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Assessment of Groundwater Resources in Selected Areas of Al Ain in the U.A.E.

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Assessment of Groundwater Resources in Selected Areas of Al Ain in the U.A.E.

By

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Abstract

The sustainable development of any region depends on the availability of water resources. In arid and semi-arid regions, the shortage in freshwater resources constitutes the major constraint against the expansion in agricultural and industrial activities. Therefore, every possible effort should be made to assess, develop and sustain the limited freshwater water resources in such regions.

The United Arab Emirates (UAE) is located in an arid region, where the climate is harsh and the renewable freshwater resources are very limited. Despite the severe shortage in water resources, water is misused and sometimes wasted. The per capita daily consumption in the UAE is estimated at 700 l/d which is among the highest consumptions in the world including those countries with excess water resources. On the other hand, the country has experienced a rapid development over the last three decades. Vast areas have been cultivated and green belts have been created around cities and along the highways. Many new industries were established in the different Emirates. As a result, the water demands to meet the rapid development in the different sectors have increased considerably during the same period. This increase in demand was partially covered by the expansion in the development of desalination water. Nevertheless, the groundwater resources have been overexploited for agricultural purposes. Many private farms were developed and hundreds of pumping wells were constructed. Records indicate that groundwater resources are currently under the risk of possible depletion not only because of the excessive pumping but also due to the limited recharge from rainfall.

This study presents a comprehensive analysis of the groundwater resources in some selected areas in Al Ain. The study area included Al Hayer, Gummed, Nahil and part of Al Khadar. Previous reports, information and data were critically reviewed and discussed. The hydrogeological setting and main hydrogeological parameters for the study area were reviewed. Available records for the groundwater levels were analyzed and contour maps were developed for the equipotential lines, depth to groundwater and drawdown in the different years. These maps were compared to provide a better understanding for the groundwater system and the flow pattern in the study area. As compared to the records of 1991, the maximum drawdown in the groundwater levels was about 17 m at the central part of the study area. On the other hand, contour maps were developed to assess the change in the water quality over the last two decades. It is concluded that the change in the groundwater quality is limited and it can be used for unrestricted irrigation purposes.

A two-dimensional finite-element model (SUTRA) was employed to simulate the groundwater condition is the study domain. Argus-One was used as pre-processor and post-processor for SUTRA. The model was calibrated for the groundwater measurements of the year 2001 and was then used to predict the groundwater levels for the year 2010 assuming the same pumping rates. The expected decline in the groundwater levels within the study domain varied between 5 m near the boundaries and 9.5 m at the central part. Due to the limited availability of data, the results of the model should be regarded as qualitative rather than quantitative. Finally, recommendations were proposed to protect and sustain the groundwater resources.

Keywords: groundwater, assessment, analysis, development, modeling, Al Ain.

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List of Abbreviations

amsl	above mean seawater level
bmsl	below mean seawater level
d	day
FD	Forestry Department
G	gallons
GCC	Gulf Corporation Council
GWD	Groundwater Department
GWRP	Groundwater Research Project
GNUP	pressure boundary coefficient factor
K	Weighted average hydraulic conductivity
k_i	Hydraulic conductivity computed at time t_i
km	kilometer
l	liter
m	meter
M	million
MAF	Ministry of Agriculture and Fisheries
MED	Multiple Effect Desalination
mg	milligram
mm	milliliter
NDC	National Drilling Company
ppm	parts per millions
Pe_m	Peclet number
RO	Reverse Osmosis
S_w	molecular diffusivity
SUTRA	A finite element simulation model for saturated-unsaturated, fluid density-dependent ground-water flow with energy transport or chemically-reactive single-species solute transport.
t	time
TDS	total dissolved solids
TLSR	transmission loss stream flow routing
USGS	United States Geological Survey
y	year
WED	Al Ain Water and Electricity Department
ΔL_L	local distance between element sides along a streamline
α_L	longitudinal dispersivity
ΔL_T	local distance between element sides across a streamline
α_T	transversal dispersivity
$\|V\|$	absolute groundwater flow velocity
ε	porosity of porous medium
σ_s	specific storativity
σ_w	solid grain thermal conductivity

Chapter 1. Introduction

1.1. Importance of Water in Arid Regions

All life on earth is dependent, one way or another, on water. Without which no life could exist, not only for mankind but also for fauna and flora. Water is the symbol of life. Water resources are of strategic national importance and thus the development of knowledge to enable their sustainable management and use must be of a high national priority at all levels. This is even more emphasized in arid and semi-arid regions where renewable freshwater is scarce and sometimes totally absent.

The total amount of water in the globe is constant and has neither decreased nor increased throughout the history. However, the location of water availability may change over time. Like all other substances, water can neither vanish nor created but it may transform from one state to another. For example, surface water can be transformed to groundwater and vise versa. Based on the hydrologic cycle, the movement of water in the globe is an endless process.

Arid areas receive too little precipitation to support dry land agriculture or domestic livestock grazing. In contrast, semi arid areas are of adequate moisture at some time during the year to produce forage for livestock. There are even some years in semi-arid areas where the dry land crop production is successful. Water resources in arid and semi-arid regions are mainly climate driven. In such areas, the evaporation and evapotranspiration rates are far higher than the rainfall. Both of the arid and semi-arid climates are characterized by extreme variability with commonly occurring droughts and infrequent periods of above average rainfall resulting in flash floods. In basic climate terms, a desert can be defined as an area which receives little or no rainfall and experiences no season of the year in which rain regularly occurs (Nicholson, 1995). The common feature of semi-arid, arid and desert regions is the shortage of water and the harsh climatic conditions.

Groundwater resources constitute the main, if not the only, source of renewable freshwater in arid and semi-arid areas. However, because of the very limited natural recharge, either from rainfall events or surface water bodies, aquifers in arid regions areas are exposed to depletion and water quality deterioration. In some areas, the groundwater is regarded as fossil water.

About a third of the land surface in the world is either arid with less than 250 mm of annual precipitation or semi-arid with annual precipitation between 250 mm and 500 mm. The lack of freshwater resources in these regions constitutes a major deterrent to their sustainable development. On the other hand, growing population, rising standard of living, and expanding opportunities exert increasing demands for varied needs for water. These needs may be domestic, agricultural, industrial, waste disposal, power generation, navigational, transportation, recreational, and so on.

The water shortage has already become commonplace in many parts of the world, including those that are not arid or semi-arid. In many of those parts where water is plentifully available now, it is expected that by the middle of this century they will start experiencing severe water shortages. The per capita share of freshwater has dropped significantly due to burgeoning population and the attendant increasing need for water. The global population increased from 5.27 to 6.06 billion during the period 1990-2000 (WHO and UNICEF, 2000). Meanwhile, the total amount of available freshwater remained constant, if not decreased due to mankind activities and the associated contamination of the freshwater resources. Notwithstanding these shortages, water continues to be used unwisely, wasted and polluted. Insufficient water at the right place at the right time with the right quality requires, more than ever before, improved management, efficient utilization, and increased conservation of limited freshwater resources. These demands can only be met if water resources are properly managed.

Water scarcity in arid and semi-arid regions is rapidly becoming part of a wide-spread environmental concern. The twin phenomena of depletion of existing water resources together with the pollution of these resources are causing a growing problem in these areas.

1.2. Water Resources in the GCC Countries: An Overview

The geomorphology of the Gulf Cooperation Council (G.C.C) countries is typical in the desert while the topography is different at the Oman Mountains to the east and Asir Mountains to the southwest of Saudi Arabia. The average annual rainfall in the G.C.C countries varies between 70 and 140 mm (arid conditions as rainfall is less than 250 mm/y). The precipitation at the mountains areas in Oman and southwest of Saudi Arabia is high, reaching about 500 mm/y. The surface runoff from the Oman Mountains recharges the areas in Oman and the United Arab Emirates.

The average annual volume of rainfall in the G.C.C. countries is about 205.93 billion m^3 (ACSAD, 1997). Saudi Arabia and Oman have the highest share of 158.47 and 37.6 billion m^3, respectively. The UAE and Kuwait receive 6.72 and 2.27 billion m^3 of annual rain water, respectively. Qatar and Bahrain receive very small quantities of rain water (Al- Rashed and Sherif, 2000).

The total surface runoff resulting from rainfall is estimated as 4.83 billion m^3/y. Saudi Arabia and Oman have portions of 3.21 and 1.47 billion m^3/y, respectively (Khouri and Deroubi, 1990; Al–Zubari, 1997). The UAE has a portion of 0.15 billion m^3/y of surface runoff while Kuwait, Bahrain and Qatar have portions together less than 2 million m^3/y (Abdulrazzak, 1995). A small amount of surface runoff (less than 20%) is used for irrigation or artificially recharges the aquifers.

Groundwater resources in the G.C.C. countries are either partly renewable resources in shallow alluvial aquifers or non renewable resources (or fossil water) in the deep aquifers. The non renewable groundwater reserves exist in the thick extensive sequences of sedimentary formations. These formations are composed of sandstone, limestone, and dolomite and overly basement rock formations known as the Arabian shield. Shallow aquifers have good quality water with total dissolved solids between 250 and 4000 ppm.

The total reserve of groundwater in the alluvial deposits is about 115.5 billion m^3 of which 84 billion m^3 exists in the largest single alluvial reservoir of Saudi Arabia (Khouri et al., 1986; Ukayli and Husain, 1988; and Abdualrazzak, 1994). Groundwater reserves in the deep aquifers of the Arabian shelf (fossil groundwater in deep sedimentary formations) are estimated at 2330 billion m^3 while the average annual recharge is about 2.7 billion m^3 only.

The total volume of groundwater extracted from the deep aquifers in the last two decades approached 300 billion m^3 of which 254.5 billion m^3 were pumped from Saudi Arabia alone for agricultural purposes. The deep aquifers were recharged with about 54 billion m^3 during the last two decays (Abdulrazzak, 1994).

There are many desalination plants in the G.C.C. countries that have been installed to meet the fresh water demands. In 1997, the combined capacities of all desalination plants in the G.C.C. countries were 2.14 billion m^3 with a total production of 1.7 billion m^3. By the year 2010 Saudi Arabia will produce 1.1 billion m^3/y (Sahlawi, 1999). In 2010, the total productions of Saudi Arabia, United Arab Emirates and Kuwait will be in the order of 1.5 billion m^3/y, about one third of the total world water production from desalination plants.

Many wastewater treatment plants were constructed in the G.C.C. countries at the tertiary and secondary level (Al–Saati, 1995; Al Muzaini and Ismail, 1994; Al Hajj, 1995 and Al–Zubari, 1997). In the year 1999, the total volume of wastewater in the GCC countries was 0.82 billion m^3, of which about 0.74 billion m^3 was treated. The recycled volume of the treated wastewater in the same year was 0.254 billion m^3; about one- third of the available waste water. The remaining water (0.486 billion m^3) was spilled into the sea. The recycled water is used in developing greenery areas, road ornamentals, and highways landscaping (Viswanathan and Al–Otaibi, 1999). In 1993, the UAE developed 106 million m^3 of treated wastewater to irrigate golf courses, parks and highways (Abdulrazzak, 1995). By the year 2010, the production volume of the treated wastewater in the GCC countries is expected to reach 1.57 billion m^3 (Viswanathan and Al-Otaibi, 1999).

1.3. Water Resources in the UAE

The United Arab Emirates consists of seven Emirates located between 22° 40′ to 26° 10′ north latitudes 51° 00 and 56° 25′ east longitudes. Figure 1.1. The Arabian Gulf lies to the northwest of the UAE and Gulf of Oman is located along its eastern coast. The mainland occupies a total area of about 84000 km^2.

The UAE is located in an arid area where rainfall is scare, random and infrequent. It varies between 20 and 140 mm/y. The UAE receives an average volume of 6.72 billion m^3 of annual rain water A Sherif. 2000). 14% of the total rainfall water is lost as surface runoff and base flow, which amount to 181 Mm^3. Measurements of rainfall in the UAE started in 1934. The maximum recorded average rainfall was 671.2 mm in 1995, measured at Khor Fakkan (Ministry of Agriculture and Fisheries, 1995). The mean daily pan evaporation is estimated as 9.75 mm (Rizk et al., 1995).

For the Abu Dhabi Emirate the maximum annual rainfall was 250 1982) and the minimum annual value was 2 mm (recorded in 2001), based on the records over the last two decades. For Al Ain area, the maximum annual rainfall was 162.5 mm (recorded in 1996) and the minimum annual value was 0.8 mm (recorded in 2001). values are based on the measurements between 1994 and 2001.

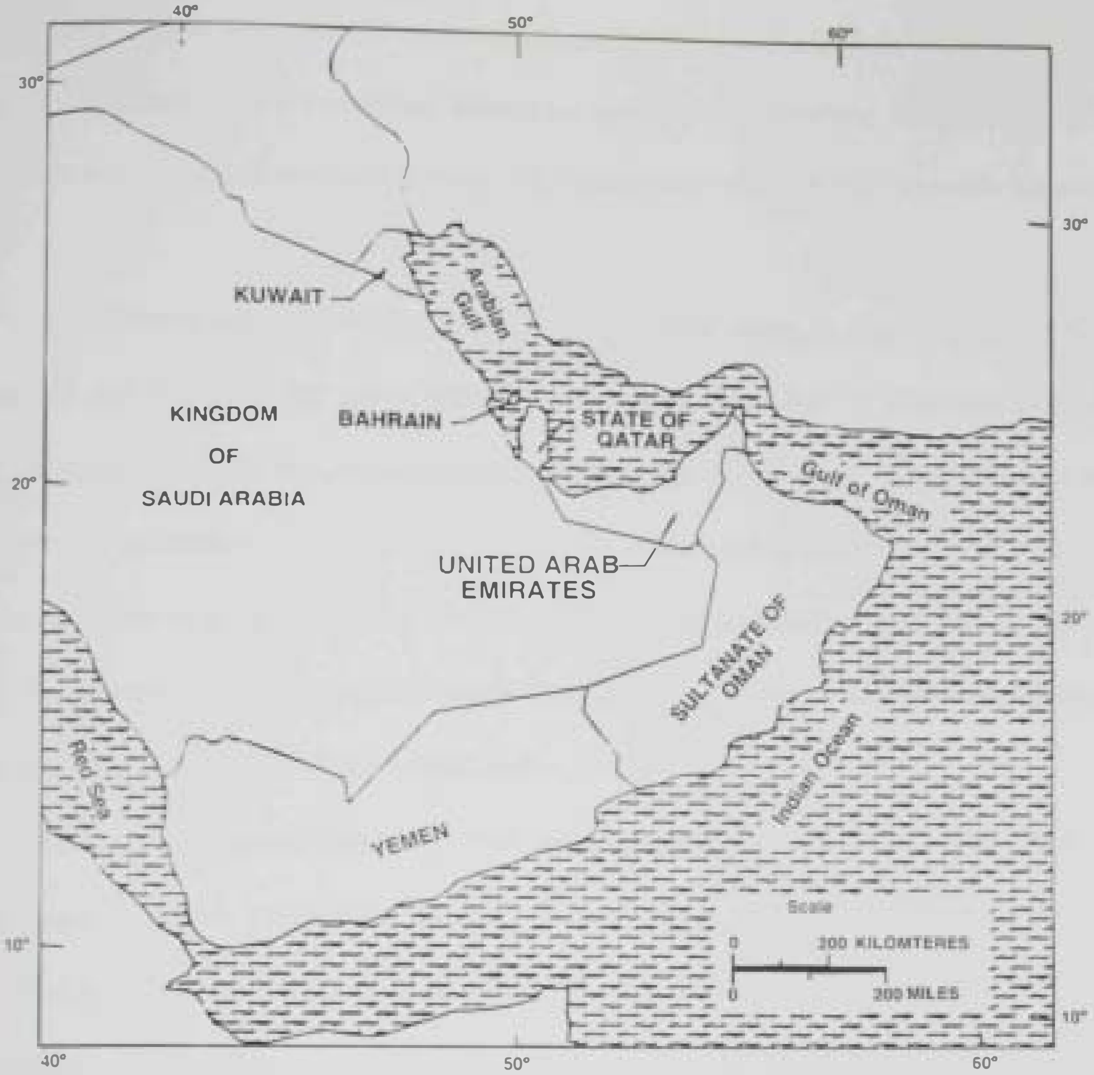


Figure 1.1. Location map for the United Arab Emirates.

Many dams have been constructed along the main wadis over the last two decades in the UAE to intercept the surface water and recharge the groundwater systems. These dams along with other recharge facilities are expected to conserve 60 Mm^3 of water (UAE University, 1985). The most recognized and active dams in the UAE include Ham (Al Fujairah), Al Beeh (Ras Al Khaimah), Gulfa (Ajman), Zukt (Al Fujyrah), Al-Tuween (Al Fujairah), Iden (Ras Al Khaimah), Al-Geel (Ras Al Khaimah) and Hadf (Ajman). In 1995 the volumes of water associated with these dams were 8.6, 6.65, 0.55, 8.5, 6.8, 1.5, 0.48 and 1.9 million m^3, respectively. A total of about 45 dams of different sizes have already constructed and another 27 dams are currently under construction (Ministry of Agriculture and Fishers, 2001). The authorities and concerned Ministries in UAE are devoting considerable efforts and resources to enhance the surface water harvesting and reduce the undesirable impacts of floods.

Groundwater constitutes the main natural source of water in the UAE. Its aquifer is unconfined and underlies the gravel plains which extend from Ras Al Khaimah to Al Ain. The tremendous increase in groundwater pumping in the different areas has caused a rapid decline in the subsurface water table throughout the hydrogeological system with some local depression cones ranging from 50 to 100 km in diameter at Al Dhaid, Hatta, Al Ain and Liwa areas. As a result, several shallow wells have been terminated and saltwater intrusion problems were encountered in the coastal areas.

The depths of groundwater below the ground surface vary from one area to the other. For example, in Liwa, Diba, Khor Fakkan, Kalba, Shaam and Khatt areas the groundwater table is located at a depth of 5 m or less. In Al Shwaib, Madinat Zayed and Al Madam areas, the depth to the groundwater table is in the order of 10-25 m. In Al Wagan, Al Hayer, Jabal Hafit, Al Faiyah, Al Jaww plain, Hatter and Massif areas, the groundwater table is located 20-25 m below the ground surface. In addition, depths of 50-100 m exist in Wadi Al Bih and Al Ain areas. In Al Dhaid, the groundwater is encountered at depths of more than 100 m.

The analysis of 200 groundwater samples collected from various fields (NDC, 1996) indicated the presence of local, intermediate and regional groundwater flow systems which affect salinity, quality and type of groundwater. Groundwater salinities of 230-1000 (mg/l) exist in Al Jaww plain, Masafi and Shwaib areas. Salinities of 1000-3500 (mg/l) are reported in Al Ain, Diba, Hatta, Khatt and Al Fujyrah areas, whereas salinities of 3500-6500 (mg/l) are recorded in Ras Al Khaimah, Madinat Zayed, Liwa and Dubai Areas. Groundwater with salinity greater than 10,000 (mg/l) exists in Dhaid, west and south of Al Ain and Kalba areas.

In the coastal areas the groundwater salinity may reach that of the seawater. Therefore, most of the available groundwater in the country is either brackish or saline.

The UAE is one of the leading countries in the development of the desalination water. Desalination plants are constructed to bridge the gap between freshwater demands and freshwater availability. Many large membrane systems and thermal desalination plants have been constructed. The UAE produces about 12% of the total fresh water production from all desalination plants in the world. The construction of the small scale desalination plants increased in Abu Dhabi Emirate due to the increase in oil exploration basis and the construction of new villages. Al Taweela, Jabal Ali and Umm-El Nar are among the large capacity (MSF) plants in the world (Aly, 1998).

The yearly water production from the desalination plants in the UAE is shown in Table 1.1. The production of desalinated seawater increased from 721.6 MG (3.276 Mm^3) in 1991 to 1027.93 MG (4.667 Mm^3) in 2001. The production of desalinated groundwater increased from 550.09 MG (2.497 Mm^3) in 1991 to 2184.2 MG (9.916 Mm^3) in 2001. For the same period, the total production from MED plants increased from 989 MG (4.49 Mm^3) in 1998 to 4156 MG (18.868 Mm^3) in 2001. As a result, the net production of desalinated water rose from 1271.69 MG (5.773 Mm^3) in 1991 to 7368.13 MG (33.451 Mm^3) in 2001.

Wastewater recycling is used in the UAE to supply water for irrigation of green areas along the highways, greenbelts, and city gardens. In addition, it can be used for cooling in many industries. In 1993, the annual production of wastewater in the UAE was 106 Mm^3 /y of which 62 Mm^3 /y were used for irrigation purposes of green areas along highways and green areas in the cities (Abdulrazzak, 1995). In 1995 and 1998 the annual production of wastewater reached 500 and 881 Mm^3, respectively. On the other hand, the annual treated wastewater reused for irrigation purposes and groundwater recharge reached 108 and 182.3 Mm^3, in the same years, respectively.

Table 1.1. Yearly desalinated water production in Million Gallons (Federal Electricity and Water Authority, 2002).

RO[1] Plant	1991	1992	1993	1994	95	96	97	98	99	2000	2001
Desalinated water produced from seawater in Million. Gallons.											
Qidfa1	186.35	109.74	223.59	262.80	211.50	198.00	258.00	277.00	288.40	188.50	146.92
Qidfa2	295.90	521.01	546.63	435.64	567.10	596.20	568.00	677.00	666.60	615.53	640.24
Al zawra	239.34	262.57	253.39	175.00	324.13	334.40	331.00	297.00	107.80	323.31	240.77
Total S/W Prod.	721.60	893.32	1023.61	873.44	1102.73	01128.6	.001157	.001251	01062.8	1127.34	1027.93
Desalinated water produced from groundwater in Million Gallons.											
Umm Al Qewain	384.25	379.76	477.96	944.89	623.62	622.60	810.92	759.00	827.20	825.12	813.46
Burairat	165.84	88.53	213.80	228.42	176.69	191.40	215.38	185.00	182.60	190.10	347.61
Ajman					631.89	589.60	578.60	334.00	437.80	849.49	1003.65
Seh Al Fehlain								2.20	11.00	16.36	11.19
Rafaq								4.40	2.20	3.65	2.51
Helew								2.42	2.20	5.71	5.79
Total G/W Prod.	550.09	468.29	691.76	1173.31	01432.2	01403.6	01604.9	1287.02	.001463	1890.43	2184.20
MED[2] Desalinated water											
Al Nakheel								989.00	1052.00	1753.00	2146.00
Ajman										554.00	1451.00
New Qidfa										295.00	559.00
Total MED Prod.								989.00	1052.00	2602	4156
Grand Totals	1271.69	1361.61	1715.37	2046.75	2534.93	2532.20	2761.90	3527.02	3577.80	5619.77	7368.13

[1] RO = Reverse Osmosis
[2] MED = Multiple Effect Desalination

1.4. Water Resources in Al Ain Region

Based on the records of rain gauges maintained by the Ministry of Agriculture at Masfut and Howaylat, the average annual rainfall on the catchment's area of Al Ain is estimated as 155 mm. The natural recharge based on 10% of average rainfall over the catchments areas (1,460 km^2) is 23 million m^3/y. In Al Ain region there are no watercourses, which discharge into the sea, even in heavy flood. A wadi dam will increase percolation into the aquifer upstream of the dam at the expense of reduced percolation downstream of the dam. However, there will be less evaporation loss.

Al Ain region has been subdivided into groundwater provinces to the north and south of an east west line roughly through Jabal Hafit. These provinces are referred to as the Al Ain catchments and the southern catchments respectively. Figure 1.2.

Groundwater flow lines throughout the region are aligned east west. Recharge to the northern area is from the Oman Mountains and groundwater flows through the freshwater zone which lies along the mountain front, and into the desert. Although the recharge to the southern area is also from the Oman Mountains, there are no water resources development up-gradients, and pumping of groundwater from this area will not affect the northern area even in the long-term.

Effluent from the domestic water supply will either percolate to the water table through septic tanks or sewerage system for treatment or reuse as irrigation water. It is estimated that about two thirds of the public domestic and trade supply represents a gain through effluent returns. For planning purposes, assuming some degree of control on private garden watering in the future, effluent returns are assumed to be 70% of the public domestic and trade supply.

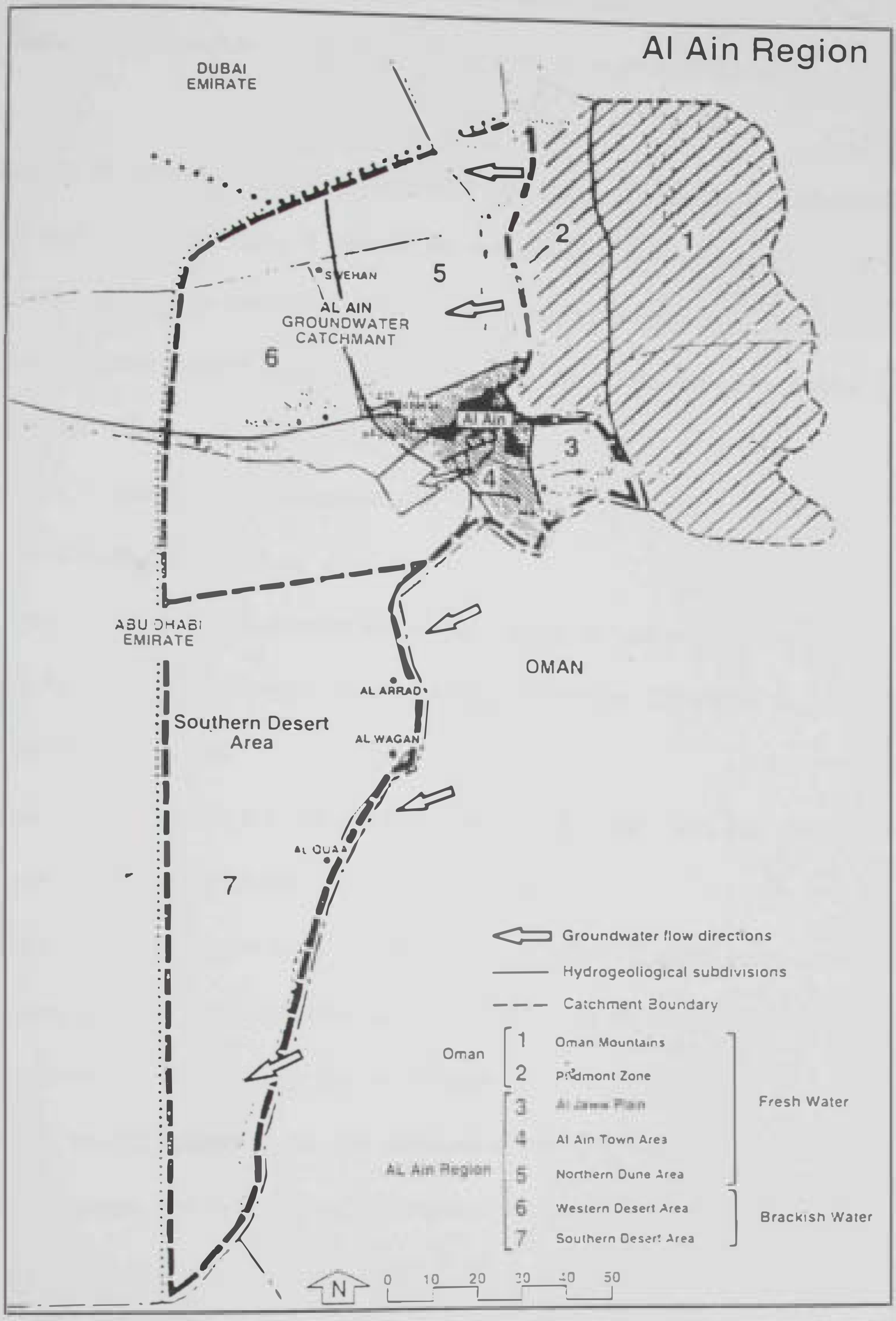


Figure 1.2. Subdivision of Al Ain area (NDC and USGS, 1993).

1.5. Objectives

The ultimate objective of the study is to assess availability and sustainability of groundwater resources in some selected areas of Al Ain. These areas have been selected based on the pumping activities and availability of data. The specific objectives of the study are given as follows:

1. Review of previous studies and relevant geological, hydrological, hydrogeological and meteorological data. It should be noted that some of these data are time independent such as geological features and some hydrogeological parameters while others are time dependent such as subsurface water levels and groundwater quality. Emphasis will be devoted to the hydrogeological system in Al Ain area.
2. Provide a quantitative assessment for the main hydrogeological features in the selected study area.
3. Assess the groundwater conditions in the study area and present the equipotential lines for the hydrogeological system during the period 1991-2001 to evaluate the groundwater depletion.
4. Assess the changes in the groundwater quality in the study area and present the iso-concentration lines to identify the most affected areas.
5. Predict the equipotential lines in the study area after 10 years assuming the same pumping activities. A numerical model SUTRA will be employed to simulate the groundwater conditions in the horizontal view.
6. Provide recommendations for the sustainable use of groundwater resources in the UAE in general and Al Ain Area in particular.

1.6. Contrast between previous studies and the current research

Several studies have been conducted in the UAE and Abu Dhabi Emirate during the last three decades to assess the available water resources. These studies include among others IWAQO and Bin Ham Well Drilling Establishment (1985a, 1985b, and 1985c, 1986a, 1986b, 1986c, 1986d and 1986e). The drilling activities and geophysical studies near Al Ain and in the sand dune area south and west of Al Ain were included in these reports. Gibb and Partners (1969, 1970a, and 1970b) discussed the lenses of fresh water trending east-west through Al Ain area and considered the ancient wadis as channels for groundwater movement. Hydroconsult (1978) were the first to suggest that Jabal Hafit was a source of considerable recharge to the groundwater of the sand dune area north and west of Al Ain. Kimrey et al. (1987) provided additional information in their assessment of groundwater in Abu Dhabi Emirate.

German Water Engineering GmbH studied the water-wells fields at Umm Ghafa and Shabak. The Regional Development Committee of Oman (1986) made pertinent surface-and groundwater studies of ten basins with water flowing west into Abu Dhabi Emirate from the Oman Mountains. Saines and Ansari (1985) reported on water-well drilling program that includes information on groundwater parameters in the Zarub Gap area near Bureimi, Oman. Brandt (1985) studied Al Ain water resources as a component of a master development plan for the Planning Department of Al Ain. The Abu Dhabi Planning Department (1989) compiled existing data on water production, consumption and future requirements in order to make recommendations concerning future water development in the vicinity of Al Ain. Data kept by the National Drilling Company under its Groundwater Research Project (GWRP) in Abu Dhabi Emirate and Al Ain are reliable and include information on each drilled well, subsurface water-level fluctuations, geologic and lithologic data from test holes, hydraulic data collected during aquifer tests, water level data, water chemistry data and locations of geophysical surveys, water quality, and satellite-images.

Halcrow and Partners (1969a, 1969b, 1969c, and 1969d) investigated the available water resources in the northern Emirates. Most of the previous investigations were more general than specific.

This study provides an overview of the groundwater resources in some selected areas in the vicinity of Al Ain. Data have been integrated from various sources including, among others, National Drilling Company (N.D.C), Al Ain Distribution Company, Municipality and Town Planning Departments, Department of Agriculture and Animal Resources, Ministry of Communications, Al Ain Airport and Electricity and Water Authority. Based on their importance as aquifers and the availability of data, the selected areas included Al Hayer, Gummed, Nahil and Al Khadar. Detailed analysis has been conducted to assess the groundwater depletion, sustainability and quality in these areas. In addition, a two dimensional finite element model, SUTRA, has been employed to predict the subsurface water after 10 years assuming the same pumping activities. In brief, the current study presents a comprehensive analysis for the groundwater conditions in the selected areas.

1.7. Limitations of the study

This investigation represents an attempt to provide a precise picture for the groundwater conditions and flow quality patterns in the selected aquifers. Relevant information and data were gathered from various sources and every possible effort was made to compile the data. Nevertheless, it was not possible to bridge the gap of missing information in some cases. The following points elaborate the limitations of the study.

- Water level and water quality data are not available for most of the observation wells prior to the year 1991. Therefore, such a year (1991) was considered as a reference time datum (initial conditions) for comparison purposes.

- The static water levels for many wells in certain years were completely missing. On the other hand, some wells were dried and others were sealed due to the increase of the chromium element.
- Most of the geometric and hydrogeological parameters including the hydraulic conductivity, porosity, transmissivity, and dispersivity, are missing. Only few are available.
- The salinity of the groundwater either at the production or observation wells is not measured on a periodic or systematic manner but rather at a random basis.
- The pumping records for many wells are missing in the farming areas. Information on the pumping rates is not precise in many cases. Therefore, estimates for pumping rates were made to whenever necessary.

Chapter 2. Geological and Hydrogeological Aspects

2.1. Stratigraphy and Structures

The units which contain groundwater in U.A.E include a rock sequence ranging in age from the Permian to Quaternary periods, Figures 2.1 and 2.2. This sequence is ordered from oldest to youngest strata as follows:

a) *Paleozoic*: It deals with the Permian rocks with Khuff formation.

b) *Mesozoic*: The age of rock sequence can be divided into Triassic (Lower, Middle and Upper), Jurassic (Lower, Middle and Upper) and Cretaceous (Lower, Middle and Upper). The Triassic includes the Triassic and Permian rocks and the Jurassic contains Hith anhydrite and Arab formation. The Cretaceous age of rock sequence includes Limestone marl and sandstone, Semail igneous complex, Hawasina complex, and Musandam limestone.

c) *Tertiary-Cenozoic*: This age sequence can be divided into Paleocene, Eocene, Oligocene and Miocene. Marl and limestone are the common rocks in this sequence.

d) *Quaternary-Pliocene*: The common rocks in this sequence are Eolian sand, Unconsolidated surficial deposits of gravel, Gypsum deposits, and Sabkha deposits.

The UAE can be divided into five structural provinces, (Rizk et al., 1997):

1. Rus Al Jibal: Rus Al Jibal area has thrust faults sloping in the east and south directions.
2. Diba Zone: It is a topographically low area and extends for 30 km from northeast to southwest, with an average width of 20 km. The Diba zone separates between Musandum calcareous sequence in the north and the ophiolite sequence in the south. The stratified rocks of tectonic boundaries exist in this zone.
3. Ophiolite Sequence: The Wadi Ham fault (north west–southeast) and Wadi Thawban fault (east-west) represent the northern part of this sequence. There is a clear change in rock type on both sides of the valley.

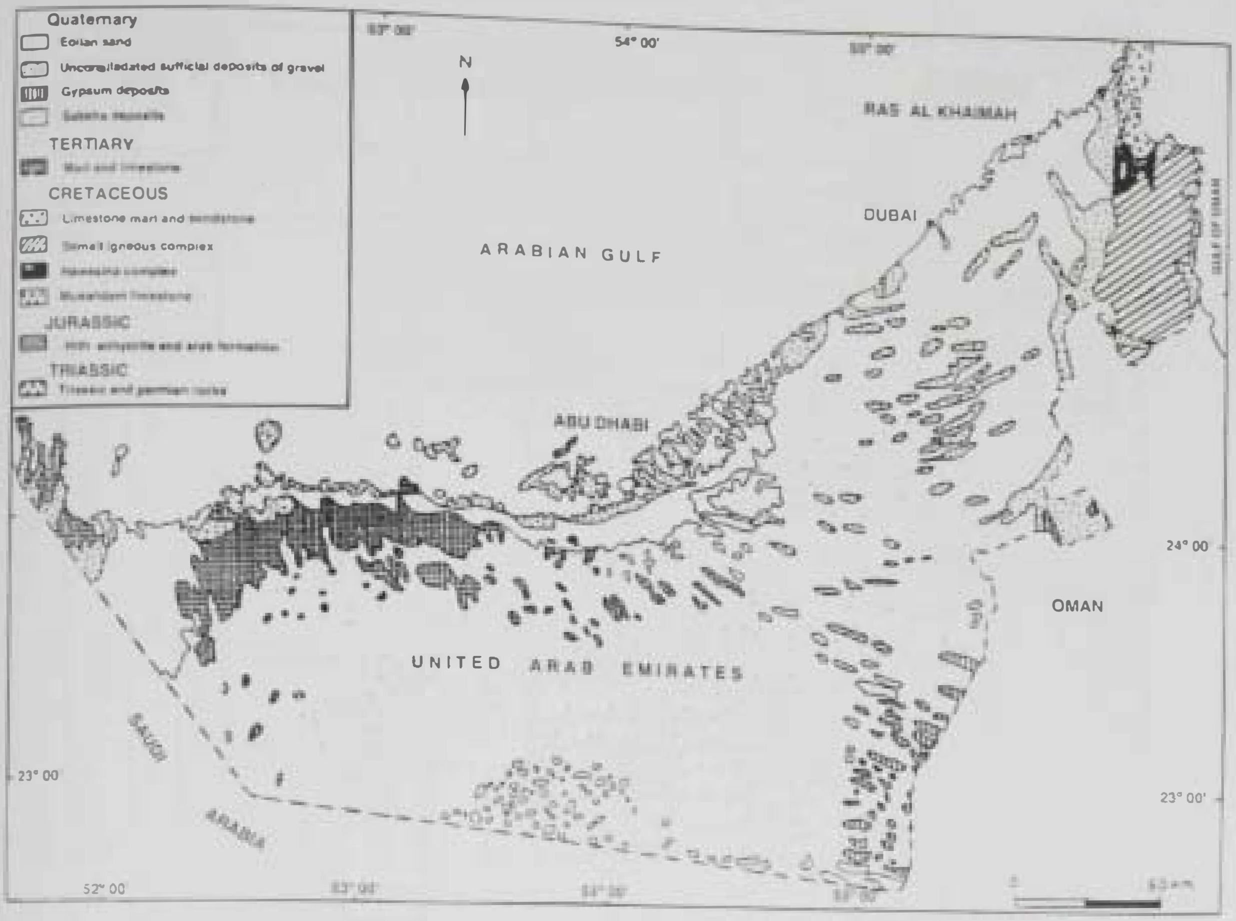


Figure 2.1 Geological map of U.A.E (simplified from the geological map of U.A.E. by Kansas Geological Survey, 1990).

4. Hatta Zone: The folding and rock stratification in this zone are parallel to the longitudinal direction of the tectonic opening in the west-northwest direction.
5. Western region: The past late Maestrichtian calcareous deposits and associates rocks were subjected to folding along the western slopes along the northern Oman Mountains. The upper cretaceous–lower tertiary boulder beds and calcareous rocks represent the boundary between the north Oman Mountains in the south and Schisa sands in the north.

The Geomorphological map of the U.A.E. is given in Figure 2.3 indicating the mountains areas, gravel plain, different types of dunes and coastal sabkhas.

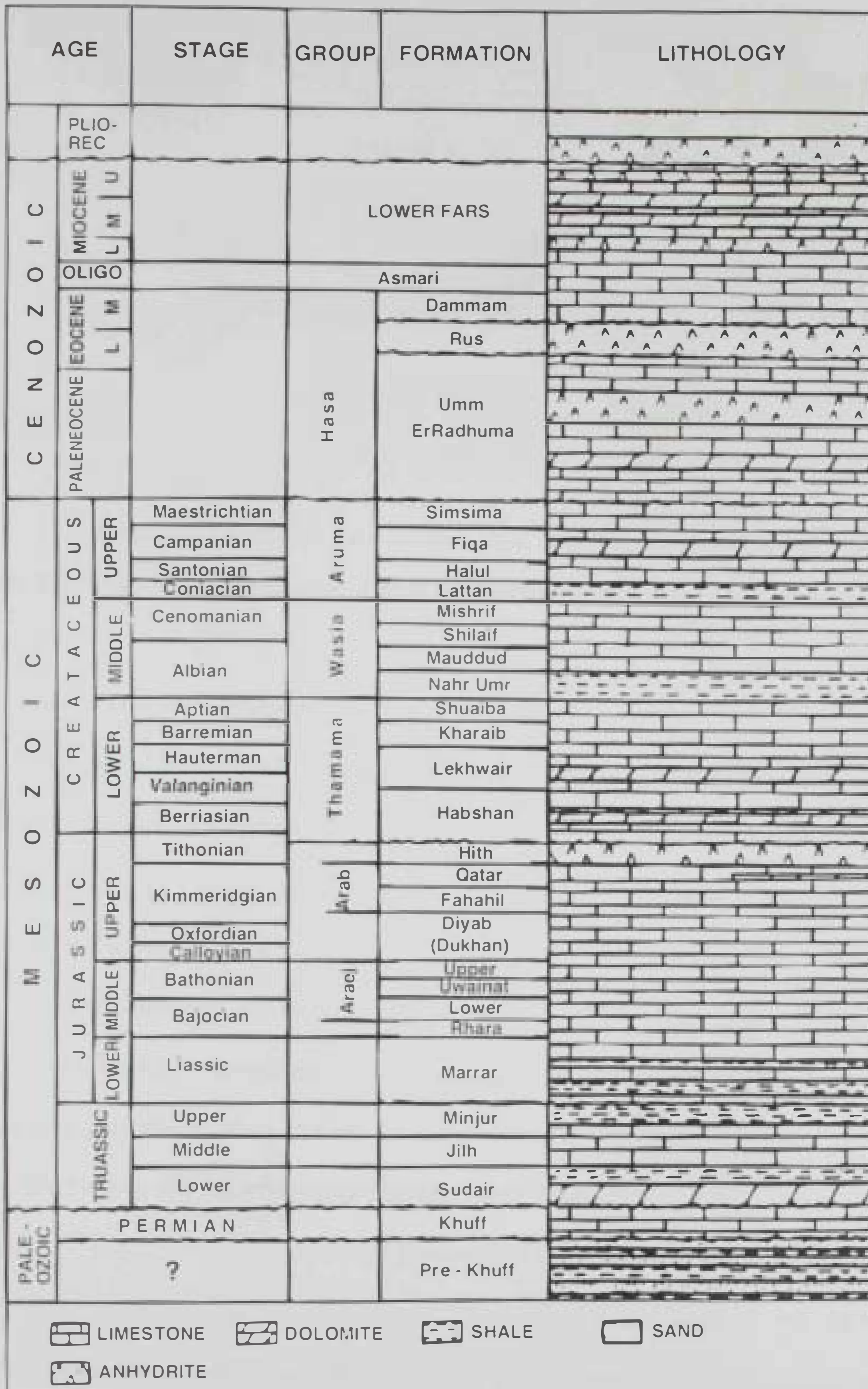


Figure 2.2. Generalized stratigraphic column for Abu Dhabi area, Al-Sharhan (1989).

Figure 2.3. Geomorphological map of U.A.E. (simplified from the U.A.E. National Atlas, 1993).

2.2. Groundwater Flow Systems

Three types (local, intermediate, and regional) of groundwater flow systems exist in U.A.E, Figure 2.4. The local groundwater flow system is limited to the eastern mountains where the hydrologic cycle is relatively fast. The groundwater in this system has a good quality as the total dissolved solids are in the range 500-1500 mg/l and HCO_3^- water type. This groundwater has a short residence time and contains Mg^{+2} ions. Such systems exist in Massafi, Al Jaww plain, Khatt (Ras Al Khaimah) and Maddab (Al Fujairah) springs. The second system is the intermediate groundwater flow system. In this system, the groundwater is mainly brackish (1500-10000 mg/l), and has a moderate residence time. It belongs to the SO_4^{-2} water type and contains Ca^{+2} ions. The occurrence of this groundwater is in Al Ain Al Faydah (Al Ain). The last one is the regional groundwater flow system. The groundwater of this system is discharged into the coastal areas. Its salinity is greater than 10000 mg/l. It has a long residence time and belongs to the Cl^{-1} water type. Sodium ion (Na^+) is the dominant cation in this system (Rizk et al., 1997).

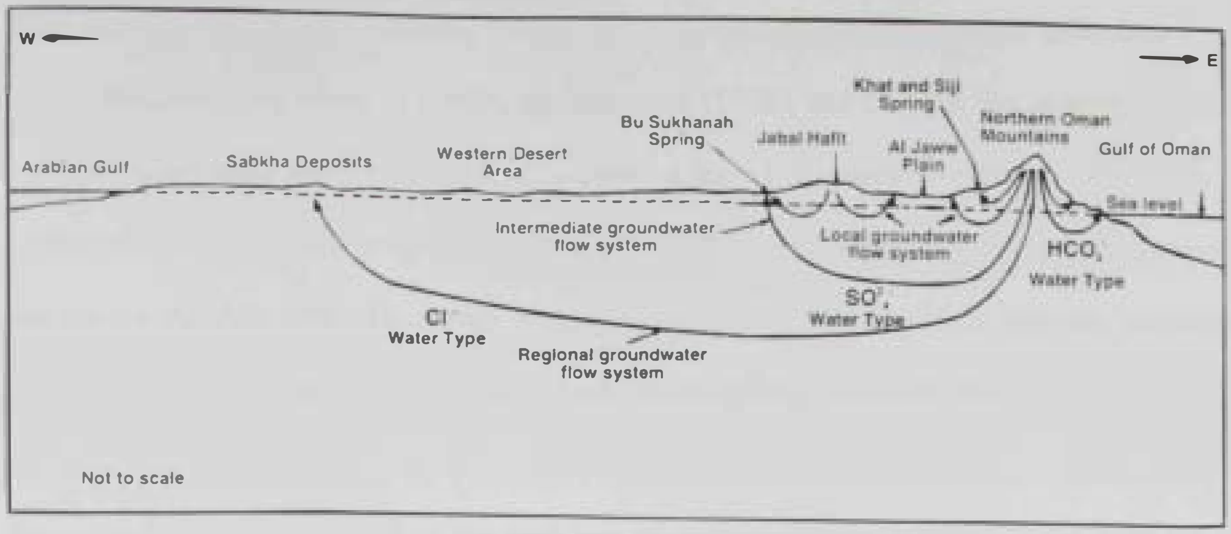


Figure 2.4. Different groundwater flow systems in U.A.E. (NDC and USGS, 1993).

2.3. Classification of Aquifers

There are several aquifers in the U.A.E. each of which has its own characteristics and water potentiality. These aquifers can be classified as given hereafter.

a- The Limestone Aquifers

These aquifers are found in the north and east, and are composed of limestones and dolomites. The rocks of these aquifers are well stratified, hard, dens and non-porous at the surface in Wadi Al Bih. The tectonic structure in the limestone can be described as antiforms of regional dimension. The Jabal Hafit area south of Al Ain city is an example of this aquifer.

b- Ophiolite Aquifer

The Ophiolite sequence in the east is jointed and subjected to faulting. Groundwater in this area occurs only in joints and fractures, (Entec, 1995).

c- Gravel Aquifers

A large quantity of fresh groundwater in U.A.E occurs in the alluvial deposits of the piedmont plains bounding the eastern mountains from the east and west. These aquifers can be distinguished into the eastern gravel aquifer, the north western gravel aquifer and the western gravel aquifer. Recharge of the gravel aquifer in Al Ain area comes from rain that falls on the western flank of the Oman and run through wadis where it infiltrates into subsurface. Gibb and Partners (1969), Hydroconsult (1978), and German Engineering (1982), outlined water-table maps for the gravel aquifer in the Al Ain Area. Woodward and Menges (1991) used oil exploration uphole seismic data to develop a water-table map for the gravel aquifer in Al Ain area. This map suggests that buried paleodrainage network contains saturated alluvial fill and may form large fresh water aquifers in Al Ain area.

d- Sand Dune Aquifer

Sand dunes cover about 74% of the total area of U.A.E. The elevations of these sand dunes change from sea level at the western coast to 250 m above ground level at the Liwa-Al Batin basin in the south central part.

Previous studies indicated a fresh water aquifer in the Quaternary sand dunes between Liwa and Madinat Zayed. Preliminary investigations showed the presence of similar fresh water in the sand dunes of the Bu Hasa oil field. Rizk et al. (1997) indicated a possibility of the occurrence of fresh water lenses in the sand dunes between Al- Wagan and Liwa.

2.4. Rainfall and Groundwater Recharge

The rainfall in the U.A.E depends on climatic conditions, geographic location and local topography. Records show that most of the rainfall is encountered in the winter months of December, January, February and March. March has the highest records. This rain is of light to moderate intensity, widespread and related to the frontal mechanism.

Isolated rain occurs in summer due to the convection mechanism associated with the monsoon currents. These storms are generally heavy, isolated and confined to the eastern mountains. The areas of these eastern mountains represent about 5% of the total area of U.A.E and they receive about 30% of the total annual rainfall. Also, 90% of the total annual rainfall occurs during February and March.

Based on the available records, the mean annual rainfall in U.A.E varied between a minimum of 10 mm in 1946 and a maximum of 340 mm in 1957. In general, the rainfall increases in the north and east and decreases in the south and west, Figure 2.5.

A 10 year cycle for the rainfall pattern is observed in the mean annual rainfall for the 1934 – 1996 periods, Figure 2.6. Similar cycles were recorded by Rizk et al. (1997) for Al Ain area. These cycles produce enough rain that can recharge the groundwater.

The data for the total monthly rainfall (mm) of Dubai, Sharjah, Ras Al-Khaimah and Fujairah were obtained from the Ministry of Communications (Meteorological Department), Tables A1, A2, A3 and A4 (Appendix A). The accumulative rainfall (mm) in the U.A.E for the years 1996 through 2001 is shown in Table 2.1. The maximum recorded rainfall in 1996 was (291.6 mm) in Fujairah while the minimum recorded rainfall was (103.2 mm) in Abu Dhabi during the same year. In 1997, the maximum accumulative rainfall was 318.9 mm and was recorded in Sharjah. In Ras Al Khaimah, the maximum value was 225.8 mm and was recorded in 1998. The similar values for other years were recorded as 73.9 mm in Sharjah in 1999, 31.4 mm in Fujairah in 2000 and 21.1 mm in Fujairah in 2001. In addition, the minimum accumulative rainfall was recorded as 115.2 mm in Abu Dhabi in 1997. For the other years, the minimum values were recorded as 79 mm in Al Ain in 1998, 13.2 mm in Abu Dhabi in 1999, 4.7 mm in Abu Dhabi in 2000 and 0.8 mm in Al Ain in 2001. The rainfall contributes to the groundwater flow system in three ways:

- Rainfall on rocks of the mountain uplands. The subsurface water is then transported to the westward through fractured rock strata.
- Overland runoff into intermontane alluvial valley sediment and subsequent shallow subsurface that transports water westward through gaps.
- Surface water that discharges through the intermountain gaps as stream flow during periods of intense rainfall in the mountains.

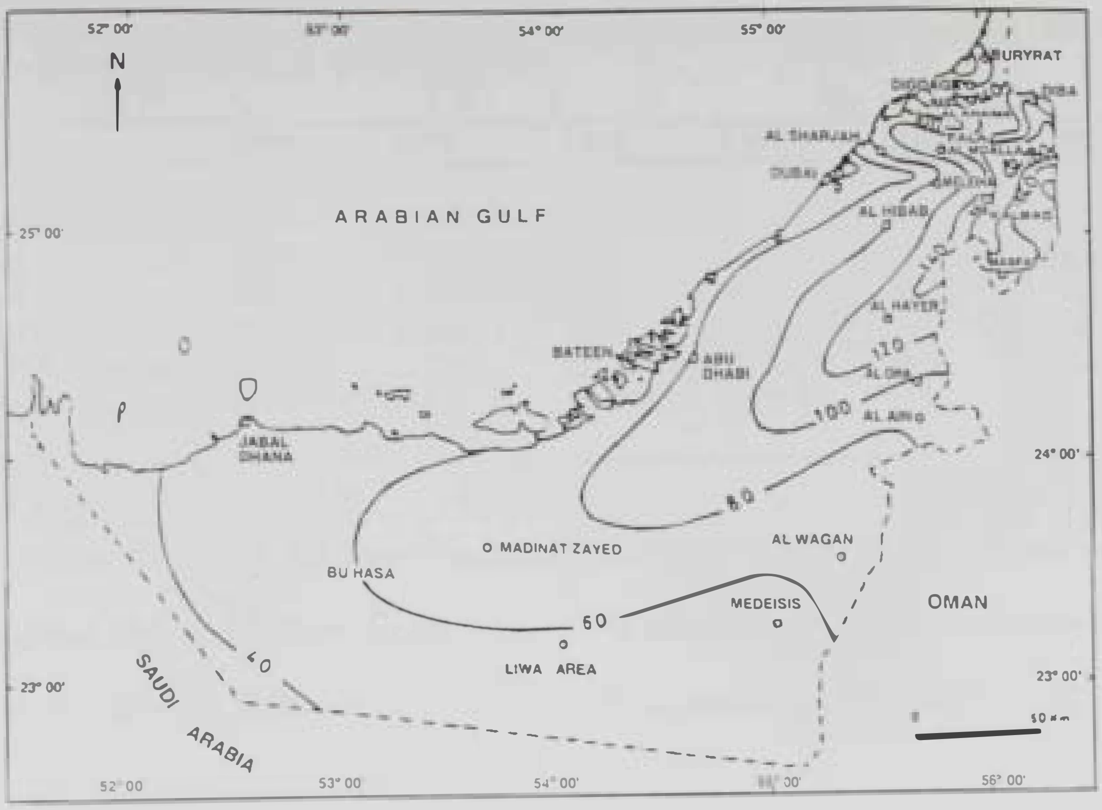


Figure 2.5 Average rainfall intensity for the period 1976-1996 (Rizk et al.. 1997).

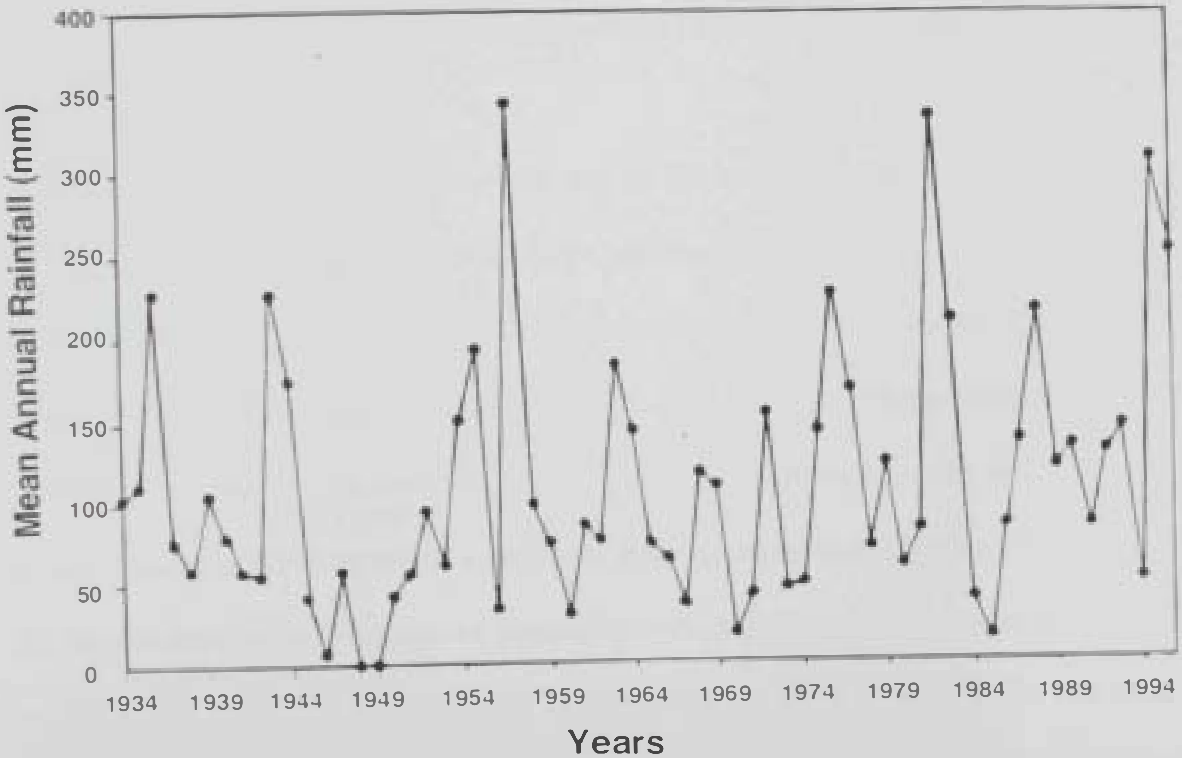


Figure 2.6. Mean annual rainfall (mm) for the period 1934-1996 (Rizk et al., 1997).

Table 2.1. Accumulative rainfall (mm) in the different Emirates for the period 1996-2001 (Ministry of Communication, U.A.E., 2002).

Area	1996	1997	1998	1999	2000	2001
Abu Dhabi	103.2	115.2	119.7	13.2	4.7	2
Al Ain	162.5	134.9	79	23	31.3	0.8
Dubai	228.6	271.7	110	44.5	24.2	8.8
Sharjah	231.9	318.9	180.3	73.9	15	9
Ras Al Khaimah	290.2	315.9	225.8	68.4	30.9	16
Fujairah	291.6	252.1	87.3	42.2	31.4	21.1

Water flows from the Oman Mountains towards the Arabian Gulf in the northeast of the regional groundwater flow system. Most of the groundwater flow in eastern Abu Dhabi Emirate occurs in the shallow strata, alluvium in Al Ain aquifer (N.D.C and USGS, 1993).

2.5. Al Ain Aquifer

Al Ain Aquifer is relatively thin. It has a surficial water-table unit. The permeability of the aquifer is small to moderate and it overlies a thick basal unit of very small permeability.

2.5.1. Extent and thickness

The bottom of Al Ain aquifer is not defined on the basis of geologic formation boundaries, but is determined by Petrophysical-Log analysis and is defined as the base of the permeable shallow sediment (Jorgensen, 1990). Petrophysical Log analysis indicates that the aquifer is composed of interbedded rock and sediment with hydraulic characteristics ranging from permeable to nearly impermeable. The near surface permeable rocks in the eastern Abu Dhabi Emirate (excluding eolian sand dune) have thickness ranging from 27 to 151 m, Table B1 (Appendix B). The thickness of permeable rock in Al Jaww plain ranges from about 45 m near the northeastern of Al Jaww plain to about 130 m near the west flank of Jabel Hafit and 100 m in the southeast, Figure 2.7. The thickness of permeable rocks generally decreases to 50 m in the westward of the eastern Abu Dhabi Emirate.

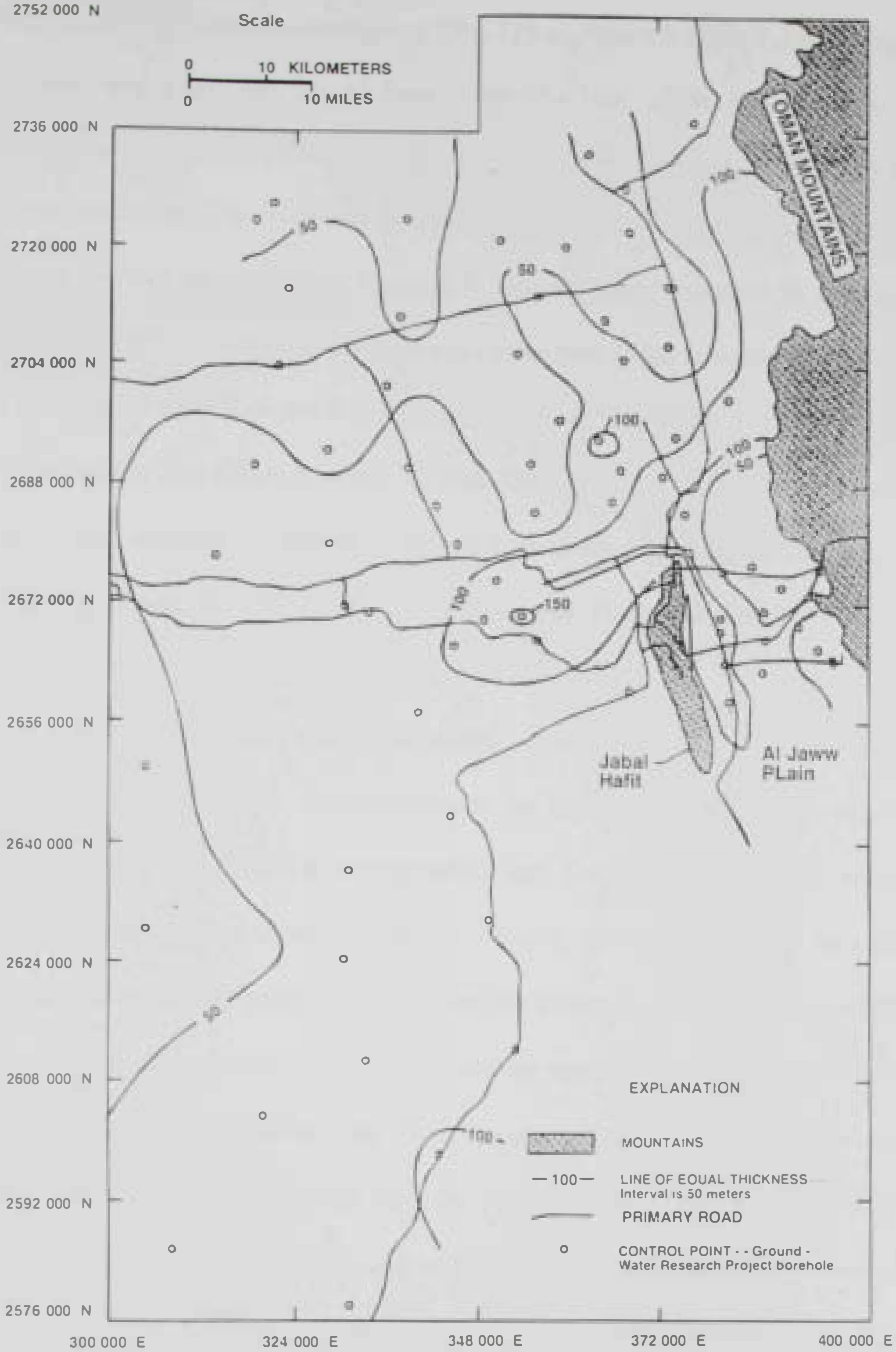


Figure 2.7. Thickness of near surface permeable sediments, excluding Eolian dune sand (NDC and USGS 1993).

Al Ain aquifer has thickness of about 17 to 127 m, Figure 2.8 and Table B2 (Appendix B). In western and south western Al Jaww plain, the base of the aquifer approximately coincides with the base of the Pliocene rocks and the aquifer thickness is 100 m greater than the alluvium thickness. The thickness of the aquifer is more than 75 m along the Oman Mountains in the northern dune area, Figure 2.8. This thickness decreases to less than 50 m about 20 km west of the mountain. In the north central part of the area, the aquifer thickness is varied between 30 and 50 m and it is slightly more than 50 m in the extreme northwestern corner of the eastern Abu Dhabi Emirate. At Jabal Hafit, the aquifer thickness is about 75 to 100 m thick at the northern and western edges of it. In addition, the aquifer thickness is large along a 30 km linear trend north-northwest of Jabal Hafit area, which indicates the occurrence of major subsurface structural blocks in the aquifer.

2.5.2. Hydraulic characteristics and well yields at Al Ain

The assessment of the hydraulic characteristics of the matrix material and its water content can be carried out by the analysis of petrophysical logs. The petrophysical logs were used to determine the lithology, correlate formations, identify permeable zones, estimate total dissolved-solids and quantify geohydrologic properties (Jorgensen and Petricola, 1993).

The hydraulic properties of the aquifer such as transmissivity, aquifer thickness, and hydraulic conductivity were estimated by using the petrophysical logs, Table B2 (Appendix B). The transmissivity of the aquifer and the storage coefficient can be calculated by measuring water levels in the pumping well and the observation well(s) and determining the pumping rate under steady state conditions. The preliminary well evaluation and estimation of the aquifer properties were made using short term tests or yield tests, Table B3 (Appendix B). The long term aquifer tests were made by drilling observation wells with small diameter boreholes. The yield tests for some wells help to estimate well efficiencies from step draw down tests. The aquifer hydraulic data were obtained as given in Table B4 (Appendix B).

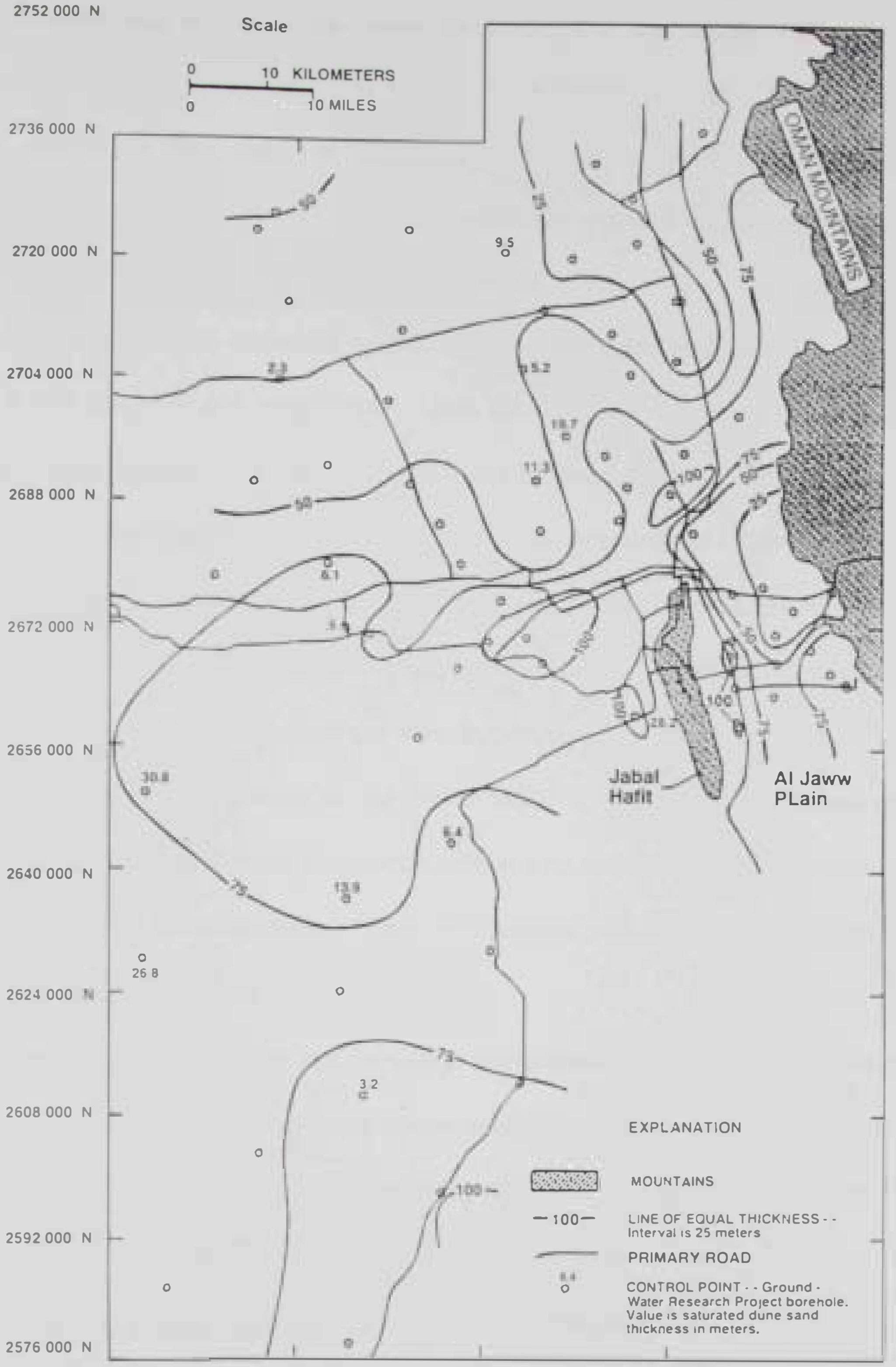


Figure 2.8. Thickness of Al Ain aquifer (NDC and USGS, 1993).

Significant differences between the hydraulic conductivity determined from analysis of petrophysical logs and yield tests were observed (NDC and USGS, 1993). In addition, many assumptions and approximations exist in the petrophysical logs. Yield tests give more accurate estimation than logs. The two methods are not always comparable because the screened section of the well may include permeable material in the confining unit. In addition, all the permeable zones may not be screened.

The values of the hydraulic conductivity are relatively high at wells GWP-17 and GWP-18, 100 and 184 m/d respectively, Table B4. The corresponding values in Al Jaww plain are relatively small. For Example, the hydraulic conductivity for well GWP-15 is 0.7 m/d, Table B4. This significant difference refers to the existence of a thick section of clean gravel that transmits water to wells GWP-17 and GWP-18; whereas this gravel section is thin in the well GWP-15. The later well is overlaid by layers of clay and marl (NDC, 1992 a).

Specific yields can be determined from two-well aquifer tests. The specific capacity is another parameter which relates to the well's yield. It is defined as the ratio between drawdown and pumping rate and it is greatly affected by well efficiency. The well efficiency is defined as the ratio between the drawdown in a pumped well and the total drawdown.

2.5.3. Basal confining system

The basal confining system with less permeable rocks exists beneath the Al Ain aquifer. The altitude of the top of the basal confining system is about 250 m near the Oman Mountains and about 50 m near the western edge in the northern dune area, Figure 2.9. In Al Jaww plain, this altitude ranges from 360 m at Zarub Gap to 150 m near Jabal Hafit. The basal confining system consists of slightly permeable mudstone, clay stone, evaporite, and limestone units of the Fars formations in the Al Jaww plain and the western part of the study area. There are large formations of the basal confining system in the north and north east of Al Ain. There are difficulties to define the base of the confining system due to the following:

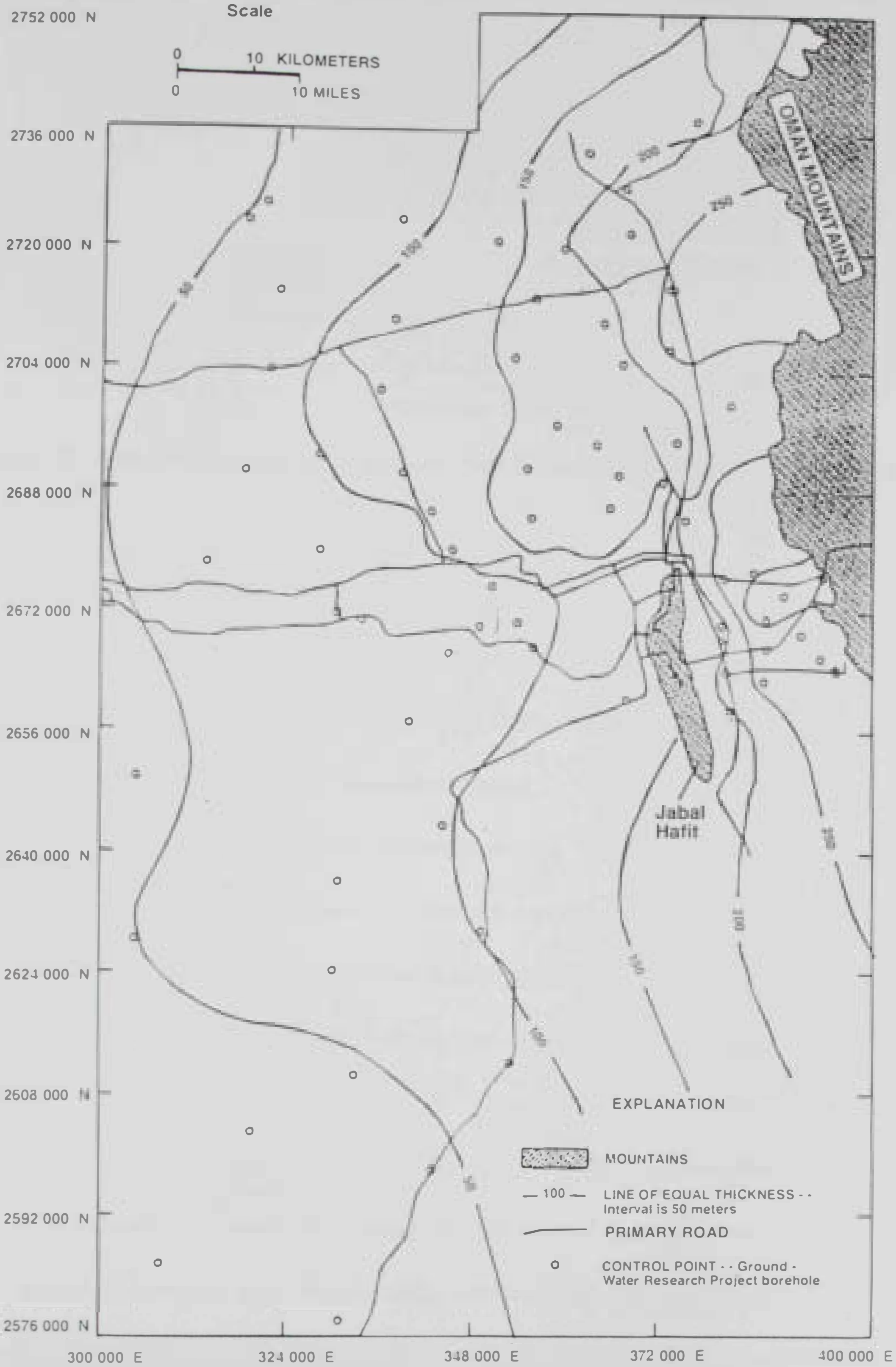


Figure 2.9. Altitude of top basal confining system (NDC and USGS, 1993).

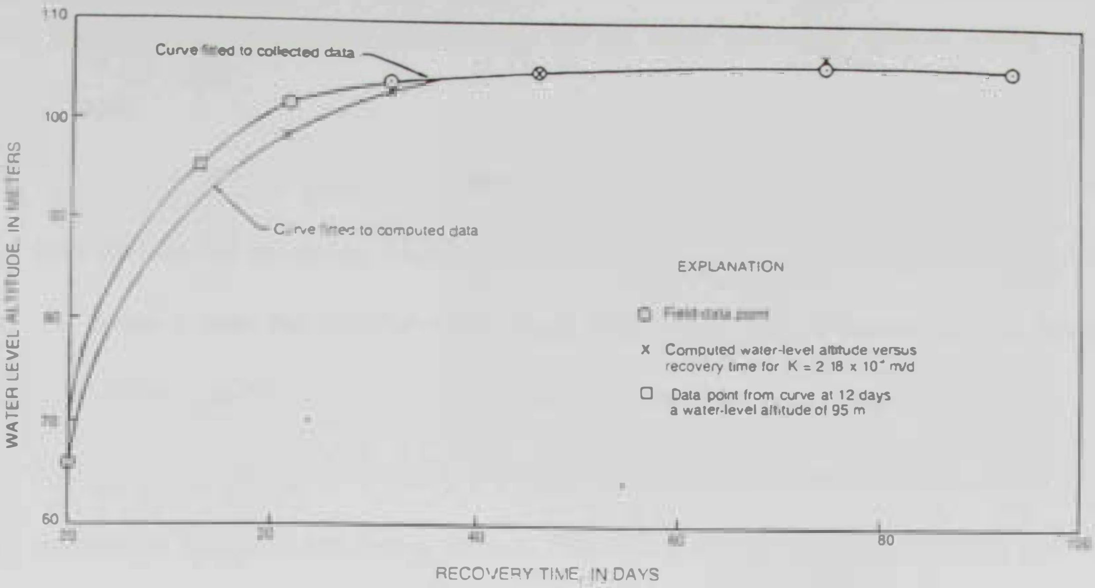


Figure 2.10. Analysis of water-level recovery data for well GWP-49 (NDC and USGS 1993).

- Limited data on the hydrogeologic properties.
- Lack of data to recognize the impermeable boundary.

The basal confining system includes all geologic strata below the base of Al Ain aquifer.

2.5.4. Hydraulic characteristic of the basal system

The composition of the permeable materials in the basal confining system affects the hydraulic characteristic of the aquifer. A recovery test for well GWP-49 near Al Aushush is the only known hydraulic data for the basal confining system, Figure 2.10.

The hydraulic properties of the upper part of the confining system were estimated by using the Hooghoudt method (Luthin, 1957). This method was used because there were no permeable sections to be analyzed by the log-analysis model. The weighted–average value of K is used to calculate the water level values. The weighted average is computed by $K = \sum t_i k_i / \sum t_i$, for i = 1, 4 where k_i is the hydraulic conductivity computed at time, t_i. There were deviations from field data by plotting the values of water level versus the recovery time, Figure 2.10. These deviations occurred in the earlier part of the recovery (21 and 31 days).

Finally, the estimated hydraulic conductivity of the basal confining system tested is about 2.18×10^{-4} m/d.

The potentiometric head in the basal confining system near well GWP- 49 is slightly higher than that in the overlying Al Ain aquifer. The water from the basal confining system can move upward into the aquifer with small flux under the difference in the hydraulic gradient. The basal confining system yields small quantities of water with poor quality.

The boundary between brackish water and saline water exists above the bottom of the deep boreholes in the basal confining system, Figure 2.11. The brackish water has a thickness of about 200 m near Zarub Gap. This thickness becomes slightly more than 500 m along the east side of Jabal Hafit while it ranges between 100 to 200 m in the northern dune area. The areas in the northeast and south have larger thickness.

2.6. Occurrence and Movement of Groundwater

A predevelopment map of water levels is required for the assessment of the long term water-level changes in Al Ain aquifer. No historical water-level data exist before mid sixties. The data published by Gibb and Partners (1969), Halcrow and Partners (1969) and Hydroconsult (1978) were used to construct the predevelopment water level map. The map was based on few records of water levels and is thus may not be accurate.

The levels of the predevelopment water table in Al Ain aquifer ranged from 350 m above mean sea level near the Oman Mountains to 60 m at the northwest limit of the eastern investigated area. A large mound of groundwater exists near Jabal Hafit. This conclusion was based on water- levels from seismic uphole-survey data collected between 1981 and 1982 (Woodward and Menges, 1991a). The steeper hydraulic gradient was established due to the difference in altitude of about 80 m between Al Jaww plain east of Jabal Hafit and gravel plains west of Jabal Hafit. The groundwater mound indicates the following:

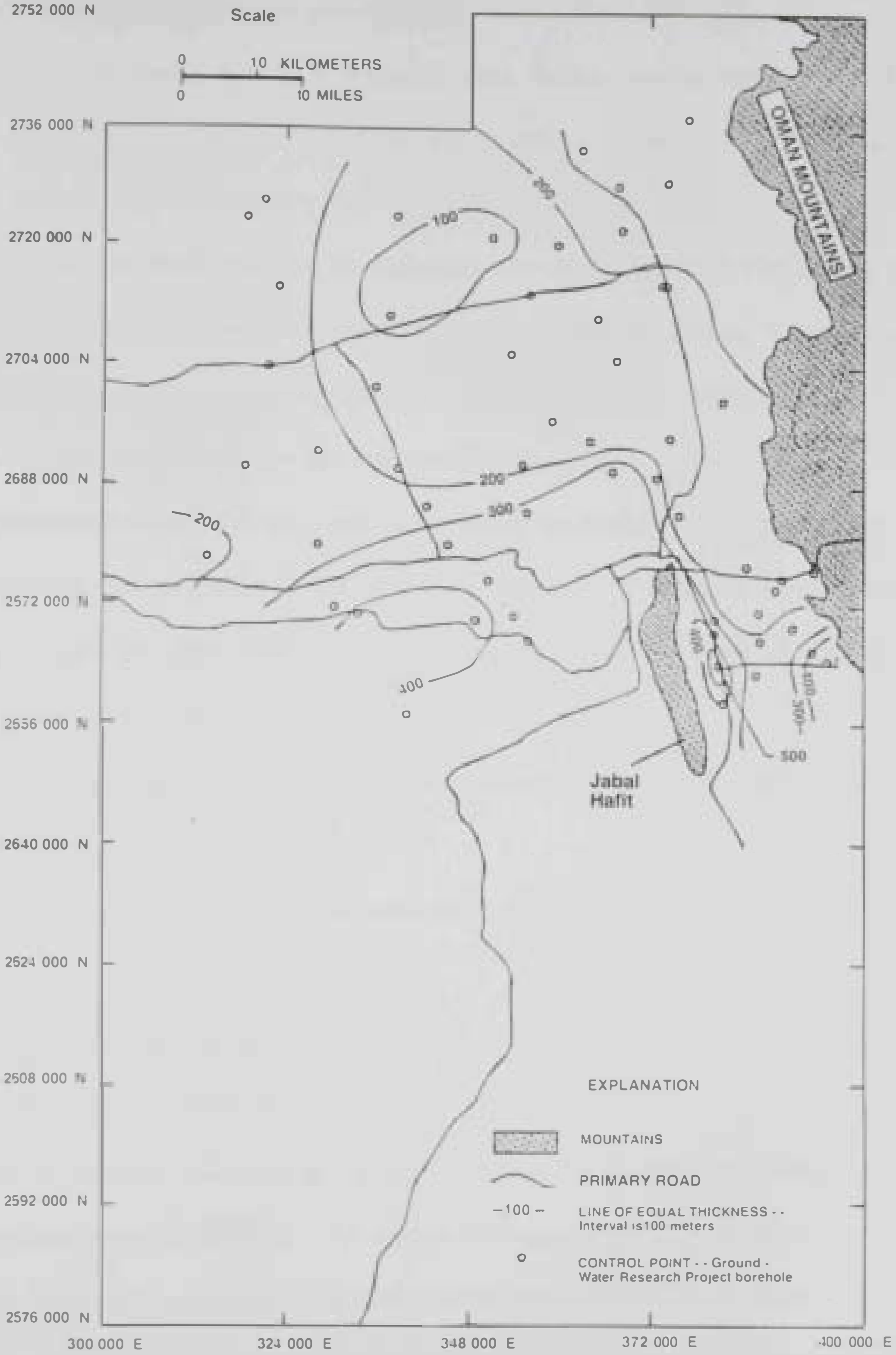


Figure 2.11. Thickness of the brackish water in the basal confining system (NDC and USGS, 1993).

- Infiltration of the rainfall through the permeable units of Jabal Hafit.
- Upward movement of groundwater through fractures of the Jabal Hafit.

In the current study, data were collected from various sources including Al Ain Groundwater Department (GWD), Al Ain Water and Electricity Department (WED), Forestry Department (FD), Al Ain Municipality, and Al Ain Town Planning Department. Data were also obtained from Abu Dhabi National Oil Company, Abu Dhabi Company for Onshore Oil Operations, Geophysical Company limited, Robertson Research Group, Schlumberger Middle East, air port meteorological stations at Abu Dhabi, Dubai, Sharjah and Ras Al Khaimah, and Ministry of Agriculture and Fisheries (MAF).

A groundwater research project was conducted by the National Drilling Company of Abu Dhabi (NDC) and the United States Geological Survey (USGS) in the eastern part of Abu Dhabi Emirate in 1988. The investigated area included four basic physiographic provinces, Figure 1.2 as follows:

1. Mountainous areas of exposed bedrock, mainly near the Oman Mountains, but including Jabal Hafit.
2. Piedmonts and alluvial plains on the western flank of the Oman Mountain.
3. Al Ain urban area.
4. A nearly continuous expanse of eolian sand and associated dune land forms in the northern dune area and the southern dune area.

Thirty six satellite images (maps) at the scale of 1:20,000 and eleven images at the scale of 1:50,000 were produced for the eastern investigated area. In addition, about 93 boreholes were drilled during the project of which 77 were petrophysically logged and 68 were tested for yield. The logs were used to design individual wells, determine geohydrologic properties, delineate lithology, and estimate the water quality.

Static water levels were measured between August 1990 and May 1991. Most data were stored in a GIS database. Such data contain, among others, well construction, drill rig activity reports, lithologic logs, petrophysical logs, interpreted lithologic logs, water-level records, water pumping records, records of chemical analyses of water samples, uphole-survey data and meteorological data.

The depth to the groundwater table decreases with distance from the Oman Mountain from 30 m in the eastern part of the study area to about 3 m in the western part. The regional water level in Al Ain aquifer is shown in Figure 2.12. There were depressions in water levels in some areas due to groundwater withdrawals during 1990-1991. The largest water level depression was about 790 km^2 and extended west from Al Ain to Abu Samra and south from Al Zaala to Seh Sabra (Al Maqam depression). Al Maqam depression started as disconnected groups of smaller depressions in Jahar, Saad, Zaala, and Meya, and Maqam well fields. The maximum drawdown in Meya, Jahar and Saad together and Zaala were 80, 50 and 40 m, respectively.

The second largest depression was Al Wagan depression. It occupied an area of 470 km^2 around Al Wagan and Al Ageer farms. The decline in water- levels ranged between 15 and 20 m throughout the area.

Al Qua depression is another depression which extended over an area of about 405 km^2. The maximum water level decline in this depression was about 60 m in its eastern part. Sweihan depression was the next largest depression which extended over an area of 190 km^2 and had a maximum drawdown of about 25 m.

The Hili depression was relatively a small depression which had an oval shape and extends over an area of 40 km^2. The maximum depth of this depression was about 60 m. Finally, the smallest depression was located near Al Khaznah over an area of 30 km^2 and had a maximum water- level decline of about 12 m. The decline in the water- level resulted into:

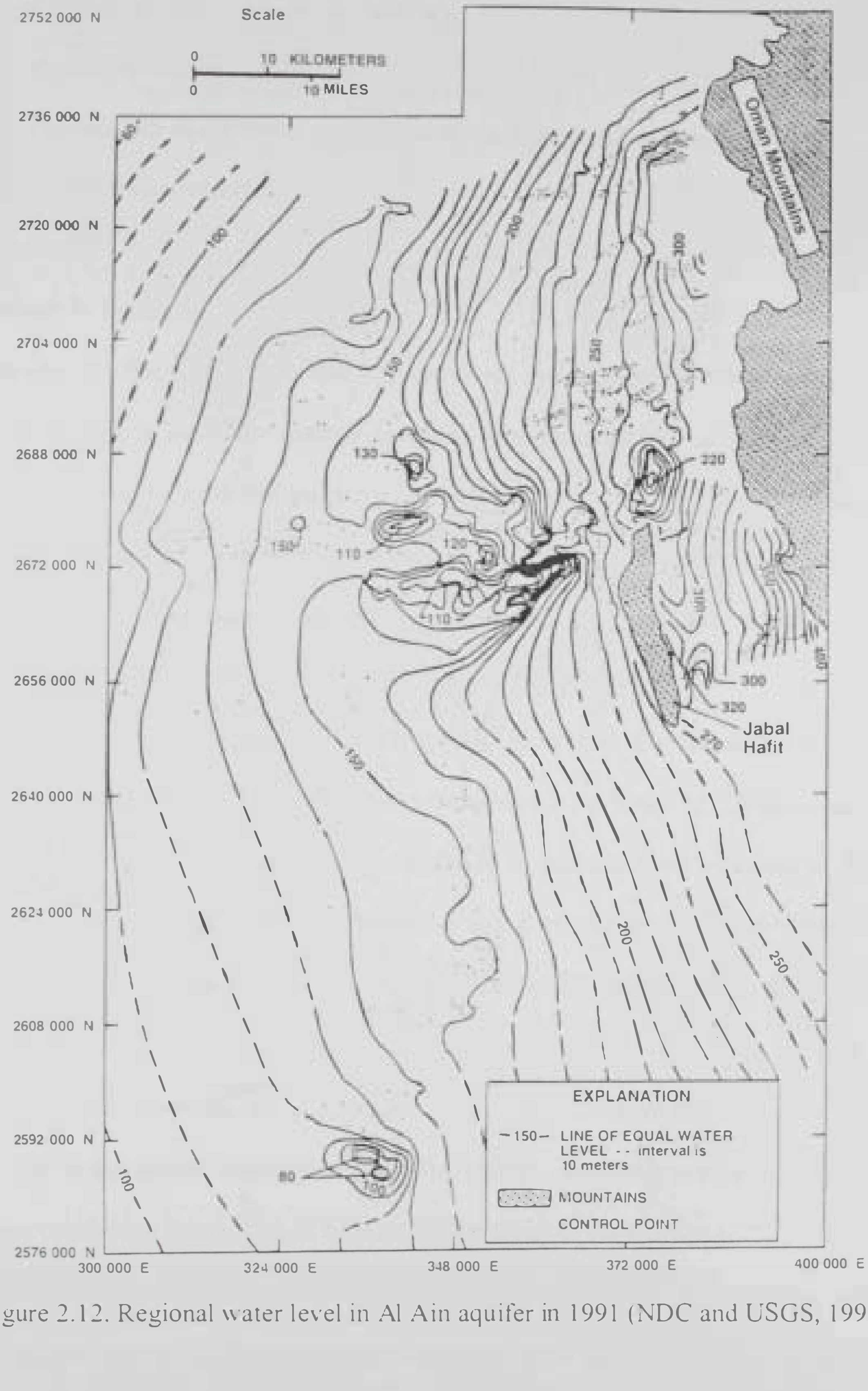


Figure 2.12. Regional water level in Al Ain aquifer in 1991 (NDC and USGS, 1993).

- Raise the water costs due to drilling of new wells and lifting the water with higher electricity costs.
- Disrupting the regional groundwater flow patterns when large quantities of groundwater are intercepted.
- Degradation of the water quality due to the flow of saline water vertically (upcoming of low quality water).

2.7. Water in Storage

The aquifer specific yield is required to compute the water in storage. The aquifer-thickness is given in Figure 2.8. This contour map provides the thickness of each grid cell. The thickness of fresh water in the aquifer is shown in Figure 2.13. The aquifer is composed of interbedded permeable and slightly-permeable layers. The thickness of the permeable material is not uniform. As a result, neither the aquifer thickness map nor the fresh–water thickness map represents the total thickness of permeable material.

Different values of specific yield that range from 0.01 (boreholes GWP-29, 61, and 62) to 0.27 (borehole GWP-39) are found in the eastern area, Table B2. By using an average specific yield of 0.08, the total volume of water in Al Ain aquifer is estimated at 17.6×10^{10} m^3. This volume can be divided into fresh water with a volume of 19.1×10^9 m^3 (about 11% of the total volume) and brackish water with a volume of 15.7×10^{10} m^3 (about 89% of the total volume).

The basal confining system has a total storage volume of brackish water of about 1.3×10^9 m^3 in the eastern investigated area. The storage coefficient was estimated as 0.0005. Confined conditions were assumed with negligible effect of compaction of the mudstone and clay stone that compose the basal confining system. The compaction of very fine sediments may cause the water in storage to occupy a larger area in the aquifer (NDC and USGS, 1993).

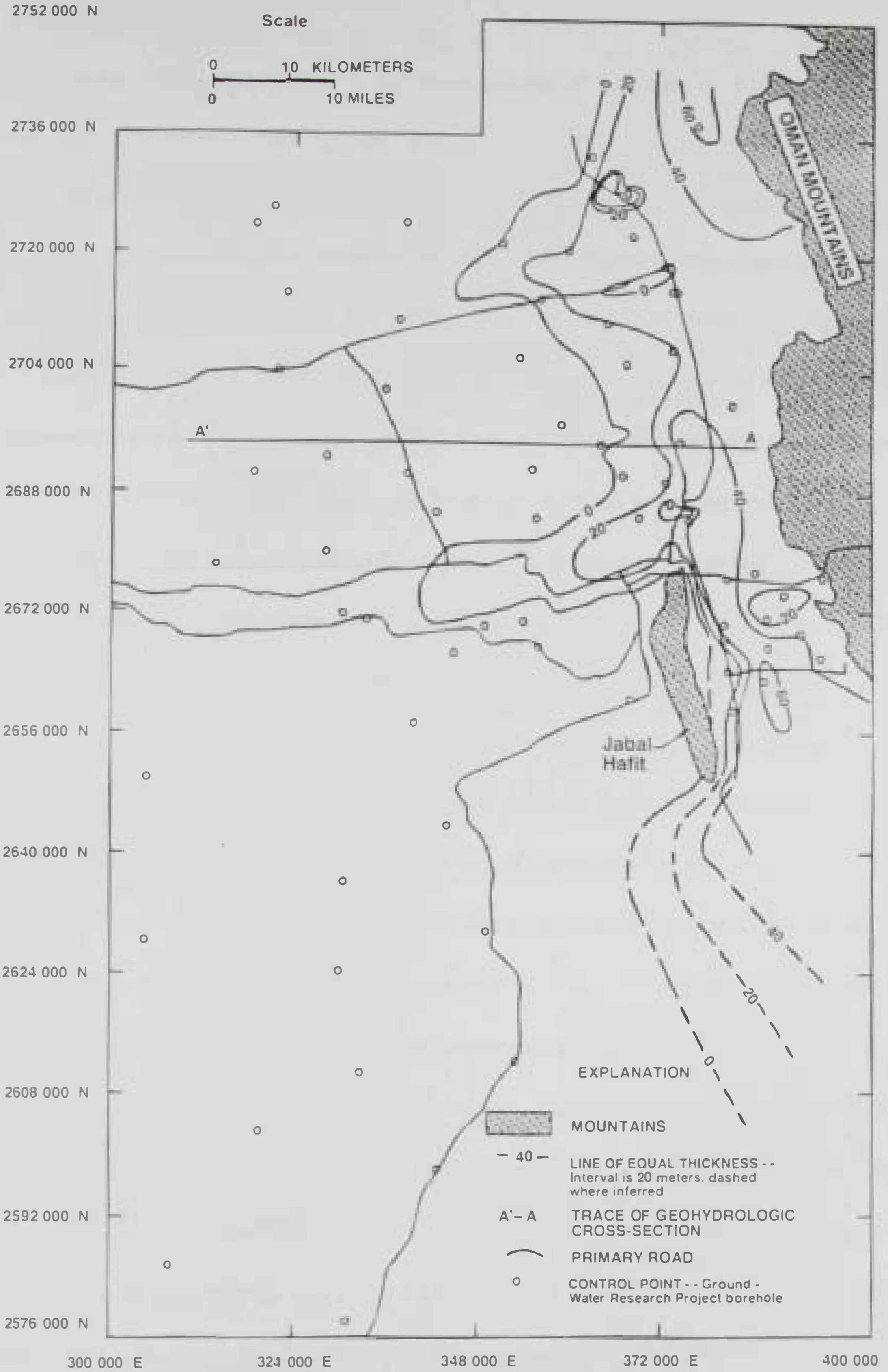


Figure 2.13. Thickness of freshwater in Al Ain aquifer (NDC and USGS, 1993).

2.8. Recharge and Discharge

Rainfall on the Oman Mountains is the main source of recharge to Al Ain aquifer. This rainfall would infiltrate to recharge the system. The infiltration is reduced in areas where a cover of thick mantle of eolian sand exists. The average annual precipitation is 100 mm measured at the meteorological station in Al Ain. The measured annual pan evaporation for the Emirates ranges between 3,400 and 4,400 mm (Halcrow and Partners, 1969).

Recharge to Al Ain aquifer from the Oman Mountains is attributed to three sources:

- Groundwater underflow through gaps (gaps are defined as drainage–basin exit points).
- Infiltration of flood flows carried on to the piedmont plain overlying the aquifer.
- Groundwater flow through fractured bedrock along the entire mountain front.

The transmission-loss stream flow-routing (TLSR) model was used to estimate the recharge from the first two sources. This model requires different information including, among others, drainage–basin area, stream–channel length and basin geometry, average annual rainfall, magnitude of storm event, and vertical hydraulic conductivity of stream channel alluvium. The cumulative effects of individual rainfall events in a certain drainage basin during a year were represented by the TLSR model which uses the mean annual rainfall event (a storm with average recurrence interval of about 2.33 years). The mean annual rainfall event is about 55 mm for the eastern investigated area.

The surface runoff, channel loss (infiltration of water in stream channels) and overland loss were calculated by using the TLSR model. Overland loss includes losses to evapotranspiration, soil moisture, deep percolation and upland recharge. The average annual recharge for a certain drainage basin is equal to the sum of computed channel loss and upland recharge. The entire computed surface runoff was assumed to recharge Al Ain aquifer along the wadi channel. Figure 2.14. The mountain drainage basins, gaps, and estimated average annual rainfall values are shown in this Figure.

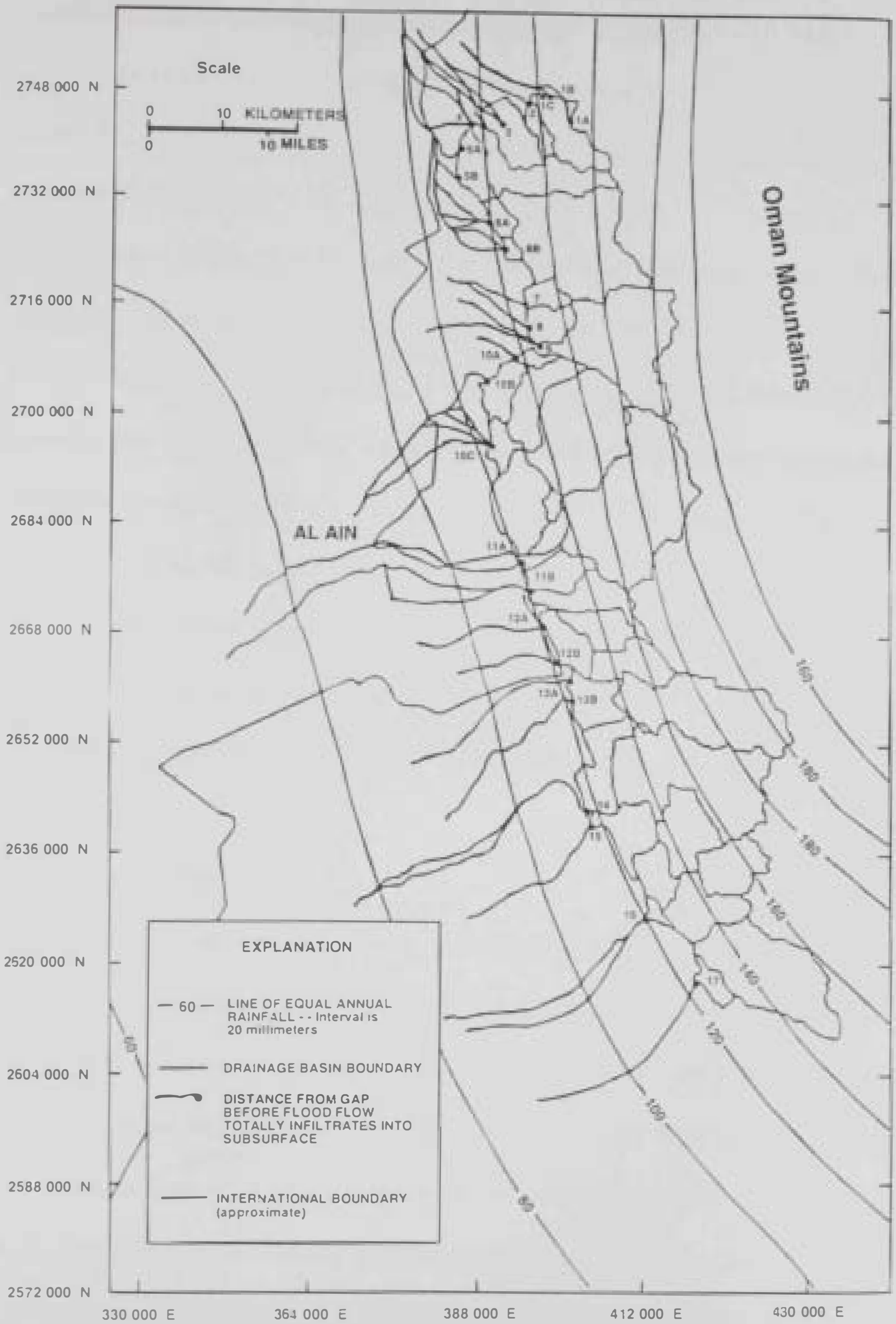


Figure 2.14. Annual rainfall, drainage basins, gaps and extent of flood flow near eastern boundary of the study area (NDC and USGS, 1993).

A summary of the computed values of average annual groundwater underflow and surface runoff collected in individual gaps is given in Table B5 (Appendix B). The calculated cumulative average annual groundwater underflow through gaps near the eastern investigated area is about 1.5 m^3/s (about 47.3 million m^3/y), while the cumulative average annual surface runoff is about 0.12 m^3/s (about 3.785 million m^3/y).

It is difficult to assess the direction of groundwater flow after it leaves a gap. Previous studies in Oman (Sutton, 1987; Maizels, 1987; Maizels and Mc Bean, 1990) describe the change in direction of under flow through gaps with time and with volume of recharge. Other studies indicated that underflow through gaps follows paleo channels caused by present--day wadis. The flow direction of the groundwater from gaps can be shown by the regional potentiometric map of Al Ain aquifer. Figure 2.12.

There are many fractured bed rocks in the Oman Mountains. The flow of wadi several months after a rainstorm leads the fractured bed rock to act as a groundwater reservoir recharging the shallow aquifers in Al Ain (NDC and USGS, 1993).

2.9. Recharge from Precipitation

There are differences in the recharge of two surface group areas which are represented by dune areas and interdune areas. Figure 2.15. Dincer et al. (1974) related the recharge to mean annual precipitation and mean grain size of the sand. Besler (1982) reported that the mean grain size of sand dunes in and near the eastern investigated area ranged from 0.14 mm to 0.22 mm with an average of 0.18 mm. Dincer et al. (1974) stated that the mean annual precipitation is much less than 150 mm which is the required value for recharging the dunes with mean grain size of 0.2 mm. As a result, little recharge occurs in the eolian sand of Al Ain aquifer.

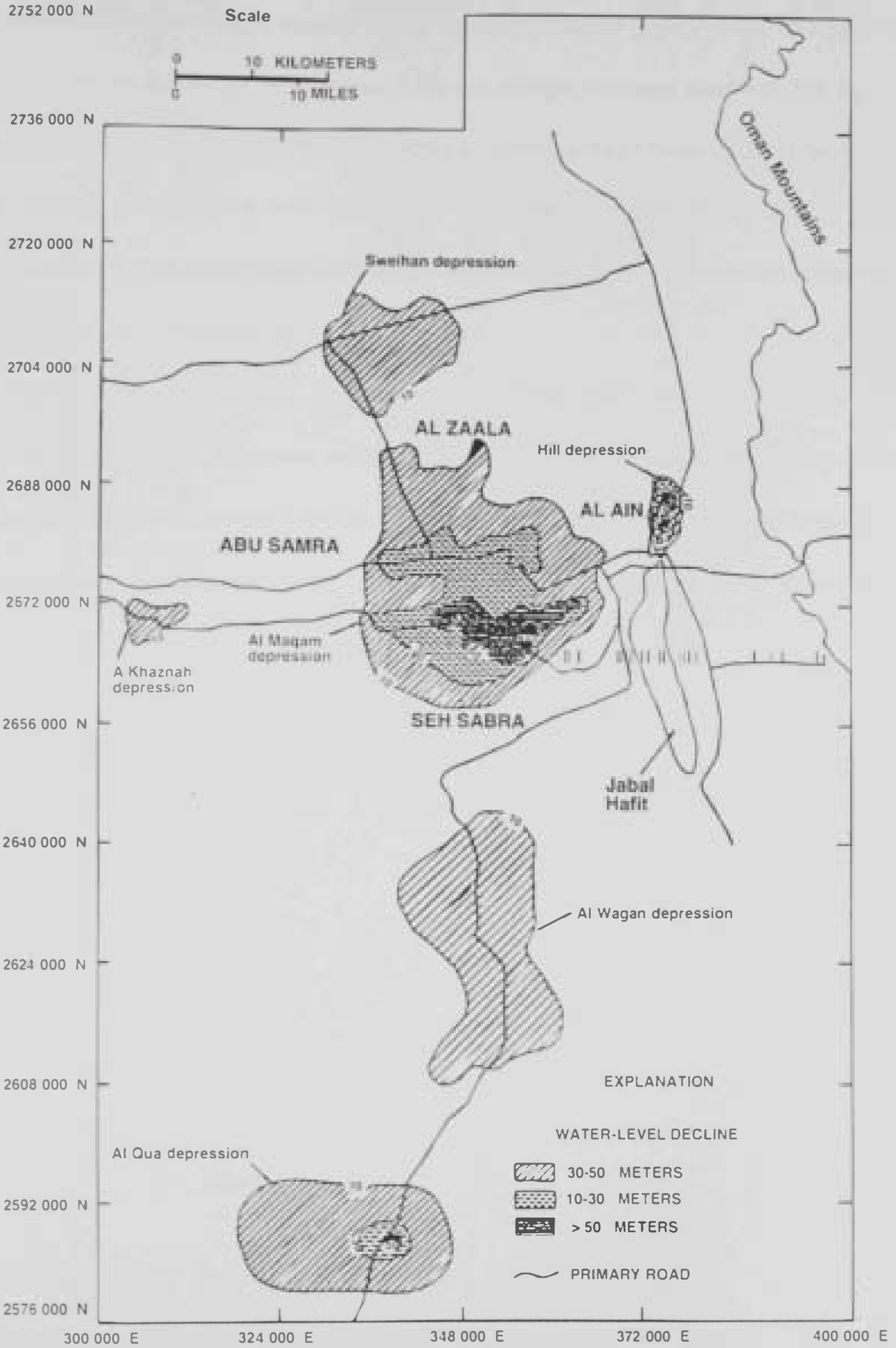


Figure 2.15. Generalized extent of eolian sand dunes (modified from Hunting Geology and Geophysics Ltd, 1979a).

The results obtained from the TLSR showed that 5% of the average annual precipitation recharges Al Ain aquifer when it falls on course gravel plains and alluvial fans in and adjacent to the Oman Mountains. This percentage becomes less than 5% for areas of fine–grained materials at or near the land surface or with a steep slope. The recharge from the average annual precipitation will exceed 5% for areas with pounded runoff in permeable beds. In addition, this percentage will also exceed 5% for areas with excess irrigation water (more than the water-holding capacity of the soil).

Al Ain aquifer is also recharged from Jabal Hafit where precipitation rapidly percolates its permeable limestone rocks. Other sources that recharge Al Ain Aquifer include irrigation returns flow, upward vertical recharge from deeper rocks, and infiltration of water lost from leaky water-transmission lines. The total recharge of these three sources is relatively small.

Chapter 3. Quantitative and Qualitative Assessment

3.1. Identification of the Study Domain

The main objective of the study is to assess the groundwater conditions in some selected areas of Al Ain. The selection of areas was based on the importance of the aquifers and the availability of data that would allow for quantitative analysis. To that end the selected areas included Al Hayer (northeast of Jabal Al Mohayer), Gummed and Nahil (northwest of Jabal Al Mohayer), and part of Al Khadar area in the North West. These areas are located between the coordinates 360000 UTM and 380000 UTM in the east and 2710000 UTM and 2727000 UTM in the north, Figure 3.1. In the following sections, the study area and selected areas are used interchangeably; both refer to the study domain identified by the above coordinates.

Al Hayer area is located about 25 km north of Hili and extends for about 10 km. It constitutes a part of the north sand dunes. Several shallow gravel wadis separate the wells of Al Hayer area. Wadi Al Mashaq is an example of these wadis. Many plants grow in the wadis as compared to the other areas of the sand dunes. The drilling of several wells show the existence of simple sequence of layers containing sand and gravel with clay and shale's aquifers. The grain size of the sand increases with depth.

3.2. Local Conditions

The average thickness of the aquifer in Al Hayer area is about 20 m. Rainfall on Oman Mountains is the main source of groundwater recharge. The water flow direction depends on the topography of the area. The main gap that recharges Al Hayer area is Al Mahdah gap in the south east and wadi Samayni in the north east.

The area has good groundwater quality with salinity of about 1150 ppm. Sodium cations are the main cations in the groundwater in the area ordered as $Na^{+}>Mg^{2}>Ca^{2}$. The anions are ordered as: $(HCO_3)^{-} > Cl^{-} > (SO_4)^{-2}$.

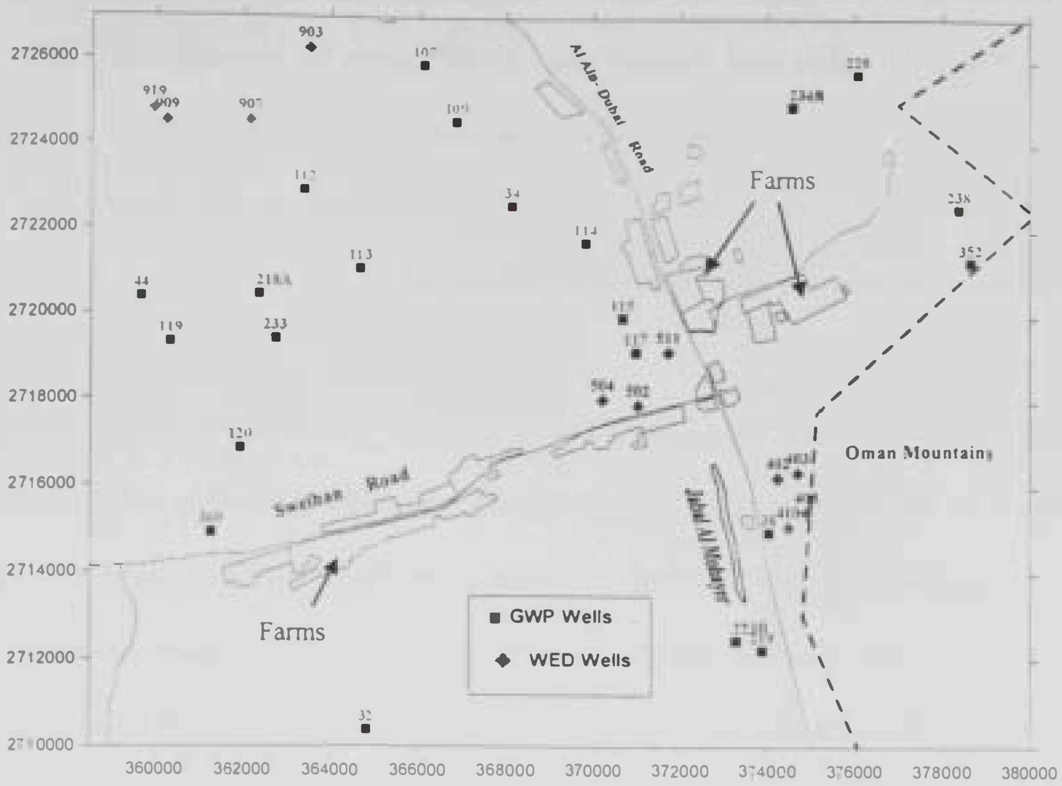


Figure 3.1. Location map for the selected wells and the study area.

Various plants in the farms that can survive under medium salty water are irrigated with the groundwater. The amount of boron in the groundwater of Al Hayer reaches 0.1 ppm. The maximum percentage of boron that can be absorbed by the sensitive plants reaches 1.3 ppm. Al Hayer has the best water quality followed by Gummed, Nahil and Sweihan, respectively.

The capillary rise and evapotranspiration affect the movement of groundwater flow toward the west. As a result, more evaporation occurs leaving chemical constituents to precipitate such as calcium carbonate ($CaCO3$) that close the pores between the grains and prevent infiltration. In addition, the quality of water might be deteriorated (Saqar, 1980).

The geologic formations in Al Khadar area carry a limited amount of water. The hydrogeologic features are improved only near the surface. The subsurface water channels resulted from wadis are the main source for groundwater recharge.

Al Ain Distribution Company drilled its own wells with depths reaching 200 ft in Al Hayer area and at a distance of about 500 m from farmer's new wells. This setting was considered to avoid the interference between the depressions in groundwater levels in the two areas and hence ensure the sustainable yield of the wells. Several random agricultural wells were drilled to depths of about 700 ft. As a result, some of these wells were dried and others have salty water.

There are three huge surface water reservoirs in Al Hayer area. One of them has a capacity of 2 million gallon/day while the other two reservoirs have a capacity of 1 million gallon/day. The location of these reservoirs is shown in Figure 3.2. The groundwater is stored in these reservoirs where the water pipelines from Al Hayer, Shuwaib and Al Khadar are collected. The groundwater is pumped to Al Ain reception station and Hili station in order to be mixed with desalinated water before supplying Al Ain city (Al Ain Distribution Company, Personal Communications, 2001).

In the current study, 34 wells are considered for the analysis of the groundwater conditions. Twenty three wells belong to National Drilling Company (NDC), while 11 wells belong to Al Ain Distribution Company (WED), Figure 3.1. These wells are selected in a way to allow the proper presentation of the static water level (swl) and total dissolved solids (TDS) for the area. The total depth of these wells ranges between 41.15 m and 161.5 m. Four of the WED-wells are located in Al Hayer area, east of Jabal Al Mohayer (WED- 402, WED- 403, WED- 408, and WED- 410), while 3 wells exist along Sweihan road, north of Jabal Al Mohayer, (WED- 502, WED- 504, and WED- 511). The other four wells named WED- 903; WED- 907, WED- 909, and WED- 919 are located in Al Khadar area. Wadi Khab passes through Sweihan well field. The permeable sediments fill the bottom of this wadi. The flow in this wadi recharges the groundwater.

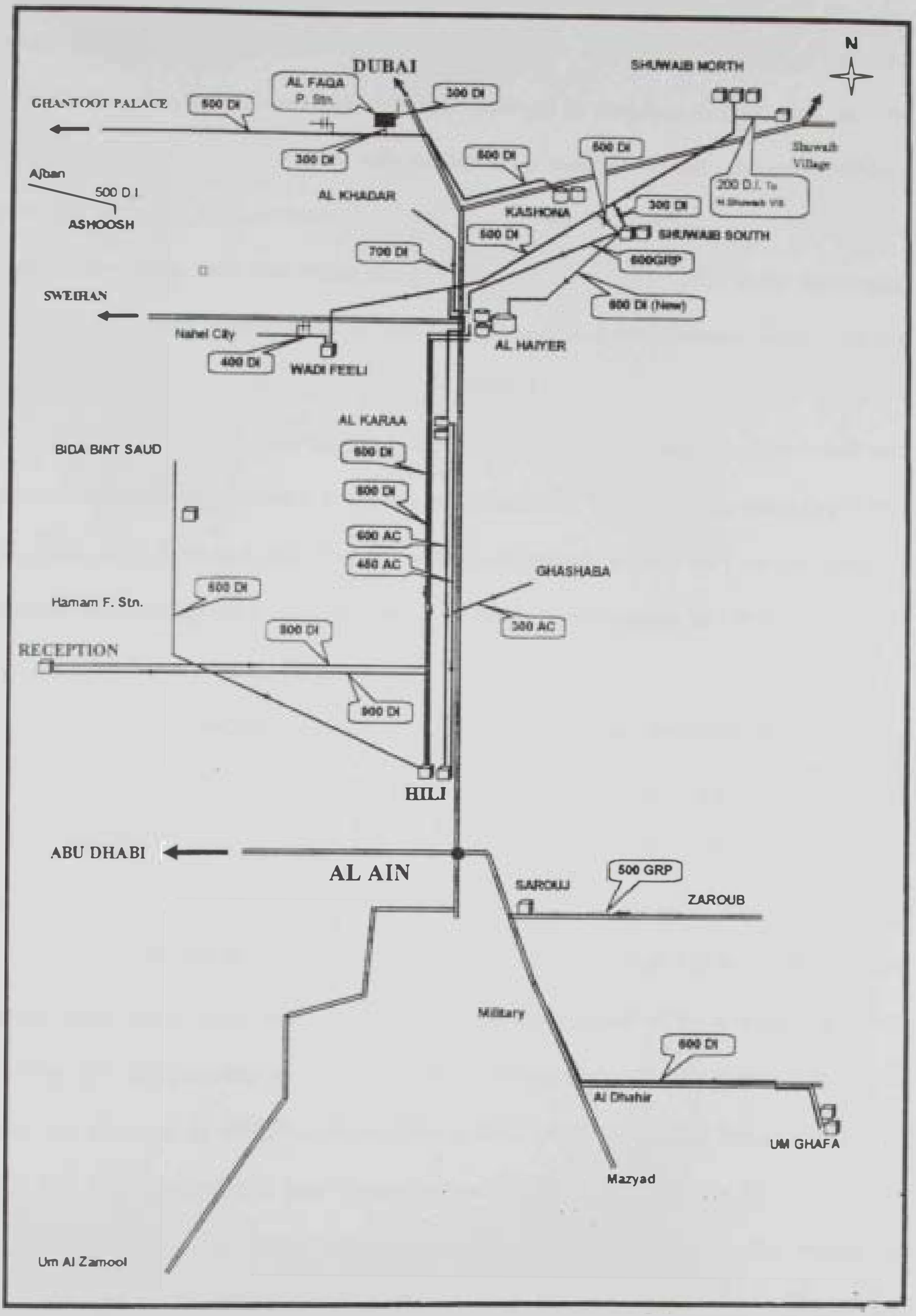


Figure 3.2. General layout of the main water distribution system in Al Ain (Al Ain Distribution Company, 2002).

3.3. Analysis of Groundwater Levels

Groundwater is one of the main sources for water supply to Al Ain area. Because of the rapid development in the agricultural activities, improvement in pumping technologies, and the wealth of the country, farmers were able to drill large number of wells targeting different depths. On the other hand, abounded wells (due to dryness or over salinity problems) were replaced. New farms were established and thousands of wells were drilled in the fresh water horizons. The water extraction from the storage caused a considerable decline in the groundwater level. As a result, deeper wells were drilled.

In order to assess groundwater conditions and its sustainability, drawdowns and depths of the static groundwater levels are considered for different years including 1991, 1993, 1995, 1997, 1999 and 2001. Because water level records prior to 1991 are not complete and sometimes missing, all comparisons are done based on the records of 1991. As indicated before, data has been collected from different sources.

Figure 3.3 represents the equipotential lines in the study domain above the mean seawater level (msl) in 1991. The equipotential lines were of equal spacing and uniform hydraulic gradient with an average value of 3.1×10^{-3} indicating uniform flow conditions. It may also be concluded that the hydrogeological system was almost under equilibrium conditions. In other words, the total influx into the system through rainfall events, excess irrigation water, lateral flow, and others (if any) was almost equal to the total out flux from the system through pumping activities, later flow, evaporation and evapotranspiration, and others. The direction of the groundwater flow is from Oman Mountains towards the west, Figure 3.3. The equipotential lines ranged between 205 m and 270 m above msl. The maximum depth to the static water level reached 42 m below the ground surface west of Al Hayer area and north of Sweihan road. However, it should be noted that depths to the subsurface water can not be representative to the groundwater flow and pattern as they are

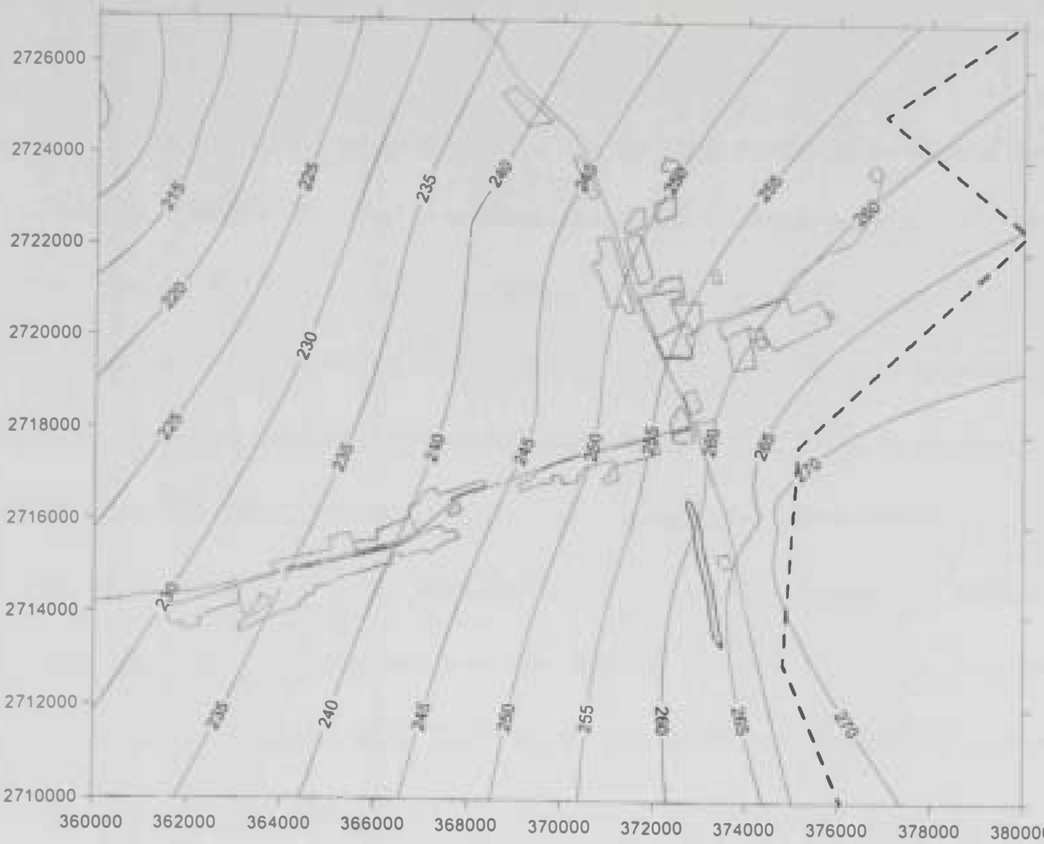


Figure 3.3. Equipotential lines (meters amsl) as measured in 1991.

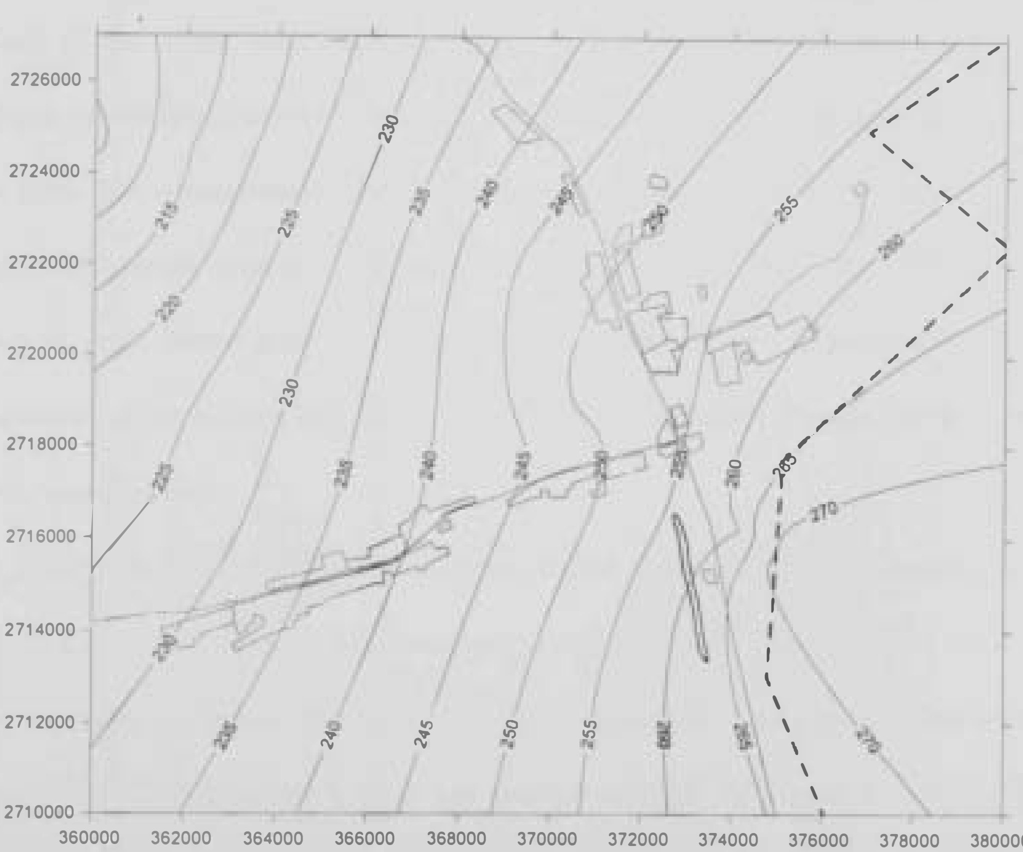


Figure 3.4. Equipotential lines (meters amsl) as measured in 1993.

related to the topographic conditions which may differ significantly from one point to the other.

In 1993, the equipotential lines, in general, had the same pattern as for that of the year 1991. The hydraulic gradient line had a uniform slope and the equipotential lines were of equal spacing, Figure 3.4. However, limited changes were encountered in equipotential lines 245 and 250 in the central zone of the study domain, indicating the increase in groundwater pumping north of Sweihan road and west of Al Hayer area and the decline in the water level in the central zone. The maximum depth of the static water level below the ground surface was 52 m, which is about 10 m lower than that observed in 1991, Figure 3.5. It should be noted, however, that the groundwater flow can not be deduced from this map as the measurements are not referenced to a fixed point. The maximum drawdown (difference between water levels in 1991 and 1993 at the same location) was about 3.6 m in the north east of Jabal Al Mohayer. The decline in the water levels was less than 1 m in the entire western half of the study area, Figure 3.6. Indeed a subsurface water rise of 0.2 m was observed near the western boundary, possibly due to termination of pumping in this area.

In 1995, the equipotential lines 240 through 265 became closer to each other in the central zone of the study area as compared to the years 1991 and 1993, Figure 3.7, indicating an increase in groundwater pumping from the area north of Sweihan road and west of Al Hayer. However, at the eastern and western boundaries of the study domain, no change in the water levels was observed.

In 1997, many of the equipotential lines shifted to the east more as compared to the year 1995, Figure 3.8. Distances between equipotential lines decreased, in the central part, indicating a steeper hydraulic gradient. This phenomenon was very much emphasized in equipotential lines 240 through 270 in the western side of Al Hayer area and north to Sweihan road. For example, the intersection of equipotential line 245 with the southern boundary of the study area was at 367000 UTM in 1995. In 1997, the same line intersected

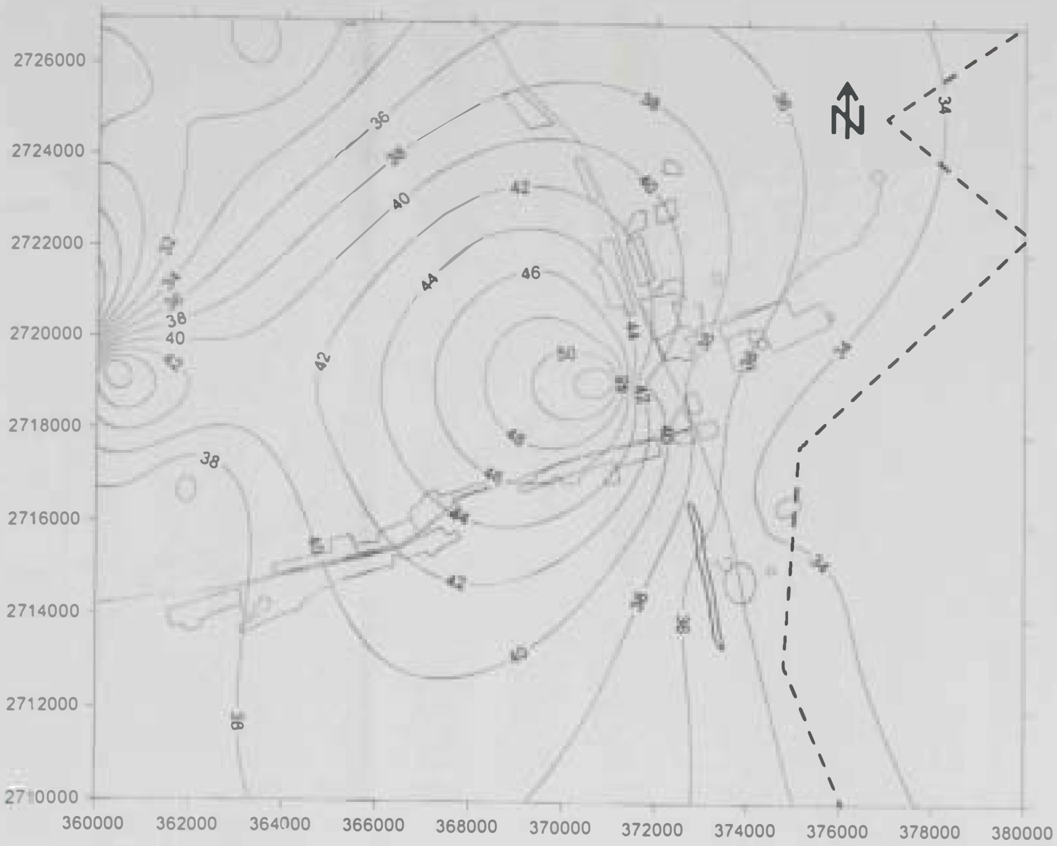


Figure 3.5. Contour map for the depth of groundwater (m) below ground surface (1993).

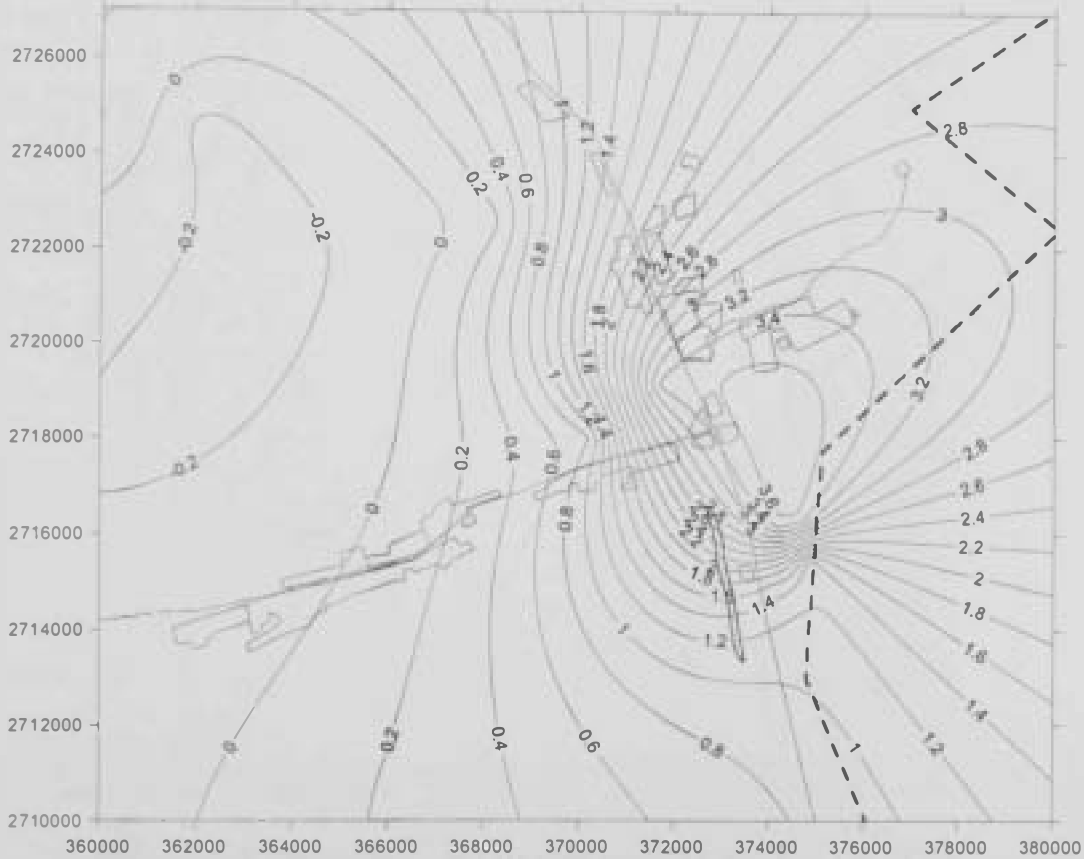


Figure 3.6. Contour map for the drawdown (m) in 1993.

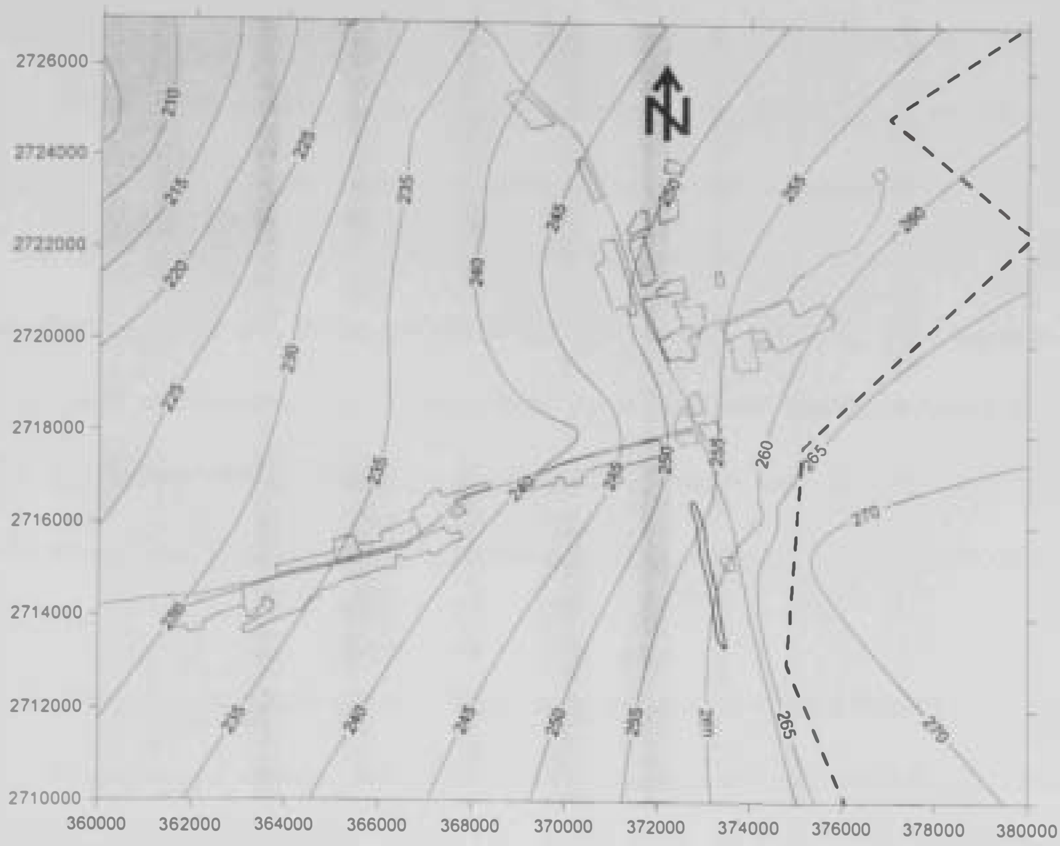


Figure 3.7. Equipotential lines (meters amsl) as measured in 1995.

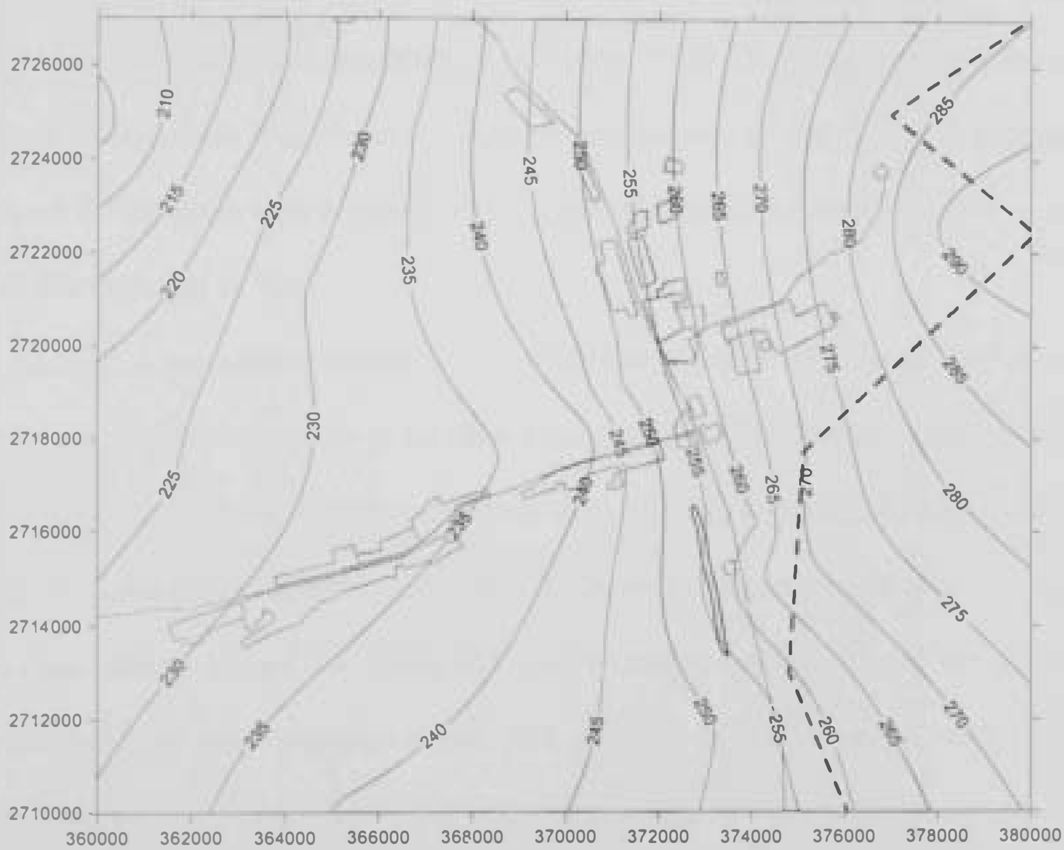


Figure 3.8. Equipotential lines (meters amsl) as measured in 1997.

the southern boundary at 370000 UTM. In other words, the subsurface water level at the point of 370000 UTM on the southern boundary declined from about 252 m in 1995 to about 245 m (aswl) in 1997. The same analysis can be applied to other equipotential lines.

As compared to the water levels in 1991, the maximum drawdown was about 10 m north of Sweihan road and in the middle of the study area, Figure 3.9. This increase in the drawdown was encountered due to the establishment of new vegetable farms that were irrigated with groundwater. The drawdown in the western side of the study area was relatively small (less than 3.0 m). The pumping of groundwater was mostly encountered in the central part.

In 1999, the equipotential lines shifted more toward the eastern side of the study area. Distances between equipotential lines decreased indicating a steeper hydraulic gradient in the middle study area, Figure 3.10. Based on the records of 1999, equipotential line 230 intersected the southern boundary of the study area at 364200 UTM, while in 1997 the same line intersected the western boundary at 2710800 UTM. A remarkable decline in the subsurface water levels was observed southern western part of the area. For example, the water level for the point with a coordinate of 366000 UTM(E) declined from 241 m in 1997 to about 232 m (amsl) in 1999.

In 2001, a remarkable decline in the subsurface water level in the middle of the area was observed. Reference is made to the distortion of equipotential line 230 and the very steep hydraulic gradient between equipotential lines 265 and 230, Figure 3.11. Almost all of the equipotential lines moved to the eastern side. The hydraulic gradient in the study domain was non-uniform (steeper toward the middle and east) indicating over pumping in the central area. The intersection of the equipotential line 220 with the boundary of the study area was changed from western side (1999) to the southern side (2001). The maximum drawdown was about 17 m in the west of Al Hayer and north of Sweihan road, Figure 3.12. Therefore, as compared to records of 1991, the maximum drawdown increased from 3.6 m in 1993 to 10 m

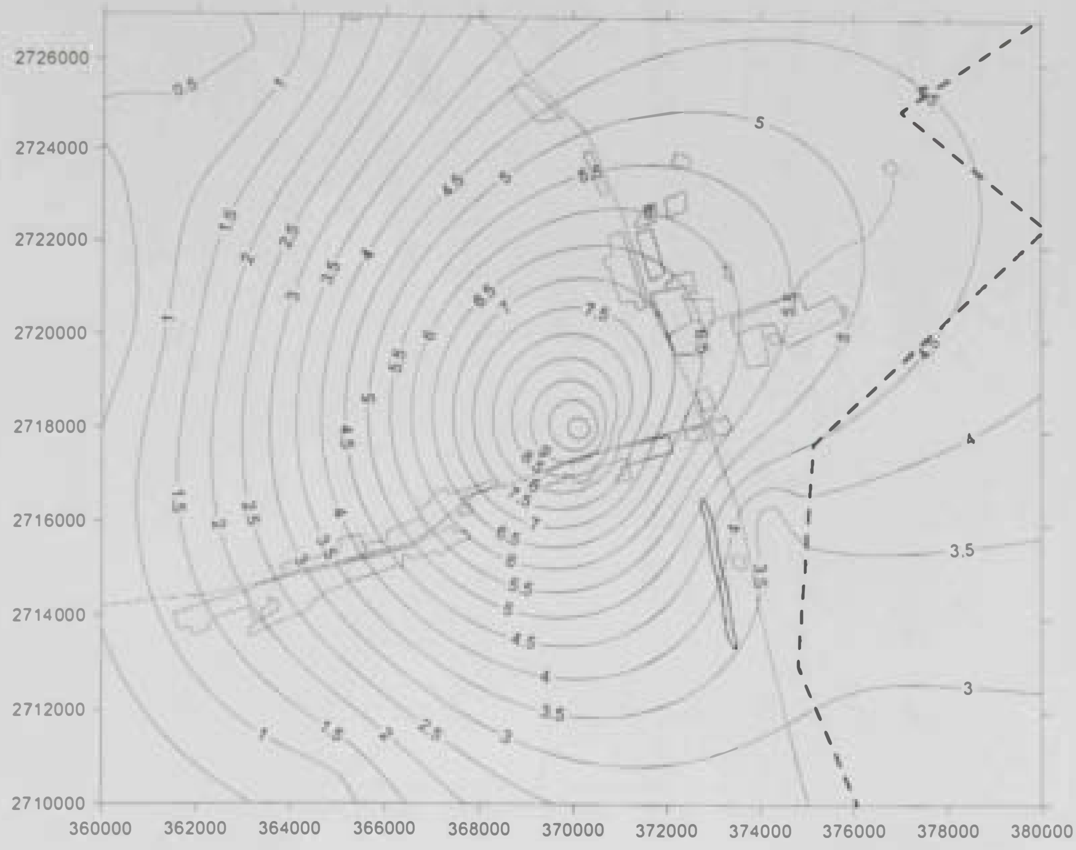


Figure 3.9. Contour map for the drawdown (m) in 1997.

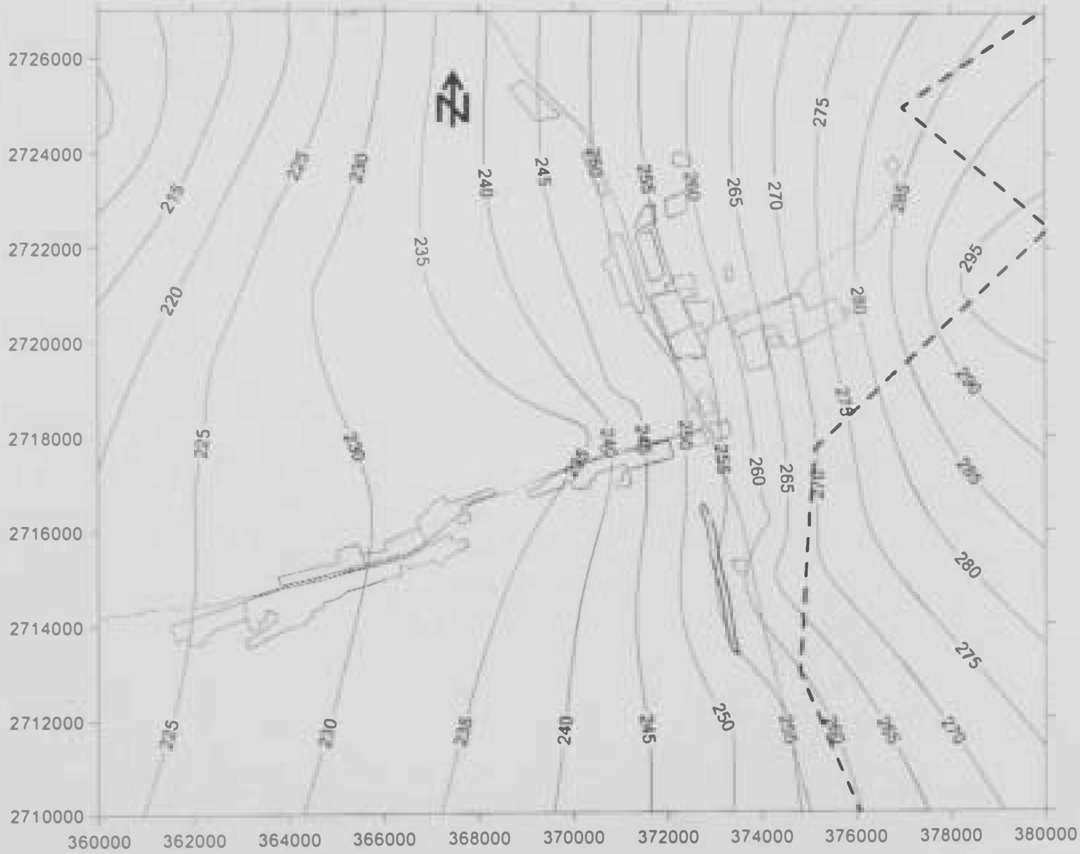


Figure 3.10. Equipotential lines (meters amsl) as measured in 1999.

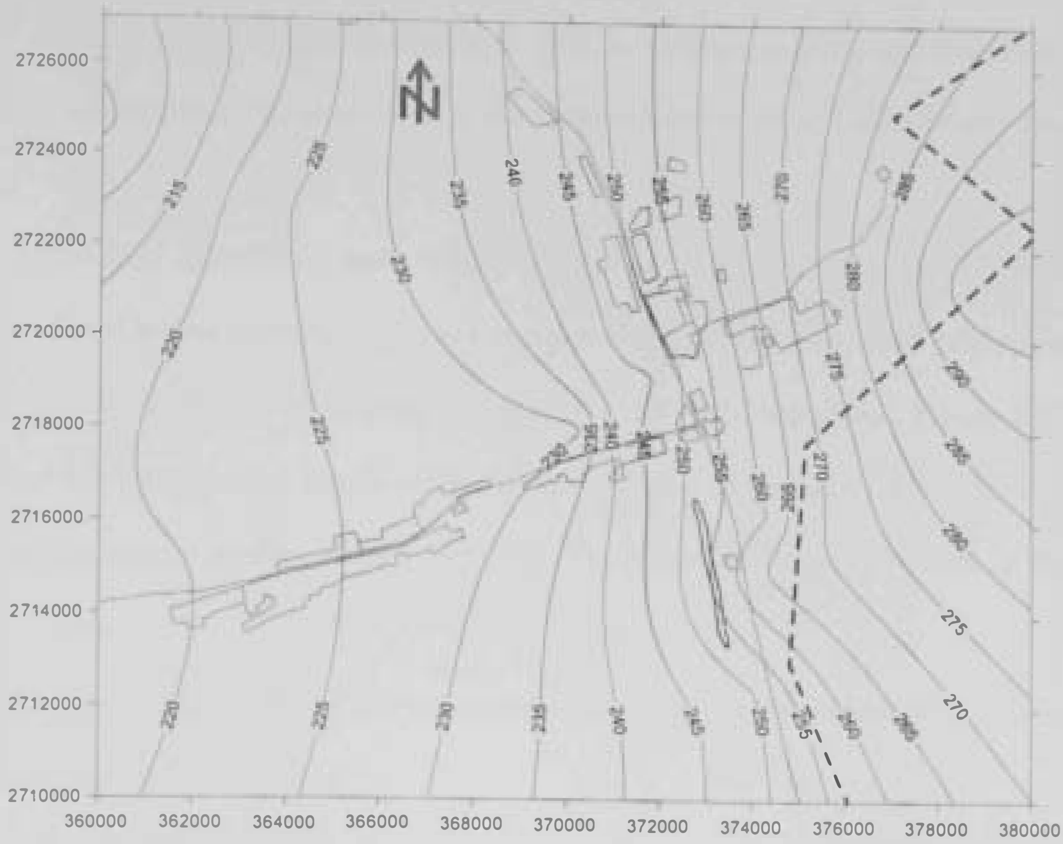


Figure 3.11. Equipotential lines (meters amsl) as measured in 2001.

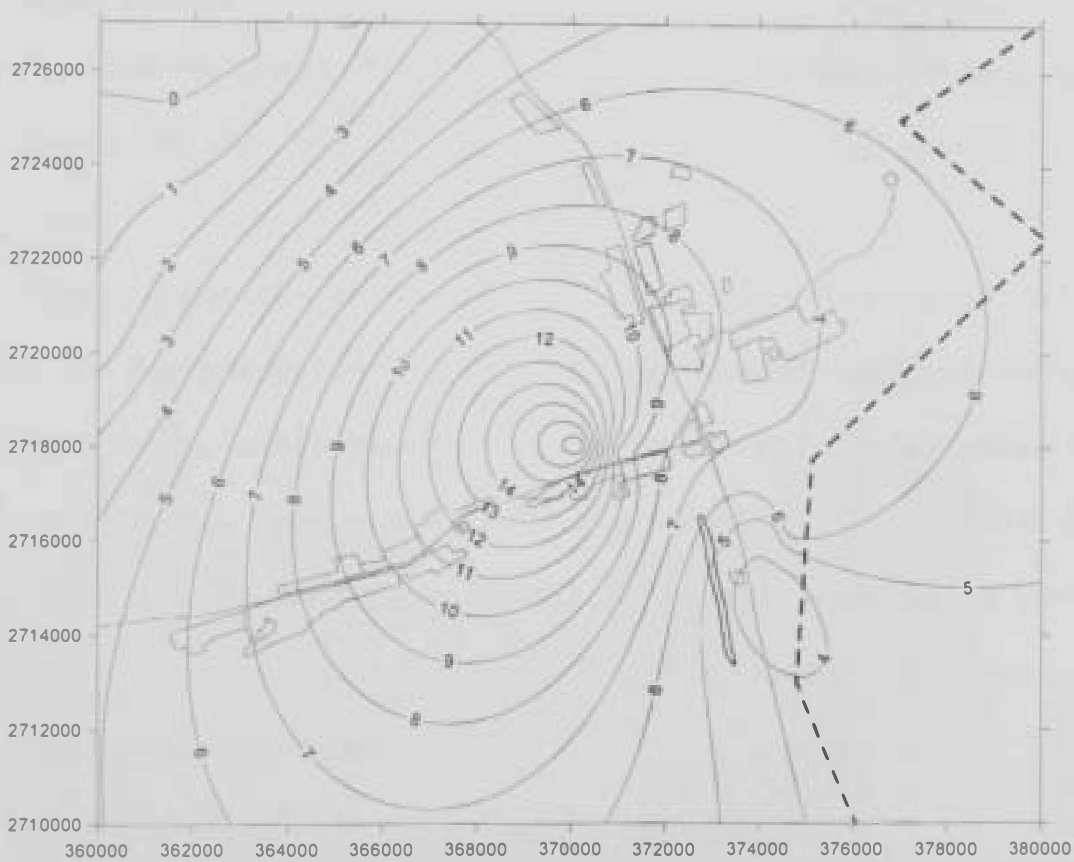


Figure 3.12. Contour map for the drawdown (nı) in 2001.

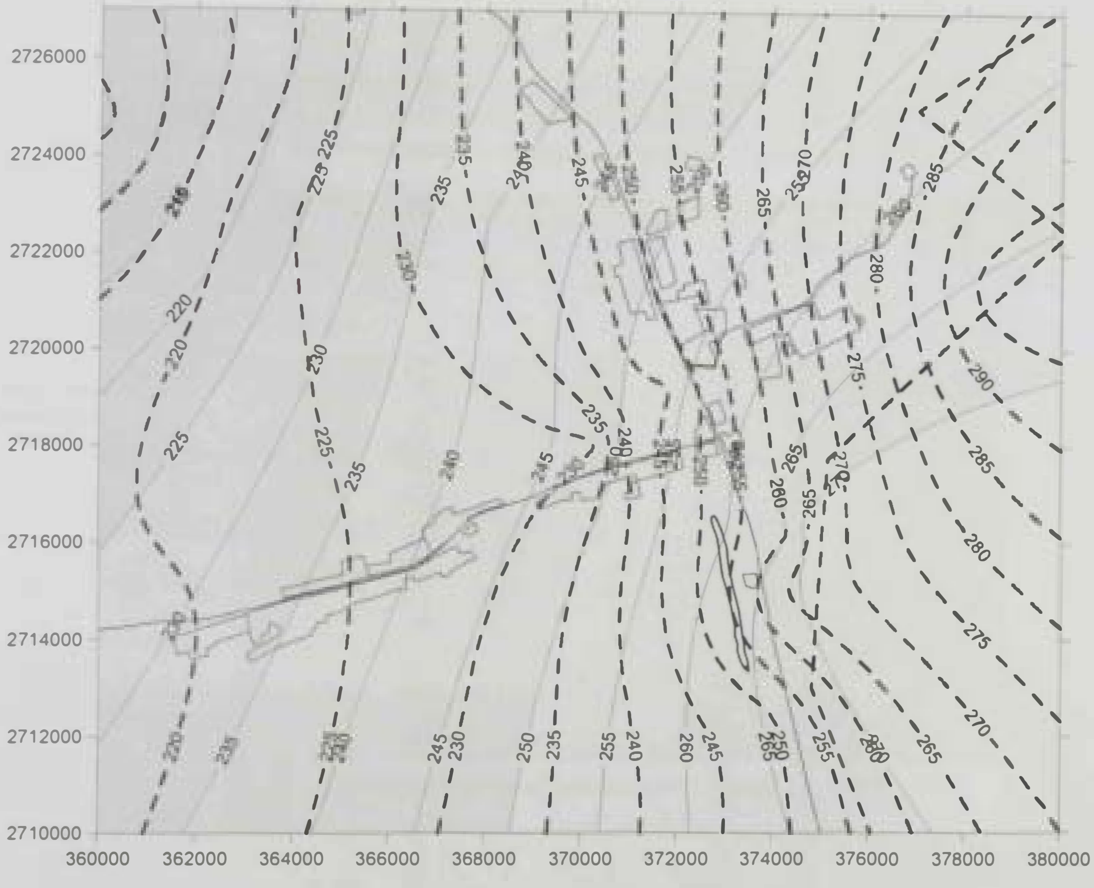
in 1997 and 17 m in 2001. This is consistent with the increase in the groundwater pumping during the same period. The drawdown in the extreme north west of the study area was very limited.

The change in the static water level during the years 1991, 1997 and 2001 can also be represented and assessed by selecting one equipotential line and follow its migration from one year to the other. To that end, equipotential line 230 was considered, Figure 3.13. It is noted that this equipotential line is shifted toward the east of the study area over the years indicating the relative decline in the water level. The following observations can be deduced from the Figure.

1. The maximum decline in the subsurface water table is encountered in the middle and southern parts of the area.
2. The change in the water levels in the northern side is relatively small indicating limited pumping activities.
3. The drawdown between 1997 and 2001 (4 years) was much bigger than the drawdown between 1991 and 1997 (6 years). Therefore the current rate of groundwater depletion is high.

Figure 3.14 presents a comparison between the groundwater levels in 1991 and 2001 (10 year). The flow patterns (levels and directions) have changed significantly during this period. The drawdown varied between zero in the northwestern part of the study area to about 17 m in the central part. Examples of the decline of groundwater levels in some wells during the period 1991 to 2001 are given in Figure 3.15. The effect of the rainfall events on groundwater recharge and recovery can also be observed. However, this recovery has a limited impact on the long term analysis.

Figure 3.13. Location of equipotential line 230 in 1991, 1997 and 2001.



Records of 1991 ——— Records of 2001 - - - - -

Figure 3.14. Comparison between equipotential lines (m aswl) in 1991 and 2001.

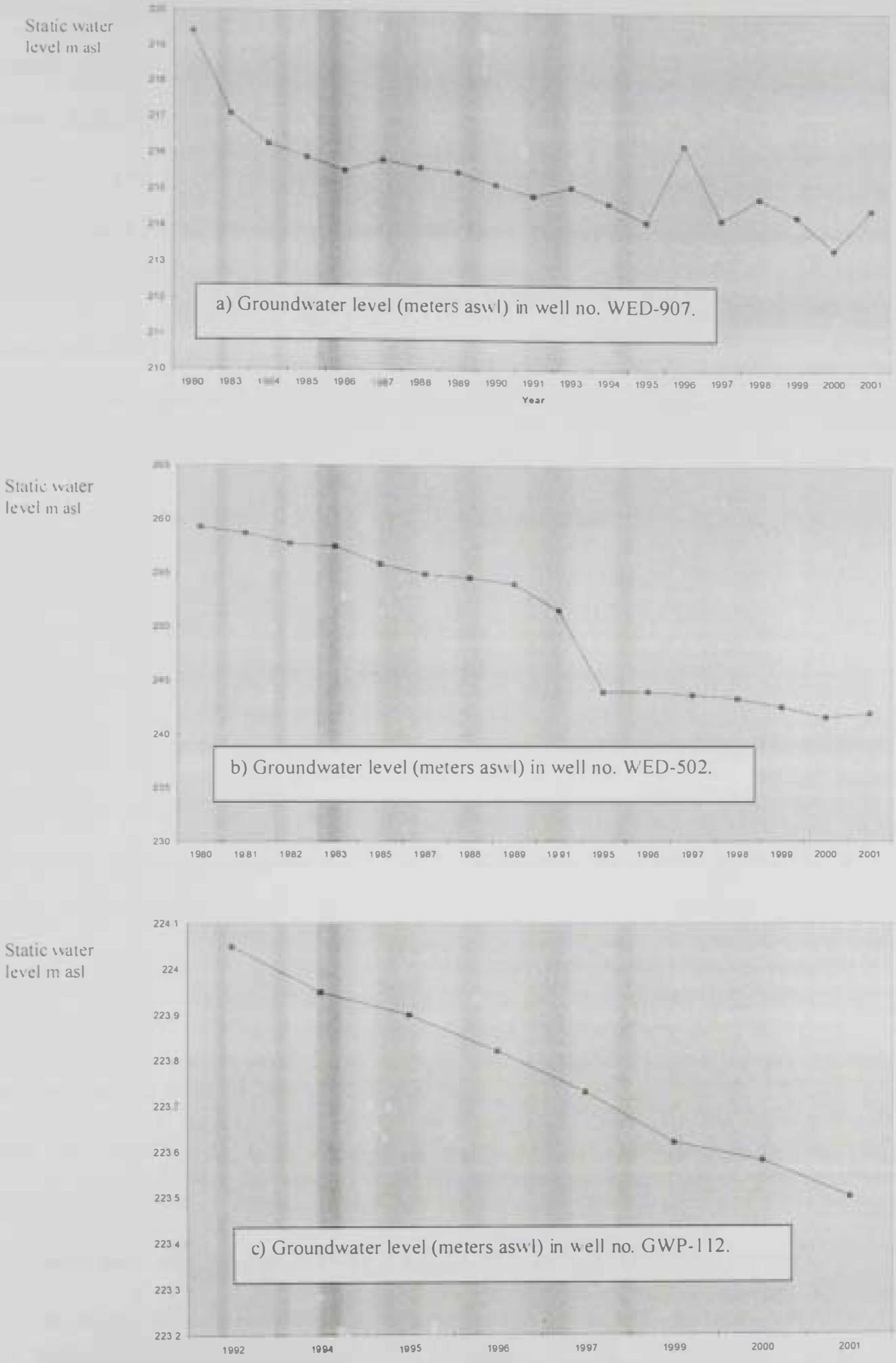


Figure 3.15. Examples of the groundwater decline in some wells.

3.4. Analysis of the Groundwater Quality

The groundwater quality may vary from one location to the other and may also change in the same location over time. Generally, the decline in the water levels would cause deterioration in the water quality. In other words, excessive pumping without sufficient replenishment would yield to higher groundwater salinity. Indeed, this is one of the major problems in almost all of the arid and semi arid regions where rainfall is limited scattered and infrequent. Under such conditions, the originally fresh groundwater resources may become unsuitable for drinking and irrigation purposes.

Based on the available date for the study area, equi-concentration maps are presented for different years to assess the changes in the water quality. Fortunately, total dissolved solids (T.D.S) for some wells were available over the last two decades.

In 1982, the T.D.S. within the study area varied from a minimum of 350 ppm near the eastern boundary (upstream side) to a maximum of about 950 ppm at the northwestern area of the domain, Figure 3.16. The equi-concentration lines indicated a small and gradual increase in the groundwater salinity from east to west. The freshwater condition prevailed throughout the study area. Like all groundwater systems under natural conditions, the salinity increased in the flow direction. The groundwater quality in Al Hayer area was of good quality with a T.D.S of about 400 to 500 ppm.

In 1983, the salinity increased slightly in the study area with an average value of about 100 ppm, Figure 3.17. A local salinity increase in a small area near Jabal AlMahyar was observed. The T.D.S varied between 450 ppm and 1050 ppm and the pattern of salinity distribution remained the same as for the year 1982. The total dissolved solids at Al Hayer area ranges between 450 and 550 ppm. In 1987, the salinity improved slightly in the eastern part of the study area, perhaps due to some rainfall events and the associated groundwater replenishment, Figure 3.18. However, in the western side the change in salinity was nominal. Within the study area, the salinity varied from 400 ppm to about 1050 ppm. Therefore, it can

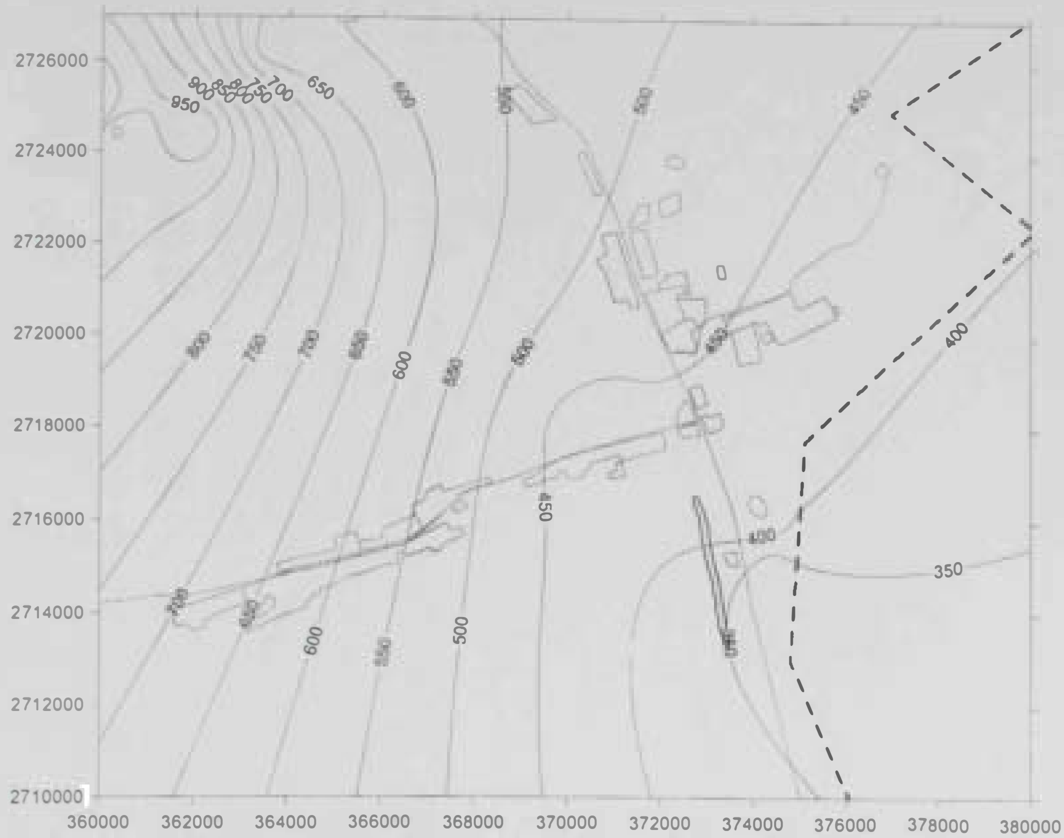


Figure 3.16. Salinity distribution (TDS) in the study area as measured in 1982.

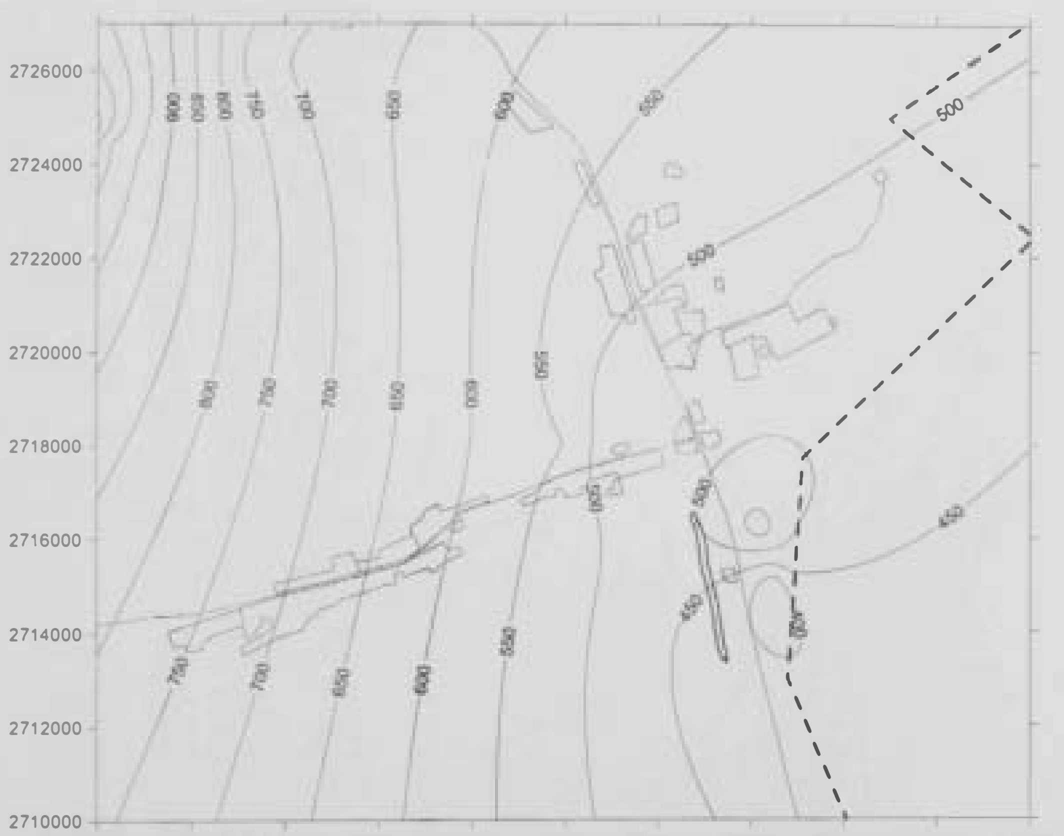


Figure 3.17. Salinity distribution (TDS) in the study area as measured in 1983.

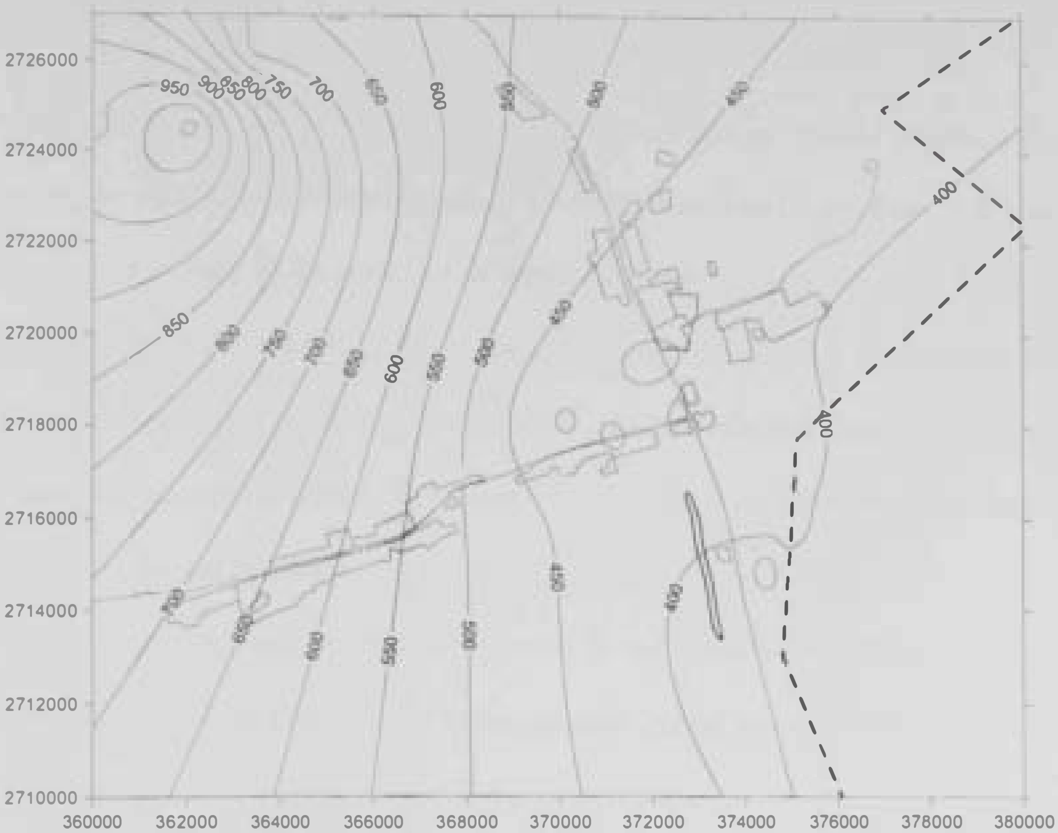


Figure 3.18. Salinity distribution (TDS) in the study area as measured in 1987.

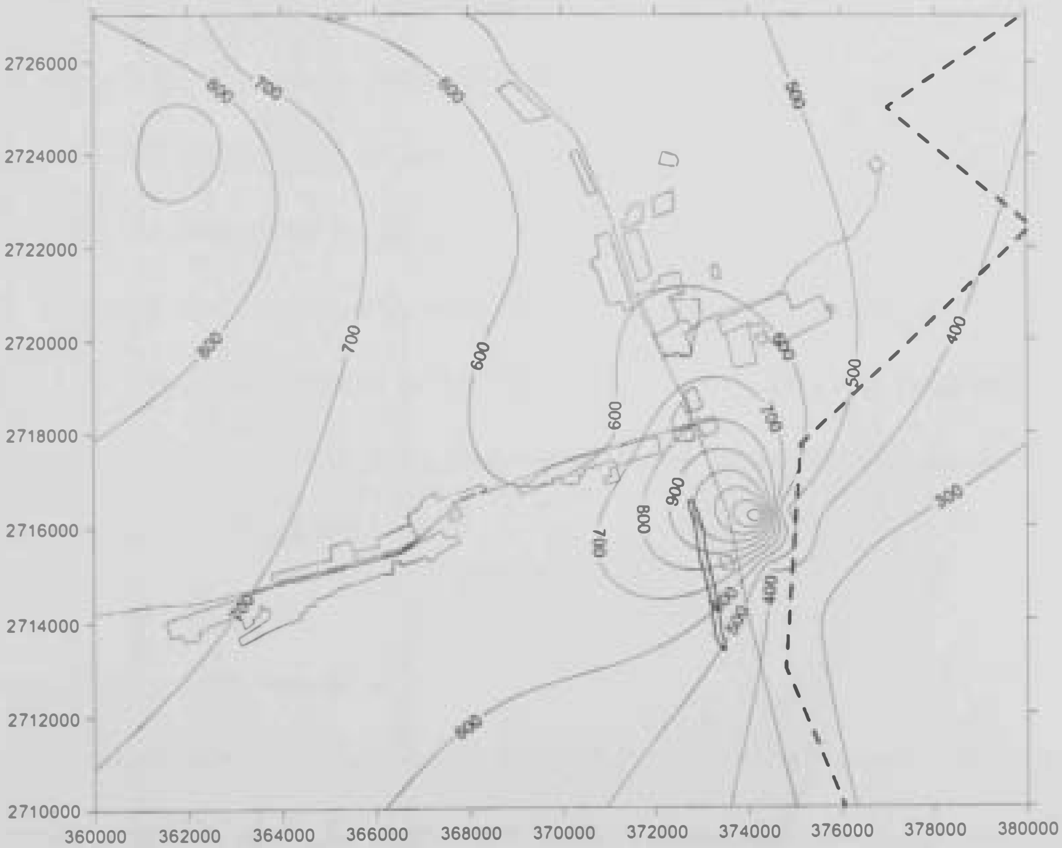


Figure 3.19. Salinity distribution (TDS) in the study area as measured in 1995.

be concluded that no deterioration in the groundwater quality was observed between 1982 and 1987.

In 1995, the salinity in the study area varied between 300 ppm and 1300 ppm, Figure 3.19. However, the salinity in the western part of the study area remained below 1000 ppm. A local increase in the salinity in the area east of Jabal Al Mohayer and south of Al Hayer area was encountered where the salinity reached about 1300 ppm indicating an increase in the pumping activities in this area. As compared to 1987, the groundwater quality has generally improved with the exception of the local area east of Jabal Al Mohayer. This may be attributed to rainfall events that might have occurred in 1995.

In 1999, the highest salinity was encountered in the same area as for the year 1995, Figure 3.20. However, area of high salinity increased than that of the year 1995 indicating the continuous pumping of the groundwater. A limited change in the T.D.S was observed throughout the study domain.

The comparison between the groundwater salinity in the years 1982 and 1999 is presented in Figure 3.21. The salinity in the year 1982 is represented by the solid- black lines, while the dashed-lines represent the salinity in 1999. With the exception of the area east of Jabal Al Mohayer, the changes in the salinity were very limited. East of Jabal Al Mohayer, the salinity increased from about 400 ppm in 1982 to about 900 ppm in 1999. The deterioration in the groundwater quality in the study domain was limited to a small area. It is also concluded that the quality of the groundwater is still good and can be used for unrestricted agricultural purposes.

3.5. Discussion and Possible Solutions

The groundwater level in the study area is under continuous decline over the last two decades after the expansion in the development of farms. The maximum decline in the water table reached about 17 m during the period 1991-2001.

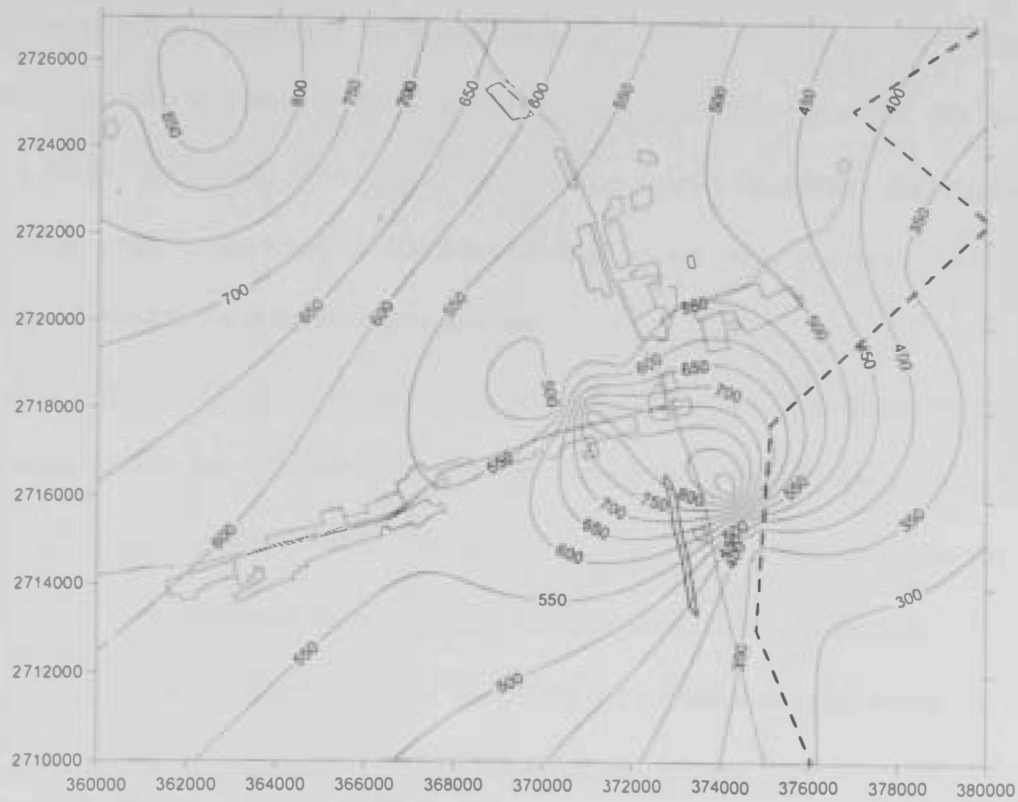


Figure 3.20. Salinity distribution (TDS) in the study area as measured in 1999.

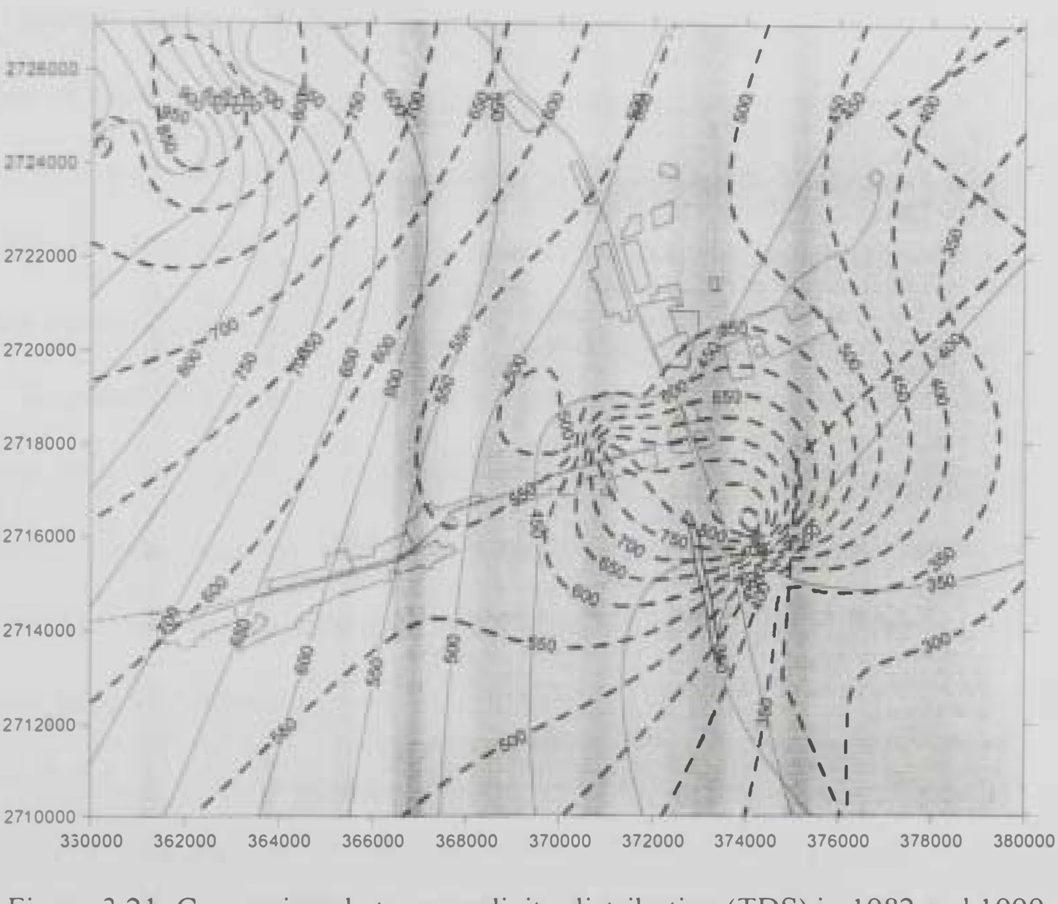


Figure 3.21. Comparison between salinity distribution (TDS) in 1982 and 1999.

The effect of rainfall on the groundwater recovery is limited in both magnitude and duration. The natural recharge from annual rainfall does not encounter the groundwater pumping from the study area under the current rates. Therefore, the decline in the groundwater level is expected to continue as long as no measures are taken to limit the pumping and protect the groundwater resources.

Although significant decline in the groundwater levels has been encountered, the groundwater quality has not deteriorated at the same rate. This may be attributed to several reasons including, among others, the good quality of the entire groundwater in the hydrogeological system under consideration, therefore regardless of the pumping the quality is not affected much, the proximity of the study area from a natural source of freshwater recharge, and the semi-isolation of the hydrogeological system from other horizons of lower water quality.

Several measures could be taken to sustain the groundwater resources in the area. The adoption of modern irrigation systems (such as drip, bubblier and sprinklers) is expected to save 60% or more of irrigation water consumption depending on the farm size and type of crop. The use of the leaky pipe irrigation in which the capillary action of the soil draws water from the pipe would also reduce the groundwater consumption.

Recycling of wastewater and its restricted utilization in agriculture activities would also help sustain the groundwater resources. In addition, the reuse of wastewater will reduce the environmental pollution to the acceptable levels (Dean and Lund, 1981). In general, wastes will be less hazardous by physical, chemical or biological treatment. Al Hayer sewage treatment plant is designed to treat sewage flow of 644 m^3/d resulted from a population of 2300 persons.

The construction of new wells to replace the abandoned ones should be fully controlled and perhaps forbidden in some areas that are under severe risk. Otherwise, the aquifer will be fully depleted. All wells should be fitted with meters and the groundwater consumption should be constrained to certain amounts which if exceeded some charges could be applied. Laws on the groundwater use should be formulated.

Education of farmers is very important to ensure groundwater conservation. Farmers can be given advice on the crop water requirements and the types of crops most suited to the soil type and water quality. On the other hand, T.V programs, publications, announced statements, water week and any other means to show the importance of the groundwater and how to save it would enhance the awareness among the public and on the long term the habit of water conservation will be developed.

Chapter 4. Numerical Simulation of the Groundwater Flow Conditions

4.1. Introduction

Groundwater flow can be simulated both analytically and numerically. Analytical methods are based on the solution of closed form equations, while numerical methods are based on the approximate or iterative solutions. Each method has its own advantages and disadvantages as compared to the other.

Analytical models are generally simpler in formulation and application and do not require detailed input parameters (data). They provide accurate results when applied to small-scale problems, e.g., upconning phenomenon below pumping wells. However, analytical models often require simplified assumptions and idealized domains.

Numerical models are relatively adaptable and flexible and could be applied to heterogeneous systems and irregular domains. Many well-developed and verified numerical codes are already available and can be easily employed to almost every case. These models include, among others, MODFLOW, MOC, MOCDENSE, and SUTRA. The main disadvantage of the numerical methods is the need for detailed field data in space and time that might not be available. Analytical solutions are often employed to verify numerical models for idealized domains, flow and boundary conditions.

In this study the USGS model, SUTRA (Voss, 1984), is employed to simulate the groundwater conditions. The model is used with Argus-One GUI to represent the domain and develop the input data. Argus-One was also used to view the output of the different simulation runs. The study domain was discretized into a number of smaller quadrilateral elements. The numerical model was calibrated first and was then used to predict the equipotential lines for the year 2010. The simulation exercise was limited to the flow due to the limited data regarding the transport parameters.

4.2 The SUTRA-Argus Environment

4.2.1 General

A USGS finite element model, SUTRA is employed in this study. SUTRA simulates fluid movement and the transport of either energy or dissolved substances in subsurface environment. It employs a two dimensional hybrid finite element and integrated finite difference method to approximate the governing equations that describe the two interdependent processes:

1- Fluid density dependent saturated or unsaturated groundwater flow, and either,

2- a- Transport of a solute in the groundwater, in which the solute may be subject to equilibrium adsorption on the porous matrix, and both first-order and zero order production or decay, or

b- Transport of thermal energy in the groundwater and solid matrix of the aquifer.

4.2.2. Capabilities and limitations

SUTRA may be employed for areal and cross-sectional modeling of saturated zone flow and solute transport. It can be employed to model natural or man-induced chemical species transport, including processes of solute sorption, production and decay.

SUTRA uses quadrilateral elements in cartesian or radial cylindrical coordinate systems. The mesh may be coarsened employing (pinch nodes) in areas where transport is unimportant or considerably small. Hydraulic conductivities may be anisotropic and may vary both in direction and magnitude through out the system as may other aquifer and fluid properties. The boundary conditions and other stresses such as sources and sinks can be time dependent in the sense that they can vary from one time step to the other. One should always notice that SUTRA requires spatial and temporal discretization for the simulation of rapid variation either in the piezometric heads or in the concentrations. A special reference is made here to the region near the shore boundary where the cyclic flow exists and the concentration gradient is relatively high.

Although SUTRA is mainly developed to simulate two space dimensions, the thickness of the two dimensional region may vary from one point to the other. In other words, the third dimension is introduced, while all hydraulic and transport parameters are not allowed to vary in that direction. Fluid density may be constant or vary as a function of solute concentration or fluid temperature. SUTRA tracks the transport of either solute mass or energy in the flowing groundwater through a unified equation which represents the transport of either solute or energy.

Solute transport is simulated through numerical solution of a solute mass balance equation where solute concentration may affect fluid density. The single solute species may be transported conservatively, or it may undergo equilibrium sorption (through linear, Freundlich or Langmuir isotherms). The solute may be produced or decay through first or zero order process. Dispersion processes modeled by SUTRA include diffusion and two types of fluid velocity dependent dispersion. The first type is the dispersion process for isotropic media in which direction independent values for longitudinal and transversal dispersivities are assumed. The second type is the dispersion process for anisotropic media. This process assumes that longitudinal dispersivity varies with the angle between the flow direction and the principal axis of aquifer permeability when anisotropic conditions exist.

SUTRA is structured in a modular, top-down programming style that allows for code readability and eases any desirable modifications. Fluid pressures and solute concentrations or temperatures at each node in the studied domain after each time step are obtained. The velocities are evaluated at the centroid of each element.

4.2.3. Organization of SUTRA

SUTRA (V06902D) is written in ANSI-STANDARD FORTRAN-77 and may be compiled and executed under most operating systems and on most computers. Many SUTRA applications require considerable array storage and computational effort. These applications must be carried out on large, fast scaler machines such as mainframes, minicomputers, work stations and

386-or-better microcomputers with math co-processors and at least a few Mbytes of memory, or on vector/array processing machines.

SUTRA package contains 25 files (including one that contains a copy of a text file (SUTRA.DOC). The set of files includes:

(1) SUTRA main routine (MAIN.FOR),

(2) 24 SUTRA subroutines contained in three files:

    (a) USUBS.FOR, with two user-programmable routines,

    (b) SUBS1.FOR and SUBS2.FOR, with all other subroutines,

(3) two mesh data generation routines (MGENREC.FOR and MGENRAD.FOR),

(4) nine input data sets consisting of three data sets required to run each of three examples from the SUTRA documentation,

(5) three output data sets with results from these three examples,

(6) one routine for calculation of hydrostatic pressure data at specified pressure boundaries (PBCGEN.FOR),

(7) a file for compiling and loading SUTRA problems under 640 K bytes using DOS/Microsoft-Fortran-4.0 or 5.0 (MSFOR.BAT), a file for running SUTRA which has been compiled under Microsoft Fortran (MSUTRA.BAT),

(8) a file for compiling and loading SUTRA problems up to available extended memory size on a 486 microcomputer using Lahey F77L-EM/32 Fortran 3.0 (L3FOR.BAT), a file for running SUTRA which has been compiled under Lahey Fortran (LSUTRA.BAT),

(9) a file executable under DOS on PC systems with an 8087/287/387 co-processor that was created using the SUTRA routines listed in (1) and (2), and the Microsoft-Fortran-5.0 system with the utility files listed in (7), above (SUTRA.EXE, requires 531 Kbytes).

4.2.4. Modeling via SUTRA

For problems in regional scale the real situation is geometrically simplified to be easier to solve. First the simplified domain must be discretized in space and time.

4.2.4.1. Discretization: Adequate discretization is vital for two reasons:

1) The ability of a model to represent the variations in system parameters and to simulate complex processes depends on the fineness of discretization.

2) The accuracy and stability of the numerical methods used to represent system processes, in particular, transport, depends on the spatial and temporal discretization. A better discretization is always obtained by making existing discretization finer, but the finer the discretizations are, the more computationaly expensive the simulations become. The only way to explicitly check for inadequate discretization of a system is to simulate with a discretization that is assumed to be adequate and then with a significantly finer discretization and compare results. If there are no significant differences in the results, then the coarser simulation indeed has been adequately discretized.

4.2.4.2. Guidelines: For adequate discretization, the following guidelines should be considered:

1) Nodes are required where boundary conditions and sources are specified. As accurate simulation of processes near these specified points to be required, then a finer mesh is needed in these areas.

2) A finer mesh is required where parameters vary faster in space. Thus, finer mesh is required at high concentration gradient (near sea side) in saltwater intrusion problems. A rule-of-thumb is that at least five elements should divide the front in order to guarantee that the simulated front width arises from simulated physical processes rather than from spreading due to inadequate discretization.

3) The spatial stability of the numerical approximation of the unified transport equation depends on the value of a mesh Peclet number, Pe_m, given by:

$$Pe_n = \left(\frac{\Delta L_L}{\alpha_L} \right) \quad (1)$$

where ΔL_L is the local distance between element sides along a streamline of flow. Stability is guaranteed in all cases when $Pe_m \leq 2$, which gives a criterion for choosing a maximum allowable element dimension, ΔL_L, along the local flow direction. This criterion significantly affects discretization. Spatial stability is usually obtained with SUTRA when

$$Pe_m \leq 4 \quad (2)$$

A discretization rule-of-thumb for simulation with SUTRA which guarantees spatial stability in most cases is:

$$\Delta L_L \leq 4\alpha_L \quad (3)$$

Taken in combination with the considerations of guideline (2) requiring at least five elements across a front, the previous rule implies that a minimum front width which may be simulated when the mesh is designed according to ΔL_L. 4 α_L is 20 α_L.

4) Discretization for transverse dispersion also may be related to dispersivity. Although an exact guideline is not given, the object of transverse discretization is to make the local element perpendicular to a streamline small relative to the total transverse dispersivity:

$$\Delta L_L < \alpha_T + \frac{1}{|V|}\left[\varepsilon S_w \sigma_w + (1-\varepsilon)\sigma_s\right] \quad (4)$$

where ΔL_L is the local element dimension transverse to the flow direction. In the case where the transverse mixing rather than diffusion dominates the transverse dispersion an adequate but stringent rule-of-thumb may be, $\Delta L_T < 10\ \alpha_T$.

5) Radial meshes with a well require very fine discretization near the center axis to accommodate the sharply curving pressure distribution. The radial element dimensions may increase outward and become constant at, for example, a size of 4 α_L.

6) Discretization in time is done by choosing the size of time steps. The adequacy of temporal discretization may be tested only by comparing results of simulations carried out with different time step sizes. For saturated flow simulation, temporal discretization begins with fine time steps which may become significantly larger as the system response slows. For transport simulation, changes in concentration or temperature at a point in a space are often due to the movement of fronts with the fluid flow. Therefore, adequate discretization of these parameters in time is always related to both fluid velocity and spatial gradients in the parameters. The higher the longitudinal spatial gradient and fluid velocity, the smaller the time step required for adequate temporal discretization. A general guideline is that relatively sharp fronts require time discretization which allows them to move only a fraction of an element per time step. Broad fronts with low gradient in concentration or temperature have adequate temporal discretization when time steps are chosen to move the front one or more elements per step.

After preparing mesh and choosing adequate discretization, nodes and elements in the mesh must be numbered. As SUTRA uses the method of banded matrix for solving equations, careful numbering of the nodes is necessary for minimizing the bandwidth which is critical to computational efficiency.

The program dimensions are calculated by adjusting the dimensions of a three large arrays RM, RV, and IMV. All vector and array dimensions in the SUTRA computer code which may vary between simulations are combined in these three arrays. The dimensions required for these arrays, RMDIM, RVDIM, and IMVDIM, must be specified in the main program to values greater than or equal to those required. The required values are given by the following relations:

$$RMDIM = 2(NN)(NBI)$$

$$RVDIM = (NNV)(NN)+(NEV+8)(NE)+(NBCN)*3$$
$$+(NOBS+1)(NTOBS+2)*2+NTOBS+5$$

$$IMVDIM= (NE)*8+NN+(NPINCH)*3+NSOP+NSOU$$

+(NBCN)*2+NTOBS+12, where

NN	= number of nodes
NE	= number of elements
NBI	= full band width of matrix
NSOP	= number of fluid source nodes
NSOU	= number of solute or energy source nodes
NPBC	= number of specified pressure nodes
NUBC	= number of specified concentration or temperature nodes
NBCN	= NPBC+NUBC
NPINCH	= number of pinch nodes
NOBS	= number of observation nodes
NTOBS	= number of observation time steps (max)
NNV	= number of vectors NN long= approx.30 vectors
NEV	= number of vectors NE long= approx.10 vectors

4.2.5. Argus-One

Argus-One is an independent Geographical Information System (GIS) for numerical modeling. Using a conceptual model approach, combined with export capabilities, Argus-One can be considered as an application development environment for development and deployment of graphical user interfaces for numerical models.

Argus-One provides a user environment where geospatial (map-type) information (or coverage) may be synthesized in preparation for use as input to numerical models. Like other GIS systems, the various types of geospatial information are stored and viewed in coverages or layers which can be viewed and interact with directly from the screen.

Export scripting of Argus-One enables to export the synthesized information to input files for numerical modeling at the exact format the model requires. Combining the export scripting and the conceptual model approach, Argus-One offer a model independent environment which enables to use it as a pre-processor for the model. At the same time, it also enables to interchangeably use geospatial coverages with Argus-one.

Argus-One is composed of the two main modules. The first is the GIS module encompassing information layers (nodal information, boundary conditions, domain out lines, and other), data layers (data on grid and interpolation of data), and maps layers (import text, DXF, GIS shape files and images). The second is the mesh and grid module encompassing finite element mesh layers and finite difference grid layers. Complex finite element and finite difference meshes can be created.

4.3. Simulation of Flow and Results

4.3.1. Study domain and boundary conditions

The study domain includes Al Hayer (east of Jabal Al Mohayer), Gummed and Nahil (west of Jabal Al Mohayer), and part of Al Khadar area in the North West. These areas are located between the coordinates 360000 UTM and 380000 UTM in the east and 2710000 UTM and 2727000 UTM in the north, Figure 3.1. Therefore, the total area of the study domain is 20 x 17 km (340 km^2). The domain was discritized into 8524 quadrilateral elements using the automatic mesh generation module of Argus-One, Figure 4.1. To ensure the convergence of the numerical solution very acute angles of the quadrilateral elements were avoided. This intensive mesh was employed to ensure an accurate representation of the hydrogeological system. The numerical simulation was considered in the areal (horizontal) view. Because, the changes in the groundwater's total dissolved solids within the area is limited (Figures 3.16 through 3.21), the assumption of constant density flow was applied. In other words, the change in water concentration does not affect groundwater flow pattern.

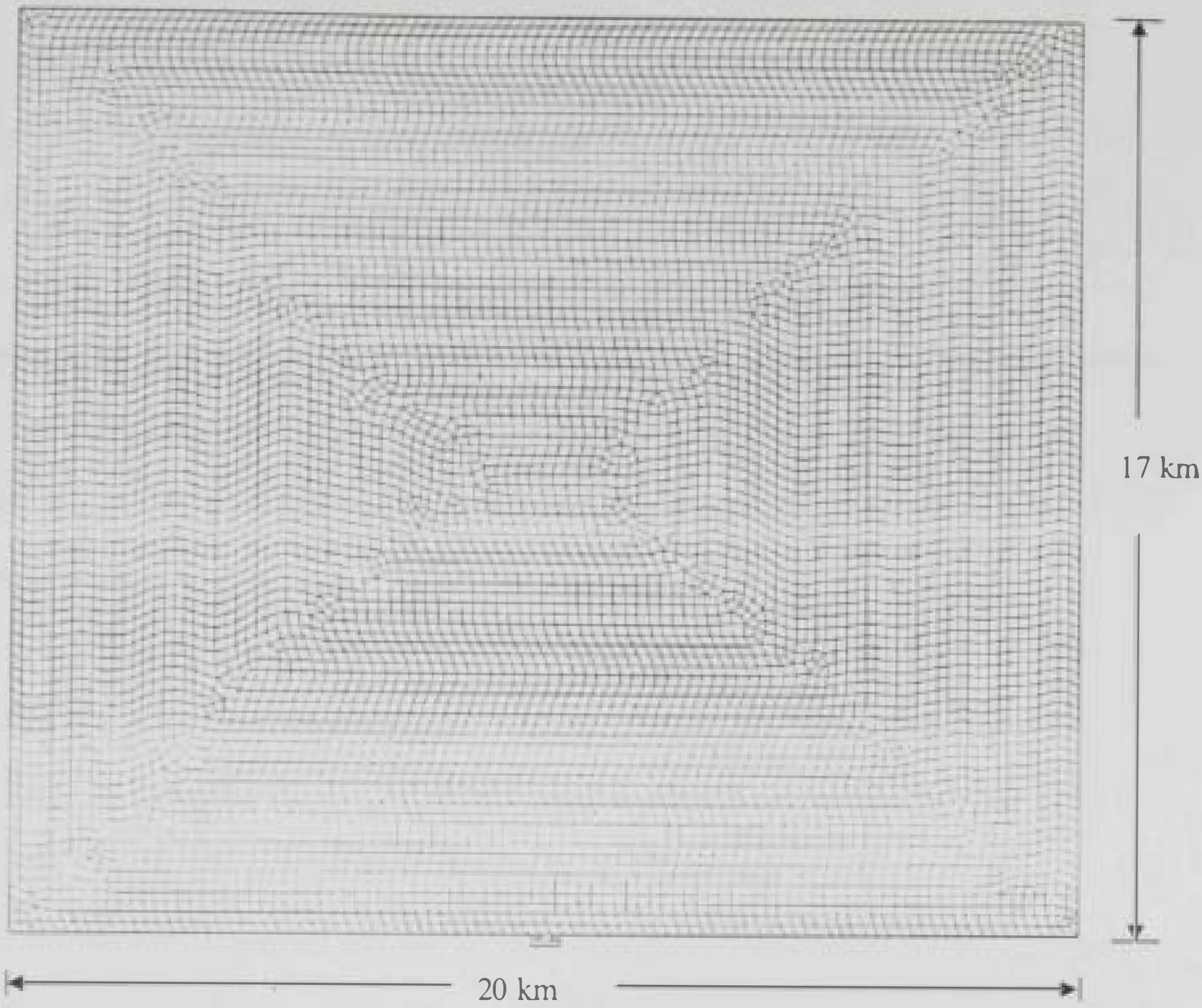


Figure 4.1. Discritization of the study domain into 8524 quadrilateral elements.

The boundary conditions for the water levels were taken from the available measurements for the year 2001, Figure 3.11. Therefore, the water levels at several points located on the boundaries were introduced to the model as prescribed levels. It should be noted, however, that SUTRA allows for some deviation from prescribed head boundaries. The degree of deviation depends on a coefficient (GNUP) to be identified by the user.

Due to the limited data regarding the transport parameters including dispersivities in the longitudinal and lateral directions, adsorption coefficient, diffusion and others, the simulation exercise was limited to the groundwater flow. The quality of the groundwater was not considered. The simulation was conducted under unsteady flow conditions.

4.3.2. Model parameters and calibration process

All hydraulic parameters including the hydraulic conductivity, porosity, specific yield and storativity were adopted from Table B1 through B4 (Appendix B). Based on the available records (Al Ain Distribution Company Report, 2002) the current pumping from the study area is estimated at about 12 million gallons/day. However, many wells that have been constructed in the recent years in different farms are not monitored. Therefore, it is believed that the total groundwater discharge from the study area is significantly higher than this figure. For modeling purposes, groundwater pumping activities are considered to be located in the farming areas only.

Initially, the groundwater level in the study domain was assumed to vary linearly between 300 m (aswl) at the eastern side to 200 m (aswl) at the western side. Specified head were then imposed at some nodal points located at the boundaries. The simulation was conducted under transient state conditions so that the variation in water levels can be observed overtime. Different simulation runs were considered and the hydraulic parameters were adjusted from one run to the other in order to simulate the measured groundwater levels in year 2001.

Figure 4.2 presents a comparison between the measured and simulated groundwater levels for the year 2001. The agreement between the measured and simulated levels is quite good as most of the equipotential lines nearly coincide. For a given point, the difference between the measured and simulated groundwater levels was, in general, less than 40 cm. Indeed the difference was less than 20 cm for almost one half of the study domain, Figure 4.2. The maximum difference between the measured and simulated levels was about 95 cm and was encountered along equipotential lines 220 and 230. This limited discrepancy in the equipotential lines may be attributed to some unknown hydrogeological parameters or pumping activities.

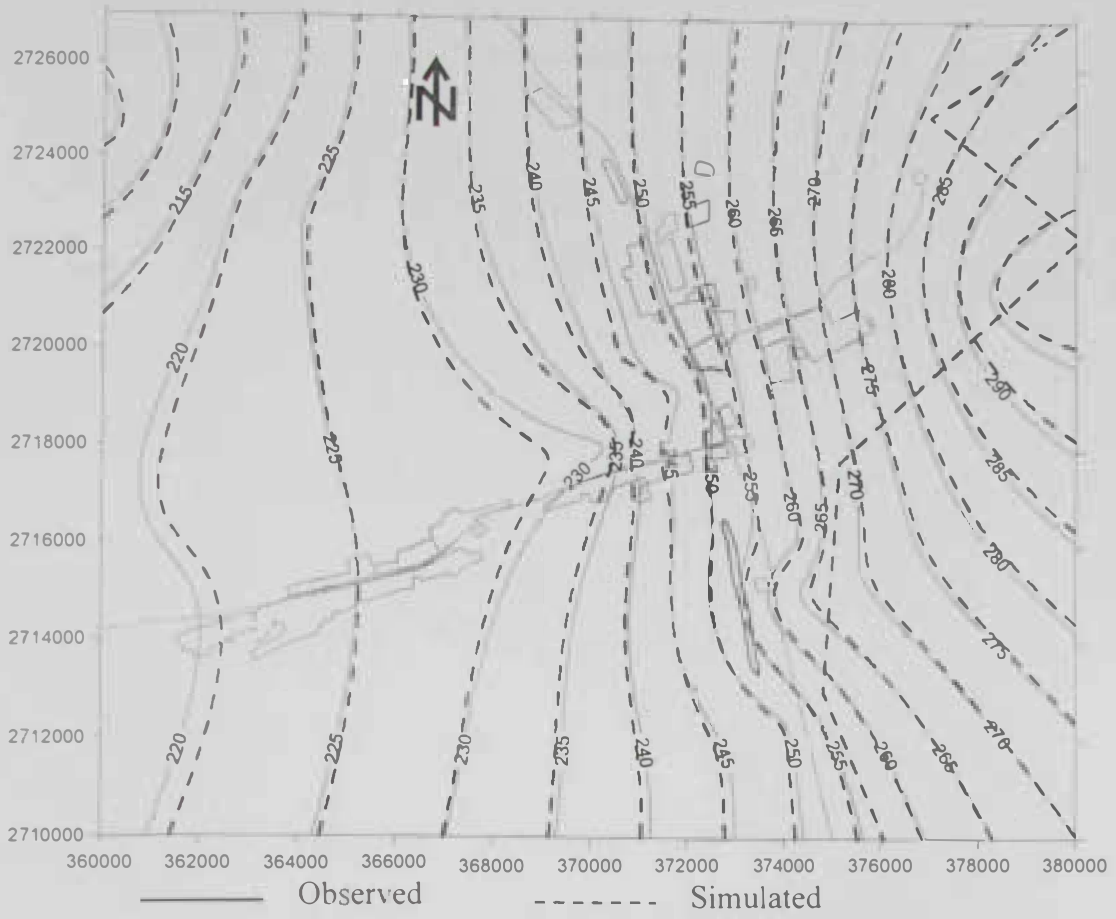


Figure 4.2. Comparison between measured and simulated equipotential lines for 2001.

4.3.3. Prediction of groundwater levels in 2010

The SUTRA model has been employed to predict the groundwater levels in the study domain in the year 2010. The calibrated hydraulic and hydrogelogical parameters were used in this simulation and the pumping activities were considered constant throughout the simulation time. The head coefficient for the boundaries GNUP was set equal to 0.1 to provide some flexibility for the specified heads at the boundaries.

The initial groundwater levels for this run were taken from the obtained results of the year 2001. The initial time step was taken as 1 day (86400 sec.) and the multiplication factor for the time interval was set equal to 1.1. The total simulation time was set equal to 3650 days (10 years from 2001 to 2010).

Figure 4.3 presents the resulted equipotential lines for the year 2010. As compared to

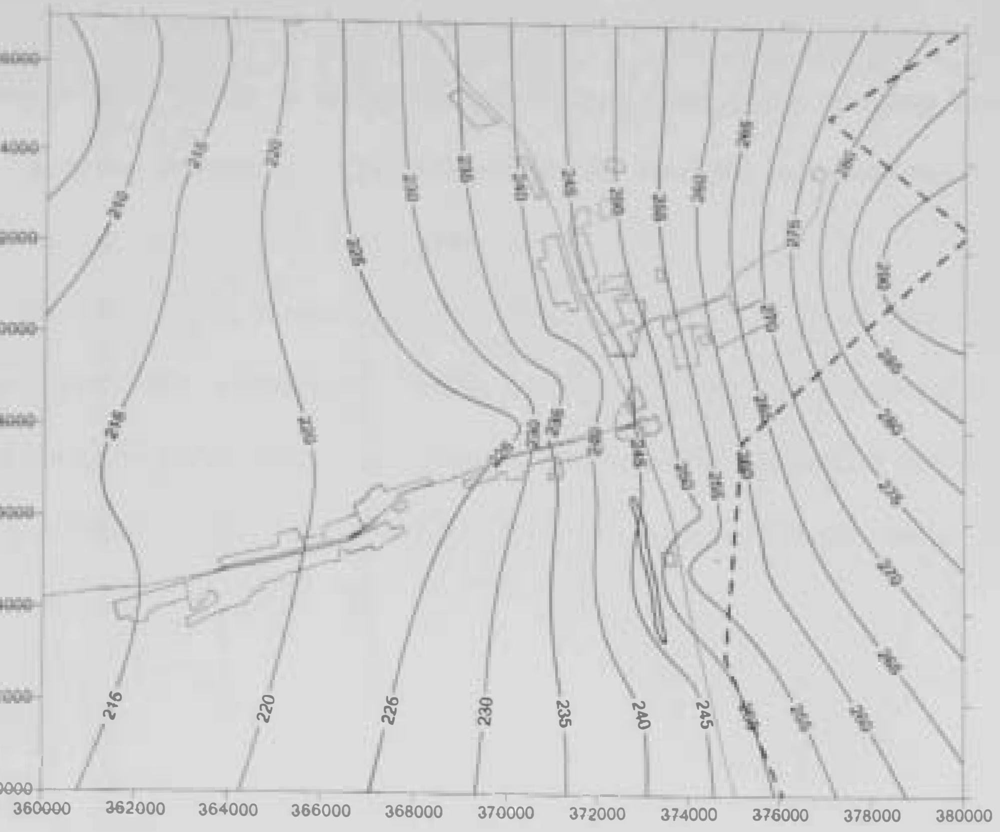


Figure 4.3. Predicted equipotential lines for the year 2010.

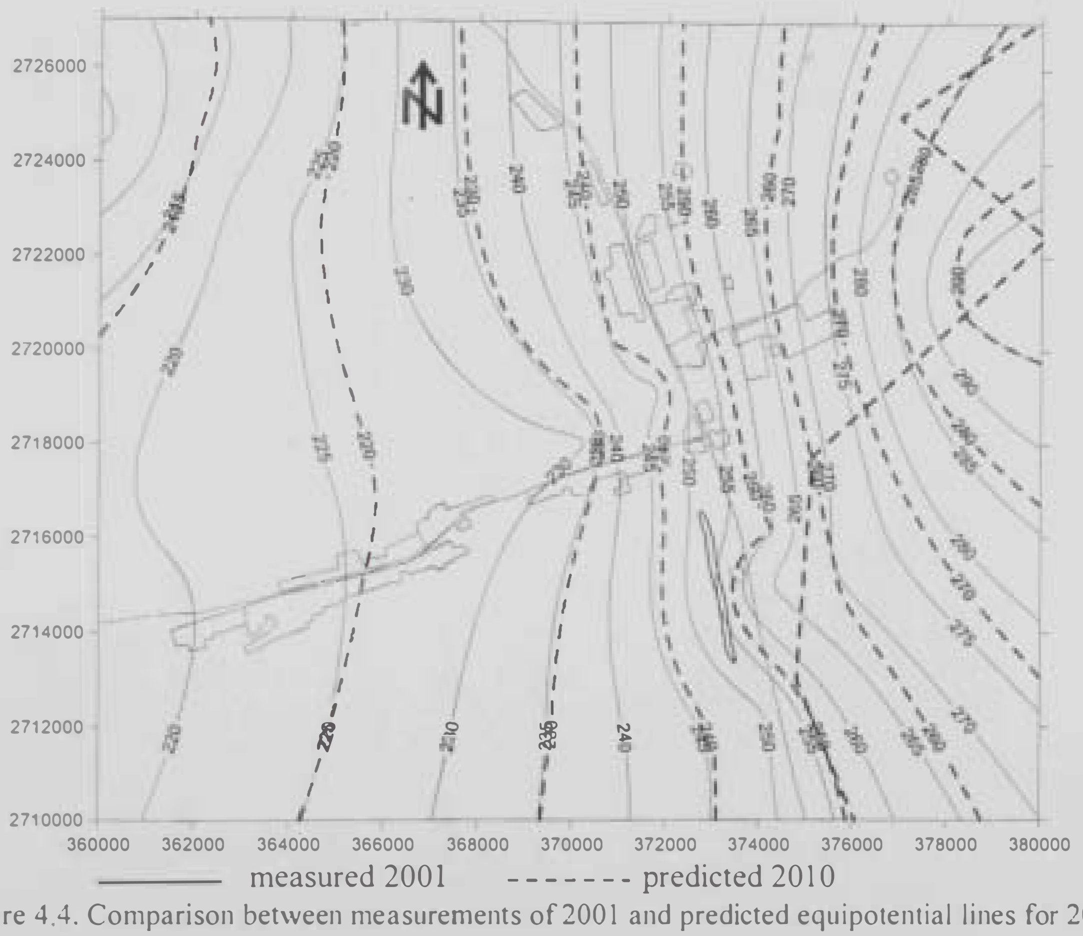


Figure 4.4. Comparison between measurements of 2001 and predicted equipotential lines for 2010.

the year 2001, the average decline in groundwater levels varied between 5 m near the boundaries to about 9.5 m in the central areas where most of the pumping activities are located. Figure 4.4 presents a comparison between the available measurements of 2001 and the simulated equipotential lines for the year 2010.

It should be noted, however, that the results of this simulation should be regarded as qualitative rather than quantitative. This is mainly attributed to the missing information regarding the hydrogeological data and pumping activities. Nevertheless, it can be concluded that the groundwater levels in the study area would continue to decline under the current pumping activities.

Chapter 5. Summary and Conclusions

5.1. Summary

The increase of population in the different countries around the globe along with the associated increase in agricultural and industrial activities has led to the water shortage problem over the last few decades. The limited availability of freshwater resources has already become commonplace in many parts around the world. The problem is more severe in arid in semi-arid regions where renewable freshwater resources are very limited. The twin phenomena of depletion of exiting fresh water resources together with the pollution of these resources are causing a growing problem in these areas. The UAE is an example of such countries with limited fresh water resources.

Despite the severity of the water shortage problem in the UAE, the water is used unwisely and wastefully. The per capita consumption in the UAE (around 700 l/d) is one of the highest in the world including those countries located in wet regions with very high rainfall intensities. Large-scale desalination plants have been constructed over that last few decades to bridge the gap between water consumption and water availability in the UAE.

Serious attempts are made by the concerned ministries in the UAE to alleviate the water shortage problem. Many retention and detention dams have been constructed over the last two decades to collect the surface water runoff in the main wadis and recharge the groundwater. These dams are also designed to prevent the undesirable consequences of flash floods. A total of 45 dams of different sizes have already been constructed and another 27 dams are currently under construction. Wastewater treatment plants have been constructed and large amounts of treated wastewater are being used in developing green areas and other restricted irrigation practices. The recharge of the groundwater through dams and the reuse of the treated wastewater are expected to help sustain the groundwater resources in the country.

The main objective of this study is to assess the availability and sustainability of groundwater resources in some selected areas of Al Ain. Although many studies on the water resources, in general, and groundwater resources, in particular, in the UAE exist, the current research provides a comprehensive assessment and analysis for the groundwater resources in four areas in Al Ain; namely, Al Hayer, Gummed, Nahil, and Al Khadar.

The stratigraphy and structures in the UAE were reviewed and the groundwater flow systems were outlined with some information of the water type in the different areas. The aquifers are classified as limestone aquifers, ophiolite aquifers, gravel aquifers and sand dunes aquifers. The relationships between rainfall and groundwater recharge in the different Emirates of the country were discussed.

Emphasis was devoted to Al Ain aquifer. The extent, thickness and the hydraulic characteristics of the aquifer were presented and discussions were provided on the basal confining system and its hydraulic characteristics. The occurrence and movement of the groundwater and the changes in the groundwater levels and main depressions at Al Ain area were discussed. The aquifer storage and specific yields were elaborated and the groundwater recharge through gaps and precipitations were presented.

Thirty four wells were selected for the analysis of the groundwater conditions in the study area of which 23 wells belong to the National Drilling Company and 11 wells belong to Al Ain Distribution Company. Contour maps were developed for the equipotential lines and drawdown for different years including 1991, 1993, 1995, 1997, 1999 and 2001 were presented to demonstrate the changes in groundwater levels over the last decade. A comparison between the equipotential lines for the year 1991 and 2001 was made and examples were given for the drawdown in some wells.

The quality of the groundwater in the study area was also investigated. Contour maps for the equiconcentration lines were presented for different years. The changes in the groundwater quality over the last two decades were assessed. Possible measures and alternatives for groundwater conservation were discussed.

A finite element model (SUTRA) was employed to simulate the groundwater condition in the study area. The model was used with Argus-One GUI to represent the study domain, develop the input data, and present the outputs. The study domain was discretized into 8524 quadrilateral elements. The model was calibrated first using the available groundwater measurements for the year 2001 and was then used to develop the equipotential lines for the year 2010.

5.2. Conclusions

Based on the results of this study, the following conclusions can be made:

1- Despite the severe shortage in renewable freshwater resources in the UAE. the per capita water consumption (about 700 l/d) is among the highest rates in the world including those countries with plenty of renewable water resources.

2- Groundwater resources in the UAE, in general, and in the studied area, in particular, are subject to depletion due to the limited natural recharge from rainfall as well as the excessive pumping for agricultural purposes.

3- The available data regarding the groundwater resources are not only limited but also scattered. Data are not available under one cover and are not stored in one database.

4- As compared to the measurements of 1991, the maximum decline in the groundwater level was 3.6 m in 1993, 10 m in 1997, and 17 m in 2001. These values were generally recorded at the center of the study area.

5- The decline in the groundwater levels in the northern part of the study domain is relatively small indicating limited pumping activities in these areas or perhaps more recharge.

6- The quality of the groundwater during the last two decades, since 1982 has remained within the acceptable levels despite the continuous decline in the groundwater levels. Within the study area, the salinity varied between 350 ppm and 1300 ppm and only very small areas had a salinity level higher than 1000 ppm. Therefore, the quality of the groundwater is still good and can be used for unrestricted irrigation.

7- The SUTRA model has been used successfully to simulate the groundwater conditions under the current conditions and predict the groundwater levels in the year 2010.

8- Based on the results of the numerical model, the additional decline in the groundwater levels by the year 2010 is expected to vary from 5 m near the boundaries of the study domain to about 9.5 m in the central part of the area where most of the pumping activities are located.

9- Due to the lack of information, the results of the numerical model should be regarded as qualitative indicators rather than quantitative assessment.

5.3 Recommendations

The following recommendations are made.

1. A dynamic Geographical Information System (GIS) database should be developed for all the hydrogeological data in the UAE. This database should be accessible for all officials, researchers and scientists in the various fields of water resources development, protection and management.
2. Emphasis should be devoted to the development of water conservation plans at the national level. In other words an integrated water master plan for the country should be developed in which all issues related to the conservation and sustainability of water resources, in general, and groundwater, in particular, are addressed.

3. Launching national programs for public awareness regarding the importance of water conservation is a key element in the water conservation master plan.
4. The construction of new groundwater pumping wells should be fully controlled by concerned authorities. The pumping rates should also be monitored to avoid over pumping practices.
5. Modern irrigation techniques such as drip, bubbler and sprinkler should be employed whenever possible.
6. The treated wastewater can be fully utilized in the development of green areas and other restricted irrigation purposes as well as in the recharge of groundwater aquifers. This would help sustain the groundwater resources in the country.

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Appendix A: Rainfall Data

Table A1: Total monthly rainfall (mm) Dubai area during 1967-2002 periods (Ministry of Communications, U. A. E., 2002).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Sum
1967	-	-	-	-	-	-	0	0	0	0	TR	11.4	11.4
1968	2.8	90.4	TR	TR	0	0	0	0	0	0	TR	19.1	112.3
1969	75.9	2	0	5.8	0	0	0	0	0	3.3	0.3	0	87.3
1970	15.7	0	TR	0	0	0	0	TR	0	0	0	TR	15.7
1971	TR	TR	TR	1.8	0	0	0	0	0	0	10.8	1.3	13.9
1972	1.3	1.4	68.1	60	0	0	0	0	0	0	TR	4.5	135.3
1973	44.4	0	0	TR	0	0	TR	0	0	0	0	TR	44.4
1974	4.7	25.5	TR	TR	TR	0	0	TR	0	0	0	5.1	35.3
1975	42.7	26.8	TR	5.3	0	0	TR	0.4	0	0	0	0	75.2
1976	5.2	75	29.6	19.9	0	0	TR	0	0	TR	0	1.6	131.3
1977	24.8	30.1	6.5	16.6	0	0	0	TR	0	TR	4.1	3.2	85.3
1978	0	35.2	4.1	3.1	TR	0	TR	0	0	0	0	0	42.4
1979	TR	TR	49.2	0	0	0	0	TR	0	0	0	34.7	83.9
1980	1.2	36.7	4.5	0	0	0	0	TR	0	0	0	TR	42.4
1981	TR	0.7	15.6	33.1	12.9	0	TR	TR	0	0	0	0	62.3
1982	11.2	73.6	109.1	TR	0.0	0.0	0.0	TR	0.0	0.0	6.0	12.6	212.5
1983	23.5	49.0	20.0	14.2	TR	0.0	0.0	TR	0.0	0.0	0.0	TR	106.7
1984	TR	0.0	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.7	22.8
1985	5.7	0.0	3.1	TR	TR	0.0	0.0	0.0	0.0	0.0	TR	0.2	9
1986	13.9	11.1	15.8	1.4	0.0	0.0	TR	0.0	0.0	0.0	5.8	75.7	123.7
1987	0.0	TR	82.9	5.5	0.0	0.0	0.0	TR	0.0	0.0	0.0	13.7	102.1
1988	1.3	190.4	0.3	20.3	0.0	0.0	0.5	0.0	0.0	0.0	0.0	7.8	220.6
1989	TR	14.3	32.7	9.1	0.0	0.0	TR	0.0	0.0	0.0	17.0	70.3	143.4
1990	42.3	70.8	1.3	7.9	0.0	0.0	0.0	0.3	0.0	0.0	0.0	TR	122.6
1991	27.7	4.3	22.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.2	71.7
1992	31.4	38.4	1.3	43.7	TR	0.0	0.0	TR	0.0	0.0	0.0	44.9	159.7
1993	2.1	83.6	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	88
1994	7.5	TR	2.0	2.0	0.3	0.0	TR	0.0	1.3	0.0	0.3	0.0	13.4
1995	0.0	9.3	43.4	0.5	0.0	0.0	33.2	0.0	0.0	0.0	0.0	130.6	217
1996	48.6	20.0	155.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	228.6
1997	67.5	TR	118.5	3.2	0.0	0.0	0.0	0.0	0.0	42.8	30.7	9.0	271.7
1998	81.9	21.4	5.4	0.8	0.0	0.0	TR	0.0	0.0	0.0	0.0	0.5	110
1999	0.3	37.2	7.0	0.0	0.0	0.0	TR	TR	0.0	0.0	0.0	0.0	44.5
2000	0.3	0.0	Tr	0.0	0.0	0.0	0.0	0.0	0.0	Tr	6.2	17.7	24.2
2001	7.8	TR	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.8
2002	3.8	0.6	24.4	0.6									

TR=TRACE: LESS THAN 0.05mm.

Max.	81.9	190	155	60	12.9	0	33.2	0.4	1.3	42.8	30.7	131	271.7
Min.	0	0	0	0	0	0	0	0	0	0	0	0	8.8

Note: Max. and Min. rainfall values are recorded for the period 1971-2001.

Table A2: Total monthly rainfall (mm) Sharjah area (Ministry of Communications, U. A. E., 2002).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Sum
1934	10	0	48	0	0	0	0	0	0	0	1	45	104
1935	2	106	0	0	0	0	0	0	0	0	0	4	112
1936	48	1	2	3	0	0	0	0	0	0	113	63	230
1937	1	25	16	0	0	0	0	0	0	0	0	34	76
1938	31	5	0	0	0	0	0	0	0	0	0	22	58
1939	59	36	1	11	0	0	0	0	0	0	0	1	108
1940	46	7	7	0	0	0	0	0	0	0	20	0	80
1941	0	2	26	30	0	0	0	0	0	0	0	0	58
1942	1	41	0	0	0	0	0	0	0	0	0	13	55
1943	53	62	17	4	0	0	0	0	0	0	0	91	227
1944	0	2	0	0	0	0	0	0	0	0	0	174	176
1945	39	0	1	0	0	0	0	0	0	0	0	2	42
1946	0	0	7	0	0	0	0	0	0	0	0	0	7
1947	27	7	24	0	0	0	0	0	0	0	24.4	9.6	92
1948	0	41	5	0	0	0	0	0	0	15.6	2.5	8.1	72.2
1949	4.5	0	NA	NA	NA	NA	NA	NA	0	Tr	45	9	58.5
1950	18.6	2	10.2	Tr	2.1	0	0.3	0	0	0	3.3	8.8	45.3
1951	0.7	Tr	14.4	0	5.9	0	0	0	0	0	0	36.4	57.4
1952	65.2	Tr	0.5	2.4	Tr	0	0	0	0	0	0	27.8	95.9
1953	0	53.2	0.5	1.7	Tr	0	0	0	0	0	0	4.5	59.9
1954	0	59.6	17.4	Tr	0	0	0	0	0	0	69.4	0.2	146.6
1955	88.2	0.4	50.1	0	Tr	0	0	Tr	0	0	0	56.1	194.8
1956	7.1	Tr	1	0.5	0	Tr	15.6	0	5.4	0.7	0	2.9	33.2
1957	95.1	4.9	2	154	0.6	0	0	Tr	Tr	0	76.7	12.1	345.4
1958	16	Tr	0.1	0	0	0	3	0	0	0	19.2	61.7	100
1959	56.8	4	Tr	Tr	0	0	0	Tr	0	Tr	12.2	3.2	76.2
1960	7.8	Tr	4.8	19.6	0	0	0	0	Tr	Tr	Tr	3.3	35.5
1961	8.6	34	14.6	28.8	0	0	Tr	Tr	Tr	Tr	Tr	Tr	86
1962	Tr	0	Tr	0.3	0	Tr	Tr	0	0	0	0	7.5	7.8
1963	Tr	2.4	13.2	8.4	120.6	0	8.3	0	0	0	30.4	3.4	186.7
1964	29.4	29.6	2.8	Tr	0	Tr	Tr	0	0	0	Tr	80.7	142.5
1965	59.7	Tr	0.7	11.8	Tr	0	Tr	0	Tr	0	0	1.4	73.6
1966	0.3	59.1	0	Tr	0	0	0	Tr	0	0	0	Tr	59.4
1967	Tr	3.4	6.9	1.2	Tr	Tr	Tr	Tr	Tr	Tr	Tr	3.6	15.1
1968	1.6	76.3	Tr	0.3	Tr	Tr	Tr	Tr	Tr	Tr	Tr	17.2	95.4
1969	112.5	0.3	Tr	5.2	Tr	Tr	Tr	Tr	Tr	19.5	Tr	0.3	137.8
1970	30.3	0.5	Tr	Tr	Tr	Tr	Tr	2.4	Tr	Tr	Tr	Tr	33.2
1971	4.9	0.6	0.2	5.1	Tr	Tr	Tr	Tr	Tr	Tr	27.8	14.2	52.8
1972	12	0	114.8	5.6	0	0	0	0	0	0	0	Tr	132.4
1973	45	6.7	0	0	0	0	0	0	0	0	0	0	51.7
1974	3.1	0	0	0	0	0	0	0	0	0	0	0	3.1
1975	167.4	0	0	0	0	0	0	0	0	0	0	0	167.4
1976	0	128.2	20	19.9	0	0	0	0	0	0	0	1.6	169.7
1977	34.6	29.8	13.1	14.7	0	0	0	0	0	Tr	41.6	5.4	139.2
1978	0	25.6	11.1	2.5	Tr	0	Tr	0	0	0	Tr	0	39.2
1979	4	Tr	68.2	0	0	0	0	Tr	0	0	0	57.1	129.3
1980	1.2	38.2	28.6	0	0	0	0	0	0	0	0	1.7	69.7
1981	Tr	0.3	21.8	37.7	20.6	0	Tr	Tr	0	0	0	0	80.4
1982	2.7	82.4	156.4	Tr	Tr	0	0	0	0	0	15	15.8	272.3
1983	26.4	85.7	25.9	20.1	0	0	0	0.6	0	0	0	3.9	162.6
1984	0.5	Tr	7.6	0	0	0	0	0	0	0	0	9.2	17.3
1985	5.7	0	2	0.7	Tr	0	0	0	0	0	0	0.2	8.6
1986	21.2	24.5	6.7	2.5	0	0	Tr	0	0	0	0.5	49.9	105.3
1987	0	Tr	90	1.2	0	0	0	Tr	0	0	0	7.2	98.4
1988	1.4	142.9	0.5	17.7	0	0	0.7	0	0	0	0	4	167.2
1989	Tr	13.8	40.4	6.5	0	0	0.5	0	0	0	18.5	59.7	139.4
1990	30.4	75.3	1.2	8.2	0	0	0	Tr	0	0	Tr	Tr	115.1
1991	15.1	3.2	21.6	Tr	0	0	0	0	0	0	0.7	17.9	58.5
1992	29.3	34.8	0.7	43.7	Tr	0	0	Tr	0	0	0	35	143.5
1993	2.1	95.8	1	Tr	0	0	0	0	0	0	0	2.2	101.1
1994	14.2	Tr	3.7	0.2	3	0	Tr	0	9.2	0	Tr	Tr	30.3
1995	0	33.4	58.4	0.9	0	0	53.1	0	0	0	0	146.5	292.3
1996	53.3	24.5	152.6	1	0	0	0	0	0	0	Tr	0.5	231.9
1997	71.6	Tr	125	2.7	0	0	0	0	Tr	63.4	39.1	17.1	318.9
1998	97.8	18	17.5	16.5	0	0	29.6	0	0	0	0	0.9	180.3
1999	29.8	37.2	6.9	0	0	0	Tr	Tr	0	0	0	Tr	73.9
2000	Tr	0	0.2	Tr	0	0	Tr	0	0	Tr	2	12.4	14.6
2001	8.2	Tr	tr	0	0	0	tr	0	0	0	0.8	0.8	9.8
2002	3.6	0.2	29.4										

Table A3: Long term total monthly rainfall (mm) Ras Al-Khaimah area during 1976-2002 periods (Ministry of Communications, U. A. E., 2002).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Sum
1976	NA	NA	25.6	28.7	0	0	0	0	0	12.2	1.8		68.3
1977	73.2	43	12.9	41.5	0	0	0	0	0	0	18.8	7.3	196.7
1978	0	39.3	3.9	0	0	0	0	0	21	0	0.5	0	64.7
1979	13.7	0	63.1	0	0	0	0	0	0	0	0	99.4	176.2
1980	2.4	46.2	12	0	0	0	0	0	0	0	0	1.7	62.3
1981	1.3	0.7	19.1	27.6	29.9	0	0	0	0	5.6	0	0	84.2
1982	6.0	120.7	128.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	89.6	35.5	380.5
1983	28.4	39.5	53.9	7.8	0.0	0.0	0.0	2.8	0.0	0.0	0.0	4.2	136.6
1984	2.8	0.0	8.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.1	29.6
1985	4.7	0.0	4.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	14
1986	13.0	14.6	12.9	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	24.7	65.7
1987	0.0	2.4	96.8	2.0	0.9	0.0	0.0	2.0	0.0	0.0	3.6	8.8	116.5
1988	17.8	121.7	2.2	18.0	0.0	0.0	8.5	0.0	0.0	0.0	0.6	8.1	176.9
1989	0.0	20.5	22.9	6.9	0.0	0.0	0.0	0.0	0.0	0.0	3.0	39.6	92.9
1990	26.6	72.2	0.8	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	106.9
1991	31.6	8.3	85.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.5	152.3
1992	34.5	92.7	2.2	29.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	43.0	201.5
1993	19.0	160.3	1.6	TR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	189.9
1994	34.3	0.0	6.3	0.0	TR	0.0	TR	TR	0.3	0.0	0.0	0.0	40.9
1995	TR	25.7	53.3	0.9	0.0	0.0	20.4	0.0	0.0	0.3	0.0	183.8	284.4
1996	70.2	29.9	175.4	0.8	0.0	0.0	0.0	0.0	0.0	2.0	3.5	8.4	290.2
1997	58.6	TR	123.1	29.0	0.0	0.0	TR	0.0	0.0	38.7	80.5	12.1	342
1998	92.5	37.9	82.1	44.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.5	265
1999	4.3	52.0	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.5
2000	Tr	0.0	Tr	0.0	0.0	0.0	0.0	0.0	6.2	0.0	Tr	24.7	30.9
2001	14.2	TR	1.8	0	0	0	0	0	0	0	0	0	16
2002	4.4	1.7	16.3										

NOTE =TR=TRACE=LESS THAN 0.05 mm.

Table A4: Long term monthly total rainfall (mm) Fujairah area during 1988-2001 periods (Ministry of Communications, U. A. E., 2002).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	**Sum**
1988	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1989	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1990	0.0	0.0	0.0	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.1
1991	1.4	37.5	30.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	4.4	77.2
1992	39.2	22.9	2.4	44.8	0.0	0.0	0.0	0.0	0.0	8.5	0.0	18.6	136.4
1993	9.7	61.4	6.2	0.0	0.0	0.0	0.0	7.5	0.0	0.0	0.0	63.9	148.7
1994	119.4	0.0	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	125.5
1995	0.0	3.3	104.8	4.3	1.0	0.0	44.1	0.0	0.0	2.2	0.0	325.2	484.9
1996	111.4	20.4	149.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	291.6
1997	43.0	0.0	121.8	21.2	0.0	0.0	0.0	1.0	0.0	40.9	23.8	0.4	252.1
1998	54.0	17.2	4.3	8.5	0.0	0.0	1.4	0.0	0.0	0.0	0.0	1.9	87.3
1999	17.2	9.3	12.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	0.0	42.8
2000	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.7	6.4	31.4
2001.0	13.9	0.0	1.0	0.0	0.0	0.0	Trace	0.0	0.0	0.0	Trace	6.2	21.1

Appendix B: Aquifer Characteristics

Table B1: Thickness of near-surface permeable material, aquifer thickness, thickness of saturated eolian dune sand, and fresh-water thickness in Groundwater Research Project wells (National Drilling Company, United States Geological Survey-Groundwater Research Project, 1993).

[m, meters; nd, no data; est, estimated]

Ground-water project well number	UTM Coordinates x (m) y (m)	Land-surface altitude (m)	Water-level altitude (m)	Thickness of near surface permeable material (m)	Aquifer thickness (m)	Thickness of saturated eolian dune sand (m)	Fresh-water thickness (m)
1	393675.8 2677489.5	408.20	381.5	nd	nd	0.0	nd
2	393665.5 2677553.0	408.41	381.5	nd	nd	0.0	nd
3	393634.2 2677490.7	407.90	381.5	nd	nd	0.0	nd
4	393649.1 2677498.4	408.05	381.5	nd	nd	0.0	nd
5	389344.6 2675789.0	377.34	351.7	nd	nd	0.0	nd
6	386313.8 2667305.7	342.52	322.2	72	51.3	0.0	51
7	380942.0 2664080.4	322.30	300.5	102	80.3	0.0	0
8	393220.5 2665971.9	379.92	358.2	110	88.0	0.0	29
9	390728.0 2669147.5	369.65	347.9	102	80.3	0.0	39
10	381480.3 2658958.7	317.41	302.2	117	102.1	0.0	40
11	385939.[illegible] 2662909.3	337.[illegible]	319.1	81	62.0	0.0	62
11A	385903.1 2662911.2	337.75	319.1	81	62.1	0.0	62
12	333515.6 2670609.1	175.55	156.4	75	70.8	0.0	0
13	344764.0 2666213.0	191.50	170.0	104	88.2	0.0	0
14	380303.5 2668360.8	320.60	298.0	130	106.9	0.0	40
15	386144.1 2671155.0	348.52	325.1	40	16.2	0.0	18
16	384530.3 2677390.0	343.36	321.5	46	23.9	0.0	24
17	388463.8 2674345.8	367.30	341.9	43	17.2	0.0	20
18	393546.3 2676791.5	403.39	378.6	44	19.4	0.0	22
19	3[illegible]0702.6 2676523.7	320.10	301.7	50	31.9	0.0	nd
20	395299.9 2664216.2	389.59	371.0	107	88.1	0.0	nd
21	375639.1 2684295.2	288.63	279.0	55	45.2	0.0	45
22	367988.3 2660340.9	233.98	228.7	76	104.4	28.2	0
23	35[illegible]886.5 2667117.2	213.30	195.5	131	113.3	0.0	0
24	374413.8 2694660.7	291.83	273.3	94	76.0	0.0	42
25	367278.2 2704858.7	302.95	252.1	64	61.9	0.0	31
26	366911.3 2690173.8	265.10	250.0	84	77.9	0.0	6
27	3[illegible]8860.3 2696782.8	247.50	224.6	41	60.9	19.7	17
28	364028.1 2694232.7	254.55	241.6	107	93.7	0.0	0
29	355025.6 2690927.2	226.50	213.4	30	41.8	11.3	0
30	373439.0 2706793.3	303.15	271.3	30	20.0	0.0	18

Table B1: Thickness of near-surface permeable material, aquifer thickness, thickness of saturated eolian dune sand, and fresh-water thickness in Groundwater Research Project wells -- Continued

Ground-water project well number	UTM Coordinates x (m)	UTM Coordinates y (m)	Land-surface altitude (m)	Water-level altitude (m)	Thickness of near surface permeable material (m)	Aquifer thickness (m)	Thickness of saturated eolian dune sand (m)	Fresh-water thickness (m)
31	373283.9	2706781.7	301.26	270.6	30	21.2	0.0	20
32	364805.0	2710366.8	278.68	240.4	46	44.0	0.0	14
33	372609.1	2689331.1	285.32	268.6	137	126.5	0.0	14
34	368115.2	2722562.3	282.71	243.6	38	23.4	0.0	23
35	381470.4	2699614.0	320.66	295.7	107	84.8	0.0	25
36	374106.5	2728997.9	286.55	271.3	nd	nd	nd	nd
37	367645.9	2728527.5	255.87	236.2	43	23.0	0.0	23
38	374014.2	2714939.1	297.13	277.4	34	19.9	0.0	21
39	362759.0	2733315.5	224.19	201.7	40	20.2	0.0	19
40	376882.1	2737707.6	260.34	241.7	81	62.1	0.0	62
41	373344.3	2714969.6	293.23	273.4	nd	nd	0.0	nd
42	373366.0	2714965.3	293.51	273.4	nd	nd	0.0	nd
43	355960.7	2713581.2	233.75	212.2	67	48.6	0.0	50
44	359657.0	2720368.6	237.40	214.3	27	16.5	0.0	20
45	350923.4	2721237.5	201.63	108.7	37	46.1	9.5	26
46	338364.9	2724045.4	150.29	129.5	56	35.6	0.0	0
47	321045.8	2726021.4	105.38	101.3	52	50.7	0.0	0
48	353262.6	2705555.1	220.00	210.0	46	51.0	5.2	0
49	318709.3	2723584.5	106.73	100.8	55	48.9	0.0	0
50	337523.4	2710488.8	161.55	148.8	52	39.0	0.0	0
51	322909.2	2714174.4	129.83	119.5	38	33.9	0.0	0
52	321768.8	2703596.6	134.22	130.4	34	35.8	2.3	0
53	328144.3	2692411.4	142.94	145.6	44	44.2	0.0	0
54	335705.3	2701050.7	165.04	154.2	47	36.4	0.9	0
55	338640.1	2690163.6	176.98	162.8	69	54.4	0.0	0
56	318638.6	2690281.9	152.20	133.8	62	44.1	0.0	0
57	342417.6	2685084.1	184.62	168.8	82	66.4	0.0	0
58	328223.7	2679855.1	146.26	148.8	73	79.2	6.1	0
59	313695.8	2678194.3	146.06	133.1	64	63.2	0.0	0
60	330451.6	2671452.4	161.76	153.1	88	88.9	0.5	0
61	345170.0	2679918.9	192.44	171.7	76	64.6	0.0	nd
62	353884.9	2670381.1	210.69	190.7	151	131.0	0.0	0

Table B1: Thickness of near-surface permeable material, aquifer thickness, thickness of saturated eolian dune sand, and fresh-water thickness in Groundwater Research Project wells -- Continued

Ground-water project well number	UTM Coordinates x (m)	y (m)	Land-surface altitude (m)	Water-level altitude (m)	Thickness of near surface permeable material (m)	Aquifer thickness (m)	Thickness of saturated eolian dune sand (m)	Fresh-water thickness (m)
73	348780.3	2669781.2	200.78	179.0	117	108.0	0.0	nd
74	350445.6	2675177.8	208.99	180.2	113	90.1	0.0	nd
75	355639.1	2684435.5	220.86	196.4	30	6.0	0.0	0
76	369033.2	2684691.5	269.06	258.3	nd	nd	0.0	Est 32
77	365786.1	2685922.0	268.16	246.3	78	68.1	0.0	nd
78	395194.4	2664639.0	388.43	369.5	nd	nd	0.0	nd
79	373466.0	2714681.9	295.83	264.1	nd	nd	nd	nd
80	380371.1	2670276.1	323.50	298.8	nd	nd	nd	nd
81	304743.8	2649858.7	132.88	121.0	46	76.5	30.8	nd
82	339715.7	2657083.3	172.28	164.0	92	86.5	0	nd
83	344073.5	2643409.9	167.72	165.0	62	68.0	6.4	nd
84	349200.1	2629570.2	181.22	165.0	69	62.4	0	nd
85	329346.9	2635843.3	143.53	142.2	74	87.7	13.9	nd
86	330069.0	2624087.0	144.66	139.0	56	56.5	0.4	nd
87	332940.5	2610534.1	138.85	136.0	86	88.9	3.2	nd
88	304208.7	2628878.5	122.92	114.0	37	64.3	26.8	nd
89	319622.0	2603060.5	119.28	118.5	72	71.2	0	nd
90	352997.1	2612228.0	172.12	162.0	85	65.2	0	nd
91	307686.2	2585567.2	102.98	101.9	56	55.4	0	nd
92	330972.1	2578105.9	122.97	119.5	91	88.0	0	nd
93	342902.8	2598118.1	149.18	142.5	105	99.1	0	nd

Table B2: Hydraulic or geohydrologic properties determined from petrophysical logs (National Drilling Company, United States Geological Survey-Groundwater Research Project, 1993).

[m^2/d, square meters per day; m, meters; m/d, meters per day]

Ground- water project well number	Transmissivity (m^2/d)	Al Ain aquifer thickness [1] (m)	Hydraulic conductivity (m/d)	Specific yield
23	760	113.3	6.70	0.17
26	2.0	77.9	.03	.01
27	26.9	60.9	.44	.08
29	.2	41.8	.01	.01
30	.4	20.0	.02	.09
32	9.7	44.0	.22	.06
33	633	126.5	5.00	.09
38	25.9	19.9	1.37	.12
39	148	20.2	7.31	.27
40	71.9	62.1	1.16	.06
43	59.3	48.6	1.22	.11
44	3.0	16.5	.18	.07
45	1,320	46.1	28.7	.08
46	152	35.6	4.26	.24
47	27.4	50.7	.54	.06
49	21.0	48.9	.43	.07
50	8.3	39.0	.21	.05
51	.9	33.9	.03	.07
52	777	35.8	21.7	.23
53	211	44.2	4.76	.13
54	.3	36.4	.01	.02
55	10.9	54.4	.20	.05

Table B2: Hydraulic or geohydrologic properties determined from petrophysical logs -- continued

Ground- water project well number	Transmissivity (m^2/d)	Al Ain aquifer thickness [1] (m)	Hydraulic conductivity (m/d)	Specific yield
56	26.3	44.1	0.60	0.09
57	53.1	66.4	.80	.05
58	9.0	79.2	.11	.02
59	49.1	63.2	.78	.05
60	38.7	88.9	.44	.05
61	.8	64.6	.01	.01
62	3.7	131	.03	.01
63	961	108	8.90	.10
64	71.3	90.1	.79	.11
65	.1	6.0	.01	.03
67	3.6	68.1	.05	.03
81	250	76.5	3.27	.11
82	452	86.5	5.23	.10
83	82	68.0	1.21	.07
84	23.6	62.4	.38	.06
85	286	87.7	3.26	.08
86	157	56.5	2.78	.08
87	1,700	88.9	19.1	.16
88	193	64.3	3.00	.11

1 Thickness is the difference between predevelopment water level and the bottom of the aquifer as determined from petrophysical-log analysis.

Table B3: Estimation of the aquifer properties (National Drilling Company, United States Geological Survey-Groundwater Research Project, 1993).

Ground water project number	Well ᵃ depth (meters below gs)	Screen length (meters)	Location UTM[8] Y Coordinate	Location UTM[8] X Coordinate	Location Area Name	Ground-surface elevation (meters)	Date pumped (day/month/year)	Time pumped (minutes)	Pump setting[7] (meters)	Static water level (meters below gs)	Drawdown (meters)	Pumping rate (m^3/hr)	Specific capacity (m^2/hr)	Specific conductance, water (µS/cm)	Remarks
1	52.9	37.5	2677489.5	393675.8	Zarub Gap	408.2	--	--	--	30.92	--	--	--	--	Existing well. Not pumped. First water level measurement 10/11/88
2	58.7	23.5	2677553.0	393665.5	Zarub Gap	408.2	--	--	--	31.42	--	--	--	--	Existing well. Not pumped. First water level measurement 10/11/88
3	457.0	6	2677490.6	393634.2	Zarub Gap	407.9	--	--	--	32.13	--	--	--	--	Uncased borehole. Not pumped
4	39.6	6.1	2677498.4	393649.1	Zarub Gap	408.0	--	--	--	31.23	--	--	--	--	Very small yield.
5	42.7	6.7	2675789.0	389344.6	Al Jaww Plain	377.3	--	--	--	32.29	--	--	--	--	Small yield.
6	170.7	110.2	2667305.7	386313.8	Iraqia	342.5	07/10/89	465	140.8	18.62	110.96	4.46	0.040	1,960	On site measurement of specific conductance was 2,100 µS/cm at 83° C after 450 minutes of pumping.
7	113.9	40.6	2664080.4	380942.0	Al Dahir	322.3	26/09/89	300	103.6	24.00	64.70	11.96	0.185	2,870	Laboratory measurement of specific conductance; dissolved solids of 1,952 mg/l.
8	731.5	6	2665971.9	393220.5	Umm Ghafa	379.9	--	--	--	28.14	--	--	--	--	Not cased or pumped. Very small yield indicated by attempts to air lift pump.
9	611.4	6	2669147.6	390727.9	Al Jaww Plain	369.6	--	--	--	29.68	--	--	--	--	Not cased or pumped. Very small yield indicated by attempts to air lift pump.
10	786.4	6	2658958.7	381480.3	Mazyad	317.4	--	--	--	15.60	--	--	--	--	Not cased or pumped. Very small yield indicated by attempts to air lift pump.
11	488.3	6	2662911.2	385903.1	Umm Ghafa	337.8	--	--	--	26.50	--	--	--	--	Uncased; crooked hole. Not pumped.
11A	110.3	63.6	2662909.3	385939.8	Umm Ghafa	337.8	26/10/89	300	84.8	26.69	9.27	23.24	2.51	530	Good yield and water quality.

Table B3: Estimation of the aquifer properties -- continued.

Ground water project number	Well [a] depth (meters below gs)	Screen length (meters)	Location			Ground-surface elevation (meters)	Date pumped (day/ month/year)	Time pumped (minutes)	Pump setting [c] (meters)	Static water level (meters below gs)	Drawdown (meters)	Pumping rate (m^3/hr)	Specific capacity (m^2/hr)	Specific conductance, water [illegible]	Remarks
			UTM [b]												
			Y Coordinate	X Coordinate	Area Name										
12	223.9	52.8	2670609.1	333515.6	Seh Al Miah	175.6	16/12/89	510	122.00	23.85	32.09	17.80	0.555	2,860	
13	372.0	122.0	2666213.0	344764.0	Gharaba forest	191.5	20/12/89	450	122.00	46.46	25.95	22.30	0.859	8,450	
14	253.4	168.2	2668360.7	380303.5	Coca Cola plant	320.6	26/12/89	460	122.00	28.00	23.36	20.29	0.875	1,500	
15	53.4	23.2	2671155.0	386144.1	Iraqia	348.5	30/11/89	480	48.80	26.51	9.84	11.30	1.148	1,250	
16	99.7	29.0	2677389.9	384530.3	Al Jaww Plain	343.4	9/2/90	29	94.50	33.28	60.32	--	--	1,760	Not a valid test. Over-pumping emptied well; slow recovery indicated small yield.
17	50.4	17.4	2674345.8	388463.8	Al Jaww Plain	367.3	27/1/92	4320	45.11	25.95	6.06	81.75	13.49	487	Excellent yield and water quality.
18	51.7	17.4	2676791.4	393546.3	Zarub Gap	403.4	3/2/92	1920	45.11	27.30	8.45	65.53	7.75	484	Excellent yield and water quality.
19	40.8	11.6	2676523.7	380702.6	Al Jaww Plain	320.1	20/2/90	450	30.50	19.34	1.59	5.69	3.58	365	Excellent water quality.
20	232.1	156.6	2664216.2	395299.9	Umm Ghafa	389.6	20/5/90	300	186.00	20.36	77.80	14.80	0.190	2,400	
21	609.6	8	2684295.2	375639.1	Hili	288.6	--	--	--	69.81	--	--	--	--	Not cased. Air lift pumping gave no yield.
22	221.7	81.7	2660340.9	367988.3	Ain Al Faydah	234.0	20/7/90	300	54.90	6.78	1.09	28.10	25.78	14,400	Large yield; saline water.
23	180.2	40.6	2667117.2	355886.5	Wadi Al Ain	213.3	13/8/90	320	143.30	35.53	39.89	3.07	0.077	19,000	Specific conductance greater than nearby wells.
24	75.6	29.0	2694660.7	374413.8	Bida Bint Saud	291.8	28/8/90	300	57.90	23.38	10.66	19.95	1.871	990	
25	155.0	86.8	2704858.7	367278.2	Bida Bint Saud	303.0	24/9/90	300	103.60	52.11	16.56	14.71	0.888	1,800	
26	98.3	46.4	2690173.8	366911.3	Bida Bint Saud	265.1	26/11/90	245	85.36	14.22	2.45	27.73	11.32	2,600	Good yield, fairly good water quality.
27	47.4	11.6	2696782.8	358860.2	Bida Bint Saud	247.5	13/10/90	300	39.63	26.68	6.08	10.52	1.720	2,410	
28	168.5	81.2	2694232.7	364028.1	Shabak well field	254.5	30/10/90	300	39.63	13.80	9.34	25.76	2.750	3,400	Fairly good yield, only fair water quality.

Table B3: Estimation of the aquifer properties -- continued.

Ground water project number	Well [*] depth (meters below gs)	Screen length (meters)	Location: UTM[1] Y Coordinate	Location: UTM[1] X Coordinate	Location: Area Name	Ground-surface elevation (meters)	Date pumped (day/ month/year)	Time pumped (minutes)	Pump setting[7] (meters)	Static water level (meters below gs)	Drawdown (meters)	Pumping rate (m^3/hr)	Specific capacity (m^2/hr)	Specific conductance, water [illegible]	Remarks
29	85.3	17.6	2690927.2	355025.6	Shabak well field	226.5	11/11/90	300	76.22	11.96	29.86	11.06	0.370	13,300	Poor water quality.
30	54.8	11.6	2706793.3	373438.9	Qurra well field	303.2	16/12/90	200	51.82	38.72	2.46	26.22	10.66	962	Good yield; excellent water quality.
31	57.0	11.6	2706781.7	373283.9	Qurra well field	301.3	23/12/90 16/6/91	300 4,320	50.91 51.83	37.52 37.56	2.13 6.04	25.82 52.28	12.12 8.660	710 720	Excellent water quality. Good yield; excellent water quality
32	87.8	34.8	2710366.8	364804.9	Near Mamoud Bin Ali farms	278.7	7/1/91	300	81.71	38.16	8.64	15.50	1.794	900	Fair yield; excellent water quality
33	146.3	92.7	2689331.1	372609.1	Wadi Towayya	285.3	8/12/90	300	123.48	24.57	34.23	22.87	0.670	3,100	Estimated 2, 100 mg/l TDS.
34	68.6	23.5	2722562.2	368115.2	Al Ain -Dubai highway	282.7	19/1/91	300	67.98	42.29	4.31	22.39	5.190	1,010	Good yield, excellent water quality
35	152.4	δ	2699614.0	381470.4	Wadi Towayya	320.7	--	--	--	--	--	--	--	--	Construction stopped, well abandoned.
36	59.6	34.8	2728997.87	374106.4	Kashuna	286.6	11/3/91	200	52.74	17.12	23.65	7.42	0.310	4,200	
37	61.1	40.6	2728527.53	367645.87	Al Khader	255.9	6/3/91	300	52.74	26.32	10.73	23.08	2.150	2,050	
38	45.2	11.6	2714939.11	374014.17	Al Mohayer	297.1	15/5/91	1,440	40.55	30.34	5.21	24.84	4.880	540	Good yield, excellent water quality
39	68.1	34.8	2733315.52	362759.08	Al Faqaa	224.2	22/3/91	300	56.70	25.69	9.39	22.43	2.390	2,250	About 1,500 mg/l TDS.
40	87.9	63.8	2737707.61	376882.05	Shwaib	260.3	30/3/91	300	77.70	19.11	29.43	19.30	0.660	1,100	About 737 mg/l TDS.
41	51.8	δ	2714969.61	373344.331	Jabal Mohayer	293.2	--	--	--	30.88	--	--	--	--	Uncased, to be used as observation well.
42	62.9	17.6	2714965.32	373365.94	Jabal Mohayer	293.7	28/4/91 6/5/91	1,440 1,440	57.30 56.09	31.08 31.16	0.15 0.94	49.98 85.14	98.00 90.57	2,200 2,500	At start of pumping, specific conductance was 1,850, about 1,240 mg/l, TDS.
43	172.8	112.9	2713581.20	355960.71	Sweihan road	233.8	6/8/91	300	123.70	26.72	106.38	10.00	0.094	6,310	About 4, 200 mg/l TDS.
44	53.9	23.2	2720368.64	359657.03	Jabeeb	237.4	26/5/91	300	48.78	20.56	4.77	20.79	4.360	1,300	About 871 mg/l TDS
45	35.7	11.6	2721237.50	350923.23	Old Kadar Well Field	201.6	8/6/91	300	32.01	17.16	4.88	21.16	4.330	4,500	About 3,020 mg/l TDS.
46	66.1	34.8	2724045.40	338364.89	Al Aushush	150.3	8/7/91	80	62.80	26.17	35.58	8.46	0.240	4,200	About 2,810 mg/l TDS.

Table B3: Estimation of the aquifer properties -- continued.

Ground water project number	Well * depth (meters below gs)	Screen length (meters)	Location: UTM[8] Y Coordinate	Location: UTM X Coordinate	Location: Area Name	Ground-surface elevation (meters)	Date pumped (day/month/year)	Time pumped (minutes)	Pump setting[7] (meters)	Static water level (meters below gs)	Drawdown (meters)	Pumping rate (m³/hr)	Specific capacity ([illegible]/hr)	Specific conductance, water (µs/cm)	Remarks
47	93.8	46.4	2726021.39	321045.82	Al Aushush	105.4	--	--	--	--	--	--	--	9,280	Not tested, well plugged.
48	67.1	29.5	2705555.11	353262.64	Bida Bin Salma	220.0	19/7/91	150	63.11	11.96	49.97	7.78	0.170	9,950	Small yield, poor water quality.
49	306.3	6	2723584.50	318709.31	Al Aushush	106.7	--	--	--	0.62	--	--	--	--	Not developed.
50	60.3	17.5	2710488.83	337523.42	Sweihan	161.6	27/2/92	300	56.40	23.59	30.18	21.00	0.690	4,300	About 2,880 mg/l TDS.
51	81.5	29.0	2714174.41	322909.23	Nasasah	129.8	20/2/92	720	57.62	7.93	12.60	16.21	1.280	19,000	Fair yield, saline water.
52	51.4	11.6	2703596.62	321768.81	Nasasah	134.2	4/3/92	300	47.56	4.29	25.36	20.10	0.790	14,680	Fair yield, poor water quality.
53	72.8	23.2	2692411.38	328144.30	Al Lieseily	142.9	26/3/92	400	63.72	7.35	19.23	20.30	1.050	11,000	Poor water quality.
54	72.0	40.6	2701050.76	335705.31	Al Mishaab	165.0	10/3/92	1,440	65.73	24.99	20.67	18.12	1.200	14,100	Fair yield.
55	70.9	34.8	2690163.62	338640.10	Saih Al Salem	177.0	20/3/92	360	65.72	31.15	18.35	6.81	0.360	7,100	Small yield.
56	72.2	17.4	2690281.93	318638.58	Al Nissoriya	152.2	5/4/92	1,440	53.66	18.49	10.87	50.76	4.670	9,400	Good yield; poor water quality.
57	103.9	40.6	2685084.10	342417.60	Al Zeela	184.6	12/4/92	720	82.31	50.93	15.29	11.68	0.760	10,600	Low yield; poor water quality.
58	84.4	46.3	2679855.12	328223.18	Remah	146.3	21/4/92	1,440	60.82	9.61	12.64	82.40	6.520	5,560	About 3,720 mg/l TDS.
59	93.6	34.8	2678194.28	313695.82	Al Khazna	146.1	6/5/92	720	80.20	13.84	10.37	81.23	7.830	5,880	About 3,940 mg/l TDS.
60	104.2	64.0	2671452.44	330451.67	Al Ankah	161.8	11/5/92	720	76.22	19.64	10.83	34.62	3.200	4,100	About 2,750 mg/l TDS.
61	150.3	46.4	2679918.93	345133.21	Al Saad	192.4	10/9/91	300	128.63	77.97	40.38	9.45	0.230	4,470	Small yield.
62	279.0	116.0	2670381.17	355884.93	Al Maqam	210.7	25/5/92	300	152.44	40.94	81.74	6.06	0.074	3,660	Small yield; fair water quality.
63	314.2	121.8	2669781.17	348780.33	She Al Miah	199.8	26/8/91	300	228.60	47.72	80.75	11.96	0.150	15,200	Small yield; poor water quality.
64	149.4	81.3	2675177.80	350445.63	South Al Saad	208.6	28/9/91	300	123.68	85.02	56.21	4.30	0.076	2,160	Small yield; fairly good water quality.
65	311.0	6	2684435.51	355639.20	Al Jahar	220.9	18/5/92	250	76.21	20.41	44.83	11.25	0.250	12,200	Small yield; poor water quality.
66	79.1	29.0	2684691.50	339033.22	Wadi Towayya	269.1	9/10/91	1,440	73.17	13.98	18.44	17.13	0.930	7,420	About 4,970 mg/l TDS.
67	147.8	58.0	2685922.06	365786.16	Wadi Towayya	268.2	25/10/91	540	111.6	19.94	26.30	15.50	0.590	7,420	About 4,970 mg/l TDS.
68	42.8	17.4	2664638.95	395194.36	Wadi Sa'a	388.1	6/11/91	6.5	40.24	21.00	39.46	--	--	2,070	Very small yield.

Table B3: Estimation of the aquifer properties -- continued.

Ground water project number	Well [α] depth (meters below gs)	Screen length (meters)	Location: UTM[β] Y Coordinate	Location: UTM[β] X Coordinate	Location: Area Name	Ground-surface elevation (meters)	Date pumped (day/month/year)	Time pumped (minutes)	Pump setting[γ] (meters)	Static water level (meters below gs)	Drawdown (meters)	Pumping rate (m³/hr)	Specific capacity (m²/hr)	Specific conductance, water (µS/cm)	Remarks
79	89.0	δ	2705601.67	371071.52	Qarn Sabah	292.4	15/1/92	92	85.95	31.93	52.77	6.47	0.120	3,070	Small yield, good water quality.
80	91.4	δ	2670276.10	380371.14	Mazyad	323.5	10/2/92	720	79.27	28.96	16.02	19.26	1.200	1,530	Excellent water quality.
81	46.4	29.0	2649858.69	304743.83	Bida Harib	132.9	1/6/92	300	29.86	11.94	2.73	17.50	6.410	25,200	Good yield, poor water quality.
82	62.0	35.4	2657083.73	339715.73	Seah Sabra	172.3	8/6/92	600	56.40	13.80	9.68	16.56	1.710	22,200	Fair yield, saline water.
83	41.4	29.0	2643409.93	344073.48	Umm Salmien	167.7	16/6/92	300	35.06	10.85	18.99	20.23	1.060	12,600	
84	181.4	75.3	2629570.23	349200.14	Al Ageer	181.2	25/6/92	173	76.29	20.04	23.29	30.33	1.430	7,400	Fair water quality.
85	93.9	40.6	2635843.34	329346.88	Al Arad	143.5	3/9/92	300	76.52	1.33	23.05	34.60	1.500	46,800	Saline water.
86	64.6	29.0	2624087.05	330068.96	Za'aba	144.7	3/7/92	350	48.78	5.26	27.52	27.76	1.010	21,000	
87	64.5	46.4	2610534.10	332940.47	Al Humran	138.9	26/8/92	300	57.92	3.24	41.36	17.00	0.410	14,800	
88	67.6	46.3	2628878.52	304208.67	Al Yaeela	122.3	--	--	--	8.29	--	--	--	78,000	Well filled with sand. Water sample only.
89	67.2	29.0	2603060.53	319622.04	Al Raquiat	118.9	21/8/92	300	45.73	2.11	49.25	9.13	0.180	55,800	Saline water.
90	106.7	91.4	2612227.97	352997.14	Al Wagan	172.1	21/7/92	500	77.74	20.08	29.11	22.17	0.760	7,100	Aquifer test.
91	55.5	40.7	2585567.25	307686.17	Al Qua	103.0	11/8/92	300	18.29	1.04	6.24	16.35	2.620	200,000	Saline water.
92	106.6	51.7	2578105.87	330972.10	Al Wagan	123.0	31/7/92	300	77.72	5.35	54.72	4.40	0.080	28,900	Very small yield.
93	105.1	92.0	2598118.06	342902.80	Al Wagan	148.6	17/8/92	300	78.66	6.49	22.70	37.36	1.640	14,000	Fair yield, poor water quality.

α Well depth is the cased and screened depth except for uncased boreholes. For uncased boreholes, the depth is the drilled depth.

β UTM, Universal Transverse Mercator grid coordinate (see section on "Cartography" for explanation).

γ Pump-setting measurements are from the top of the casing.

δ Uncased borehole.

Table B4: Summary of hydraulic characteristics of Al Ain aquifer and well efficiencies determined by analyses of data obtained during pumping and recovery at project wells (National Drilling Company, United States Geological Survey-Groundwater Research Project, 1993).

[m^2/d, square meters per day; m, meters; m/d, meters per day; --, no data; T, transmissivity; obs., observation; avg., average S, storage coefficient; WED, water and Electricity Department; >, greater than]

Ground-water project well number	Transmissivity[1] (m^2/d)	Aquifer thickness (m)	Hydraulic conductivity (m/d)	Storage coefficient	Well efficiency (percent)	Comments
6	8.8	51.3	0.2	--	--	T from recovery test
7	8.4	80.3	.1	--	--	T from recovery test
11A	117	62.1	1.9	0.0046	--	Obs. well data, T avg. of 2 values
13	157	88.2	1.8	.000339	--	Obs. well data, T avg. of 3 values, S avg. of 2 values
14	557	106.9	5.2	.0029	--	Obs. well data
15	11.9	16.2	.7	--	--	No obs. well
17	1,720	17.2	100	.046	54	T and S avg. of 2 values from obs. well data
18	3,570	19.4	184	.0748	8	T and S avg. of 3 values from obs. well data
22	713	104.4	6.8	--	40[2]	
23	1.8	113.3	.02	--	--	Very low yield
24	57.0	76.0	.8	--	40[2]	
25	38.0	61.9	.6	--	40[2]	
26	261	77.9	3.4	--	40[2]	
28	405	93.7	4.3	.004	--	T avg. of 6 values
30	5,320	20.0	266	.00077	--	Obs. well data, T avg. of 3 values from obs. well T avg. of 3 values from obs. well WED-102
31	1.200	21.2	56.6	.000445	--	
32	26.0	44.5	.6	--	40[2]	
33	13.5	126.5	.1	--	40[2]	Avg. of 2 valuees, no obs. well
34	87.0	23.4	3.7	--	40[2]	T avg. of 2 values

Table B4: Summary of hydraulic characteristics of Al Ain aquifer and well efficiencies determined by analyses of data obtained during pumping and recovery at project wells -- continued

Ground-water project well number	Transmissivity [1] (m^2/d)	Aquifer thickness (m)	Hydraulic conductivity (m/d)	Storage coefficient	Well efficiency (percent)	Comments
37	40.0	23.0	1.7	--	40[2]	T avg. of 2 values
38	1,740	19.9	86.4	0.00137	--	T and S avg. of 2 values from obs. well WED-412
39	89.0	20.2	4.4	.000455	--	T avg. of 3 values, S ave. of 2 values from obs. well
40	174.0	62.1	2.8	--	--	Recovery test from pumping well
41	5,800	--	--	.0000086	--	Karstic limestone
42	6,000	--	--	--	--	Karstic limestone
44	187	16.5	11.3	--	--	T avg. of 2 values
45	75.0	46.1	1.6	--	40[2]	
50	6.5	39.0	.2	--	67	No obs. well, computer analysis T=5.06
51	77.0	33.9	2.3	--	12	No obs. well, computer analysis T=10.90
52	10.4	35.8	.3	--	45	No obs. well, computer analysis T=5.45
53	25.7	44.2	.6	--	25	No obs. well, computer analysis T=60.39
54	4.9	36.4	.1	--	--	Well still developing, computer analysis T=6.21
55	112	54.4	2.1	.0064	--	Well still developing, T and S avg. of 2 values from obs. well
56	94.4	44.1	2.1	--	55	No obs. well, computer analysis T=35.60
57	12.0	66.4	.2	--	53	No. obs. well
58	244	79.2	3.1	--	88	No. obs. well

Table B4: Summary of hydraulic characteristics of Al Ain aquifer and well efficiencies determined by analyses of data obtained during pumping and recovery at project wells -- continued

Ground-water project well number	Transmissivity [1] (m^2/d)	Aquifer thickness (m)	Hydraulic conductivity (m/d)	Storage coefficient	Well efficiency (percent)	Comments
59	214	63.2	3.4	--	93	No obs. well
60	253	88.9	2.8	--	97	No obs. well
61	25.6	64.6	4.3	0.00086	--	T and S avg. of 2 values from obs. well
67	67.3	68.10	1.0	--	6	No obs. well
80	23.6	--	--	--	45	T avg. of 2 values
81	266	76.5	3.5	--	40[2]	
82	28.4	86.5	.3	--	48	T avg. of 2 values
83	19.0	68.0	.3	--	31	T avg. of 2 values
84	18.0	62.4	.3	--	40	T avg. of 2 values
85	82.0	87.7	.9	--	14	T avg. of 2 values
86	18.0	56.5	.3	--	40[2]	T avg. of 2 values
87	29.0	88.9	.3	--	8	T avg. of 2 values
89	8.0	71.2	.1	--	40[2]	
90	274	65.2	4.2	.00728	49	T avg. of 2 values from obs. well
91	431	55.4	7.8	--	6	T avg. of 2 values
93	17.0	99.1	.2	--	65	T avg. of 2 values

1. Transmissivity values were adjusted where well efficiencies were determined or estimated.

2. Estimated well efficiency.

Table B5: Recharge estimates determined from transmission-loss and streamflow-routing model for drainage basins near the eastern study area (National Drilling Company, United States Geological Survey-Groundwater Research Project, 1993).
[Km^2, square kilometers; m^3/sec, cubic meters per second; m, meters; km, kilometers]

Drainage basin[1]	Gap name	Area (km^2)	Modeled basin recharge[2] (m^3/sec)	Modeled runoff (m^3/sec)	Model channel width (m)	Modeled runoff distance from gap (km)	Modeled runoff enters study area
1A, B, C	HADF	62.0	0.030	0.0021	42.7	16.1	NO
2	SHIBAK	18.0	.006	.0010	45.7	21.6	NO
3	KHURAYMAH	56.5	.020	.0033	54.9	29.8	YES
4	MAYHAH	91.7	.033	.0033	51.8	55.4	YES
5A	MAQAM	36.7	.009	.0007	45.7	10.6	YES
5B	WASA		.009	.0007	45.7	10.6	YES
6A	SUMEINI N	266	.079	.0053	70.1	29.8	YES
6B	SUMEINI S		.071	.0052	60.9	35.4	YES
7	UWAYNAH	21.6	.010	.0016	48.8	14.0	NO
8	RIMRAMA	34.4	.018	.0023	51.8	16.2	NO
9	SHARM	209	.088	.0096	67.1	29.0	NO
10A	SIBHAH	327	.002	.0004	48.8	6.3	NO

Drainage basin[1]	Gap name	Area (km^2)	Modeled basin recharge[2] (m^3/sec)	Modeled runoff (m^3/sec)	Model channel width (m)	Modeled runoff distance from gap (km)	Modeled runoff enters study area
10B	KAHAL		0.019	0.0050	57.9	46.8	YES
10C	MAHDAH		.155	.0105	67.1	51.2	YES
11A	ZARUB	532	.145	.0148	67.1	64.8	YES
11B	SHIK		.145	.0148	67.1	64.8	YES
12A	LIHASI	144	.047	.0061	54.9	25.1	YES
12B	HAMAD		.022	.0031	54.9	31.3	YES
13A	AJRAN N	244	.074	.0018	54.9	25.9	YES
13B	AJRAN S		.074	.0018	54.9	25.9	NO
14	SHUKAYYAH	308	.156	.0116	73.2	82.4	NO
15	SIDDRAT	54.2	.027	.0048	54.9	22.2	NO
16	AL FATAH	258	.145	..0080	60.9	67.2	NO
17	KHUBAYB	208	.132	.0047	67.1	27.8	NO
TOTAL		2,871.1	1.516	0.1225			

1 Number corresponds to locations shown on Figure 2.23
2 Assumed to be groundwater underflow beneath gap for steady state conditions

ومن المتوقع أن يتراوح الانخفاض في مناسيب المياه الجوفية في منطقة الدراسة ما بين ٥م و ٩,٥ م في عام ٢٠١٠ بالمقارنة بالوضع الحالي وقد تم وضع العديد من التوصيات في نهاية الدراسة التي تهدف إلى الحد من ظاهرة نضوب الخزانات الجوفية بدولة الإمارات العربية المتحدة بصفة عامة .

الطالبة: فاطمة عبداللطيف خليفه محمد الشحي
ماجستير موارد مياه

ملخص الرسالـــــة

عنوان الأطروحة

تقييم مصادر المياه الجوفية في مناطق مختارة بالعين في دولة الإمارات العربية المتحدة

إن عملـية الـتطور والتنمـية المسـتدامة لأي بقعة في العالم تعتمد على مدى توفر مصادر المياه الصالحة للاستخدام في الأغراض المختلفة ومن ثم فإن الجهود المبذولة في تقييم مصادر المياه لا بد وأن تتواصل نظرا لقلة هذه المصادر المائية وتعرضها للشح في دولة الإمارات العربية المتحدة .

تقـع دولـة الإمارات العربية المتحدة ضمن مجال المناطق القاحلة والتي تتميز بندرة الأمطار وعدم انتظامها الأمر الذي يهدد بنقص في تغذية المياه الجوفية . ونظرا لأهمية موارد المياه في مجالات الزراعة والصناعة والاسـتهلاك المحلـي فقد ظهرت أهمية الدراسة الحالية والتي تتناول تقييم مصادر المياه الجوفية في مناطق مختارة بالعين طبقا للمعلومات والبيانات المتوفرة . وتشمل الدراسة الحالية المناطق الآتية : الهير ، غمض ، ناهل ، وجزء من منطقة الخضر في العين .

لقـد تـم عمـل تقييم كمي للمياه الجوفية في هذه المناطق من خلال إنشاء خرائط كنتورية وذلك خلال المدة الزمنـية ما بين ١٩٩١ و ٢٠٠١م . كما تم عمل خرائط أخرى لتقييم نوعية هذه المياه ومدى اختلافها على مـدار الأعـوام طـبقا للبيانات المتوفرة وبالإضافة إلى ذلك فإنه قد تم التنبؤ بمناسيب المياه الجوفية في عام ٢٠١٠م بافـتراض نفـس ظروف الضخ الحالية وذلك باستخدام برنامج (SUTRA) والذي تم تصميمه في هيئة المساحة الجيولوجية بالولايات المتحدة الأمريكية .

وقـد أظهـرت نتائج الدراسة وجود انخفاض ملحوظ في مناسيب المياه الجوفية في الفترات السابقة وأن هذا الانخفـاض مسـتمر حتى الآن . ويقدر الانخفاض الحالي في مناسيب المياه الجوفية بمناطق الدراسة بحوالي ١٧م بالمقارنة بعام ١٩٩١ . أما ملوحة المياه الجوفية فهي لم تتأثر كثيراً في منطقة الدراسة باستثناء المناطق الزراعـية ذات الاسـتهلاك العالـي للمياه حيث ترتفع ملوحة هذه المياه تدريجيا وذلك في منطقة شرق جبل المحبير وغرب الهير مع بقاء جودة المياه الجوفية بمنطقة الدراسه بشكل عام في مجال المياه العذبة .

الطالبة: فاطمة عبداللطيف خليفه محمد الشحي

جامعة الإمارات العربية المتحدة
عمادة الدراسات العليا

تقييم مصادر المياه الجوفية في مناطق مختارة بالعين في دولة الإمارات العربية المتحدة

رسالة مقدمة من الطالبة

فاطمة عبد اللطيف خليفة محمد الشحي

بكالوريوس هندسة كيميائية
كلية الهندسة والبترول - جامعة الكويت (١٩٨٥)

استكمالاً لمتطلبات الحصول على درجة الماجستير
في
علوم موارد المياه

جامعة الإمارات العربية المتحدة
عمادة الدراسات العليا
ديسمبر ٢٠٠٢ م

﴿ءأنتم أنزلتموه من المزن
أم نحن المنزلون﴾