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Hydrogeologic Setting and Characterization of the Aquifer System in Al Wagan Area, South Al Ain, UAE

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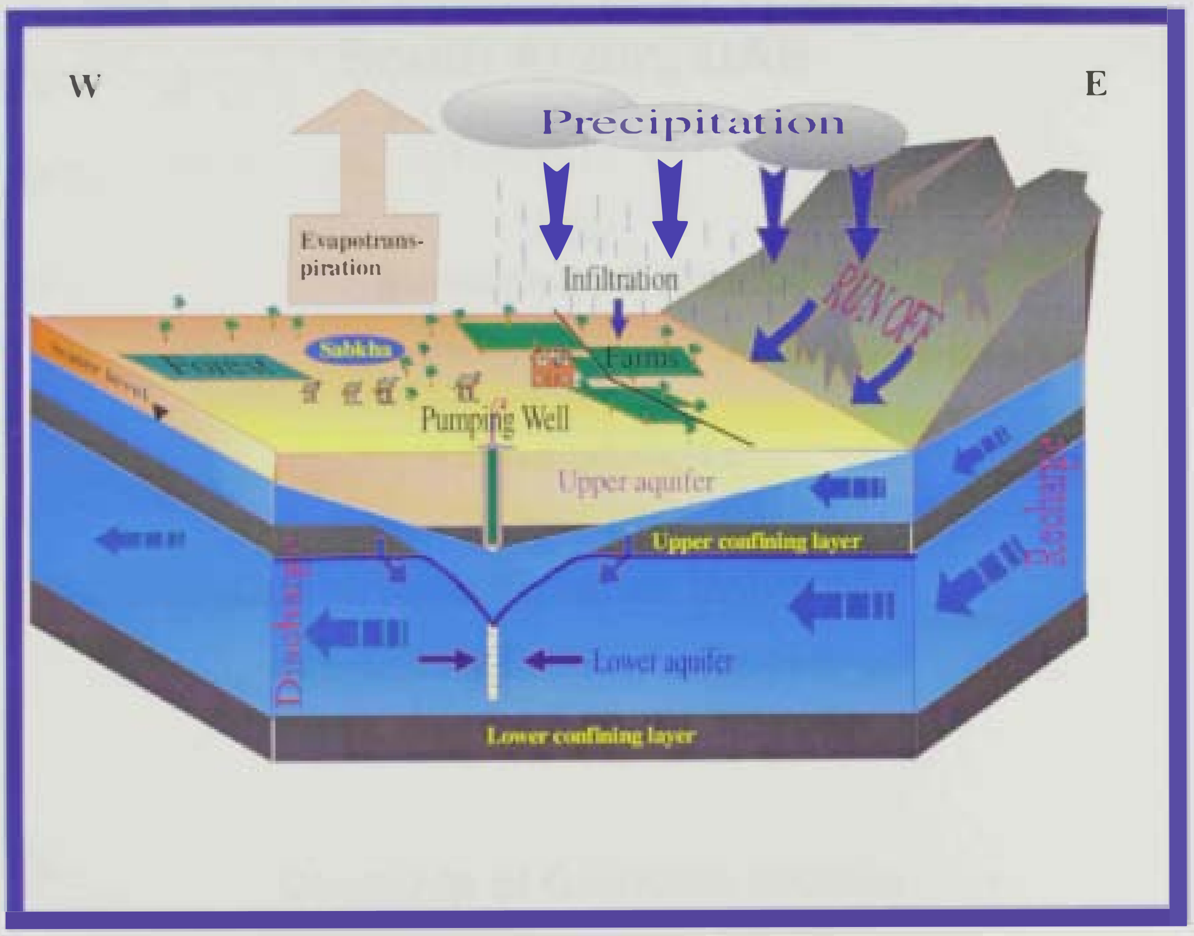

Mohamed Ali Khalifa

United Arab Emirates University
Deanship of Graduate Studies

Hydrogeologic Setting and Characterization of the Aquifer system in Al Wagan Area, South Al Ain, UAE

By
Mohamed Ali Khalifa

A Thesis Submitted to

Deanship of Graduate Studies
United Arab Emirates University

In Partial Fulfillment [illegible]
Water Resources

Deanship of Graduate Studies
United Arab Emirates University

June, 2004

United Arab Emirates University
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Thesis Title

Hydrogeologic Setting and Characterization of the Aquifer System in Al Wagan Area, South Al Ain, UAE.

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Hydrogeologic Setting and Vulnerability Assessment of the Lower Brackish Groundwater Zone to Saline Water Intrusion in Al Wagan Area, South Al Ain, UAE

A Thesis submitted to the
Deanship of Graduate Studies
United Arab Emirates University

In Partial Fulfilment of the Requirements for
M.Sc. Degree in Water Resources

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June 2004

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DEDICATION

To The Memory of Dearest Mother …….

To My Sincere Wife …..

My Beloved Daughters Salma and Basma …..

My Dear Son Ahmed

CONVERSION FACTORS

Multiply	By	To Obtain
centimeter (cm)	0.3937	Inch
millimeter (mm)	0.0394	Inch
meter (m)	3.281	Foot
micromhos per centimeter @ 25° Celsius (μ mho/cm)	1.000	microSiemens per centimeter @ 25° Celsius
millimeter (mm)	0.0394	Inch
square kilometer (km^2)	0.3861	square mile
Hectare	2.471	Acre
Acre	4047	square meter
Donum	1000	meters
Cubic meter per hour (m^3/hr)	4.403	gallon per minute

Temperature in degree Celsius (° C) may be converted to degrees Fahrenheit (° F) as follows :

° F =1.8 x (° C) + 32.

Sea level: In this report, "sea level" refers to the Nahrwan Datum of 1967.

ACKNOWLEDGMENTS

Praise to *ALLAH*, the Lord of Universe, who had blessed me with countless blessings in my life, and provided me with the knowledge, power and patience to carry out this study.

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Last but not least, I would like to thank all my colleagues in the Ground-Water Research Program, of Al Ain, who directly or indirectly, helped me through their cooperation and support.

Abstract

Al Wagan area lies to the south of Al Ain City of the eastern region of Abu Dhabi Emirate along the Sultanate of Oman-United Arab Emirates borders. Al Wagan area is important for agriculture in the eastern region of Abu Dhabi. Ground water is the primary source of irrigation in the area. The main source of recharge to the ground-water-flow system of the entire eastern region of Abu Dhabi Emirate is rainfall on the Oman Mountains. Ground water flows in an east-west direction because most of the recharge at higher elevations is or near the Oman Mountains.

The ground-water-flow system of Al Wagan area consists of the upper, unconfined, aquifer, the lower, confined, aquifer, and the intervening confining layer. The upper aquifer refers to the saturated part of most the unconsolidated deposits of Quaternary age. Below the Quaternary deposits, is a clay layer acting as a confining layer separating the upper aquifer from the underlying lower aquifer. The conglomerate layer of the Post Fars Formation primarily comprises the lower aquifer. Water within the upper aquifer is generally more mineralized than water in the lower aquifer.

The purpose of this study is to present:

1. A geohydrologic description of the lower aquifer and the upper aquifer in the study area,
2. An assessment of the changes of quality of the brackish ground water that might result from large and prolonged withdrawals in the area, and
3. A description of the simulation of flow in the ground-water system.

Annual well withdrawals from the two aquifers were tabulated from records of the Agriculture and Forestry Departments of Al Ain and the Ground-Water Research Program monitoring wells. The potentiometric surface of the lower aquifer is declining because of large withdrawals for irrigation.

Geochemical analyses support the conclusion that the salinity of brackish ground water of the lower aquifer in Al Wagan area increased with percentage ranged from 2 % to 74 % from 1996 to 1998.

A three-dimensional, three-layer ground-water-flow model was constructed to help understand the ground-water-flow system. Model results indicate vertical flow occurs between the three model layers; possibly explaining the observed increased salinity of the lower aquifer.

The use of the flow model as a predictive tool showed that if the current pumping rates of the wells will continue in the future, this might lead to a complete aquifer depletion of the upper aquifer at the north of the study area.

As a result of this study the following recommendations can be made in order to avoid more depletion of the aquifer and deterioration of the water quality:

1. Minimize aquifer depletion, by reduction and of pumping rates and number of wells in each farm.
2. Regulate ground-water use.
3. Enhancement of the observation well network.
4. Better well constructions.

Chapter I

INTRODUCTION

1.3 Geological Framework

The geologic description of the study area is mainly based on analysis of lithologic and petrophysical logs contained in a GWRP report (Menges and others, 1993). In addition, analysis of the lithologic and petrophysical logs and lithologic analysis of drill cuttings from 20 additional boreholes drilled between 1993 and 2000 in and around the study area are used to construct the stratigraphic description.

The stratigraphic sequence in the study area consists of sand dunes (eolian deposits), Quaternary Alluvium, Post Fars formation, Upper Fars formation, and the Lower Fars formation. The Alluvium, consisting of gravel, sand, and silt layers is present beneath the sand dunes, and outcrops at the surface in the eastern part of the study area close to the Omani borders. The description of the Fars units will be detailed in Chapter. III.

1.4 Hydrogeological Framework

The main source of recharge to the ground-water-flow system of the entire eastern region of Abu Dhabi Emirate is rainfall on the Oman Mountains. This rainfall takes three distinct directions leading to three major recharge components into the flow system: subsurface underflow in alluvial deposits channeled through intermountain gaps, surface runoff channeled through intermountain gaps, and flow from fractured bedrock along the entire mountain front (Imes and others, 1993). Ground water flows in an east-west direction as a result of the recharge at higher elevations near the Oman Mountains.

The aquifer system consists of the unconfined upper aquifer comprised of the alluvium deposits, the confining leaky marl layer, and the confined lower aquifer comprised of the Post Fars formation sediments. The water salinity of the upper aquifer is higher than that of the lower aquifer due to high evaporation rates. Over the years, the salinity of the lower aquifer has been increasing which is believed to be caused by the downward movement of water from the upper aquifer.

1.5 Literature Review

Few previous studies have been conducted on the groundwater system in Al Wagan area. In 1985, a project has been carried out by Ministry of Agriculture and Fisheries to explore the groundwater potential of the clastic intervals in the Mid-Tertiary Fars Formation (Ministry of Ag. & Fish. Project Report, 1985). For this purpose two boreholes were drilled 3 km North of Al Wagan with a distance of 30 m between the wells. The main borehole was drilled to a depth of 410 m, and the auxiliary borehole was drilled as a piezometer, reached 240 m only.

Two aquifer units were distinguished on the basis of lithology of the two-drilled boreholes. The upper aquifer extended from the surface to a depth of 235 m. A clayey zone of 15-meter thickness separates the upper aquifer fro aquifer is determined to be 120 meters thick extending from 250 m downwards to 370 m. The upper aquifer consists mainly of dolomites, limestone with chert, including small gravel and pebbles. The clayey layer is described as reddish clayey limestone and is assumed to act as a semi-pervious layer. The lower aquifer consists mainly of gravel and sand.

Based on an airlift test in the upper aquifer and a pumping test in the lower aquifer the following hydraulic parameters were estimated. The upper aquifer has a hydraulic conductivity of about 1.5 m/day. The lower aquifer has a hydraulic conductivity of about 0.03 m/day. The hydraulic conductivity of the confining layer was estimated to be 10 to 100 times lower than that of the lower aquifer. While the specific yield of the upper aquifer was estimated to be 0.02%, it was not possible to determine reliable values for the storage coefficients of the lower aquifer and the confining layer from the available test data.

During the pumping test performed in the lower aquifer, it was observed that the lower aquifer is artesian and confined by the clayey layer. In addition, the water level drop observed in the piezometer well during the pumping test showed that his clayey confining layer is not completely impervious, and recharge occurs through it.

It was concluded that the flow direction in the lower aquifer is parallel to the surface flow, i.e. from East to West. Since the lower aquifer is artesian, its recharge area must be in higher areas. During wadi floods, it is likely that the upper aquifer recharges the lower one, while its water level is raised above that of the lower aquifer. The discharge of the

CHAPTER ONE

INTRODUCTION

1.1 Problem Statement

Al Wagan area (Fig. 1) is located in the eastern region of Abu Dhabi Emirate, it constitutes one of the most important agricultural areas in the Emirates. Ground water is the primary source of irrigation in the area.

In the last three decades, the ground-water levels have declined dramatically because withdrawals have exceeded the average recharge rates for many years. Fig. 2, modified from Imes and others, 1993, shows ground water system exhibits five major depressions, and Al Wagan area is one of these depressions. Imes and others (1993) reported that groundwater levels have dropped 10 to 30 meters in al Wagan area. Such large drowdawns necessitate a thorough understanding of the hydrogeologic setting and characterization of the aquifer system in Al Wagan area so that viable ground water management alternatives can be developed. Therefore, delineation of hydrogeologic setting and characterization of the aquifer system in Al Wagan area forms the major objective of this study.

1.2 Physical and Geographical Settings

Al Wagan area lies to the south of Al Ain City and includes the villages of Al Arad, Al Ageer, Za'aba, Al Wagan North, Al Wagan South, Al Humran, and Al Oya along the Sultanate of Oman-United Arab Emirates border. The study area is characterized by its low topographic features, land surface is generally flat to gently undulating linear depressions that typically are intersected by sand dunes. The sand dune area is part of the northeastern edge of Rub Al Khali Desert of south-central Saudi Arabia (Fig. 1). Landscape in the dune area is dominated by elongate, compound dunes approximately 30-50 m high, tens of kilometers long and from 10 m to 1 km wide. These large linear dunes trend east-west to southeast-northwest directions. The interdunal lowlands contain clay, silt, sand, and (or) salt encrustations associated with Sabkhas. These interdunal lowlands constitute the major agricultural activity and forestry areas.

upper aquifer is likely to occur both by evaporation and to the lower aquifer, during floods.

Later Imes and others, (1993), have carried out an extensive work on the ground-water resources of the Eastern region of Abu Dhabi Emirate, including Al Wagan. As part of the project, The Ground-Water Research Program drilled a large number of wells in different selected sites to develop a better understanding of the ground-water flow system and for long-term (20 years) ground water monitoring in Al Wagan area.

Imes and others (1993) have determined that the upper aquifer extends from Oman maintains to Arabian Gulf in east-west direction covering almost entire Abu Dhabi Emirates. They have also found that the aquifer thickness varies from 27 to 151 meters.

In addition, a groundwater flow model was constructed to assess the understanding of the groundwater flow system in the eastern region, including the area of Al Wagan. The model was designed to simulate the flow system in the upper aquifer only, since it is considered as the main fresh water aquifer in the entire eastern region. The finding of this simulation study is used as the basis of the predevelopment period simulation of the Al Wagan area.

1.6 Objectives and Scope of the Study

The objectives of this study is to present:

1. A geohydrologic description of area and characterization of the aquifer system,
2. Long term simulation of flow in the ground-water system and identify the interaction between the upper and lower aquifer upon the prolonged withdrawals from the lower aquifer, and

An assessment of the changes of quality of the brackish ground water

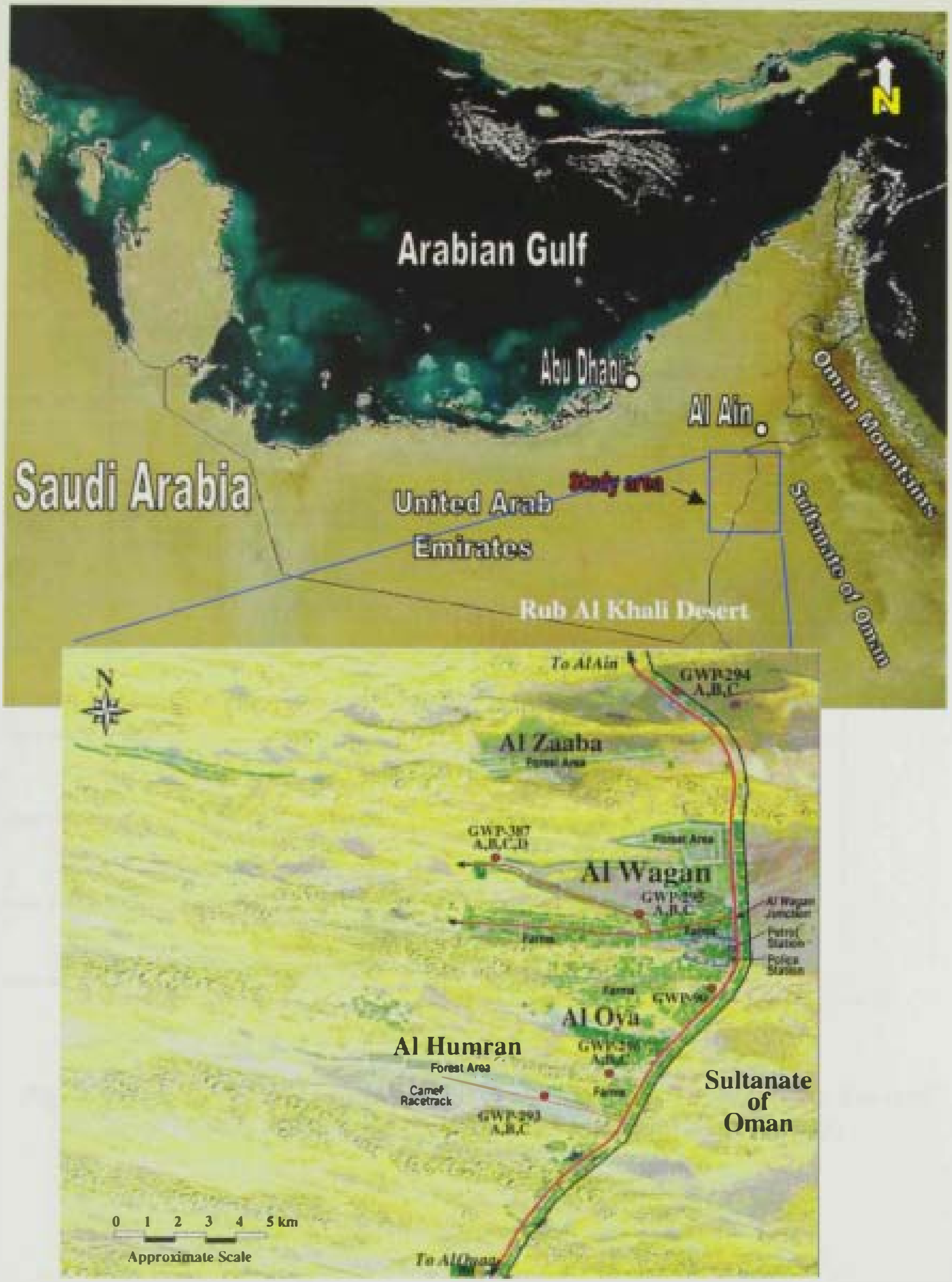


Fig. 1. Location of the Wagan area in the Eastern Region, Abu Dhabi Emirate

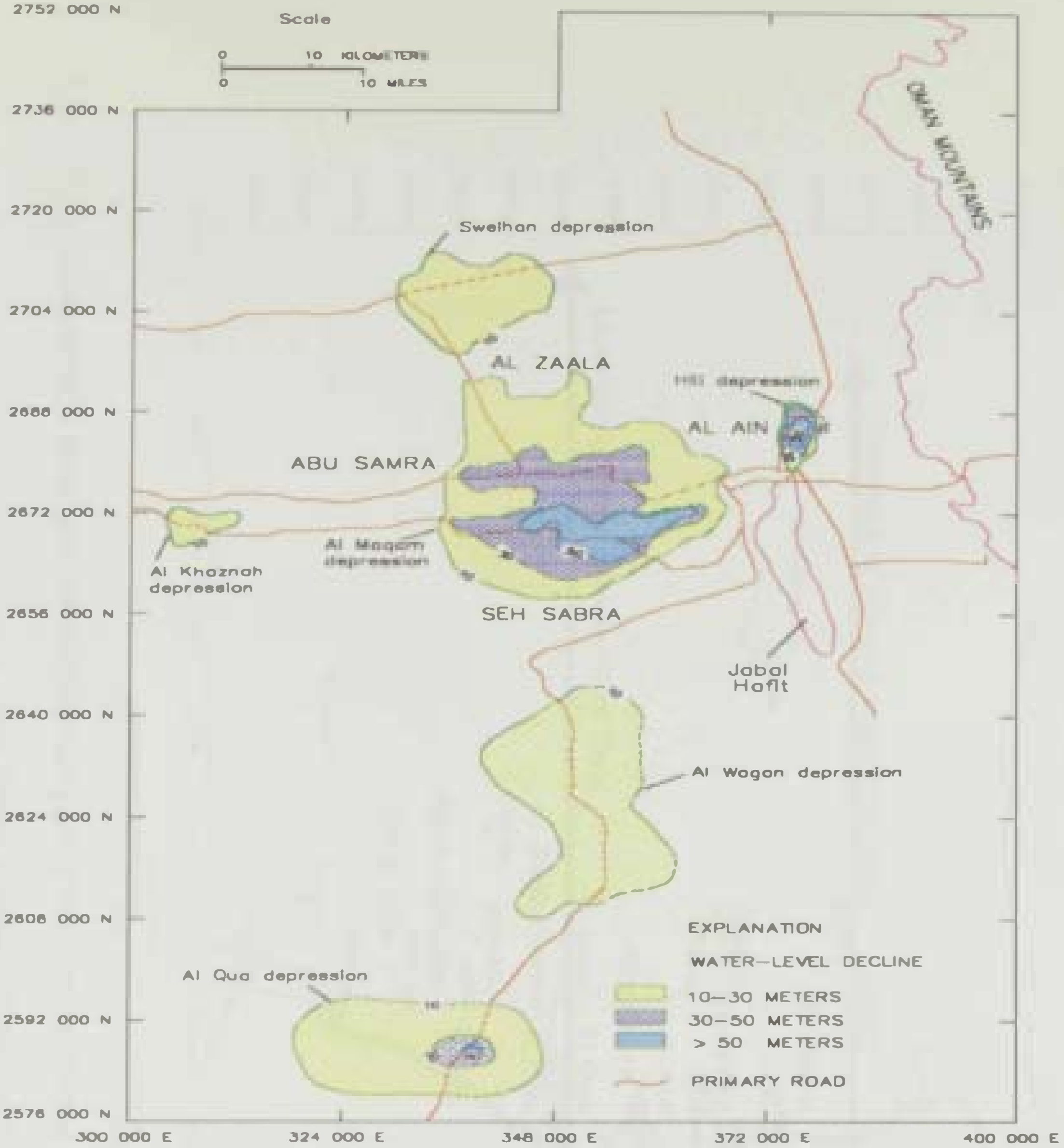


Fig. 2. Water level decline from predevelopment (1980) to 1991,in the Eastern Region, Abu Dhabi Emirate, UAE (after Imes and others, 1993)

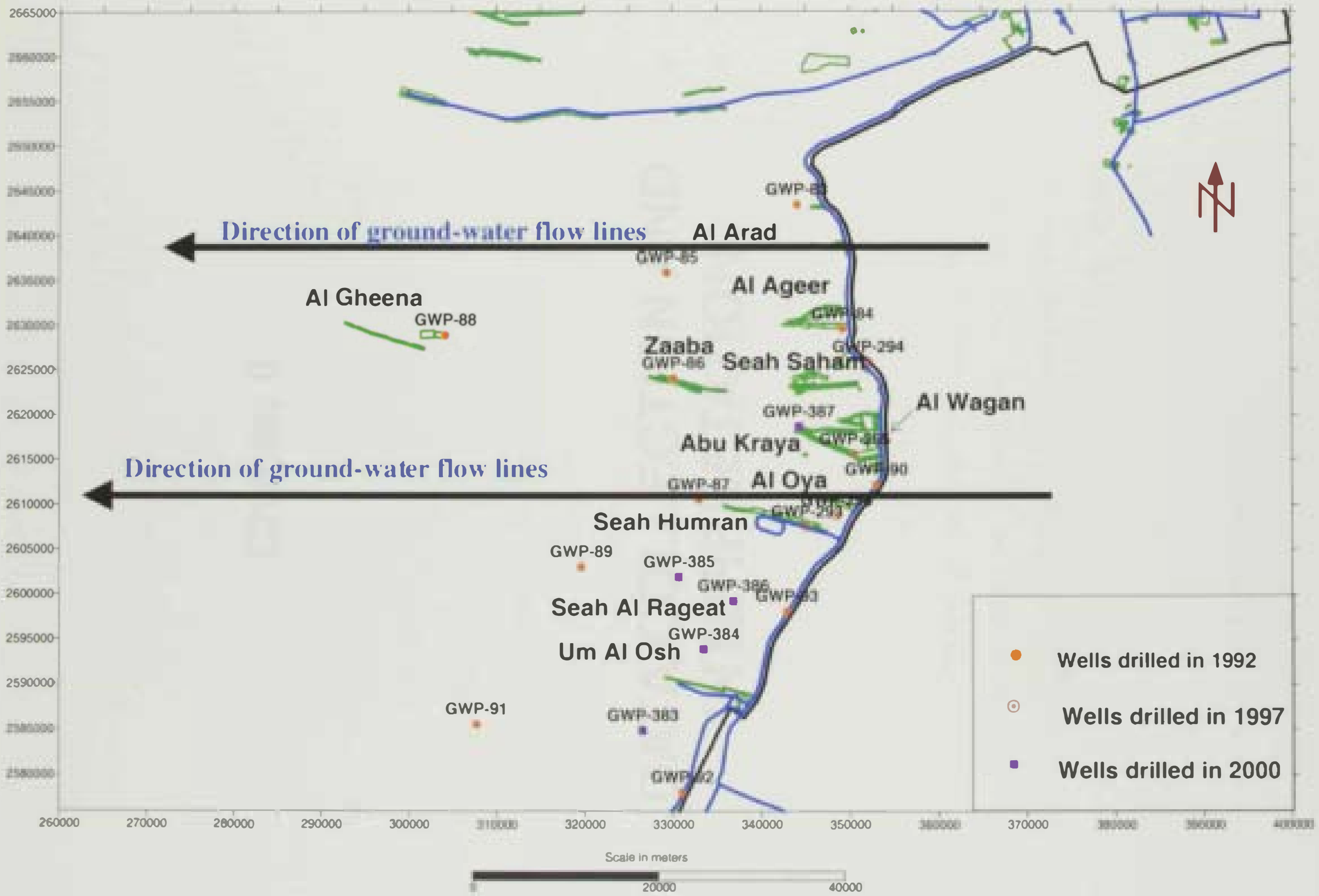


Fig. 3. Ground-water flow lines and Wells drilled as part of the Ground-Water Research Program of Al Wagan study area, Abu Dhabi Emirate, 1992-2000

Chapter II

DATA COLLECTION AND INTERPRETATION

CHAPTER TWO

DATA COLLECTION AND INTERPRETATION

Drilling data, petrophysical logs, pumping test data, water level monitoring in certain wells, and water sample analyses were used in this study. The data is analyzed to derive the following information:

1. Define geologic and hydrogeologic settings.
2. Determine hydraulic properties of aquifers.
3. Determine water level changes.
4. Determine water quality distribution.

2.1 Data from Well-Drilling

The GWRP has initiated an extensive drilling project to develop a better understanding of the ground-water flow system and for long-term (20 years) ground water monitoring in Al Wagan area. As part of this project from 1997 to 2000, GWRP has drilled a large number of wells at nine sites in the study area (Fig. 3). Each site consisted of three "nested" wells, each well completed in a different zone namely upper aquifer, confining layer and the lower aquifer.

The purpose of constructing nested wells at one location is to monitor water level changes in each water zone during pumping tests. In addition to the pumping tests results, the analysis of the logs and drill cuttings from these nested GWRP wells were the main source of information to define the hydrogeologic framework in the study area: 1) define the hydrogeologic framework especially the lateral and vertical extent of confining unit, aquifers, and ground-water zones 2) to document the general ground-water chemistry and 3) to monitor changes in ground-water levels and quality. During drilling of each well, sample cuttings were collected at 3.3 m intervals and described on site; these descriptions were checked later at the GWRP cuttings lab.

2.2 Petrophysical logging

Log interpretation can help identifying lithology, correlating formations, identifying permeable zones, estimating total dissolved-solids content, and estimating values for some of hydraulic aquifer properties such as aquifer thickness. The lithological information derived from the logs may be used to correlate some other aquifer properties such as hydraulic conductivity and storage coefficient.

2.2.1 Types of Petrophysical Logs and Their Applications in Groundwater Studies

Petrophysical logs are of great importance in estimating some of the lithologic and hydraulic properties of aquifers. Log interpretation can help identifying lithology, correlating formations, identifying permeable zones, estimating total dissolved-solids content, and estimating values for some of hydraulic aquifer properties such as aquifer thickness. The lithological information derived from the logs may be used to correlate some other aquifer properties such as hydraulic conductivity and storage coefficient. The type of the petrophysical logs along with their applications in groundwater studies are listed in Table 1.

2.2.1 Determination of Lithology

Petrophysical logs were used in conjunction with drill cuttings to discern lithology, to identify formations, and to determine formation thickness. Typical log responses are correlated to lithology as determined by both log analyses and by correlation with drill cuttings. When the typical log responses to the different lithologies of an area are known, lithology can be implied by noting the log response. In this manner, formations can be identified and correlated from one borehole to another.

Table 1. Petrophysical logs used in ground-water applications

Petrophysical log	Application
❖ Electric, sonic, or caliper made in open holes ❖ Nuclear logs made in open or cased	❖ Lithologic and stratigraphic description
❖ Calibrated sonic logs in open holes ❖ Calibrated neutron or gamma-gamma logs in open or cased holes	❖ Total porosity or bulk density
❖ Calibrated long-normal log resistivity logs	❖ Effective porosity or true resistivity
❖ Natural gamma logs	❖ Clay or shale content
❖ No direct measurement by logging. May be related to porosity	❖ Permeability
❖ Caliper, sonic or borehole televiewer	❖ Secondary permeability-fracture, solution openings
❖ Calibrated neutron logs	❖ Specific yield of unconsolidated aquifers
❖ Possible relation to formation factor derived from electric logs	❖ Grain size
❖ Electric, temperature or fluid conductivity	❖ Location of water level or saturated zones
❖ Calibrated neutron logs	❖ Moisture content

Lithology, such as sandstone, limestone and dolomite, can be determined from cross plots of neutron porosity and bulk density. Cross plots of neutron porosity versus travel time (sonic) are useful in determining lithology for consolidated formations. For unconsolidated formations, the compensated sonic log is a useful indicator of clay content. While the natural gamma log is useful in distinguishing among formations of similar lithology that have clastic material from different sources (Jorgensen and Petricola, 1994). An example interpretation of a petrophysical-log run in the borehole for well GWP-86 is presented in Fig. 4A. Also shown are the major stratigraphic units and well-construction information in Fig 4B.

In the eastern part of Abu Dhabi Emirate, much of the alluvium sediments are of ophiolitic origin. These sediments have very low natural-gamma radioactivity because of their lack of clay minerals, and the gamma-ray log showed very small intensity at the upper part of the aquifer system. However, In well GWP-86 (Figs.4A and B), the bottom of the alluvium sand and gravel layer can be recognized by the increasing activity of the natural gamma ray, which reached up to a value of 33 counts/second. This was the point it was determined from drill cuttings that the marl layer started at depth 26 m (85 feet) and continued downward till depth 37 m (121 feet). This change of lithology was confirmed with a major increase in the sonic and density log recordings due to the higher bulk density of marl than the unconsolidated sand and gravel. Then there exists a section of interbedding layers of gravel and sandy marl which is deduced mainly from cuttings and which appears as a wiggling section in gamma ray logs.

The conglomerate layer appears between 50 m to 61 m (164 ft- 200 ft), the natural gamma log records low values (less than 18 counts/second) indicating low clay content. The same low values also occur for the density. Both density and sonic logs record low values for highly porous materials. The cuttings showed that the lithology is conglomerate. Therefore, low reading from both density and sonic logs confirmed this lithology identification. Since the bulk density value of the porous conglomerate is less than the dense marl and the travel time of the sonic log decreases with the increasing porosity the reduction in sonic log readings are expected.

The section from 61 m to 95 meters has been identified to be conglomerate interbedded with mudstone from drill cuttings. The presence of mudstone interbeds must cause large fluctuations in all three logs of the gamma ray, density and sonic logs as observed in the Fig. 4A.

The bottom of the lower aquifer determined to be gypsiferious mudstone. Such a change in lithology is apparent from the dramatic changes in all three types of logs. Gamma ray log records very low values, density logs show very high values and sonic logs indicates very low values which are all consistent with low clay content and very low porosity of the unit. This procedure was applied for the rest of the GWP boreholes that were logged by Schlumberger, where a complete suite of logs was conducted (see table 1).

2.2.2 Determination of Porous and Permeable Zones

Qualitative interpretations of permeable zones, which will yield water easily to a well, were made from logs by inspection of the resistivity (or induction) log and the sonic log. In most clastic material, permeability is primarily an inverse function of clay content. Jorgensen and Petricola (1993) stated that the sonic log of boreholes in the study area is a better clay indicator than the gamma-ray log or the spontaneous-potential log, which are the usual clay indicators elsewhere. Although they did not specify how to use sonic logs to determine the clay content quantitatively, they provided Table 2 for the typical compensated sonic-log travel times in the eastern area of Abu Dhabi Emirate.

Table 2. Typical compensated sonic log travel times in the eastern area

Material	Travel time (microseconds per foot)
Partially saturated formations	>225
Clay	170-225
Water of fresh mud	190
Sand and gravel, clean	50-130
Limestone and marl	45-70
Dolomite, sandstone, anhydrite, or gypsum	45-60

Most permeable aquifer material, such as sand and gravel, is resistive and can be primarily identified with their high resistivity values in the resistivity log. These zones then are checked on the sonic log and Table 3 to qualitatively evaluate their clay contents. If the zones are generally resistive and sonic log values fall in the relatively clay-free ranges in Table 2, then these zones are identified as probable permeable zones. Then the process of flow testing of the aquifer in those zones is preceded to confirm the above conclusion. This procedure is applied for well number GWP-86, where the upper permeable zone exists between 18-26 m (59-85 ft), where low natural gamma was recorded (i.e. clay-free formation) versus medium neutron porosity (average 40%), and less travel time in the sonic log due to bore spaces in the formation. The same situation was recorded at the interval between 50-61 m (164-200 ft), but with higher clay content which indicates less permeability.

We also have used the following correlations (Timur, 1968, and Jorgensen and Petricola, 1993) employed in a commercial logging program LOGAN2 to estimate the hydraulic properties of the aquifers as provided in Table 3.

$$k \approx \frac{1x10^{4}\phi^{4.5}}{S_{wi}^{2}} \qquad (1)$$

$$S_{s} \approx \frac{9.807x10^{3}}{E_{m}} \qquad (2)$$

Table 3 gives the results of the log interpretations and those correlations applied in LOGAN2.

Table 3. Hydraulic properties determined for the lower aquifer from petrophysical logs for the lower aquifer, for GWRP borehole, Al Wagan area, south Al Ain, Abu Dhabi Emirate.

Well Number	Transmissivity (m^2/d)	Lower Aquifer Thickness (m)	Hydraulic Conductivity (m/d)	Specific Yield
GWP-83	82	68	1.21	0.07
GWP-84	23.6	62.4	0.38	0.06
GWP-85	286	87.7	3.26	0.08
GWP-86	157	56.5	2.78	0.08
GWP-87	1,700	88.9	19.1	0.16
GWP-88	193	64.3	3	0.11

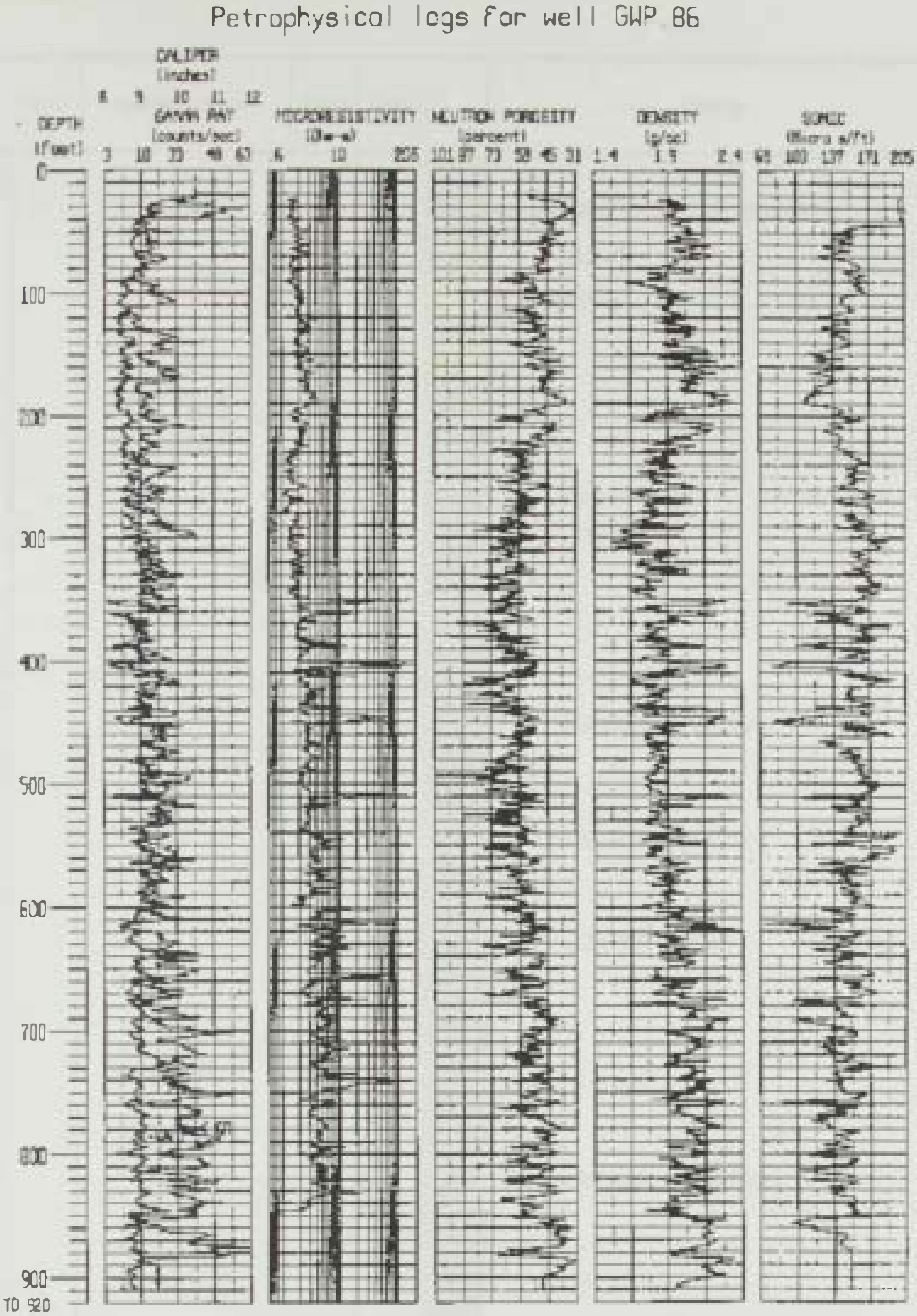


Fig. 4A. Petrophysical logs of GWP-86

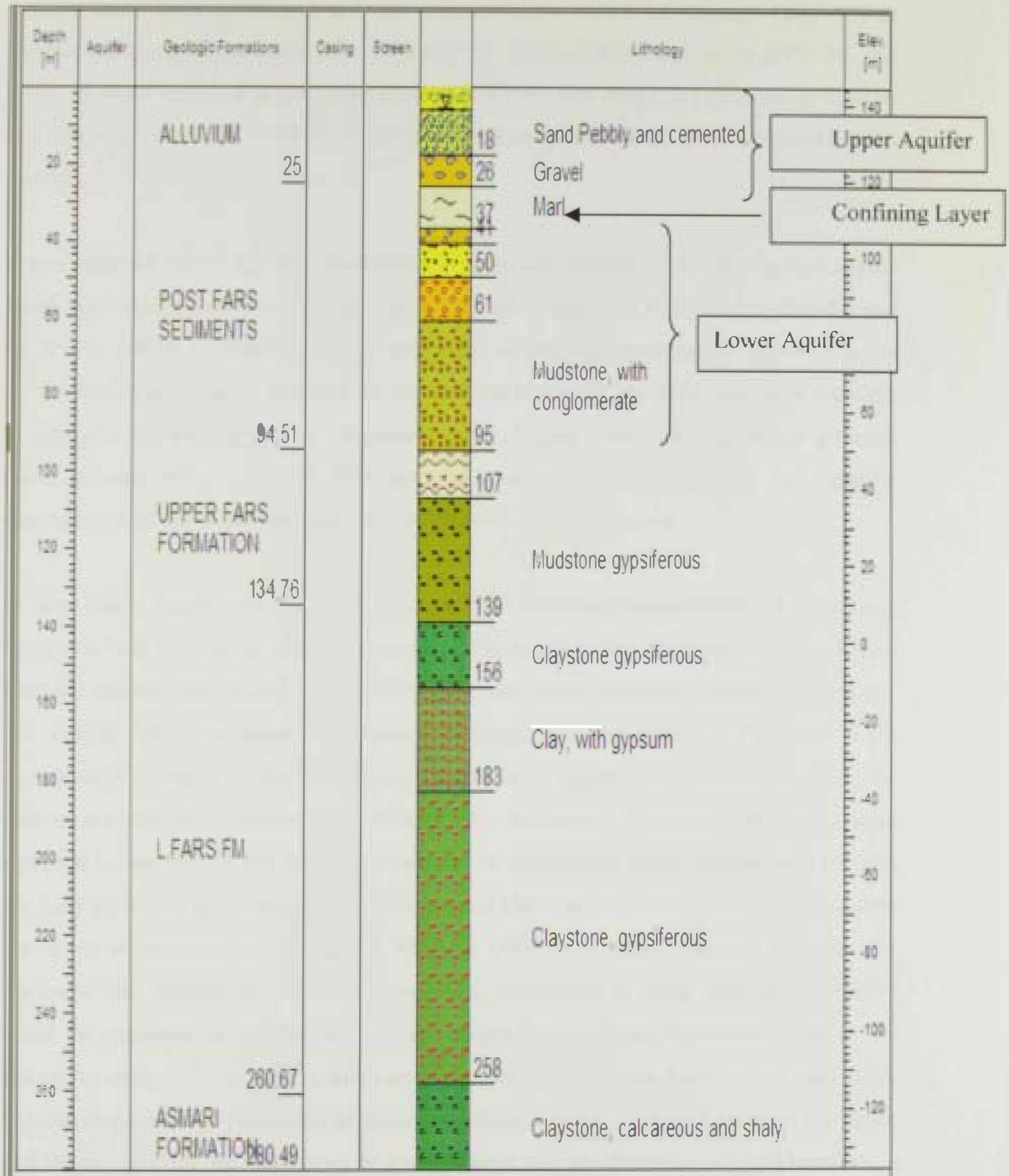


Fig. 4B. Major stratigraphy units in the borehole for well GWP-86, Al Wagan area, south Al Ain, Abu Dhabi Emirate.

2.3 Aquifer Testing

Aquifer tests were performed at nine selected wells (GWP-83 through GWP-93) at various locations in the study area. (See Fig. 3). Among these test wells GWP-84, and GWP-89 were screened in the lower aquifer, GWP-83 was screened in the upper aquifer, and GWP-85, GWP-86, GWP-87, GWP-88, GWP-90 and GWP-93 were screened in both aquifers.

It was assumed that in all cases a semi-log straight-line section would develop in Cooper-Jacob type plotting of the data. Actual testing procedures are described by Tawfiq and Al Amin (1997). Depending on the well yield during the development phase, a pump with a discharge capacity between 10 and 250 cubic meters per hour was set in the well. Pumping tests were generally conducted for a 5-hour period during which periodic measurements were made of drawdown in the well, discharge rate, and specific conductance of the water samples collected from the discharge line.

In most cases, single-well tests were conducted to determine transmissivity of the aquifer for which both drawdown and recovery data collected from the pumping well. Analytical methods assume that the aquifer is a homogeneous porous medium of infinite extent, the test well is fully penetrates the saturated thickness, and the saturated thickness is not significantly changed by the drawdown in unconfined aquifers. In confined aquifers, the well is assumed to penetrate the whole aquifer thickness. Because GWP wells were screened to tap part of the saturated thickness in unconfined upper aquifer, and they do not fully penetrate the lower aquifer; they are not ideal for test wells. See Fig. 5 showing the screened portions of the aquifer of well GWP-84. Also, because the saturated thickness was reduced by pumping, as much as 50 percent at some sites, transmissivity could be expected to decline as the tests progressed. These conditions lead to the following complications. First, due partial screening there must be an extra head drop. Second, there exists a possibility of communication or water exchange between the upper and lower aquifers via well bore or even behind the unscreened casing. Therefore, a layered leaky aquifer model should be utilized to account the effects of both rather than a single homogeneous unconfined or confined aquifer.

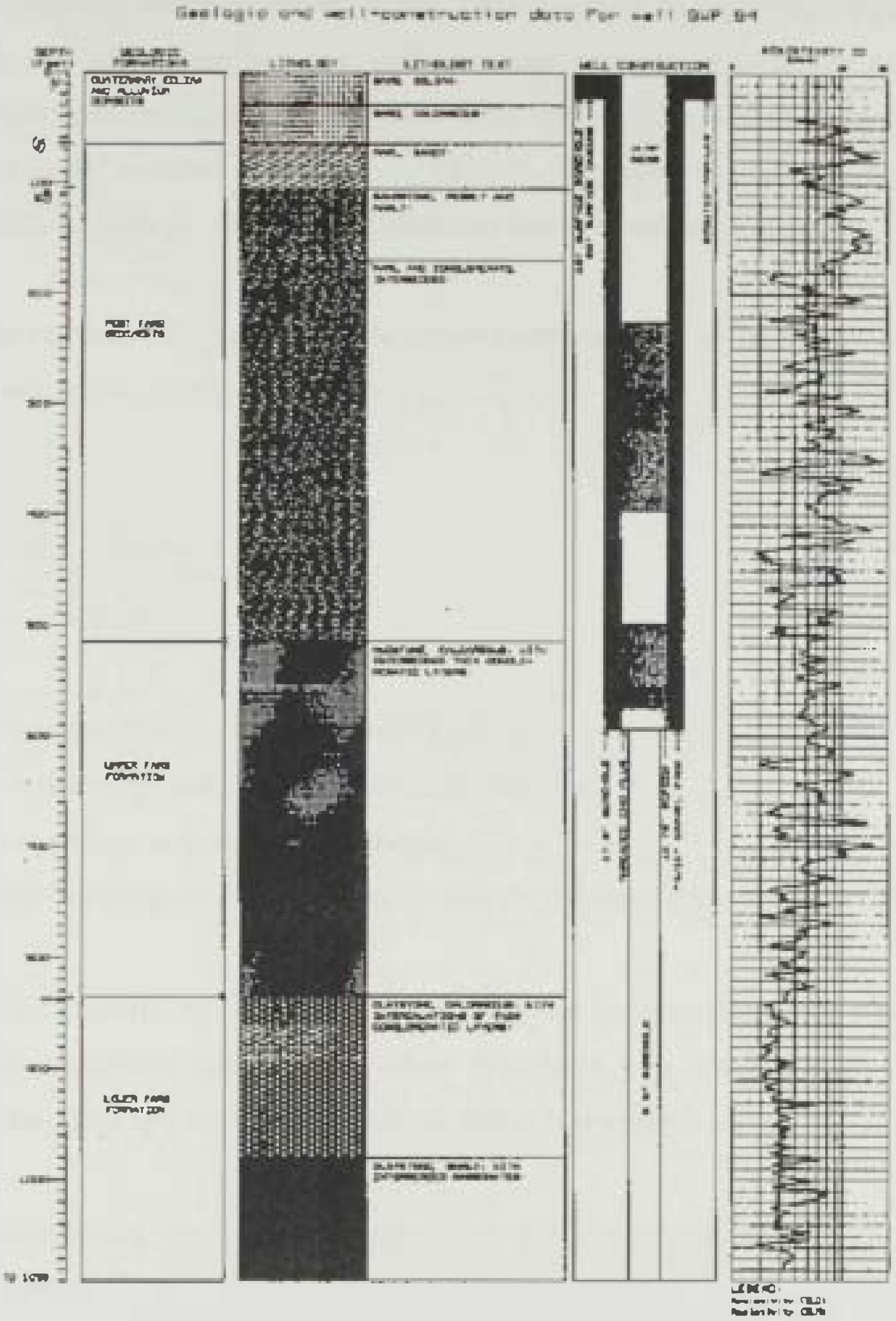


Fig. 5. Well construction diagram of GWP-84

Tawfiq and others assumed that the whole system acts as an unconfined aquifer. Also based on the information that the total saturated thicknesses were not screened, the transmissivity values calculated from these well tests are assumed to be less than actual one and termed "apparent transmissivity values". Therefore, in using the transmissivity values obtained from the following analysis one has to exercise great caution.

Transmissivity was calculated using the similogarithmic plots of drawdown and recovery (Cooper and Jacob, 1946):

$$T = \frac{2.3Q\Delta \log t}{4\pi\Delta s} \qquad (3)$$

Where:

T is transmissivity, in square meters per day;

Q is discharge rate, in cubic meters per day;

Δs is change in drawdown, in meters; and

$\Delta \log t$ is change in the logarithm of time for the same period of drawdown change.

Equation 3 is strictly valid for confined aquifer test interpretation, however, it can be applied to unconfined aquifer tests where drawdown is a small portion of the total saturated thickness and the delayed drainage effect is negligible.

Tawfiq recommend the following procedure for the test interpretation during the pumping period:

1. Plot values of drawdown (s) versus the corresponding time (t) on semilog paper (t on logarithmic scale), and drawdown (s) on linear scale.
2. Fit a straight line through the plotted points, ignoring the early data (first 20 minutes), which likely are influenced by casing storage. The late data were also not used in some cases where there was a flattening of the drawdown curve. This flattening was considered to indicate leakage from semiconfined layers above or

below the screened interval or delayed drainage of water from the affected area within the cone of depression.

3. Determine the change in drawdown in drawdown over one log cycle.
4. Substitute the values of Δs, and Q into equation (1) and compute T.

Because it is difficult to control the discharge rate during a pumping test, it is often more reliable to estimate transmissivity using recovery plots rather than drawdown plots. For the recovery plots calculations are made using the following equation:

$$T = \frac{2.3Q\Delta\log(t/t')}{4\pi\Delta s'} \tag{4}$$

Where

s` is residual drawdown, and t/t' is the ratio of total time since pumping started to time since pumping stopped.

Fig. 6 and 7 show straight-line portions of the drawdown and recovery tests conducted in the well GWP-86. In order to analyze the test commercial software, Aquifer Test was utilized. The software allows the user to exercise his expertise and choose the straight-line portions at his discretion. Note that while the larger t value range is selected for the drawdown, small value range of t/t' is selected for the recovery plot. The transmissivity and specific yield valued are automatically calculated by Aquifer Test.

The plots of the tests in the other wells are shown in Appendix A. Table 4 summarizes the hydraulic properties obtained for these 9 GWRP wells, in Al Wagan area, south Al Ain, UAE.

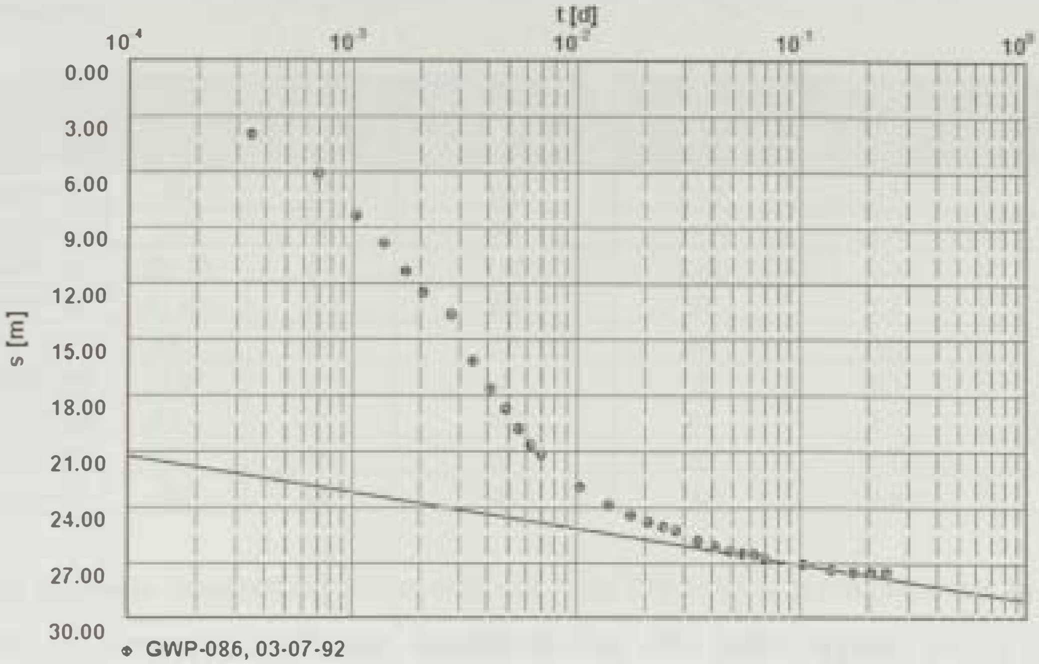


Fig. 6 Drawdown plot of GWP-86

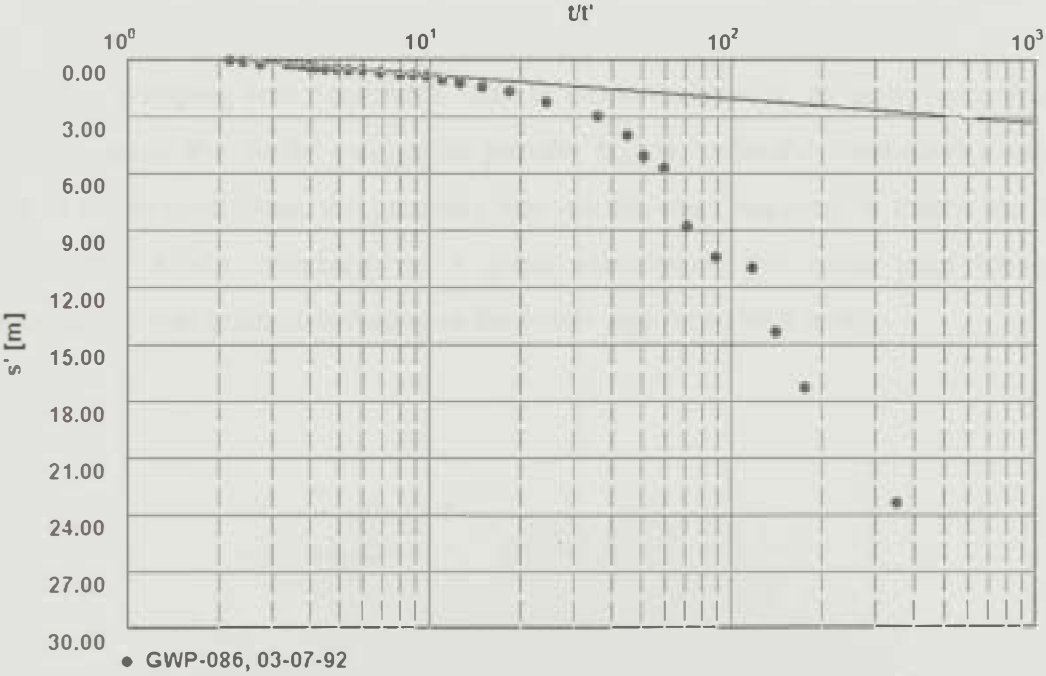


Fig.7 Recovery plot of GWP-86

Table 4. Hydraulic properties of the lower aquifer determined from aquifer-test analyses, for GWRP borehole, Al Wagan area, south Al Ain, United Arab Emirate.

Well ID	Screen Interval (m)	Sat. Thick. (m)	T (m^2/d) (drawdown)	T (m^2/d) (recovery)	K (m/d) (drawdown)	K (m/d) (recovery)
GWP-83	29	50	190	210	3.8	4.2
GWP-84	106	56	59	N/A	1.1	N/A
GWP-85	65.43	87	110	170	1.3	2.0
GWP-86	41.86	55	63	97	1.1	1.8
GWP-87	46.4	89	70	82	0.8	0.9
GWP-89	29	71	4	2	0.1	0.0
GWP-90	91.4	51	190	81	3.7	1.6
GWP-91	40.7	46	67	85	1.5	1.8
GWP-93	92	99	80	160	0.8	1.6

The hydraulic conductivity value obtained from GWP-83 is the highest one in Table 4. This is compatible with the assumption that the upper aquifer has a hydraulic conductivity than the lower one. Also note that hydraulic conductivity values obtained from GWP-84 and GWP-89 are quite lower than the other conductivity results. This also confirms the much lower hydraulic conductivity assumption in the lower aquifer.

Since the pumping test conditions lead to complications in an exact modeling of the system, during the model calibration process higher hydraulic conductivity values than what was obtained from the pumping test results were required to match the observed water table levels. Similarly, as a gross assumption the value used for hydraulic conductivity was generalized all over the lower aquifer to be 8 m/d.

Chapter III

HYDROGEOLOGIC SETTING

CHAPTER THREE

HYDROGEOLOGIC SETTING

This chapter presents the geologic and hydrologic settings underlying Al Wagan area. Understanding these settings is necessary for understanding the ground-water-flow system. In this study, the flow system consists of the upper aquifer, the lower aquifer, and the intervening confining layer. Table 5 summarizes the Stratigraphic data for Ground-Water Research Program boreholes in Al Wagan area. The definitions of and relation between the two aquifers are discussed in details in the following sections.

3.1 Geologic Setting

A geological map and a stratigraphic column schematic of the study area are presented in Fig. 8 A and B.

3.1.1 Eolian Deposits

Eolian deposits consisting of sand dunes form the first layer in the stratigraphic setting. Sand dunes form a nearly continuous layer that covers most of the study area particularly in the western part. Petrophysical logging and lithologic descriptions of boreholes indicate a sharp transition zone at the base of the dune sand from the underlying alluvium deposits (Fig. 9). Large velocity values in the sonic logs and small densities relative to the underlying ophiolitic sand and gravel are the most characteristic “fingerprints” of the eolian deposits.

Eolian deposits consist of coarse- to fine-grained sand that is moderately to poorly sorted (Hunting Geology and Geophysics Ltd., 1979b and 1979c). Quartz is the most predominant mineral in the deposits; other minerals include carbonates, ophiolites and chert. The reddish-orange color of the sand is due to staining of iron oxides. This color becomes more creamy and buff to the west because of the increase of marine carbonates in the deposits.

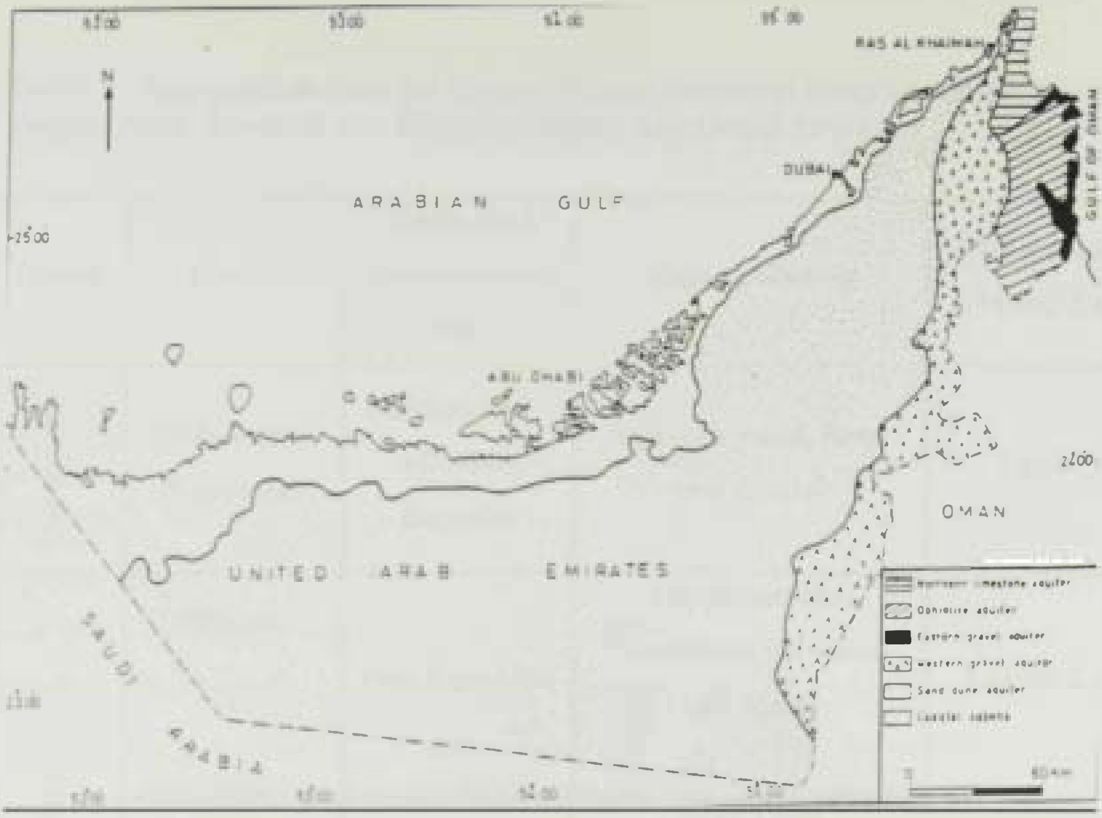


Fig. 8A. The main aquifers identified in UAE (after Rizk Z, 1993.)

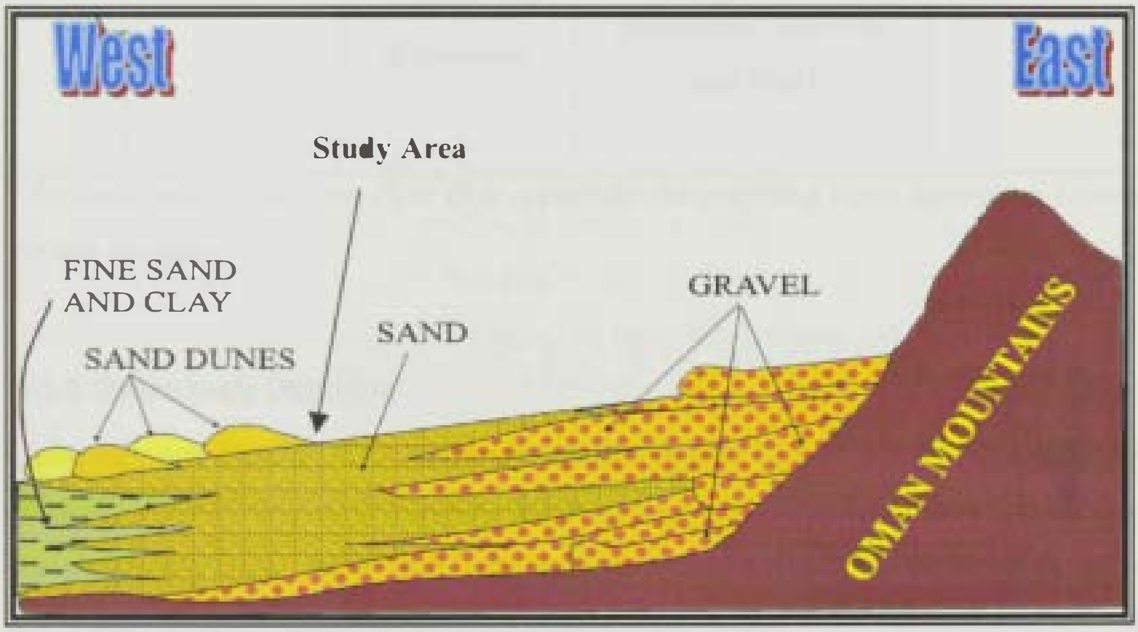


Fig. 8B. Schematic cross section of the formation of alluvial fans (gravel) near the Oman Mountains, Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate (not to scale).

Table 5. Stratigraphic data for Ground-Water Research Program boreholes in Al Wagan Area, South Al Ain, Eastern Region, Abu Dhabi Emirate

Period	**Epoch**	**Geological Formation or Unit**	**Major Lithology**	**Hydrogeological Model Unit**
Quaternary	*Holocene to Pleistocene*	**Eolian and Alluvium Deposits**	**Siliceous Sand, Sand and Gravel**	**Layer 1**
Tertiary	*Pliocene*	**Post Fars Unit**	**Conglomerate, Sandstone, Siltstone and Marl**[1]	**Layers 2 & 3**
	Miocene	**Upper Fars Formation**	**Sandy and Conglomeratic Mudstone, Siltstone and Marl**	

[1] *the marl layer of the Post Fars Unit resembles the confining layer separating between the two aquifers*

3.1.2 Quaternary Deposits

Quaternary-age deposits in the study area consist of near surface and surficial sediments of mixed alluvial, eolian, and locally Sabkha (evaporites) origins. In most areas, these deposits overly older rocks with varying thickness. Alluvium (in the form of coarse gravel and coarse sand) is derived from alluvial fans formed at the foothills of the Oman Mountains (Figs. 8A and B). No sand dunes are present in the fans (well number GWP-294). Thinner alluvial deposits are present in the middle part of the study area and are overlain by moderately thick (on average 10 m) sand dunes (well number GWP-86).

In the western part of the area, the eolian deposits are up to 30 m deep. Indurated calcareous sand of eolian origin underlies the sand dunes, but no sand or gravel of ophiolitic origin is present (well number GWP-88).

3.1.2.1 Quaternary Alluvium

Quaternary alluvium is composed of a thin sequence of sand and gravel with interbeds of silt and clay. Most of these coarse clastic units contain a clay-rich matrix that usually is calcareous. The bulk of the alluvium has been deposited after transport within wadi systems draining westward from ophiolitic source rocks in the Oman Mountains (Figs. 9 and 10). Towards the west where the alluvium becomes more fine-grained, it is affected by wind action. In this area, the surface is covered partly by sand dunes and, therefore replaced progressively by interbedded sand, silt, and calcrete. The sand and silt typically has cross-laminated, brown or white and calcareous, with scattered pebbles. The sand and silt tend to be more firmly cemented than the conglomerates.

3.1.2.2 Inland Sabkha

The inland Sabkhas in the study area are distributed widely. They are found between sand dunes and ridges in closed topographic depressions where surface water can be collected and be evaporated (fig 9). Most Sabkhas in the southern and western parts of the study area are located where water table is at or near land surface. Surface of the Sabkha consists of flat, featureless, salt-encrusted ground with saline ground water at shallow depths (usually less than 10 m below land surface). Sabkha deposits consist of a mixture of very fine to medium-grained sand, silt, clay, and some evaporitic deposits such as halite and gypsum. These calcareous deposits tend to develop at the western most discharge points of surface runoff from large piedmont wadis. The Sabkha surface is resistant to erosion, rough in texture and generally mottled, because of the variable moisture content at the surface. A profile through the upper 20 to 40 cm of a typical

Sabkha generally is moist, well defined, and parallel to undulating millimeter-scale stratification with sparse, very small crystalline salt masses (Imes and others, 1993).

3.1.3 Fars Formation

Based on GWRP boreholes drilled in the southern area, the Fars Formation is composed of two units: the Lower and Upper Fars. In the eastern part of the study area, the Post Fars sediments overlie the Lower and Upper Fars and underlie the Quaternary deposits. The Post Fars Formation was encountered in the following wells: GWP-83, 84, 85, 86, 87, 90, 293, 294, and 296 (Fig. 11). The Post Fars was not encountered in boreholes located to the south and west of the wells listed above. The Post Fars is easily distinguished from the Quaternary Alluvium by a marl unit separating the two units.

The Upper Fars Formation consists mainly of variegated pebbly sandstone, siltstone, mudstone, and marl (Hunting Geology and Geophysics Ltd., 1979a, 1979b, 1979c, and 1979d; Bown and others, 1991). The maximum thickness of the upper formation is 151 m in borehole GWP-83. In general the Upper Fars Formation tends to be thicker towards the northeast end part of study area, and thins to the southwest (Fig. 12).

The Lower Fars Formation consists of evaporite beds of anhydrite, gypsum, halite and celestite interbedded with claystone, mudstone, and minor limestone and dolomite. Variegated pebbly sandstone, siltstone, mudstone and marl compose the rock of the upper Fars (Hunting Geology and Geophysics Ltd., 1979b and 1979b, Bown and others, 1991).

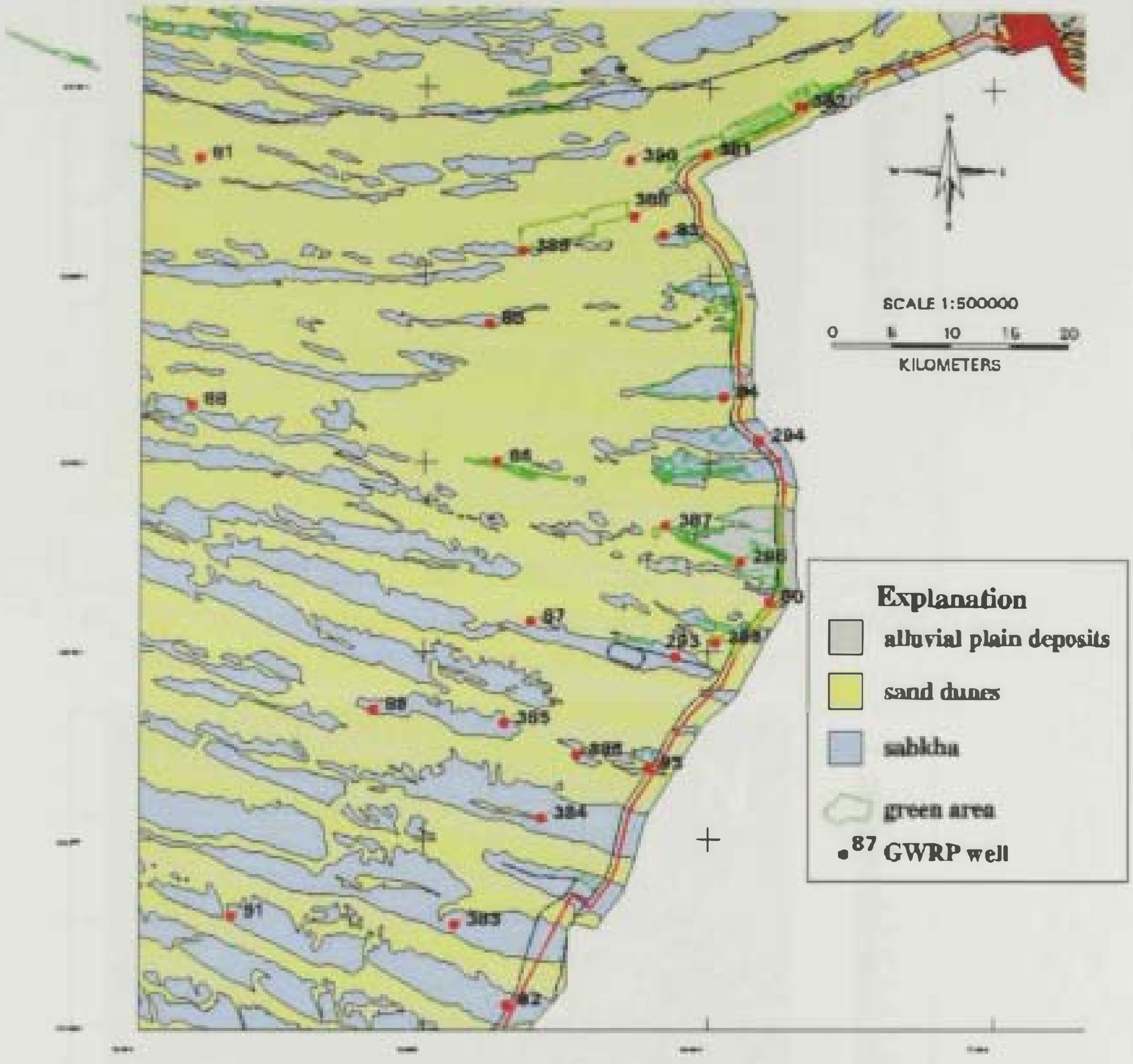


Fig. 9. Distribution of sand dune and interdunal Sabkha in Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate

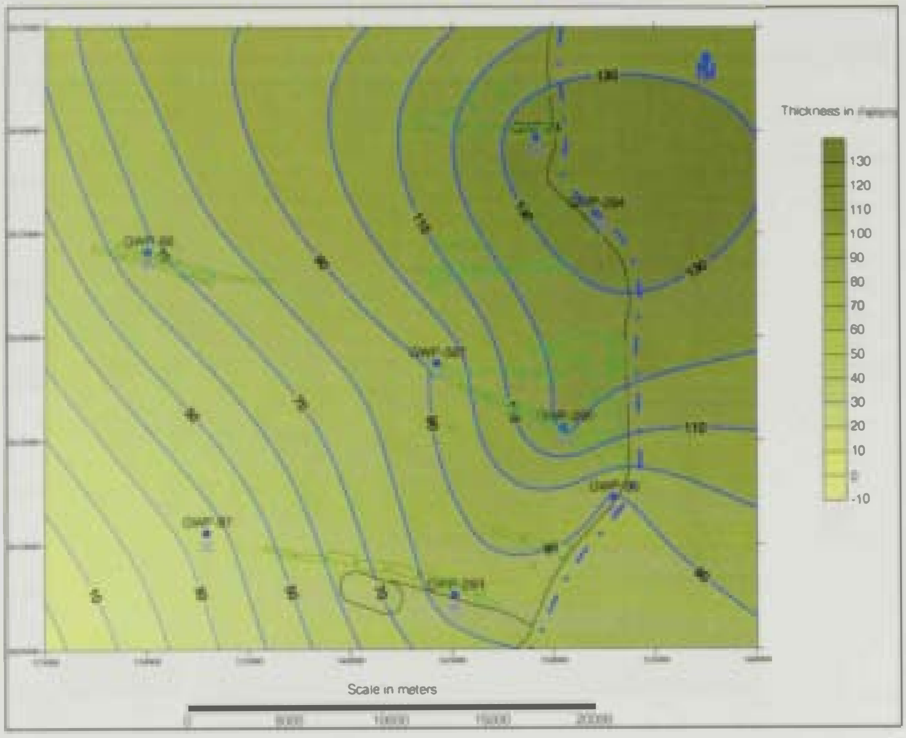


Fig. 10. Thickness map of the Quaternary Alluvium in Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate

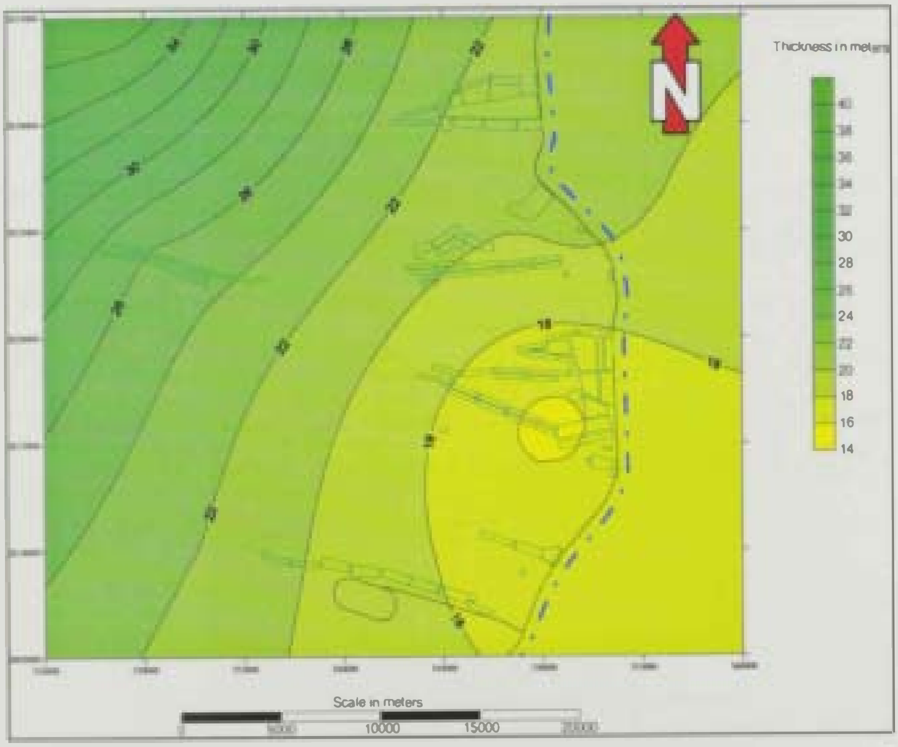


Fig. 11. Thickness of the Post Fars formation, Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate

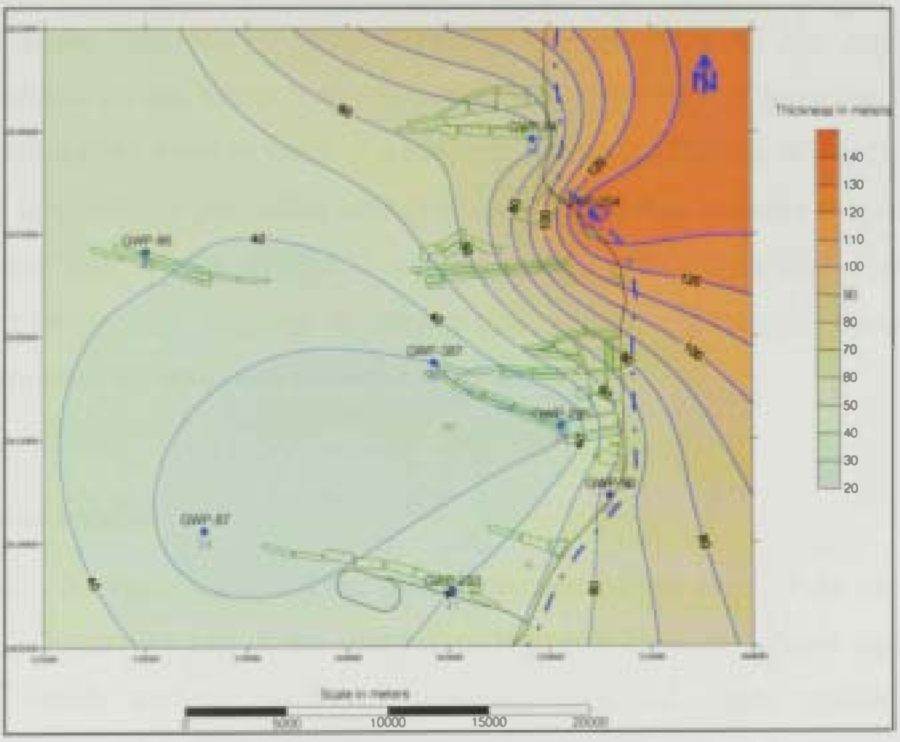


Fig. 12. Thickness of the Upper Fars formation, Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate

3.2 Hydrologic Setting

Most ground water in the eastern area of Abu Dhabi Emirate is in shallow deposits, generally in the Quaternary Alluvium, usually referred to as Al Ain Aquifer. Water-bearing material present beneath Al Ain aquifer may yield limited quantities (usually less than 360 m^3/day) of water to wells. Data collected from the Ground Water Department in Al Wagan area indicate permeable zones within a section that includes evaporites that are much deeper than Al Ain aquifer (Imes and others, 1993). Data were compiled from borehole petrophysical logging in conjunction with the lithologic description drill cuttings from GWRP wells drilled in the study area.

3.2.1 Upper aquifer

In this study, the upper aquifer refers to the saturated part of most of the unconsolidated deposits of Quaternary age in the study area (Fig. 10). This unconfined aquifer extends over the whole emirates. Note, however, that the upper aquifer is highly compartmentalized in terms of its water salinity. For example, salinity in the southern part of the upper aquifer (i.e. Al Wagan area) is much greater than that in the northern part (for example Al Hayer area, north Al Ain).

This compartmentalization can be explained by the following factors: (1) the recharge areas are located at remote distances from the parts of the aquifer in Al Wagan. Therefore, the ground water has to travel for longer distances before reaching to that part of the upper aquifer. This allows natural dissolution of the mineral content of the rocks resulting in higher salinity of the regional groundwater in the southern parts of the upper aquifer than those in the northern part, which is closer to the recharge area.
(2) Effect of water level variation being close to the surface in al Wagan area and the effect of inland Sabkha conditions such as arid region climate. The water levels are deep towards the northern part, less evaporation takes place and as a result fresh water exists in northern parts. In the Al Wagan area however, inland Sabkha conditions dominates causing high amounts of evaporation and hence more salinity levels in the upper aquifer

(3) Lower permeability of in Al Wagan area than northern parts of the aquifer, leading to long travel and dissolution times.

Some of the dune sand deposits of recent age were also considered to be part of the upper aquifer. Test drilling and interpretation of borehole logging data indicate that the area of dune sand is underlain by a thick layer of Quaternary deposits ranging in thickness from 5 to 145 meters (Fig. 15). Such conditions of stratigraphic arrangement may lead to saturated thicknesses up to 160 meters.

The configuration of the water-level elevations presented in Fig. 13 and 14 (predevelopment map of upper and lower aquifers) gives a general indication of the direction of the water flow from the east to the west for the two aquifers in Al Wagan area in 1980. In some of the areas, eolian sand constitutes the upper part of the upper aquifer, where the ground-water level becomes shallow and very close to the surface.

Transmissivity of the upper aquifer is affected by the thickness of the sediments, the degree of cementation, and their saturated thickness. The values of transmissivity of the upper aquifer range from 87.5 to 1025 m^2/d. The main zones with high transmissivity exist in western area; Fig. 13 shows the thickness of the upper aquifer (Imes and others, 1992).

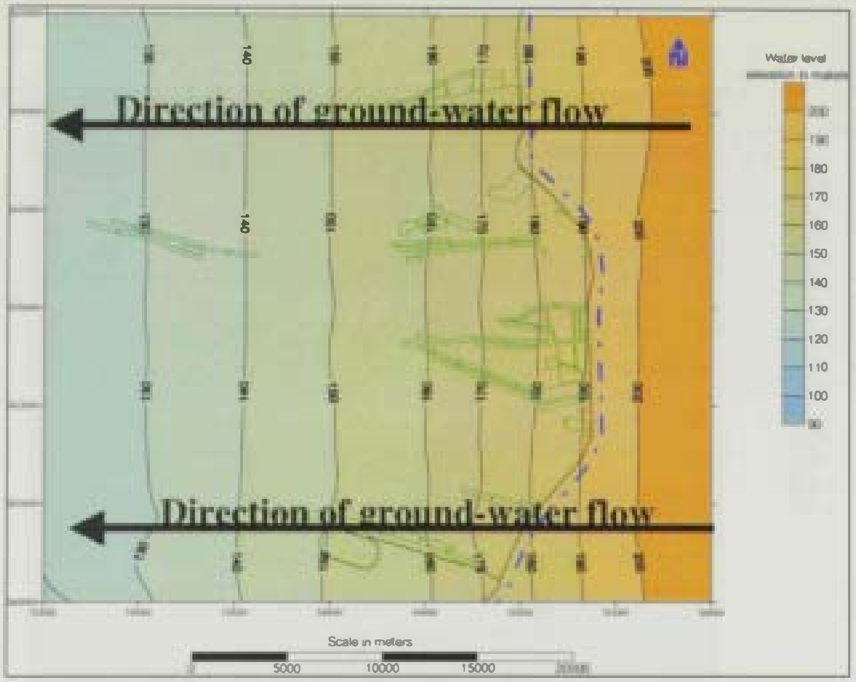


Fig. 13. Predevelopment water level map of the upper aquifer and the direction of regional ground-water flow, Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate.

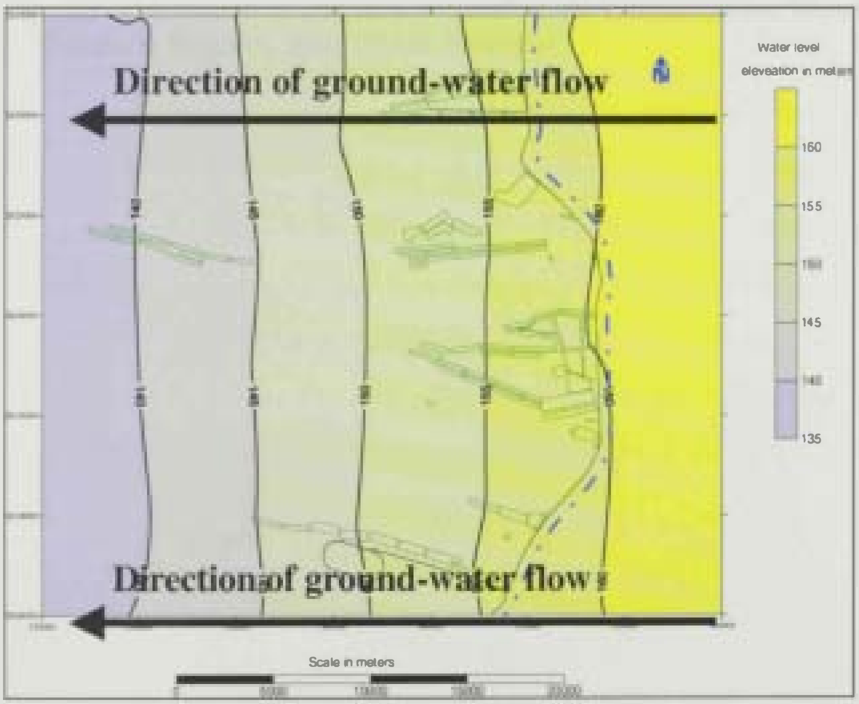


Fig. 14. Predevelopment water level map of the lower aquifer and the direction of ground- water flow, Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate.

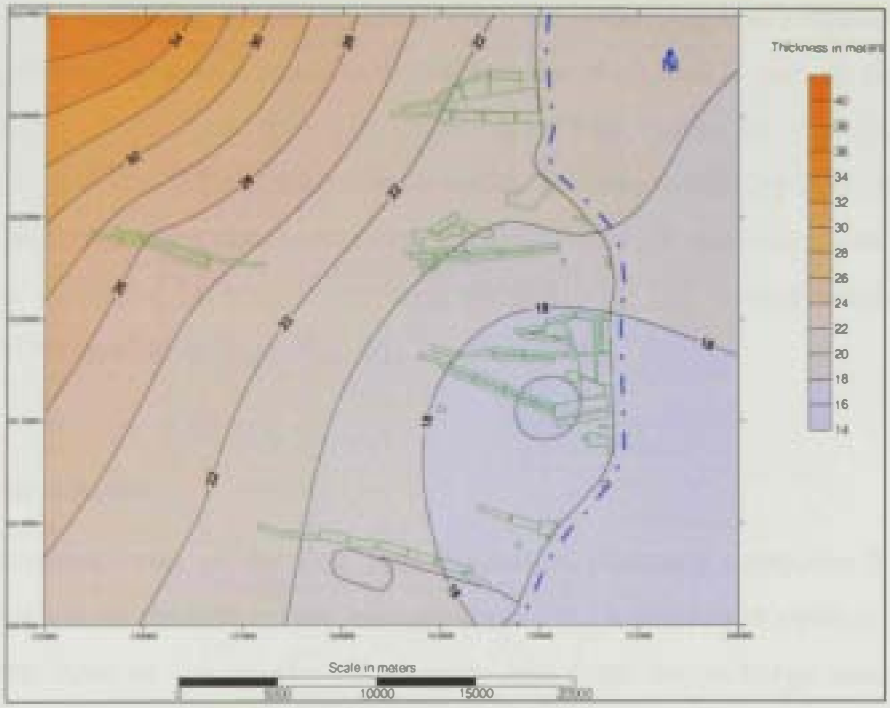


Fig. 15. Thickness of the upper aquifer, Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate.

3.2.2 Confining layer

Below the Quaternary deposits, is a marl layer ranging from 3 to 70 m thick acting as a confining layer separating the upper aquifer from the underlying lower aquifer. This well-defined confining layer is a marl layer (calcareous clay) that is part of the Post Fars Formation, or as mentioned previously to the Upper Fars Formation where the Post Fars Formation is missing. This marl layer functions as leaky confining layer that restricts vertical flow between the upper and lower aquifers in the ground-water system. Leakage through the confining layer is determined primarily by the vertical conductivity and thickness of the confining layer (Fig. 16).

3.2.3 Lower aquifer

The conglomerate layer of the Post Fars Formation primarily composes the lower aquifer, which is 65 m thick on the average (Fig. 17). In the lower aquifer, regional ground-water flow of the aquifer also trends east from the recharge areas in the eastern Oman Mountains to the discharge areas in the west of the study area towards the Arabian Gulf (fig 14).

Transmissivity estimates for the lower aquifer in the study area have an average value of 480 m^2/d based on aquifer test analyses. The study area is located in a region of relatively low transmissivity (as compared to surrounding areas) that extends from Al Wagan North to the south. Because of the relatively low transmissivity, flow through the lower aquifer generally is at low rates (average value 360 m^3/day). This low transmissivity explains the large drawdown recorded in the last 10 years because of over pumping for irrigation purposes from the lower aquifer for irrigation (Imes and others, 1993).

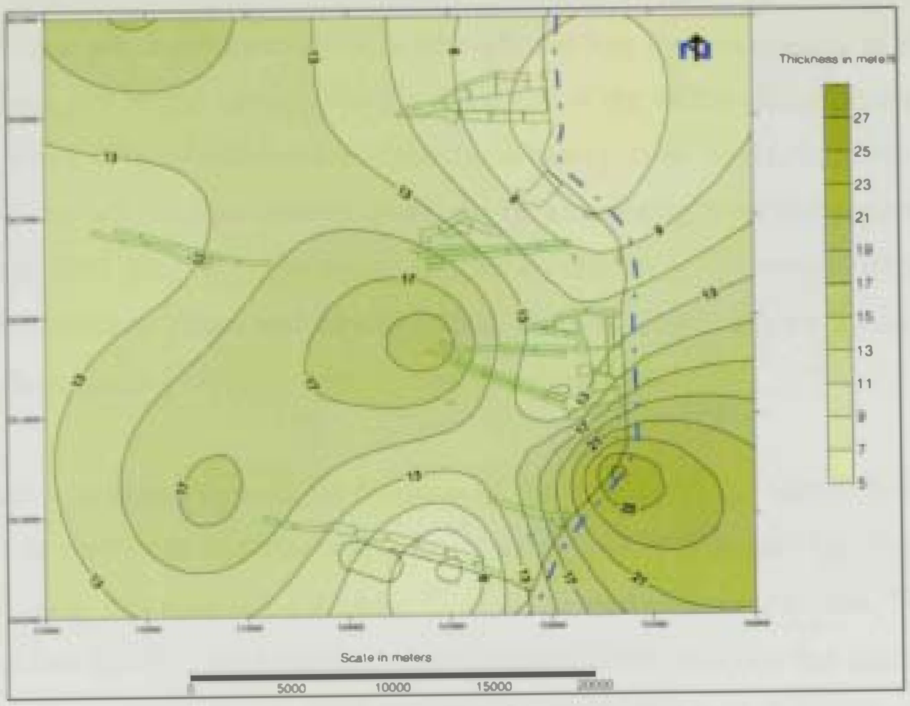


Fig. 16. Thickness of the confining layer, Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate.

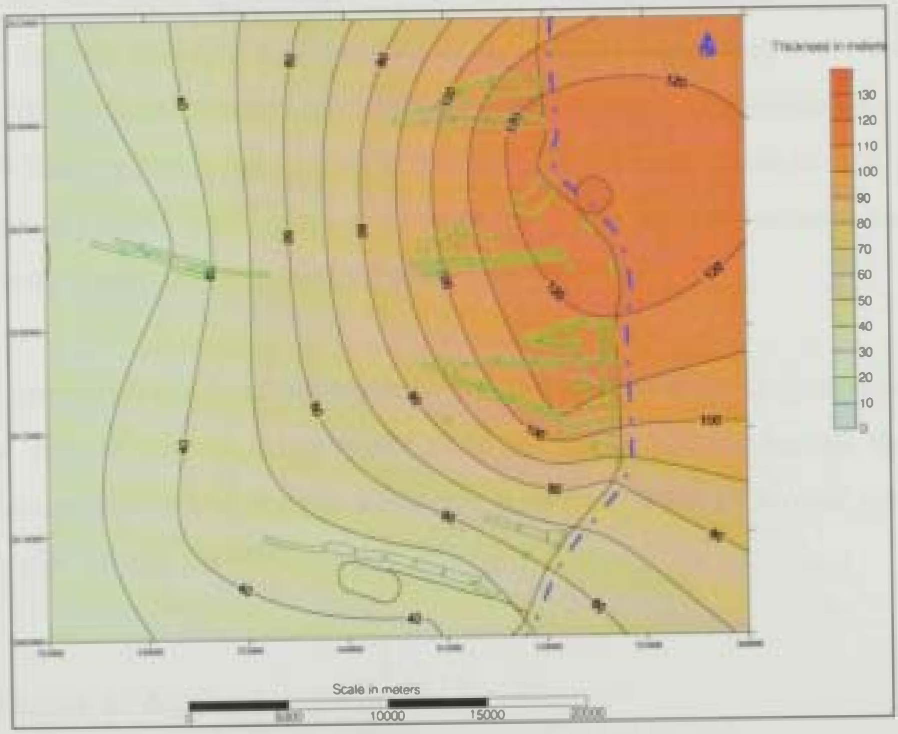


Fig. 17. Thickness of the lower aquifer, Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate.

3.3 Conceptual Model of ground-water system

Although there are discontinuous zones of high and low transmissivities in the ground-water system, and lateral variation in the thickness of the different formations is present the study area can be considered conceptually as having three layers, from top to bottom, the section consists of upper aquifer underlain by a confining layer that separates it from the lower aquifer (Fig. 18). The upper aquifer consisting of Quaternary deposits has a higher transmissivity (Imes and others, 1993), than the lower aquifer characterized by having a clayey matrix content, cementation, and induration.

Fresh water is assumed to enter on landside of the aquifer on the eastern borders of the study area at the Oman Mountains and flows along a long flow path (approximately 55 kilometers long) that ends at the Arabian Gulf to the west of the study area. The geologic formations that underlie the Emirate contain many soluble minerals that dissolve readily in ground water. Water becomes progressively more saline as it moves through the aquifers. Due to three main reasons the fresh ground water becomes more saline in the upper aquifer, and hyper saline water (more than 30,000 mg/L) in inland Sabkha areas of Al Wagan: (1) path of the fresh ground water from the recharge area to Al Wagan area is quite long. (2) Arid zone climate leads to very small amounts of precipitation, and surface runoff. (3) The shallow ground water levels in Al Wagan area leads to high evaporation rate. The fresh ground water moving through the lower aquifer becomes only brackish since it is not exposed to the in land Sabkha conditions.

The large pumpage from brackish water of the lower aquifer for irrigation purposes has resulted in vertical flow of saline water from the upper aquifer through the confining layer or through poorly constructed wells that permits leakage of ground water between the two aquifer through the well annulus.

3.3.1 Recharge to Aquifers

The recharge to the aquifer has two components. The principle source of recharge to the ground-water system (both upper and lower aquifers) is rainfall on the Oman Mountains east of the study area and on the study area. The second component of the recharge is local precipitation. The average annual precipitation at a meteorological station in Al Ain is about 100 mm; annual pan evaporation for the Emirates, as measured in Sharjah, is estimated to be between 3,400 and 4,000 mm (Halcrow and Partners, 1969a). However, in areas covered with thick layers of eolian sand, direct infiltration of rainwater rarely recharges the aquifer.

3.3.2 Recharge from the Oman Mountains:

Flow in the system underlying the eastern boundary of the study area is derived from three major recharge components:

1. Subsurface underflow in alluvium deposits channeled through intermountain gaps,
2. Surface runoff channeled through intermountain gaps, and
3. Flow from fractured bedrock along the entire mountain front (Imes and others, 1993).

3.3.3 Recharge from precipitation:

Recharge from precipitation is water that recharges the water table through the unsaturated zone and adds water to storage in an aquifer. The surficial features of the study area generally can be divided into two primary groups with respect to regional recharge potential, dune areas and interdune areas (Fig. 9). There is a difference in the recharge within each group.

The work of Dincer and others (1974) regarding infiltration and recharge through sand dunes in arid zones indicated that recharge from precipitation on sand dunes can be empirically related to mean annual precipitation and mean grain size of 0.20 mm, the mean annual precipitation of about 150 mm or more in order to result in recharge through the dunes. Besler (1982) reported that the mean grain size from five sand samples collected from dune crests (in and near the entire Eastern area) ranged from 0.14 to 0.22 mm, with an average of 0.18 mm. Large, sustained rainfalls are required to produce enough water to offset potential evapotranspiration and to allow rainwater to infiltrate to the water table and recharge the aquifers. Unfortunately, mean annual precipitation in the study area is much less than the precipitation of 150 mm (Dincer and others, 1974) at which recharge in sand dunes is probable. Therefore, little recharge to the upper aquifer is considered to occur in areas where the surface cover is eolian sand.

The upper aquifer is recharged, however, by infiltration of precipitation in interdune areas and gravel plains. Results from TLSR model (Ostercamp, written communication, 1992) suggested that about 5 % of the average annual precipitation that falls on coarse gravel plains and alluvial fans in and adjacent to the Oman Mountains recharges the aquifer. The recharge percentage would be less than 5% for areas that have fine materials at or near the land surface. Also, the recharge percentage could be more than 5% for areas where irrigation water is applied in excess of the moist capacity of the soil.

3.3.4 Discharge from Aquifers

Natural discharge from the upper aquifer is by underflow, by evapotranspiration, and by seepage to inland Sabkhas. Water moves as underflow from the upper aquifer westward towards the Arabian Gulf. Discharge also occurs through the process of evapotranspiration when the water table in the aquifer is close to the land surface that water can be evaporated directly through soil pores, or wherever plant roots can intercept ground water. These conditions are presumed to be present in Al Wagan area where depths to the water table are 4 meters or less (Besler 1982). When the altitude of the water table in the aquifer is higher than the altitude of the land surface, inland Sabkhas are present as a result of discharge from the aquifer.

Natural discharge from the lower aquifer is by underflow to the west. Withdrawal by wells is the greatest source of discharge from the lower aquifer. Between 1980 and 2000 water was withdrawn mainly for agricultural and municipal uses in Al Wagan area

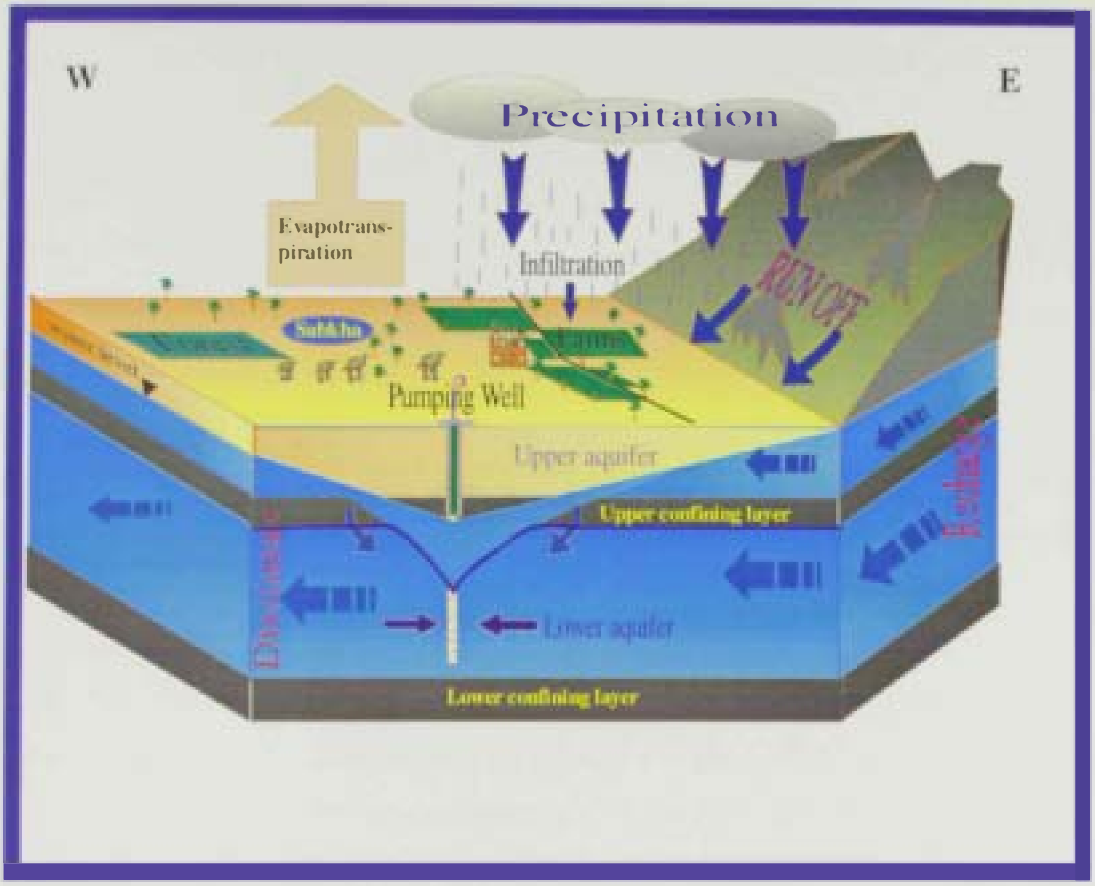


Fig. 18. Conceptual model of ground-water system of Al Wagan area, South Al Ain, Eastern Region, Abu Dhabi Emirate (not to scale)

Chapter IV

WATER LEVEL AND WATER QUALITY CHANGES

CHAPTER FOUR

WATER LEVEL AND WATER QUALITY CHANGES

4.1 Water Level Changes

Prior to the development of Al Wagan area, the water level was close to the land surface, and sometimes intersecting the land surface resulting in inland Sabkhas. In addition to agricultural and urban expansion, and the subsequent withdrawal of large quantities of ground water from both the upper and lower aquifers have resulted in lowering water levels in the upper aquifer. Evidences of the interaction between the two aquifers will be discussed in detail later in this study, and will be supported by aquifer test results and results of a ground water flow model for the two aquifers.

Annual well withdrawals from the two aquifers were tabulated from records of the Agriculture and Forestry Departments of Al Ain and the GWRP monitoring wells. The potentiometric surface of the lower aquifer is declining because of large withdrawals for irrigation. This decline is seen in water level records of many GWRP wells located in and near farm areas (Fig.3). For instance, water levels declined more than 30 meters in well GWP-84 (Fig. 19) and more than 14 meters in well number GWP-90 (Fig. 20) from 1992 to 2001.

Water levels in GWP-294 A, B and C declined at similar rates although water was only being withdrawn from the lower aquifer in the area during aquifer test pumping of GWP-294 A, these results indicate vertical flow between the two aquifers as leakage through the confining layer, thereby showing that the upper and lower aquifers are hydrologically connected (Fig21). GWP-294 A and C are screened in the lower aquifer and GWP-294 B is screened in the upper aquifer (Fig.22). The same results were achieved when pumping GWP-295 B, which was screened, in the lower part and water levels were declined in the other wells (Fig 23).

In some cases, water levels rose in wells located away from the heavily pumped agricultural and forested areas, for example well GWP-93 (Fig. 24). Being far from the agricultural areas, these wells were not influenced by the heavy pumping. Therefore; the water levels were not expected to decline. The increase however, is probably due to the increased recharge resulted from the increase in precipitation after 1996 and distance from withdrawal areas (Fig. 25).

Fig. 19. Hydrograph of well number GWP-84, Al Wagan area, UAE

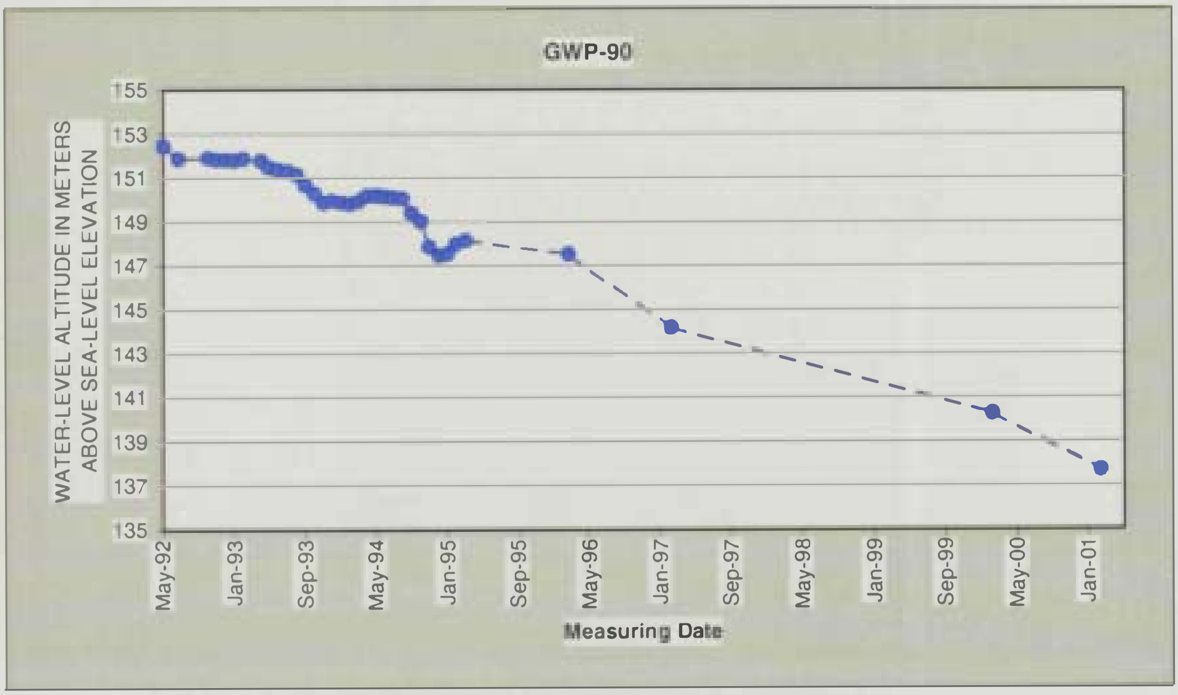


Fig. 20. Hydrograph of well GWP-90, Al Wagan area, UAE

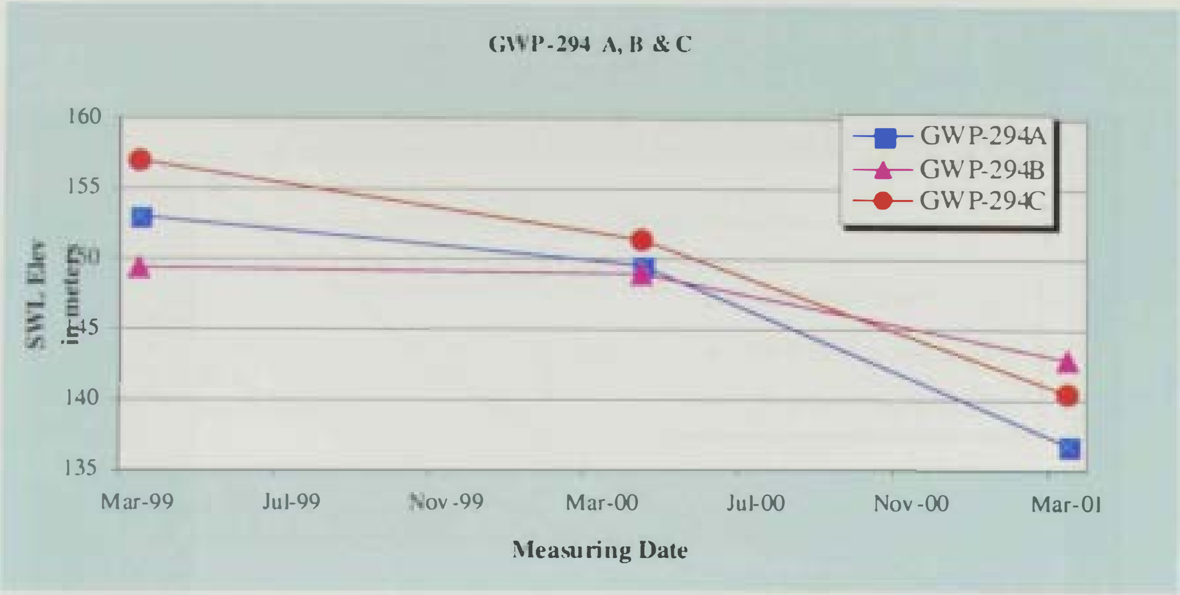


Fig. 21. Hydrograph of wells GWP-294 A, B, and C, Al Wagan area, UAE

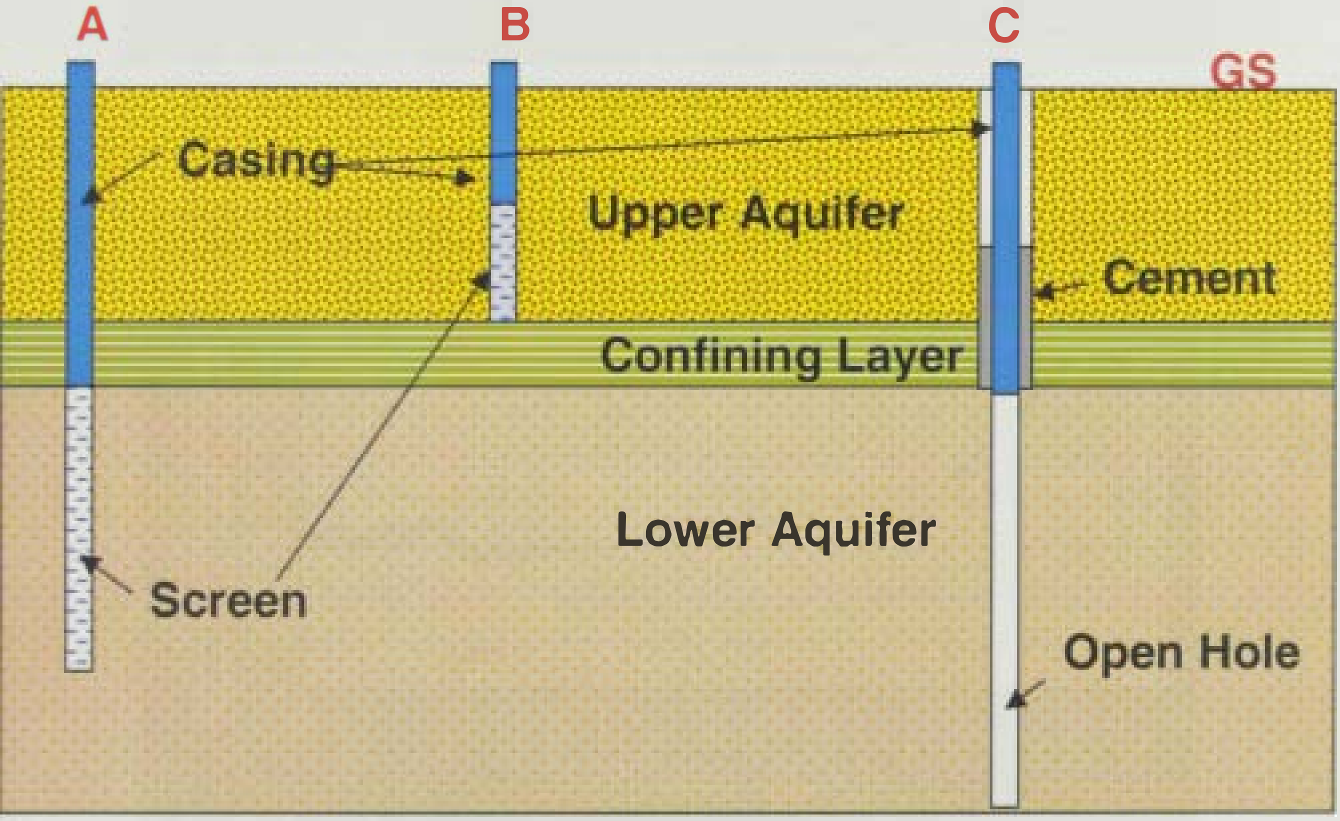


Fig 22. Well constructions of GWP-294 A, B and C

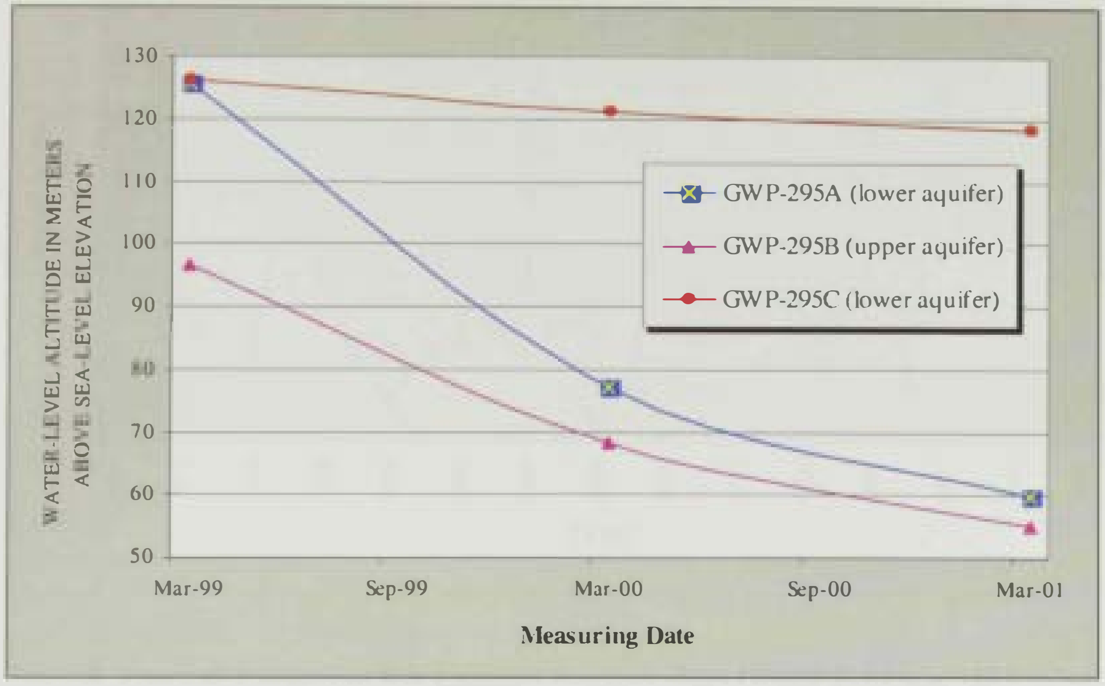


Fig. 23. Hydrograph of wells GWP-295 A, B, and C, Al Wagan area, UAE

Fig. 24. Hydrograph of well GWP-93, Al Wagan area, UAE

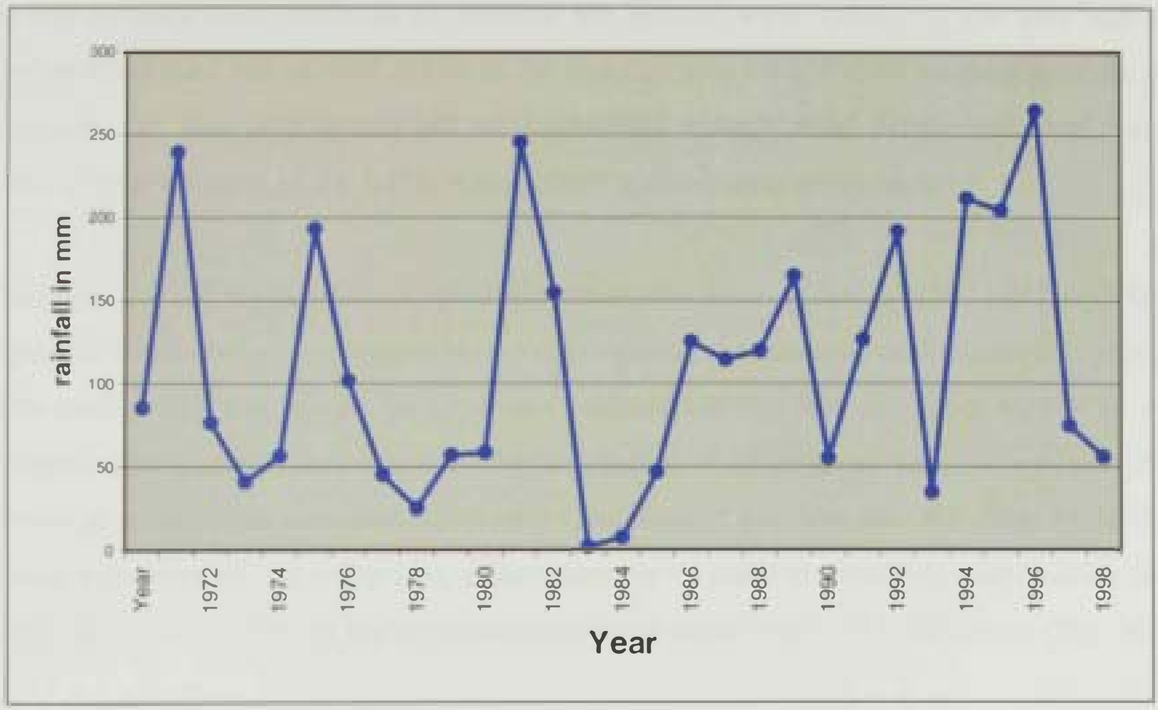


Fig. 25. Rainfall Pattern in the Eastern Region, Abu Dhabi Emirate, UAE (Data obtained from Agricultural Meteorological Station- Al Ain)

4.2 A Survey of Water Quality

Water samples were analyzed to describe the general water quality of the area and to define the lateral and vertical extent of the brackish water body. Geochemical analysis of the data can also help understand the hydrologic system in Al Wagan area and, help determine the source of the saline water, and if active intrusion is occurring.

Initially, GWRP wells were sampled for major and trace elements from 1992 to 2000. Specific conductance was logged versus depth during the petrophysical borehole logging. The quality of water within the Quaternary deposits comprising the upper aquifer in Al Wagan area is largely controlled by the dissolution of minerals as water flows from the recharge areas in the east westward toward the coast of the Arabian Gulf (Fig. 1). In the western borders of the study area, saline water is mixed with brackish water within the upper aquifer, resulting in higher concentrations of some dissolved constituents (Fig. 26).

Another factor affecting the high salinity in the upper aquifer is evaporation of ground water, which reaches land surface in the Sabkha. Pumpage of ground water from the lower aquifer for agricultural purposes has probably caused downward movement of saline water from the upper aquifer into the lower aquifer.

Table 6. Chemical analyses of water from wells in Al Wagan area, UAE

Well ID	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	NO_3 (mg/L)	Alkalinity (mg/L)	EC (uS/cm)	TDS (ppm)	pH
GWP-83	430	250	2200	54	3450	2200	_	0	58	12600	8646	7.4
GWP-84	280	210	1000	20	2100	750	_	10.2	48	7290	4402	7.4
GWP-85	750	735	10250	150	12300	7150	_	55.3	84	46700	31461	7.4
GWP-86	635	470	3700	70	5850	3450	_	24.8	60	21200	14244	7.3
GWP-87	480	315	3000	42	3950	2900	_	0	75	15200	10739	7.5
GWP-88	2200	1550	18000	450	29500	4700	_	115.1	44	72900	56579	7
GWP-89	1100	1050	11500	200	18500	4550	_	88.5	45	56200	37041	7.2
GWP-90	180	160	1200	23	1550	1250	_	7.1	67	6700	4415	7.4
GWP-92	960	475	5000	160	7900	2800	_	24.8	40	26900	17443	7.2
GWP-93	170	165	2700	41	3400	2350	_	0	148	14000	8921	7.3

Chloride is the constituent of most interest in Al Wagan area. The concentration of chloride ion ranged between 1,550 to 29,500 mg/L in 10 GWP wells. The concentration of sodium cation ranges between 1,000 to 18,000 mg/L. Also, high concentrations of Sulphate were recorded due to the natural dissolution of evaporite deposits (gypsum and anhydrite) associated with the Sabkha deposits of the upper aquifer (table 5).

Water within the upper aquifer is generally more mineralized than water in the lower aquifer and the extent of inland migration of this mineralized water is dependent on the natural hydrologic conditions and alteration to those conditions. Values of dissolved solids, chloride, and specific conductance used to define freshwater, brackish water and saltwater in this report are given in Table 6, these parameters vary both vertically and laterally in the study area.

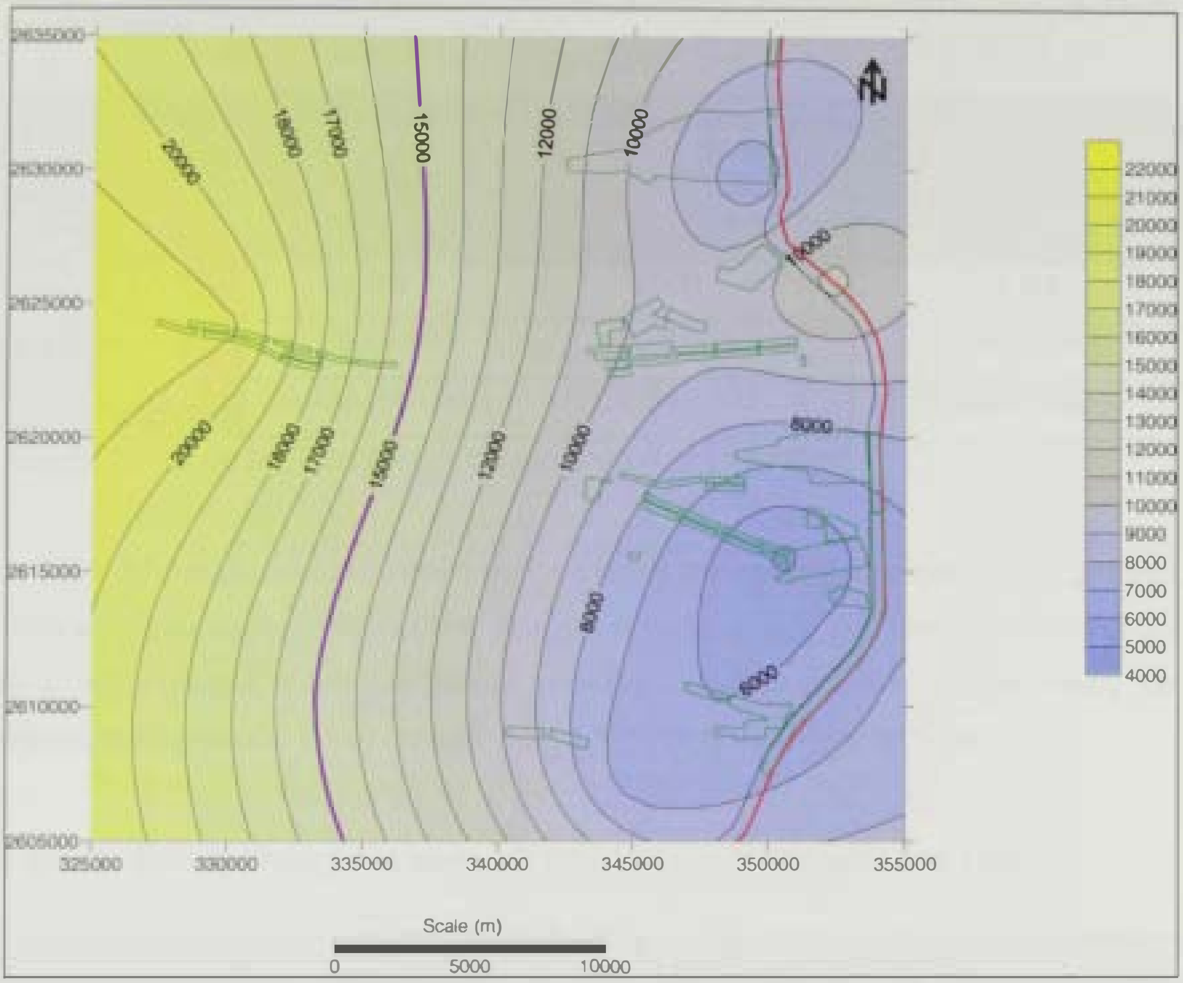


Fig 26. Electric Conductivity of Ground Water of the Lower Aquifer, Al Wagan Area, South Al Ain, Eastern Region, Abu Dhabi Emirate

Table 7. Simple ground water classifications for freshwater, brackish water and saline water based on dissolved solids, chloride concentrations, and specific conductance.

Category	Dissolved solids (mg/L)	Chloride concentration (mg/L)	Fluid specific conductance (µS/cm)
Fresh water	>1,000	>500	>1,500
Brackish water	1,000-10,000	500-5,000	1,500-15,000
Saline water	10,000-100,000	5,000-50,000	15,000-150,000

(mg/L, milligram per liter; µS/cm, microsiemens per centimeter)

In 1999 Al Ain Agriculture Department estimated the salinity of ground water pumped from each area during 1996 to 1998. Five to ten wells in each area were sampled and the data was averaged to get the general condition of water salinity changes during the period, the increase in salinity ranged from 2 % to 74 % as shown in Table 7.

Table 8. Salinity changes in wells 1996 to 1998 in Al Wagan area, UAE

Area	1996 Average Salinity (ppm)	1997 Average Salinity (ppm)	1998 Average Salinity (ppm)	Salinity Increase (ppm) 1996-19981	Percentage
Abu Kraya	5259	6134	9135	3876	74 %
Al Wagan East	------	2977	3828	851	29 %
Seeh Al Raheel	------	3232	3672	440	14 %
Al Zahra	------	4319	4662	343	8 %
Al Oya	5399	5743	------	344	6 %
Al Wagan West	4368	4658	4605	237	5 %
Al Arad	6209	------	6305	96	2 %

Water samples were analyzed to describe the general water quality of the area and to define more precisely the lateral and vertical extent of both the brackish and more saline water bodies. The geochemical analyses of the data can help understand the hydrologic system in Al Wagan area and, in particular, the recharge process. The data can be used to determine the source of saline water, and to determine if active intrusion or flushing is occurring from the upper to the lower aquifer.

Chapter V

GROUND-WATER FLOW MODEL

CHAPTER FIVE

GROUND-WATER FLOW MODEL

MODFLOW, a modular, three-dimensional, finite-difference, ground-water flow model (McDonalds and Harbaugh, 1984) was used to simulate the response of stresses on the flow system in the lower aquifer and to simulate groundwater flow in the conceptual model presented in chapter

5.1 Theory

Compared with ground-water flow rates in the two aquifers, rates of leakage through the confining layer are quite small. However, the confining layer leakage can be important. Over large areas with significant vertical hydraulic gradients, even very small hydraulic conductivities permit significant amounts of leakage; this leakage in turn, may control the regional flow. Thus, to simulate the behavior of an aquifer and confining layer system, one must often account for the leakage through the confining layers.

The partial differential equation which describes the no steady flow of ground water in a system involving an aquifer bounded by confining layers such as shown schematically in Fig. 15 is:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}-R+L \qquad (5)$$

where

$$L=-K'_z\,\frac{h_{source}-h}{b'} \qquad (6)$$

The terms on the left-hand side of Eqn. 5 represent horizontal flow through the aquifer where h is head and T_x and T_y are components of transmissivity.

The placement of T_x and T_y within the partial derivatives allows for spatial variation of these parameters (heterogeneity). The x and y subscripts on T indicate that the transmissivity in each of these direction may be different; i.e. the aquifer may be anisotropic. S is the storage coefficient; R is a source term, which is defined to be intrinsically positive to represent recharge. If withdrawal of water occurs R = -W, where W is the withdrawal rate. The last term on the right-hand side (L) represents leakage through confining bed, where K'_z is the vertical hydraulic conductivity of the confining bed, and b' is the thickness of the confining, h_{source} is the head in the source reservoir on the other side of the confining bed (Anderson, M., and Woessner, W., 1992).

Several assumptions were made about the flow system in order to apply the flow model to the flow system in the upper and lower aquifers. These assumptions were:

1. Flow is horizontal in the upper and lower aquifers;
2. Aquifers are heterogeneous;
3. Aquifers are anisotropic;
4. The effects from stress on the flow system beyond the artificial boundaries used in the model was minimal;
5. The density of water was uniform and was that of the fresh water;
6. Temperature in each aquifer was constant;
7. Flow components in each aquifer were parallel to the planes of the model grid; and
8. Flow across the confining bed is perpendicular to flow in the aquifers.

The importance that the assumptions made about the flow system are reasonable is crucial. When assumptions made about the flow system for the model are valid, these model results can be interpreted with some degree of confidence. However, if the assumptions are invalid, model results warrant little confidence.

5.2 Grid Design and Boundary Conditions

The configuration, boundary conditions, groundwater recharge and discharge areas, and flow directions are critical components of any groundwater-flow model. Field data, geological maps, and other data sources provide the hydrogeologic data necessary to form a clear picture or conceptual model of the natural system.

5.2.1 Grid Design

A three-layer finite difference model was built. Each layer was allowed to have varying thickness. For instance, thickness of the cells of the first layer varied from 20 to 30 meters. The upper aquifer was represented by the first layer (upper) layer of the model. The lower aquifer was represented by the third (lower) layer of the model. The marl-confining layer was represented as the intermediate layer between the two aquifers.

The areal extent of the aquifers was divided into a grid system of 50 rows and 50 columns into a matrix of 2500 grid blocks, or 'cells'. The finite-difference grid used to represent the ground-water flow system in Al Wagan area is shown in Fig. 27. Each square within the grid is referred to as a cell. The dimensions of each cell are 600 meters. Each cell represented a surface area of 360,000 m^2. Cells were either active, inactive or represented a boundary condition. In an active cell, the hydraulic head was allowed to vary in response to recharge to and discharge from the ground-water system.

Hydraulic conductivity assigned to each cell was first achieved using the maps established from pumping test analysis results. In addition, petrophysical log interpretations regarding lithology were utilized for the consistency of assigned values with previously encountered values for those lithologies.

Hydraulic conductivity values were calibrated using a Visual MODFLOW tool called PEST (Parameter Estimation). The purpose of PEST is to assist in data interpretation and in model calibration. PEST adjusts model parameters until the fit between model output and field observations is optimized. At the end of the parameter estimation process, PEST records the optimized value of each adjustable parameter together with its 95 % confidence interval. It tabulates the set of field measurements, their optimized model-calculated counterparts, and the difference between each pair

The hydraulic conductivity distribution for the upper and aquifer is shown in Fig. 28. The lower aquifer was represented by the third layer of the flow model (Layer number two is representing the confining layer). An average value of 8 m/d of the hydraulic conductivity for the lower aquifer was used in the flow model for simplification (Fig 29). While the confining layer was given a value of 0.00016 m/d as an average hydraulic conductivity.

5.2.2 Boundary Conditions

Two types of boundary conditions were used in the flow model, namely noflow and constant head boundaries (Fig. 27). The model grid in horizontal plane is oriented in such a way that model rows are parallel to the regional groundwater flow lines. This allowed the placement of the hydraulic noflow boundaries running along the East-West direction. In other words, the northern and southern noflow boundary cells are parallel to the northern and southern flow lines passing along the borders of the model area. Constant-head boundaries were used in the model to represent the ground-water recharge along the eastern borders consequently. Constant-head boundaries were used also to represent the natural discharge from the ground water flow system to the west towards the Arabian Gulf. No change in the water level can occur at constant-head cells. The same boundary conditions were applied for both the lower and upper aquifers.

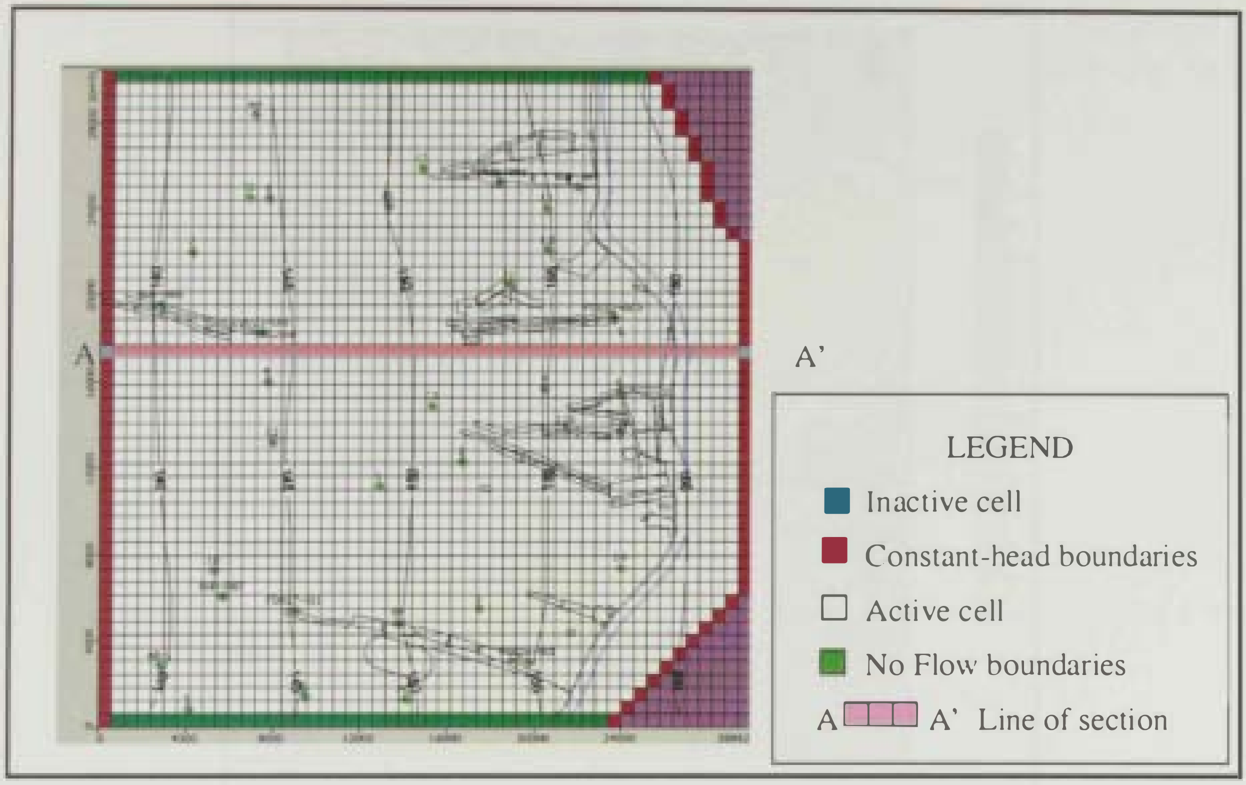
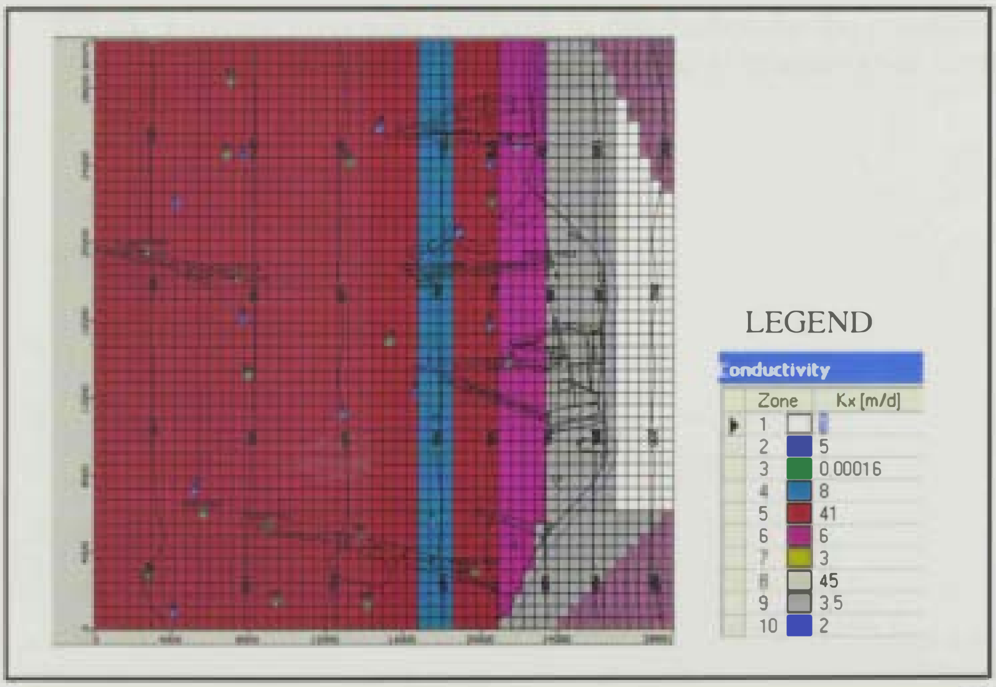


Fig. 27. Model grid and boundaries distribution of Al Wagan model area, UAE.



	Zone		Kx [m/d]
▶	1	☐	[illegible]
	2	🟦	5
	3	🟩	0 00016
	4	🟦	8
	5	🟥	41
	6	🟪	6
	7	🟨	3
	8	⬜	45
	9	⬜	3 5
	10	🟦	2

Fig. 28. Hydraulic conductivity values and distribution of the upper aquifer, Al Wagan model area, UAE.

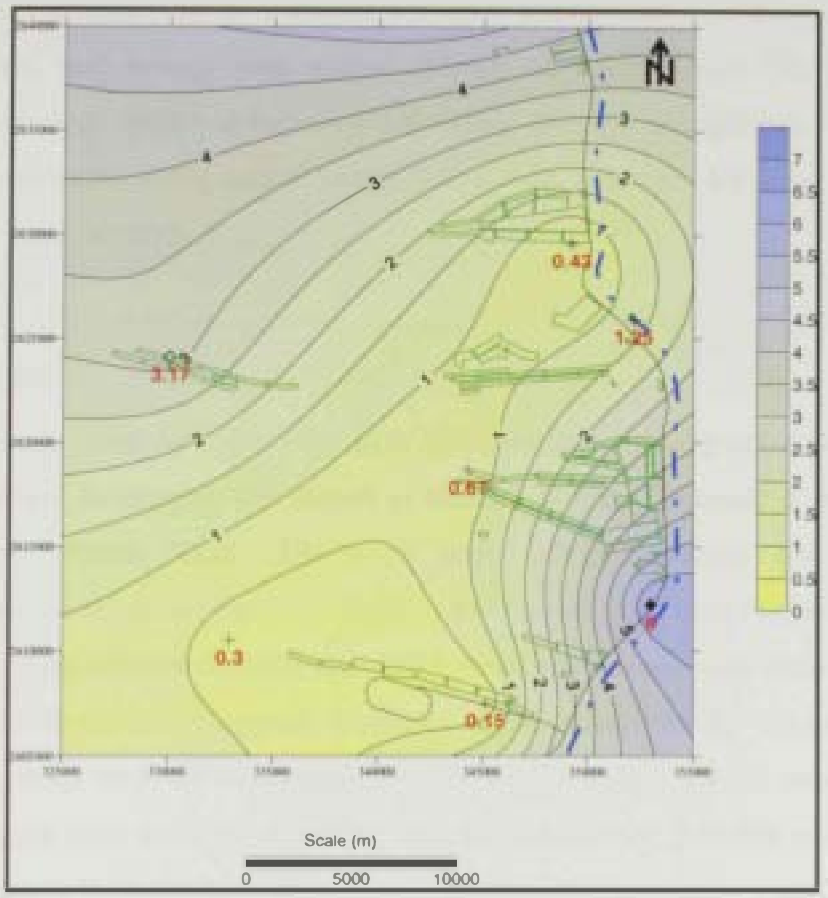


Fig 29. Average Hydraulic conductivity distribution for the combined system as obtained from pumping tests, Al Wagan area, UAE

5.3 Recharge

Recharge was assumed to be constant for each stress period as the product of the recharge factor and average precipitation during the stress period (derivation of the recharge factors was described earlier in this study). Average precipitation for each stress period was computed from annual precipitation data available for three precipitation stations in or near the study area.

5.4 Discharge

Natural discharge from the upper aquifer is by underflow, by evapotranspiration, and by seepage to inland Sabkhas. Water moves as underflow from the upper aquifer westward towards the Arabian Gulf. Discharge also occurs through the process of evapotranspiration wherever the water table in the aquifer is close to the land surface that water can be evaporated directly through soil pores, or wherever plant roots can intercept ground water. These conditions are presumed to be present in Al Wagan area where depths to the water table are 4 meters or less. When the altitude of the water table in the aquifer is higher than the altitude of the land surface, inland Sabkhas are present as a result of discharge from the aquifer.

Natural discharge from the lower aquifer is by underflow to the west. Withdrawal by wells is the greatest source of discharge from the lower aquifer. Between 1980 and 2000 water was withdrawn mainly for agricultural and municipal uses in Al Wagan area.

5.4.1 Estimating Evapotranspiration

Evapotranspiration is a term applied to the combined processes of evaporation of water from land and water surfaces (Inland Sabkhas) and transpiration by plants. Evapotranspiration is the largest component of the water budget and also the most difficult to measure. Ground-water evapotranspiration occurs where the depth to the water table is less than about 4 meters. Imes and other (1993) used satellite imagery to locate the approximate eastern limit of significant evaporation as the transiention between dark-colored gravel plains to the east and light-colored material to the west (Fig. 9). This color transiention apparently is caused by the ophiolitic gravels being covered by light-colored evaporitic salts from the evaporation of brackish and saline ground water. Pan evaporation has been estimated at about 0.0095 m/d (Halcrow and Partners, 1969a).

5.5 Pre-development Simulation (1980)

The initial condition simulation (or pre-development) was chosen to be 1980, a year that preceded large-scale withdrawal by wells from the lower aquifer. Withdrawal by wells prior to 1980 was assumed to have been negligible. The calibration process of the pre-development simulation is a trial and error process by which input parameters are varied through a range of reasonable values until the model output approximately replicates observed data. The calibration of the model was evaluated by the comparison of observed and simulated heads for the upper and lower aquifers. Water levels measured in 14 wells in the upper aquifer were used for calibration of layer 1 and water-level measurements of 21 wells within the lower aquifer were used for calibration of layer 3. Observed and simulated water level contours are shown on Fig. 30 and 31. Black contour lines represent the observed water levels, and the red contour lines represent the model-simulated water levels. The simulations showed the average difference between simulated and observed water levels is less than 1 m for both upper and lower aquifers. Fig. 32 and 33 show the scatter diagrams of observed versus simulated water levels in observation wells in the upper and lower aquifers respectively. These diagrams show that all the simulated water levels fall within the 95 % confidence interval, which reflects the degree of matching between the simulated and the observed water levels. The upper aquifer, confining layer and lower aquifer are represented by zones 1, 2 and 3 respectively (fig 34). The zone budget of the pre-development simulation was prepared based on the calculation made by the flow model is shown in Fig. 35.The quantity of water inflow (about 55,741 m^3/d) of the upper aquifer (zone 1) was much higher than that of the lower aquifer, due to the precipitation recharge, the same difference was observed in the quantity of the water outflow (about 55,743 m^3/d) due to evapotranspiration in the upper aquifer (Fig. 35).

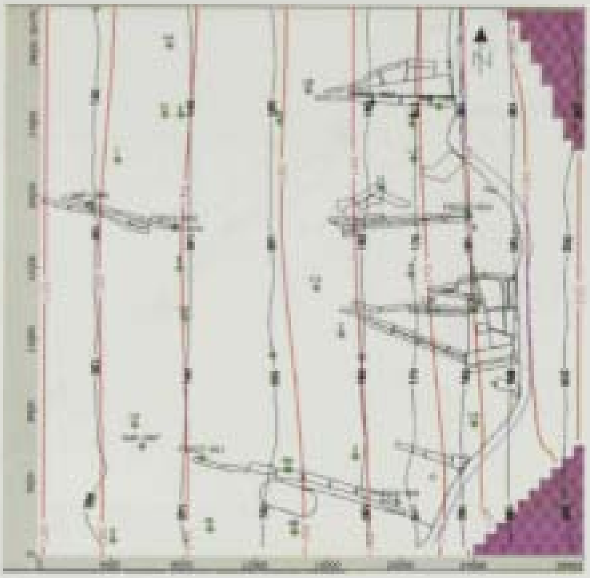
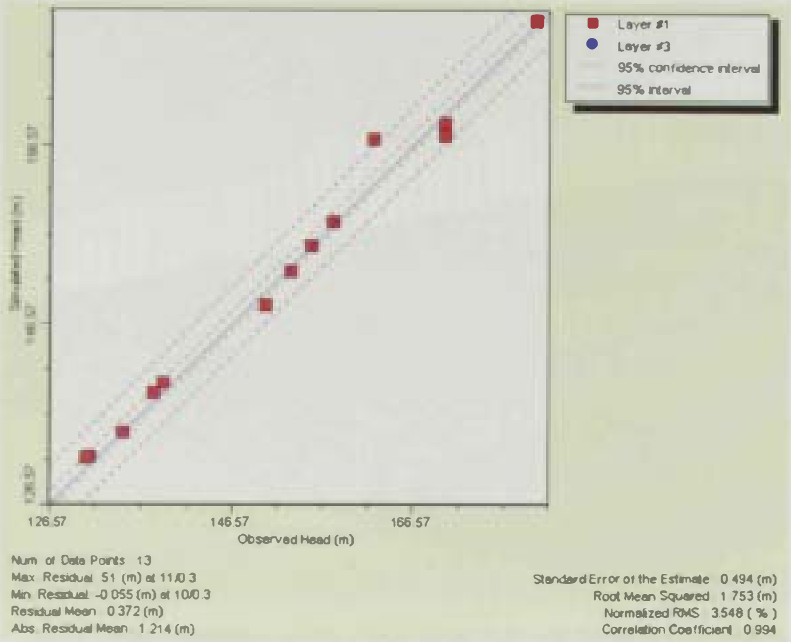


Fig. 30. Observed versus simulated water level elevations in the upper aquifer for the pre-development simulation, Al Wagan area, UAE.

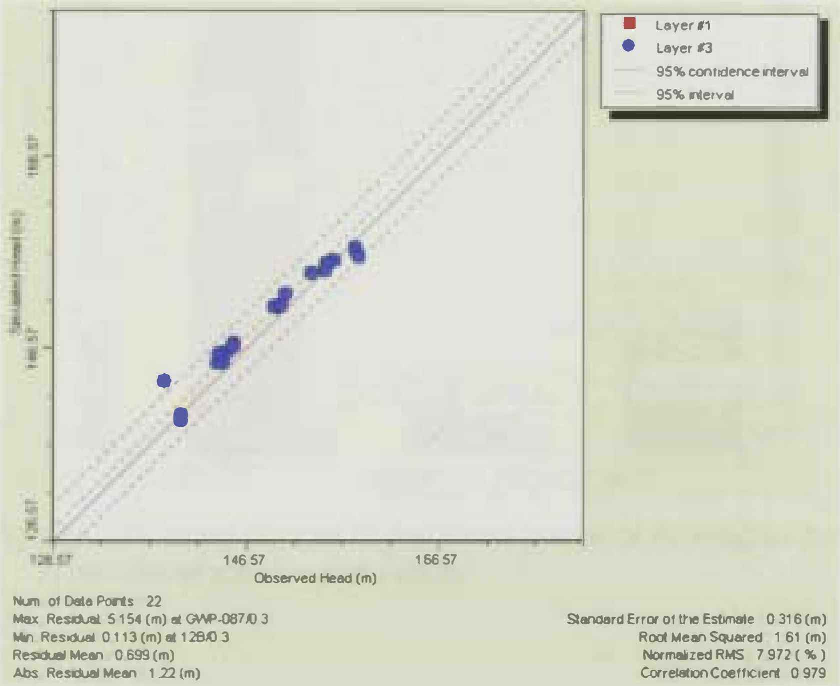
Fig. 31. Observed versus simulated water level elevations in the lower aquifer for the pre-development simulation, Al Wagan area, UAE.



Num of Data Points 13
Max Residual 51 (m) at 11/0 3
Min Residual -0 055 (m) at 10/0.3
Residual Mean 0 372 (m)
Abs Residual Mean 1 214 (m)

Standard Error of the Estimate 0 494 (m)
Root Mean Squared 1 753 (m)
Normalized RMS 3.548 (%)
Correlation Coefficient 0 994

Fig. 32. Observed versus calculated heads in the upper aquifer for the pre-development simulation, Al Wagan area, UAE.



Num of Data Points 22
Max Residual 5 154 (m) at GWP-087/0 3
Min Residual 0 113 (m) at 128/0 3
Residual Mean 0 699 (m)
Abs Residual Mean 1 22 (m)

Standard Error of the Estimate 0 316 (m)
Root Mean Squared 1 61 (m)
Normalized RMS 7 972 (%)
Correlation Coefficient 0 979

Fig. 33. Observed versus calculated heads in the lower aquifer for the pre-development simulation, Al Wagan area, UAE.

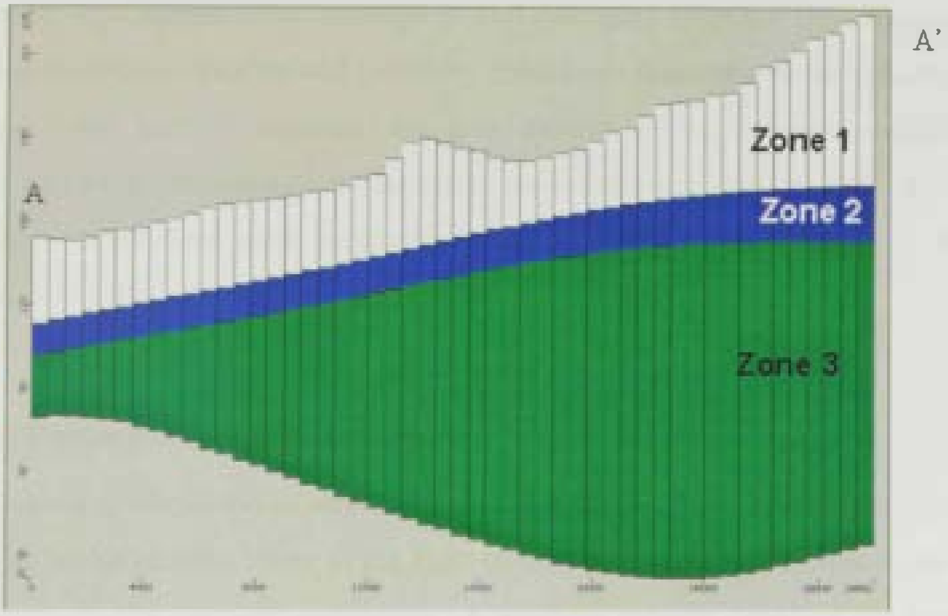


Fig. 34. Cross section along the line AA' of Al Wagan model area, UAE.

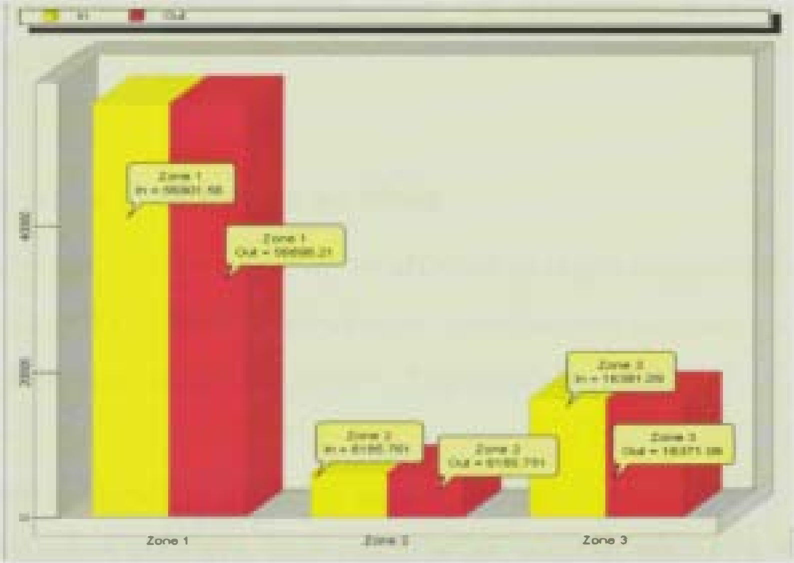


Fig. 35. The zone budget of the three zones of Al Wagan model area, in pre-development simulation.

5.6 Transient Simulation

The objective of the transient simulation was to use the flow model to reproduce a known set of hydrologic responses as recharge to and discharge from the flow system changed over time. Aquifer properties and boundary conditions described in the pre-development simulation were used to represent the flow system in the transient simulation. The transient simulation represented the aquifers conditions from 1980 to 2000. Results from the transient simulation were compared to the available measurements for the period 1995 and 2000 (Fig. 36 to 45).

5.7 Data Preparation and Model Input

During transient simulation, unlike the pre-development simulation, storage volume changes as recharge adds water to the flow system or discharge removes water from the flow system in the transient simulation. A uniform specific yield of 0.1 was used to represent the storage in the lower aquifer. Reported specific yield in the aquifer ranged between 0.06 to 0.1 for the upper unconfined aquifer and Specific storage of 0.005 for the lower confined aquifer (Imes and others 1993). The distribution of farm and forest wells is shown in Fig. 36.

5.7.1 Ground-Water Withdrawals by Wells

Withdrawal by wells was the major factor affected storage changes in the ground-water system by the year 2000. Annual withdrawals from the two aquifers by wells tabulated from records of the Agriculture and Forestry Departments of Al Ain.

The potentiometric Surface of the lower aquifer system is declining due to the excessive pumping for irrigation purposes. Each stress period corresponded to a well is averaged for the length of the stress period. Averages were summed for each section to represent withdrawal from the corresponding cell. Each stress period represented a subdivision of the total transient simulation period in which withdrawal by wells and recharge were considered constant.

5.7.1.1 Forest irrigation

Withdrawals for forest irrigation was based on data collected from the Forestry Department of Al Ain. It was estimated that the annual water consumption of one square meters of forest area is approximately 0.276 m^3/year. To obtain the amount of water required to irrigate one cell of the model area, the following equation was used:

Amount of water discharged per year per cell = 0.276 * 360,000 = 99,360 m^3/year/cell

Amount of water discharged per day per cell = 99,360 ÷ 365 = 272.2 m^3/day/cell

It was estimated that 10 % of the irrigation water is returned back to the aquifer as return flow, leaving of the 90 % estimated as ground water discharge from wells, or approximately 245 m^3/day/cell.

The number of total working forest wells was reduced to about 50 percent starting from the year 2000, thus; the pumping rate was reduced from 245 m^3/day/cell to 120 m^3/day/cell for forest areas north of the model area in Al Ageer, Seah Saham, Zaaba, and Al Gheena (Fig 3).

5.7.1.2 Farm irrigation

Imes and others, (1993; p. 245), estimated an irrigation application rate of 0.6 m/y for farm irrigation. This rate is within the range of 0.41 m/y to 1.5 m/y required to irrigate various crops in the UAE. Thus, using the same calculations used above for forest irrigation the daily consumption per cell can be estimated as follows

Amount of water discharged per year per cell = 0.6 * 360,000 = 216,000m^3/year/cell

Amount of water discharged per day per cell = 216,000÷ 365 = 592 m^3/day/cell

If 10 % of the irrigation water is considered to be return flow, the 90 % or approximately 533 m^3/day/cell is estimated as ground water discharge from wells. Fig. 32 shows the distribution of farms and forests wells in the model simulation.

5.8 Results of Transient Simulation

Aquifer characteristics used to define the flow model were tested by comparing water levels simulated by the flow model to water levels measured from existing wells in the study area. The water level from the transient simulation of the upper and lower aquifers for the year 1995 was compared to water-level measurements of the two aquifers for the same year. Also, water level from the transient simulation of the upper and lower aquifers for the year 2000 were compared to water-level measurements of the two aquifers for the same year.

If the flow model were to perfectly represent the groundwater flow system, the contours shown in Fig. 37,38, 41 and 42 would coincide exactly. Because this was not the case, the differences in the contours can be ascribed to errors. Possible sources of errors include, but not are limited to, variations in aquifer characteristics unaccounted for the model, errors involved in preparing the maps based on water-level measurements, or model assumptions made about the aquifer system that were not reasonable. Whatever the source of the differences, results from the model compared reasonably well to measurements available for the upper and lower aquifers.

The comparisons of observed and simulated water levels of both upper and lower aquifers (Fig. 39, 40, 43 and 44) indicate that the combination of aquifer properties used in the transient simulation came closest to reproducing measured water levels in the two aquifers. All the simulated water levels were included in the 95 % confidence interval.

The zone budget for the year 2000 shown in Fig. 45 indicates more contribution of the lower aquifer due to withdrawal for irrigation purposes in this period. Also, it indicates the leakage behaviour of the confining zone between the two aquifers.

Fig. 36. Distribution of farm and forest well in the Al Wagan model area.

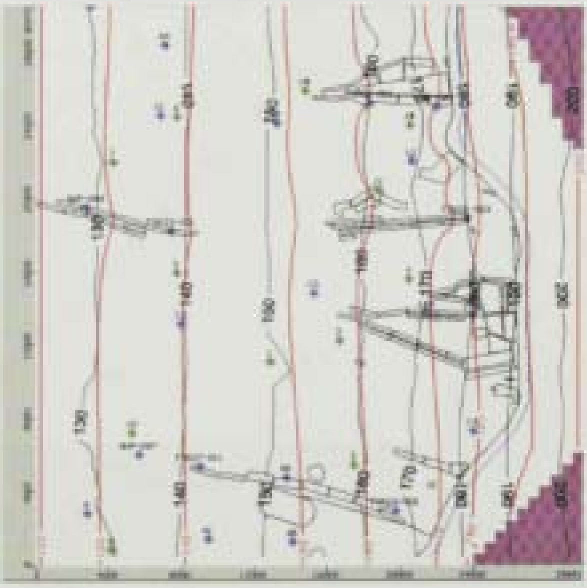


Fig. 37. Observed versus simulated water level elevations in the upper aquifer for the 1995 transient simulation, Al Wagan area, UAE.

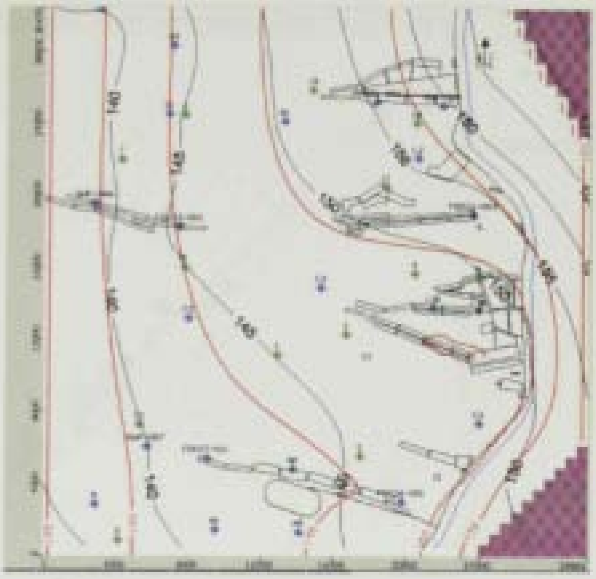
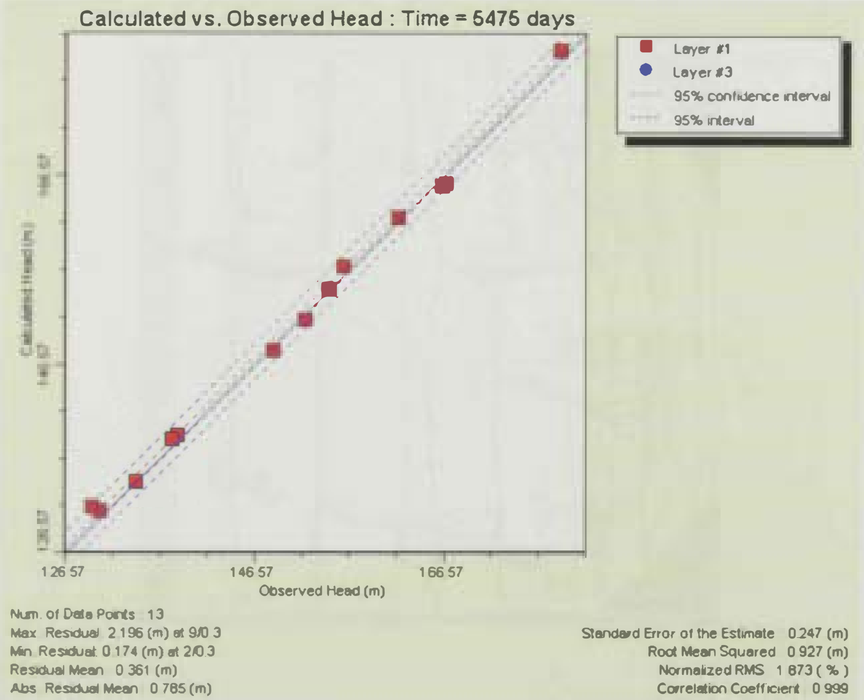


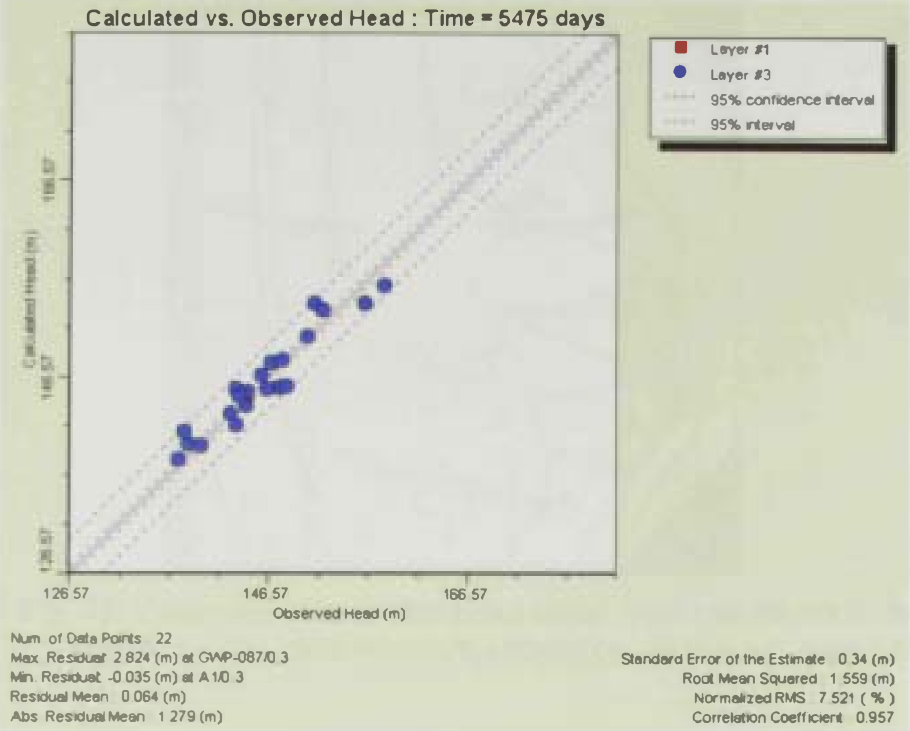
Fig. 38. Observed versus simulated water level elevations in the lower aquifer for the 1995 transient simulation, Al Wagan area, UAE.



```
Num. of Data Points  13
Max  Residual  2 196 (m) at 9/0 3
Min  Residual 0 174 (m) at 2/0 3
Residual Mean  0 361 (m)
Abs  Residual Mean  0 785 (m)
```

```
Standard Error of the Estimate  0 247 (m)
Root Mean Squared  0 927 (m)
Normalized RMS  1 873 ( % )
Correlation Coefficient  0 999
```

Fig. 39. Observed versus calculated heads in the upper aquifer for the 1995 transient simulation, Al Wagan area, UAE.



Num of Data Points 22
Max Residual 2 824 (m) at GWP-087/0 3
Min. Residual -0 035 (m) at A 1/0 3
Residual Mean 0.064 (m)
Abs Residual Mean 1 279 (m)

Standard Error of the Estimate 0 34 (m)
Root Mean Squared 1 559 (m)
Normalized RMS 7 521 (%)
Correlation Coefficient 0.957

Fig. 40. Observed versus calculated heads in the lower aquifer for the 1995 transient simulation, Al Wagan area, UAE.

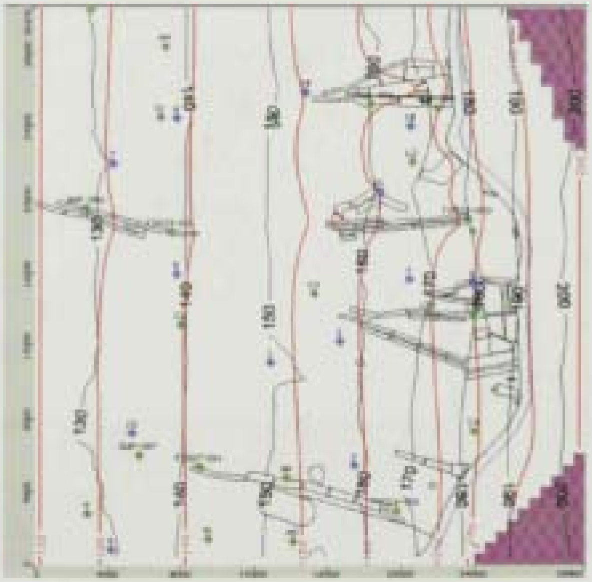


Fig. 41. Observed versus simulated water level elevations in the upper aquifer for the 2000 transient simulation, Al Wagan area, UAE.

Fig. 42. Observed versus simulated water level elevations in the lower aquifer for the 2000 transient simulation, Al Wagan area, UAE.

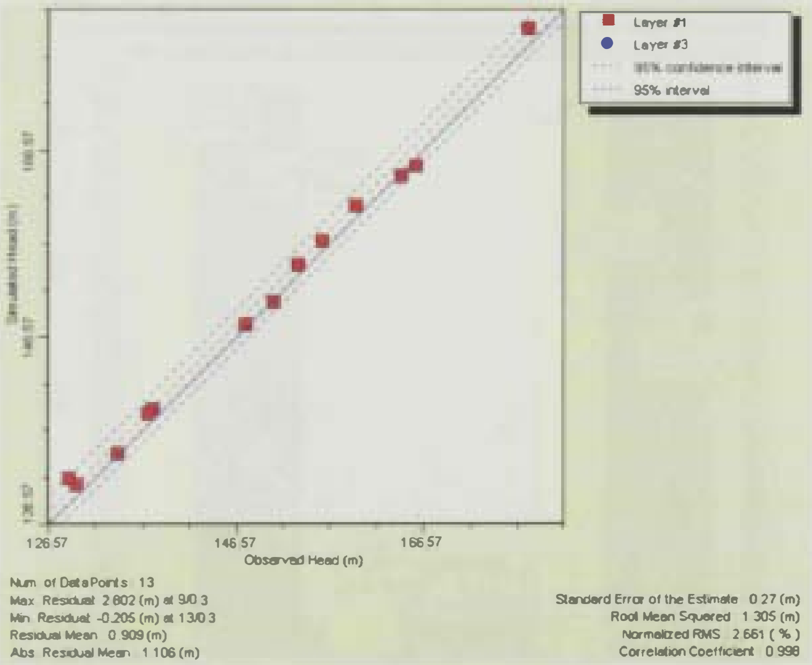


Fig. 43. Observed versus calculated heads in the upper aquifer for the 2000 transient simulation, Al Wagan area, UAE.

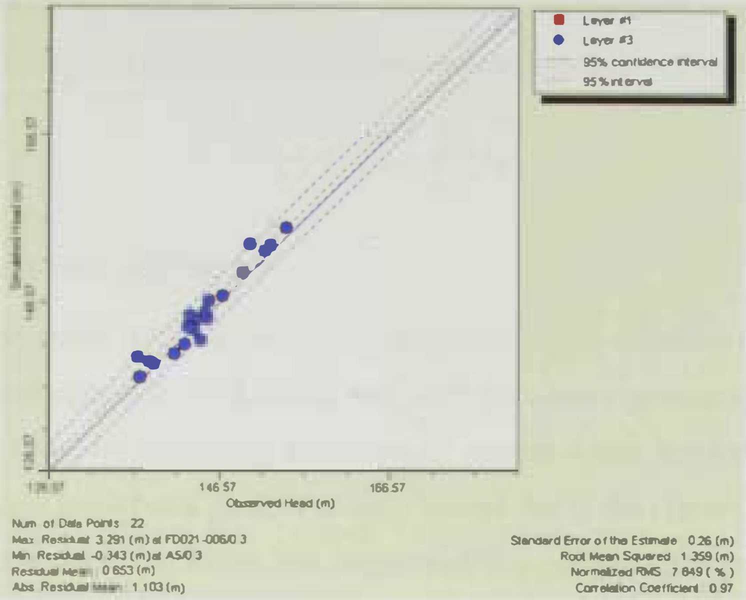


Fig. 44. Observed versus calculated heads in the lower aquifer for the 2000 transient simulation, Al Wagan area, UAE.

Fig. 45. The zone budget of the three zones of Al Wagan model area, in 2000 transient simulation.

5.9 Post – Audit of the Model after 2000

After the calibration for 1995 and 2000, the model was run for 2003. Fig. 46 and 47 show the result of this run, which revealed to the continuous drawdown of the water level in the upper aquifer.

5.10 Predictions into the Future

The ability of the model to simulate four different hydrologic conditions accurately, 1980 pre-development conditions, 1995, 2000, and 2003 transient conditions, lends credibility to the model as a tool for predicting the effects of ground-water development in the area. The use of the flow model as a predictive tool showed that if the current pumping rates of the wells will continue in the future, this might lead to a complete aquifer depletion of the upper aquifer at the north of the study area (Fig. 48). Fig. 49 is a cross section along the line C-C', which passes through the northern part of the model, that shows the water level in the upper part is coincide with the bottom of the upper aquifer. Further attempts were made to run the model after 2010, but dry cells started to occur in the areas of drawdown shown in Fig. 49.

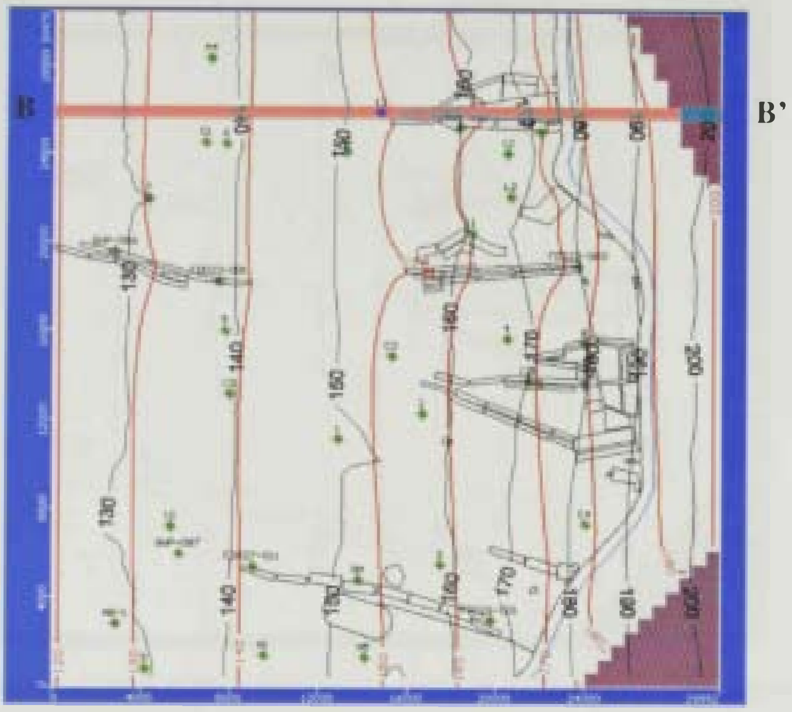


Fig. 46. Observed versus simulated water level elevations in the upper aquifer for the 2003 transient simulation, Al Wagan area, UAE.

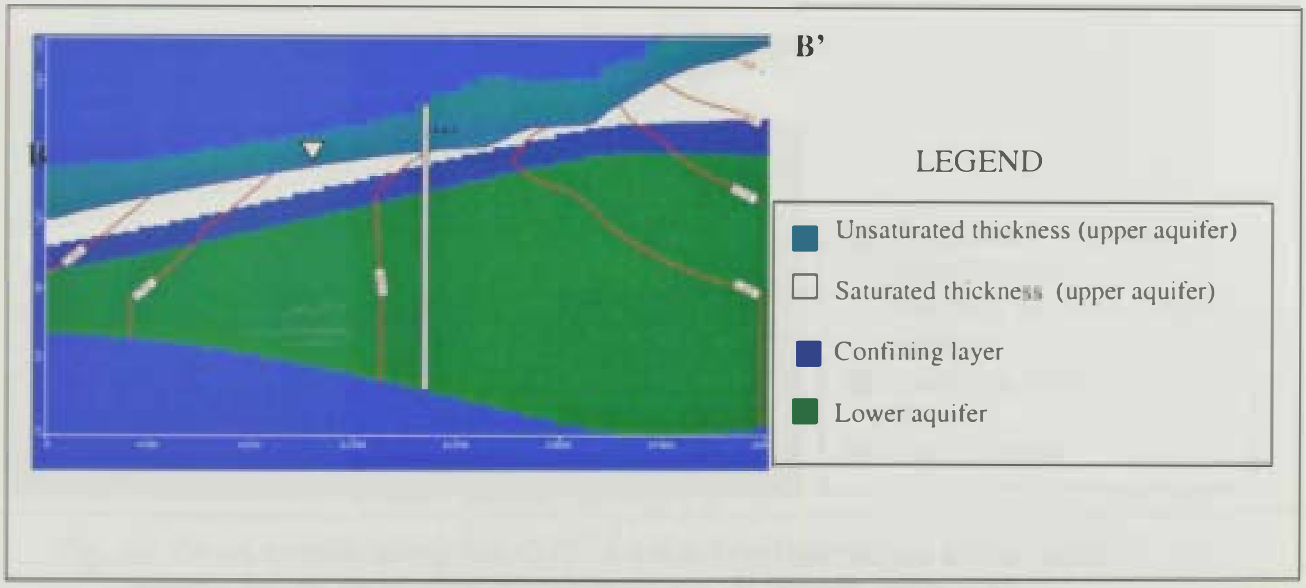


Fig. 47. Cross section along line B-B' of water level elevations in the upper aquifer for the 2003 transient simulation, Al Wagan area, UAE.

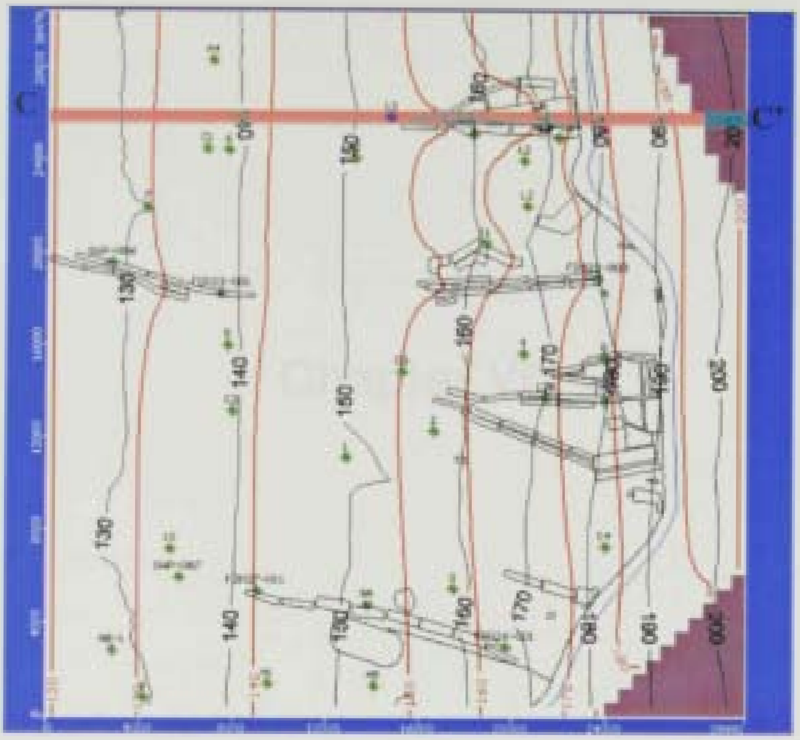


Fig. 48. Observed versus simulated water level elevations in the upper aquifer for the 2010 prediction simulation, Al Wagan area, UAE.

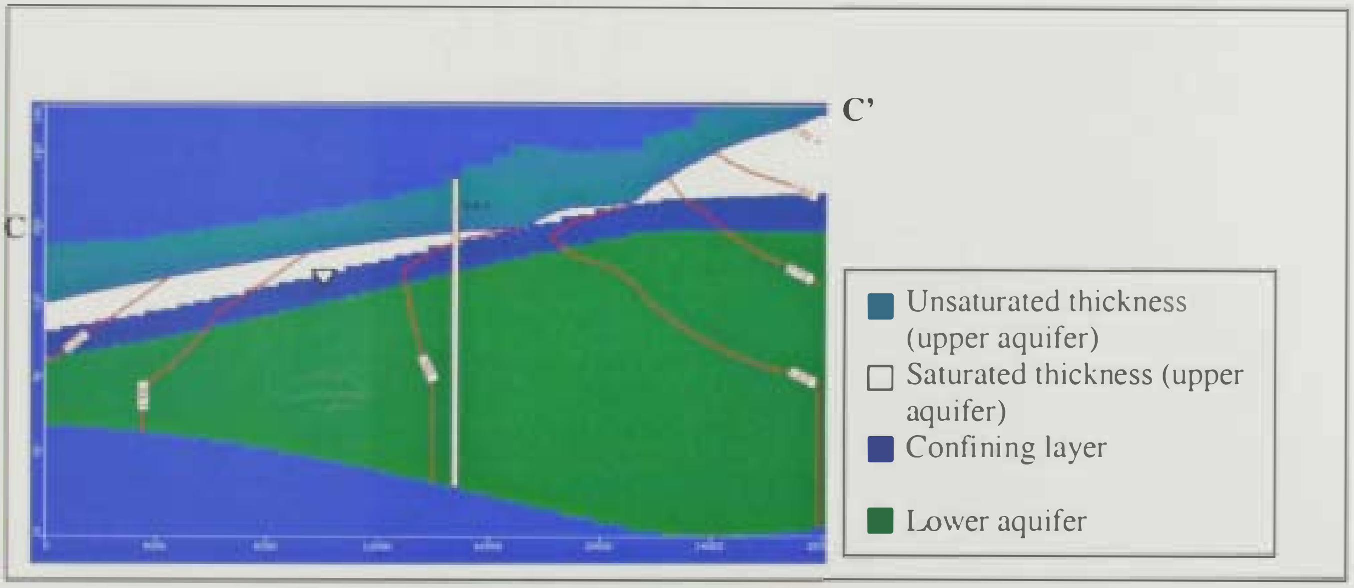


Fig. 49. Cross section along line C-C' of water level elevations in the upper aquifer for the 2010 prediction simulation, Al Wagan area, UAE.

Chapter VI

WATER BUDGET OF THE AL WAGAN AREA

CHAPTER SIX

WATER BUDGET OF THE AL WAGAN AREA

6.1 The Water Budget Equation

Water budgets were calculated to estimate the amount of water recharging the aquifer system in Al Wagan area. The water budget equation is based on the principle of conservation of mass: the total input of water must equal the total output. The shallow and lower aquifers are considered separately.

The equation for the upper aquifer is given as:

$$P + R = ET + Ru + Pu + GO_u + \Delta S_u + Re \qquad (7)$$

Where:

P = Precipitation

R = Return from irrigation infiltration

ET = Evapotranspiration

Ru = runoff

Pu = pumpage (ground-water withdrawals)

GO_u = ground-water outflow from upper aquifer (lateral)

ΔS_u = change in storage in the upper aquifer

Re = downward leakage (recharge) to the lower aquifer (vertical)

In			Out						
P	R	P+R	ET	Ru	Pu	GOu	ΔSu	Re	Total
51349.2	2670.5	54019.7	216	0	26705	51458	25714	3215	107308

Simulation results are used to evaluate each component in Eq. 7. Thus by substituting the values of the parameters in Eq.7; the value of the right hand side (P+R) equals 54,019.7, while the value of the summation of the left hand side parameters equals 107,308. The difference between the inflow (right hand side of the equation) and the outflow (the left hand side of the equation) is due to the lack of precipitation and the excessive pumpage from wells for irrigation purposes.

The residual of recharge available to the lower aquifer (Re) then can be estimated as the residual of the equation.

The equation for the lower aquifer is given as:

$$Re + GI = Pu + GO_L + \Delta S_L \qquad (8)$$

Where

Re = downward leakage (recharge) to the lower aquifer (vertical)

GI = ground-water inflow (lateral)

Pu = pumpage (ground-water withdrawals)

GO_L = ground-water outflow from lower aquifer

ΔS_L = change in storage in the lower aquifer

In			Out			
Re	GI	Re+GI	Pu	GO_L	ΔS_L	Total
6388	47004	53392	63427	13142	23175	99744

The difference between the inflow and outflow in Eq.8 is still recognized for the lower aquifer due to the excessive pumpage of water for irrigation in the area.

6.2 Conclusions based on the Water Budget

In the previous sections, the components of the water budget equations (Figs. 7 and 8) were discussed. Table 9 shows a compilation of the equations for both the upper aquifer and the lower aquifer systems. The budget for the upper aquifer shows that in 1995, 6388 m^3/d were available for recharge to the lower aquifer and outflow from the lower aquifer was about 13142 m^3/d. In 2000, 6962 m^3/d were available for recharge to the lower aquifer and outflow from the lower aquifer was 12103 m^3/d. In 2003, 7235 m^3/d were available for recharge to the lower aquifer and outflow from the lower aquifer was 11482 m^3/d. For future prediction, in 2010, 7771 m^3/d were available for recharge to the lower aquifer and outflow from the lower aquifer was 10250 m^3/d.

Although ground-water outflow from the lower aquifer was reduced with time, the amount of water recharged to the lower aquifer from the upper aquifer through the confining layer has increased; this might explain the apparent deterioration of water quality in the brackish water of the lower aquifer.

Table 9. Components of the water budgets for 1995,2000, 2003, and 2010 average conditions, in cubic meters per day.

	Steady state		1995		2000		2003		2010	
	Upper Aquifer									
	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
Storage	0	0	28250	630	27384	417	12876	1388	9910	186.39
Constant Head	6657	51913	4543	51453	4551	51048	6014	48127	6628	47150
ET	0	209	0	216	0	217	0	215	0	209.83
Wells	0	0	0	26705	0	26705	0	15705	0	15705
Precipitation	46829	0	46829	0	46829	0	46829	0	46829	0
Zone 2 to 1	2255	0	2535	0	2674	0	2722	0	2848.4	0
Zone 1 to 2	0	3622	0	3166	0	3062	0	3018	0	2977
Total	55741	55743	82158	82170	81438	81449	68440	68453	66215	66228
	Lower Aquifer									
Storage	0	0	28711	5537	23614	5601	19679	51	15413	0
Constant Head	11901	13418	47004	11453	50555	10574	48020	10034	50472	8951.5
Wells	0	0	0	63427	0	63427	0	63427	0	63427
Precipitation	0	0	0	0	0	0	0	0	0	0
Zone 2 to 3	3772	0	6388	0	6962	0	7235	0	7771	0
Zone 3 to 2	0	2255	0	1689	0	1530	0	1448	0	1298.2
Total	15673	15673	82103	82105	81131	81132	74934	74960	73656	73677

6.3 Discussion of Flow-Model Results

A ground-water-flow model is a numerical approximation of the natural flow system, and as such, it can represent the natural flow system but cannot duplicate it exactly. Assumptions and simplification are necessary in the design of a model, and results of simulations must be interpreted with this in mind. Constant-head boundaries have the potential to provide an unlimited supply of water (Anderson and Woessner 1992).

If the flow model were to perfectly represent the ground-water flow system, the contour shown in Fig.s 25, 26, 32, 33, 36 and 37 would coincide exactly. Because this was not the case, the differences in the contours can be ascribed to errors. Possible sources of errors include, but are not limited to, variations in aquifer characteristics unaccounted for in the model, errors involved in preparing the maps based on water-level measurements, or model assumptions made about the aquifer system that were not possibly accurate.

Generally, accuracy of a numerical model based on the finite-difference method improves with additional data, smaller cell size, and layer number of layers, property values and better defined hydrogeologic geometry can also result in a model that more closely represent actual flow conditions. In most cases, however, the necessary detailed information is unavailable.

In the 1995 simulation, the amount of leakage through the confining layer to the lower aquifer was 6388.10 m³/day, while in 2000 simulation was 6961.60 m³/day, which represents about 8 to 10 percent of the total water inflow to the lower aquifer. This indicates vertical flow through the confining layer. Fig. 50 illustrates how leakage of the flow system might occur.

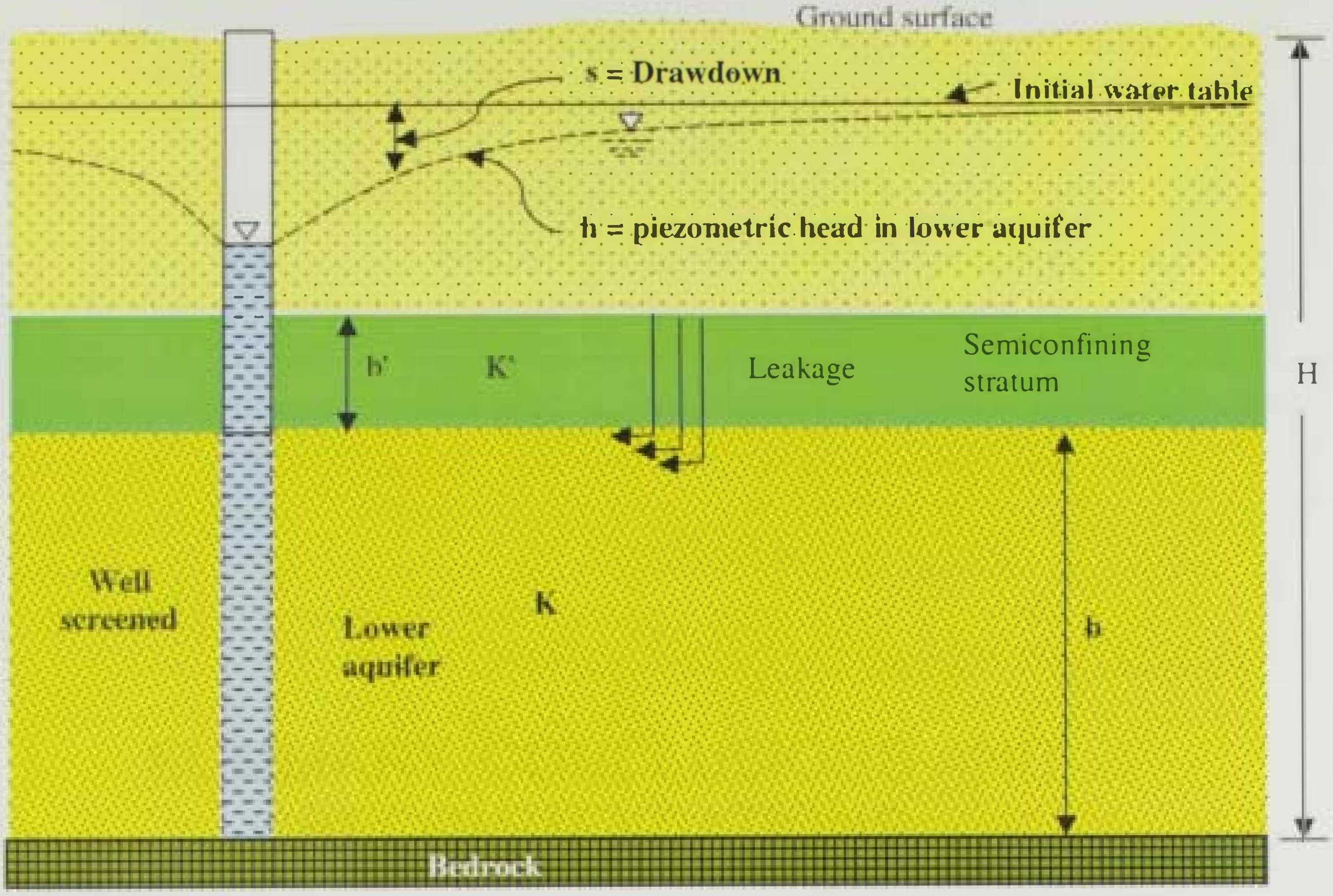


Fig. 50. Leakage from the upper aquifer through the confining bed to the lower aquifer.

Chapter VII:

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Chapter VII:

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY AND CONCLUSIONS

Ground water is the primary source of irrigation in Al Wagan area. The main aquifer, i.e., the lower aquifer, consists of sandy and conglomeratic mudstone, and siltstone. Although the deposits are poorly permeable, they can yield as much as 26705 m^3/day to wells.

The principle source of recharge to the ground-water system (both upper and lower aquifers) is rainfall on the Oman Mountains east of the study area and on the study area. Large, sustained rainfalls are required to produce enough water to offset potential evapotranspiration and to allow rainwater to infiltrate to the water table and recharge the aquifers. In areas covered with thick layers of eolian sand, direct infiltration of rainwater rarely recharges the aquifer. The average annual precipitation at a meteorological station in Al Ain is about 100 mm; annual pan evaporation for the Emirates, as measured in Sharjah, is estimated to be between 3,400 and 4,000 mm. Flow in the system underlying the eastern boundary of the study area is derived from three major recharge components: subsurface underflow in alluvium deposits channeled through intermountain gaps, surface runoff channeled through intermountain gaps, and flow from fractured bedrock along the entire mountain front.

The ground-water-flow system is conceptualized as a three-layer model, from top to bottom; the section consists of upper aquifer underlain by a confining layer, which separates it from the lower aquifer.

A three-dimensional, three-layer ground-water-flow model was constructed to help understand the ground-water-flow system. The modeled area encompasses about 914 km^2, extending from Al Ageer in the north to Seah Al Humran in the south, and from the Oman –UAE borders to the east to Al Gheena in the west.

Stresses and parameters included in the model were pumped wells, recharge, and transmissivity. The model simulates pre-development flow conditions as of 1980. Measured water-level data from 35 wells were used to evaluate pre-development conditions in the two aquifers. Observed water levels were compared to simulated water levels and were within a few centimeters to one meter, with only one more than 5 meters. Transient simulations were selected for the years 1995, 2000, and 2003. Reasonable matching between the simulated and observed heads was achieved. Model results indicate vertical flow occurs between the three model layers; possibly explaining the observed increased salinity of the lower aquifer.

Geochemical analyses support the conclusion that the salinity of brackish ground water of the lower aquifer in Al Wagan area increased largely in some parts such as 74 %, and quite slightly in some parts such as 2% as shown in Table 8.

7.2 Recommendations

- The ability of the model to simulate four different hydrologic conditions accurately, 1980 pre-development conditions, 1995, 2000, and 2003 transient conditions, lends credibility to the model as a tool for predicting the effects of ground-water development in the area.
- The use of the flow model as a predictive tool showed that if the current pumping rates of the wells will continue in the future, this might lead to a complete aquifer depletion of the upper aquifer at the north of the study area.
- Also the piezometric heads of the lower aquifer might be dramatically affected by the continuous pumpage, which might result in more deterioration of the water quality of the lower aquifer.
- As a result of this study the following recommendations can be made in order to avoid more depletion of the aquifer and deterioration of the water quality:
    1. Minimize aquifer depletion.
    2. Regulate ground-water use.
    3. Enhancement of the observation well network.
    4. Better well constructions.

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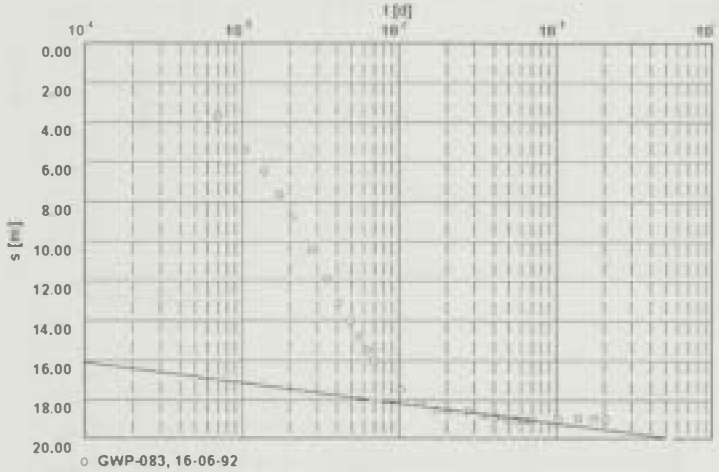
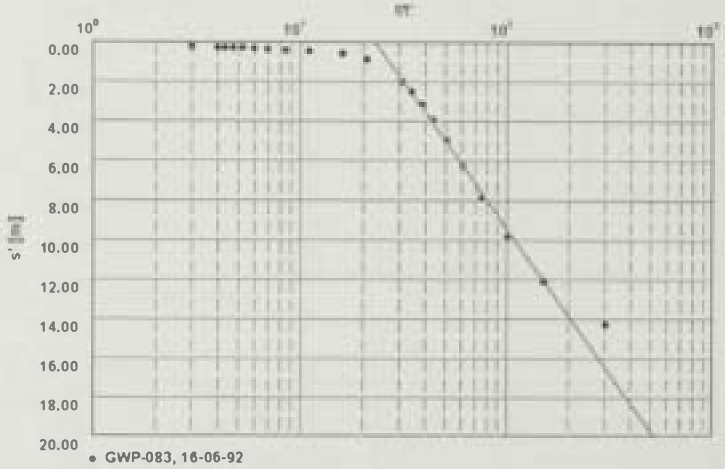
Appendix A

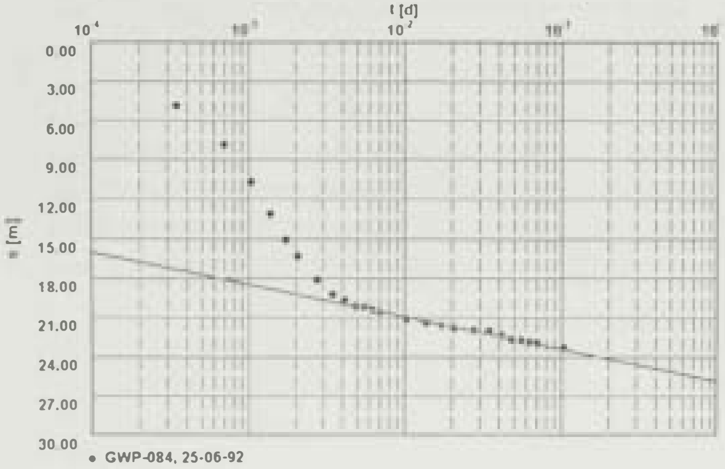
Aquifer-Test Analyses of Selected GWRP Wells

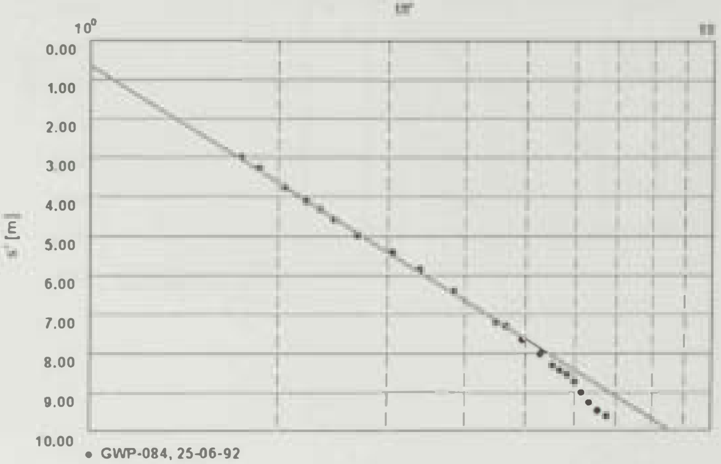
Discharge

Recovery









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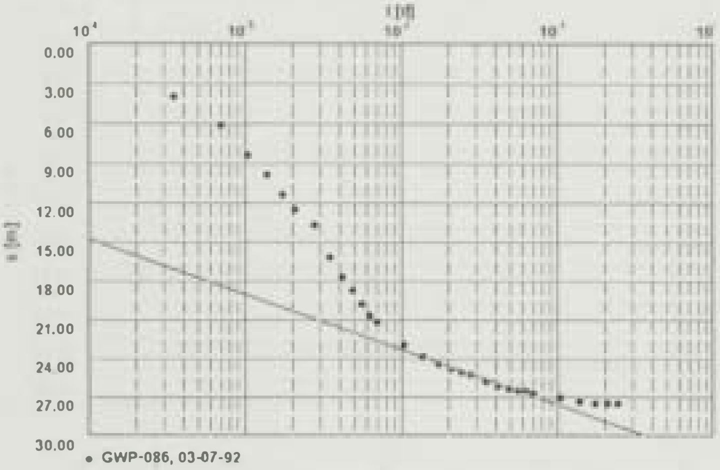

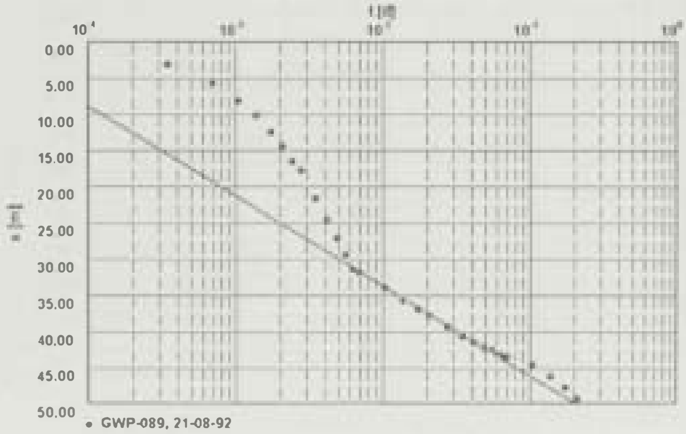

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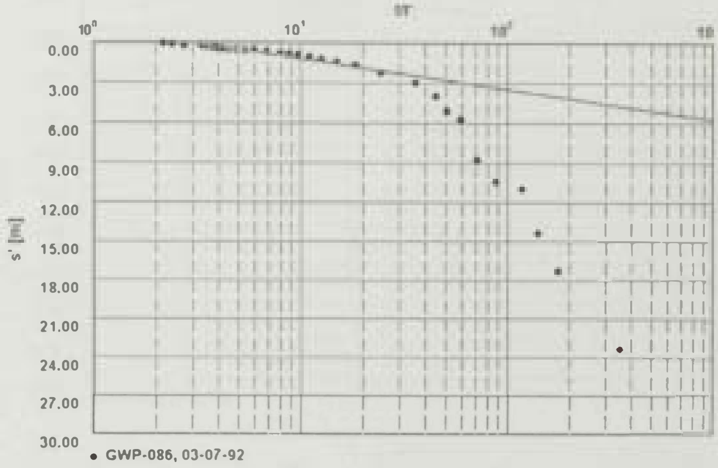
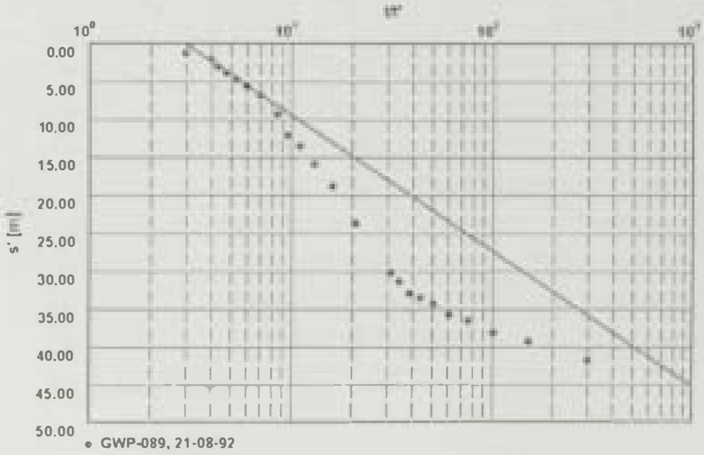
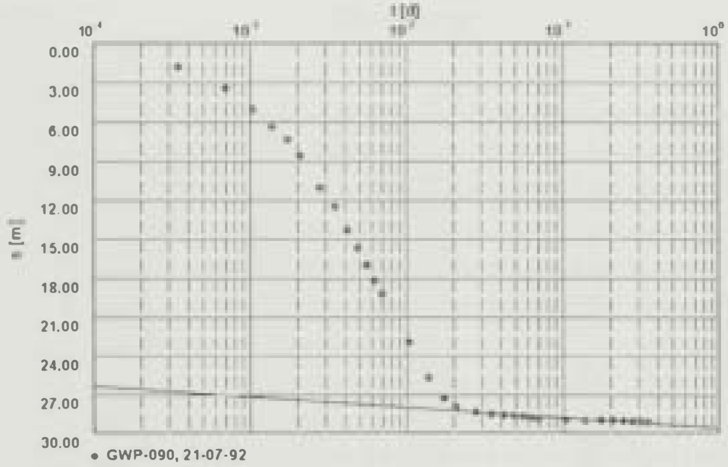
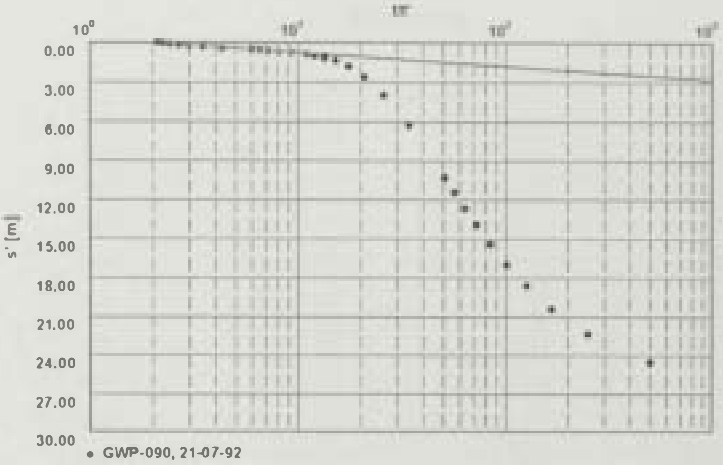


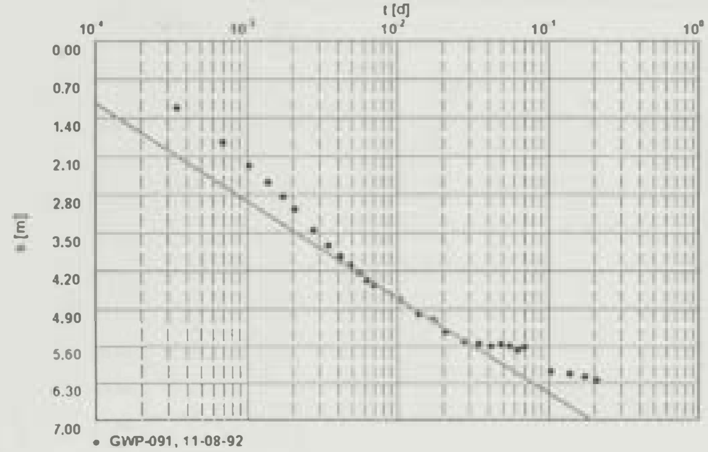


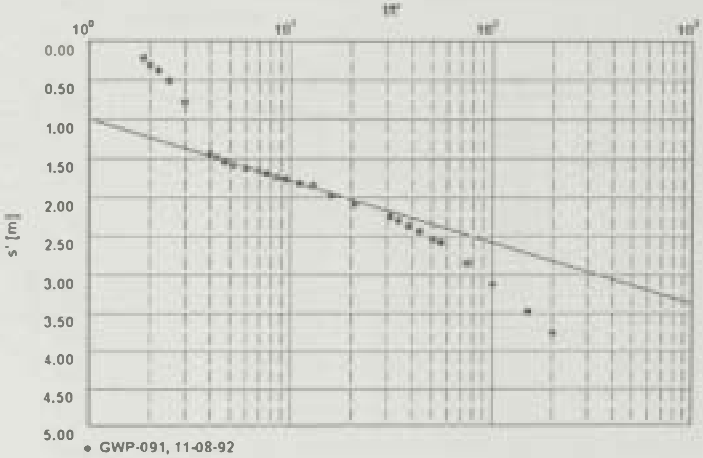
Discharge

Recovery









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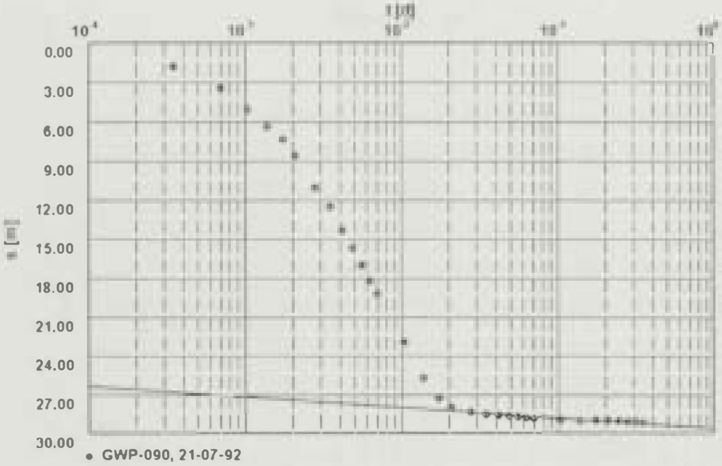

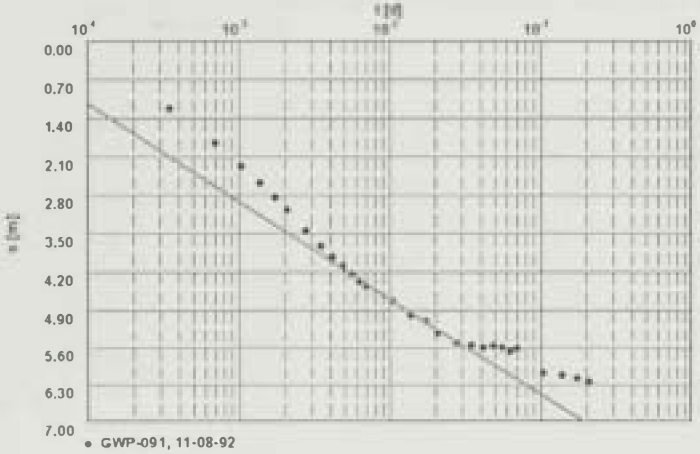

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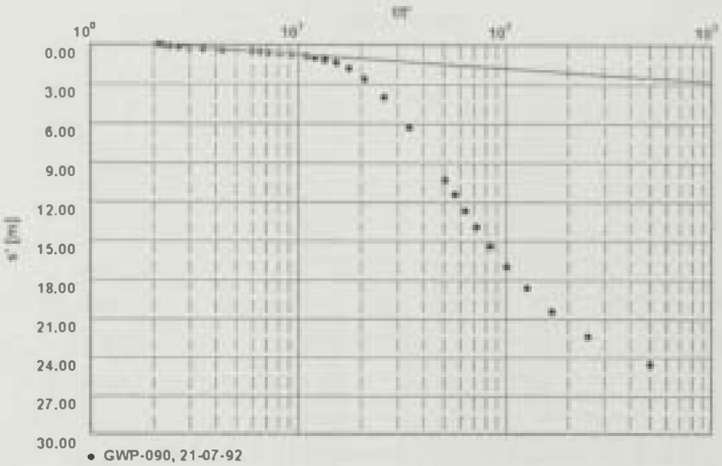

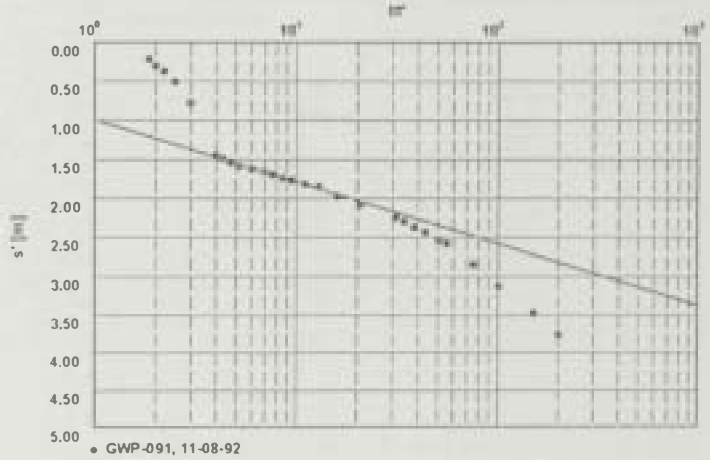

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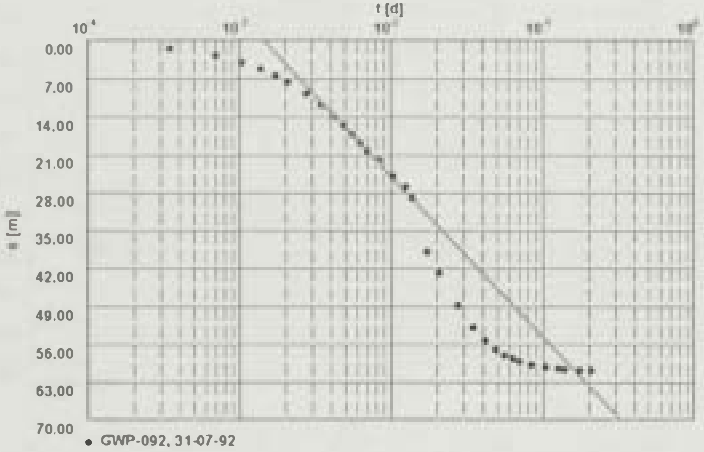

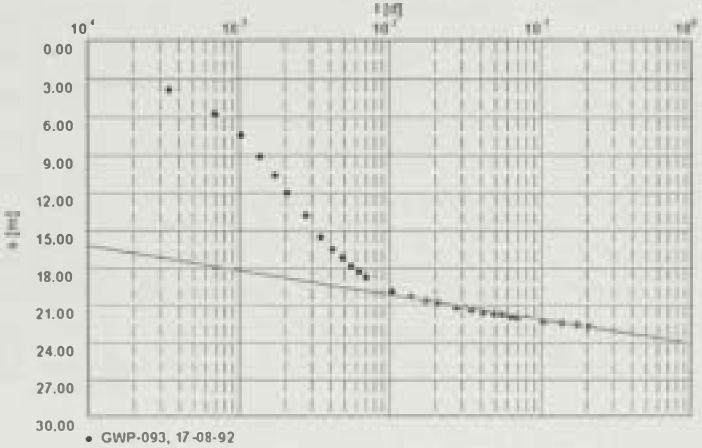

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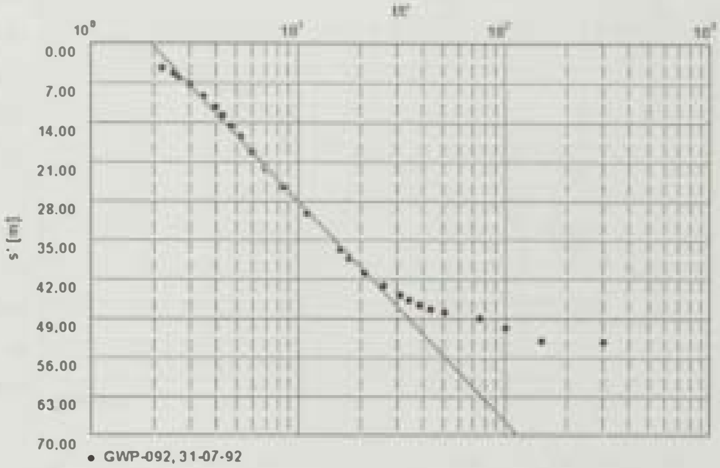

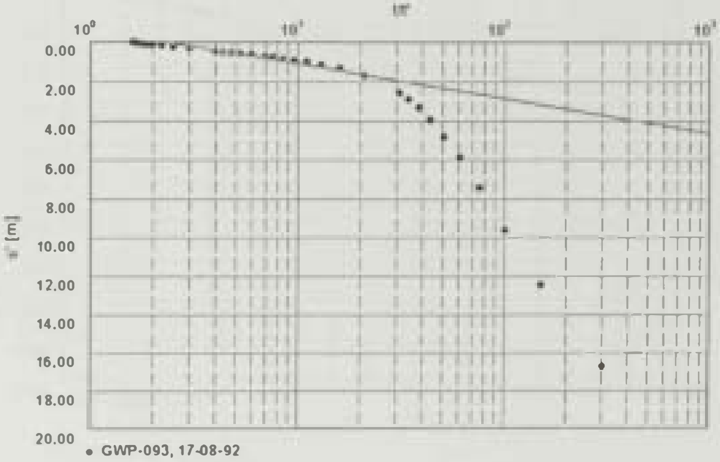

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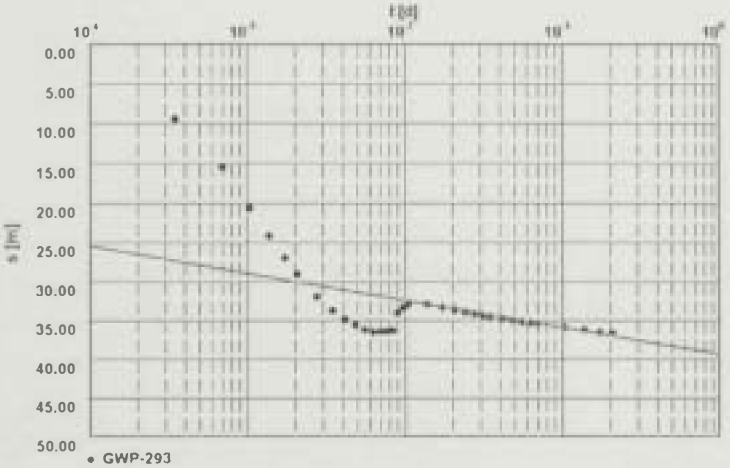

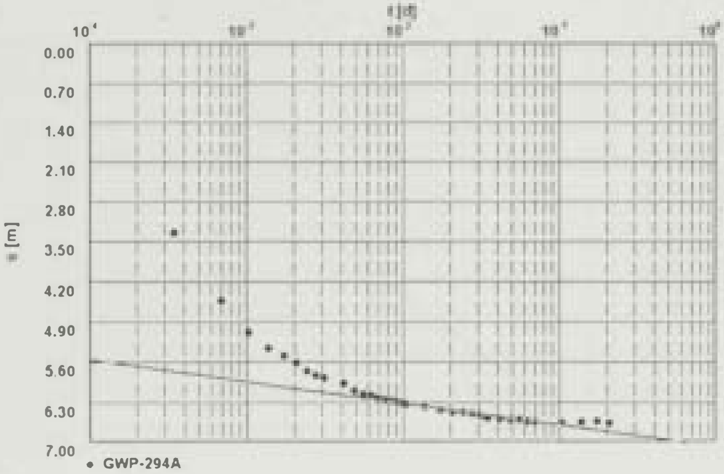

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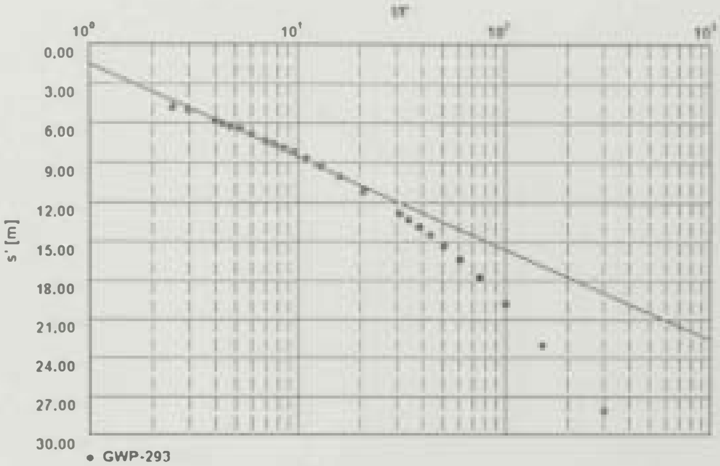

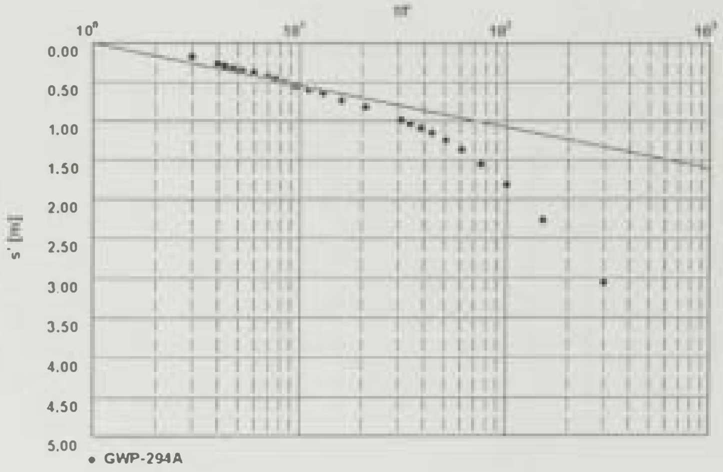

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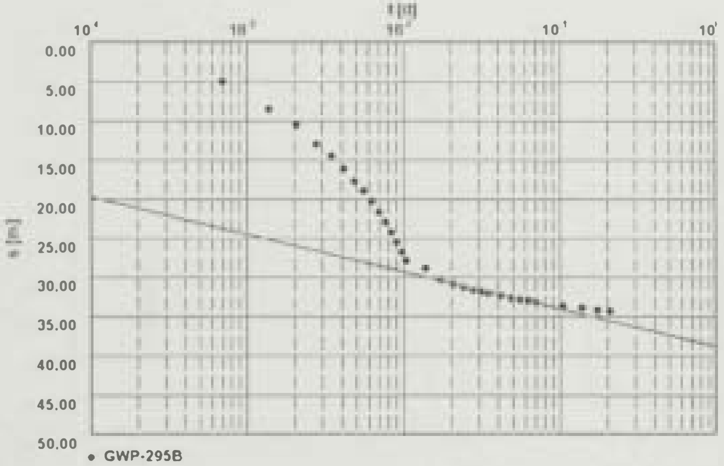

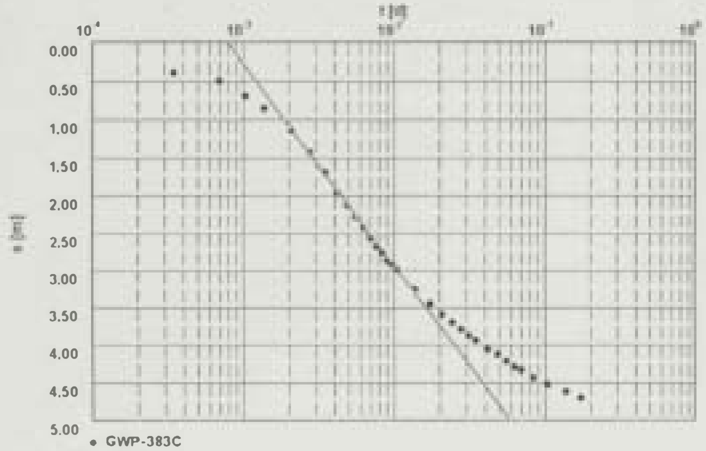

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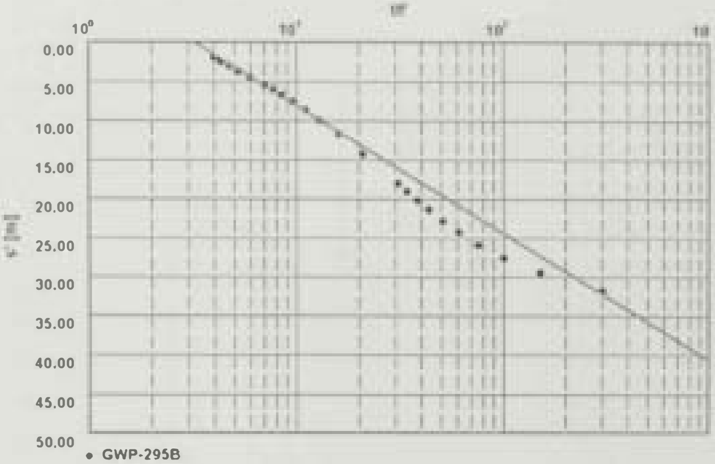

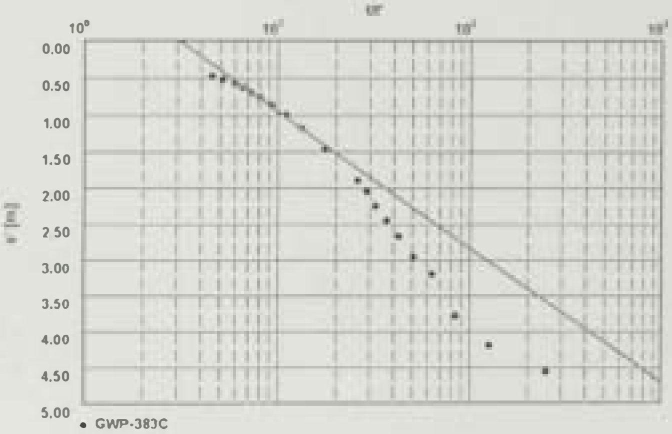

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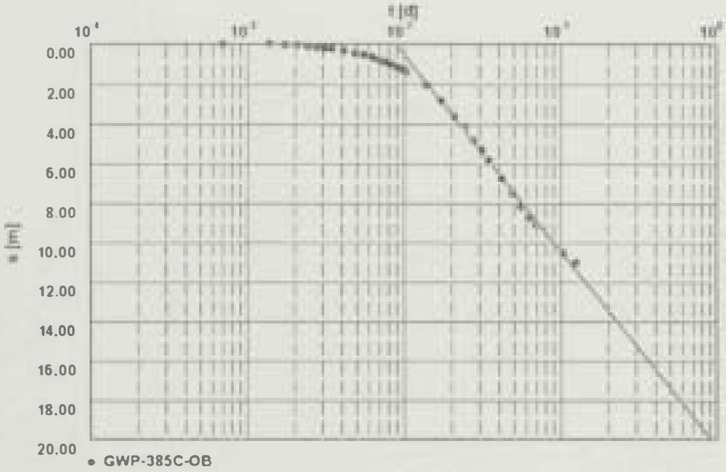

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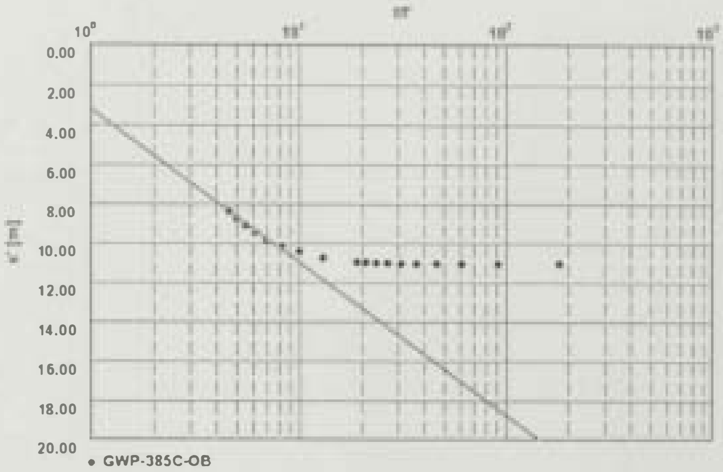

ملخص الرسالة

تقع منطقة الوجن جنوبي مدينة العين بالمنطقة الشرقية من إمارة أبو ظبي بامتداد الحدود بين دولة الإمارات العربية المتحدة وسلطنة عمان. ولمنطقة الوجن أهمية خاصة من الناحية الزراعية بالمنطقة الشرقية من إمارة أبو ظبي.وتشكل المياه الجوفية المصدر الرئيسي لمياه الري بالمنطقة. ويأتي مصدر التغذية للمياه الجوفية للمنطقة الشرقية بصفة عامة من مياه الأمطار التي تهطل على جبال عمان والتي تقع ناحية الشرق. وتتخذ خطوط فيض المياه الجوفية الاتجاه من الشرق للغرب حيث تأتي معظم المياه للتغذية من المناطق العالية بجبال عمان.

يتكون النظام المائي الجوفي لمنطقة الوجن من الخزان العلوي الغير حبيس والخزان السفلي الحبيس والذي يفصل بينهما طبقة حابسة. ويعود الخزان الجوفي العلوي للجزء المشبع من الرسوبيات الغير متماسكة والتي يعود تاريخها للعصر الرباعي ، وتلي هذه الرسوبيات الرباعية الأصل طبقة من الطين حيث تعمل تلك الطبقة كحاجز يفصل بين الخزان العلوي والخزان السفلي الذي يتكون من طبقة من الكونجلوميرات يتبع تكوين ما قبل الفارس.

وتهدف هذه الدراسة إلى عمل وصف هيدروجيولوجي للخزانين العلوي والسفلي بمنطقة الوجن ، وتفسير التغيرات التي حدثت لنوعية المياه المتوسطة الملوحة والتي نتجت عن الاستنزاف المستمر للمياه الجوفية بالمنطقة ، بالإضافة إلى عمل وصف كمي لتدفق المياه الجوفية للنظام المائي الجوفي.

تتميز المياه الجوفية المحتواة في الخزان العلوي بوجود نسبة عالية من الأملاح المذابة تفوق تلك الموجودة بالخزان السفلي. وتؤكد التحاليل الجيوكيميائية على أن ملوحة مياه الخزان السفلي قد زادت في منطقة الوجن بنسبة تتراوح ما بين ٢ % إلى ٧٤ % في الفترة ما بين عامي ١٩٩٦م إلى ١٩٩٨م.

وقد استخدمت بيانات السحب من الآبار المسجلة لدى دائرة الزراعة والإنتاج الحيواني بالعين وكذلك برنامج دراسات المياه الجوفية لإمارة ابو ظبي حيث دلت على هبوط مستوى سطح المياه في الخزان السفلي كنتيجة للكميات الكبيرة من المياه التي تضخ من الآبار لأغراض الزراعة.

تم من خلال هذه الدراسة إنشاء نموذج رياضي لمحاكاة تدفق المياه يتكون من ثلاث طبقات ثلاثية الأبعاد للمساعدة في توضيح عمل النظام المائي الجوفي. وقد أدى استخدام نموذج المحاكاة كأداة للتنبؤ بما سيحدث في المستقبل أنه إذا ما استمر الحال على ما هو عليه بالضخ للمياه الجوفية بالمعدلات الحالية فإن الخزان الجوفي السفلي سيتعرض للجفاف التام وخصوصا بالمنطقة الشمالية من منطقة الوجن.

وبناءا على نتائج هذه الدراسة فقد تم طرح بعض التوصيات للدراسات المستقبلية منها ضرورة التقليل من معدلات الضخ الحالية إما بخفض إنتاجية الآبار و/أو التقليل من عدد الآبار المخصصة لكل مزرعة بالمنطقة ، وأيضا إلى ضرورة تنظيم استخدامات المياه وذلك بعمل حصر شامل لآبار الضخ في منطقة الدراسة وعدد المزارع ومساحتها وكذلك أماكن إنشاء الغابات واستخدام النباتات والأشجار التي تتحمل ملوحة مياه عالية. واقتراحات بضرورة إنشاء محطات رصد وآبار مراقبة إضافية بالمنطقة ، كما أن ضرورة الاهتمام بطريقة حفر وإنشاء الآبار أصبحت حاجة ملحة لوقف التسرب ما بين الخزانين العلوي والسفلي.

جامعة الإمارات العربية المتحدة
عمـــادة الدراســـات العليـــا

عنون الرسالة

الوضع الهيدروجيولوجي وتوصيف نظام الخزان الجوفي بمنطقة الوجن جنوب العين، دولة الإمارات العربية المتحدة

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