# UNITED NATIONS

E

## ECONOMIC AND SOCIAL COUNCIL

1974~1999
ESCWA

Distr.
LIMITED
E/ESCWA/ENR/1999/IG.1/5
15 April 1999
ORIGINAL: ENGLISH

**Economic and Social Commission for Western Asia**

Committee on Water Resources
Third session
Beirut, 21-22 April 1999

Item 11 of the provisional agenda



# SUSTAINABLE MANAGEMENT OF GROUNDWATER IN PALEOGNE-AQUIFER SYSTEM IN EASTERN ARABIAN PENINSULA

---

Note: This document has been reproduced in the form in which it was received, without formal editing.

99-0400

# SUSTAINABLE MANAGEMENT OF GROUNDWATER IN PALEOGENE-AQUIFER SYSTEM IN EASTERN ARABIAN PENINSULA

**Dr. Walid A. Abderrahman**
Manager, Water Resources Development Section, Research Institute, King Fahd University of Petroleum and Minerals, P.O. Box 493, Dhahran 31261, Saudi Arabia

## ABSTRACT

The Paleogene aquifer system is the major water supply source for different purposes in several Gulf Countries in the Eastern Arabian Peninsula. Development of effective groundwater management scheme is essential for long term maintenance of long term productivity and quality of the aquifer system. To achieve this goal, several factors have to be considered especially: availability of enough hydrogeological information, effective monitoring program of the groundwater conditions on local and regional levels, understanding of the actual behavior of the aquifer system and efficient national and regional cooperation. Numerical simulation techniques have been utilized to develop a groundwater flow model for Paleogene aquifer system in local area of the coastal belt of the Eastern Province of Saudi Arabia. The simulated system included the Alat, the Khobar, and the Umm Er Radhuma aquifers with intervening Alat marl and Rus aquitards. Calibrated hydraulic properties have indicated that the aquifers are highly fissured at the structural highs such as Dammam dome and Qatif anticline. The calibrated model was subsequently utilized to predict the responses of aquifers over a planning horizon of 22 years (1998-2020) under various pumping alternatives. The model results indicated that the Khobar and the Alat aquifers are very productive along the Dammam-Qatif belt, and less productive at Abqaiq region. The Umm Er Radhuma aquifer has demonstrated relatively low declines in water levels through out the study area indicating very high productivity. Continuation of the present pumping trends will continue to lower water levels. Implementation of the water conservation measures for municipal purposes alone will reduce the expected drawdown by 50%. Similar approaches can be utilized for the Paleogene aquifer system on regional scale in the Eastern Arabian Peninsula for developing effective groundwater management schemes.

## INTRODUCTION

Groundwater resources from the Paleogene aquifers namely Umm Er Radhuma (UER) and Dammam are important water supply sources for several Gulf countries in the Eastern Arabian Peninsula. These countries have witnessed comprehensive developments in industrial, agricultural and social sectors especially during the last two decades. This has coupled with high growth rates in populations. Consequently, groundwater pumping has increased drastically to satisfy the growing demands. Several local negative impacts such as decline in water levels and change in quality have been experienced in several parts of the aquifer system. This is due to mismanagement of aquifer systems by over pumping of groundwater from large number of wells clustered in small areas. A comprehensive and collective national and regional efforts should be taken to define a feasible, efficient and long term groundwater management scheme to maintain the sustainability of these aquifers. There are several problems which hinder the achievement of this goal. Further investigations and actions are needed to solve these problems. Examples of these problems are:

- lack for enough hydrogeological information and data on local and regional levels,
- lack for effective monitoring program of the groundwater conditions on local and regional levels,
- misunderstanding of the actual behavior of the aquifer system on regional level.
- Lack for enough national and regional cooperation

Therefore, It is essential to overcome all above limiting factors to achieve effective and long term management plans for efficient groundwater utilization. This paper describes briefly these limiting factors. It also provides an example of the use of numerical techniques for understanding the groundwater behavior under different water abstraction alternatives to define and select the suitable long term water pumping scenario which protects the sustainability of the aquifer system in the region.

## AREAS OF FURTHER INVESTIGATIONS AND ACTIONS ON THE PALEOGENE AQUIFER SYSTEM

### 1. The Availability of Enough Hydrogeological Information

The availability of enough hydrogeological information about the Paleoegene aquifer system on local and regional levels are essential to understand the groundwater conditions and to develop sound management schemes. These information include detailed surface and subsurface geological maps, well logs, drilling reports, initial water levels, historical changes in water levels, historical water quality data, historical water pumping, hydraulic properties of the aquifers, recharge, topographic maps, soil information, and weather data. Several geological and hydrogeological studies on regional levels were carried out during the last two decades on the Paleogene aquifers in the Eastern Province of Saudi Arabia such as: Power et al, 1966; Italconsult, 1969; BRGM, 1977; GDC, 1980; Abderrahman, 1990; Abderrahman and Rasheeduddin, 1994; Abderrahman et al, 1995; and Rasheeduddin, 1988. But, there is a lack for a detailed, updated and regional hydrogeological study or information which help in understanding the present groundwater conditions on regional levels to be used as a sound base for development of future groundwater management plans. There are also other problems related to data collection such as:

- lack for enough expertise.
- lack for reliable data collection techniques.
- lack for effective linkage between data source and research organizations.
- lack for specialized offices or agencies for data.
- Lack for effective quality control procedures on the collected data.

The availability of the hydrogeological data requires timely data collection using reliable techniques and specialized expertise, effective data compilation and quality control, in addition to direct link between data sources and research organizations on local and regional levels. The presence of a specialized office as a water data source on regional and national levels is an important tool to provide the required data for the development of effective groundwater management scheme when required.

**2. Effective Monitoring Program Of The Groundwater Conditions**

One major prevailing problem for sound management of groundwater is the availability of effective monitoring network. This network is important to monitor water pumping quantities and changes in groundwater levels and quality with space and time of various Paleogene aquifers. It is extremely difficult to understand the local and regional responses of the aquifers under long term water abstraction without effective monitoring network. There are several observation wells in the region, but they do not cover all parts of the aquifers

**3. Understanding Of The Actual Behavior Of The Aquifer System On Regional Level**

The hydraulic properties of Paleogene aquifer system is affected greatly by the geological structure of the region. The lithologic succession of the Paleogene aquifer system can be divided into aquifers and intervening aquitards namely, the Umm Er Radhuma aquifer, the Rus aquitard with Midra and Saila Shales and Alveolina Limestones, the Khobar aquifer, the Orange Marl aquitard, and the Alat aquifer, Hadrukh aquitard, and the Neogene aquifer (Dam-Hufuf Fm.). Except for local facies variations, the main aquifers are represented by limestones, dolomitic limestones and dolomites. The aquitards are represented by shales, marls and anhydrites. The thicknesses of the hydrogeologic units are influenced by Domal and anticlinal strucures. The thickness increases from west to east except at the local structural highs. Hydraulic properties of these aquifers show great variations in study area which is a common characteristic of carbonate aquifers. Transmissivities and storage coefficients are mainly controlled by facies variations, joints, fissures and solution voids. Local hydrogeological studies indicated clearly that the hydrualic properties which rely on the response of single well is different greatly from the response of the aquifer under long term stress on regional level (Abderrahman et al, 1995). The measured and simulated drawdowns of UER aquifer under long term water abstraction reflects mush higher tansmissivity values than measured values (PhD research studies at KFUPM). This shows the need for understanding the unique hydrualic behavior of the heavily fissured limestone aquifers in the region to develop sound and long water management schemes on national and regional levels.

**4. National And Regional Cooperation**

The present level of cooperation between water research organizations, water application agencies and authorities, water producers and users on local and regional levels are important to achieve successful groundwater management. Unfortunately, the required link channels are not enough; or they are not existed in some countries. Consequently, the benefits from any efforts in groundwater resources will be limited and not effective. To overcome this problem, professional and effective link channels and procedures should be enhanced and/or established. The link channels should be defined by various water organizations. International and regional organizations can play important role to establish, enhance, and develop cooperation policies and links among organizations and other water authorities and users on regional and international levels.

5. **Collective Efforts And Expertise On Intra-Institutional Levels Nationally and Regionally**

The use of advanced techniques and sound procedures and information for proper groundwater management of Paleogene aquifers require teams from multidisciplinary expertise, national and international joint efforts of blended technologies, continuous upgrade of technical capabilities of various organizations. This objective can not be achieved without effective and collective efforts and expertise on intra institutional levels on local, regional and international levels. Inter and intra-institutional networking on national, regional and international levels and contributions from professional organizations are important tools to achieve successful and beneficial efforts for sound groundwater management. The success of the networking depends on its extent and available expertise. This helps in avoiding duplication of investigation efforts. Local and regional meetings, workshops, symposiums, conferences and seminars are effective tools for communications. Publications of technical information about the advancement of research in specialized journals are also helpful.

## MANAG|EMENT ALTERNATIVES FOR PALEOGENE AQUIFER SYSTEM ON LOCAL SCALE

Numerical simulation techniques have been proven to be effective tools in defining different management alternatives for developing sound groundwater use plans. There are many numerical modeling studies carried out by various researchers and agencies in the region as mentioned previously. But the applicability and accuracy of their analysis were limited. This is due to the fact that most of them have neglected the interaction between the adjacent aquifers through the intervening aquitards. Most of the models developed earlier were not updated to incorporate the changes in stress with time. This work describes the various stages involved in the development of a quasi-three dimensional simulation model of an interactive Paleogene multi aquifer system followed by a prediction stage to evaluate the effects of continuous pumping in the region (Rasheeduddin and Abderrahman, 1999). The area selected has enough hydrogeological information. The study area included the coastal belt of the Eastern Province of Saudi Arabia along the Arabian Gulf. It is bounded on the north by latitude $26^0$ 50’ 00’’N on the east by longitude $50^0$ 20’ 00’’ E, on the south by latitude $25^0$ 50’ 00’’ N, on the west by longitude $49^0$ 30’ 00’’E. It ranges 84 km from west to east and 112 km from north to south covering an area of approximately 9400 sq. km (Figure 1). It includes most of the municipal, agricultural and industrial well fields in the Eastern Province of Saudi Arabia.

### Geology

The study area is a part of the Arabian Platform which has remained stable since the end of Precambrian times. The whole sedimentary sequence constitutes a series of beds dipping gently (about $1^o$) ENE towards the Arabian Gulf away from the shield. The pattern is interrupted by some structures such as Dammam Dome at Dhahran, Qatif anticline which runs parallel to the coast, Abqaiq anticline trending north-south.

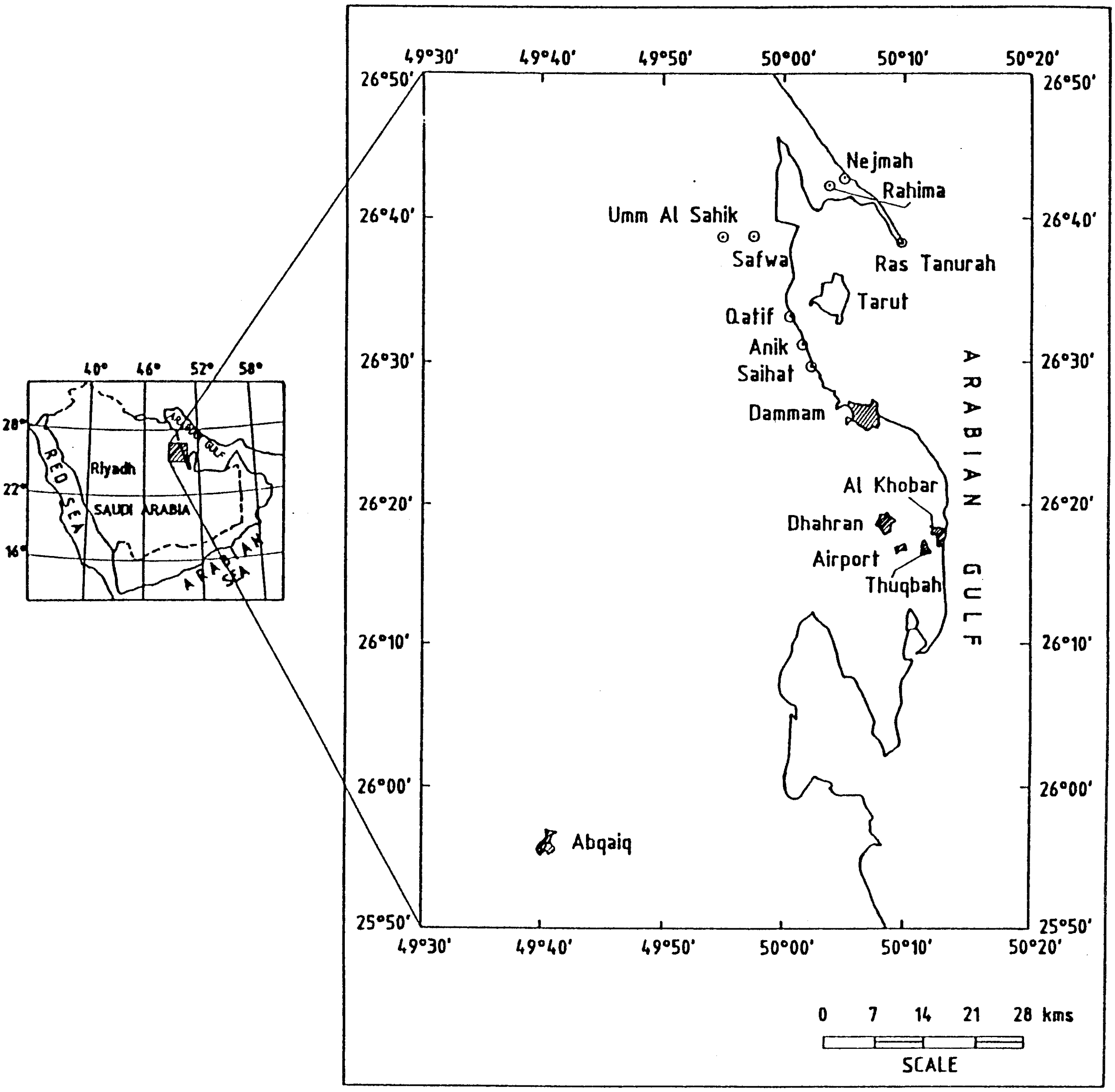



Figure 1. Location Map of the Study Area.

The geological units outcropping in the study area range from Eocene to Quaternary in age (Table 1). The Rus Formation of Eocene age crops out on the Northeastern flank of the Dammam Dome below Jabal Umm al Rus in Dhahran area about 15 to 20 km South of Dammam city. The type section cropping-out at Dammam Dome also includes the Dammam Formation of the Eocene age and the Hadrukh Formation of the Miocene age. The other parts of the study area are covered by Eolian sand and Sabkha deposits of the Quaternary age.

Based on the hydraulic properties of various units, the lithologic succession can be divided into aquifers and intervening aquitards namely, the Umm Er Radhuma aquifer, the Rus aquitard with Midra and Saila Shales and Alveolina Limestones, the Khobar aquifer, the Orange Marl aquitard, and the Alat aquifer, Hadrukh aquitard, and the Neogene aquifer (Dam-Hufuf Fm.). Except for local facies variations, the main aquifers are represented by limestones, dolomitic limestones and dolomites. The aquitards are represented by shales, marls and anhydrites. The thicknesses of the hydrogeologic units are influenced by Domal and anticlinal strucures. The thickness increases from west to east except at the local structural highs. Hydraulic properties of these aquifers show great variations in study area, which is a common characteristic of carbonate aquifers. Transmissivities and storage coefficients are mainly controlled by facies variations, joints, fissures and solution voids. The detailed description of each hydrogeological unit can be referred in Powers et. al., BRGM (1977), Italconsult (1967) and GDC (1980).

## MODELLING APPROACH

On the basis of the results of the previous studies the aquifer system as defined for modeling is reflected in lithostratigraphic sketch of Table 1. It identified three main aquifers namely: the Alat, the Khobar and the Umm Er Radhuma aquifers separated by two intervening aquitards. The Alat marl aquitard separates the Alat and Khobar aquifers and the Rus Formation, Midra-Saila Shale and Alveolina Limestone aquitard lies between the Khobar and Umm Er Radhuma aquifers. The Neogene aquifer of Dam Formation in the study area is a perched water table aquifer of very limited importance and is, therefore not considered in the present study.

Numerical modeling is a well-founded approach in analyzing groundwater management issues. An *aquifer view point* as defined by Anderson and Woessner ( 1992) has been used to develop a quasi-three dimensional model. Lateral flows in aquifer layers and vertical flows in aquitard units were simulated in the modeled system. Allocating appropriate leakance values to the aquitards simulated vertical flows. Storativity of the aquitard units were ignored to avoid the need to have nodes within the aquitard layers. MODFLOW, developed by McDonald and Harbaugh 1988; has been used in the present study. Boundaries of the present modeling study were determined by reviewing the available hydrogeologic data. The northern and south-eastern boundaries of the study area represented as no-flow (impermeable) boundaries ( a special case of Neumann type conditions). The western and southwestern

Table 1. Generalized lithostratigraphic succession of the study area.

| AGE | | FORMATION | MEMBER | ROCK UNIT | GENERALIZED LITHOLOGIC DESCRIPTION | THICKNESS (m) | HYDROGEOLOGIC UNIT |
|---|---|---|---|---|---|---|---|
| QUATERNARY | | SURFICIAL DEPOSITS | | | Gravel, sand and silt | 3 - 30 | Variable productivity depending on recharge |
| Tertiary | Neogene | | Hofuf | | Sandy marl and sandy limestone | 0 - 95 | Local Aquifer |
| | | | Dam | | Sandy marls, silty clays and skeletal limestones | 0 - 100 | |
| | | | Hadrukh | | Silty marls and shales, sandy limestones | 0 - 90 | |
| | Eocene | Dammam | Alat | Limestone | Skeletal detrital limestones | 0 – 110 | Aquifer |
| | | | | Marl | Dolomitic marls with limestone intercalations (orange color) | 0 – 35 | Aquitard |
| | | | Khobar | | Skeletal-detrital, porous and friable limestones, dolomitic limestones | 0 – 75 | Aquifer |
| | | | Alveolina limestone | | Limestones interbedded with shales and marls | 0 – 20 | Aquitard |
| | | | Midra and Saila shales | | Blue and dark grey, fissile shales with gypsiferous lenses | 0 – 20 | |
| | | Rus | | | Chalky limestones; anhydrite, dolomitic limestone & shales | 20 – 110 | |
| | Paleo-cene | Umm Er Radhuma | | | Partially dolomitized chalky limestones, detriatal skeletal limestone | average 300 | Aquifer |
| Cretaceous | | Aruma | | | Varicolored limestone, subordinate dolomite and shale | | Poor Aquifer |

RD02

boundary of the study area were modeled as head dependent boundaries. The eastern boundary in all the three aquifers was assigned a constant head boundary (Drichlet conditions) to allow under flow towards the Gulf. The head dependent boundary could have been more appropriate along the eastern coast, but there is no sufficient information to assume any sort of source and water level data away from the gulf coast. The study area was discretized into uniform square grid of 28 rows and 21 columns in each aquifer, with a grid spacing of 4km. This grid spacing was judged adequate in view of the available data, computational time. The resulting network consisted of 588 cells in each aquifer. Apart from the outer boundaries there were some inactive cells representing internal now-flow boundaries in the Alat and the Khobar aquifers at the locations where the aquifer is completely eroded. Figure 2 shows the finite difference grid and boundary conditions in all the three aquifers.

Initial assessments of input parameters such as transmissivities, storage coefficients, and vertical leakance values were mainly derived from the results earlier studies by Italconsult (1969) and GDC (1977). Moreover, the distribution of transmissivity patterns in carbonate aquifers, is generally governed more by fracturing, presence of fissures and karstification. Apart from the available data, information on geological structures and flow patterns were used in developing the initial values of transmissivites and storage coefficients. Vertical flows through the aquitard layer is a function of the vertical hydraulic conductivity and the thickness of the confining unit, and the head difference between the two adjacent aquifers. Anticlines and domal structures in the study area were assigned high values vertical leakance and low values at the synclines and at the places where the thickness is very high.

**Calibration and Verification Of The Model**

In the preset study , a trial and error procedure was adopted to calibrate the model. The input parameters such as transmissivities, storage coefficients and vertical leakances were suitably adjusted after each simulation run until a good match was obtained between computed and observed heads. Calibration of the model was carried out in two sequential stages: a steady state calibration and a transient calibration. The model was calibrated against the piezometric surface of the year 1967. The extraction rates of the year 1967 were used as stress input to the model. After successful calibration of the single layered sub-system, a multi-layered system in which heads in all the three aquifers were computed. The calibrated transmissivities, storage coefficients and vertical leakances from single layered calibration stage were used as input to the multi-layered system. Several runs were made in order to arrive a satisfactory fit with the observed aquifer responses, illustrated by the year 1967 hydraulic heads.

Based on the available extraction data and established patterns of aquifer and aquitard parameters from steady state calibration, the model was calibrated for the period of 1968-1980. Initial conditions were those of the calibrated heads during the final multi-layer simulation run. The simulation period was divided into thirteen stress periods. Boundary

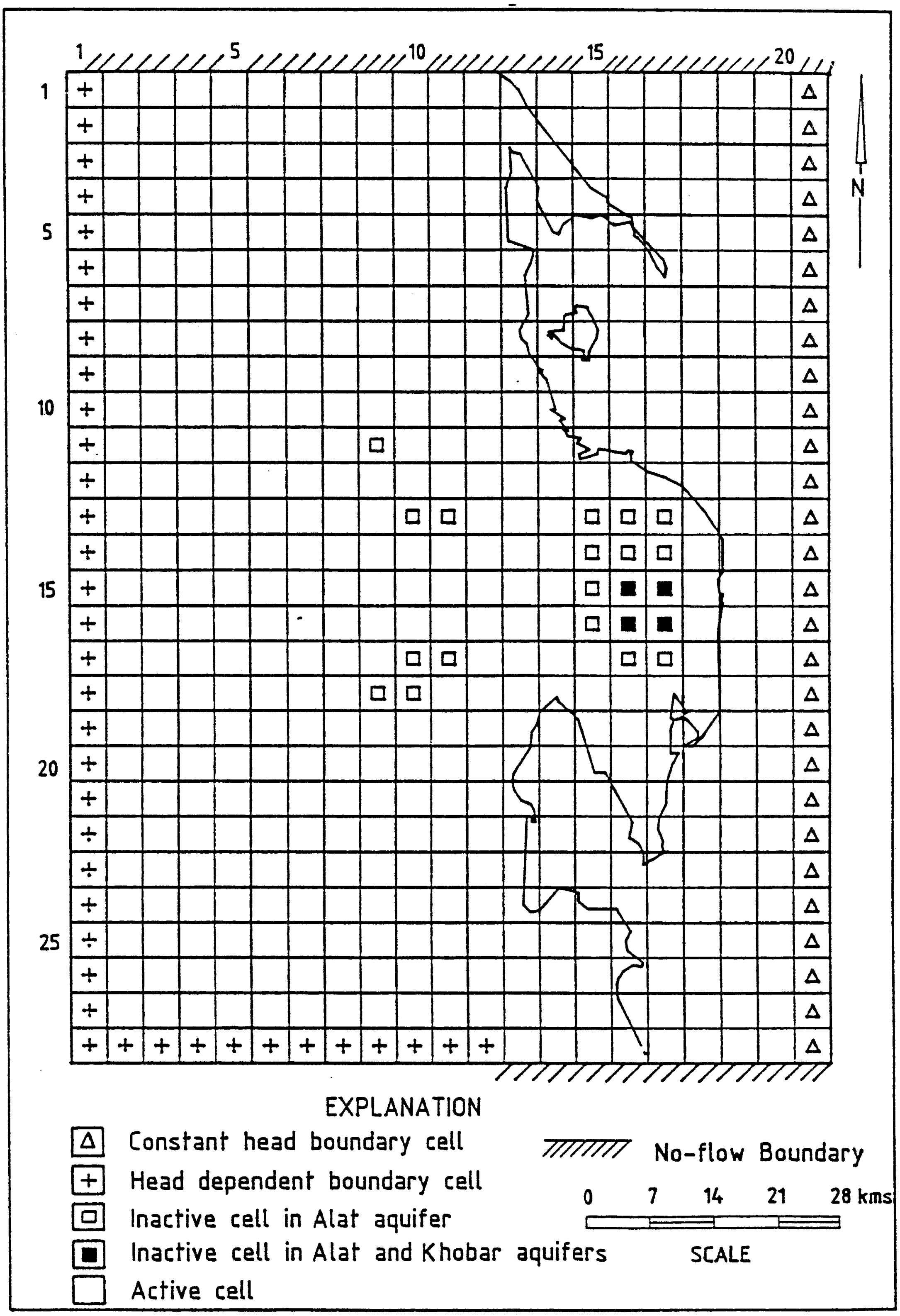


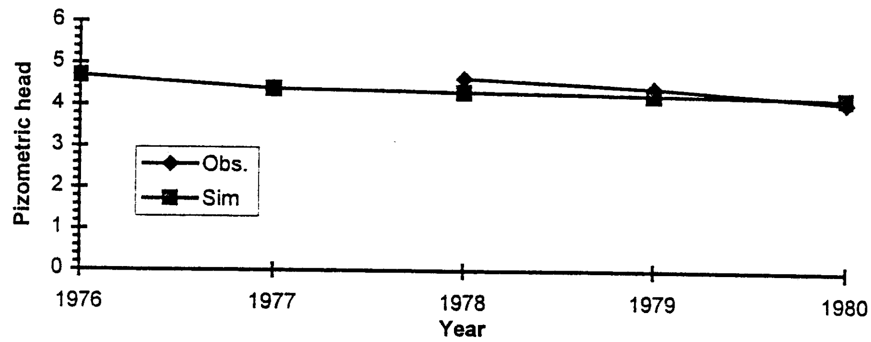

Figure 2. Finite Difference Grid and Boundary Conditions

conditions were similar to the steady state simulation. Storage coefficient was the primary parameter estimated during the transient calibration. The transient calibration results were evaluated by comparing the temporal variations in simulated heads with those of the observed water level data at certain locations. Figures (3a, 3b and 3c) show water level hydrographs of simulated and observed heads at selected cells in all the three aquifers. The results indicate reasonably good agreement between the two heads, considering the fact that each observation cell represents a larger area than an observation point. In many simulation studies the important results are not the computed heads but the changes in heads caused by stresses. As long as the model simulates the changes in head patterns correctly it can be assumed that it is a valid representation of the system under study.

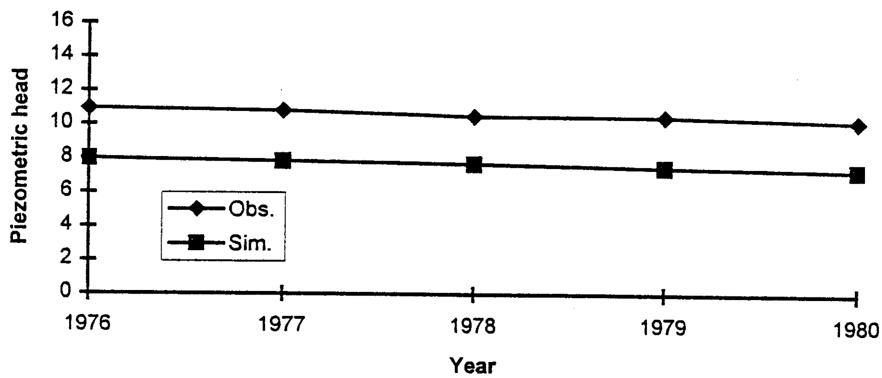
The ranges of calibrated values in all the three aquifers are shown in Table 2. The Umm Er Radhuma aquifer has the highest transmissivities compared to the Alat and the Khobar aquifers. In general, all the three aquifers exhibit relatively low transmissivities at Abqaiaq in southwest of the modeled region due to compact limestones without a dolomitic facies. Fairly high values at Dammam dome, and other anticlinal structures due to presence of extensive fissures, joints, and solution collapse structures in the aquifer units. It is also noted that the model calibrated transmissivity values in all the three aquifers are much greater than the pump test values. It is most likely due to the scale effect of karstification and fracturing. The model has a regional scale with 4x4 km cells; therefore the results produced by the model are representative of larger segment of aquifer, whereas, because of inherent heterogeneous distribution of porosity and permeability in karstified carbonate aquifers, the results produced by the conventional pump-test analysis represent only a very small part of the aquifer, possibly a part that is not representative of a larger segment. The calibrated storage coefficient values are higher at Dammam dome where aquifers between confined and unconfined in nature. The vertical leakance values of Alat marl and Rus aquitards are again higher in the vicinity of Dammam dome and anticlinal structures. This is due to the reduction in thickness and absence of anhydrite in Rus Formation.

Table 2: Calibrated Hydraulic properties of aquitards and aquifers

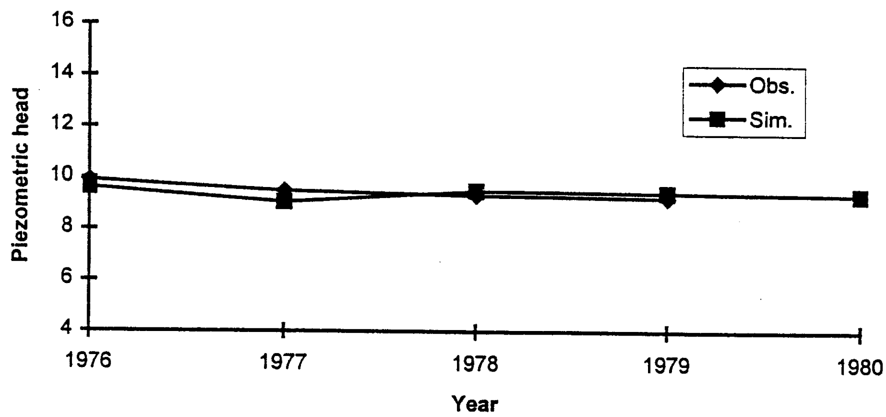
| **Hydrogeologic unit** | **Transmissivity ($m^2$/day)** | **Storage Coefficcient** | **Vertical Leakance ($d^{-1}$)** |
|---|---|---|---|
| Umm Er Radhuma aquifer | 7300 - 112000 | $4x10^{-5}$ - $2x\ 10^{-3}$ | - |
| Khobar aquifer | 712 - 45200 | $2x10^{-6}$ - $2x\ 10^{-4}$ | - |
| Alat aquifer | 410 - 36700 | $2x10^{-4}$ - $2x\ 10^{-2}$ | - |
| Rus aquitard | - | - | $1.0x10^{-11}$ - $9x\ 10^{-3}$ |
| Alat Marl aquitard | | | $1.0x10^{-9}$ - $9.5x\ 10^{-3}$ |




a) Alat aquifer at Cell 14, 18




b) Khobar aquifer at cell 5, 11




c) Umm Er Radhuma aquifer at cell 15,15

Figure 3. Water level hydrographs at selected cells in each aquifer for comparison between observed and simulated heads (in meters above mean sea level)

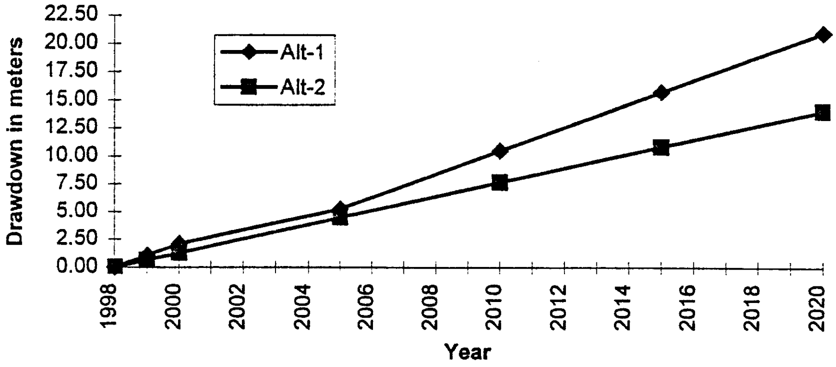
## 4. MANGEMENT ALTERNATIVES

A successfully calibrated model is used for predicting the future conditions of water levels under various alternative stresses. A planning horizon of 22 years (1998-2020) was selected for two alternative schemes in this study.

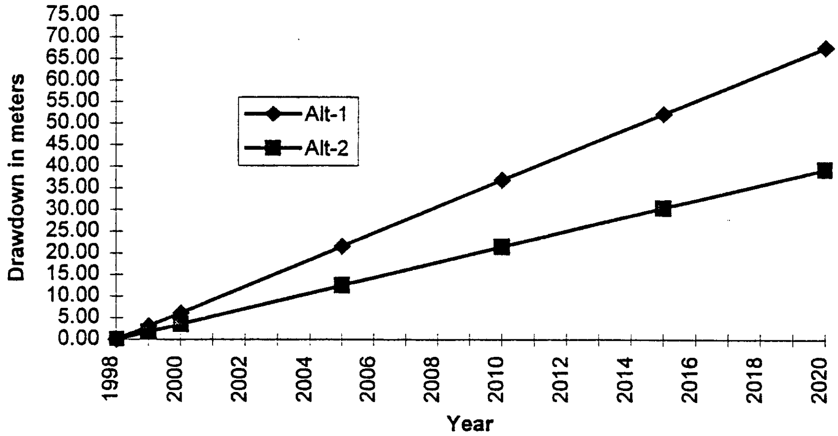
*The first alternative scheme* assumes that the groundwater *extraction trends observed until 1998 will continue without modifications until the year 2020.* The total extraction at the end of the year 2020 is 165.35 $Mm^3$ ,939.67 $Mm^3$, 345.52 $Mm^3$, in the Umm Er Radhuma , the Khobar, and the Alat aquifers respectively. Results of this assumption show a large cone of depression centered around Rahimah-Nejmah near Ras Tannurah (cell 4,15) in the Alat aquifer and the maximum drawdown is about 21m (Figure 4a). Drawdown elsewhere in Alat aquifer is between 4-8m. The Khobar aquifer reflected two cones of depressions, one at Abqaiq and another at Qatif. The maximum drawdown at Abqaiq (cell 23,4) was about 67.54m (Figure 4b) and at Qatif 12.54m. The Umm Er Radhuma aquifer has shown a little response to this high pumping. A small cone of depression at Qatif with a maximum drawdown of about 7m has been noticed. This is not due to the effect of pumping at Qatif, but due to the vertical leakage contribution from Umm Er Radhuma aquifer to the overlying Khobar and Alat aquifers. The drawdown at other areas such as Dhahran (cell 16,18) was between 2.5 and 5 m (Figure 4c). The low drawdown values were mainly due to high transmissive nature of the Umm Er Radhuma aquifer.

*The second alternative scheme* deals with "Conservation" of groundwater resources. The conservation is referred to more efficient use of existing supplies through a variety of conservation measures to reduce water demands, improve water use efficiency, and reduce losses. This is likely to play an important role in arid and semi arid regions where water is a limiting factor in the national development. The need for water conservation in the kingdom is essential due to scarcity of water resources and increasing cost of water and wastewater treatment. The study by Khan and Abdulrazzakh, (1986) indicated that if the present usage patterns, attitudes, policies and regulations are continued the average per capita water use will be 358 liters in the year 2000. It is also noted from their study that the projected per capita use in the year 2000 for the major cities in the kingdom can be reduced by one-half to one-third by applying various conservation techniques. Their analysis show that the combined effects of water saving devices, low pressure in water mains and public education programs can reduce the per capita water use by 30%. It is assumed in this study that neither increase nor decrease in water use for agricultural purposes will occur during the whole planning period in the study area.

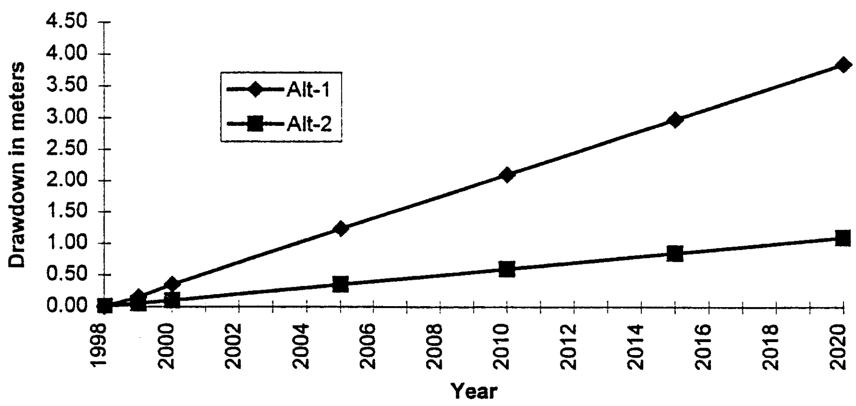
It is assumed, in this alternative that the conservation effects will continue from 2000 to 2020, with 30% reduction in the total extractions of alternative I. In order to reflect the conservation assumptions, the pumping values in municipal well fields were reduced by factors representing a gradual (linear) conservation effect starting from the year 2000. The




a) Alat aquifer at Ras Tannurah (Cell 4,15)




b) Khobar aquifer at Abqaiq (23,4)




c) Umm Er Radhuma Aquifer at Dhahran-AlKhobar (16,18)

Figure 4 Drawdown Vs Time graph in different aquifers total extraction rates at the end of year 2020 were 115.74 $Mm^3$, 657.77 $Mm^3$, and 241.86 $Mm^3$ in the Alat, the Khobar, and the Umm Er Radhuma aquifers respectively. Results of this alternative showed a cone of depression centered around Rahimah-Nejmah near Ras Tannurah in the Alat aquifer. The maximum drawdown was about 14.4m instead of 21 m in alternative I (Figure 4a). Drawdown elsewhere in Alat aquifer was about 3m instead of 4-8m in alternative I. In the Khobar aquifer there were two cones of depressions, one at Abqaiq and another at Qatif. The maximum drawdown at Abqaiq was about 39.3m instead of 67.54m in alternative I (Figure 4b), and at Qatif it was 3.14m instead of 12.54m in alternative I. A cone of depression at Qatif with a maximum drawdown of about 4m was noticed instead of 7m in alternative I. At Dhahran and Al-khobar the maximum drawdown was found to be about 1m instead of 3.85m in alternative I. The drawdowns in other areas were less than one meter instead of 2.5 -5 m. In Umm Er Radhuma aquifer, the drawdowns at Qatif were 2.6m instead of 4m in alternative I. The drawdowns elsewhere in the region were about one meter. Hydrographs at selected observation points in major cities show almost 50% reduction in drawdowns compared to that of the alternative I (Figures 4a-4c). However the water levels did not stabilize by the end of the year 2020. It is expected that the water levels will continue to decline uniformly beyond that time, but the rates will be reduced to almost one-half of those in alternative I.

It should be noted that the simulated drawdowns are only average values over cells of rather large mesh. Therefore, they do not represent the actual drawdowns in individual wells. Because the effective radius of a simulated pumping well for a finite difference grid interval of 4 km would be 832m, the actual drawdown in individual pumping wells or well field would be much higher than the simulated ones (Pricket, T. A., 1967). Thus the induced draw down may cause dewatering of the aquifers in individual pumping wells. Here the term dewatering refers to the lowering of water levels below the top elevation of the aquifer. Drawdowns at Abqaiq were very high, and this may lead to dewatering of khobar aquifer in individual wells or well fields at cells (21,5 and 23,4). The Umm Er Radhuma well field at Dhahran (cell 15,16) exhibits dewatering prior to beginning of this planning period (Table 3).

Table 3. Dewatering in individual wells by the end of Year 2020.

| Aquifer | Area | Model Cell (Row, Col) | Top Elev.of Aquifer m (msl) | Head at the end of the year 2020 in meters (Datum is mean sea level) | |
|---|---|---|---|---|---|
| | | | | Alternative 1 | Alternative II |
| Khobar | Abqaiq | 21, 5 | -51 | -28.21 | -8.77 |
| Khobar | Abqaiq | 23, 4 | -45 | -47.83 | -17.24 |
| UER | Dhahran | 15,16 | 8.0 | 4.8 | 6.74 |

## CONCLUSIONS

Maintenance of long term productivity and quality of groundwater in Paleogene aquifer system in Gulf Countries in the Eastern Arabian Peninsula require enough hydrogeological information, effective monitoring program of the groundwater conditions on local and regional levels, understanding of the actual behavior of the aquifer system and enough national and regional cooperation. The given example of the use of numerical simulation techniques to develop a groundwater flow model for the Paleogene aquifer system on local level has provided reasonable aquifer and aquitard hydraulic parameters. Structural highs show higher transmissivities due to fissured nature of the formations. Vertical conductivities are also greater at structural highs due to low thickness and absence of anhydrites in aquitard units. The model results have shown that the Alat and Khobar aquifers are very productive along the Dammam-Qatif belt, and less productive at Abqaiq. The Umm Er Radhuma aquifer is a highly productive aquifer through out the study area. If the existing trends in abstraction rates are continued, the water levels in all the aquifers will not stabilize until the year 2020 and continue to decline uniformly beyond that time. Conservation methods with 30% reduction in municipal well field pumping would be more effective in reducing the amount of drawdowns to almost one half of the previous alternative by the end of year 2020. Similar approach can be utilized to define effective groundwater management schemes for the Paleogene aquifer system on regional scale.

## ACKNOWLEDGMENT

The author wishes to acknowledge the Research Institute of King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, for support in completing this study.

## REFERENCES

Abderrahman, W.A. and M. Rasheeduddin, (1994), Future groundwater conditions under long-term water stresses in an arid urban area. *Water Resources Management-an International Journal*, vol. 8, no 1, pp. 245-264.

Abderrahman, W.A., M. Rasheeduddin, I. M. Al-Harazin, J.M. Esuflebbe, and B.S. Eqnaibi, (1995), Impacts of management practices on groundwater conditions in the eastern province, *Saudi Arabia. Hydrology Journal*, vol. 3, no. 4, pp. 32-41.

Abderrahman, W.A., (1990), The effects of groundwater use on the chemistry of spring water in Al-Hassa Oasis: *Journal of King Abdulaziz University*, Earth Sciences, vol. 3, Special Issue: First Saudi Symposium on Earth Sciences, Jeddah, 1989, pp. 259-265.

Anderson, Mary P. and Woessner, William W., (1992), *Applied Groundwater Modeling - Simulation of Flow and Advective Transport,* Academic Press, Inc., p-381.

Bureau De Recherche Geologiques et Mineres (BRGM), (1977). *Al-Hassa Development Project: Groundwater Resources Study and Management Program:* Unpublished report to Ministry of Agriculture and Water, Riyadh, Saudi Arabia.

Groundwater Development Consultants (GDC), (1980), *Umm-Er-Radhuma Study: Bahrain Assignment*: Demeter House, Station Road, Cambridge, CBI 2RS, Unpublished report to Ministry of Agriculture and Water, Riyadh, Saudi Arabia.

Italconsult, *Water and agricultural development studies for area IV*, (1969), Eastern Province, Saudi Arabia: Unpublished report to Ministry of Agriculture and Water, Riyadh, Saudi Arabia.

Khan, M.Z.A., and Abdulrazzakh, M. J., "Domestic Water Conservation Technology in Arid Regions", The Arabian Journal for Science and Engineering, Vol. 11,No. 4, 405-416, 1986.

McDonald, M.G., and Harbaugh, , A. W., (1988), *A Modular Three-Dimensional Finite-Difference Groundwater Flow Model, (MDOFLOW),* Scientific Publication Co., Washington, D.C.

Powers, R. W., Ramirez, L.F., Redmond, C. D., and Elberg, E.L., (1969), Geology of the Arabian Peninsula, "U.S. Geological Survey, Professional Paper 560-D", New York, USA, p. 147.

Pricket, T. A., "Designing Pumped Well Characteristics into Electric Anolog Models", Groundwater, Vol. 5, No. 4, 38-46, 1967.

Rasheeduddin, M., (1988), Numerical modelling of Alat, Khobar, and Umm Er Radhuma aquifer system in eastern Saudi Arabia: M.S. Thesis, King Fahd University of Petroleum and Minerals, Dhahran, p. 216.

Rasheeduddin, M, and W. A. Abderrahman, (1999), Management of groundwater resources in Coastal Belt of Eastern Province, Saudi Arabia, Proceedings of the Fifth Saudi Engineering Conference, 1-4 March 1999, Umm Al-Qura University, Makkah Al-Mukarramah, Saudi Arabia, Vol. 3, pp. 327-338.