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Aquifer Characterization and Quantitative Assessment of Over Exploitation of the Shallow Aquifer in Al Maqam Al Saad Area, the Eastern Region, Abu Dhabi Emirate

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United Arab Emirates University
2002/2003

CONTENTS

FIGURES

TABLES

Aquifer Characterization and Quantitative Assessment of Over Exploitation of the Shallow Aquifer in Al Maqam Al Saad Area, the Eastern Region, Abu Dhabi Emirate

ABSTRACT

Al Maqam-Al Saad area is located to the west of Al Ain city on Al Ain-Abu Dhabi Highway. This area was chosen to be studied because of the rapid decline of the water levels in the shallow aquifer as a result of continuous heavy withdrawal of the ground water. In 1990-1991, the area was recognized as one of the major ground water depressions in the Eastern Region where more than 40 meters of drawdown were noted in the center of depression. The objective of this study is to determine the hydraulic status of the aquifer by means of characterization and to carry out a quantitative assessment of the shallow aquifer in the study area.

The characterization of the aquifer was conducted in order to assess the hydraulic conductivity in the area by means of re-analysis of previously conducted pumping tests. Pumping tests conducted in the area by the Ground-water Research Program (GWRP) were reanalyzed using Aquifer Test Software. The results of the reanalysis are displayed in maps of transmissivity and hydraulic conductivity. The hydraulic conductivity in the area is small and ranges from 1 to 5 meters per day with increasing trend from east to west. This range of values is consistent with the heterogeneous lithology of the aquifer that ranges from well sorted to poorly sorted gravel interbedded with clay

stone, siltstone, shale, and limestone. In addition to the pumping tests analysis, geological information and ground-water salinity distribution maps were also taken into consideration in the aquifer characterization and hence in the aquifer assessment.

The quantitative assessment was done by means of numerical modeling. The United States Geological Survey (USGS) ground-water model, MODFLOW, was used to simulate the water level decline in the area and to show that the aquifer storage is being rapidly depleted. The model was calibrated to steady-state conditions by changing aquifer hydraulic properties and boundary conditions until the simulated water levels matched predevelopment water levels (before 1980). A transient calibration was achieved by reasonably matching the water levels produced from the transient simulation by those observed in the years 1990 and 1995.

By 1997 most of the shallow aquifer in Al Saad area (the center of the cone of depression) became dry; in addition, a new intensive agricultural development was initiated in the south and southwest of Al Saad area. Therefore a post-audit was performed to the model in order to account for the new developments. The post-audit was calibrated to the water levels of 2003 in which a reasonable matching was obtained between the simulated and the actual and water levels.

Predictive model simulations for 2005 and 2015 were produced under the assumption that 2003 pumping rates would continue to the year 2015. The simulations indicated that by the year 2005 some wells will dry out and by 2015 a large portion of the shallow aquifer in the study area will be dry. The model indicated that there are many uncertainties in the available data and more data are needed in order to produce more sensitive and refined model. This model can be used as a guide for future data collection activities and as a management tool for the water resources in the area provided that the uncertainties are taken into consideration.

The main conclusion of this study is that the large drawdown occurs due to combination of three factors: heavy ground-water extractions, little recharge, and low conductivity. Thus, the following recommendations can be made in order to alleviate the exploitation of aquifer: Limit the abstraction rate by prioritizing its uses, regulate ground-water use, monitor and assess ground-water conditions, enhance the replenishment of ground water by developing the ground-water recharge facilities, and minimize contamination of fresh water aquifer.

ACKNOWLEDGMENTS

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INTRODUCTION

Problem Statement

Ground-water resources are particularly important in the Emirate of Abu Dhabi because it is located in an arid region in which the ground-water resources represent the only source of natural fresh and brackish water. Therefore, the conservation and protection of the precious ground-water resources is considered one of the main priorities of the decision makers in the Emirate. In the last three decades, the ground-water levels have dramatically declined in some areas and the water quality deteriorated in others as a direct result of the phenomenal growth of the Emirate's population and the ambitious plans of farm distribution, gardening, and forestry all over the Emirate.

Figure 1, borrowed from Imes and his coauthors, (1993), shows the changes occurred in the ground-water level between the year 1990-1991 and pre-development period. This figure was produced by feeding the difference of the water-level measurements between the two periods in AUTOCAD. The figure shows that the shallow ground-water system in the Eastern Region of Abu Dhabi Emirate is consisting of five major ground-water depressions. Out of these five depressions, Al Maqam-Al Saad depression was selected to be the subject of this Thesis in which the probable causes of its occurrence will be investigated through aquifer characterization and aquifer assessment (numerical model). This water-level depression is considered the largest both in surface area affected and in magnitude of drawdown, extends west from Al Ain to Abu Samra and south from Al Zaala to Seh Sabra. The surface area of the depression (within the 10-m decline contour) was about 790 km^2 and the drawdown at the center of the depression was more than 50 meters.

A ground-water (numerical) model of the Al Maqam al Saad area can provide valuable information regarding the possible causes of the water depression in the area and can provide viable alternatives for management and protection of the shallow aquifer. No numerical model can provide useful information without reliable characterization of the aquifer. Thus, this study undertakes the aquifer characterization in the study area as the first part of the study and then, incorporate the data resulted from the aquifer characterization into a quantitative assessment of overexploitation of the shallow aquifer.

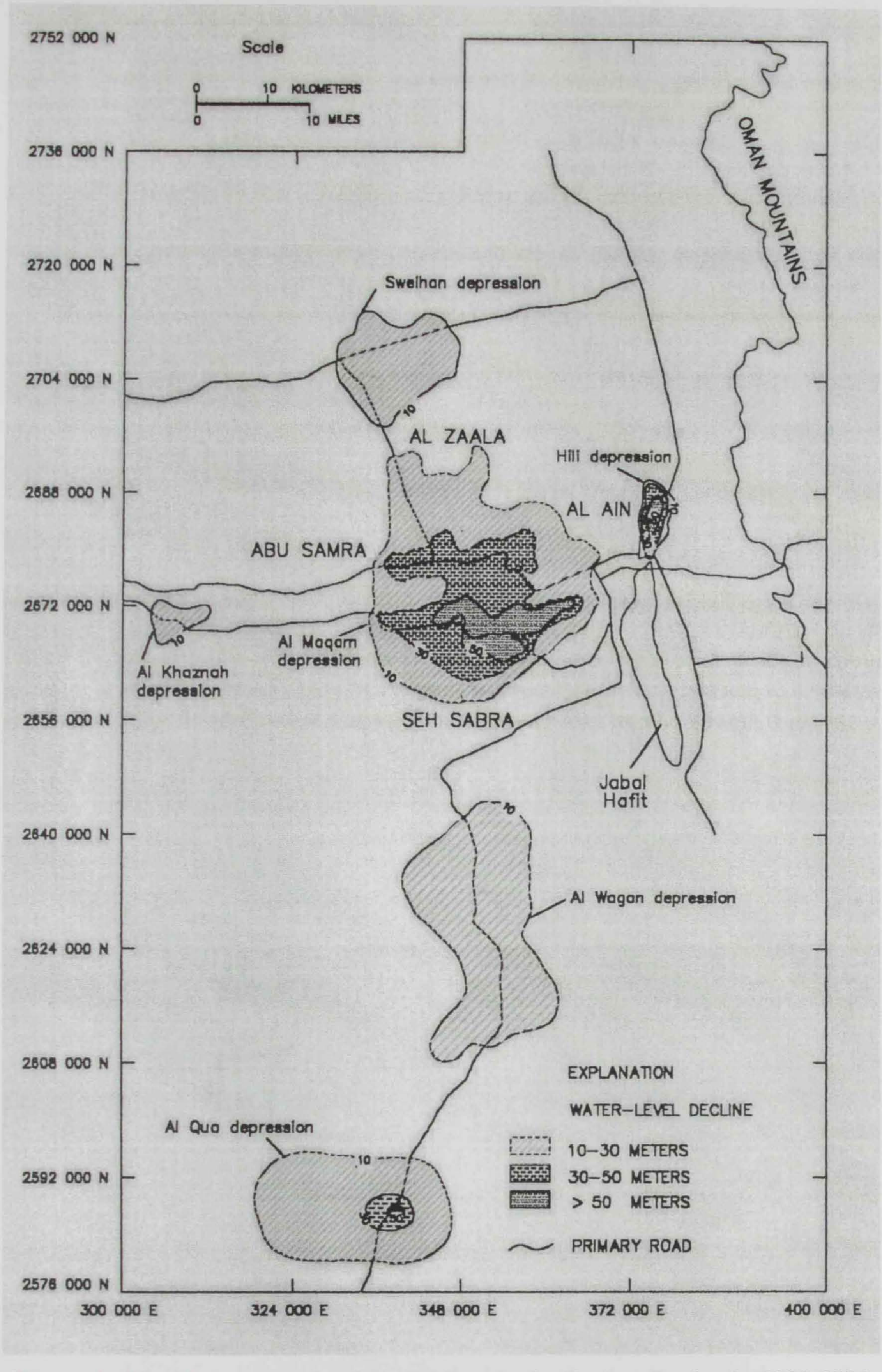


Figure 1. *The Major water-level depressions in the Eastern Region in 1990-1991 [After Imes, et, al., 1993].*

General Description of the Study Area

Figures 2 and 3 show maps of north Eastern part of the Abu Dhabi Emirate and the study area respectively. These maps were produced from satellite images using ARC/INFO facilities in the GWRP. The study area is located to the west of Al Ain city in Abu Dhabi Highway. It is considered one of the pumpage centers in the Eastern Region. It contains major villages like Al Maqam, Al Saad, Al Yaher, Al Suliemat, and Abu Samra. Various types of cultivation are widespread in the area such as private farms and gardens, parks, trees for street cultivation and forests. The area contains many landmarks like the army school, the aviation collage, Al Ain International Airport, and the ruler's palace. Beside the withdrawal of ground–water for agricultural purposes, a number of municipal wells were also drilled in the area for domestic water supply. In addition to the ground water, the area receives some desalinated water from the seawater desalination plants in Abu Dhabi.

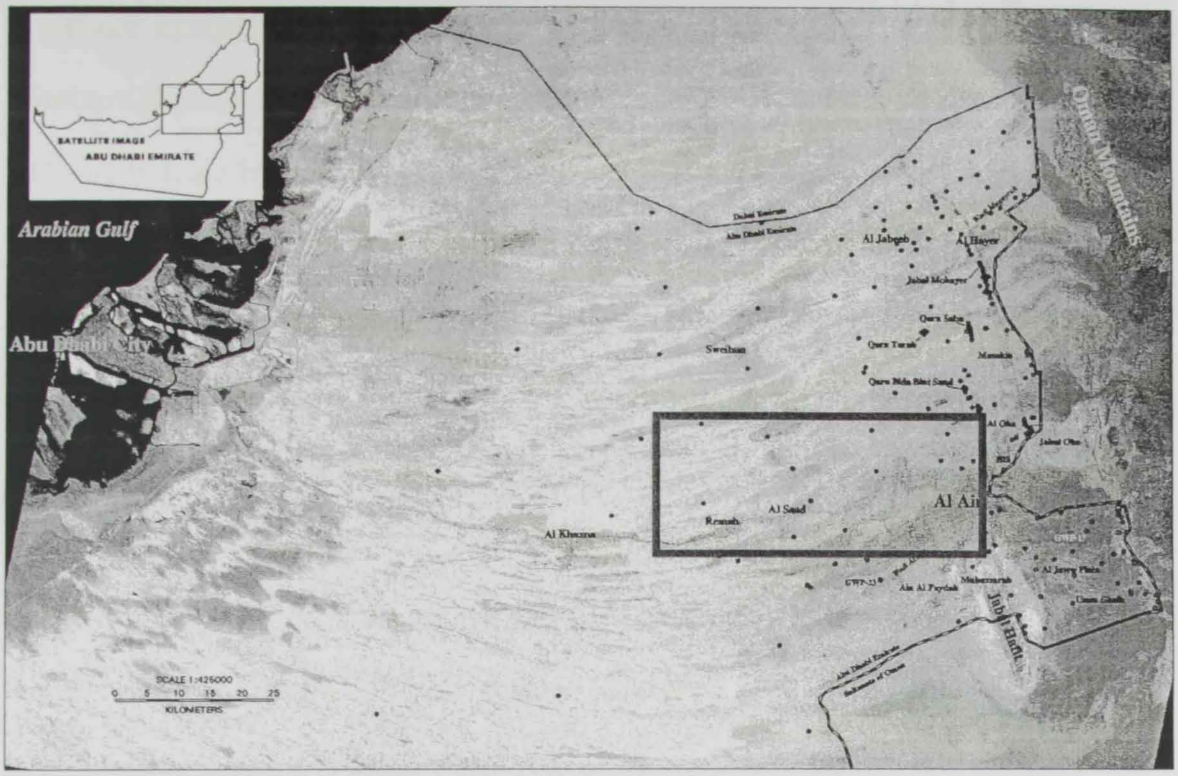


Figure 2. *Satellite image for the northeastern part of Abu Dhabi Emirate; the approximate location of the study area is marked by the red rectangle.*

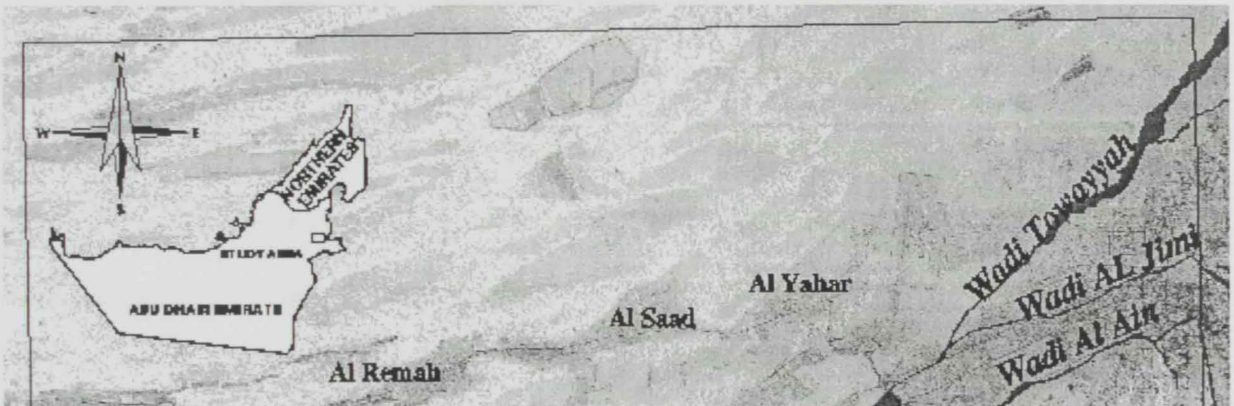


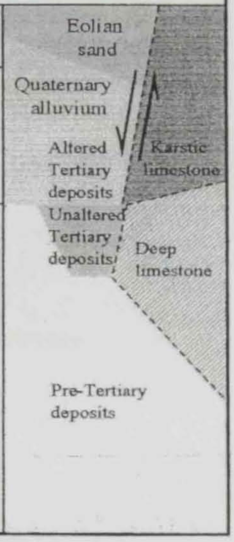
Figure 3. *Location of Al Maqam-Al Saad area. Red areas indicate wadies and the green areas indicate cultivation.*

Geologic Framework

Statigraphy and Structure

The hydrologic framework of the shallow aquifer in the Eastern Region is shown in table 1 and figure 4 borrowed from Bright (1998). Table 1 shows the positions of these hydrogeological units in the regional stratigraphy column. The shallow aquifer is basically restricted to the Quaternary alluvium, and the altered tertiary deposits. Quaternary alluvium 10-50 meters thick layer of gravel occur as a single saturated column in the north eastern corner of the study area representing the structural low occurring between the Al Oha ridge and Hafit Mountain. Presence of alluvium in the study area can be traced as a channel extending from the mountain gap to a considerable distance towards west. Across the mountain gap, the alluvium is linked to the alluvium in Oman and recharged from both the surface and subsurface water passes through the gaps. The continuity of alluvium as a single saturated column is limited to few kilometers. In the rest of the channel, alluvium is joined with the Pliocene-Miocene sediments to form an unconfined aquifer. In general, the cemented zone of the alluvium rarely shows layering with carbonate and gypsum bearing layers which is common to the Pliocene-Miocene sediments.

Table 1. *Geologic Framework of the Eastern Region of Abu Dhabi Emirate [after Bright, 1998].*

Age	Geologic sequence	Approximate thickness (meters)	Hydrogeologic unit	
Quaternary	Eolian sand	25	Unsaturated overburden	
	Alluvium	30	Surficial aquifer system	
Pliocene - Miocene	Post-Fars Upper Fars	200		
Miocene - Oligocene	Lower Fars Fm. Asmari Formation	500	Basal confining system	
Paleocene - Eocene	Dammam Formation Rus Formation Umm er-Radhuma Fm	1,200		
Cretaceous	Simsima Formation Qahlah Formation Juweiza Formation	3,000		

Altered tertiary deposits can be divided to Mid Tertiary clayey carbonate deposits. (Miocene-Eocene) and Late Tertiary clastic deposits, (Pliocene-Miocene). Mid Tertiary clayey carbonate deposits (Miocene-Eocene) is the lower part of the eastern edge of the study area is covered by the formations of anticlinal structure of Hafit Mountain. The anticline is plunging to north and younger sediments are partially exposed over the surface. The southern part of the anticline is fully exposed to the surface as a mountain which acts as a barrier to the flow from the east. The mountain core is composed of the rocks belonging to Mid and Early Tertiary (Warrak, 1987). The northern plunge is partly subsurfaced and ground water occurrence is associated with Mid Tertiary sediments. In general, the Mid Tertiary sediments are marls and clayey carbonates of lower Fars, Asmari, and Damam where ground-water productivity can be expected depending on the original carbonate content and effect of secondary processes like carbonate dissolution. The gap between the Al Oha ridge of Huwayyah anticline and Hafit Mountain is the area which both the surface and ground water passes into the study area. This gap is about 17 kilometer long and covered by the alluvium and Mid Tertiary deposits in the northward plunge of the Hafit anticline.

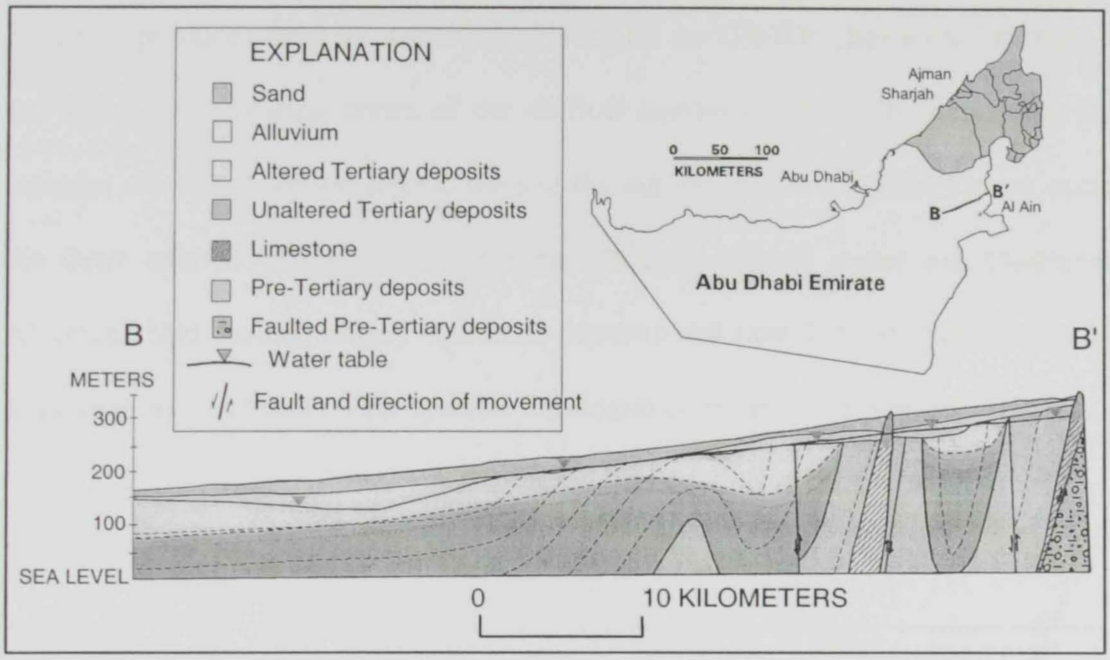


Figure 4. *Cross-section of Al Ain shallow Aquifer [after Bright, et. al, 1998].*

Late tertiary deposits of Post Fars and upper Fars are the major lithological groups deposited in the Pliocene–Miocene period. The lower Fars formations (Miocene-Oligocene) generally consist of low permeable lithologies and rarely contain desirable ground water. The post and upper Fars sequence has wide lateral and vertical extents. In general, it occurs as deposits in synclines of tightly folded sedimentary structures. The sedimentary character varies depending on the sediment basin and the age of the sediments in the sequence. The older sediments are coarser and tightly packed in a calcium carbonate bound finer clast matrix. The younger sediments are clast bound but finer and the cementation is weak. The wells in the east of the study area penetrated older sediments while wells in the west penetrated younger sediments, which lie in the center of the basin. The Post Fars-upper Fars sequence consists of a repeating structure of thin multiple layers of clastics, carbonates and clay associated sediments, and evaporates.

Lithology of Shallow Aquifer

Figure 5, produced from an unpublished work by the GWRP, shows the lithology of the major water bearing zones of the shallow aquifer of the study area. The area includes all major hydrogeological units of the regional shallow aquifer system except the dune aquifer. The major lithologies bearing ground water are Quaternary Alluvium, Mid Tertiary clayey carbonate deposits and Late Tertiary clast Associated sediments (see Appendix-1 for specific lithologies of some of the pumped wells).

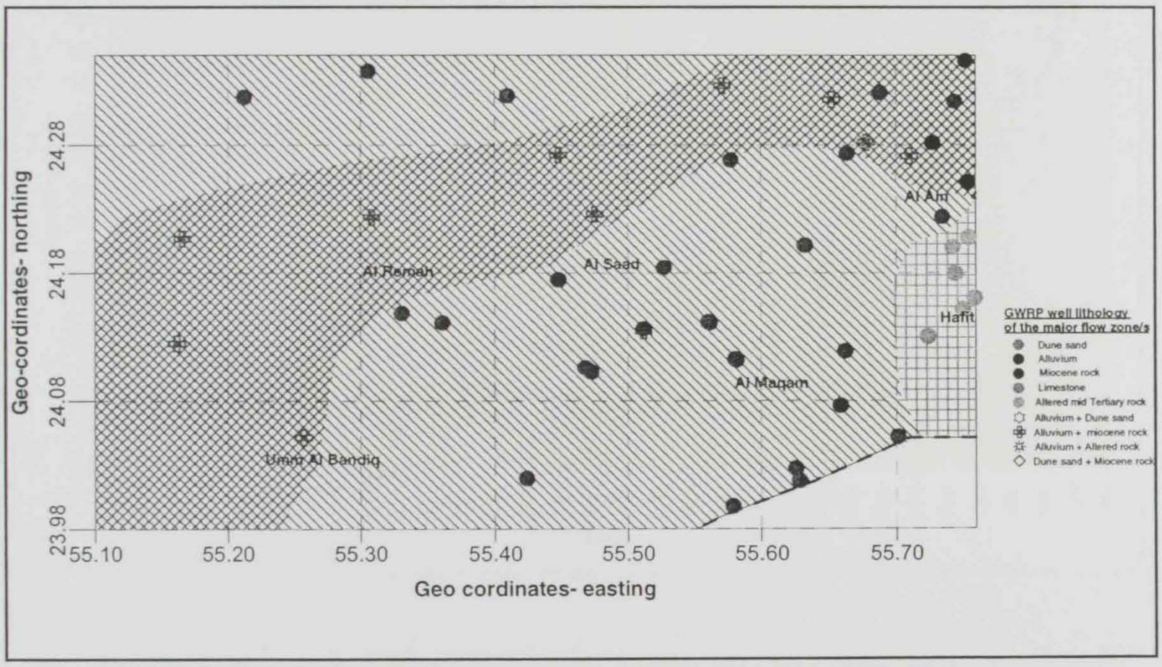


Figure 5. *Lithology of the study area [modified from unpublished work by the GWRP].*

Hydrologic framework

Effective Rainfall

After studying over 100 monitoring wells and the available rainfall data records in the region, the specialists in the GWRP suggested that higher single rainfall occurrences exceeding 200 mm or continuity of annual rain around 120 mm for three days and more could yield an affective recharge to the area. Figure 6 shows the annual rainfall events based on the data collected from the Metrological station of the Agriculture Department in Al Ain. Rain occurred in 1972, 1982, 1987, 1988, 1989, 1990 1995, 1996, and 1997 in quantities that were enough to recharge the aquifer.

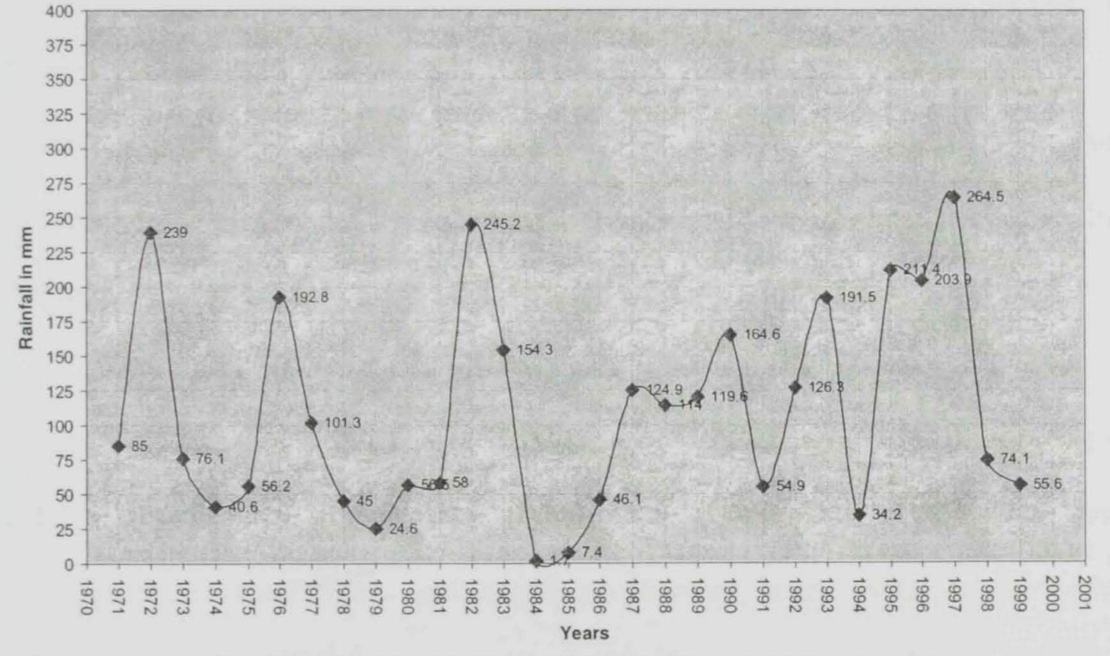


Figure 6. ***Rainfall Pattern in the area.*** *[Data obtained from Agricultural Metrological Station _Al Ain].*

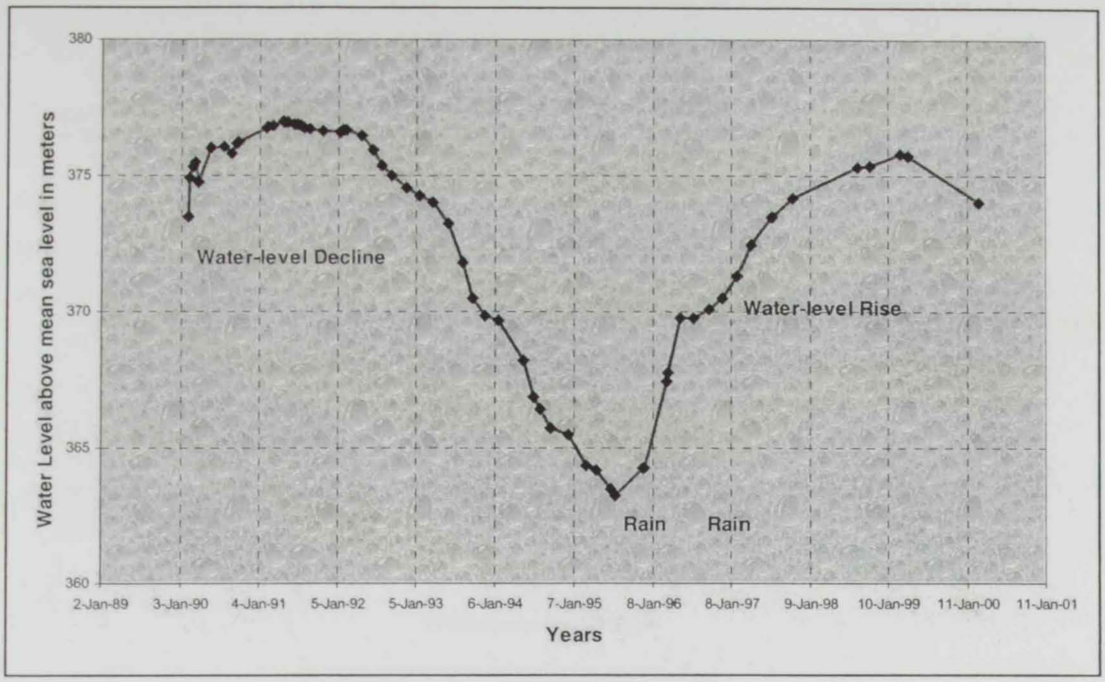


Figure 7. *Recharge pattern in the gravel.*

Water-level fluctuations

In addition to the ground-water underflow from Oman Mountains, rare rainfall events represent the only other natural recharge source in the area. In the Emirate of Abu Dhabi, rainfall is a rare and erratic. While many years pass without rain, heavy rain events can occur within few days. When heavy rain occurs it has a significant effect to the land surface and ground-water resources. Some events that last only for few days can cause heavy floods and significant increase in the water levels in the recharge areas. The GWRP has constructed a monitoring network where many wells in the recharge areas are measured periodically and also during and after each rainy event. Figure 7 shows typical recharge pattern in a representative well in Zaroub gap (main recharge area) where water level increased about 12 meters as a result of a recent rainfall event. Such water-level rises are common feature of the gravel formation, the recharging source of the study area.

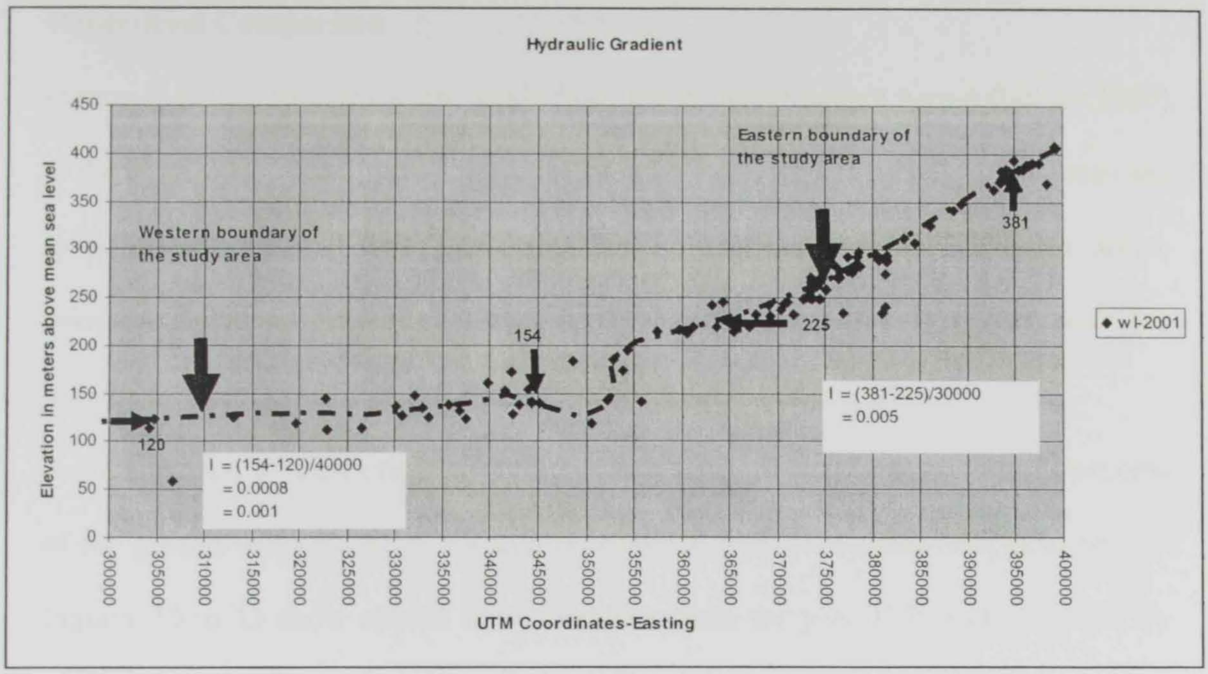


Figure 8. *Hydraulic gradient.*

Hydraulic gradient

The hydraulic gradient is the difference between two water-level measurements divided by the distance. Figure 8 shows the water table position measured in the GWRP wells in the year 2001 in the Eastern Abu Dhabi Emirate. In the regional map, the majority of data points lie around a number of major flow paths that extend from Abu Dhabi–Oman border to the west, particularly around a line extending from Buraimi to the west through Al Saad, Remah, and Kazna. In figure 8, the study area is shown in the middle part of the regional flow path where the gradient is moderate compared to high and low gradients in the east and the west respectively. In this figure, the ground-water depression can be seen in the center of the figure.

Water-level Comparison

Figures 9 to 13 represent water levels from the predevelopment period (before 1980) to the year 2003. The figures show contours of water-levels in meters above mean sea level (mamsl) and the flow path directions through vectors. The maps are drawn using the Universal Transverse Mercator (UTM) coordinates that defines the positions in metric system, therefore, the x-y units of the maps are meters.

A smooth, east to west oriented vector pattern representing the natural flow patterns of the ground water in the study area is apparent during the predevelopment period. Figures 10 to 13 show altered flow directions from the year 1990 and onward. By 1990-1991, excessive pumping from wells has created the water-level depression and altered the natural flow direction toward this depression that would otherwise flow to natural discharge areas toward the west. The observed water levels in Figures 12 and 13 show an additional dramatic drop within a year from 1995 to 2003. Another observation toward figure 13 is that the center of the water depression is shifted toward the southwest of the original center.

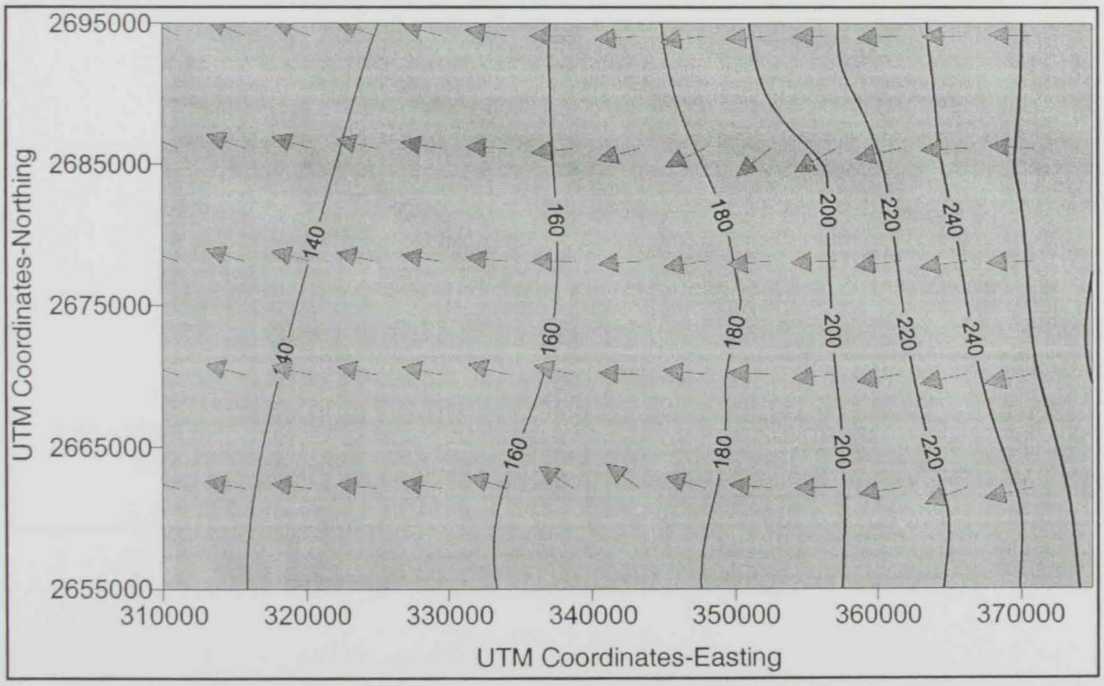


Figure 9. ***Water levels and flow patterns during the predevelopment (before 1980).***

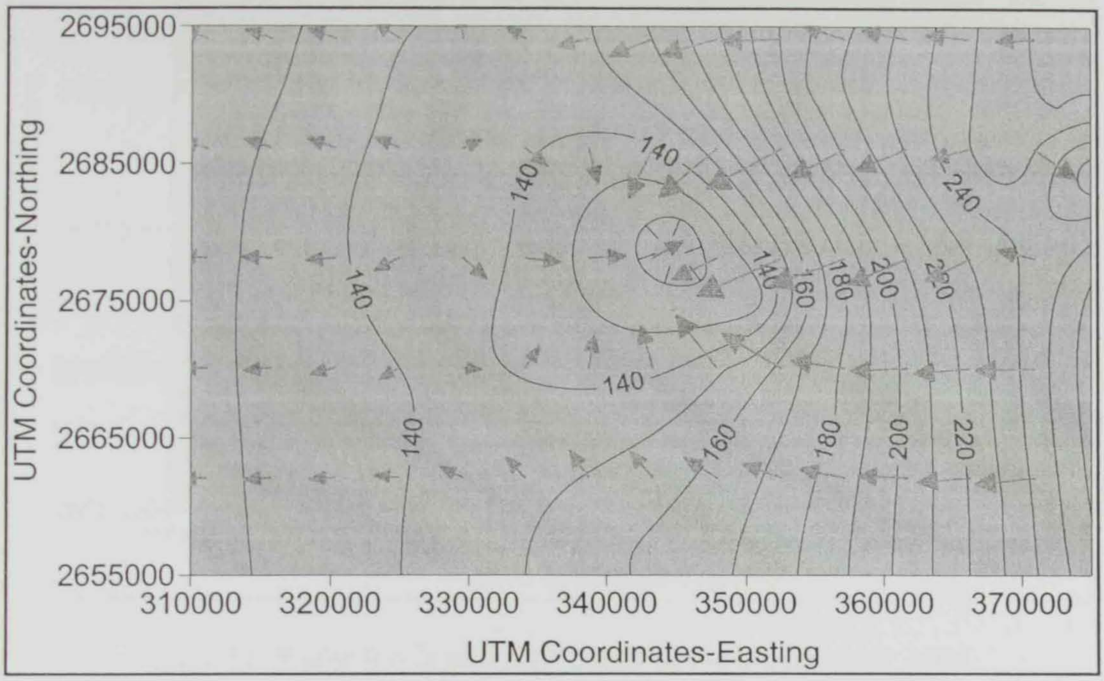


Figure 10. *Water levels and flow patterns during the years 1990-1991.*

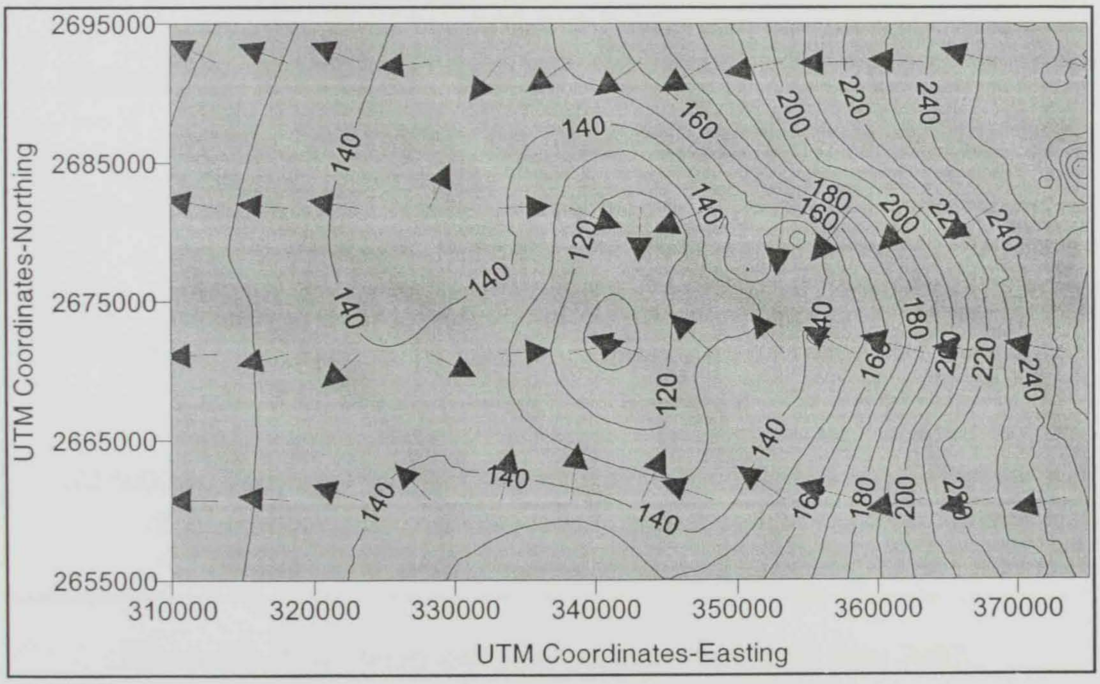


Figure 11. *Water levels and flow patterns during the year 1995.*

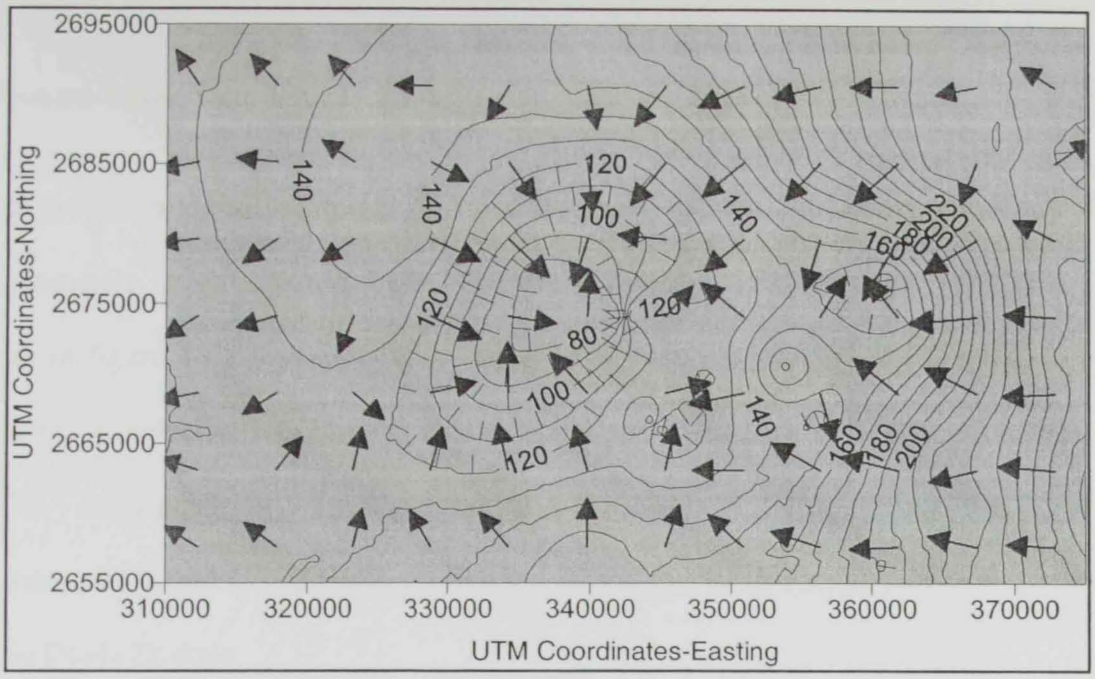


Figure 12. *Water levels and flow patterns during the year 2000.*

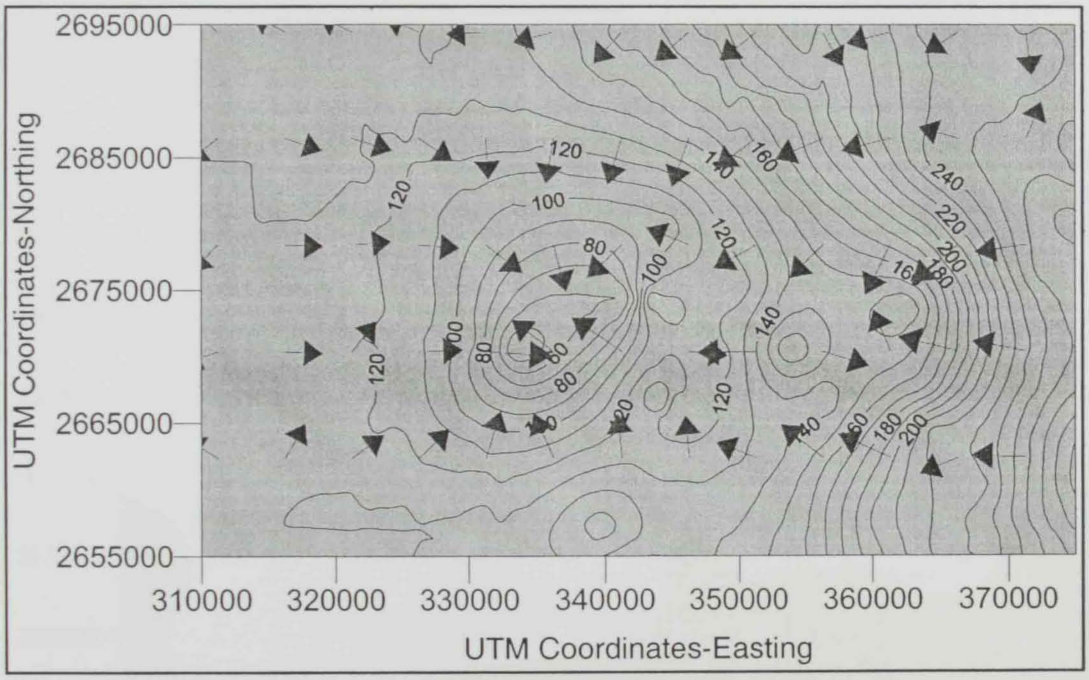


Figure 13. *Water levels and flow patterns during the year 2003.*

Ground-water Salinity

The amount of dissolved solids (TDS) in the ground water is generally considered as the measure to differentiate fresh, brackish and saline water aquifers. The salinity map in figure 14 is based on water samples obtained from the GWRP wells. The Electric Conductivity (EC) was measured for these samples and then converted to TDS. After studying a large number of water samples, the following relationship between TDS and EC has been established by the GWRP for the ground water in the Abu Dhabi Emirate.

$$TDS= (0.63 - 0.67)*EC$$

The used factor depends on the area of the ground water sample in the Emirate. In the Eastern Region, a factor close to 0.63 is used, while in the western region a factor of about 0.67 is used (Al Badi, 1996).

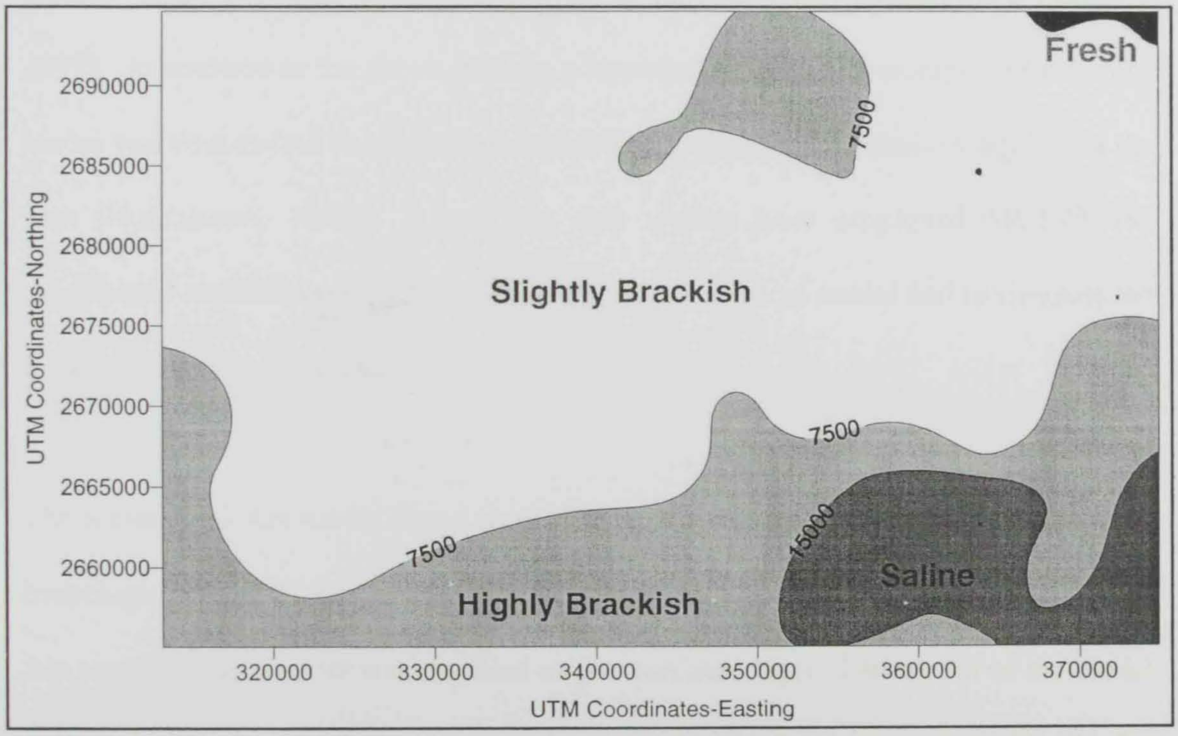


Figure 14. ***Ground-water salinity distribution.***

The study area is covered mainly by the brackish water except for two small areas in the northeastern corner which contains fresh water and in the west of Hafit Mountain which contains saline ground water. In the northeastern corner area where the fresh ground water occurs, the saturated thickness is fully covered by the Quaternary alluvium deposits. The western part is located in the Pliocene- Miocene deposits that possibly affected by the saline water discharging along and through the western limb of the Hafit Mountain. The central region of Hafit Mountain is known by presence of brackish–saline thermal ground-water occurrences and interconnected cave systems of dissolved carbonates.

Previous ground-water modeling studies

One regional and three site specific models were developed to simulate the flow patterns of the ground water in the shallow aquifer in the Eastern Region of Abu Dhabi Emirate. The models are: Al Ain area [Imes et. al, 1993] Al Jabeeb (1) [Kendy et al, 1998] Al Jabeeb (2) [Silva, et al, 1999] and Umm Ghafa [Khalifa, 1999]. In addition to the above models, a hypothetical artificial storage and recovery model was constructed to study the feasibility of recharging the shallow aquifer in the area [Hutchinson, 1999]. All of the four studies have employed MODFLOW (McDonald and Harbaugh, 1988) to construct the numerical model and to simulate the flow in the concerned areas.

The regional Al Ain model [Imes et. al, 1993] was designed primarily to estimate the hydrologic budget of the regional aquifer system and the regional transmissivity of Al Ain aquifer. The aquifer was modeled as one confined layer. The results of the model indicated that the majority of the pumped ground water comes from the aquifer storage. The model estimated the rate of release of water from the storage is about 8.8 cubic meters per second.

The primary purpose of the first Al Jabeeb model [Kendy et al, 1998] was educational, namely, to train The Ground-Water Research Program staff on the use of the ground-water flow models and to demonstrate the value of models in ground-water investigations. Although the model is based on reasonable data range of hydrologic parameters, more study is needed to refine the model simulations. Nevertheless, the model provides probable future forecasting for the sequences on the ground-water aquifer in the area if the present pumping rates continues.

The second Al Jabeeb model [Silva, et al, 1999] is the simulation of ground-water salvage in northeastern Abu Dhabi Emirate model was constructed in 1999 as a continuation of Al Jabeeb model. In this simulation, the model was used to predict the extent of the water-level decline in Al Jabeeb area if the 1995 pumping rates continued for the next 20 years. The results of the simulation indicated that the aquifer will be depleted by then. However, the model indicted that the aquifer depletion could be alleviated by drilling capture wells to capture about 35,000 cubic meters per day of through flow that would normally be lost to the desert beyond the model boundary.

Umm Ghafa model [Khalifa, 1999] simulates the hydrologic conditions in Umm Ghafa area in the southeast of Al Ain to demonstrate the severity of water-level declines caused by pumping. The model indicted that the sustainable yield for the aquifer has been exceeded. The model was used as a predictive tool to forecast the water-level decline in the year 2005 and 2015. The model predicted that if the 1995 pumping rates continued to the year 2015, a complete aquifer dewatering would occur.

Predictions have been made for different scenarios under the assumption that the mid ninety withdrawal rates were unchanged and continued for the future. As the withdrawal rates were increased considerably in most of these model areas during the last 5-10 years, these models have a limited value unless updated according to the changes occurred. However, these models can be used to compare the predicted and actual impacts on the aquifer storage by early and present withdrawals. Unfortunately, no post-audit work has been pursued for these models.

An Artificial Storage and Recovery (ASR) model was constructed to simulate three hypothetical scenarios for aquifer storage recovery of freshwater [Hutchinson, 1999]. The first simulation is a well model, whereby 1,000 cubic meters per day are injected for 200 consecutive days and then recovered at a rate of 1,000 cubic meters per day for 50 days on an 8-ASR-cycle schedule lasting 2,000 days. The second simulation is a pond model, whereby 1,000 cubic meters per day seeps through the bottom of an infiltration pond for 245 consecutive days and then a downgradient recovery well is pumped at 1,000 cubic meters per day for 120 days for a cyclic schedule lasting 1,825 days, or 5 years. The third simulation is a strategic reserve model, whereby 1,000 cubic meters per day are allowed to seep through an infiltration pond for 3 years and subsequent recovery is by 15 wells pumping a total of 15,000 cubic meters per day for 10 days. The conclusions of the model simulations indicate that aquifer storage recovery is a viable alternative for augmenting the depleted aquifer near Al Ain and for creating a reservoir of freshwater for emergency withdrawal.

Considering the utility of the above models for the specified areas and the importance of investigating the shallow aquifer exploitation in Al Maqam Al Saad area, there raised the need to develop a numerical model for better understanding of the ground-water system and to be used as a management tool. Based on this need we have constructed a two part study consisting of aquifer characterization and ground-water simulation. The two parts of the study are detailed in the following sections.

AQUIFER CHARACTERIZATION

Studies on the evaluation of the relationship between the complexity of ground-water models and the overall uncertainty in model prediction have lead to significant findings regarding ground-water modeling. Evaluation of the relationship between the model complexity and the overall uncertainty in its prediction involves a comparison of the prediction error associated with using different models to the error associated with parameter uncertainty. Massman and Hugley in 1995 have shown that in many cases the error associated with parameter uncertainty greatly outweighs the error due to the choice of mathematical/numerical model used. In other words, inaccuracies in flow and transport parameters and their spatial variations will cause more error in the predictions than what will result due to a simplified mathematical model use. This conclusion reached by Massman and Hugley indicates that aquifer characterization is/must be a significant component of ground-water simulation studies. In general, aquifer characterization may be defined as the process of describing various aquifer characteristics by using all available data. The most important feature of aquifer characterization is that it is a coordinated multidisciplinary study for constructing a unified picture of the reservoir which is compatible with all sources of information. Therefore, it involves the integration of geological (lithology, stratigraphy, and structure), geomorphological, hydrologic, geochemical, geophysical (well logging) and engineering (core/sieve analysis, pumping and tracer testing) data.

One of the objectives of aquifer characterization is to improve understanding of the individual and collective role of geological and petrophysical properties that control fluid flow and solute transport in the aquifer of interest. The geological and petrophysical characteristics include faces distribution, depositional environment and basin description, pore and grain size and permeability and dispersivity distributions and so on. The spatial variations in aquifer characteristics such as permeability, porosity, dispersivity, thickness, presence of discontinuities (fissures, fractures, joints, and faults), rock faces and rock characteristics lead to aquifer heterogeneity. Once such features are specified honoring all available data, an accurate conceptual geological model may be constructed where identification of different flow units within the aquifers including their size, geometry, internal variation and continuity is also of great importance. Then, the conceptual models can be transformed into a numerical model which adequately represents the aquifer and used as an effective tool for aquifer management.

This study involves integration of geological, hydrologic, geochemical and engineering data to construct conceptual and numerical models of the shallow aquifer in Al Maqam Al Saad area. Special attention is given to characterization of geometry (areal extension and thickness), determination of the physical and hydraulic boundaries and the distributions of two engineering properties, namely the hydraulic conductivity, and the specific yield of the aquifer.

Data Compilation and Classification

The data used in this study was obtained from the Ground-Water Research Program (GWRP) database and reports. The GWRP operates monitoring stations that provide continuous records of water-level and salinity changes in selected observation wells to document short-term fluctuations related to recharge and withdrawal of water. In addition, monthly water-level measurements are collected from approximately 60 observation wells in areas of heavy ground-water use to document the effects of pumpage on water levels. An Emirate-wide network of about 300 wells which are measured annually to document long-term changes in water levels throughout the Emirate. Water samples are collected from selected wells at various intervals to document changes in water quality in areas affected by agricultural development.

In addition to these activities the GWRP compiles ground-water data from many entities in the Emirate that collect information about ground-water resources. Much of this information has been entered into the GWRP ground-water database to facilitate review and analysis.

The data used in this study consists of observed water levels, pumping tests, and lithologies. Figure 15 shows the wells drilled by the GWRP in the study area. The data obtained from these wells were utilized in deferent parts of this report. Pumping test data used in the transmissivity calculation are tabulated in Appendix 1, while the lithology and well construction data are provided in the Appendix 2.

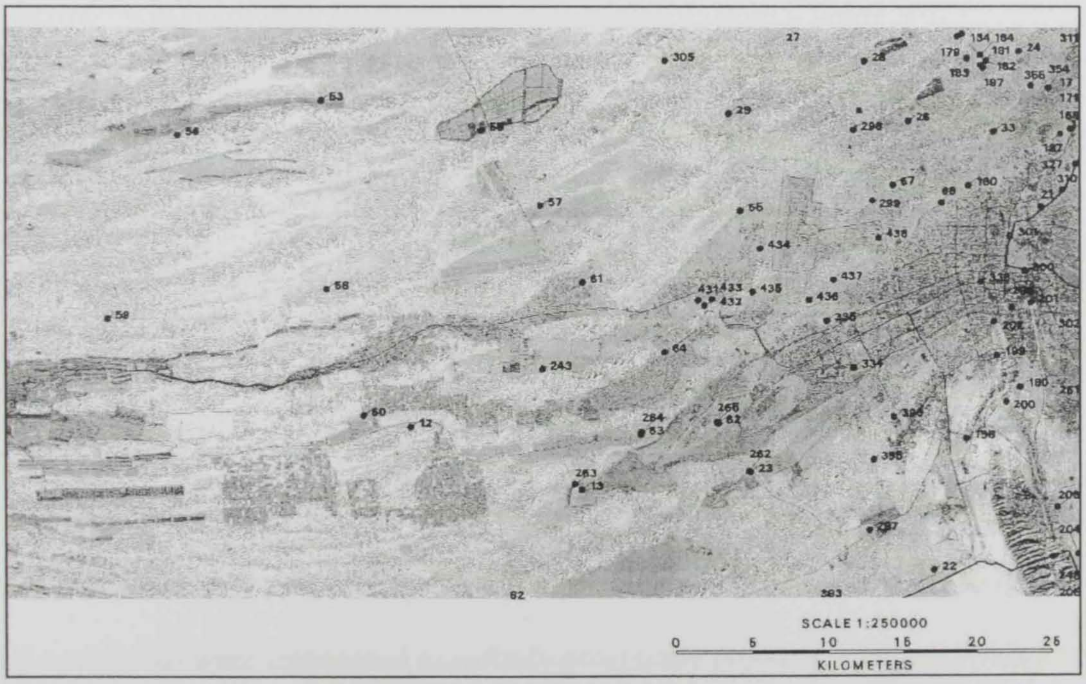


Figure 15. *The GWRP wells drilled in the study area.*

Characterization of the Shallow Aquifer

The analysis of the pumping tests conducted for over twenty wells in the study area is used to construct a transmissivity and a conductivity distribution map of the shallow aquifer. The tested wells were drilled by the Ground-Water Research Program (GWRP) as part of a drilling program intended to evaluate the ground-water resources in Abu Dhabi Emirate.

The tests were analyzed using automated pumping test analysis software, Aquifer Test for Windows. The software automatically generates the desired curve, but it is left for the user's professional judgment to adjust the curve in order to get the best fit for any particular set of data. In this particular analysis, the curves, when possible, were based on the middle data. The early and the late data were excluded because the early data might be influenced by casing storage, and the late data, when the curve gets flatter, might be influenced by leakage from the above formation or delayed yield.

In addition, the salinity map is utilized in specifying hydraulic and physical boundaries. Finally, geomorphological and geological observations are also incorporated in assigning the cell conductivities in certain areas.

Well construction

A common practice in drilling wells in the area is to drill wells penetrating all zones with the purpose of maximizing the water production. Geologic and geophysical logs (if conducted) were interpreted to identify potentially productive zones. Well screens were installed in those zones considered likely to yield water of useable quality. In this practice of well construction, the well annulus is either left open or filled with gravel. In both cases, the annulus will form a conduit for water to flow from one zone to another during pumping. When a pump test is conducted on such wells, the whole aquifer is treated as one layer. Hence, the hydraulic conductivity values obtained from the pumping tests of such wells represent an average conductivity value for the entire screened thickness of the aquifer.

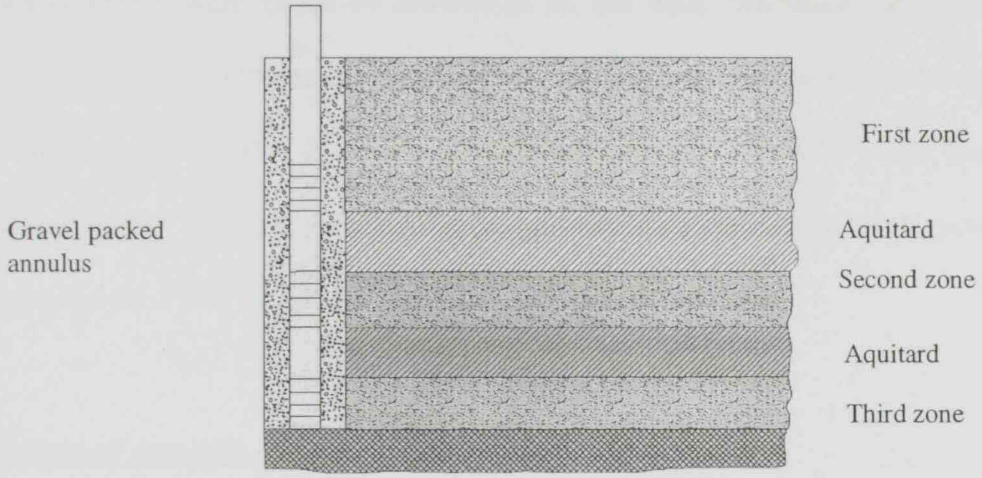


Figure 16. ***Diagram of the typical well construction in the region. Multi-screened well with gravel packed annulus with no isolation in between the zones.***

Testing Practices

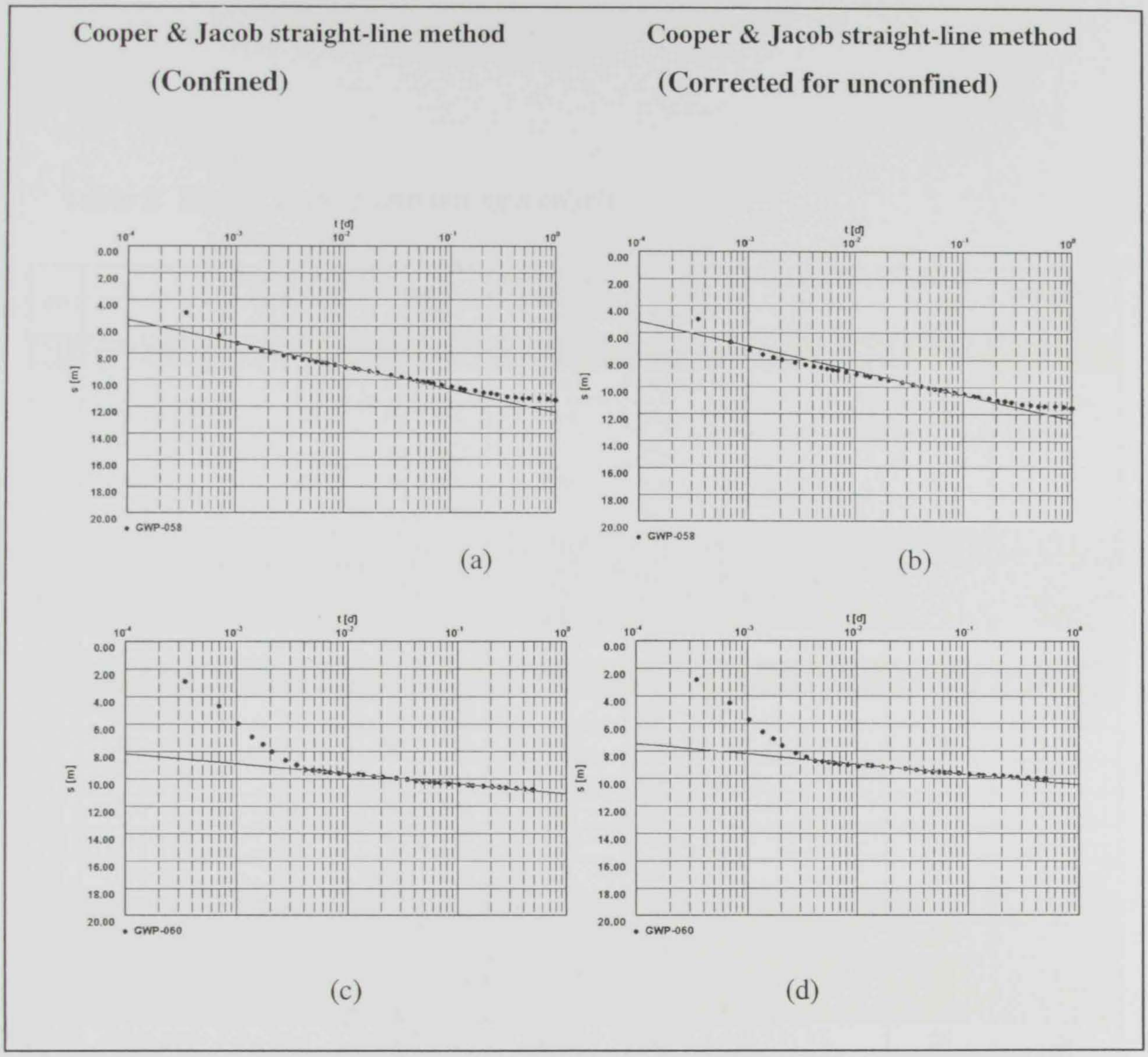
According to Tawfiq and Nasr (1997), single-well pumping test is the usually applied method when testing the wells in the area for which drawdown and recovery data are collected from the pumping well. In some cases, already existing wells at the site are used as observation wells; in other cases, special observation wells were constructed.

Depending on the estimated well yield, a pump with a proper discharge capacity is set in the well. A discharge line was usually laid 100 to 300 meters in a downhill direction to avoid any return flow to the well during the testing period. Prepumping (static) water- level measurements are recorded. Well discharge is measured directly by observing the time required to fill a known capacity container.

Pumping tests are generally conducted for a 5-hour period during which periodic measurements were made of drawdown in the well, discharge rate, and specific conductance. Sometimes the water level declines below the pump intake and the test has to be stopped early. In other cases the test continued beyond 5 hours, maybe up to several days. Generally, after the pump was shut off, water-level recovery was measured for 2 to 5 hours.

Method of Analysis

The pumping tests were analyzed using Cooper & Jacob straight-line method and Theis & Jacob method for the recovery tests. These two methods are originally developed specifically for the analysis of the confined aquifer tests, but they are commonly used to evaluate the unconfined aquifer as well. In addition, the software provides an optional correction factor for this method when used to analyze the unconfined aquifer. However, by analyzing and comparing some tests using both ways (the original method and the correction) no significant difference in the results was noted (see the examples figure 17). The only noted difference was the shifting up to the curve while the slope remained the same. Hence, the estimated values of corrected transmissivity values did not change significantly as seen in table 2, showing the uncorrected and corrected transmissivities from figure 17. Accordingly, the tests were analyzed using Cooper & Jacob straight-line method without applying the correction factor.



Cooper & Jacob straight-line method (Confined)

Cooper & Jacob straight-line method (Corrected for unconfined)

(a) (b)

(c) (d)

Figure 17. *Comparison between using the corrected and the uncorrected Cooper & Jacob straight-line method.*

Table 2. Transmissivity (m^2/d) comparison without correction and with correction.

Method (uncorrected)	Method (corrected)
0.6 (a)	0.62 (b)
2.09 (c)	2.06 (d)

Results

The results of the analysis are summarized in the following table (See Appendices 1, 2, and 3 for data, lithology, and graphs respectively):

Table 3. ***Results of the pump testing analysis.***

s/n	well	transmissivity (pumping) (m^2/d)	graph reference	transmissivity (recovery) (m^2/d)	graph reference	transmissivity (m^2/d) (average)	saturated thickness (m)*	conductivity (m/d)
1	GWP-014	20	Fig 1_3_D	4	Fig 1_3_R	12	92	0.13
2	GWP-023	0.6	Fig 2_3_D	0.5	Fig.2_3_R	1	63	0.01
3	GWP-024	21.2	Fig 3_3_D	10.9	Fig.3_3_R	16	68	0.24
4	GWP-027	150	Fig 4_3_D	17	Fig.4_3_R	84	57	1.5
5	GWP-028	100	Fig 5_3_D	100	Fig.5_3_R	100	95	1.1
6	GWP-033	6.7	Fig 6_3_D	3.5	Fig.6_3_R	5	116	0.04
7	GWP-050	60	Fig 7_3_D	24	Fig 7_3_R	37	52	0.72
8	GWP-051	60	Fig 8_3_D	70	Fig 8_3_R	65	59	1.1
9	GWP-052	128	Fig 9_3_D	140	Fig 9_3_R	134	35	3.83
10	GWP-053	193.0	Fig 10_3_D	166.0	Fig.10_3_R	180	37	4.85
11	GWP-054	21	Fig 11_3_D	100	Fig 11_3_R	60	21	2.86
12	GWP-055	4.0	Fig 12_3_D	3.4	Fig.12_3_R	4	39	0.10
13	GWP-058	198.0	Fig 13_3_D	198.0	Fig.13_3_R	198	72	2.75
14	GWP-059	236.0	Fig 14_3_D	274.0	Fig.14_3_R	250	52	4.7
15	GWP-060	209.0	Fig 15_3_D	98.0	Fig.15_3_R	154	75	2.05
16	GWP-066	6.2	Fig 16_3_D	4.6	Fig.16_3_R	5	100	0.05
17	GWP-067	15.7	Fig 17_3_D	74.5	Fig.17_3_R	45	79	0.57
18	GWP-080	11	Fig 18_3_D	10	Fig.19_3_R	10	92	0.11
19	GWP-081	105.0	Fig 19_3_D	154.0	Fig.18_3_R	130	76	1.70
20	GWP-082	25.0	Fig 20_3_D	425.0	Fig.20_3_R	225	80	2.81
21	GWP-083	7.5	Fig 21_3_D	6.0	Fig.21_3_R	7	50	0.14
22	GWP-084	53.9	Fig 22_3_D	12.1	Fig.22_3_R	33	56	0.59
23	GWP-086	63.4	Fig 23_3_D	53.2	Fig.23_3_R	58	55	1.06
24	GWP-089	2.1	Fig 24_3_D	1.6	Fig.24_3_R	2	71	0.03
25	GWP-090	119.0	Fig 25_3_D	92.6	Fig.25_3_R	106	51	2.07
26	GWP-093	83.0	Fig 26_3_D	93.0	Fig.26_3_R	88	99	0.89
27	GWP-206B	170	Fig 27_3_D	185	Fig.27_3_R	177	70	2.5

*Data for the saturated thickness is for the year 1995 and calculated as the difference between the water level and the bottom of the aquifer (Tawfiq et. al., 1997). The yellow color is for wells that are in the vicinity of the study area.

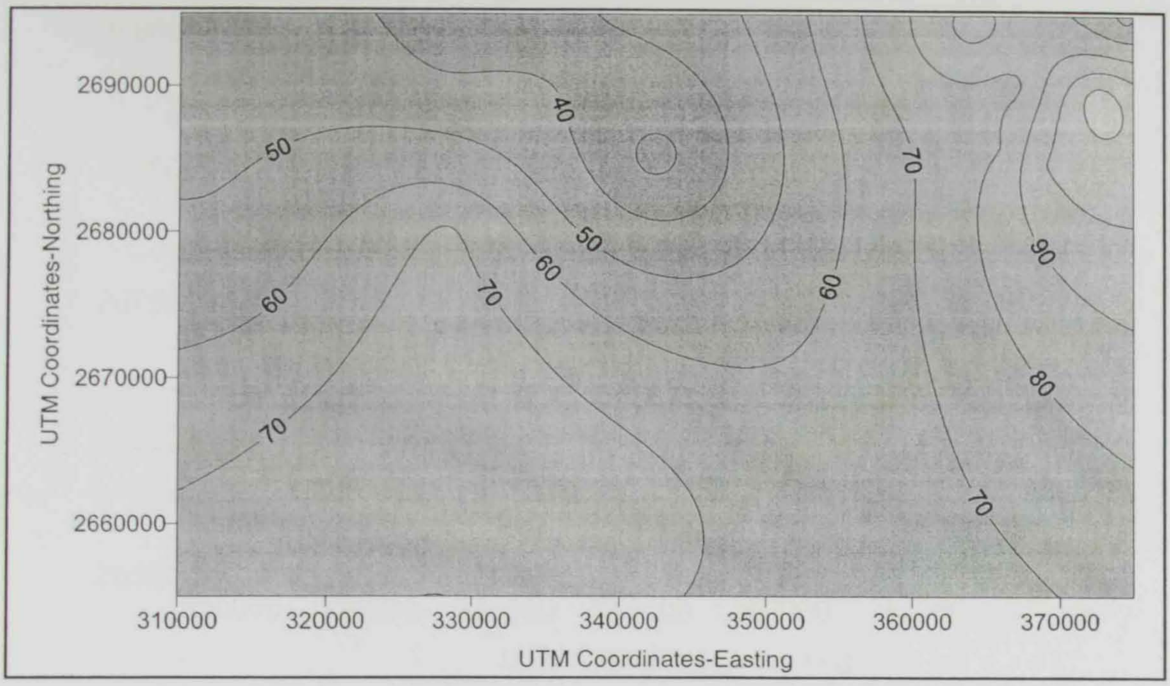


Figure 18. *Saturated Thickness in meters*.

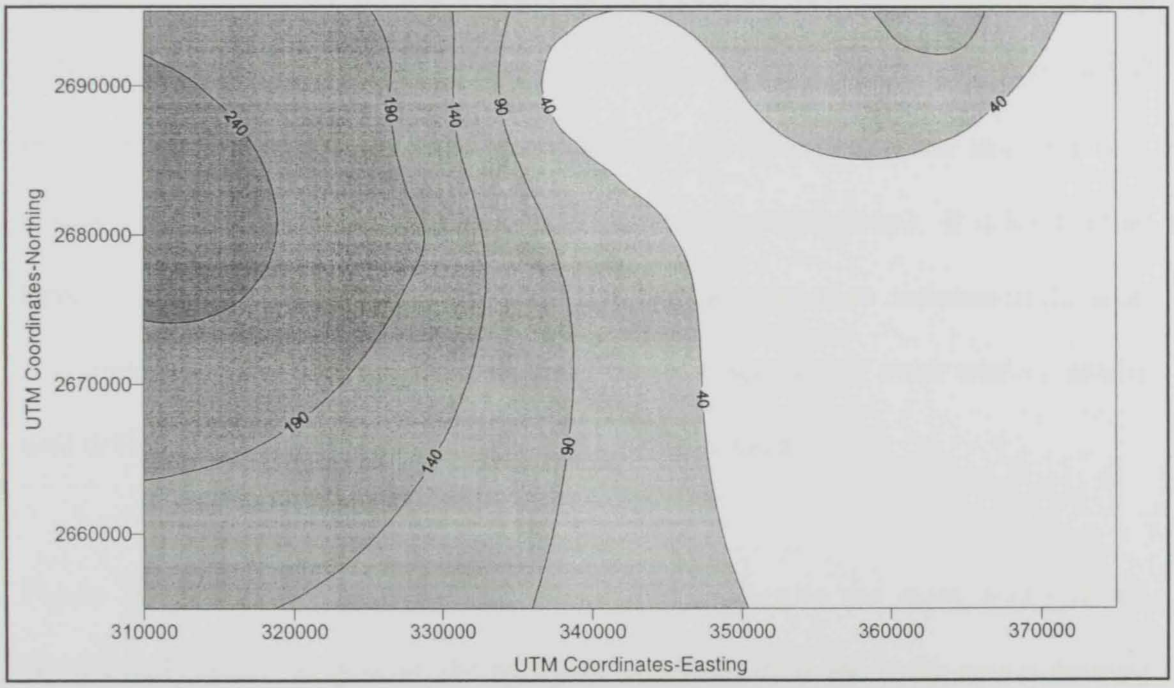


Figure 19. *Estimated aquifer transmissivity(m^2/d).*

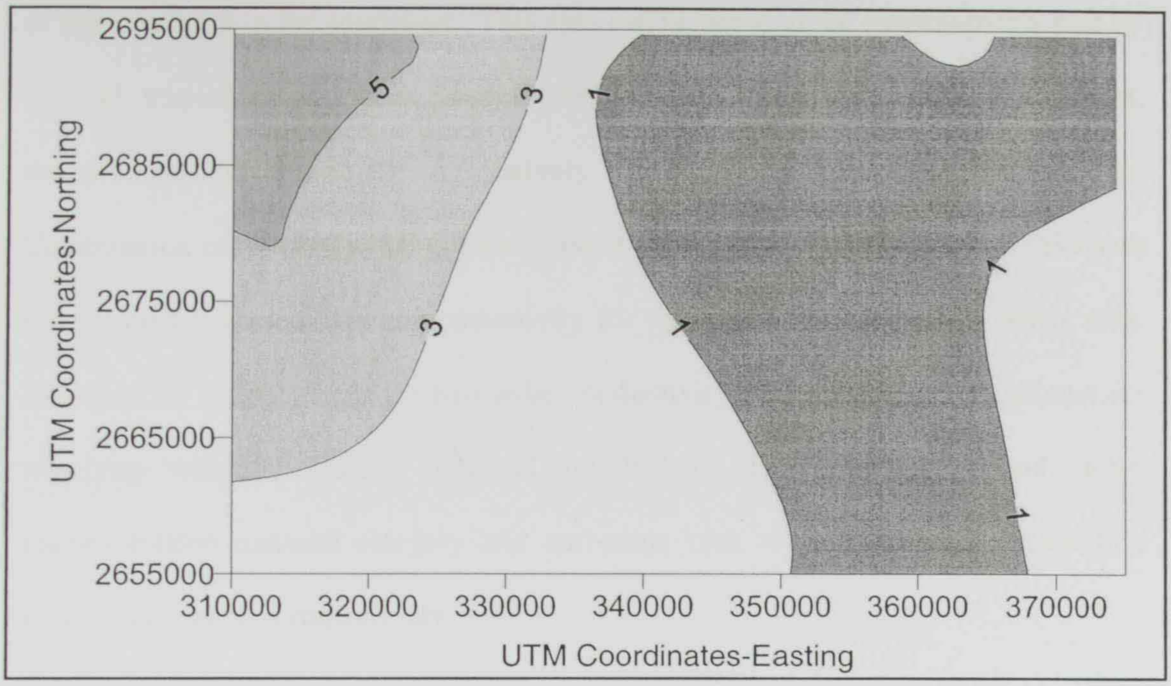


Figure 20. *Hydraulic Conductivity distribution (m/d).*

Hydraulic Conductivity Distribution in the Shallow Aquifer

The ability of the aquifer to transmit water can be described by its hydraulic conductivity or by its transmissivity. Transmissivity is the product of the hydraulic conductivity and the saturated thickness. Hydraulic conductivity is the volume of water that will flow during a unit time through a unit area under a unit hydraulic gradient. It is known that large variations in well yields from wells small distances apart are common in the area. A completed well at one location may yield adequate supplies of water while a nearby well drilled by the same technique may yield very little water.

Figure 20 shows the contours of the conductivity values in the study area that are considerably small. In general, the hydraulic conductivity in the study area is ranging from 0.1 to 5 m/day. The saturated thickness and the association of least cemented matter either from the alluvium or from the younger Miocene sequence play a major role. A considerable amount of finer material is included in to the saturated thickness of the area lying in the southwest. This area can be noted in the transmissivity plot by the high transmissivity values ranging from 90-250. In the saturated thickness plot, the southwestern region shows relatively less thickness than the eastern region. Combination of relatively higher transmissivity and relatively low saturated thickness has resulted higher hydraulic conductivity for the western region of the study area. The order of magnitude of the hydraulic conductivity values in the west and east are matching with the values obtained by Bower (1979) for fine sand under unconsolidated material category and carbonate rock with secondary permeability under rock category respectively.

The saturated thickness defined here is the distance from the lower lying major confining bed to the water table. In general this zone is layered with number of clay and silt associated semi/low permeable layers. As some of these have nothing or very little to contribute, the affective saturated thickness may considerably less than the values given in this table.

It should be noted that the conductivity values obtained from this exercise are to be considered as approximate values that give a general idea about the conductivity of the aquifer in the study area. The values can not be considered as precise values because of the well construction pattern which mainly targeted toward maximizing the well yield rather that conduct scientific pumping testing of specified zones.

Specific Yield

Among the major hydrological units in the shallow aquifer, only alluvium has sufficient pumping test data to make a reasonable estimation for the specific yield of the aquifer. In general, in the alluvium aquifer specific yield ranges from 0.02 to 0.18 (*Al Aidarous et. al.*, 1993). There are few tests conducted in the study area having an observation well to estimate the aquifer specific yield. As these tests were conducted for relatively shorter periods of time, the obtained values may or may not represent the long-term effective specific yield of the aquifer. A range between 0.06-0.001 has been considered by GWRP as plausible specific yield in a study conducted in the study area (unpublished work by the GWRP). As the aquifer in the west of the study area is less cemented, slightly higher value for specific yield can be expected.

CONSTRUCTION OF THE NUMERICAL MODEL

Conceptual model

In the conceptual model of the study area (figure 21) three layers were assumed, unsaturated, saturated, and confining layer. The three layers were assumed to be extending horizontally in the whole study area. The unsaturated layer consists of unconsolidated partly cemented soil that extends to a depth ranging from 30 to 50 meters. The saturated layer constituting the unconfined aquifer has a thickness ranging from 90-50 meters from east to west. The confining layer consists of low permeability rocks.

The hydrogeologic features of the unconfined aquifer are included in Table 4.

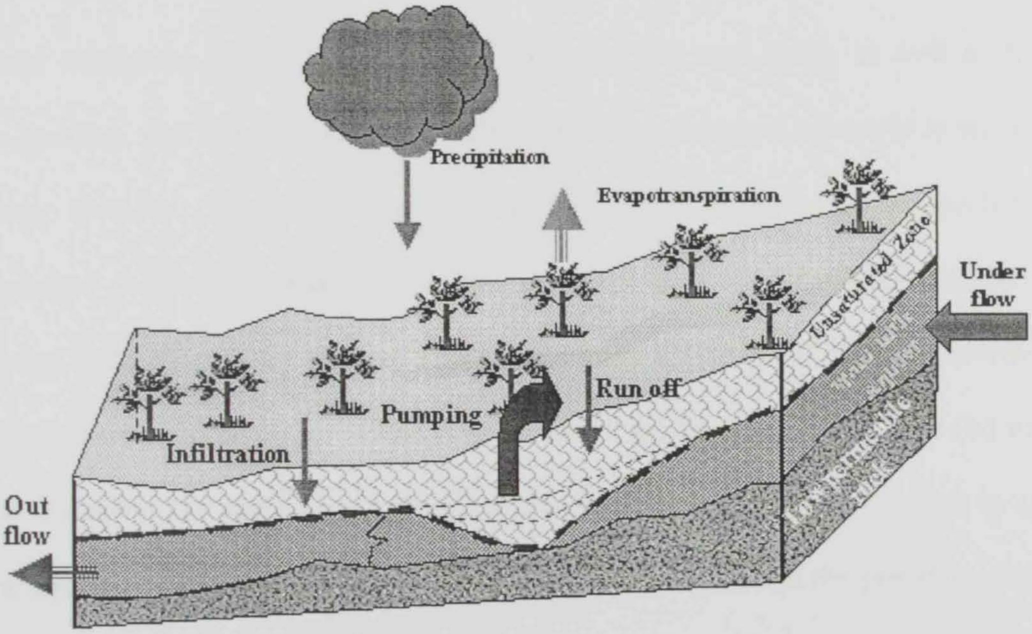


Figure 21. *The Conceptual model of the study area.*

Table 4. *Summary of the hydrologic features of the shallow aquifer.*

	West of study area	**East of study area**
Formation	Finer and less cemented lithology	Coarser more cemented lithology
Transmissivity	90-240 m^2/d	1-90 m^2/d
Saturated thickness	< 70m	60-100m
Hydraulic conductivity	1-6 m^2/d	<1 m^2/d
Hydraulic gradient	0.001	0.005
Inflow factors (represented in green arrows) are estimated to be**10 to 15 million cubic meters per year** (in steady state) Out flow factors are represented by red arrows are estimated to be **10 to 15 million cubic meters per year** (steady state)		

Numerical Model

A numerical finite-difference model of ground-water flow of the study area was constructed and calibrated for the steady-state predevelopment conditions and for transient conditions caused by pumping from municipal well fields as well as from farms, gardens, and forestry and wells. The model was designed primarily to simulate the water- levels for different time periods in order to get an insight of the reasons behind the dramatic declines of water levels in the area. The modeled area is bounded by the following UTM coordinates: Eastern coordinates from 310000 to 375000 and Northern coordinates from 2655000 to 2695000. The model grid contains 2600 cells (65 rows and 40 columns), the grids are equally distributed therefore each cell represents an area of one square kilometer. This grid area seems reasonable based on the previous models constructed in the area.

The ground-water flow is simulated by a two-dimensional modular model developed by McDonald and Harbaugh (1984). The model uses one layer to represent the shallow aquifer in the area. The layer is modeled as an unconfined unit.

Confining Bed

The confining bed (Aquifer Bottom) is demarcated through borehole lithologies, well completion reports, water levels data and geophysical logs. The confining bed is composed of layers of unaltered tertiary deposits; claystone, mudstone, evaporite; and limestone. Because there is no sharp contrast of unconformity exists between the shallow aquifer and the confining bed, the base of the aquifer is defined as the depth at which the intrinsic permeability is less than 1000 millidarcies (equivalent to 0.8 m/d hydraulic conductivity). Therefore, the basal confining system in the modeled area is characterized by very low permeability and saline ground water with no evidence of any hydraulic connection with the upper shallow aquifer. Hence, the base of the shallow aquifer is modeled as an impermeable barrier to ground-water flow. A map for the bottom of the aquifer was prepared using the SURFER software. The map shows that the bottom of the aquifer is gently sloping toward the west.

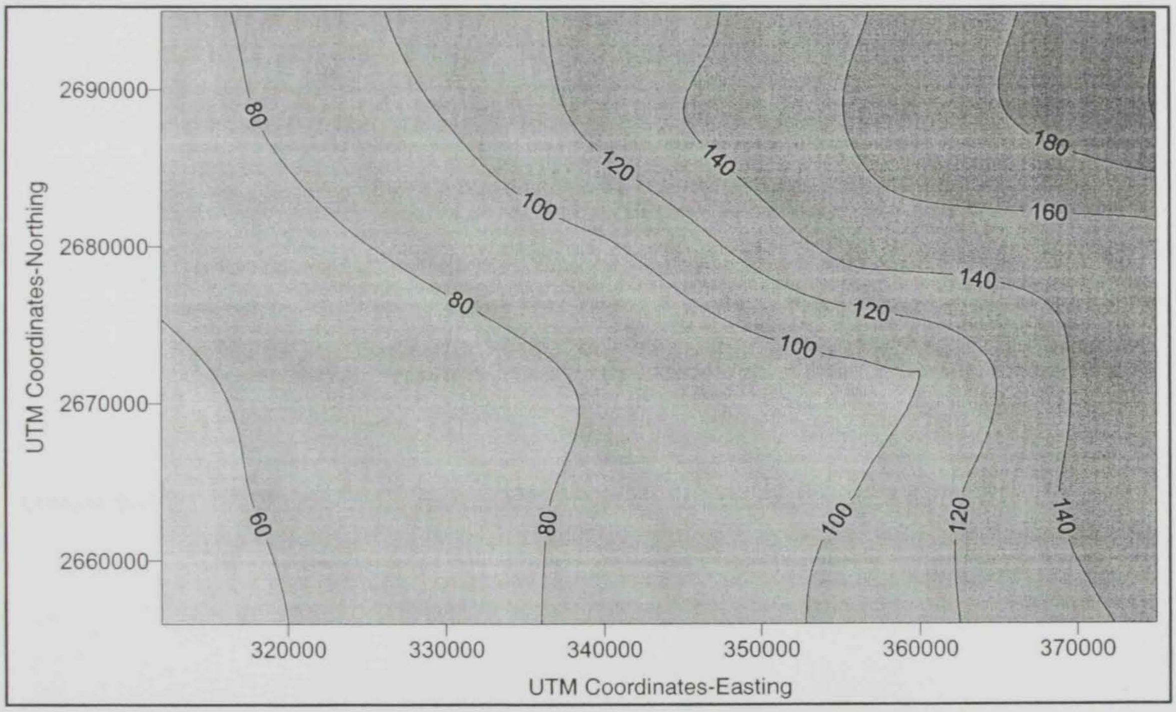


Figure 22. *The elevation of the confining bed in meters above mean sea level.*

STEADY STATE SIMULATION

The steady state is the first step of model construction in which the user simulates the aquifer in its steady (undisturbed) state or before any significant pumpage is introduced. The steady state calibration is useful for identifying hydraulic conductivity distribution characteristics. The following sections deal with the input parameters required to simulate the steady state of the aquifer.

Hydraulic Conductivity

The hydraulic conductivity value for each grid block is assigned in light of the hydraulic conductivity map prepared in the aquifer characterization section. As it is shown in figure 23, the conductivity values used in the model for the calibration of the steady state are reasonably similar to that obtained from the aquifer characterization. Colors in the figure represent conductivity values as follows: light blue; 1m/d, dark blue; 2m/d, white; 3 m/d, red; 4 m/d, and green; 5 m/d. In general, this map is consistent with the map produced in the aquifer characterization section with exception of the southwest corner. In aquifer characterization map the area has a value of about 2 m/d while in this map, the value is 1 m/d. The conductivity value of 1 m/d is plausible for this area because the salinity map (Figure 14) shows the ground water in this area as saline. Ground-water salinity is most often associated with stagnation or very little movement (very little conductivity) of water which allows sufficient time to dissolve minerals in the water.

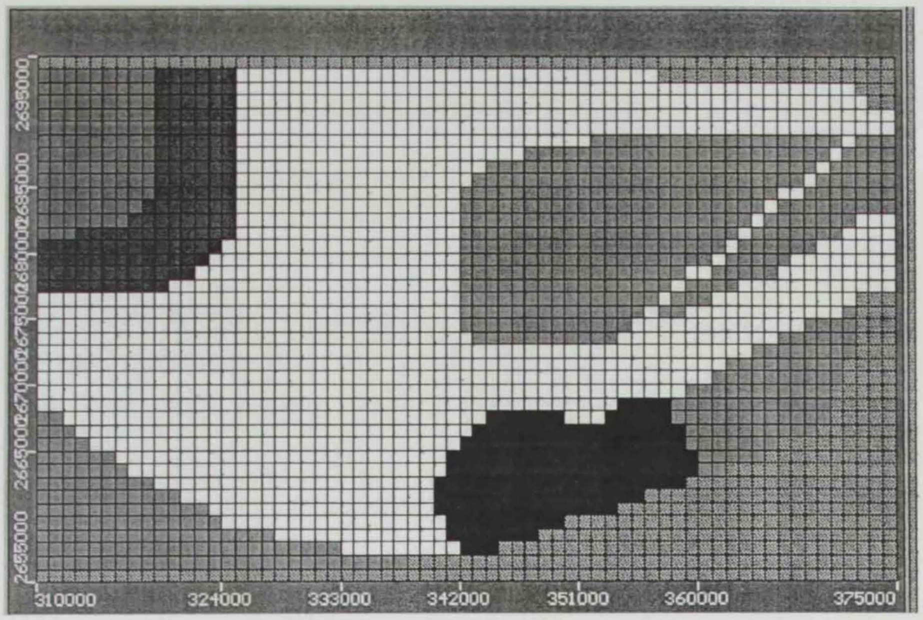


Figure 23. *Hydraulic conductivity distribution in the model. The inactive cells are shown in gray.*

Recharge, Constant Head, and Inactive Cells Boundaries

Figure 24 shows the boundaries of the model. The natural recharge distribution of about 7 million cubic meters per year was used in the model. Originally the recharge was estimated to be 10 million cubic meters for the study area, but in order to calibrate the model with the given parameters; this amount had to be reduced to 7 million cubic meters per year. Subsurface flow component of the recharge is applied to the model at the active cells nearest to the gap. Surface-runoff flow is applied to the wadies downstream from each gap by prorating the flow to cells representing the existing wadi channel. The recharge in the gaps represents part of the eastern boundary of the model because of the nature of the regional ground-water flow system. The western boundary of the area is a constant head boundary of 125 meters above mean sea level which was selected in accordance with water-level distribution during the predevelopment period. The boundaries in the south, north, and significant part of the east are inactive cells shown as the gray colored squares in the model that represent the hydraulic flow boundaries of the system.

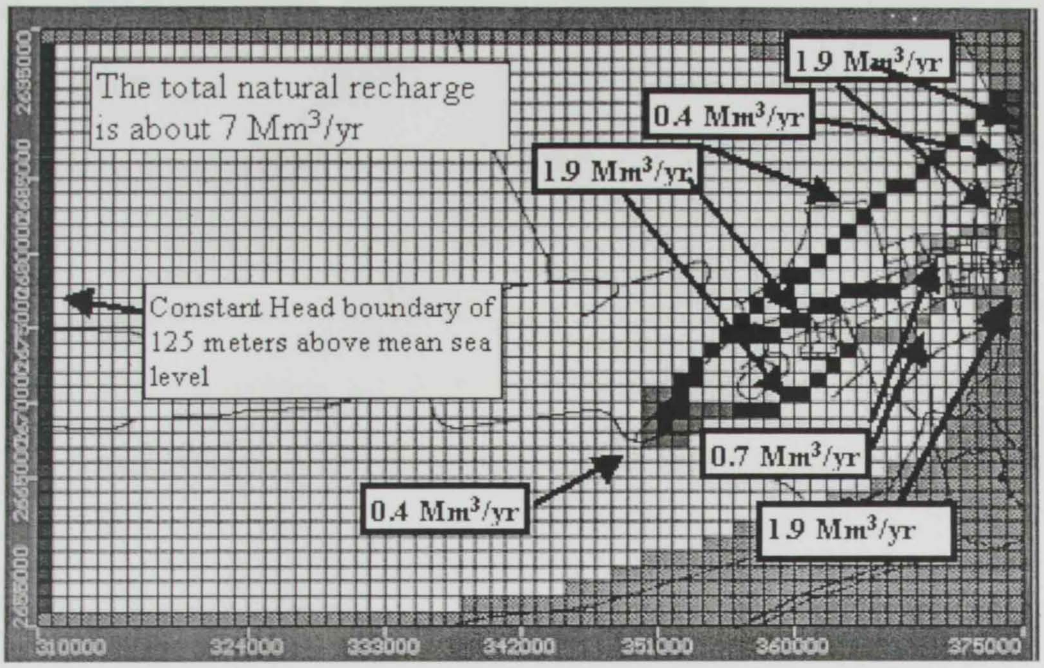


Figure 24. *Recharge, constant head, and inactive cells distribution in the model.*

Other Parameters

The other parameters used in the calibrated model are: specific yield value of 0.04, porosity value of 0.2, and an evapotranspiration rate of 1.650 meters per year with an extinction depth of 4 meters where evaporation becomes insignificant.

Calibration

Model simulations commonly undergo "calibration", a process whereby the differences between simulated and measured hydraulic heads (and flow volumes) are minimized by adjusting initial values and estimates of various hydraulic properties of the simulated ground-water flow system. The calibration process is 'trial and error' procedure, which involves continuous modification of the aquifer hydrologic parameters until an acceptable agreement between the simulated and measured hydraulic heads is reached. Initially the actual aquifer parameters were used in the model, but as we get closer to the calibration target, the input parameters have to be fine tuned and modified.

Calibration Target

The predevelopment period, assumed to be before 1980, is generally accepted as the period where the steady state flow conditions prevail in the area. In that period the ground-water extraction activities were minimal and did not disturb the balance between the natural recharge and discharge in the area. Therefore, the water contours for that period were used for the calibration of the steady state conditions of the model.

Calibration Figures

The steady state conditions were calibrated to the predevelopment water levels. Figure 25 shows that the water levels calculated by the model (red) are closely matching the measured (black). This indicates that a proper calibration of the steady state conditions was achieved.

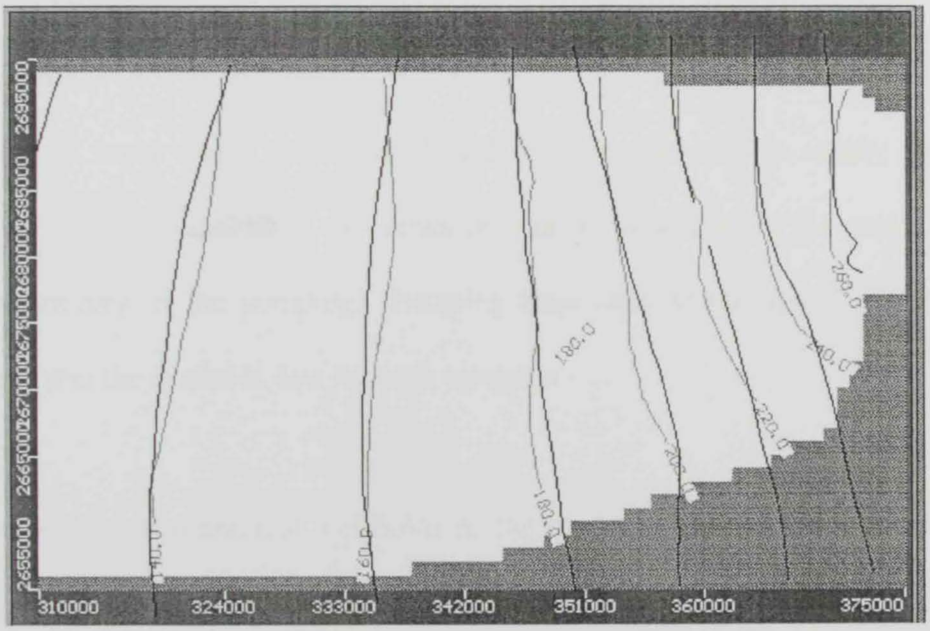


Figure 25. *Observed (black) vs. simulated (red) contour lines during the steady state conditions.*

TRANSIENT SIMULATION

For the transient (or the pumping) simulation, each year from 1971 to 2003 was treated as a pumping or stress period where the withdrawal rate is constant throughout the year. The period used for future prediction from 2003 to 2015. Estimated ground-water withdrawals at WED well fields and estimated consumptive use by forests, farms, gardens, were used to simulate the effect of pumping on ground-water water levels in the shallow aquifer.

Induced recharge

Induced recharge is caused either by irrigation return flow or by the infiltration from the excess water from the desalinated water brought to the area from Abu Dhabi. The induced recharge is represented in the model by subtracting the estimated amount of this recharge from the estimated amount of the withdrawal (estimated to be about 10% of the withdrawal rate).

Withdrawals

Thousands of water wells have been drilled in the study area to supply water for agricultural and municipal uses. No actual records are available for the pumping rates for each category of the pumping. Pumping rates used in the model are estimates calculated from the available data for each category:

Municipal

There are only two municipal wellfields in the modeled area Al Saad and Seah Al Meyah. Yearly estimated withdrawals for both fields were obtained from the Water & Electricity Department. Based on these withdrawals, the withdrawal per node was calculated as shown in tables 5 and 6.

TABLE 5. ESTIMATED ANNUAL WITHDRAWAL FROM AL SAAD WELLFIELD.

Al Saad												
Year	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Total wells/operating wells	10	10	10	10	10	10	10	10	10	10	10	10
Total discharge (m^3/day)	5900	6300	7200	10500	10300	11300	10500	9300	4600	4200	3900	2400
Discharge per well (m^3/day)	590	630	720	1050	1030	1130	1050	930	460	420	390	240

TABLE 6. ***ESTIMATED ANNUAL WITHDRAWAL FROM SEAH AL MEYAH WELLFIELD.***

Seh Al Meyah												
Year	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Total wells/operating wells	----	----	----	10	10	10	10	10	10	10	10	10
Total discharge (m^3/day)	----	----	----	11700	13900	13100	12000	9400	7300	8900	11300	13300
Discharge per well (m^3/day)	----	----	----	1170	1390	1310	1200	940	730	890	1130	1330

By around 1995, both wellfields started to distribute desalinated water coming from Umm Al Nar Desalinated station in Abu Dhabi instead of the depleting ground water in the area.

Gardens

The data required to make this estimation was obtained from the Gardens Section of and the Sewage Treatment Section in Al-Ain municipality.

Assumptions-

- In 1982 and 1989-2003 the number of wells inside Al-Ain is assumed to be 35% of the total wells in the whole of Al-Ain region (i.e inside and outside Al-Ain town).
- The number of working wells during the years 1983-1988 and 1995 was obtained from actual data.

- 90% of the cumulative wells were assumed to be working every year.
- 95% of the sewage discharge was assumed to be in the model area
- 10% of the net garden pumpage was considered to be irrigation return

Calculation

Average well capacity= 15 m^3/hr (an approximate figure was obtained from the gardens section)

Pumpage can be divided into Winter pumpage and Summer pumpage as follows:

Winter pumpage- = # of working wells * 15 m^3/hr * 7 hr /day * 182.5 days /yr

Summer pumpage = # of working wells * 15m^3/hr *12hr/day * 182.5 days/yr

By taking the average working hours of both seasons, the annual or yearly average can be estimated as follows:

Annual pumpage = # of working wells * 15m^3/hr * 9.5hr/day * 365 days/yr

Or

Annual pumpage **= # of working wells * 52012**

In addition, the following assumptions were made during the calculation:

Gardens net pumpage (Mm^3/yr) = Pumpage - sewage discharge

90% of this pumpage is distributed over 40 nodes

m^3 /day/node = 90% of Garden net pumpage * 1**6/ (365*40)

Table 7. *Yearly ground-water requirements for the Gardens inside the modeled area.*

Year	Number of wells inside the model area	cumulative Sum	Working wells (90% of the previous column)	Pumpag/ year (Mm**3/yr)	Sewage discharge (Mm3/yr)	Sewage discharge in the model area(95%of the previous column)	Garden net pumpage (Mm3)/yr	90%of the net pumpage	m3/day/ node
1982	46	46	41	2.15	2	1.9	0.25	0.23	16
1983	31	77	69	3.60	2	1.9	1.70	1.53	105
1984	28	105	95	4.92	3	2.85	2.07	1.86	127
1985	42	147	132	6.88	4	3.8	3.08	2.77	190
1986	34	181	163	8.47	5	4.75	3.72	3.35	229
1987	27	208	187	9.74	6	5.7	4.04	3.63	249
1988	16	224	202	10.49	6	5.7	4.79	4.31	295
1989	17	241	217	11.27	7	6.65	4.62	4.16	285
1990	8	249	224	11.67	7	6.65	5.02	4.51	309
1991	26	275	248	12.89	8	7.6	5.29	4.76	326
1992	23	299	269	13.99	9	8.55	5.44	4.90	335
1993	30	329	296	15.42	11	10.45	4.97	4.47	306
1994	44	373	336	17.47	12	11.4	6.07	5.46	374
1995	22	395	356	18.49	12	11.4	7.09	6.39	437
1996	30	425	383	19.90	13	12.35	7.55	6.79	465
1997	35	460	414	21.54	13	12.35	9.19	8.27	566
1998	29	489	440	22.90	15	14.25	8.65	7.78	533
1999	40	529	476	24.77	17	16.15	8.62	7.76	531
2000	42	571	514	26.73	18	17.1	9.63	8.67	594
2001	35	606	545	28.37	20	19	9.37	8.43	578
2002	50	656	590	30.71	21	19.95	10.76	9.69	663
2003	45	701	631	32.82	22	20.9	11.92	10.73	735

Forestry

The ground-water withdrawal for the Forestry Department was estimated by two different procedures:

The first method of estimation was based on the data obtained from the forestry Department. An example of the data obtained is shown in Table 8 for Al Maqam forest. The table shows the number of wells in the forest, the discharge in gallons per minute of each well, the number of working hours per day, and the number of years the well has been in use.

Table 8. *An example of the data obtained from the forestry Department*.

Well no.	Discharge (gph)	Number of hours in use per day	Number of years in use
1	667	17	6
2	665	17	14
3	1525	17	14
4	3015	17	6
5	2195	17	10
6	1552	24	8

1) Al Maqam forest is distributed over 5 nodes in the model. The estimated withdrawal is as follows:

    a) Divide the total amount of recharge by the number of the wells and multiply it by the average number of working hours per day to find the average discharge per day per well:

    $$\frac{9619\,g/h}{6\,wells}\times 18\,hours/day = 28800\,g/d/well$$

    b) Convert the gallons to cubic meters:

    28800 g/d/well * 0.004546 = 130 m^3/d/well

    c) Divide by the number of nodes allotted for the forest in the model:

    $$\frac{130\text{ m3/d/well}}{5\text{ nodes}} = 25\,m3/d/well$$

    d) Multiply the previous amount by the number of wells in each year to obtain the withdrawal rate for each of the five nodes per year.

Table 9. *Estimation of ground-water for Al Maqam forest based on the available data.*

Years in use	**Year**	**New wells**	**Old wells**	**Total**	**Discharge per node (m^3)**
14	**1981**	2	0	2	45
13	**1982**	2	0	2	45
12	**1983**	2	0	2	45
11	**1984**	2	0	2	45
10	**1985**	1	2	3	68
9	**1986**	0	3	3	68
8	**1987**	1	3	4	90
7	**1988**	0	4	4	90
6	**1989**	2	4	6	135
5	**1990**	0	6	6	135
4	**1991**	0	6	6	135
3	**1992**	0	6	6	135
2	**1993**	0	6	6	135
1	**1994**	0	6	6	135
0	**1995**	0	6	6	135

The second method is applied when there are no information available about the number of wells in the forests. In this case, the forest areas, obtained from the forestry Department are used for pumpage estimation. The area of the forest is multiplied by the value of 2100 cubic meter per year per hectare which represents the estimated water requirement of a hectare of cultivated forest area per year (Hutchison, 1996). The total pumpage for each forest is then divided by the number of the assigned nodes for the forest.

Farms

Withdrawal from the various farms in the modeled area is divided into the following farm areas: Al Ain, Al Maqam, Al Yahar, Al Saad, Remah and Abu Samra, Sulaimat, affrostation, Seh Garabah, Al Anja, Seh Al Meyah, and Al Zaala. From the Statistical

Bulletin of the Agricultural Department we get the total farm area in the Eastern Region where we calculated the total water consumption by multiplying the total area of farm in the Eastern Region by: 0.6 meters per year –falaj discharge (Hutchinson, 1996). Then we estimated the withdrawal percentage for each of the above areas from the total withdrawal. Finally, we calculated the withdrawal from each node specified to the areas. Table 10 is an example of such calculation.

Table 10. *An example of farm water consumption estimation*.

				10 nodes
Year	**Farm pumpage** in the eastern region (Mm3/yr)	**Al Ain (5%)**	**90% of the previous column**	**m3/day/node** (pervious column*1**6/(365*10))
1971	0.2	0.0	0.0	2.5
1972	1.0	0.1	0.0	12.3
1973	3.0	0.2	0.1	37.0
1974	5.0	0.3	0.2	61.6
1975	8.0	0.4	0.4	98.6
1976	11.0	0.6	0.5	135.6
1977	13.0	0.7	0.6	160.3
1978	14.0	0.7	0.6	172.6
1979	15.0	0.8	0.7	184.9
1980	21.0	1.1	0.9	258.9
1981	25.0	1.3	1.1	308.2
1982	32.0	1.6	1.4	394.5
1983	42.0	2.1	1.9	517.8
1984	62.0	3.1	2.8	764.4
1985	61.5	3.1	2.8	758.2
1986	61.0	3.1	2.7	752.1
1987	66.0	3.3	3.0	813.7
1988	68.0	3.4	3.1	838.4
1989	71.0	3.6	3.2	875.3
1990	83.0	4.2	3.7	1023.3
1991	85.0	4.3	3.8	1047.9
1992	86.0	4.3	3.9	1060.3
1993	91.0	4.6	4.1	1121.9
1994	95.0	4.8	4.3	1171.2
1995	119.8	6.0	5.4	1477.1
1996	140.2	7.0	6.3	1728.4
1997	159.4	8.0	7.2	1964.6
1998	214.9	10.7	9.7	2649.6
1999	233.0	11.6	10.5	2872.5
2000	257.6	12.9	11.6	3176.1
2001	260.9	13.0	11.7	3216.3
2002	292.6	14.6	13.2	3608.0
2003	328.2	16.4	14.8	4046.1

Figure 26 shows the pumping wells inside the modeled area for all types of the above mentioned withdrawals. The figure shows the pumpage concentration in Al Maqam-Al Saad areas.

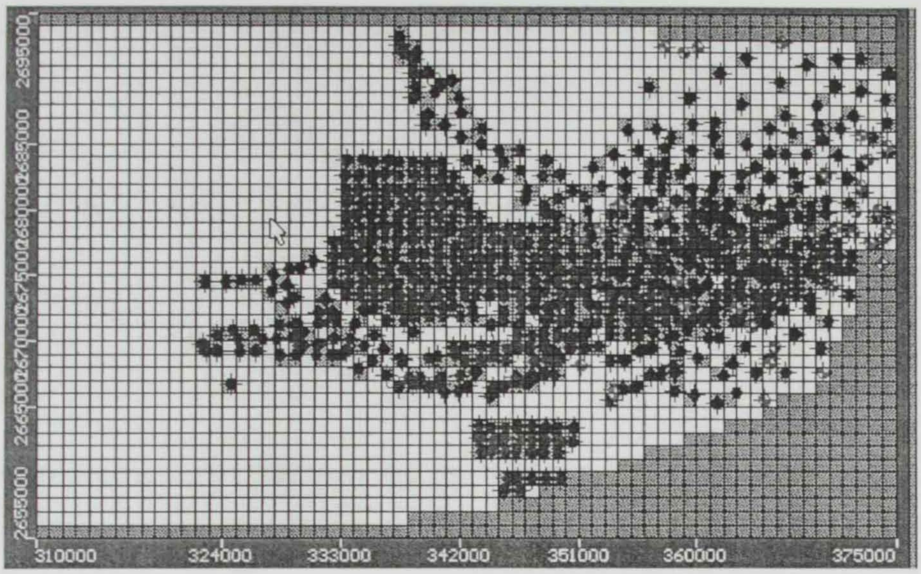


Figure 26. ***Pumping wells in the model are shown in red circles.***

Transient Calibration

Because estimates of the magnitude and distribution of ground-water withdrawal rates are an approximation of the actual current and historical situation, it is not possible to use the transient model to predict detailed changes in the potentiometric surface resulting from changes in pumping; instead, the transient model was used to simulate the trend of the contour lines and the approximate depth, shape, and shape of the cone of depression.

During the trial-and-error calibration, adjustments were made to the values of estimated pumpage until a reasonable resemblance was reached between the shape and extent of the cone of depression were reached between the observed and simulated water levels for the years of 1990 and 1995. Figures 27 and 28 are for the observed and simulated water levels respectively while figures 29 and 30 are for the observed and simulated water levels in 1995. By comparing the observed to the simulated water levels in both years it can be seen that a reasonable calibration was reached for the transient state conditions of the model.

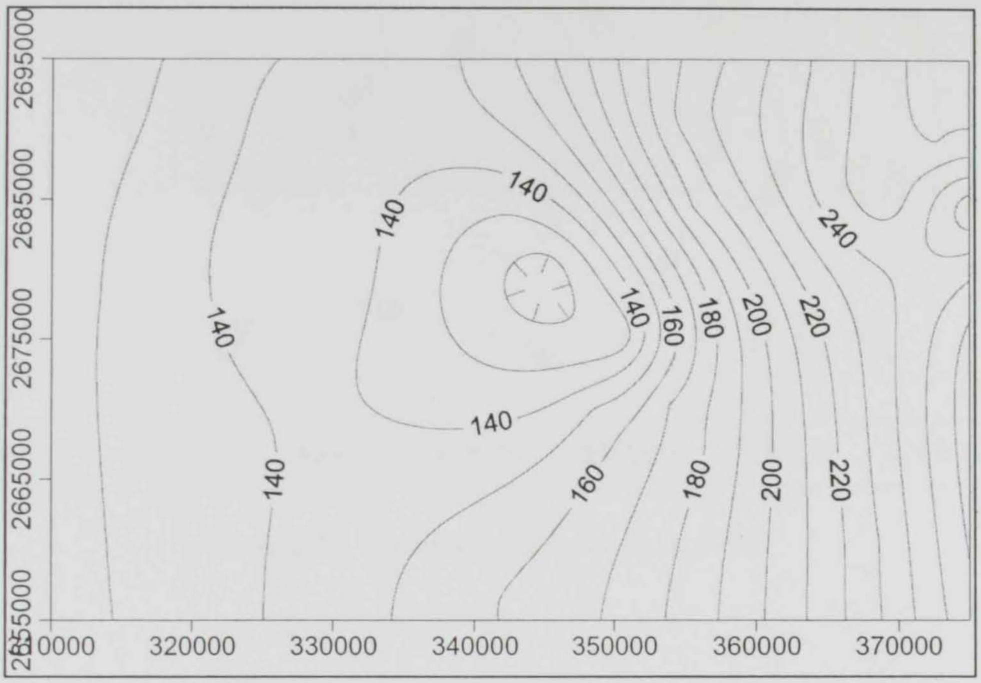


Figure 27. *Observed water levels in 1990.*

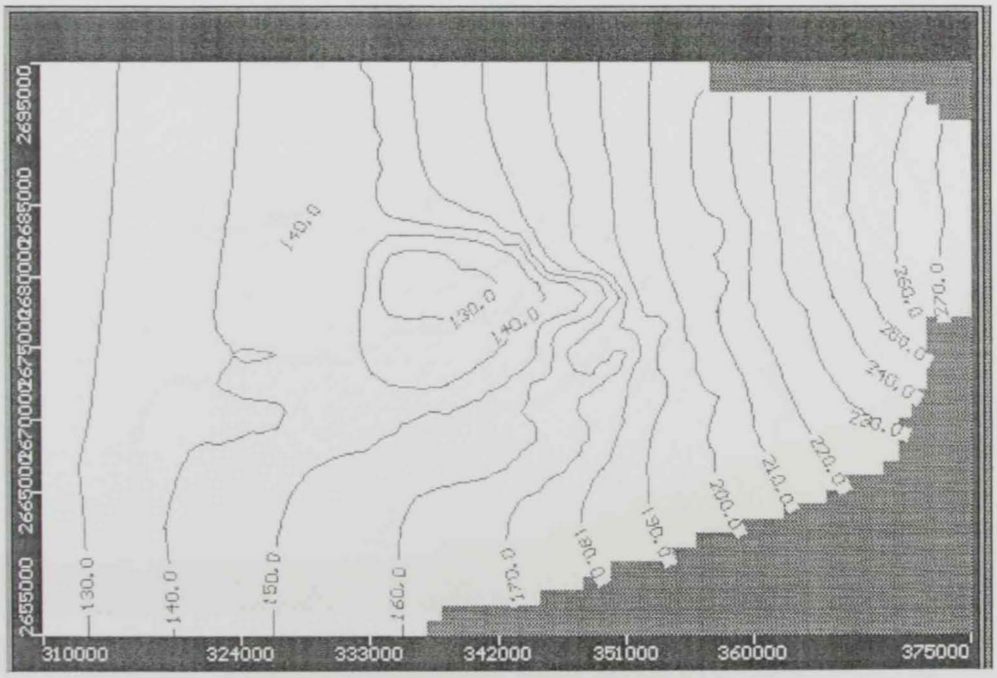


Figure 28. *Simulated water levels in 1990.*

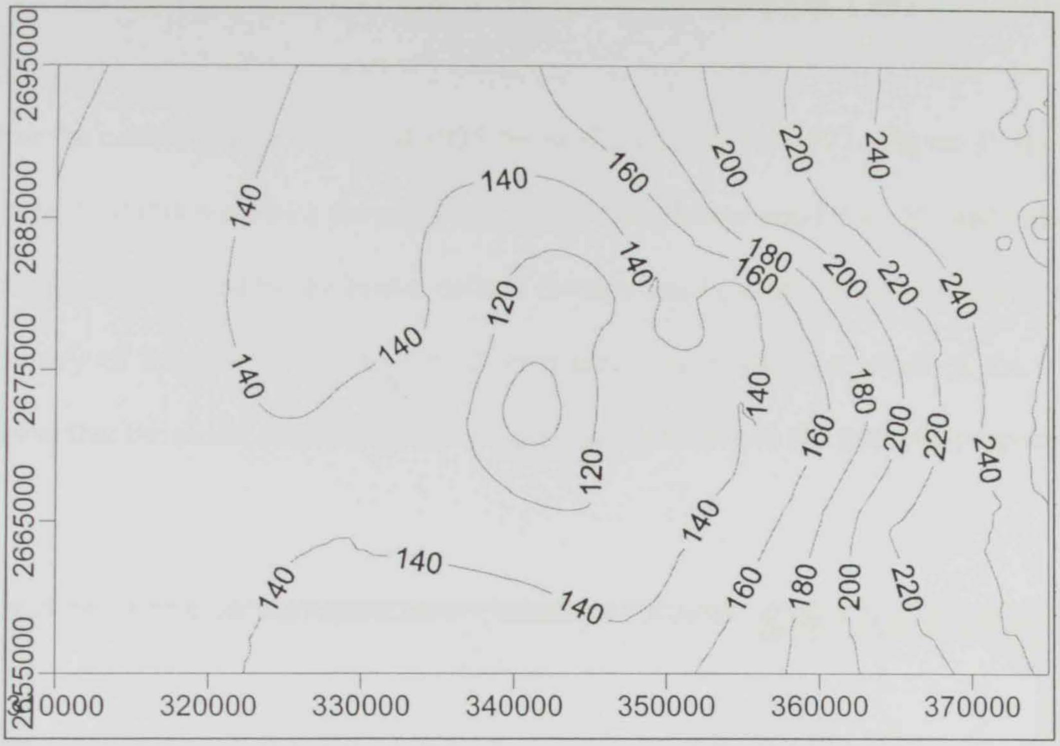


Figure 29. *Observed water levels in 1995.*

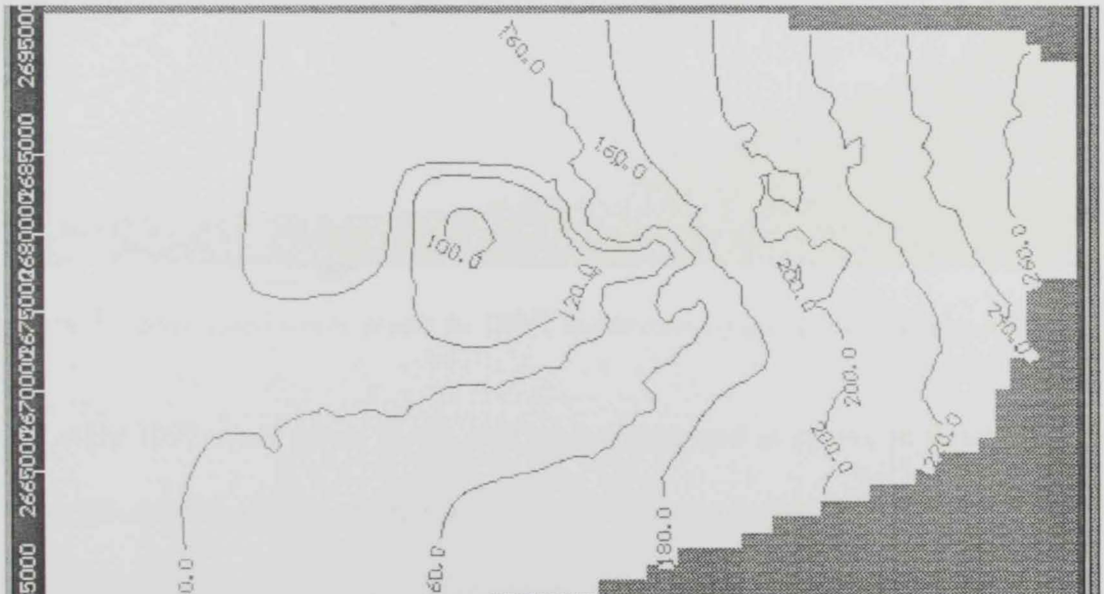


Figure 30. *Simulated water levels in 1995.*

POST- AUDIT OF THE MODEL AFTER 1997

After the calibration for 1991 and 1995 the model was run for 1997. Figure 31 shows the result of this run which revealed that part of the shallow aquifer in Al Saad village went dry as indicated by the brawn cells in the simulated model. In order to verify the accuracy of this run, a visit to the effected area was made. The result of the visit proved that the model simulation is reasonably accurate due to the following aspects:

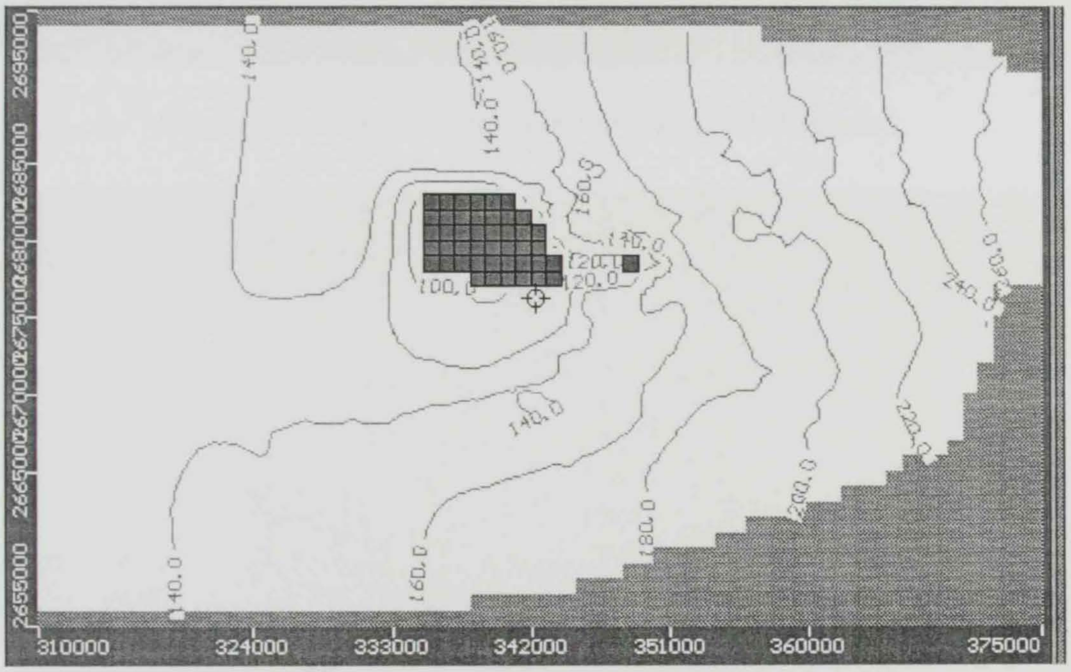


Figure 31. *Simulated water levels in 1997, the brown squares indicate dry wells.*

1- By 1997 many farms in the area were abandoned as shown in figures 32 and 33, the two pictures were taken during a recent site visit to the area.

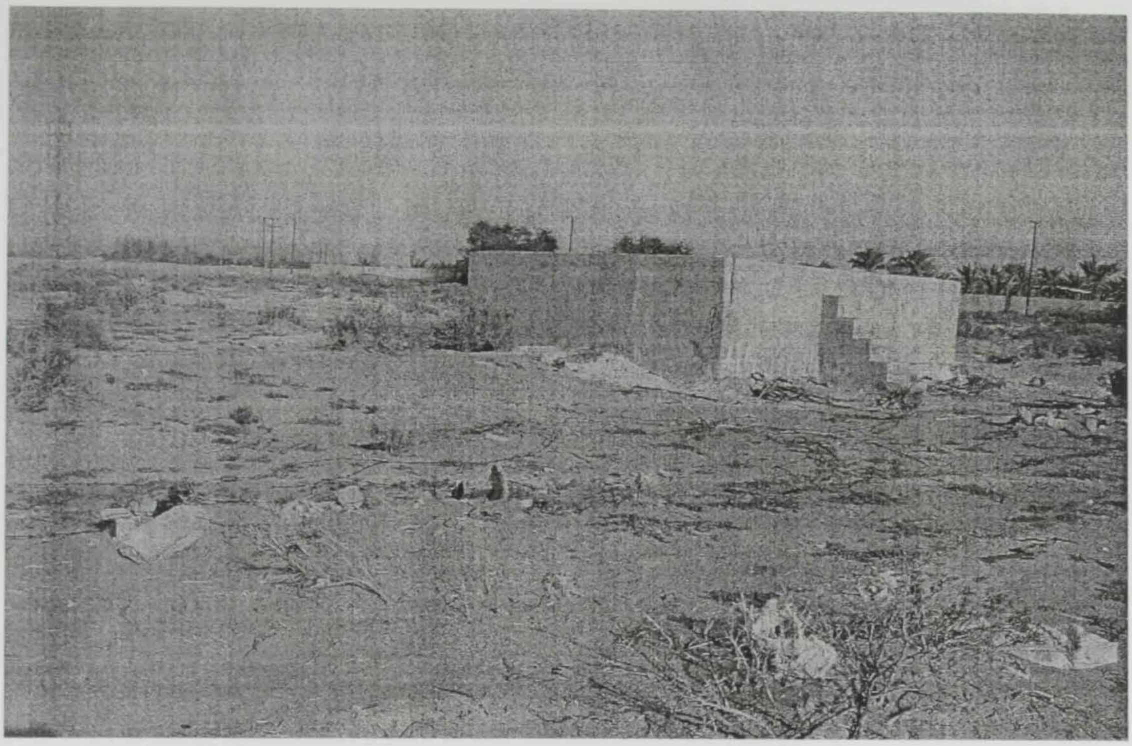


Figure 32. *Abandoned farm in the area of investigation.*

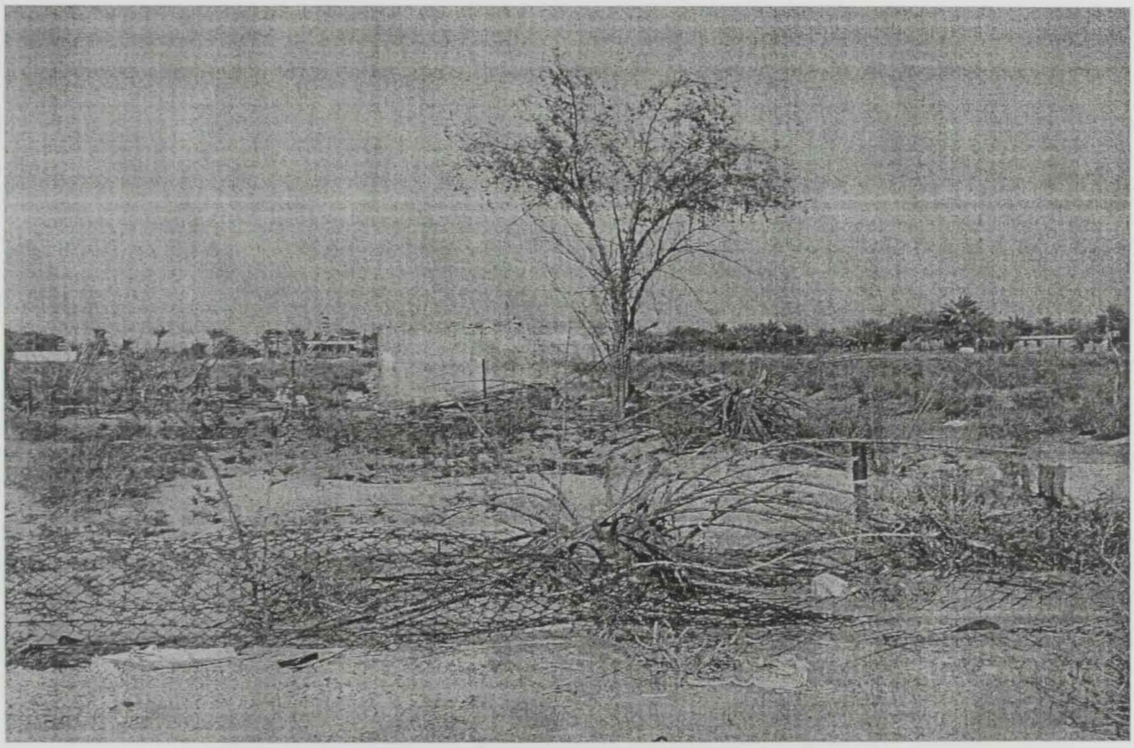


Figure 33. *Another example of abandoned farms in the area of investigation.*

Upon asking about the reasons behind abandoning these farms, the local farmers responded that many wells in the shallow aquifer became dry. As a result, the owners deepened their wells below the shallow aquifer which resulted in producing quantities of lower yield of more saline water which were not sufficient to sustain the farms. Consequently, the government compensated the most affected farms in the area by new farms to the southwest of Al Saad area (the future new center of the cone of depression in the area).

2- By lowering of the water level in Al Saad area the discharge rate from the wells will decrease because the water column over the submersible pump intake was reduced as a result of the intensifying drawdown. Therefore the discharge rate from the well should be reduced accordingly. The commonly used water pumps in the area are electrical, 6 inch 15-20 horse power submersible pumps. Pump performance curves show the relation between the depth of water and the pump discharge. Typical pump performance curves for submersible pump are shown in figure 34 below.

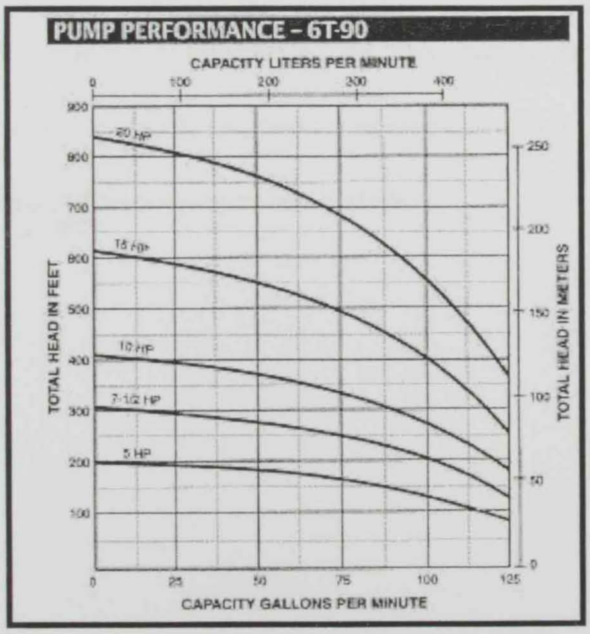


Figure 34. *Typical Performance curves for 15-20 hp pumps used in the farms* (*After Berkeley Pumps*)

The common practice in the area is to install an electrical submersible pump and use it as long as there is any discharge from the well. When the well becomes dry, a new well is drilled in the vicinity. Very rarely the pump gets replaced when the discharge rate decreases.

3- Another factor that also contributed to the lowering of the water level in the area and hence, decreasing the discharge rate of the wells in Al Saad is the extensive agricultural development that started in 1997 in the south and the southwestern area of Al Saad, which created a new cone of depression that led to head difference for water to flow from Al Saad to the cone area in the south west.

Therefore, due to the above mentioned factors, a post-audit of the numerical model has to be conducted in which about 70 wells were removed from Al Saad area and the discharge rate was reduced by 75% in the rest of al Saad wells. On the other hand, many wells were added to the southwest of Al Saad area with more discharge rate applied to the wells at the center of the new intensive development. Figure 35 shows the pumping wells used in the post-audit simulation.

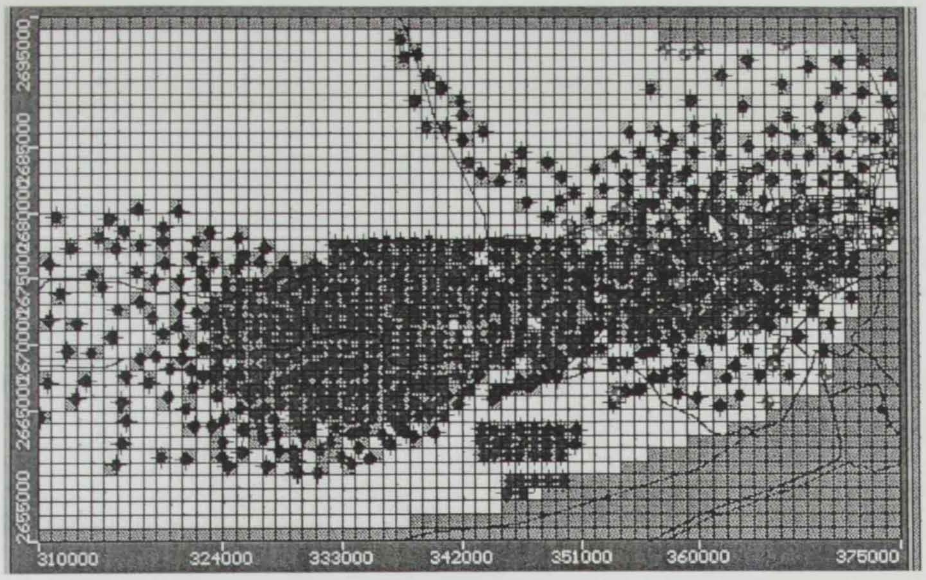


Figure 35. *Pumping wells in the model modified as a result of the post-audit.*

Calibration of the post-audit

The post-audit simulation was calibrated to the actual 2003 water level map (figure 36). The result of this calibration is shown in figure 37 were the simulated location, size, and extent of the cone of depression are reasonably close to the actual values depicted by the actual water levels map.

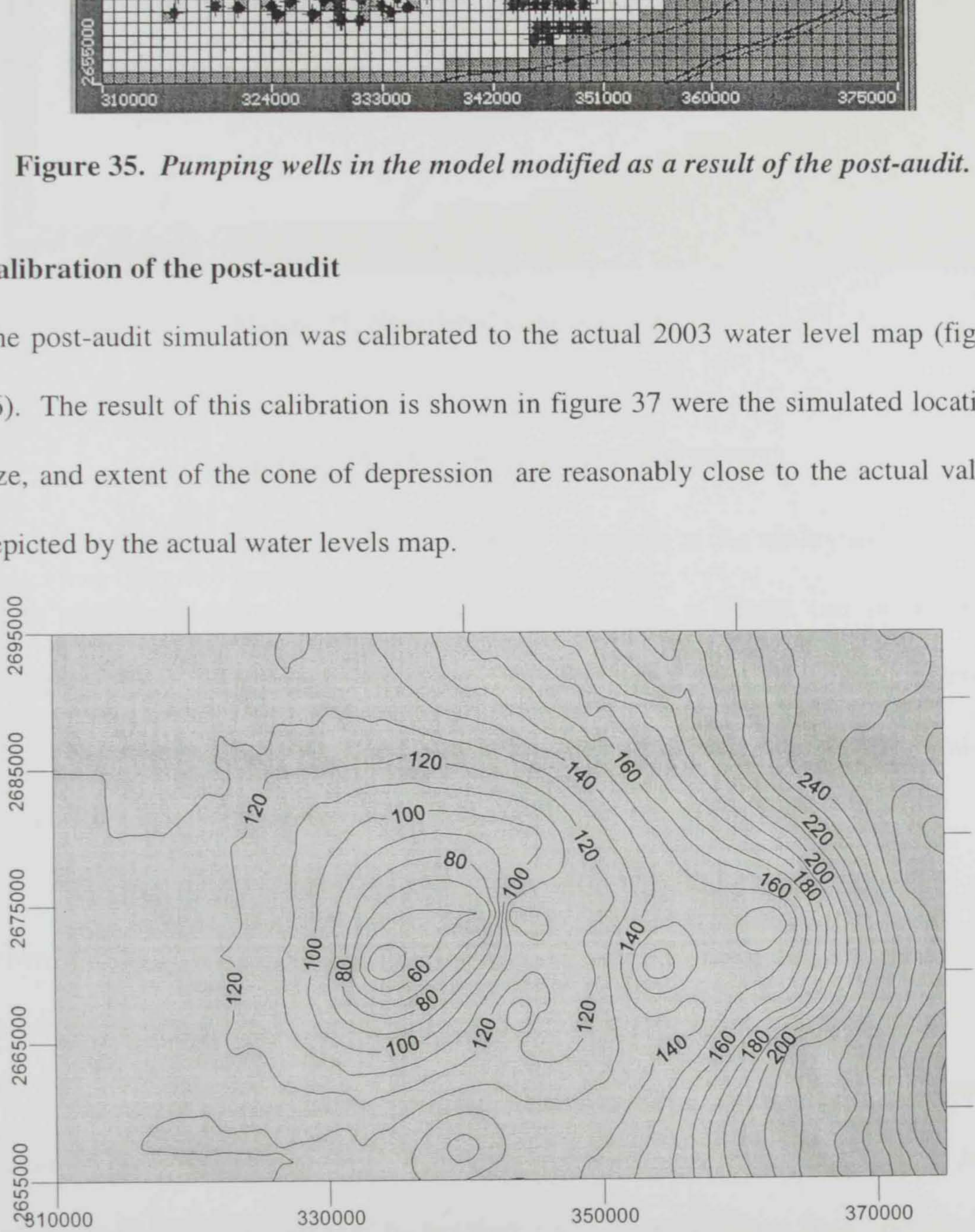


Figure 36. *Observed water levels in 2003.*

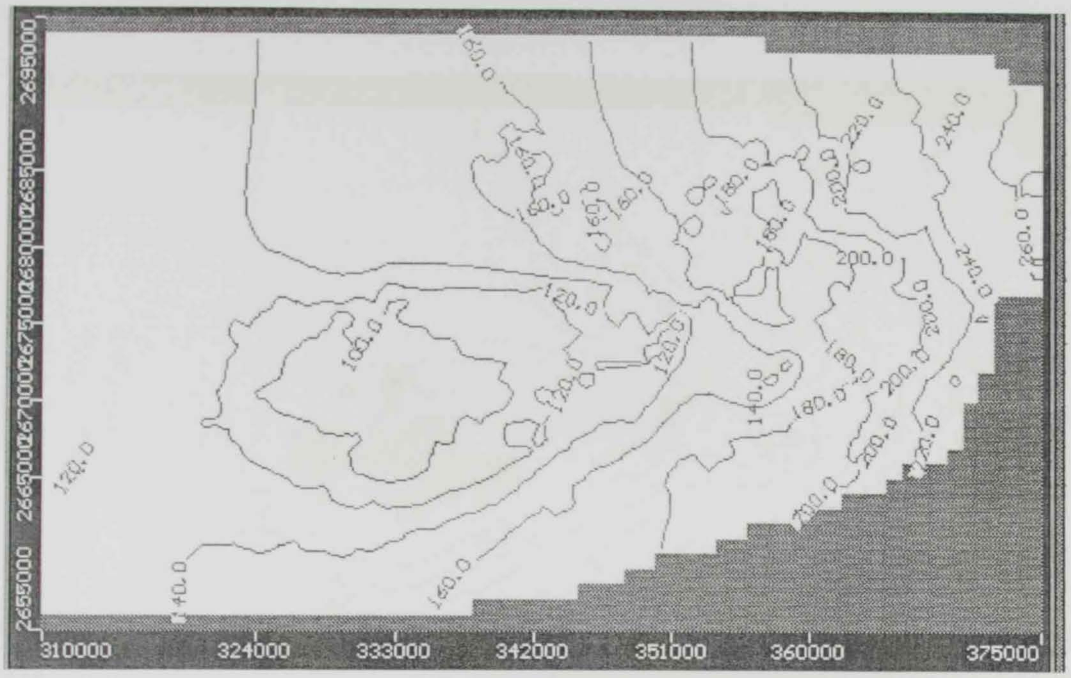


Figure 37. *Simulated water levels in 2003.*

PREDICTIONS INTO THE FUTURE

One of the benefits of ground-water modeling programs is the ability to predict the future conditions under various scenarios. Therefore, a model can be a useful management tool. This model was used to predict water levels and assess potential effects of continued pumping at 2003 rates for 2005 and 2015. One stress periods of ten years in length was used to simulate the period from 2005 to 2015.

When the water-levels were simulated for the year 2005 (figure 38), two things occurred. First, a huge water-level decline occurred that rendered some cells to go dry. Then, it appeared that the cone of depression reached the saline southeastern border. This indicates that some wellfields may be rendered useless, and the fresh water may be gradually replaced by brackish water from the saline zone. By the year

2015 (figure 39) this trend intensified and the shallow aquifer storage in the area is greatly depleted.

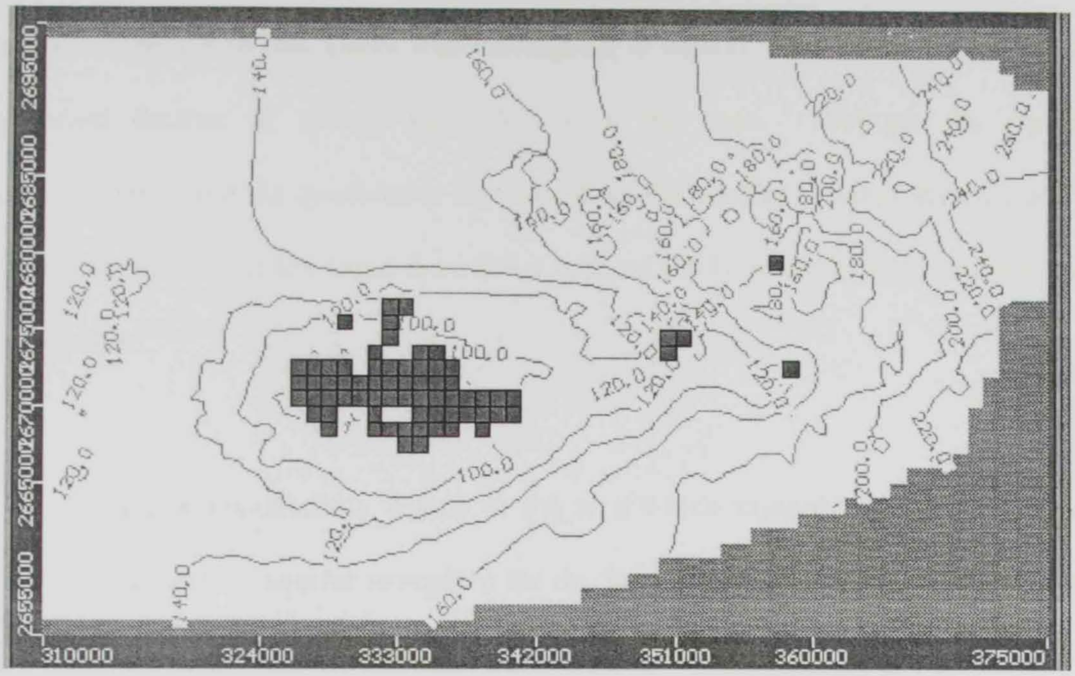


Figure 38. *The status of the shallow aquifer in 2005 as predicted by the model, the brawn squares indicate dry cells.*

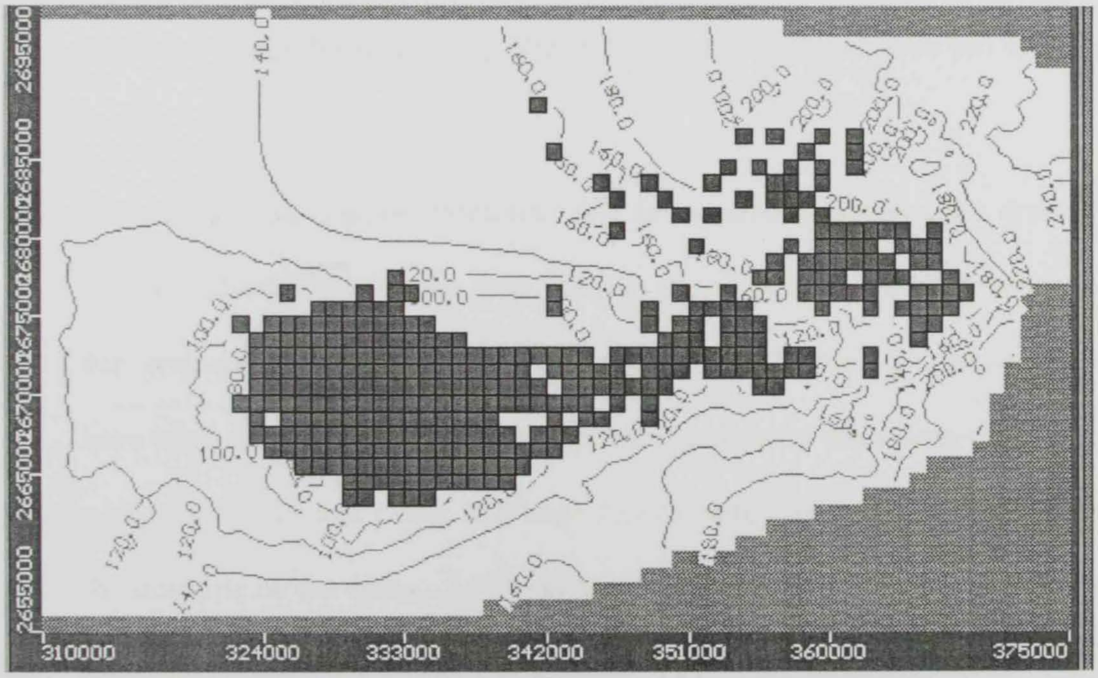


Figure 39. *The status of the shallow aquifer in 2015 as predicted by the model.*

CONCLUSIONS

The main objective of this Thesis was investigated to explore the probable causes of the significant decline of ground-water levels in the area. Through the aquifer characterization and the quantitative assessment of the aquifer in the study area and it can be concluded that the large drawdown is most likely a result of combination of three factors:

1. Very low conductivity values in the area which minimize the possibility of recharging the aquifer to replace the discharged ground-water quantities. This was very obvious from the pumping test analysis and the produced conductivity map. The area generally contains conductivity values of less than 10 meters per day.
2. Low, erratic, and rare rainfall events in the area in which the high temperatures minimize its aquifer recharging effects from the occasional wadi run off even further.
3. The heavy ground-water extraction that is required to support the dramatic agricultural expansion in the area. During the eighties of the last century, Al Ain area embarked into an extensive cultivation schemes. Numerous farms have been distributed to the locals, gardens and parks have been established within the towns and cities, and huge forests were cultivated in the rural and the outskirts of the cities. Al Maqam- Al Saad area is considered one of the pumping centers in the eastern region. In addition, Al Ain city located to the east of the study area is also considered a main pumping center which

intercept much, if not all, of the ground-water underflow from Oman Mountains.

Simulation results predicted that if pumping rates of the year 2003 continue to the year 2005 some of the wells in the center of depression will go dry. When the rates of 2003 continue to 2015, the aquifer will be heavily exploited and wells may go dry in significant part of the aquifer. In addition, the water quality of the shallow aquifer will deteriorate as the saline water from the southern boundary gradually intrude and contaminate the fresh and slightly brackish water in the aquifer.

The model can be improved by obtaining more field parameters that reduce the uncertainty and the need for estimation. Hydraulic conductivity values are essential for any ground-water flow model. Accurate and precise hydraulic conductivity values can't be obtained without proper well construction and well-designed pumping tests. Ground-water discharge rates used in the model are roughly estimated since there are no actual measurements of pumping rates in the area. Better values or actual measurements of ground-water discharge rates will significantly improve the model.

Finally, it is important to note that this model is mainly intended to demonstrate the possible applications of ground-water modeling. There are many uncertainties and estimations that limit the model, in its present form, from being used as a reliable management tool.

RECOMMENDATIONS

As a result of this study, the following recommendations can be made in order to alleviate the exploitation of aquifer and work toward making a national strategy of conserving and protecting the ground-water resources in the area:

1. Minimize the aquifer depletion: in order to minimize the aquifer depletion, the abstraction from fresh ground-water reserves has to be limited and regulated by reserving fresh ground water for municipal supplies or other high priority uses and by halting or severely curtailing the irrigation of vegetable farms with fresh ground water.
2. Regulate ground-water use: Currently there are no or minimal regulation for using the ground water. Wells, in many cases are drilled without permits or proper supervision. Drilling and the ground-water abstraction can be controlled by issuing permit for wells and regulating pumping by installing discharge meters on the wells.
3. Monitor and assess ground-water conditions by maintaining a network of observation wells, compiling ground-water information from all sources in a central repository, and by conducting hydrologic studies and research
4. Enhance replenishment of ground water by developing the ground-recharge facilities (spreading grounds, recharge basins to capture wadi flow) and implementing artificial recharge projects (recharge excess desalinated water, reclaimed waste water, urban runoff).

5. Minimize contamination of fresh water aquifers by limiting the vegetable farming in areas underlain by fresh ground water, by developing zoning regulations to restrict activities or industries in areas underlain by fresh ground water (landfills, factories, dairies, chicken farms, chemical storage facilities), and by developing well construction standards to minimize risk of interaquifer mixing.

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APPENDIX 1: The Water-Level Data Used For Producing the Conductivity Map

gwp023		gwp-024		gwp-028	
Discharge (m3/d) = 73		Discharge (m3/d) = 479		Discharge (m3/d) = 618	
Pumping duration (min) = 320		Pumping duration (min) = 300		Pumping duration (min) = 500	
Time (minutes)	Depth to water (meters)	Time (minutes)	Depth to water (meters)	Time (minutes)	Depth to water (meters)
0	36.63	0	20.68	0	20.68
2	37.17	0.5	22.52	0.5	22.52
6	39.48	1	24.09	1	24.09
8	40.4	1.5	25.76	1.5	25.76
10	41.3	2	27.06	2	27.06
15	43.45	2.5	28.06	2.5	28.06
20	45.52	3	29.3	3	29.3
30	49.41	4	31.75	4	31.75
40	52.93	5	33.2	5	33.2
50	56.2	6	34.99	6	34.99
60	59.85	7	36.37	7	36.37
80	64.7	8	37.65	8	37.65
100	66.96	9	38.85	9	38.85
150	69.84	10	39.85	10	39.85
200	74.7	15	43.63	15	43.63
250	75.73	20	46.38	20	46.38
300	76.33	25	47.94	25	47.94
320	76.52	30	48.59	30	48.59
321	75.96	40	49.01	40	49.01
322	75.52	50	49.18	50	49.18
323	75.06	60	49.23	60	49.23
324	74.64	70	49.33	70	49.33
325	74.07	80	49.35	80	49.35
326	73.52	90	49.4	90	49.4
327	73.13	100	49.5	100	49.5
328	72.58	150	49.6	150	49.6
329	72.16	200	49.67	200	49.67
330	71.73	250	49.63	250	49.63
340	67.74	300	49.63	300	49.63
350	64.46	350	49.69	350	49.69
360	61.72	400	49.74	400	49.74
370	59.82	450	49.75	450	49.75
380	58.12	500	49.79	500	49.79
390	56.63	501	45.25	501	45.25
400	55.31	502	43.07	502	43.07
420	53.33	503	41.12	503	41.12
440	51.69	504	39.31	504	39.31
460	50.32	505	37.7	505	37.7
480	49.07	506	36.14	506	36.14
500	48.13	507	34.61	507	34.61
		508	33.36	508	33.36
		509	32.09	509	32.09
		510	31.01	510	31.01
		515	26.98	515	26.98

		520	24.7	520	24.7
		525	23.3	525	23.3
		530	22.52	530	22.52
		535	22.05	535	22.05
		540	21.84	540	21.84
		545	21.67	545	21.67
		550	21.56	550	21.56
		560	21.4	560	21.4
		570	21.36	570	21.36
		580	21.29	580	21.29
		590	21.24	590	21.24
		600	21.2	600	21.2
		650	21.11	650	21.11
		700	20.99	700	20.99
		750	20.92	750	20.92
		801	20.85	801	20.85
		852	20.79	852	20.79
		900	20.73	900	20.73
		950	20.7	950	20.7

gwp033		gwp-053		gwp055		gwp058	
Discharge (m3/d) = 549		Discharge (m3/d) = 534		Discharge (m3/d) = 162		Discharge (m3/d) = 1987	
Pumping duration (min) = 300		Pumping duration (min) = 300		Pumping duration (min) = 360		Pumping duration (min) = 1440	
Time (minutes)	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**
0	25.31	0	8.09	0	31.75	0	10.35
1	27.71	0.5	9.23	0.5	31.87	0.5	15.55
1.5	29.16	1	10.33	1	33.03	1	17.39
2	30.97	1.5	11.2	1.5	33.96	1.5	18.07
3	31.63	2	11.97	2	33.88	2	18.42
4	33.04	2.5	12.71	2.5	34.58	2.5	18.68
5	34.45	3	13.39	3	34.99	3	18.85
6	35.38	4	14.57	4	37.09	4	19.09
7	36.34	5	15.63	5	37.2	5	19.26
8	37.23	6	16.53	6	38.16	6	19.4
9	38.07	7	17.37	7	39.01	7	19.54
10	38.79	8	18.07	8	39.9	8	19.62
15	41.61	9	18.73	9	40.6	9	19.69
20	43.87	10	19.3	10	41.4	10	19.78
25	45.66	15	21.64	15	43.52	12	19.91
30	47.31	20	23.41	20	44.4	15	20.08
35	48.72	25	24.3	25	44.7	18	20.21
40	49.92	30	24.91	30	45.05	20	20.28
45	50.93	40	25.73	40	45.36	25	20.44
50	51.8	50	26.16	50	45.7	30	20.58
60	53.2	60	26.34	60	46.29	40	20.79
70	54.2	70	26.54	70	46.74	50	20.97
80	54.93	80	26.64	80	47.29	60	21.13
90	55.51	90	26.73	90	47.5	70	21.26
100	56	100	26.79	100	47.77	80	21.34
150	57.54	150	26.98	150	48.79	90	21.43
200	58.41	200	27.08	200	49.4	100	21.52
250	58.91	250	27.18	250	49.4	120	21.66
300	59.54	300	27.24	300	50.1	150	21.81
301	52.8	350	27.31	360	50.38	180	21.96
302	47.3	400	27.32	361	49.28	200	22.04
303	43.08	401	25.14	362	48.4	250	22.17

304	39.29	402	23.16	363	47.58	300	22.33
305	36.16	403	21.34	364	46.84	350	22.42
306	33.01	404	19.79	365	46.15	400	22.52
307	30.78	405	18.3	366	45.4	500	22.68
308	29.26	406	17	367	44.9	600	22.77
309	28.09	407	15.83	368	44.45	700	22.83
310	27.4	408	14.77	369	43.97	800	22.87
320	26.18	409	13.84	370	43.55	1000	22.84
330	25.98	410	13.06	375	42.75	1200	22.89
340	25.86	415	10.6	380	40.5	1400	22.98
350	25.79	420	9.57	390	38.81	1440	22.99
360	25.73	430	8.94	400	38.55	1441	15.36
		440	8.76	410	36.85	1442	14.36
		450	8.67	420	36.25	1443	13.95
		460	8.6	430	35.76	1444	13.76
		470	8.56	440	35.35	1445	13.58
		480	8.53	450	34.97	1446	13.45
		490	8.5	460	34.66	1447	13.33
		500	8.48	480	34.17	1448	13.22
		520	8.44			1449	13.14
						1450	13.05
						1452	12.92
						1455	12.75
						1458	12.63
						1460	12.55
						1470	12.26
						1480	12.04
						1490	11.85
						1500	11.76
						1510	11.64
						1520	11.52
						1530	11.44
						1540	11.38
						1560	11.23
						1590	11.12
						1620	11.01

gwp059		gwp060		gwp066	
Discharge (m3/d) = 1950		Discharge (m3/d) = 831		Discharge (m3/d) = 411	
Pumping duration (min) = 720		Pumping duration (min) = 720		Pumping duration (min) = 1440	
Time (minutes)	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**
0	14.65	0	20.43	0	14.4
0.5	19.7	0.5	23.34	0.5	15.07
1	21.32	1	25.14	1	15.53
1.5	21.85	1.5	26.43	1.5	15.88
2	22.22	2	27.37	2	16.12
2.5	22.37	2.5	27.95	2.5	16.32
3	22.5	3	28.49	3	16.52
4	22.64	4	29.1	4	16.81
5	22.76	5	29.43	5	17.02
6	22.86	6	29.75	6	17.25
7	22.93	7	29.79	7	17.42
8	23.01	8	29.85	8	17.57
9	23.07	9	29.93	9	17.7
10	23.12	10	29.99	10	17.82
15	23.34	12	30.07	15	18.34
20	23.5	15	30.17	20	18.65
25	23.63	18	30.08	25	18.98
30	23.74	20	30.12	30	19.29
40	23.92	25	30.25	40	19.83
50	24.04	30	30.3	50	20.3
60	24.12	40	30.38	60	20.7
70	24.21	50	30.48	70	21.09
80	24.29	60	30.61	80	21.31
90	24.35	70	30.67	90	21.49

100	24.41	80	30.68	100	21.65
150	24.59	90	30.71	150	23.04
200	24.73	100	30.72	200	23.99
250	24.81	120	30.79	250	24.79
300	24.88	150	30.85	300	25.47
350	24.91	180	30.9	350	26.06
400	24.97	200	30.94	400	26.59
500	25.01	250	30.98	500	27.5
600	25.07	300	31	600	28.51
700	25.03	350	31.06	700	29.86
720	25.02	400	31.1	800	31
721	17.35	500	31.15	900	31.48
722	17.77	600	31.19	1000	31.7
723	17.54	700	31.24	1200	32.28
724	17.42	720	31.26	1360	32.6
725	17.3	721	27.15	1440	32.81
726	17.24	722	25.53	1441	29.93
727	17.15	723	24.53	1442	29.43
728	17.08	724	23.81	1443	29.1
729	16.92	725	23.26	1444	29.09
730	16.95	726	22.84	1445	29.04
735	16.7	727	22.51	1446	29.02
740	16.52	728	22.21	1447	28.97
750	16.3	729	21.84	1448	28.89
760	16.12	730	21.5	1449	28.83
770	15.98	732	21.08	1450	28.78
780	15.84	735	20.82	1452	28.67
790	15.76	738	20.7	1455	28.5
800	15.67	740	20.64	1458	28.38
810	15.6	750	20.5	1460	28.29
820	15.55	760	20.38	1465	28.1
840	15.43	770	20.27	1470	27.95
870	15.29	780	20.24	1480	27.68
900	15.18	790	20.22	1490	27.45
		800	20.21	1500	27.25
		810	20.2	1510	27.08
		820	20.19	1520	26.92
		840	20.18	1530	26.77
		870	20.17	1540	26.68
		900	20.16	1560	26.41
				1590	26.18
				1620	26
				1640	25.91
				1688	25.8
				1740	25.7
				1791	25.6
				1840	25.4
				1890	24.64
				1940	24.1

gwp067		gwp-081		gwp-082	
Discharge (m3/d) = 372		Discharge (m3/d) = 420		Discharge (m3/d) = 397	
Pumping duration (min) = 540		Pumping duration (min) = 300		Pumping duration (min) = 600	
Time (minutes)	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**
0	14.65	0	12.45	0	12.45
0.5	19.7	0.5	13.6	0.5	13.6
1	21.32	1	14.1	1	14.1
1.5	21.85	1.5	14.32	1.5	14.32
2	22.22	2	14.43	2	14.43

2.5	22.37	2.5	14.52	2.5	14.52
3	22.5	3	14.57	3	14.57
4	22.64	4	14.68	4	14.68
5	22.76	5	14.74	5	14.74
6	22.86	6	14.79	6	14.79
7	22.93	7	14.83	7	14.83
8	23.01	8	14.87	8	14.87
9	23.07	9	14.9	9	14.9
10	23.12	10	14.92	10	14.92
15	23.34	15	15.01	15	15.01
20	23.5	20	15.08	20	15.08
25	23.63	25	15.1	25	15.1
30	23.74	30	15.14	30	15.14
40	23.92	40	15.15	40	15.15
50	24.04	60	15.14	60	15.14
60	24.12	70	15.16	70	15.16
70	24.21	80	15.17	80	15.17
80	24.29	90	15.18	90	15.18
90	24.35	100	15.18	100	15.18
100	24.41	150	15.18	150	15.18
150	24.59	200	15.18	200	15.18
200	24.73	250	15.18	250	15.18
250	24.81	300	15.18	300	15.18
300	24.88	300.5	13.8	300.5	13.8
350	24.91	301.5	13.2	301.5	13.2
400	24.97	302	13.1	302	13.1
500	25.01	303	13	303	13
600	25.07	304	12.95	304	12.95
700	25.03	305	12.93	305	12.93
720	25.02	306	12.88	306	12.88
721	17.35	307	12.85	307	12.85
722	17.77	308	12.82	308	12.82
723	17.54	309	12.79	309	12.79
724	17.42	310	12.77	310	12.77
725	17.3	315	12.7	315	12.7
726	17.24	320	12.65	320	12.65
727	17.15	330	12.59	330	12.59
728	17.08	340	12.56	340	12.56
729	16.92	350	12.55	350	12.55
730	16.95	360	12.54	360	12.54
735	16.7	370	12.53	370	12.53
740	16.52	380	12.52	380	12.52
750	16.3	390	12.51	390	12.51
760	16.12	400	12.49	400	12.49
770	15.98	420	12.46	420	12.46
780	15.84				
790	15.76				
800	15.67				
810	15.6				
820	15.55				
840	15.43				

870	15.29				
900	15.18				

gwp-083		gwp-084		gwp-086	
Discharge (m3/d) = 485		Discharge (m3/d) = 729		Discharge (m3/d) = 666	
Pumping duration (min) = 300		Pumping duration (min) = 300		Pumping duration (min) = 350	
Time (minutes)	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**
0	12.45	0	12.45	0	12.45
0.5	13.6	0.5	13.6	0.5	13.6
1	14.1	1	14.1	1	14.1
1.5	14.32	1.5	14.32	1.5	14.32
2	14.43	2	14.43	2	14.43
2.5	14.52	2.5	14.52	2.5	14.52
3	14.57	3	14.57	3	14.57
4	14.68	4	14.68	4	14.68
5	14.74	5	14.74	5	14.74
6	14.79	6	14.79	6	14.79
7	14.83	7	14.83	7	14.83
8	14.87	8	14.87	8	14.87
9	14.9	9	14.9	9	14.9
10	14.92	10	14.92	10	14.92
15	15.01	15	15.01	15	15.01
20	15.08	20	15.08	20	15.08
25	15.1	25	15.1	25	15.1
30	15.14	30	15.14	30	15.14
40	15.15	40	15.15	40	15.15
60	15.14	60	15.14	60	15.14
70	15.16	70	15.16	70	15.16
80	15.17	80	15.17	80	15.17
90	15.18	90	15.18	90	15.18
100	15.18	100	15.18	100	15.18
150	15.18	150	15.18	150	15.18
200	15.18	200	15.18	200	15.18
250	15.18	250	15.18	250	15.18
300	15.18	300	15.18	300	15.18
300.5	13.8	300.5	13.8	300.5	13.8
301.5	13.2	301.5	13.2	301.5	13.2
302	13.1	302	13.1	302	13.1
303	13	303	13	303	13
304	12.95	304	12.95	304	12.95
305	12.93	305	12.93	305	12.93
306	12.88	306	12.88	306	12.88
307	12.85	307	12.85	307	12.85
308	12.82	308	12.82	308	12.82
309	12.79	309	12.79	309	12.79
310	12.77	310	12.77	310	12.77
315	12.7	315	12.7	315	12.7

320	12.65	320	12.65	320	12.65
330	12.59	330	12.59	330	12.59
340	12.56	340	12.56	340	12.56
350	12.55	350	12.55	350	12.55
360	12.54	360	12.54	360	12.54
370	12.53	370	12.53	370	12.53
380	12.52	380	12.52	380	12.52
390	12.51	390	12.51	390	12.51
400	12.49	400	12.49	400	12.49
420	12.46	420	12.46	420	12.46

gwp-089		gwp-090		gwp-093	
Discharge (m3/d) = 219		Discharge (m3/d) = 532		Discharge (m3/d) = 897	
Pumping duration (min) = 300		Pumping duration (min) = 500		Pumping duration (min) = 300	
Time (minutes)	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**	**Time (minutes)**	**Depth to water (meters)**
0	12.45	0	20.68	0	20.68
0.5	13.6	0.5	22.52	0.5	22.52
1	14.1	1	24.09	1	24.09
1.5	14.32	1.5	25.76	1.5	25.76
2	14.43	2	27.06	2	27.06
2.5	14.52	2.5	28.06	2.5	28.06
3	14.57	3	29.3	3	29.3
4	14.68	4	31.75	4	31.75
5	14.74	5	33.2	5	33.2
6	14.79	6	34.99	6	34.99
7	14.83	7	36.37	7	36.37
8	14.87	8	37.65	8	37.65
9	14.9	9	38.85	9	38.85
10	14.92	10	39.85	10	39.85
15	15.01	15	43.63	15	43.63
20	15.08	20	46.38	20	46.38
25	15.1	25	47.94	25	47.94
30	15.14	30	48.59	30	48.59
40	15.15	40	49.01	40	49.01
60	15.14	50	49.18	50	49.18
70	15.16	60	49.23	60	49.23
80	15.17	70	49.33	70	49.33
90	15.18	80	49.35	80	49.35
100	15.18	90	49.4	90	49.4
150	15.18	100	49.5	100	49.5
200	15.18	150	49.6	150	49.6
250	15.18	200	49.67	200	49.67
300	15.18	250	49.63	250	49.63
300.5	13.8	300	49.63	300	49.63
301.5	13.2	350	49.69	350	49.69
302	13.1	400	49.74	400	49.74
303	13	450	49.75	450	49.75
304	12.95	500	49.79	500	49.79
305	12.93	501	45.25	501	45.25
306	12.88	502	43.07	502	43.07

307	12.85	503	41.12	503	41.12
308	12.82	504	39.31	504	39.31
309	12.79	505	37.7	505	37.7
310	12.77	506	36.14	506	36.14
315	12.7	507	34.61	507	34.61
320	12.65	508	33.36	508	33.36
330	12.59	509	32.09	509	32.09
340	12.56	510	31.01	510	31.01
350	12.55	515	26.98	515	26.98
360	12.54	520	24.7	520	24.7
370	12.53	525	23.3	525	23.3
380	12.52	530	22.52	530	22.52
390	12.51	535	22.05	535	22.05
400	12.49	540	21.84	540	21.84
420	12.46	545	21.67	545	21.67
		550	21.56	550	21.56
		560	21.4	560	21.4
		570	21.36	570	21.36
		580	21.29	580	21.29
		590	21.24	590	21.24
		600	21.2	600	21.2
		650	21.11	650	21.11
		700	20.99	700	20.99
		750	20.92	750	20.92
		801	20.85	801	20.85
		852	20.79	852	20.79
		900	20.73	900	20.73
		950	20.7	950	20.7

APPENDIX 2: Lithology Description of Wells Used For Producing the Conductivity Map

GWP-23					w.l (ft)
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
30	casing	sand			
90	casing	limestone			
120	casing	clay	Impermeable		120.17
202	casing	limestone	Permeable		
240	screen	limestone	Permeable		
280	casing	sandstone/limestone/clay	Permeable/impermeable		
301	screen	marl/limestone	impermeable/permeable		
331	casing	limestone	permeable		
350	screen	limestone/sandstone	Permeable		
390	casing	limestone/sandstone	Permeable		
410	casing	clay	Impermeable		
503	casing	limestone	Permeable		
561	screen	limestone/sandstone/limestone	Permeable		
570	casing	limestone	Permeable		
592	casing	mudstone	Impermeable		
GWP-33					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
20	casing	sand			
50	casing	clay			
58	casing	clay			
135	screen	clay/sand/gravel/siltstone	semipermeable		83.04
196	casing	sand	Permeable		
310	screen	clay/sand/gravel/siltstone	semipermeable		
330	casing	clay	Impermeable		
425	screen	clay/sandstone/clay	semipermeable		
445	casing	clay/sand/gravel	semipermeable		
465	screen	clay/sand/gravel	semipermeable		
GWP-53					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
71	casing	sandstone	Permeable		26.54
91	screen	sandstone	Permeable		
121	casing	sandstone	Permeable		
141	screen	sandstone	Permeable		
160	casing	sandstone	Permeable		
180	screen	sandstone/mudstone	Permeable/ impemeable		
200	casing	mudstone/conglomerate	impermeable/permeable		
219	screen	sandstone	Permeable		
239	casing	mudstone/sandstone	Permeable/ impemeable		

GWP-55					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
40	casing	Sandstone			
50	casing	clay			
97	screen	Sandstone			
120	screen	siltstone	semipermeable		104.2
190	screen	Sandstone	Permeable		
211	screen	Sandstone	Permeable		
231	casing	Sandstone	Permeable		
GWP-56					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
20	casing	sand			
40	casing	clay			
50	casing	sand			
80	screen	siltstone	semipermeable		63.02
90	screen	clay	Impermeable		
100	screen	clay	Impermeable		
110	casing	clay	Impermeable		
160	casing	marl	Impermeable		
180	casing	marl	Impermeable		
219	screen	conglomerate	Permeable		
GWP-57					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
116	casing	sand/gravel			
134	screen	gravel			
155	casing	gravel			
231	screen	gravel/sand	Permeable		169.38
282	casing	sand/marl	permeable/semipermeable		
320	screen	gravel	Permeable		
341	casing	gravel/limestone	Permeable		
GWP-58					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
64	casing	sand/clay	permeable/impermeable		33.95
80	screen	clay	Impermeable		
130	screen	sandstone	Permeable		
178	screen	marl	Impermeable		
219	casing	marl/conglomerate	semipermeable		
257	screen	conglomerate	Permeable		
277	casing	conglomerate	Permeable		

GWP-59					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
104	casing	sand	Permeable		48.06
141	screen	siltstone/marl	semipermeable		
191	casing	marl	semipermeable		
248	screen	marl	semipermeable		
268	casing	conglomerate	Permeable		
278	screen	conglomerate	Permeable		
307	casing	marl	semipermeable		
GWP-60					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
72	casing	sand/gravel/marl	Permeable/impearmeable		67.03
170	screen	marl	Impermeable		
186	screen	gravel/sand	Permeable		
206	casing	sand	Permeable		
245	screen	sand	Permeable		
265	casing	sand	Permeable		
280	screen	marl	Impermeable		
300	screen	clay	Impermeable		
322	screen	sandstone	Permeable		
330	casing	sandstone	Permeable		
342	casing	clay	Impermeable		
GWP-61					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
240	casing	sand/gravel	Permeable		258.33
259	screen	gravel	Permeable		
290	casing	sand	Permeable		
423	screen	sand/clay/marl/gravel	Permeable		
443	casing	gravel	Permeable		
GWP-64					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
182	casing	sand			
250	screen	sandstone			
297	screen	clay	Impermeable		281.43
317	casing	clay	Impermeable		
360	screen	clay	Impermeable		
440	screen	sandstone	Permeable		
460	screen	marl	semipermeable		
469	screen	sandstone	Permeable		
490	casing	sandstone	Permeable		
GWP-66					
depth	**well**	**lithology**	**hydrogeology**		

(feet)	**construction**				
61	casing	sand	Permeable		47.23
137	screen	sandstone	Permeable		
239	casing	mudstone/evaporate/mudstone	semipermeable		
258	screen	evaporate	semipermeable		
GWP-67					
depth (feet)	**well construction**	**lithology**	**hydrogeology**		
82	casing	sand/sandstone	Permeable		66.89
121	screen	sandstone	Permeable		
161	casing	sand	Permeable		
180	screen	marl	semipermeable		
200	casing	marl	semipermeable		
238	screen	marl	semipermeable		
279	casing	marl	semipermeable		
336	screen	marl	semipermeable		
427	casing	marl	semipermeable		
466		marl/sand	permeable/semipermeable		
485	casing	sand	Permeable		

APPENDIX 3: The Discharge and Recovery Charts Used For Calculating the Transmissivity

These charts are generated by Aquatest program where one has to best fit the line to the segment that represents the aquifer, after fitting the line, the transmissivity values are calculated automatically.

Discharge **Recovery**

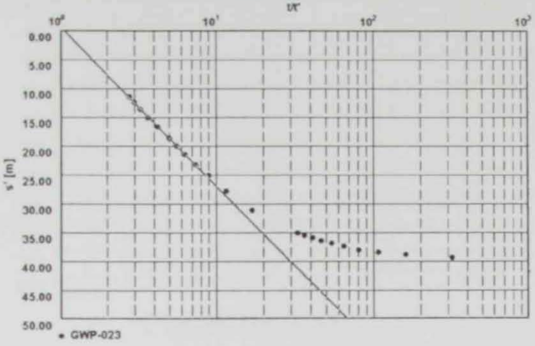


Figure 2_3_D

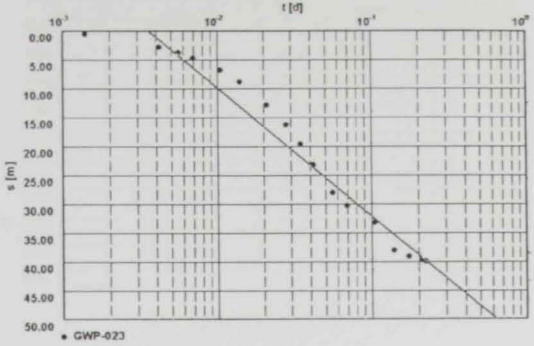


Figure 2_3_R

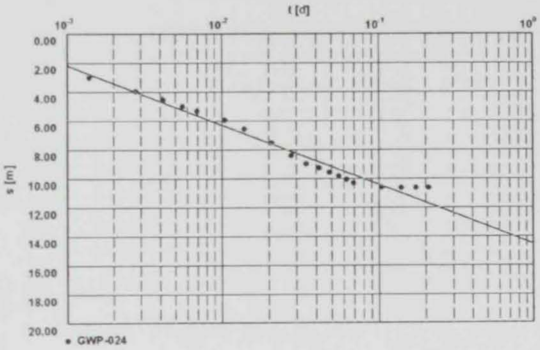


Figure 3_3_D

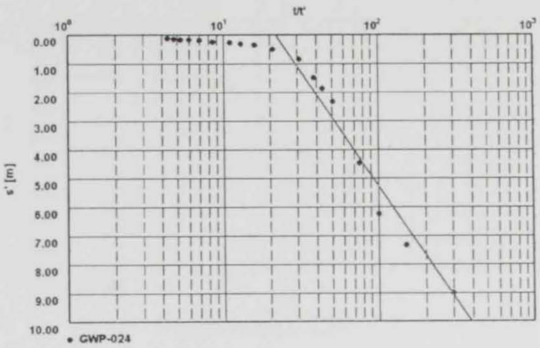


Figure 3_3_D

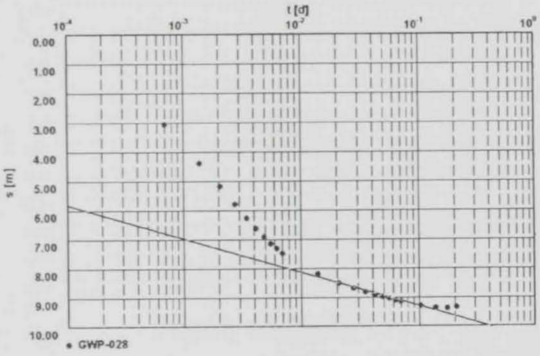


Figure 5_3_D

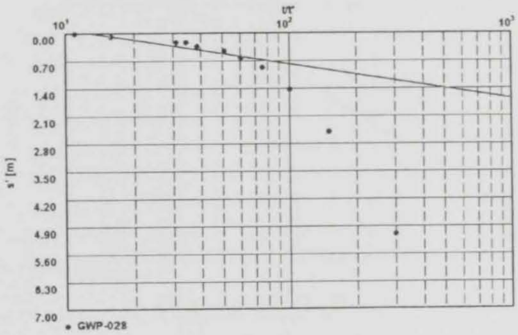


Figure 5_3_D

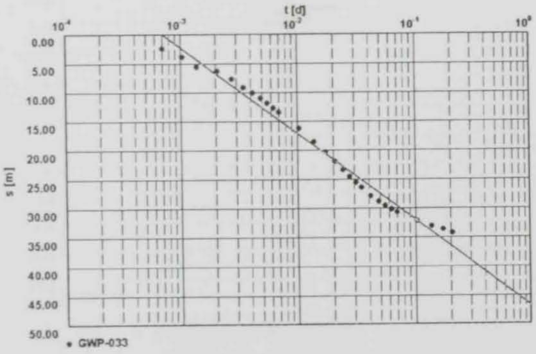


Figure 6_3_D

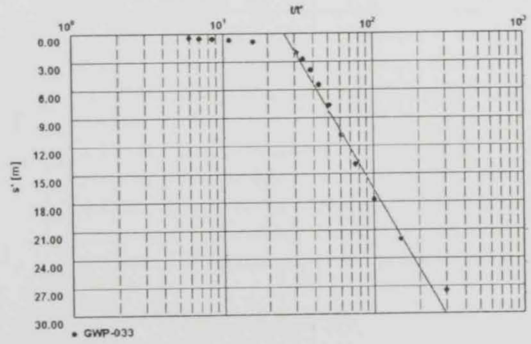


Figure 6_3_R

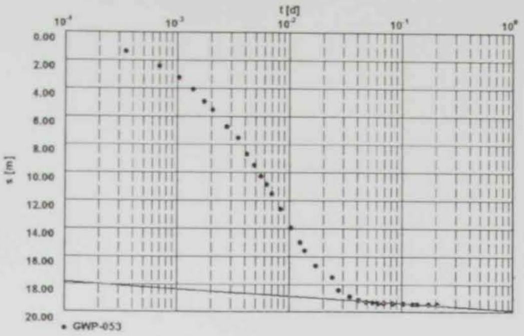


Figure 10_3_D

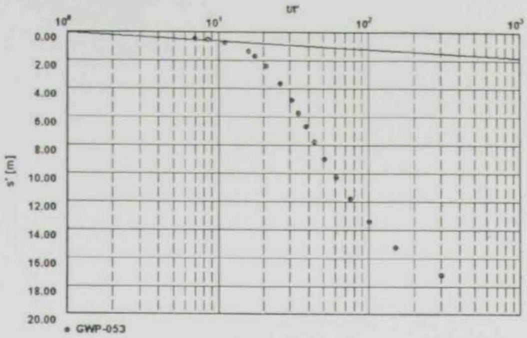
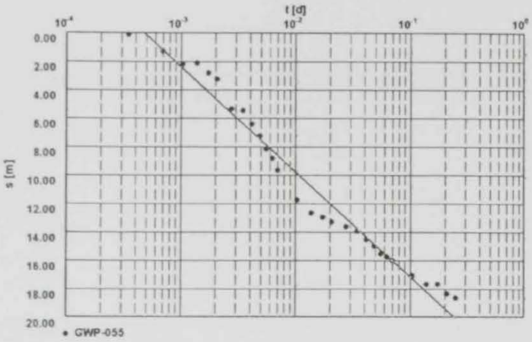


Figure 10_3_R



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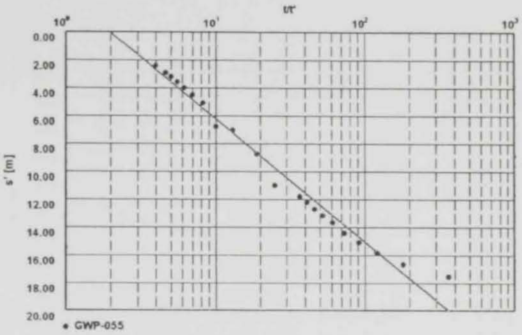


Figure 12_3_R

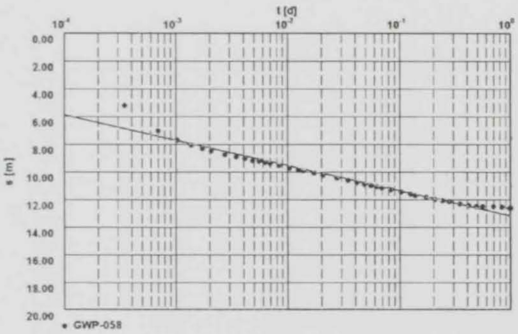


Figure 13_3_D

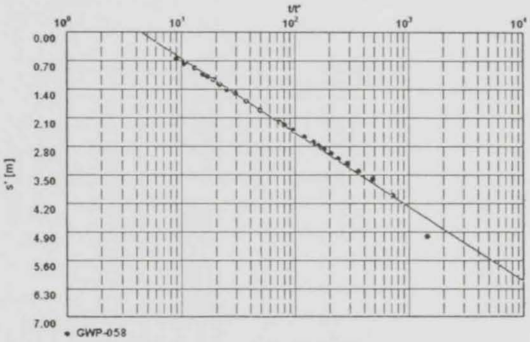


Figure 13_3_R

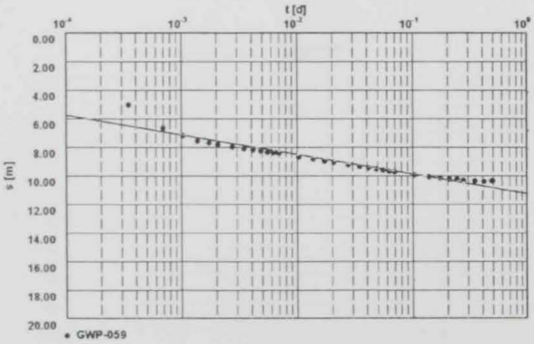


Figure 14_3_D

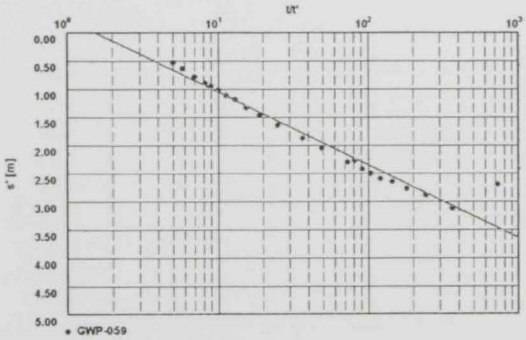
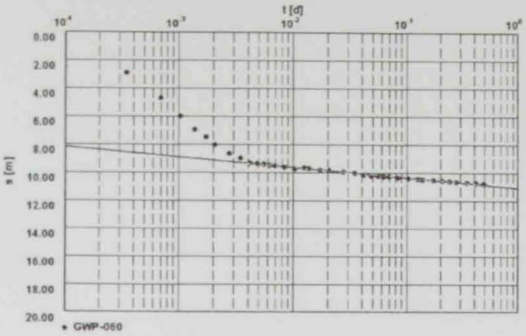


Figure 14_3_R



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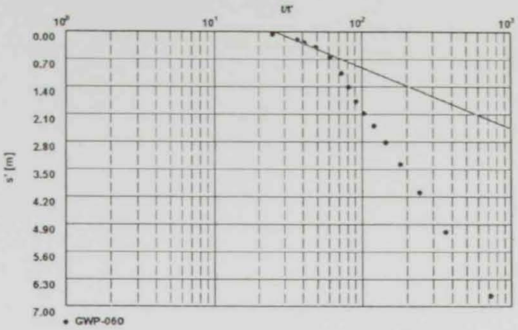


Figure 15_3_R

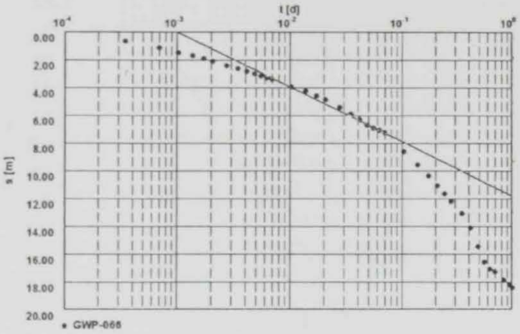


Figure 16_3_D

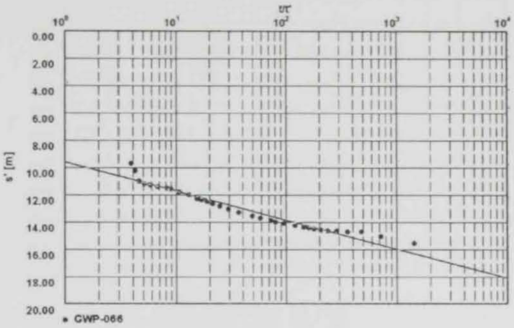


Figure 16_3_R

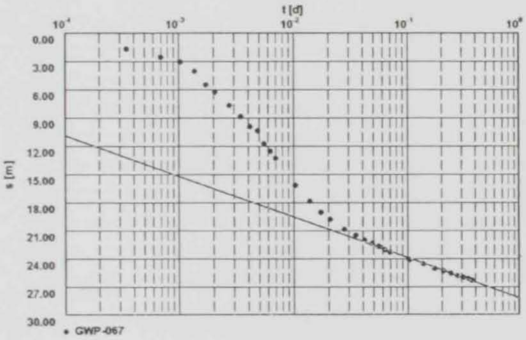


Figure 17_3_D

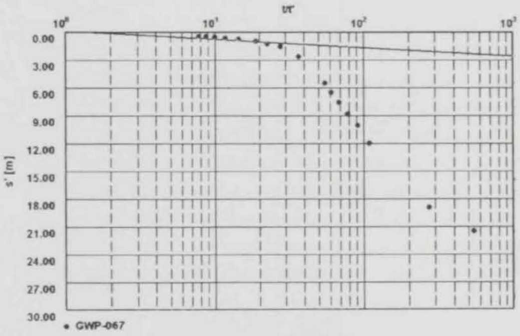


Figure 17_3_R

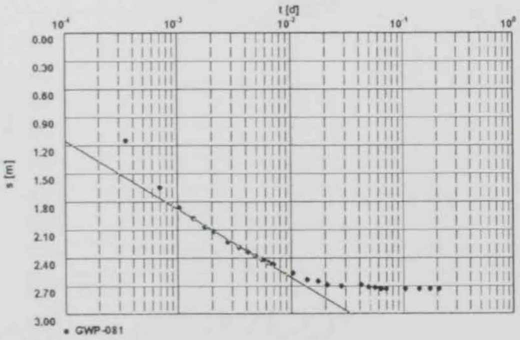
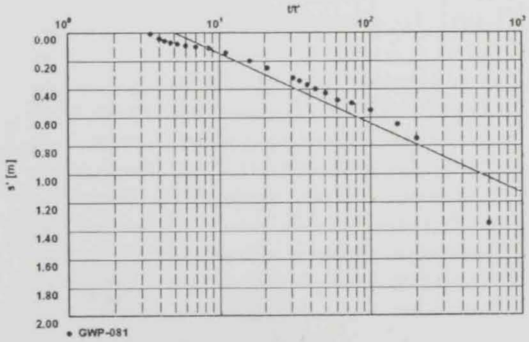


Figure 19_3_D



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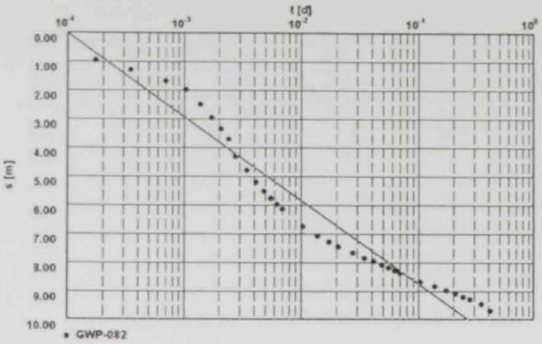

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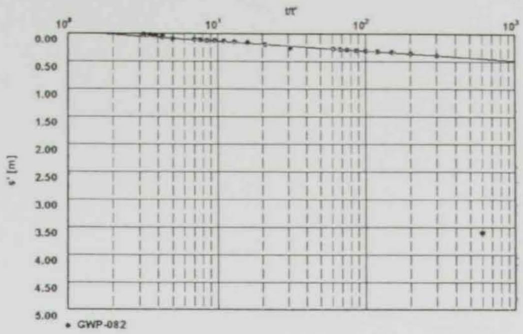

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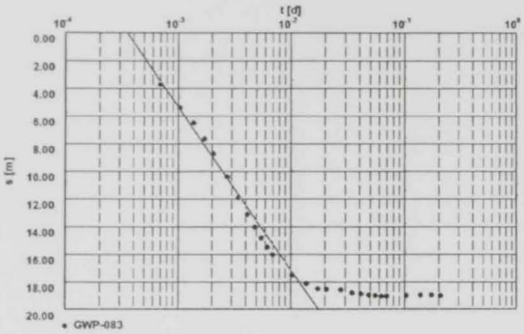

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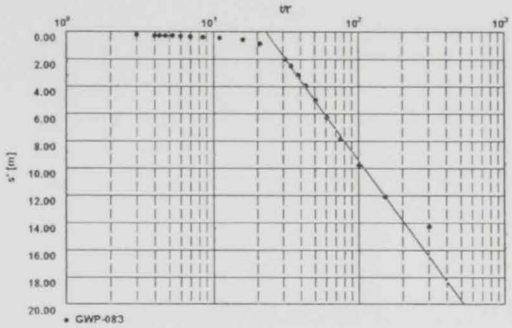

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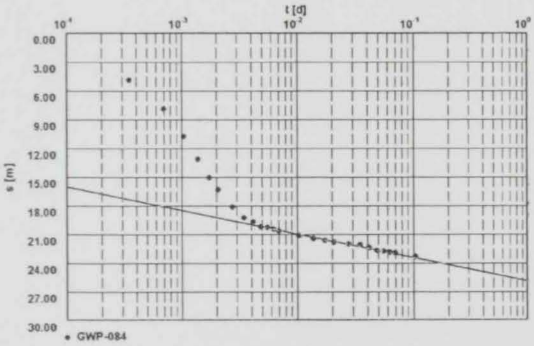

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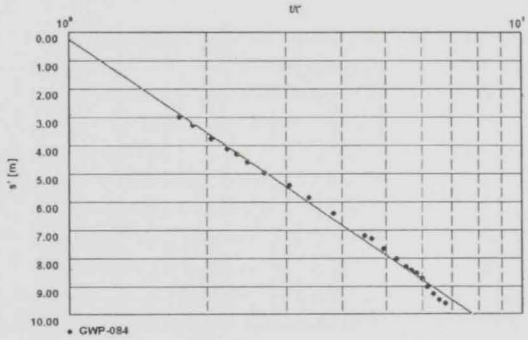

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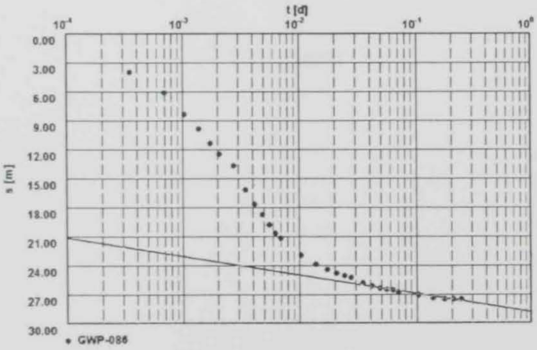

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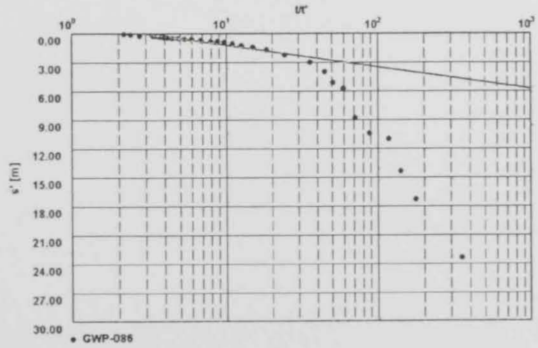

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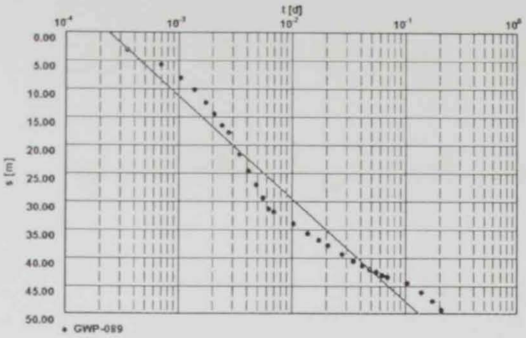

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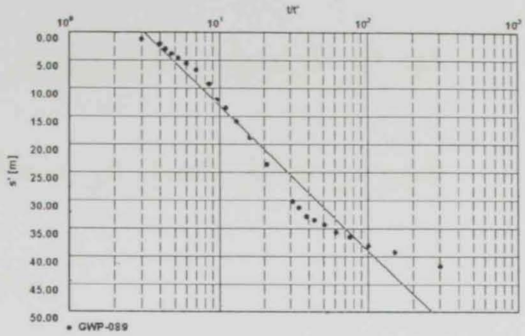

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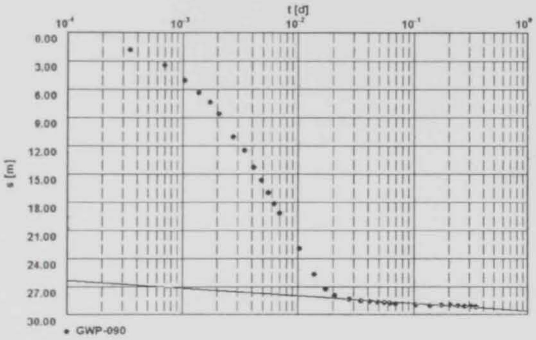
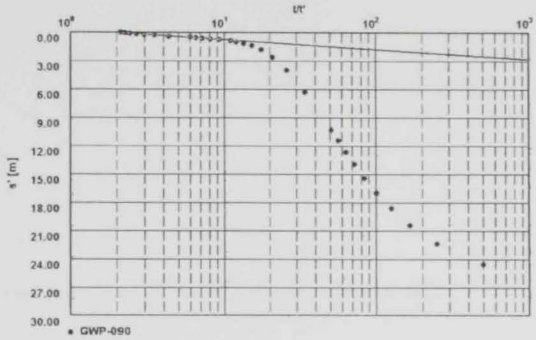


Figure 25_3_D



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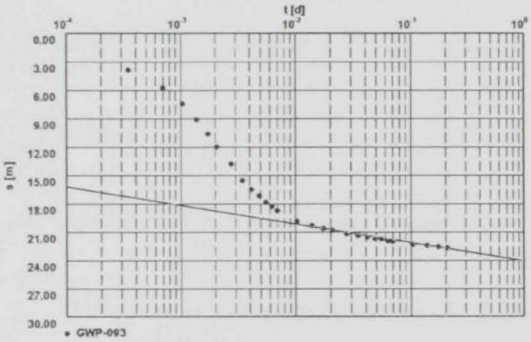

Figure 26_3_R

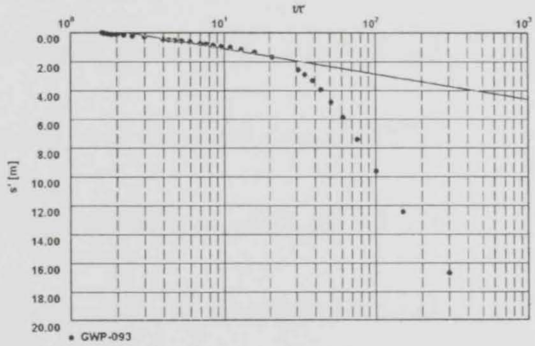

Figure 26_3_R

إجراء توصيف هيدرولوجي وتقييم كمّي لاستنزاف الخزان الجوفي القليل العمق في منطقة المقام-الساد في المنطقة الشرقية بإمارة أبوظبي

الملخص

تقع منطقة المقام-الساد في غرب مدينة العين على طريق العين-أبوظبي. وقد تم إختيار هذه المنطقة للدراسة وذلك للهبوط السريع في مستويات المياه الجوفية في الخزان الجوفي القليل العمق نتيجة للضخ المتواصل للمياه الجوفية. ففي عام ١٩٩٠-١٩٩١ أظهرت الدراسات الهيدرولوجية ان المنطقة هي من أشد المناطق في المنطقة الشرقية التي تعاني من الانخفاض الشديد في المياه الجوفية حيث تم ملاحظة ان المياه الجوفية قد إنخفضت أكثر من ٤٠ متراً في مركز الانخفاض. وتهدف هذه الدراسة الى محاولة فهم الوضعية الهيدرولوجية للخزان الجوفي بالمنطقة وذلك من خلال إجراء توصيف هيدرولوجي وتقييم كمّي للخزان الجوفي القليل العمق بالمنطقة.

وقد تم إجراء توصيف هيدرولوجي للخزان الجوفي من أجل التعرف على الموصلية الهيدرولوجية في المنطقة. ولهذا السبب، وبالاضافة الى النتائج التي توصلت اليها الدراسات والابحاث الهيدرولوجية السابقة، فقد تم إستخدام إختبارات الضخ الجوفي لإجراء هذا التوصيف. حيث تم إعادة تحليل إختبارات الضخ التي أجراها برنامج أبحاث المياه الجوفية في المنطقة وذلك باستخدام برنامج Aquifer Test . وقد تم

توضيح هذه النتائج في خرائط يمكن من خلالها التعرف على هيدرولوجية المنطقة وبالاخص توزيع معامل الناقلية الهيدرولوجية وكذلك الموصلية الهيدرولوجية . وقد اوضحت هذه التحاليل والبيانات ان الموصلية الهيدرولوجية في منطقة الدراسة صغيرة وتتراوح بين ١ -٥ أمتار في اليوم تتزايد باتجاه الغرب. ويتوافق مقدار هذه الموصلية مع الطبيعة الغير متجانسة للصخورو التراكيب الجيولوجية المكونة للخزان الجوفي حيث تتراوح طبيعة هذه الصخور من حصباء متجانسة وغير متجانسة متداخلة مع تركيبات صخرية مكونة من الصخور الطينية والطمية والجيرية.

وقد تم إجراء التقييم الكمي للمنطقة باستخدام النمذجة الرقمية. حيث تم إستخدام برنامج MODFLOW وهو برنامج من إنتاج هيئة المسح الجيولوجي الامريكية لعمل نموذج للخزان الجوفي. وقد تم استخدام النموذج لمحاكاة هبوط المياه الجوفية بالمنطقة ولإيضاح ان الخزان الجوفي يتم إستنزافه بشكل سريع. وقد تمت معايرة النموذج لحالة المياه الجوفية المستقرة أو الثابته (حالة الخزان الجوفي ماقبل مرحلة الاستنزاف وهي مرحلة ما قبل عام ١٩٨٠). كما تمت معايرة مرحلة الضخ في النموذج بمستويات المياه الجوفية في عامي ١٩٩٠ و١٩٩٥، وقد أظهرت هذه المعايرات تشابهاً مقبولاً بين النموذج وبين حالة الخزان الجوفي الطبيعية. وبحلول عام ١٩٩٧ تم جفاف بعض الابآر في منطقة الساد وانخفضت إنتاجية الباقي منها بشكل كبير وبالاضافة الى ذلك تم البدء في تنمية زراعية مكثفة في جنوب وجنوب غرب الساد، وقد استدعت هذه التطورات تعديل النموذج ليتناسب مع المعطيات الجديدة. وقد تم معايرة النموذج المعدل مع مستويات المياه الجوفية لعام ٢٠٠٣ حيث اظهر تشابهاً مقبولاً.

وقد تم استخدام النموذج للتنبوء بحالة الخزان الجوفي المستقبلية في عام ٢٠٠٥ وعام ٢٠١٥ وذلك مع إفتراض ان معدلات الضخ في ٢٠٠٣ سوف تستمر لغاية ٢٠١٥. وقد أظهر النموذج انه في عام ٢٠٠٥ سوف يتم جفاف بعض الآبار وانه بحلول عام ٢٠١٥ سوف يتم جفاف جزء كبير من الخزان الجوفي بالمنطقة.

وقد أظهر النموذج الحاجة الماسة الى جمع وتوفير المزيد من البيانات الهيدرولوجية للمنطقة حيث ان الكثير من البيانات المستخدمة في النموذج هي بيانات تقديرية. فوجود معلومات حقيقة وواقعية يمكن ان يُحسن النموذج ويزيد من كفاءته. ويمكن استخدام النموذخ في صيغتة الحالية للتعرف على نوعية البيانات المطلوب جمعها وكذلك يمكن الاسترشاد به لادارة مصادر امياه الجوفية بالمنطقه بشرط الاخذ في الحسبان ان الكثير من البيانات المستخدمة في النموذج هي بيانات تقديرية.

ويمكن الاستنتاج من هذه الدراسة ان الانخفاض الحاد في مستويات المياه الجوفية بالمنطقة يعزى الى ثلاثة عوامل: الضخ الجائر للمياه الجوفية بالمنطقة، وندرة التغذية الطبيعية، وضعف الناقلية الهيدرولوجية. ولذلك يمكن الخروج بالتوصيات التالية لتخفيف استنزاف الخزان الجوفي: تقنين استخدامات المياه الجوفية،ومراقبة حالة المياه الجوفية وإتخاذ الاجراءات التي من شأنها تعزيز التغذية الطبيعية وكذلك التخطيط لاقامة مشاريع للتغذية الصناعية.