level drawdown. The second group, 47% of them said that water level raised, 33% said water remains constant and 20% said water level draws down. The third group only 18% said that water level raised but the others 41% of them said no change on water levels of the wells and 41% said water drawdown. When asked about the frequency of increasing the borehole wells depth, most people in first and second group said that the wells drilled to higher depth from the beginning. The third group, 41% of them said the wells required deepen every 5 to 10 years and 35% of these groups said also that wells drilled to higher depth from the beginning.

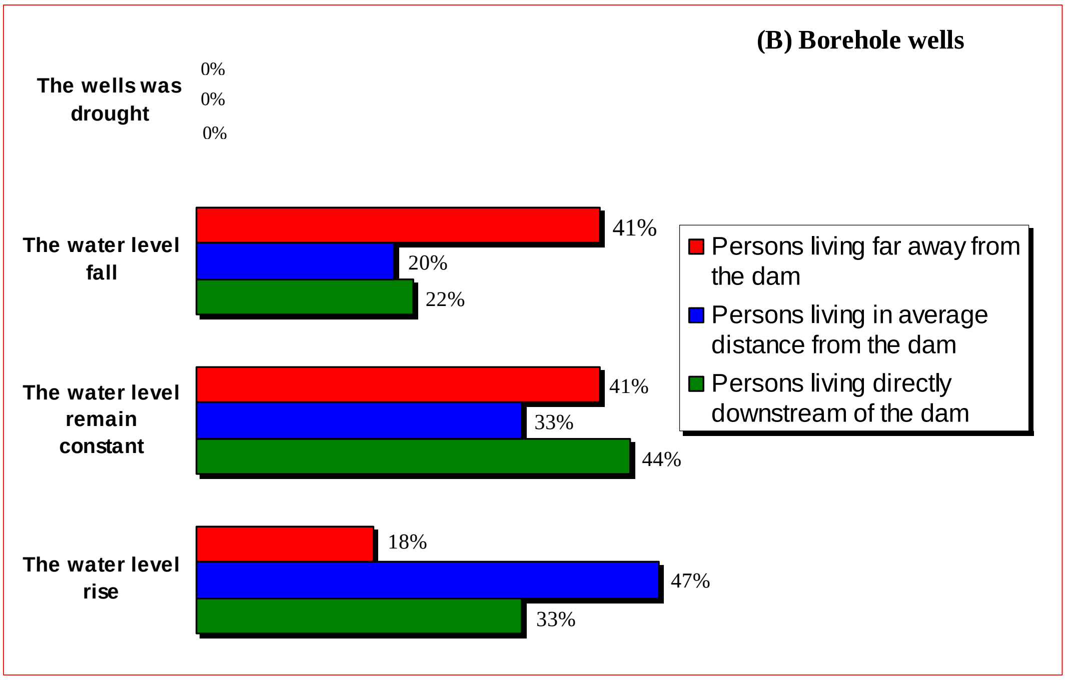


Figure 5.9 (B) people viewpoint about the effect of constructed dams on borehole wells

To sum up, it is found that surface water recharge occurs in the alluvial aquifer and clearly appears near the dams where static water table is very shallow and the recharge extended to horizontal distance equal to 1.6 km from the dam, downstream the wadi in the first graben. The effect artificial recharge decreases after a horizontal distance equal to more than 1.8 km from the dams toward the west. This is because of the following reasons:

1- The amount of water abstraction is more than the amount of water recharge by dams, due to increasing the number of wells that are used for irrigation.

2- The presence of the first graben which controls water movement downstream to the wadi except if the water quantities are very high to fill in the first graben, then the water moves downstream toward the second graben.

3- The presence of a layer of massive volcanic rocks under the alluvial aquifer at the depth between 6- 56 m which prevents deep water percolation.

4- If the quantity of water is high it will reach to the second graben. But also there is a highly water abstraction by a lot number of wells in that areas as some people said that they pump water for 15 minutes and they have to wait two days for wells recovery.

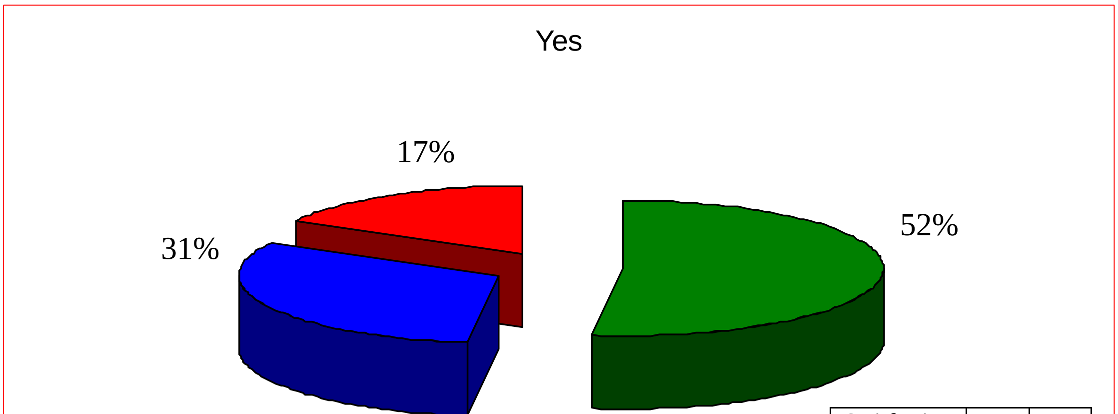
5.5 Advantage and disadvantage of the dams and ways to enhance it

5.5.1 Benefit from the dams

As the people were asked about the benefit of the existing dams, 70% of them in first and second groups said that there is a benefit from the dams which raise water levels in the wells. The other questionnaire sample i.e. the third group, most of them (90%) said that there is no benefits from the dams.

5.5.2 Problems associated with the dams

When asked about the problems that may be raised from the exciting dams, most of the people in first and second group are satisfied with the dams performance as shown in Figure 5.9. For the third group, 71% of them are not satisfied with the current dams performance and the reasons, as stated by 60% of them, is that “water didn’t reach to downstream of the wadi as in the past to recharge the surface wells and the water rarely discharge from the dams, so most of wells suffer from drought”.



Satisfaction	Yes	No
1st group	89%	11%
2nd group	53%	29%
3rd group	47%	71%

Figure 5.10 Satisfaction of people on the current performance of the dams

5.5.3 Reaction of the society to the suggested solution of the dam's enhancement

For enhancing the role of the dams to gain the most benefit form it and to make most people in the different areas around the dams satisfied, some enhancement was suggested like using injection wells, subsurface dams and discharge the water from the dam to be used for irrigation. The reaction of the people about the suggested solutions, most people in group 2 and 3 said that release the water from the dams and distribute it in equitable manner is the best solution for all people as shown in Figure 5.11. Because of the current situation i.e. dams open rarely and for short period so that water did not reach to downstream in the wadi and the benefits are only for areas near the dams. This was evident in the responses of (75%) of group two and all of group three (100%)

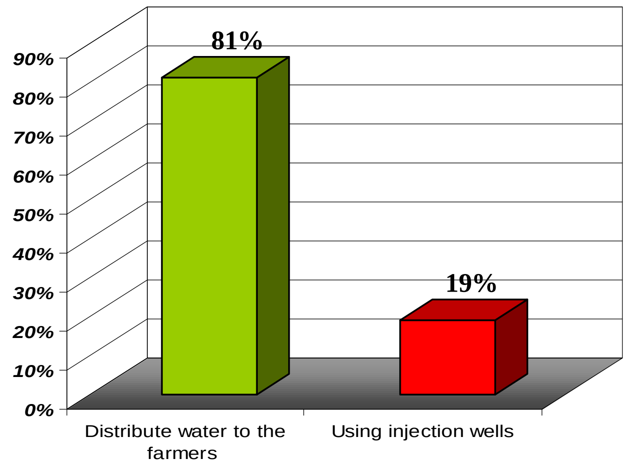


Figure 5.11 Suggestions for dams performance enhancement

5.5.4 Groundwater recharge by injection wells

The actual amount of water in the dams as shown in Figure 5.5A&B is little nevertheless the capacity of dams reaches 700,000 m^3 for Mekhtan and 156,000 m^3 for Musaibeeh dam. When people were asked about using injection wells to enhance the artificial groundwater recharge in the area, most of them (66%) refuse this idea because as stated by them the water will go out of the area, so the benefit will be out of their villages.

5.5.5 Economic side related to the dams

Water lost by evaporation represents a huge waste of our resource. The price and value of water is increased dramatically and the scarcity of water is the main limiting factor working against agricultural production in the study area. To realize the value of lost water it can be compared by the cost of future solution of water scarcity in the study area within the solution of water supply for Sana'a city in which one solutions is water desalination from Red Sea, cost 6 U.S.A $ for one cubic meter then the cost of water that is lost from Mekhtan dam is equal 6 × 46,620 m3 = 279,720 per year minus the cost of purification. This is for only one small dam. It is worth mentioning that as in the sub-basin of Sa'wan there are about four dams and in Sana'a basin the are more than 57 dams according to the study was done by GSMRB, (2004) , it could be realized how huge the amount of water which is lost in most months per one year.

5.6 Human activity and water use

According to the questionnaire, the agriculture activity is the dominant economic activity in the study area as most people (98%) have an agriculture land. The second activity is grazing which received very small percentage (about 4% from the questionnaire sample). The main agricultural crops in the area are Grape, Qat, and Vegetables.

The high percentage from the questionnaire shows that almost farmers (94%) use water for irrigation from the wells especially from borehole wells and rarely from the dug wells.

The main water resources in the study area are the direct precipitation and floods, (Runoff) which came from the wadi and from small areas after the dams were constructed as well as the groundwater resources which is the most important source for water use. The results of the questionnaire showed that about 90% of them have both dug wells and borehole wells, but they sharing borehole wells for a number of people.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

1- The average annual amount of water recharge (infiltration) from Mehktan dam equal 37,512 m^3 which is a good amount.

2- The amount of water infiltration from the dam decreases for large quantities (four times) when the water level (and volume) in the dams decreased.

3- The average annual water losses by evaporation equal to 46,620 m^3 which exceeds the amount of water infiltrating from the reservoir.

4- The amount of water evaporation from the dam's reservoir approximately doesn't change in all computation periods (i.e change a little due to surface area and weather change) but the infiltration strongly decreased when the water level decreased.

5- The permeability of the accumulation sediments in the reservoirs of dams is very low which equal to 0.00042336 m/day and (0.00028944 m/day) for Mekhtan and Musaibeeh dams respectively.

6- Surface groundwater recharge occurs in the alluvial aquifer and clearly appears near the dams and extended to horizontal distance equal to 1.6 km from the dams, (in the first subsurface graben).

7- The effect of surface artificial recharge decreases after a horizontal distance equal to more than 1.8 km.

8- Static water table depth in dug wells is increased by increasing the distance from the dams (downstream the wadi toward the west), the water table range from 4 m to 27 m. That is because of the depth of massive volcanic rock layer increased also toward the west. This layer which hold water (reserve water).

9- The maximum actual water storage recorded in the Mekhtan dam are 88508 m^3 in year 2007 and 37020 m^3 in year 2008.

10- The people who live near the dams and in middle distance from the dams (within 1.6 km distance) are satisfied with the current performance of the dams whereas people who live far from the dams are not satisfied. The results of this study (geo-electric survey) gave a good explanation of that.

11- Most of the people refused the idea of injection wells for enhancement the deep groundwater recharge.

12- Most of the people accept the idea of diverge water from the dams in equitable manner to be used for irrigation.

13- The economic value of the lost water by evaporation is very high especially when it is compared with scarcity and groundwater drawdown every year, increasing the depth of wells and the cost of the suggested solution (Sea water desalination).

6.2 Recommendations

1- The recommendation for the existing dams, looking for measurement that reduces leaks evaporation is one solutions for the current constructed dams in the study area. This solution may be

   a. Releasing and distributing water from dam's reservoir through simple pipes network system in equitable manner to be used for irrigation in order to decrease the stress on groundwater (wells abstraction) epically when water level in the dams is low (The amount of water infiltration is very low). Including the people who live at a distance more than 1.8 km. should be taken into consideration even by using simple network; one for group one and two and the other for group three. (For water distribution equally).

   b. Regular maintenance and removing sedimentation accumulation in the dams reservoirs.

   c. Wind breaks like big trees can also be used in certain circumstances, but their overall effect to reducing evaporation is likely to be small, as solar radiation rather than wind is the key driver of evaporation.

   d. With increasing value of water and increasing drought and scarcity a realistic management option is to invest in a cover over the ponds or dams to reduce evaporation. As thousand of greenhouse farming were used, it should be noted that without water one can not farm at all even if the current price of water is low but the future price will be more expensive. (It is used in some places such as in Saudi Arabia and in Australia).

2- The recommendations for the future plan of constructing water harvesting and storage techniques:

a. Constructed cascade dams is one of good method which suitable for the arid and semi arid areas where flash floods occur. To store that water in many small dams (with high depth more than surface width) is a good way for many reasons: **(1)**Increasing the areas for artificial recharge. **(2)**Distribute the storage water for more than one area to solve the social conflicts between the upstream and downstream the wadies. **(3)**The cost of those dams is cheaper than constructed one huge dam without sufficient water runoff accumulate in it (small catchment area). **(4)**Removing clay and silt accumulate in those small dams is easier and can be done by the inhabitant around those dams to get the benefits of it as soil for agriculture.

b. Other best similar water harvesting techniques are subsurface dams also having more benefits such as avoid water evaporation.

3- Activation the role of community (farmers and agriculture and water user association), involve them in the different stage of dams construction especially dams management. This will be done through increasing awareness, conduct training course, financial support and economic infinitives.

4- Adopt new idea of groundwater recharge through dams, by usefulness from the water in various uses, whether agricultural or domestic and dealing with dams as any valuable water supply project so the groundwater recharge will be achieved by decreasing the stress on it. In this case dams will be for recharge not for evaporation and recharge.

5- All of us should not forget that all of these measurements are cheaper than the future situation of water. If we take into consideration that the water in sub-basins drawdown every year and the coasty solution will be faced even after 20, 30, 50 (it doesn't matter when) since the indicators of that is very clear. (Increasing the depth of drilled wells from few meters to more than 500 m as in the study area).

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APPENDIX (1)

EXTRA INFORMATION OF MEKHTAN DAM

Extra information about Mekhtan dam

By General Directorate of Irrigation (Engineering Data Sheet) 2001

GENERAL	Dam No. 33	
Name of the Dam	Mekhtan	
Purpose of Dam:	Ground water recharge	
Location:		
3.1 Governorate:	Sana'a	
3.2 District:	Beni Husheish	
3.3 Village:	Al-Khirba	
3.4 Wadi:	Mekhtan	
3.5 Sub-Wadi:	------	
3.6 Longitude / Latitude:	N 15^{o} 22$^{/}$ 53.5$^{//}$	E 44^{o} 19$^{/}$ 52.4$^{//}$
3.7 1000m UTM North / East:	N 1700.65	E 428.3

Year of completion or status if not completed and Condition as at present
-The construction completed by GDI/MAI on 1999.

Type of Dam:	Earth fill	
Height of Dam:		
6.1 Deepest foundation level:	DNA	
6.2 Wadi bed level:	2400 m	
6.3 Full Reservoir level:	2422 m	
6.4 Max. Water Level	2424 m	(estimated)
6.5 Top of Dam level	2425 m	(actual)
7. Capacity and Area of Reservoir (1000 m^3):	as estimated in the dam site	
7.1 At Full Reservoir level: (FSL)	550	
7.2 At Max. Reservoir level:	700	
7.3 Surface Area at FSL	40,000 m^2	
8. Nearest Downstream Village / Town:	Mukhtan	
8.1 Its Distance from Dam:	800 m	
8.2 Its Population:	100	

10. Name of officer / Community in charge responsible for operation and maintenance

10.1 Designation and office:	MAI & Sa'awn Irrigation Association

B. PROJECT FEATURES:

1. Salient features of Dam

1.1 Top Width: (m)	6.5 m	
1.2 Maximum height of dam	25 m	
1.3 Side Slope upstream and downstream:	U/S is 2:1,	D/S is 1.5:1
1.4 Upstream protection:	Riprap works on the U/S face	
1.5 Length of dam at top:	104 m	(actual)

C. HYDROLOGY

1. Catchment Area (km^2) : 5.1
2. Catchment area characteristics:

2.1Shape of the catchment area:	Fan shape
2.2 lowest contour at the dam site (m):	2400
2.3 highest contour u/s of the catchment area (m):	2904
2.4 difference between the highest & lowest contours (m):	504
2.5 max. distance between the u/s & the d/s of the catchment (Km):	4.05
2.6 gradient:	12% (steep)
2.7 surface nature:	Mountainous terrain
2.8 geological description:	Cultivated terraces

3. Rainfall (mm): (by INGEMA CE &TAGDI)

3.1 Average annual rainfall:	194.8 mm
3.2 Max. Rainfall (1-day / 2-day):	100 mm
3.3 Max. Intensity amount and Duration hours:	DNA
3.4 Rain gauge stations: (Automatic / Manual):	Addab'at (Manual)
3.5 Runoff Coefficient:	0.2 (estimated according to the catchments characteristics)
3.6 Mean annual flow:	199 x 10^3 m^3

4. Spillway capacity and flood routing criteria:

4.1 Type of spillway:	Overflow provided by rock cutting
4.2 Spillway length: (m)	7.3 m
4.3 Crest level	2422 m

4.4	Spillway capacity (m^3/s) = $CBH^{1.5}$:	37.2 (C = 1.8, B = 7.3 m , H =2 m)
4.5	Whether with gates: (yes/no)	No
4.6	Type of gates (vertical/ radial / flash boards):	-----
4.7	Size of gates:	-----
4.8	Nos. of gates:	-----
4.9	Other outlet works details:	
4.10	Location:	At Wadi Center Line
4.11	Type:	Steel pipes
4.12	Nos:	2
4.13	Capacity	8//
4.14	Entrance level:	DNA
4.15	Exit level	At Wadi bed

5. Spillway downstream energy dissipation arrangements:

Nil, except the leakage of the steel pipes in the D/S.

6. Has any downstream retrogression observed (if yes – details): No

APPENDIX (2)

RESERVOIR’S SOIL TEST

Coefficient of permeability test for Mekhtan reservoir soil

الجمهوريـــــــة اليمنيـــــــة
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الإدارة العامة للبحوث والمختبرات
صنعـــاء

REPUBLIC OF YEMEN
MINISTRY OF PUBLIC WORKS
& AND HIGHWAYS
G.DIRECTORATE FOR
RESEARCHES
& LABORATORIES

Permeability Test

المشروع:	Mekhtan Dam	PROJECT:
الموقع:	Wadi Mekhtan, Sa'wan	LOCATION:
رقم الحفره :		BORE HOLE NO.:
رقم العينه :	Soil from Dam Reservoir	SAMPLE NO.:
العمق:	10 cm	DEPTH:
اخذ العينة:	Eng. Wahib Saif Al-Qubatee	SAMPLE By:
التاريخ:	05/12/2008	DATE:

Moisture Content محتوى الماء الرطوبي

3	2	1	Tin No.	رقم العلبه
32	33.5	33	Wt of Tin	وزن العلبه
108.0	109.7	109.9	Wt of Tin + Wet Soil	العلبه + التربه رطبة
93	94.4	94.6	Wt of Tin + Dry Soil	العلبه +التربه جافه
15.00	15.30	15.30	Moisture	الرطوبه
61	60.9	61.6	Wt Dry Soil	وزن التربه جافه
24.6	25.1	24.8	Moisture Content	نسبة الرطوبه
		24.9		

3	2	1	Test Number
4670	4670	4670	Weight of cell (gm)
6393	6393	6393	Weight of cell +Wet Soil (gm)
1723	1723	1723	Weight of Soil (gm)
11.6	11.6	11.6	Length of Sample (L , cm)
10.1	10.1	10.1	Diameter of Sample (D, cm)
80.12	80.12	80.12	Area of Sample (A =cm^2)
929.4	929.4	929.4	Volum of Sample (V , cm^3)
1.854	1.854	1.854	Bulck Density γ_b=gm/cm^3)
1.484	1.484	1.484	Dry Density γ_d=gm/cm^3)
1.490	1.490	1.490	Maximum Dry Density ,gm/cm^3)
100	100	100	Compaction Ratio =((γd) /MDD)*100
171.00	181.00	193.50	Initial Head in Tube (h_1=cm)
159.00	171.00	181.00	Final Head in Tube (h_2=cm)
1800	1200	1200	Time (T = sec)
0.07069	0.07069	0.07069	Area of Tube (a =cm2)
4.1371E-07	4.8474E-07	5.6958E-07	*Coefficient of permeability* (K = $(\frac{a*L}{A*t})*\ln(\frac{h1}{h2})$,cm/sec)

4.89343E-07	Av. Coefficient of permeability	4.89343E-07

Coefficient of permeability test for Musaibeeh Reservoir soil

الجمهوريـــــــة اليمنيـــــــة وزارة الأشغال العامه والطرق الإدارة العامة للبحوث والمختبرات صنعـــاء	REPUBLIC OF YEMEN MINISTRY OF PUBLIC WORKS & AND HIGHWAYS G.DIRECTORATE FOR RESEARCHES & LABORATORIES

Permeability Test

المشروع:	Musaibeeh dam	PROJECT:
الموقع:	Wadi Mekhtan, Sa'wan	LOCATION:
رقم الحفره :		BORE HOLE NO.:
رقم العينه :	Soil from Dam Reservoir	SAMPLE NO.:
العمق:	10 cm	DEPTH:
أخذ العينة:	Eng. Wahib Saif Al-Qubatee	SAMPLE By:
التاريخ:	05/12/2008	DATE:

Moisture Content محتوى الماء الرطوبي

		1	Tin No.	رقم العلبه
			Wt of Tin	وزن العلبه
			Wt of Tin + Wet Soil	العلبه + التربه رطبة
			Wt of Tin + Dry Soil	العلبه +التربه جافه
			Moisture	الرطوبه
			Wt Dry Soil	وزن التربه جافه
			Moisture Content	نسبة الرطوبه
		0.0		

		1	Test Number
		4670	Weight of cell (gm)
		6380	Weight of cell +Wet Soil (gm)
		1710	Weight of Soil (gm)
		11.6	Length of Sample (L , cm)
		10.1	Diameter of Sample (D, cm)
		80.12	Area of Sample (A =cm^2)
		929.4	Volum of Sample (V , cm^3)
		1.840	Bulck Density γ_b=gm/cm^3)
		1.472	Dry Density γ_d=gm/cm^3)
		1.482	Maximum Dry Density ,gm/cm^3)
		99	Compaction Ratio =((γd) /MDD)*100
		156.00	Initial Head in Tube (h_1=cm)
		150.00	Final Head in Tube (h_2=cm)
		1200	Time (T = sec)
		0.07069	Area of Tube (a =cm2)
		3.3452E-07	*Coefficient of permeability* (K = $(\frac{a*L}{A*t})*\ln(\frac{h1}{h2})$,cm/sec)

3.3452E-07	Av. Coefficient of permeability	Remarks:-

Sieve analysis for Mekhtan Reservoir soil

الجمهورية اليمنية
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الإدارة العامة للبحوث والمختبرات
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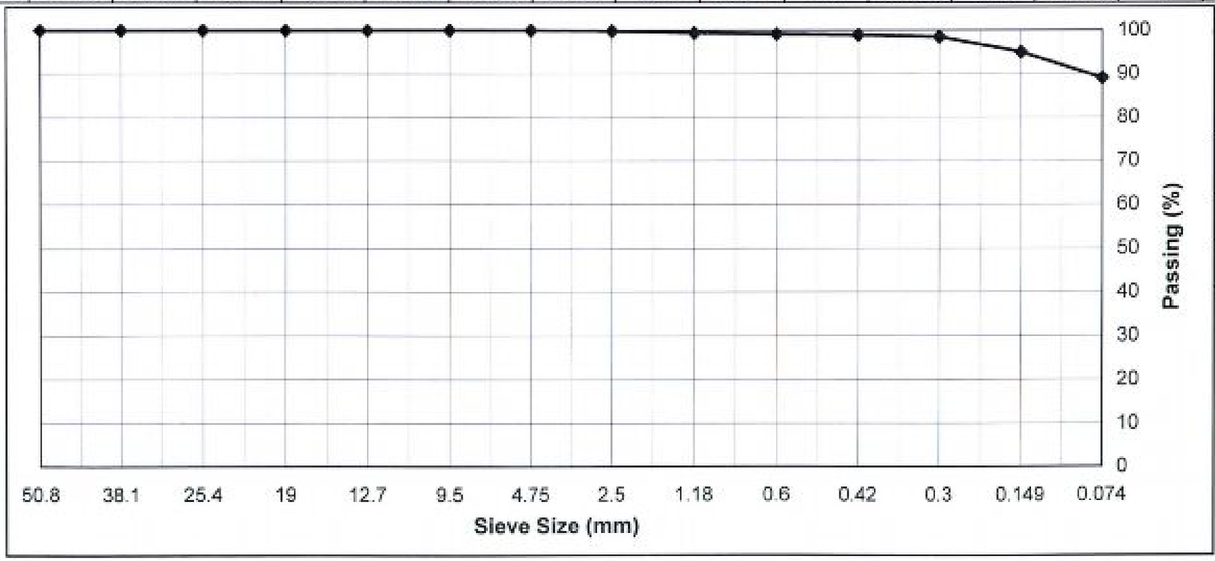
REPUBLIC OF YEMEN
MINISTRY OF PUBLIC WORKS & AND HIGHWAYS
G.DIRECTORATE FOR RESEARCHES & LABORATORIES
SANA'A

SIEVE ANALYSIS

المشروع:	Mekhtan Dam	PROJECT:	رقم الحفرة		Boring no:.
الموقع:	Wadi Mekhtan, Sa'wan	LOCATION:	عمق العينة		DEPTH OF SAMPLE
أخذ العينة	Eng. Wahib Saif Al-Qubatee	SAMPLE By.	التاريخ	05/12/2008	DATE
				1000	Wt. of agg before washing (gm) :

2"	11/2"	1	3/4"	1/2"	3/8"	4	10	16	30	40	50	100	200	PAN	ASTM Sieve
50.8	38.1	25.4	19	12.7	9.5	4.75	2.5	1.18	0.6	0.42	0.3	0.149	0.074	PAN	ASTM Sieve Size (mm)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.60	4.50	2.90	2.20	4.50	35.10	59.40	890.00	Retained wt.(gm)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.45	0.29	0.22	0.45	3.51	5.94	88.98	Cum.Retained %
100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.84	99.39	99.10	98.88	98.43	94.92	88.98	0	Passing %



88.98	FINE SOIL (%)
11.02	SAND (%)
0.00	GRAVEL (%)

Sieve analysis for Musaibeeh reservoir soil

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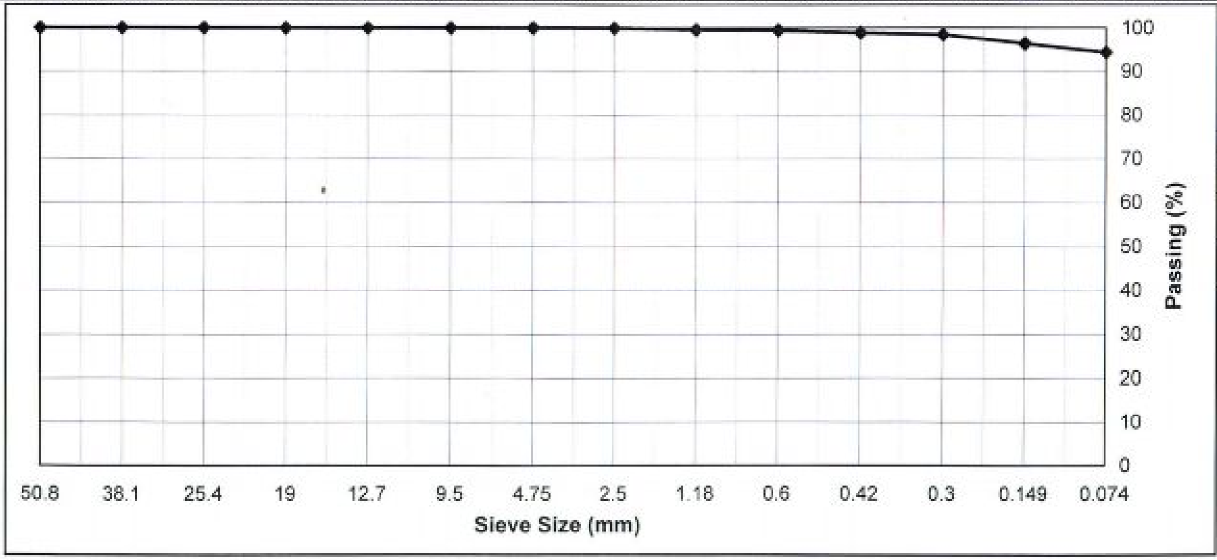
SANA'A

SIEVE ANALYSIS

المشروع:	Soil from Musaibeeh dam	PROJECT:	رقم الحفرة		Boring no:.
الموقع:	Wadi Mekhtan, Sa'wan	LOCATION:	عمق العينة		DEPTH OF SAMPLE
أخذ العينة	Eng. Wahib Saif Al-Qubatee	SAMPLE By.	التاريخ	05/12/2008	DATE
				500	Wt. of agg before washing (gm) :

2"	11/2"	1	3/4"	1/2"	3/8"	4	10	16	30	40	50	100	200	PAN	ASTM Sieve
50.8	38.1	25.4	19	12.7	9.5	4.75	2.5	1.18	0.6	0.42	0.3	0.149	0.074	PAN	ASTM Sieve Size (mm)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	2.00	0.70	2.80	2.20	10.10	10.30	472.00	Retained wt.(gm)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.40	0.14	0.56	0.44	2.02	2.06	94.34	Cum.Retained %
100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.96	99.56	99.42	98.86	98.42	96.40	94.34	0	Passing %



94.34	FINE SOIL (%)
5.66	SAND (%)
0.00	GRAVEL (%)

APPENDIX (3)

OTHER FIELD MEASURMENTS AND TOOLS

Photo shows the monitoring of water level in
the Mekhtan dam (staff gauge)

Monitoring wells water level by using Electric Sounder

Figure 1.3.: (A) Curing out questionnaire, (B) Monitoring wells water level.
(C) Monitoring dam water level. (D) Curing out geo-electrical survey.

APPENDIX (4)

GEOELECTRIC SURVEY DATA

VES No.: 1

Coordinantes: 427,875E & 1,700,666N & Ele.: 2403m

MN/2(m)	AB/2(m)	$\lfloor \rho_a (\Omega.m) \rfloor$
0.5	1.5	107.6
0.5	2.5	169.4
0.5	4	270.7
0.5	6	326.2
0.5	8	437.7
0.5	10	519.3
0.5	15	354.5
0.5	20	395.8
0.5	30	492
10	30	592.8
0.5	40	561.7
10	40	682.7
10	50	711.2
10	75	608
10	100	Obstacles
10	150	80
50	150	95.7
10	200	50
50	200	59.6
50	300	67.4

VES No.: 2

Coordinantes: 427,036E & 1,700,394N Ele.:2387m

AB/2(m)	MN/2(m)	$\lfloor \rho_a (\Omega.m) \rfloor$
0.5	1.5	21.6
0.5	2.5	21.9
0.5	4	20.9
0.5	6	23.8
0.5	8	28.1
0.5	10	33.1
0.5	15	41.6
0.5	20	49
0.5	30	62.6
10	30	54.4
0.5	40	73
10	40	65.3
10	50	75.1
10	75	90.6
10	100	89.9
10	150	74.5
50	150	69.8
10	200	65.9
50	200	61.2
50	300	62.9
50	400	60
50	500	62.7
50	600	66.7
50	700	70.6

VES No.: 3

Coordinantes: 426,899E & 1,700,435N Ele.: 2365 m

AB/2(m)	MN/2(m)	$\lfloor \rho_a (\Omega.m) \rfloor$
0.5	1.5	45.6
0.5	2.5	39.2
0.5	4	42.8
0.5	6	44.0
0.5	8	46.5
0.5	10	50.2
0.5	15	52.5
0.5	20	56.2
0.5	30	Road
0.5	30	Road
0.5	40	69.8
10	40	61.7
0.5	50	71.7
10	50	63.7
10	75	75.0
10	100	73.0
50	150	72.3
10	150	74.6
50	200	78.4
50	200	79.1
50	300	62.2
50	400	64
50	500	69
50	600	72

VES No.: 4

Coordinantes: 426,668E & 1,700,233N Ele.: 2397m

AB/2(m)	MN/2(m)	$\lvert\rho_a(\Omega.m)\rvert$
0.5	1.5	51.3
0.5	2.5	29.2
0.5	4	29.0
0.5	6	26.0
0.5	8	25.9
0.5	10	27.4
0.5	15	33.9
0.5	20	42.3
0.5	30	58.1
10	30	48.1
0.5	40	75.2
10	40	63.8
10	50	76.1
10	75	106.4
10	100	114.1
10	150	86.9
0.5	150	74
10	200	81.3
50	200	69.8
50	300	62.5
50	400	65.6
50	500	62.9
50	600	60.3
50	700	60.4
50	800	61

VES No.: 5

Coordinantes: 426,042E & 1,699,996N Ele.: 2380m

AB/2(m)	MN/2(m)	$\lfloor \rho_a (\Omega.m) \rfloor$
0.5	1.5	307.0
0.5	2.5	310.5
0.5	4	271.0
0.5	6	165
0.5	8	100.7
0.5	10	70.6
0.5	15	63.1
0.5	20	57.0
0.5	30	57.4
10	30	52.9
0.5	40	61.3
10	40	58
10	50	63.8
10	75	78.3
10	100	72.8
10	150	77
50	150	64.7
10	200	67.2
50	200	76.2
50	300	58.1
50	400	56.0
50	500	55.2
50	600	67.8
50	700	67.6
50	800	67.1

VES No.: 6

Coordinantes: 425,460E & 1,700,903N Ele.: 2300 m

AB/2(m)	MN/2(m)	$\lfloor \rho_a (\Omega.m) \rfloor$
0.5	1.5	59.6
0.5	2.5	63.2
0.5	4	67.4
0.5	6	68.6
0.5	8	67.9
0.5	10	57.5
0.5	15	64.9
0.5	20	67.6
0.5	30	62.0
10	30	54.4
0.5	40	72.1
10	40	62
10	50	74.1
10	75	100.7
10	100	115.2
10	150	124.3
50	150	120.7
10	200	108
50	200	120
50	300	103.0
50	400	105.6
50	500	97.0
50	600	99.0
50	700	102.0

VES No.: 7

Coordinantes: 424,358E & 1,701,015N Ele.:2319 m

AB/2(m)	MN/2(m)	$\lfloor \rho_a (\Omega.m) \rfloor$
0.5	1.5	255.8
0.5	2.5	235.0
0.5	4	225.6
0.5	6	161.3
0.5	8	130.8
0.5	10	121.5
0.5	15	128.4
0.5	20	124.9
0.5	30	91.8
10	30	75.9
0.5	40	79.1
10	40	68.4
10	50	53.4
10	75	38.9
10	100	32.8
10	150	39.5
50	150	42.1
10	200	45.5
50	200	46.7
50	300	48.7
50	400	48.0
50	500	50.0
50	600	52.8
50	700	52.4
50	800	52.7
50	900	52.8

VES No.: 8

Coordinantes: 424,340E & 1,700,458N Ele.: 2340 m

AB/2(m)	MN/2(m)	$\lfloor \rho_a (\Omega.m) \rfloor$
0.5	1.5	152.5
0.5	2.5	77.2
0.5	4	36.4
0.5	6	23.5
0.5	8	19.6
0.5	10	16.2
0.5	15	14.5
0.5	20	13.2
0.5	30	11.7
10	30	14.3
0.5	40	12.9
10	40	15.7
10	50	17.6
10	75	23.7
10	100	28.8
10	150	36.9
50	150	33.9
10	200	52
50	200	47
50	300	66.7
50	400	75.7
50	500	77.6
50	600	80.8

VES No.: 9

Coordinantes: 423,695E & 1,700,932N Ele.: 2390 m

AB/2(m)	MN/2(m)	$\lfloor \rho_a (\Omega.m) \rfloor$
0.5	1.5	56.8
0.5	2.5	52.7
0.5	4	61.3
0.5	6	73.7
0.5	8	80.6
0.5	10	83.5
0.5	15	87.2
0.5	20	89.4
0.5	30	102.2
10	30	112.3
0.5	40	111.3
10	40	123.8
10	50	132.9
10	75	132.6*
10	100	118.0
10	150	92.6
50	150	96.6
10	200	80.8
50	200	83.4
50	300	70.9
50	400	59.0
50	500	63.9
50	600	75.2
50	700	86.8

VES No.: 10

Coordinantes: 422,943E & 1,701,863N Ele.: 2307 m

AB/2(m)	MN/2(m)	$\lfloor \rho_a (\Omega.m) \rfloor$
0.5	1.5	60.4
0.5	2.5	48.7
0.5	4	30.8
0.5	6	18.5
0.5	8	13.0
0.5	10	11.2
0.5	15	10.8
0.5	20	13.2
0.5	30	17.7
10	30	16
0.5	40	18.6
10	40	17.1
10	50	17
10	75	23.1
10	100	26.5
10	150	33.2
50	150	48.2
10	200	36.6
50	200	53.1
50	300	61
50	400	71
50	500	84.5
50	600	94.4
50	700	101.3

APPENDIX (5)

QUESTIONNAIRE

QUESTIONNAIRE
English Version

This questionnaire aims to identify the extent benefits from the exist constructed dam in the purpose of both irrigated agriculture or for groundwater artificial recharge, suitable measurements will be suggested to enhance the role of the dams to gain the highest benefit from it.

1- Your residence related to the dam

The probable answer	Tick
Upstream of the dam	1
Directly downstream of the dam (very close to the dam)	2
downstream of the dam (an average distance from the dam)	3
In the sides of the dam	4
Far away from the dam	5

2- Do you have Agriculture Land?

The probable answer	Tick
Yes	1
No	2

3- Do you have any wells?

The probable answer		Tick
Dug wells	Yes	1
	No	2
Tube wells	Yes	3
	No	4

4 – The activity you depend on:

The probable answer	Tick
Agriculture	1
Grazing	2
Trade	3
Others:	4

5 – The source of water that use for irrigated agriculture is:

The probable answer	Tick
Water from the wells	1
Water from the dam	2
Government network	3
Water venders	4
Others:	5

6- Do you know the purpose of the constructed dam, what is it?

The probable answer	Tick
For irrigation purposes	1
For groundwater recharge purpose	2
For Protect the villages from the dangers of floods and soil erosion	3
I don’t know or other answer:	4

7 - Is Dug wells was effected by the constructed dam?

Years	The water level rise	The water level remain constant	The water level fall	The wells was drought
Early stage: 2000 - 2002	1	2	3	4
Middle stage:2003 - 2005	1	2	3	4
Recently:2006 - 2008	1	2	3	4

8 - Is Tube wells was effected by the constructed dam?

Years	The water level rise	The water level remain constant	The water level fall	The wells was drought
Early stage: 2000 - 2002	1	2	3	4
Middle stage:2003 - 2005	1	2	3	4
Recently:2006 - 2008	1	2	3	4

9- Is there any benefit from dam's water?

The probable answer	Tick
Yes	1
No	2

10 – If yes, what are these benefits?

The probable answer	Tick
irrigated agriculture	1
Rising water level in wells	2
Drinking animals	3
Entertaining	4
For washing clothes	5
Others:	6

11 - Is there any problems caused by the dam?

The probable answer	Tick
Yes	1
No	2

12 - If yes, what are these problems?

The probable answer	Tick
Health problems (Diseases)	1
Drowning	2
Conflicts between the inhabitants	3
Others:	5

13 – In general do you satisfied with the dam as it stands?

The probable answer	Tick
Yes	1
No	2

14 – If no, what kind of improvements that could be done to improve the functioning of the dam and reduce the evaporation losses, and increase the benefits for all people, closes to the dam or far away downstream the dam.

The probable answer	Tick
Distribute water directly to the farmers in just manner rather than remain in the reservoir	1
Directly inject the water from the dam to aquifer by using injection wells	2
Orientation towards building subsurface dams.	3
Others:	4

15- Is it better to recharge the groundwater directly from the dam by using injection wells?

The probable answer	Tick
Yes	1
No	2

16 – If no, why?

The probable answer	Tick
We currently get the benefits from the dam for irrigation, entremets, wash the clothes and …etc	1
We have not heard about this before what are evidences that this approach will be successful	2
Water will go away and there will be no direct benefit to the region.	3
This is unreasonable idea how we store water in the ground and we need it and then again abstract it with the cost	4
That will pollute the groundwater	5
Others:	6

17- Does the water Discharge from the dam?

The probable answer	Tick
Yes	1
No	2

18 – If yes, How?

The probable answer	Tick
Open the dam's outlet and diverge water through secondary canal in equal share	1
Open the dam's outlet and diverge water randomly	2
Open the dam's outlet and diverge water in the wadi. (Water reaches only to the areas near the dam).	3
Abstract the water directly from the dam reservoir.	4
Others:	5

19 – If no, why?

The probable answer	Tick
The discharge outlet of the dam doesn't work	1
Conflicts between the people when the water discharge from the dam	2
Depend on water from the wells only	3
Others:	4

20 – Is there any maintenance for the dam If yes, what is it?

The probable answer	Tick
Remove sedimentation from the dam's reservoir	1
Rapier any leakage	2
Control of insect which increased by the dam	3
Development the catchement area and remove any obstacles to increase water flow to the dam	4
Kept the catchments area clean.	5
No or others answer:	6

21 – When the well required deeper?

The probable answer	Tick
From 5 to 10 years	1
From 10 to 15 years	2
From 15 to 20 years	3
Others:	4

The end of the questionnaire (English Version)

تقييم التغذية الصناعية للمياه الجوفية من خلال سد مختان ــ بني حشيش ــ حوض صنعاء ــ اليمن

وطرق تحسين ذلك من منظور الإدارة المتكاملة لمصادر المياه

إعداد
وهيب سيف محسن القباطي

المشرف
الأستاذ الدكتور عدنان الصالحي

المشرف المشارك
الأستاذ الدكتور جاكسون رورش

الملخص

تعتبر السدود أحدى الوسائل الهامة لحصاد المياه والمستخدمة بكثرة في حوض صنعاء لغرض التغذية الصناعية للمياه الجوفية لكن دون أن يكون لبعض من تلك السدود نظام تصريف وإدارة للمياهها. خلال عام 2008 تم اختيار سد مختان كهدف رئيسي لهذه الدراسة وكان لا بد من التطرق لسد المصبيح والذي لم يكن مناسباً لاجراء دراسة متكاملة عليه بسبب وجود تسريب فيه ، إلى جانب أن مياهه يتم تصريفها لغرض الصيانة.

يقع السدين في وادي مختان ضمن حوض سعوان (أحد الأحواض الفرعية لحوض صنعاء) والذي يعتبر من أكثر الأحواض زيادة في كثافة عدد الأبار بالنسبة للكيلومتر المربع.

تهدف هذه الدراسة إلى (1) تقييم التغذية الصناعية للمياه الجوفية من خلال سد مختان ، (2) تقييم مدى ارتياح المقيمين في المنطقة من أداء السدين وماهي الإيجابيات والسلبيات المترتبه عنهما (3) البحث عن وسائل مناسبة لتحسين دور السدين ومدى تقبل المجتمع لتلك التحسينات.

أجريت دراسة جيوكهربائية باستخدام طريقة السبر الكهربائي العمودي (VES)، دراسة هيدرولوجية وهيدروجيولوجية (والتي تمثلت بمراقبة منسوب المياه في السدين وفي بئرين بالقرب من السدين ، تحليل معامل النفاذية للرواسب الموجودة في قاع السدين ، ومعرفة نوعية تلك الرواسب وحجم حبيباتها -sieve analysis). إجراء مقابلة مع المقيمين في المنطقة من خلال استبيان لتقيم الجانب الإجتماعي المتعلق بالسدود.

وجد من خلال هذه الدراسة أن كمية المياه المترشحة من سد مختان تقدر بحوالي 37512 متر مكعب في السنة بنسبه 42% من المياه المفقودة يومياً (التبخر+الرشح). كما وجد أن التبخر يقدر بحوالي 46620 متر مكعب في السنة بنسبة 58% من الفاقد اليومي من مياه السد. كميات المياه المترشحة تنخفض بشكل كبير عند انخفاض الماء في السد بينما يظل التبخر هو السائد يبقى تقريبا ثابت. كما أن الرواسب المتجمعة في بحيرة السدين عبارة عن رواسب دقيقة سليت وطين ، وأن نفاذيتها ضعيفة جداً.

من خلال نتائج الاستبيان أظهرت الدراسة أن المقيمن بالقرب من السدين وعلى بعد متوسط منه مرتاحين لأداء السدين وعلى العكس من ذلك لمن هم على بعد اكبر من 1.8 كم.

التحسينات التي لاقت القبول لدى غالببية المقيمين في المنطقة هي تصريف المياه من السدين بشكل عادل لتسخدم لغرض الري. ومن ضمن التوصيات الآخرى هي إزالة الرواسب المتجمعة في بحيرة السدين. وبالنسبة للخطط المستقبلية لبناء السدود ، السدود التحت سطحية والسدود الشلالية (الحواجز الصغيره) أكثر ملائمة للمناخات الجافة وشبة الجافة.