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February 13-17, 1999
State of Bahrain

Water in the Gulf, Challenges of the 21st Century

Ministry of Electricity and Water

Secretariat General of the Gulf Cooperation Council (GCC)

Arabian Gulf University Bahrain

Bahrain Center for Studies and Research Bahrain

Edited by
DR. WALEED K. AL-ZUBARI

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27 Shawal-2 Dhu'l-qa'da, 1419 H
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Preface

The Countries of the Gulf Cooperation Council (GCC) are situated within an arid to semi-arid zones and are in general devoid of reliable surface water. Water requirements in these countries are met by groundwater (91%), desalinated water (7.5%), and treated wastewater (1.8%). In the past four decades, the GCC countries have experienced high population growth rates, along with expanded urbanization, increased economic activities, expansion of irrigated farming, and improvement of standards of living. The fast pace of development has resulted in a substantial increase in freshwater demands, which are met mainly by non-renewable groundwater abstraction. This heavy dependence on groundwater resources, particularly for agricultural development, has lead to their over-drafting beyond their natural renewal capacity, causing their depletion and quality deterioration, which has reduced their readiness as a source for direct use.

Despite the efforts made by the GCC countries in the provision of alternative water supplies, represented by the expensive desalinated water for the municipal and industrial sectors and the treated wastewater for the agricultural sector, there is a clear imbalance between water available resources and demands. A problem expected to continue in the future, as water is becoming the major constraint on agricultural, urban, and industrial sustainable development. These pressing conditions call for proper planning and management of the GCC countries' limited groundwater resources, a great challenge that faces their water authorities. Thus the theme of the present conference "Water in the Gulf, Challenges of the 21st Century" was chosen to emphasize this critical situation into the next century.

As at the previous WSTA conferences (Dubai, 1992; Bahrain, 1994; and Oman, 1997), the overall goals of the conference are to encourage scientific studies and research in the different fields of water resources, to create a forum of open discussion, and to exchange experiences among the Arabian Gulf States that the WSTA engendered throughout the three previous conferences.

The objectives of the convening conference are: 1) Identify priority issues and challenges facing the GCC countries to achieve sustainable water resources development in the 21st century; 2) Assess the current status of natural and alternative water resources in relation to present and future water demands in the GCC countries; 3) Review methods for conservation and efficient utilization of water in the various consuming sectors; 4) Review measures for water resources protection and maintaining water quality for various water uses; 5) Review local experiences for management, operation and maintenance of water projects in the GCC countries; 6) Review latest technologies and research in the assessment, development and management of water resources;

The Fourth Gulf Water Conference is organized by the Water Science and Technology Association (WSTA) in cooperation with the Ministry of Water and Electricity of the State of Bahrain, the Secretariat General of the Cooperation Council (GCC) for the Arab States of the Gulf, the Arabian Gulf University, and the Bahrain Center for Studies and Research. The Conference is co-organized and sponsored by the Arab Organization for Agricultural Development (AOAD), the International Atomic Energy Agency (IAEA), the International Hydrology Program (IHP), the UN Development Program (UNDP), the UN Economic & Social Commission for Western Asia (UNESCWA), the UN Environmental Program (UNEP/ROWA), the UNESCO Cairo office, the World Health Organization (WHO/EMRO), the European Desalination Society (EDS), and the International Desalination Association (IDA).

This conference proceedings contains 85 papers assembled into three volumes, one volume in Arabic (18 papers) and the other two in English (67 papers). The conference papers were selected by the Conference Scientific Committee from over 105 abstracts received from the call of papers. Many of these were modified to meet the standards of the Scientific Committee review. Eight papers are invited from the supporting organizations and renowned regional experts to give scientific presentations in respective technical sessions, and were supported by the WSTA, UNESCO (Cairo Office), and UNEP/ROWA. Conference sessions will be held on eight topics: Water Resources Planning and Management, Groundwater Resources, Desalinated Water, Wastewater Treatment, Surface Water, Agriculture Water & wastewater Reuse in Agriculture, Municipal Water Supply, and Drinking Water.

The scientific committee wishes to express its deep appreciation to the Governments of the GCC Countries and the GCC Secretariat General, and the sponsoring regional centers and organizations who kindly supported and endorsed this conference by providing keynote speakers.

Organization of these conferences requires considerable time and effort. As in the previous WSTA conferences, individuals from various sectors

(industry, government and academia) have come forth and given generously their time. Special thanks are due to the members of the Organizing Committee, Scientific Committee, Information Committee, and Scientific Papers Coordinators and Reviewers.

Finally, we wish to acknowledge the immeasurable contributions made by the authors and their research associates who were not only willing to rework and modify their abstracts and manuscripts, but also had to meet an extremely tight time schedule. Without their efforts this document would not have been possible.

The Scientific Committee sincerely hopes that this conference will achieve its objectives and is both enjoyable and rewarding for you.

Dr. Waleed K Al-Zubari
Chairman, Conference Scientific Committee
Director, Desert and Arid Zones Sciences Program
School of Graduate Studies
Arabian Gulf University, Bahrain

TABLE OF CONTENTS

VOLUME 1

WATER RESOURCES PLANNING
AND MANAGEMENT SESSION

Challenges and New Horizons for Desalination in the Arab World into the Third Millennium 1
Prof. Mohamed Amin Mandil

Integrated Renewable Water Resources Management in Saudi Arabia 3
Ali A. Al-Jaloud and Ali A. Al-Tokhais

A New Vision to the Water Resources Planning in Qatar 15
Mohamad Abu-Yacob Al-Sulaiti

Jordan's Water Resources: Technical Perspective 35
Dr. Radwan A. Al-Weshah

Sea Water Desalination in Saudi Arabia: Economic Review and Demand Projections 37
Dr. Mohammed Abdulaziz-Sahlawi

The Role of Water Legislation in the Management of Water Resources in the ESCWA Region 45
Mohamed Abdulrazzak

Towards Higher Efficiency in the Water and Power Utilities 65
Jamil S.K. Al-Alawi

Water Resources Planning Under Unertainities 77
Dr. Muhammad Al-Zahrani, Mujtaba Shreef and Dr. Thair Husain

Future Water Supply and Demand Predictions in Saudi Arabia 93
Prof. Abdulaziz S. Al-Turbak

GIS Application in Water Resources Management and Planning 103
Jerry Johnson

Reallocation of the Dammam Aquifer Yield in Bahrain: A Linear Programming Approach 105
Ahmed R. Khater

Cross Sectional Analysis of Residential Water Consumption in the City of Riyadh 123
Saud Taher and Adnan Al Saati

Evaluation and Classification of Water Use Rate Policy Using the Points Credit Index 139
Al-Sayed, M., Al-Mershed, A. and Al-Askar, I.

BAS Experience in Condensate Water Utilization 151
Abdul-Jalil E. Mohammed and Waleed K. Al-Zubari

GROUNDWATER RESOURCES

An Overview of Nuclear Science and Technology in Groundwater Assessment/Management and IAEA Activities in the Gulf Region 161
Y. Yurtsever

Hydrogeological Conditions of Paleogene Aquifer in the ESCWA Region 175
Wolfgang Wagner & Wolfgang Muller

Application of Natural Isotopes for Hydrogeologic Investigations in United Arab Emirates 197
Zeinelabidin S. Rizk and Abdulrahman S. Alsharham

Changes in Ground-Water Quality Related to Agricultural Development in the Liwa Crescent Area, Abu Dhabi Emirate 229
Ismail Al Bady

Temporal Variation of Groundwater Chemistry in SAQ Aquifer, Qassim Region, Saudi Arabia 243
Ibrahim Abdulaziz Al-Sagaby and Mohamed Ali Moallim

The Impact of Aquifer Materials on Groundwater Quality in the Umm Gudair Area, Kuwait 257
Dr. Khaled M.B. Hadi

Spatial Design and Optimization of Groundwater Salinity Observation Network in Bahrain 275
Ali H. Al-Shaabani and Waleed K. Al-Zubari

Options for Aquifers Storage and Recovery in Kuwait 293
Al-Otaibi, M.M.

Digital Simulations of Ground-Water Salvage in Northeastern Abu Dhabi Emirate 303
Eric Silva and Fatima Al Nuaimi

Simulated Impacts of Pumping from Well Fields Near Umm Ghafa, Eastern Abu Dhabi Emirate 317
Mohamed A. Khalifa

Groundwater Resources/Salinity Modelling of the Tripoli Aquifer, Libya 331
M. El Fleet, Prof. J. Baird and Dr. J. Crowther

Assessment of the Side Effects of Groundwater Development in the West Nile Delta Region 343
Akram Fekry, Maha Abdel Salam and Ebel Smidt

Application of a Geographic Information System to the Hydrology of Abu Dhabi Emirate 357
Juanito M. Tamayo and Khalid Al Junabi

Visualizations of Abu-Jarjor Wellfield Boreholes Data Using GIS 369
Sabah Al-Jenaid

Database Software Applications for Hydrologic Studies in Abu Dhabi Emirate 379
Mohammed El Hassan and Rashid Al Nuaimi

GPS Surveying Techniques Applied to Ground-Water Exploration in Abu Dhabi Emirate 387
Danilo A. Saracho and Joel C. Visitacion

Using Geophysical Logs to Evaluate Internal Circulation in Wells, Northeastern Abu Dhabi Emirate 403
Imad Tawfiq

SURFACE WATER

Rainfall-Runoff Relationships in an Arid Area Case Study, Wadi Ahin-Oman 415
Aisha Al-Qurashi and Dr. G. Herbertson

Description of Cloud Seeding Experiment in North Libya 431
Younis Shaban Al-Fenadi

Umm Al-Nar Hydraulic Laboratory 453
An Asset to Gulf Water and Marine Researchers, Designers & Policy Makers
Khaled S. Al-Amri and Rashed A.H.A. Thabet

Rain Water Harvesting in Arid Regions 471
Dr. David N. Joudi and Dr. Yu-Si Fok

TABLE OF CONTENTS

VOLUME 2

WATER DESALINATION SESSION

New Power and Water Co-Generation Concept with Application of Reverse Osmosis (RO) Desalination 491
T. Altmann

Maintenance and Operation Experience of Co-Generation Plant 501
Saeed Mohammed Al-Shehabi

Four Decades for the Multi-Stage Flash Desalination 519
Hisham El-Dessouky, Hisham M. Ettouney and Faisal Al-Juwayhel

Desalination of Seawater and Brackish Water with Reverse Osmosis and the Disc Tube Module DT 541
Dr. -Ing. Thomas A. Peters

Reverse Osmosis Process Chemistry Relevant to the Gulf 553
Robert Y. Ning

Degradation Study of Cellulose Triacetate Hollow Fine Fiber SWRO Membranes 567
A. Mohammed Farooque and Ahamed Al-Amoudi

A New Approach to Membrane and Thermal Seawater Desalination Process Using Nanofiltration Membranes (Part 2) 577
A.M. Hassan, M.AK. Al-Sofi, A.S. Al-Amoudi A.T.M. Jamaluddin, A.M. Farooque, A. Rowaili, A.G.I. Dalvi, N.M. Kither, G.M. Mustafa and I.A.R. Al-Tisan

Improving the Permeate Flux by Unsteady Operation of a RO Desalination Unit 595
N.M. Al-Bastaki and A. Abbas

Evaluation of Ultra-Violet Radiation Disinfection on the Bacterial Growth in the SWRO Pilot Plant, Al-Jubail 603
Hassan Ahmed Munshi, N. Sasikumar, A.T. Jamaluddin and Kither Mohammed

Raw Seawater and Pre-Treatment Process Investigations at the Addur SWRO Desalination Plant—The Crux to Pre-Treatment System Rehabilitation 619
Ahmed Hashim, Waleed Al-Murbatti and Dr. Brent Ericsson

Productivity Increase of High Salinity Brackish Water Reverse Osmosis Plant—The Case of Bahrain 645
Dr. Khalid A. Burashid and Khalid E. Almansour

Effect of Various Forms of Iron in Recycle Brine on Performance on Scale Control Additives in MSF Desalination Plants 663
Abdul Ghani I. Dalvi, M.N. Kither Mohammed, Saad Al-Sulami, K. Sahul and Radwan Al-Rasheed

The Performance of Different Antiscalants in Multi-Stage Flash Distillers 679
Osman A. Hamed, Mohammad Ak. Al-Sofi, Ghulam M. Mustafa and Abdul Ghani Dalvi

A Small Size MSF Model for Field Experimentation with Ratio of Dimensions Based on Number of Tubes 693
Salah A. Abunayib

Computer Package for Design/Rating of Thermal Desalination Processes 709
Hisham M. Ettouney and Hisham El-Desouky

Rehabilitation of Multi-Stage Flashing Air Derence Jeddah Plant 729
Nassir Al-Tweergi

Investigating Intake System Effectiveness with Emphasis on Self-Jetting Well-Point (SJWP) Beachwell System 739
A.M. Hassan, A.T.M. Jamaluddin and Ali Rowaili, Ellen Abart and Robert Lovo

Corrosion Behavior of Steels in Gulf Seawater Environment 753
Anees U. Malik, Shahreer Ahmad, Ismaeel Andijani and Saleh Al-Fouzan

Vapor-Side Corrosion Monitoring in Al-Khafji Desalination Plant 769
Nausha Asrar, Anees U. Malik and Shahreer Ahmed Madeeh Al-Khalidi and Khalid Al-Moaili

Studies on the Stress Corrosion Cracking Behavior of Few Alloys Used in the Desalination Plants 783
T.L. Prakash and A.U. Malik

Long Term Electrochemical Noise Measurement for Stainless Steels Used in Desalination Plants 793
Mohmmed S. Al-Ansari and Ahmed R. Khater

Studies on Corrosion of Carbon Steel in Deaerated Saline Solutions in Presence of Scale Inhibitor 807
Ismaeel Andijani and S. Turgoose

DRINKING WATER

Comparative Study of Potable and Bottled Mineral Waters Available in the State of Kuwait 823
Khalefa M. Fraij, Mohammed K. Abd El Aleem and Hamad Al Ajmy

WASTEWATER

Technologies of Wastewater Treatment in West Asia 841
Dr. Fouad Kanbour

The Application of Flowsheeting Approach in Wastewater Treatment and Water Reuse 843
M. Alahmad, F. Abdul Aleem, K. Al-Humaizi and A. Al-Khodair

Compact Technologies for Urban Wastewater Recycling 861
Slim Zeghal, Gerard Velter and Abdelkader Gaid

On-Line Monitors for Wastewater Treatment 873
Slim Zeghal, Laurence Le Grand & Gerard Velter

Optimization of Sand Filtration Process for Tertiary Treatment 887
Dr. Khaled H. Al-Dhowalia and Eng. Ali Abdullah Al-Mutlak

Comparative Performance Analysis of Two Techniques to Renovate Tertiary Treated Wastewater 903
S. Bou-Hamad, S. Al-Shammari, M. Abdel-Jawad, S. Ebrahim and F. Al-Attram

Lime Recovery form Riyadh Water Treatment Plants 917
Ibrahim S. Al-Mutaz and Sami O.A. Al-Yousef

AGRICULTURAL WATER

Wastewater Quality and its Reuse in Agriculture in Saudi Arabia 929
Ghulam Hussain and Adnan J. Al-Saati

Water Resources Planning and Management

Challenges and New Horizons for Desalination in the Arab World into the Third Millennium

Prof. Mohamed Amin Mandil

CHALLENGES & NEW HORIZONS FOR DESALINATION IN THE ARAB WORLD INTO THE THIRD MILLENNIUM

Prof. Mohamed Amin Mandil
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Alexandria, Egypt

ABSTRACT

A number of Arab countries depend on desalination in bridging the gap between actual demand for water used for drinking and other municipal uses and what is available from the conventional water resources for such purposes. This situation has prevailed primarily in the Arabian Gulf region which made it the center of gravity for the desalination world. However, an increasing number of Arab countries will experience in the near future a drop in the per capita share of water from natural resources to the extent of experiencing water stress or even water scarcity. Hence, by the end of the first quarter of the next century (2025), it is expected that the great majority of the Arab nations will face this situation to various degrees. This is the challenge desalination industry will have to face which will dictate using all conventional and non-conventional ways and means to lower the cost of desalination down to levels within reach of countries that are expected to join the list of water-stressed or water-scarce countries. In addition, this decrease in cost will become a necessity dictated for by the economic conditions which started to cast their shadows over the conventional markets for desalination in oil-rich countries.

Review of techniques being presently under development, in the context of new horizons they are expected to create for the attainment of cost reduction, will demonstrate how desalination industry will meet the aforementioned challenges.

Integrated Renewable Water Resources Management in Saudi Arabia

Ali A. Al-Jaloud and Ali A. Al-Tokhais

INTEGRATED RENEWABLE WATER RESOURCES MANAGEMENT IN SAUDI ARABIA

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ABSTRACT

The Kingdom of Saudi Arabia is characterized by arid to hyper-arid climate, lacking any perennial streams or rivers. Available sources of water are conventional source e.g. ground water and surface water and non-conventional sources e.g. desalinated water and treated waste water. A major share of the conventional water resources are directed to agriculture. The renewable water resources are mainly derived from scarce and highly variable rainfall, which generates runoff and provides aquifer recharge. A large volume of the rain water is lost by evaporation. Therefore proper management and efficient utilization is very essential for this source. The renewable water in the Arabian shield region is stored in the alluvial aquifers and in the reservoirs behind dams as well as the rain used for direct-irrigation. About 40% of the cultivated area in Saudi Arabia lies in the Arabian Shield region consuming about 6.6 billion cubic meters of renewable water annually (MAW 1998). Various possible methods of water management in agriculture include treated wastewater reuse and saline water use, harnessing of surface water, increasing use efficiency through crop selection, drip and sprinkler irrigation, using controlled environment, use of soil conditioners to increase soil moisture.

Key words: Water Management, Water use Efficiency, Renewable Water Resource, Water Conservation.

INTRODUCTION

The Kingdom of Saudi Arabia, characterized by an arid to hyper-arid climate, constitutes an area about 5% of the total world arid zone (Bashour et al. 1983). In arid countries, the most important factor limiting agricultural production is water. Therefore renewable water resources have good potential for sustainable food production. New innovative approach in water management, particularly suited to arid regions and reconsideration of the practices developed in this region by ancient agriculturist is needed. Basically two approaches are to be considered; increasing the supply of usable water and reducing the demand for water, in which supply and demand along with conservation have to be considered as an integral system. Developing renewable water resources and improving water use efficiency will play a significant role in meeting the increasing water demand.

RENEWABLE WATER RESOURCES

(a) Background:

In the prevailing arid to hyper-arid conditions, the renewable water resources are derived from scarce rainfall providing intermittent runoff and subsurface infiltration contributing to ground water recharge of Quaternary alluvial aquifers, sub-basaltic aquifers and unconfined outcrop portions of the sedimentary aquifers.

The rain in Saudi Arabia, is generally unpredictable, but occurs mostly in winter, springs and sometimes in summer. However, two main regions can be identified on the basis of the rainfall e.g. Hijaz and Asir mountains region with two rainy seasons, i.e. continental rain in winter and monsoon rain in summer, while the rest of the country is characterized by low and scant rainfall.

Rainfall pattern shows high variability both in time and areal distribution, characterized with large extremes. While most of the country experiences low rainfall in the range of 50-125mm annually, Rub Al Khali experiences much drier climate with average rainfall <50 mm/y and in Tihama Asir region in southwest receives >500 mm/y, which constitutes more than 60% of the total runoff in the country. Sometimes large portion of the average annual rainfall may occur in single events, producing large floods which may cause large scale damage to civil structures and property. Conversely, rainfall much below the average may persist for some years, causing drought.

A significant portion of the rain evaporates, and the remaining amount infiltrates and flows in the main wadis and branching tributaries. The infiltration and runoff volume depend primarily on the rainfall intensity and duration soil type and size of the catchement area. There are 11 major drainage basins in Saudi Arabia (Table 1), covering about 1.3 million square kilometers, and generating a total runoff of over 2,000 million cubic meters annually.

(b) Harnessing of Surface Water:

Efficient utilization and effective management of the conventional water resources are the goals that the water resources planners and managers are striving hard to achieve. Some means of attaining such effective management of the renewable water resources are as follows;

(i) Surface Dams: Construction of surface dams in Saudi Arabia has been quite successful in collecting intermittent runoff, in spite of some associated constraints such as suspended sediments, reduction in the natural wadi flow, besides the cost. These dams are of earthfill, rockfill and concrete types. The main objectives of these dams are for recharge the aquifers, flood control, irrigation water supply and domestic water supplies for towns and villages. There are at present, 186 dams with a total capacity of about 775 million cubic meters (Table 2). In addition, 13 dams are under construction and many more selected sites have been studied and designed for implementation.

(ii) Rain Water Harvesting (RWH): The objective of the RWH is to collect and direct rainwater to wadis and small ponds or storage tanks, facilitate accumulation and retention of soil moisture. Most of the rain water harvesting has been practiced since old times in the higher elevations of the southwestern part of the country.

(iii) Underground Dams: Underground dams are meant to increase the storage of ground water in the alluvial aquifers, underlain by impermeable rocks. Underground dams are mainly slurry walls with steel pipes (mixed cement with bentonite), about 80 cm thick extending into the underlying bedrock. Such structure intercepts the wadi subsurface flow while allowing overflowing flood water. At present, two underground dams been constructed in Saudi Arabia in wadi Aridah and Wadi Turabah, mainly to increase ground water yield from these wadis.

(c) Utilization of Renewable Water Resources:

In the Kingdom of Saudi Arabia, the renewable water resources are utilized in different forms such as;

(i) Ground Water stored in the alluvial sediments.
(ii) Accumulated surface water behind the dams.
(iii) Direct use of rain to irrigate large areas, particularly in the southwestern region.

Renewable water resources provide significant volume of water to help meeting demand in both domestic and agricultural sectors, particularly the Arabian Shield region. From about 1.2 million ha cultivated in 1996, about 463,000 ha (or nearly 40%) are in the Arabian Shield area, utilizing about 6.6 billion cubic meters (MAW 1998). The cultivated areas during the period 1990-96 and the contribution of renewable water to the agricultural consumption is shown in table 3.

ALTERNATIVE SOURCES OF IRRIGATION WATER

(a) Treated Municipal Wastewater:

Reuse of treated wastewater can supplement overall demand for water. Adequately treated wastewater can be used for non-domestic purposes such as irrigation, industry, aquifer recharge etc. With careful planning, various industrial and agricultural demand may be met by treated wastewater, thereby releasing fresh water for municipalities which require potable water for human consumption. It is expected that treated waste water will have great impact on the future usable water supplies in arid areas.

Using treated municipal wastewater for irrigation is quite attractive where agricultural lands are close cities, because the plant nutrient are available in this water which will reduce the use of chemical fertilizer.

It is important for water reuse planning to quantify the availability of treated wastewater which will help in formulating future irrigation projects. In view of the designed capacity of the wastewater treatment plants, the total wastewater availability in some major cities in Saudi Arabia, in 1995 are as follows:

City	Qty. (m3/d)
1. Riyadh	420,000
2. Jeddah	118,000
3. Buraidah	42,500
4. Unaizah	15,000
5. Al Hassa	200,000
6. Dammam	187,143
7. Al Khobar	96,000
8. Al Qatif	30,000
9. Al Madinah	100,000

The above figures indicate that about 1.3 million m^3 of treated wastewater are available daily and can be used for Agriculture, landscaping, and some other purpose.

Recent studies (Al Jaloud et al. 1994) indicate that wastewater effluent containing 20mg N/liter is a promising substitute for inorganic nitrogen fertilizer for wheat production in Saudi Arabia, which can save about 50% in fertilizer application.

(b) Use of Saline Water:

The salt resistance plants largely determine the suitability of saline water for irrigation. Although only few crops such as barley, wheat, rye, grass, Bermuda grass and wheat grasses, date palm and prosopis spp are known to be salt tolerant.

Several plant species which have been introduced and tried in Saudi Arabia are Atriplex, Salicornia, Kochia, wheat and barley. Adoption of proper management practices such as leaching, adequate drainage, improved irrigation methods, crop selection, adoption of suitable planting techniques and fertilizer applications are important for efficient management of saline water irrigation to achieve higher water use efficiency.

WATER MANAGEMENT & WATER USE EFFICIENCY

The renewable water in Saudi Arabia is limited and require intensive management and conservation. The following methods will increase water use efficiency and reduce water biomass ratio in arid regions such as Saudi Arabia.

(a) Crop Selection:

Most crops grown under irrigation in arid regions were imported from more temperate regions. Some of these crop may need about 2,000 kg of water to produce 1 kg of usable dry matter. More research and trials are needed for crops which can use less water per unit of product.

Selection of local cultivars (varieties) and wild plant species which are surviving in arid conditions must be considered for putting them to use as food or cash crops; selecting individual water efficient plants from already domesticated crops such as barley, sorghum, pearl millet for use in the breeding programs. Many of our present staple crops appear to have originated under arid or semi-arid conditions, which suggest that appropriate genotype should be available. Although native desert plants can not be ignored, the best candidates for becoming highly useful plants with low water requirements seem to be already-domesticated ones.

(b) Methods of Irrigation:

Flood irrigation has poor water use efficiency, which is not more than 55%, extended areas will increase evaporation and soil percolation. Drip irrigation system will increase water use efficiency upto 85% because water is carried directly to the plants. Since only a small amount of soil is watered, evaporation losses are also minimized. Furthermore, the rate and time of water application can be automatically adjusted for no runoff and minimum deep percolation losses. Drip irrigation is potentially important in arid lands for many irrigated crops, and used extensively on trees, vine and row crops. In addition to drip irrigation, sprinkler irrigation system is recommended for arid land, which has a water use efficiency of more than 70% for field crops.

(c) Controlled Environment Agriculture:

High production in controlled environment can be achieved with limited amount of water. Within the enclosure, light, heat, water, humidity and nutrient are controlled and balanced to produce yield often ten times larger than those from conventional outdoor agriculture. Impressive productivity has been obtained in such controlled environment systems. Annual per ha yields of 300 t of tomatoes and 350 t of cucumbers have been obtained in controlled environment (Al Jaloud et al. 1997) compared to about 40 t in open field.

(d) Increasing Soil Water Capacity & Reducing Evaporation:

Low water holding capacity coupled with low water contents of the sandy soils minimize the water use effeciency. Technology used to increase water holding capacity and soil moisture contents will help conserve water resources. A study by Al Jaloud (1988) indicated that application of different types of soil conditioners such as PAM, U.F. and Bitumen emulsion leads to a complex change in physico-chemical properties of the soils. It was further stated that application of these materials either as surface treatment or incorporated into the soil has a great potential for decreasing evaporation losses and subsequently for increasing water shortage of the soil profile which is quite beneficial for the management of sandy soils. Also the grain yields were highly affected by the addition of soil conditioners. Surface treatment gave the highest yields for bitumen and PAM. Incorporated U.F. gave the highest yield among all the treatments.

(e) Reducing Transpiration:

Transpiration losses can be reduced in the following ways: breeding plant varieties that transpire less. Reducing air movement over crops by, for example, windbreaks of interplanted rows of taller plants. Removing unproductive leaves, and using chemical antitranspirants which acts by: closing stomata; forming a film over stomata; or cooling the leaf with reflecting coat that reduces the amount of absorbed solar energy.

(f) Inter-Cropping:

Growing two crops in the same land will increase water efficiency because the same amount of water can be utilized by the two crops and water biomass ratio will be decreased e.g. growing corn with soybean.

Some farmers in of Saudi Arabia grow alfalfa with wheat and get a better yield. Barley as grain and hay could be practiced.

(g) Reducing Evaporation from Water Surface:

Reservoirs and canals in arid lands are subject to heavy evaporation losses. Reducing evaporation from water surface is an important way to increase supply of water by minimizing water losses. This can be achieved by covering canals, reducing surface areas of water bodies and or adding some chemicals.

(h) Reducing Seepage Losses:

In most arid lands, earthen canals and reservoirs are used to convey water. Due to the high soil porosity, many of these facilities has great water losses. Seepage can be reduced if the wall of the canals, reservoirs and conduits are made watertight. Recent technology has produced many waterproof materials that may prove valuable for this purpose.

SUMMARY AND CONCLUSION

The renewable water resources in Saudi Arabia are mainly derived from scarce highly variable rainfall, characterized by large extremes, from less than 50mm to more than 500 mm annually. The remaining rainfall after evaporation generates runoff in the wadi courses and contribute to infiltration and recharge to alluvial aquifers, sub-basaltic aquifers and to the unconfined portions of the sedimentary aquifers. More than half of the generated runoff occur in southwest e.g. Hijaz and Asir Mountain regions.

The proper management of the renewable water resources under the prevailing arid to hyper-arid conditions is very essential and are mainly effected by 186 dams of various types with a total storage capacity of 775 MCM. Several dams are under construction and planned. Two underground dams in the wadis in the Arabian Shield region have been constructed to increase ground water yield. The renewable water resources are used by storing them in wadi alluvial sediments and behind dams. In addition, large areas are irrigated directly especially in the southwest. About 40% of the area under cultivation occurs in the Arabian Shield region, consuming about 6.6 billion cubic meters of renewable water in 1996.

In view of the limited availability of renewable water, this paper explores various possible methods such as agricultural use of treated municipal wastewater, saline water etc. to supplement the demand. It discusses increasing water use efficiency through selection of crops using less consumptive water, use of drip and sprinkler irrigation, agriculture and horticulture under controlled environment producing several high yield crops per year. In addition, increased soil moisture and reducing evaporation has been possible using several types of soil conditioners. Other ways and means include reducing transpiration & seepage and growing more than one crop e.g. corn and soybean, simultaneously.

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Table 1. Catchement areas & main wadis

No.	Main Catchment	Sub Catchment	Main Wadis
1.	Red Sea Coast 241,600 km^2	1a South of Jeddah 1b Jeddah Zone 1c Jeddah-Wadi Hamd 1d Wadi Hamd 1e North of Wadi Hamd	Jizan,Damad, Baysh, Hali, Yiba, Qanunah Al Lith Fatimah, Khulays Qudayd/Sitarah, Rabigh Aqiq East, Khaybar Dama, Ifal
2.	Taif-Fadat al Mislah 43,200 Km^2	—	Wajj, Liyyah, Aqiq
3.	Asir-Dawasir 180,000 Km^2	3a Asir 3b Dawasir	Turabah, Ranyah, Bishah, Tathlith Dawasir
4.	Asir-Najran	—	Najran
5.	South Tuwayq	—	Jadwal
6.	Rub al Khali	—	—
7.	Birk-Nisah-Sahaba 162,300 Km^2	7a Shield Drainage 7b Birk-Nisah 7c Sahaba	 Hawtah, Nisah, Hanifah Sahaba
8.	North Tuwayq 152,800 Km^2	8a Tuwayq Drainage 8b Remainder	Sudair, Meshgar/Namil
9.	Ar Rimah-Al Batin 174,400 Km^2	9a Ar Rimah 9b Ar Batin	Ar Rimah
10.	Nafud-NE Frontier 161,000 Km^2	—	—
11.	As Sirhan 192,300 Km^2	—	As Sirhan

MAW, 1979

Table 2. Number & types of dams in Saudi Arabia (until 1997)

Region	Earthfill	Rockfill	Concrete	Total	Capacity MCM
Riyadh	30	7	20	57	71.00
Makkah Al-Mukarramah	4	7	12	23	106.00
Madinah Al-Munawwarah	4	1	5	10	33.00
Al Qassim	3	—	1	4	3.00
Assir	11	10	31	52	385.29
Hail	11	—	3	14	8.65
Jizan	—	—	1	1	51.00
Najran	—	—	1	1	86.00
Al-Baha	2	12	10	24	30.72
Total	62	36	84	186	775.00

Table 3. Agricultural consumption of renewable water in the Arabian Shield region

Year	Kingdom of Saudi Arabia		Arabian Shield	
	Cultivated Area (in Ha)	Water Consumption (MCM)	Cultivated Area (in Ha)	Renewable Water Use (MCM)
1990	1,379,154	16,513	381,633	5,283
1991	1,519,755	18,384	362,235	5,105
1992	1,570,817	18,949	349,126	4,983
1993	1,596,404	19,641	370,498	5,312
1994	1,595,546	20,165	418,958	5,941
1995	1,302,363	19,088	456,924	6,549
1996	1,166,972	18,274	463,589	6,644

MAW, 1998

A New Vision to the Water Resources Planning in Qatar

Mohamad Abu-Yacob Al-Sulaiti

A NEW VISION TO THE WATER RESOURCES PLANNING IN QATAR

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ABSTRACT

Qatar represents an example of an ever challenging water resource planning and management in an arid country. Since the 1950's, economic development and population growth have imposed great stresses on the groundwater, the only natural water reserve. Qatar has scanty rainfall, no lakes, no rivers, or streams. To meet the water demand, the government resorted to seawater desalination. Despite the steady development of desalination capacity, the total output of the desalination plant is falling short of meeting the required demand. Groundwater quality is deteriorating, and the reserve is faced with an estimated 40% deficit. The institutional structure of the water managing bodies makes attaining the appropriate level of coordination and cooperation a difficult endeavor. The present fragmented water resources organizational framework is no longer fit to cope with the challenge of meeting the water demand with the quality required. In order to meet the water demand, there is a need to create an efficient water resource planning and management system that is capable of dealing with the present and future water supply challenge. More important is to have a central water authority to take the mission of formalizing a country water plan, coordinate all water undertakings, establish water regulations, and enforce the implementation of all policies. This paper is aimed at promoting the principal of central water resources planning in Qatar. Past and present water resources situations will be presented to set the base for justifying the principal of central planning. Main problems associated with the major water resources will be discussed and alternative solutions will be suggested. Then, the new vision to the water resources planning will be discussed and recommended.

KEYWORDS: planning, groundwater, desalination, wastewater, aquifer, irrigation, recharge, fragmented, institutional, saltwater, seawater, intrusion, demand.

INTRODUCTION

Qatar represents an example of the ever challenging water resource planning and management in an arid country. Since the 1950's, economic development and population growth have imposed great stresses on the only natural water resource. Groundwater reserve on the northern half of the country is the only natural water resource of economic value. Other small and scattered groundwater bodies exist in the southern half.

Qatar has scanty rainfall, no lakes, no rivers, or streams. To meet the water demand, the government resorted to seawater desalination. Almost all potable water consumption is supplied from seawater desalination sources. Despite the steady development of desalination capacity, the total output of the desalination plants is falling short of meeting the required demand. Groundwater quality is deteriorating, and the reserve is faced with an estimated 40% deficit. These adverse results are due to rapid population increase, economic activities, limited natural water resources, improvement of the standard of living, very costly seawater desalination, and fragmented and poor water resources management.

Even though Qatar is a geographically small country and its water problem is simple and well understood, the institutional structure of the water managing bodies makes attaining the appropriate level of coordination and cooperation a difficult endeavor. The absence of clear objective(s), comprehensive policies and plans make the task even more difficult. The attitude of managing each water resources component individually without considering its potentials in the frame of the overall water resources scheme may have worked in the past, where stresses imposed by the society on the water resources could be tolerated. The present fragmented organization of the water resources is no longer fit to cope with the challenge of meeting the water demand with the quality required. If this perception and the present pattern of water consumption continues, the water problem will constitute a major constraint and a difficult challenge to the overall economic and social development of Qatar.

Qatar is situated about halfway along the west coast of the Arabian Gulf, east of the Arabian peninsula, between latitude (27 to 24, and 10 to 26 degree north) and longitudes (45 to 50 and 40 to 51 degree east). It comprises a landmass of 11610 km^2 extending northward as a peninsula from mainland Saudi Arabia, together with a number of islands. The mainland is approximately 180 km along its north-south axis and about 85 km from east to west at its greatest breadth.

The topographically of Qatar is characterized by low to moderate relief, with the highest elevation of 103 m above mean sea level being in the south. The most significant feature is the large number of shallow depressions. These 850 depressions, are approximately circular in shape and with diameters ranging from a few hundreds meters up to about three kilometers (Lloyd et al 1987). Runoff from rainstorms accumulates in these depressions to form groundwater natural recharge basins.

Qatar lies in a region characterized by a year-round high temperature, hot dry early summer winds, high relative humidity for most of the year, and irregular and very variable rainfall. The prevailing wind direction is north and north-west although south and south-east winds occur generally in February. Openwater evaporation in Qatar has been calculated from meteorological data of three stations. The results indicated a variation from 2191 mm to 2526 mm in the total annual evaporation. Daily evaporation rates therefore vary from 2.5 mm/day during the winter months to 11.5 mm/day during the summer months (FAO, 1981).

The indigenous population of Qatar was estimated to be around 25,000 up to about the first half of 1900's (Pike, 1983; Atkinson and Eccleston, 1985). Production of oil began in 1948 and marked a new era in the history of Qatar. Immigrants started to come to the country to support the new oil industry and substitute for the shortage in the human resources. Table (1) shows the population census for 1986, 1995 and the projected estimate to 2020 (State of Qatar, 1997)

Table (1) Population Distribution 1986-2020

Year	1986	1995	2000	2005	2010	2015	2020
Population	369,079	616,644	730,310	839,385	934,176	1,005,614	1,046,913

This paper is aimed at promoting the principal of central water resources planning in Qatar. Past and present water resources situations will be presented to set the base for justifying the principal of central planning. Main problems associated with the major water resources will be discussed and alternative solutions will be suggested. Then, the new vision to the water resources planning will be discussed and recommended.

WATER RESOURCES

There are four types of water resources in Qatar: groundwater, desalted water, reclaimed wastewater, and rainfall which is the only freshwater recharge to the groundwater.

GROUNDWATER

Groundwater was the only available water resource prior to the introduction of desalination technology in the State of Qatar. Groundwater extractions for both municipal and agricultural uses have been rising steadily from 5 mcm in 1958 to 79 mcm in 1980 (FAO, 1981). Groundwater utilization for agricultural irrigation reached 244 mcm in the 1996/97 season (Qutib, 1998).

Qatar landmass is an extension of the Arabian peninsula and its geology follows the stratigraphy of Saudi Arabia. The aquifer system in Qatar is comprised of a succession of several separate layers. The aquifers of importance are the Umm er Rathuma formation (UER), the Rus formation, and the Dammam formation.

Kimery (1985) described the geological formation of Qatar in a descending order. The Dammam formation crops out over most of Qatar. The total thickness of this formation is about 50 m. The upper part is well-fractured and contained vugs and solution cavities. The Rus formation underlies the Dammam formation throughout the country, except in two areas. The Rus formation crops out in relatively small areas northwest of Doha (the capital city) and on the Dukhan anticline in west Qatar. Rus thickness ranges from less than 30 m to more than 90 m. This formation contains abundant vugs and solution channels, particularly in north Qatar. The UER formation underlies the Rus formation and extends through out the peninsula. The thickness of UER has been found to range from 270 m to 370 m. FAO (1981) stated that the hydrogeological importance of the UER in Qatar lies in the upper 20 to 100 m of the formation.

The areal extent of the groundwater in Qatar is geologically divided into two separate hydrogeological provinces, the Northern Groundwater Province and the Southern Groundwater Province (FAO, 1981; Pike, 1983; Lloyd et al, 1987). The major resource of usable groundwater in Qatar is derived from the Northern Groundwater Province (NGP). In NGP, Dammam formation (the upper-most formation) contains little or no water of hydrogeological significance. In southern Qatar usable groundwater is confined to isolated bodies of meteoric water within the Rus formation. The Alat aquifer, which is part of Dammam, is limited to southwest Qatar and contains brackish water. Figure (1) is a schematic representation of the aquifer system.

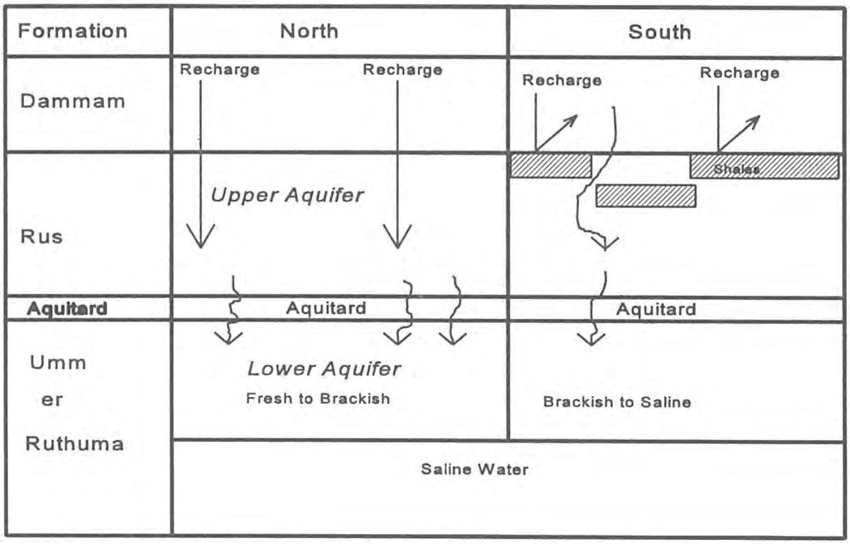

Figure 1: A Schmatic Representation of Aquifer System (modified from Pike, 1983)

For all practical purposes, the NGP system is considered as a two-layer system. Rus and UER are hydraulically connected through a leaky aquitard. The Rus/Dammam aquifer is a phreatic aquifer, while the lower UER is confined. Groundwater in both aquifers is surrounded by saline and seawater. Rainfall is the only form of recharge to the aquifer system.

The mean annual recharge to the groundwater has been estimated to be in the order of 40 mcm, of which 27 mcm was recharged to the NGP (Pike, 1983). FAO(1981), Atkinson and Eccleston (1985), and Pike (1983) estimated the total usable ground water in the NGP to be about 2500 mcm. Based on the recharge rate and other factors, the safe yield was also estimated to be 25 mcm/year. The government of Qatar implemented a natural recharge project. The project was aimed at reducing rainfall runoff evaporation and increasing infiltration. The project drilled 341 recharge wells in depressions scattered all over Qatar and was completed in 1995. As a result of this project, the recharge value from rainfall reached 155 mcm in 1994/94 season (Qutib, 1998).

Present Situation

Groundwater reserve in Qatar has lost its natural equilibrium. Groundwater is utilized heavily for agricultural irrigation and potable purposes. Qutib (1998) reported that the groundwater abstraction in the 1996/97 season reached 224 mcm, which is equivalent to 98.8% of the total abstraction.

The rural potable water supplies for 1997 (from all well-fields that are managed by the Ministry of Electricity and Water) reached only 2.7 mcm, which is equivalent to 1.2% of the total abstracted groundwater. The dominant consumer of groundwater in Qatar is the agricultural sector. Figure (2) plots the yearly consumed groundwater for irrigation. This Figure is based on data from State of Qatar (1994/95). This data is also listed in table (2).

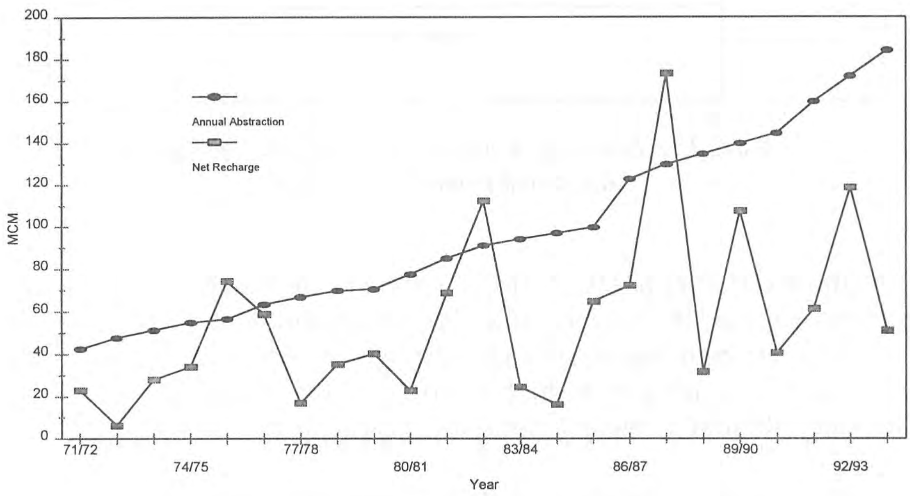

Figure 2 : Annual Abstraction and Recharge

*Table (2) Groundwater Balance in MCM for the period 1971-1994***

Year	Total Extraction	Recharge	Net Recharge	Yearly water Balance	Accu. deficit
71/72	42.58	30.36	23	19.58	19.58
72/73	47.84	12.28	6.24	41.6	61.18
73/74	51.26	33.42	28.04	23.22	84.4
74/75	54.96	38.44	34.18	20.78	105.18
75/76	56.46	77.41	74.28	-17.82*	87.36
76/77	63.32	60.97	58.8	4.52	91.88
77/78	66.75	18.1	16.79	49.96	141.84
78/79	69.78	35.85	35.3	34.48	176.32
79/80	70.45	40.69	40.3	30.15	206.47
80/81	77.42	21.58	22.94	54.48	260.95
81/82	85	56.48	68.73	16.27	277.22
82/83	91	107.64	112.42	-21.42	255.8
83/84	94.15	19.02	24.56	69.59	325.39
84/85	96.9	10.02	16.25	80.65	406.04
85/86	99.65	57.83	64.74	34.91	440.95
86/87	122.87	59.49	72.11	50.76	491.71
87/88	130	158.54	173.4	-43.4	448.31
88/89	135	16.02	31.77	103.23	551.54
89/90	140	90.53	107.53	32.47	584.01
90/91	145	22.45	40.7	104.3	688.31
91/92	160	39.21	61.21	98.79	787.1
92/93	172.1	93.68	118.82	53.28	840.38
93/94	184.2	23	51.05	133.15	973.53

*a minus sign indicates a surplus of recharge over abstraction.
**Data extracted from State of Qatar 1994/95.

The previous figure and table clearly indicate that for most years the groundwater extractions were higher than recharge, or the aquifer system safe yield. This unbalanced utilization of the groundwater reserve upset the natural hydraulic settings between the freshwater body and the saltwater body.

The over pumping of the groundwater has led to the farther in-land intrusion of the freshwater-saltwater interface. Based on an assumption that there is an excess abstraction over recharge of only 5 mcm per year, aquifer thickness of 20 m, and storage coefficient of 0.004, it was estimated that the saltwater front will advance inland by about 800 m/yr (FAO, 1981). If the same assumption is applied on the situation presented in figure (2), the accumulated saltwater intrusion is calculated to be about 29,000 m for the year 1994. FAO (1981) reported that the quality of groundwater has been monitored since 1971 and is in the process of deterioration under the impact of the increase in the total concentration of dissolved salt from both seawater intrusion and saline water upconning due to over-extraction of groundwater between 1971 to 1980. Further, State of Qatar (1994/95) reported that due to over-pumping of the aquifers, the groundwater quality deterioration amounted to a yearly rate of 6% and a yearly drop in the potentiometric surface of 3%. Also, the aquifer system has lost a large portion of its reserve. The groundwater accumulated deficit reached 994 mcm in 1994/95 (Qutib, 1998). Figure (3) along with table (2) show the yearly and the accumulated deficit from 1971/72 to 1993/94.

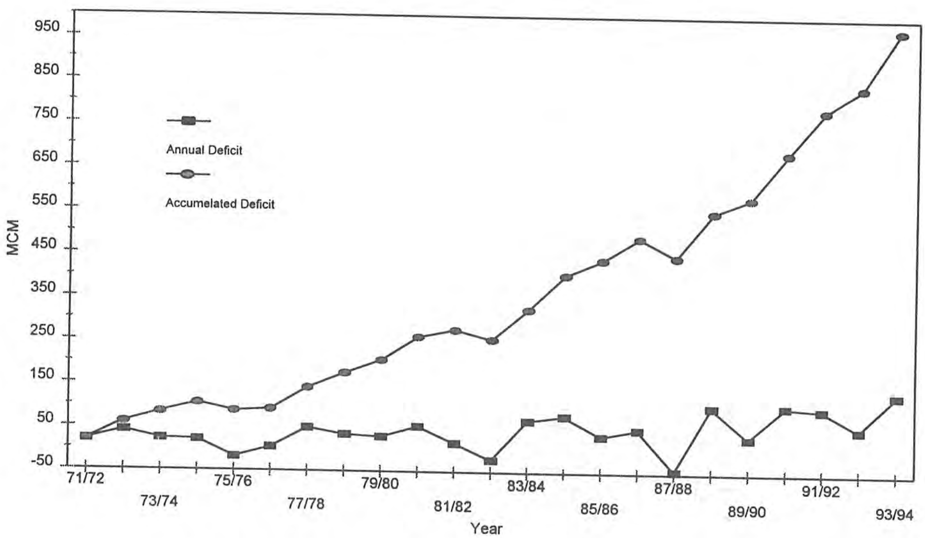

Figure 3 : Annual and Accumulated Deficit

SEAWATER DESALINATION

Qatar, as other Gulf Corporation Council Countries, depends largely on seawater desalination to meet domestic and industrial water demand. Overall, the seawater desalination provides about 98% of Qatar's domestic and industrial freshwater demand.

The first desalination plant "Doha Central" was commissioned in 1954, with a capacity of 680 m^3/d. In 1959, two additional MSF units with a capacity of 680 m^3/d each were added to this plant. Doha Central is no longer in service. Ras Abu Abboud (RAA) was commissioned in 1963 with a capacity of 6800 m^3/d. MSF units have been added to and others were put-out of service from this plant over the past 30 years. Presently, RAA runs four MSF units with a total installed capacity of 36,000 m³/d . RAA was envisaged to be put-out of service in 1999. In 1978, Ras Abu Fontas "A" (RAF "A") was introduced into service with two MSF units each with a capacity of 22,700 m³/d. RAF "A" is the largest desalination facility in Qatar. Present installed capacity of this plant is about 317,000 m³/d spread-out equally over fourteen MSF units. In 1997, Ras Abu Fontas "B" (RAF "B") was introduced into service. The production of this new plant amounted to 1,649,650 m³ in December 1997. RAF "B" has a designed capacity of 60,000 m³/d (State of Qatar 1996; Acer,1997). Figure (4) demonstrates the development of the seawater desalination capacity since 1954.

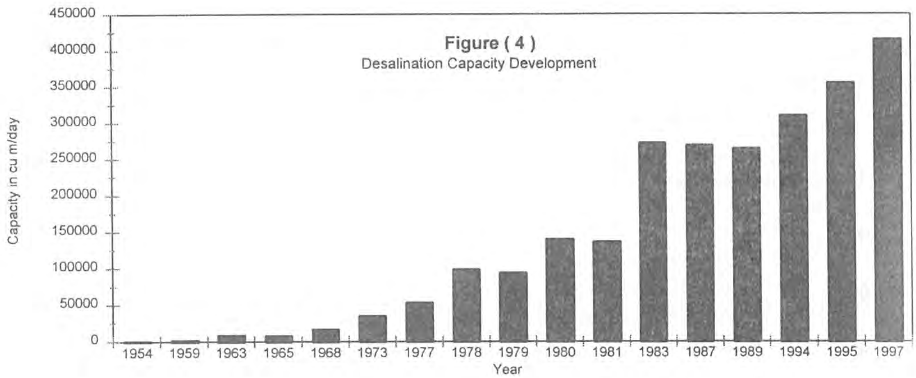

Figure 4 : Desalination Capacity Development

The present total installed capacity of RAF "A" , RAF "B", and RAA together is about 413,000 m³/d. Table (3) lists the desalting plants and their associate capacities.

Table (3) Present Desalination Plant Capacities

Plant	Type	Capacity (m³/d)	Capacity mig/d*
Ras Abu Fontas "A"	MSF	317,000	69.74
Ras Abu Fontas "B"	MSF	60,000	13.20
Ras Abu Abboud	MSF	36,000	7.92
Abu Samera	RO	680	0.15
Umm Bob	RO	1,100	0.24
North Camp	RO	1,180	0.26
Dukhan (QGPC)	MSF	9,000	1.98
Total		424,960	93.49

* mig/d: million imperial gallons per day. 220 gallons = 1 m³

In the early days of the introduction of seawater desalination, the distilled water was blended with measured amounts of groundwater. Due to the deteriorating groundwater quality, this practice has been discontinued. Production from desalination plants has been increased to fill-in for the groundwater absence. Figure (5) displays the production since 1981. According to the *1997 Annual Report Highlights* of the Water Networks Department, ME&W, production from the major desalination facilities RAA, RAF "A" and RAF "B" for the year 1997 amounted to 109,138,466 m^3.

The most challenging task to the water authority in Qatar is to meet the steadily increasing water demand for both domestic and industrial sectors. This challenge is dictated by the need for the development of sources of water with the desired quality and conveying the water to the consumers. The core of this challenge lies in providing the finance, biggest obstacle, needed to execute projects. *The MASTER PLAN FOR THE DEVELOPMENT OF WATER SUPPLY IN QATAR* (Acer,1997), calculated

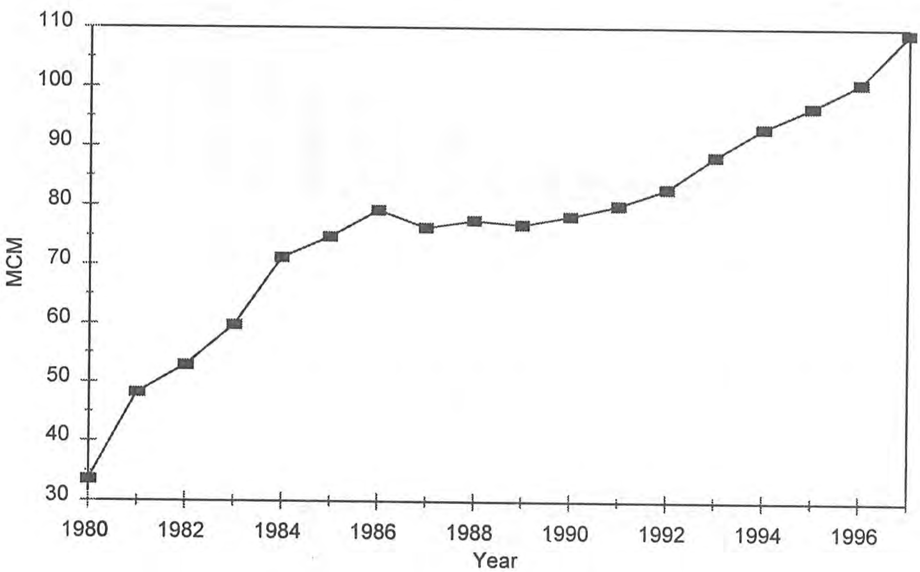

Figure 5 : Yearly Desalination Production

that by the year 1997 the domestic and industrial water demand will be 523,044 m^3/d. This study assumed that by 1997 the new desalination RAF "B" will be operational with its full capacity of 60,000 m^3/d. The anticipated shortage for 1997 will be 114,357 m^3/d. Also, the master plan calculated that the water demand for 1998 will grow to be 543,342 m^3/d. In the same year, a new plant Ras Abu Fonts "C" (RAF" C") is expected to be introduced into service and to produce about 30,000 m³/d. With that in place, the shortage in 1998 is anticipated to be 90,095 m³/d. The production of RAF "C" is expected to reach 60.000 m³/d in 1999, 90,000 m³/d in 2000, and 121,000 m³/d in 2001 onward. However, construction on RAF "C" has not yet started. Its new proposed completion date is March 2000. Figure (6) plots the anticipated water shortage.

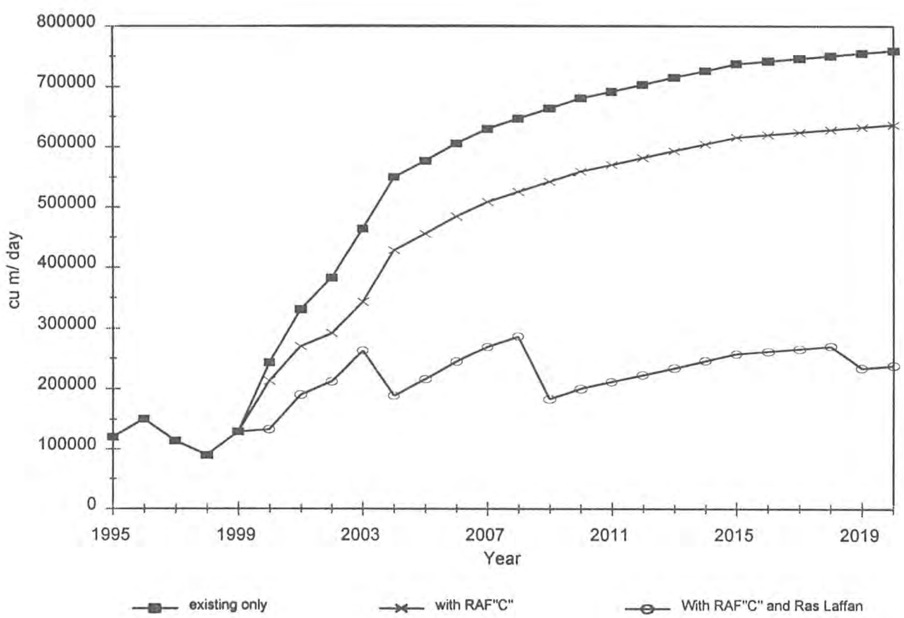

Figure 6 : Water Shortage

The upper most curve represents the water shortage with the existing desalination capacity. The middle curve represents the effect of introducing RAF "C" into the service. The curve assumes that RAF "C" will be functional in 2000. The lower curve shows the effect of introducing the new plant, Ras Laffan, which is planned to be in operation by year 2000 in northern Qatar. This plant is delayed indefinitely. Table (4) tabulates the existing desalination capacity, demand, proposed plants capacities, and deficit up to year 2020.

*Table (4) Estimated desalination Water Balance to 2020**
(after Acer, 1997)

	Existing	Daily	Planned plants capacity		Deficit		
Year	Capacity	Demand	RAF C	Ras Laffan	w/Existing	w/ RAF "C"	w/ Ras Laffan
1995	349134	469528	0	0	120394	120394	120394
1996	348224	498622	0	0	150398	150398	150398
1997	408687	523044	0	0	114357	114357	114357
1998	453247	543342	0	0	90095	90095	90095
1999	433699	563489	0	0	129790	129790	129790
2000	365054	608759	30322	80010	243705	213383	133373
2001	319139	650393	60644	80010	331254	270610	190600
2002	295500	678729	90966	80010	383229	292263	212253
2003	265497	730068	121287	80010	464571	343284	263274
2004	203671	753684	121287	240029	550013	428726	188697
2005	203671	781150	121287	240029	577479	456192	216163
2006	203671	810175	121287	240029	606504	485217	245188
2007	203671	834536	121287	240029	630865	509578	269549
2008	203671	851372	121287	240029	647701	526414	286385
2009	203671	868208	121287	360043	664537	543250	183207
2010	203671	885044	121287	360043	681373	560086	200043
2011	203671	896449	121287	360043	692778	571491	211448
2012	203671	907854	121287	360043	704183	582896	222853
2013	203671	919258	121287	360043	715587	594300	234257
2014	203671	930663	121287	360043	726992	605705	245662
2015	203671	942068	121287	360043	738397	617110	257067
2016	203671	946316	121287	360043	742645	621358	261315
2017	203671	950565	121287	360043	746894	625607	265564
2018	203671	954814	121287	360043	751143	629856	269813
2019	203671	959062	121287	400048	755391	634104	234056
2020	203671	963311	121287	400048	759640	638353	238305

* Figures in cubic meters per day

In Qatar, water is conveyed to consumers by water mains or water tankers. The bulk of consumers of potable water are in Doha. The water distribution mains in Qatar has been increasing over time. The total length of water mains (between 80 and 1400 mm DIA) reached 2,639.3 km in 1996 (State of Qatar, 1996). Table (5) outlines the development of the water mains laid and commissioned up to 1996. Despite this growth in the development of water mains, there is still a considerable number of consumers that are not connected to the water networks. Additionally, many of the water pipes in older areas of Doha are affected by the corrosive nature of the soil. This results in a significant water losses in the water mains (Acer, 1997).

Table (5): Total Length of Main Laid and Commissioned Up to 1996

Year	Yearly Addition (km)	Accumulated Length (km)
	prior	1649.00 1649
1982	130.598	1779.598
1983	200.652	1980.25
1984	57.866	2038.116
1985	61.871	2099.987
1986	30.060	2130.047
1987	36.602	2166.649
1988	38.092	2204.741
1989	46.424	2251.165
1990	31.699	2282.864
1991	35.379	2318.243
1992	98.284	2416.527
1993	65.027	2481.554
1994	59.012	2540.566
1995	56.958	2597.524
1996	41.789	2639.313

Conveying water by tankers is a common practice in Qatar. The number of water tankers used to deliver potable water in 1993 was 1135 tankers. The same number for 1996 reached 1348 tankers, a 19% increase over three years (State of Qatar, 1996). Delivering water via tankers is an expansive operation. The Ministry of Electricity and Water uses a pricing scale for hired water tankers that is based on tanker capacity and delivery distance range. As an example, the smallest hired water tanker is of a 1300 gallons capacity. Such a tanker will be paid QR1.4 per 100 gallons (QR, Qatari Riyals) for a 9 maximum filling rounds per day and within a 10 km range. Cost of such tanker comes to QR3560 per month. Other tankers in service are government owned and private. The main factors contribute to the cost of using tankers are capital and operating cost of the filling station, capital and operating cost of tankers in the case of government tankers, capital and operating cost of water main connecting the filling station, and, cost of hired tankers.

If a figure of QR5000 per tanker per month (conservatively under estimated) is assumed, the annual cost to deliver water via tankers will be about QR80 millions. Today there are twelve tanker filling stations that supply potable water in Qatar. Four of these stations are in the vicinity of Doha. 808 tankers of the 1348 used in 1996 (about 60%) were delivering water in Doha and Al-Wakrah (a suburb of Doha). If Al-Khor (a northern town) is included this percentage will increase to about 70% of the total number of tankers. That is two-third of the tankers operating in the cities. Conveying water via takers is not as safe and secure as pipes. However, the steady increase in the number of consumers, the slow expansion of water mains, and water shortage impose the utilization of water tanker. Table (6) demonstrates the increase in number of consumers over the period 1971-1996.

The current capacity of storage reservoirs is estimated to be approximately for 3.4 days supply at the peak rate of demand in 1994. This storage is also used to balance fluctuations in hourly or daily demand (Acer, 1997). No contingency storage exists to cover for breakdown in the source, repair or burst on major water mains and loss of water from bursts. Water from the desalination plants is pumped to storage reservoirs. Any failure of forwarding pumps or mains will have a major effect on the ability to supply water to the service reservoirs. An additional storage and stand-by pump must be allowed for such situations.

Table (6) Consumer Annual Growth

Year	Number of Consumers	Year	Number of Consumer
1971	9500	1984	45000
1972	11000	1985	49800
1973	11500	1986	52831
1974	12500	1987	55300
1975	13000	1988	58300
1976	16000	1989	61500
1977	18000	1990	64500
1978	22000	1991	66700
1979	25300	1992	69500
1980	28000	1993	72300
1981	32000	1994	75000
1982	36000	1995	78775
1983	42000	1996	82177

TREATED WASTEWATER

In an arid land such as Qatar, it is of extreme importance to use any available water resource that has the potential to augment the water resources of the country. The first sewage treatment plant in Qatar "Doha South" was completed in 1974 (FAO,1981). By 1978, this plant was already overloaded (Atkinson and Eccleston, 1985; Pike, 1983). In 1980, a daily discharge of 30,000 m^3 of secondary effluent was reached. Presently, Doha South produces about 50,000 m^3/d. The other major wastewater treatment facility in Qatar is Doha West. This plant produces about 40,000 m^3/d. The output of both facilities combined is about 32 mcm per year . Halcrow-Balfour (1981) estimated that by year 2000 the availability of treated wastewater will be about 36.5 mcm.

Most of the wastewater collected in Qatar is from domestic use, which originates from the consumption of desalinated seawater. Bearing in mind that desalination is an expensive operation, it is important, where feasible, to run this water more than once in the water resource system. Pike (1983) and Holmes (1989) estimated that the cost of treating wastewater in Qatar is about QR0.90/m^3. The cost of seawater desalination is about QR5.0/m^3.

In 1997, the production of treated wastewater amounted to approximately 32 mcm. While the desalination water put in the system was 109,138,494 m^3. Only about a third of the potable water put in the system ends-up as treated effluent. The main reasons behind this low rate of wastewater production are consumption of desalination water in garden irrigation, car washing, leakage in water mains, industrial consumption of desalination water that does not end-up in the wastewater system, and urban development that are not connected to sewer mains.

PRECIPITATION

Rainfall over Qatar is the primary source of freshwater and a knowledge of its amount, variability and distribution is of fundamental importance in any assessment of the country's water resources (Atkinson and Eccleston, 1986). Precipitation is limited to the winter months of November to March, but in some years outbreak of thunderstorm have occurred as early as September and October and as late as end of April (FAO,1981).

Rainfall is scanty, irregular and very variable, with wide variation from place to another and year to year. Rainfall records indicated that in 1973 the total rainfall was 30 mm, while in 1982 it reached 190 mm. In a one year, recorded rainfall over 24 hours period have approached the total annual average. Despite the considerable variation in precipitation, total rainfall in northern Qatar tends to be marginally higher than in the south (Halcrow-Balfour, 1981). FAO (1981) estimated that the northern half of Qatar receives about 60% more rainfall than the southern half. A ten-year

(1971/72- 1979/80) precipitation records from 29 different locations indicated a mean annual rainfall over Qatar of 75mm.

Al-Rafai (1989) calculated the annual total average volume of rainfall over Qatar to be about 860 mcm. In the rain season of 1987/88 this number reached 1170 mcm. The calculation was based on an annual average rainfall intensity of 74mm. This study further states, that making use of only 15% of the annual average rainfall can add about 129 MCM of recharge to the groundwater. This quantity can be stored in Dammam, Rus or UER.

MAJOR PROBLEMS IN WATER USE

WASTEFUL AGRICULTURAL USE

The agricultural use of the groundwater, renewable and nonrenewable, resources accounts for more than 90% as stated earlier. The number of groundwater wells grew from 660 in 1975 to 2635 in 1994 (State of Qatar, 1994/95). While the total extraction grew from 56.5 mcm to 184.2 mcm for the same years. An increase of about four folds in the number of wells and over three folds in the consumed groundwater. Irrigation water is delivered directly from wells or open storage pools to the plants through open and unlined earth canals. This method has a very low efficiency. A large portion of the water is lost due to high evaporation rate and seepage. An additional irrigation is also needed in recent years for leaching due to the higher salt content in the groundwater.

Groundwater in Qatar is provided to farmers free of charge. Farmers pay for their pumping cost. This fact along with the absence of enforced regulations and metering scheme encourage the uncontrolled consumption. In many farms groundwater became very salty due to saltwater upconning under wells and the encroachment of seawater into the land, resulting in salty soils. In sever cases, farms were totally abandoned.

Rectifying this situation requires a very serious consideration to the farmers education, regulating groundwater use, and conservation measures. Abandoned farms are genuine examples of how the farmer themselves loose due to their uneducated practices and a good starting point to educate farmers. If the present practice continue, not only farms near the coast will face salty water problems, but also farms farther inland will face similar problems.

DESALINATION WATER CONSUMPTION

A number of factors contribute to the inefficient desalted water consumption. These factors include water leakage, unaccounted for losses and unmetered consumption, uneducated consumption, and underpricing.

Water Losses in The Conveyance System: Acer (1997) referring to Doha water mains, stated that "it is believed there are significant water losses in the system". Also, it mentioned the existence of ongoing rehabilitation program for the pipelines in Doha. Rising water table is a very well known problem in Doha. Contribution to this problem comes from gardens irrigation, rainfall, water mains leaks, and others. Most water leakage take place due to improper design, corrosive soil, poor installation, and maintenance. Additional loss of water is believed to results from conveying water via tankers. Water losses by this method are due to tanker filling process, evaporation, leaky tankers or attachment, and delivering process.

Metering: The government made an extensive effort to install meters to consumers connected to the water network. However, many consumers are still not metered. Consumers that are served with tanker, if applicable, are charged flat rate regardless of consumption. It is very difficult to establish unaccounted for losses without metering. Even the consumers who do not pay for water consumption must have meters to give them a sense of their consumption rates.

Underpricing: Residential consumers that are required to pay for the consumption of water, are charged very small fraction of the actual cost of supplying water. The industries and the commercial establishments consumed a considerable large amount of water. They are also paying a small fraction of the cost of water.

Education: The public are generally aware of the water cost. But more awareness is needed to have a genuine appreciation to the overall process, the cost involved and environmental impact of developing further desalination capacity. Water conservation means must be promoted. However, without a known limit of consumption, many consumers do not bother to even think of conserving. A lot of desalted water is consumed in garden irrigation and car washing. A fair and reasonable quota must be established for nonpaying and paying consumers. Beyond the quota the price must reflect higher rates for higher consumption. A clear distinction must be established between water needed for sustenance, necessity and water for luxury. One important and very effective way to educate the public about the value of water and water conservation is by approaching them with the teaching of Islam.

RECLAIMED WASTEWATER

Wastewater has a potential to augment some of the water consumption. Use of wastewater is common in many part of the world and its technical issues are fairly well documented. The major obstacle to reclaimed water use is the negative public perception. The government is installing more sewer lines and connecting larger and larger number of residence and commercial developments. This promises higher rate of wastewater collection. It is very important to educate the public of the positive benefits of utilizing reclaimed water to the water resources and the environment.

RECOMMENDATION AND THE NEW VISION

In order to meet the water demand, there is a need to create an efficient water resource planning and management system that is capable of dealing with the present and future water supply challenge. A country comprehensive water plan must be in place to be the guide and a target for all water-related policies and programs. More important is to have a central water authority to take the mission of managing and formalizing a country water plan, coordinate all water undertakings, establish water regulations, and enforce the implementation of all policies. Ferderiksen (1996) suggested number of solutions to the problem of global water shortage. However, he emphasized that the obstacle to implementing these concepts in developing countries, even in time of severe drought, is the absence of the required institutional and physical infrastructure.

Presently, there are number of agencies that deal independently with water aspects in Qatar. Groundwater potable well-fields are operated by one department, while irrigation consumption is supervised by another department in a different ministry. The production of water desalination is handled by one department. The water networks and storage is managed by another department. Construction of water facilities is also shared by different entities. This fragmentation results in difficult environment to coordinate all water activities. Worse yet, the absence of a comprehensive water plan makes the matter harder. Coordination basically means to harmonize the water management activities in the water industry (Grigg, 1993). In Qatar, the need for an extensive coordination is dictated by the severe water shortage and the need to bring together all elements of water resource.

It is very essential for the success of the central water authority to have the institutional support that is of strength matching its mission. The proposed water authority would involve very complex activities. To suggest few not in any particular order:

- The establishment of a comprehensive country water plan,
- Take the executive role in the water management,
- Establish all water policies and regulations,
- Enforce the implementation of the policies and regulations,
- Take the mission of coordinating all water activities,
- Draw coordination plans channels to all water concern agencies,
- Set a reporting procedure for needed water activities,
- Determine needed water studies and research,
- Public education
- Build-up local professional capabilities, and
- Establish a water data bank.

Establishing a country water plan requires the integration of all the water fragmentation and other involved authorities that deal with matters such as the environment, and finance. Without one single body that collectively manage and control all requirement, objectives will be extremely difficult to attain. The relatively small area of Qatar and the simple nature of the water problem promote the principle of central water authority.

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GIS Application in Water Resources Management and Planning

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GIS APPLICATION IN WATER RESOURCES MANAGEMENT AND PLANNING

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ABSTRACT

Water is the most valuable resource on our planet. Therefore, we need to bring water management and conservation knowledge into mainstream governmental decision making. The geography of water is an important component in any governmental decision making process, and thus, requires the right tools for overall management and decision support. GIS provides one of the powerful tools to collate, manage, analyze, and present water resources information to decision-makers. Using GIS for managing our water resources should reach into every sector of water policy, from groundwater and surface water management and planning to water distribution and use/ reuse. This presentation will highlight how GIS is used in various water resources applications around the world to conserve this valuable resource.

Sea Water Desalination in Saudi Arabia: Economic Review and Demand Projections

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SEA WATER DESALINATION IN SAUDI ARABIA: ECONOMIC REVIEW AND DEMAND PROJECTIONS

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ABSTRACT

The cost of desalinating seawater varies widely from country to country, depending on opportunity costs of factors of production, mainly energy and capital. The opportunity cost of energy (gas) in a gas-surplus country is simply that for gathering and delivery to the desalination facilities. The cost of capital is similarly variable; it is lowest in a capital surplus country and highest in a capital-short country. Optimal choices of desalination technologies are another factor that determines the economics of desalination. This paper will provide an overview of the economics of desalination with more emphasis on Saudi experience.

Key words: Saudi Arabia, Desalination, Opportunity Cost, Process.

INTRODUCTION

Water scarcity is a major political and economical problem in the Middle East. The shortage in natural fresh water supply for domestic purposes is more acute for the Arabian peninsula countries; Saudi Arabia, Kuwait, Bahrain, Qatar, the United Arab Emirates, Oman, and Yemen, where demand for water increases annually at a rate of 3 or more percent.

These countries depend mostly on ground and sea water desalination to meet their demand for water. The limitation of fresh ground water supply has led these countries to become increasingly dependent on desalination, with Saudi Arabia becoming the world's major producer of desalinated water.

Because of the overriding concern for the health of her people, Saudi Arabia has concentrated on desalination to produce good quality drinking water rather than water reuse as a non-conventional source of water. The produced waste water effluents from the treatment of municipal sewage is reused for landscape irrigation. Desalinated water is used mainly for domestic consumption and the production of high value agricultural crops. As a result, I concentrate on the economics of desalination in this paper.

The economics of desalination varies from country to country, depending upon the opportunity cost of energy and capital as the main factors of production, and the type of desalination process. As far as desalination technologies used in the Middle East are concerned, only two technologies are proven and available for large-scale plants; Reverse-Osmosis (RO) and Multi-Stage Flash Distillation (MSF).

This paper is organized as follows. In the next section, the economics of desalination is generally discussed. Next, Saudi experience in desalination is analyzed. The paper then offers some concluding remarks and policy implications.

ECONOMICS OF DESALINATION

The main industrial processes used in water desalination are distillation and membrane[1], and both processes are different technologically. For example, while Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED) are used in the distillation process, Reverse Osmosis (RO) is widely

[1]Other methods of desalination include ion exchange, freeze desalination, solar driven process, membrane and hybrid system.

used in the membrane process. Although the political, environmental and hygiene implications of desalinating sea water are not trivial, this paper concentrates on those economic factors that are the most important determinants for selecting any particular desalination technology or process. The economic costs of desalination include the costs of production, distribution and storage. Since the method of production does not influence the distribution and storage of water, the cost of production is the most critical when evaluating the comparative advantage of different desalination methods. The production cost includes the cost of labor, energy, capital, and materials. In general, the economics of desalination depends on the cost of energy and capital requirements. MSF and RO have been found to be more economical and cost effective (compared to MED) for large-scale dual purpose plants, because of the operation and maintenance problems of scaling and fouling especially at high temperature operation. Currently, the bulk of the installed desalination capacity in the Middle East in general, and the Gulf Cooperation Council (GCC) countries in particular, is in MSF plants where water and electricity are co-produced. However, MSF plants are capital intensive and future trends favor energy efficient and less capital intensive technologies, such as MED. Most of the plants in Saudi Arabia are dual-purpose ones producing both desalted water and electricity. In this situation, there is a need to decide the product whose cost should be minimized. In Saudi case, it is the cost of desalinated water that is to be minimized.

The cost of desalination in the Middle East depends upon the opportunity costs of gas (energy) and capital. The opportunity cost of capital can only be approximately determined, but it varies from country to country. It is lowest in Abu Dhabi and Kuwait where it is almost zero, and highest in Egypt and Iran where it is \$15 per barrel of oil equivalent (boe). The cost of desalinating water, therefore, ranges between \$ 0.6/M^3 under the most favorable conditions to as high as \$ 2.5/M^3 where capital and energy are costly and where the ratio of water to electricity production is high[2] [2,3,7].

Over the past two decades, there has been a decline in the cost of desalination, due to the increased market competition and improved technical efficiency. However, we do not expect a significant reduction in costs in the near or medium term, because efficiencies are limited by metallurgical constraints and corrosion rates of current materials and the insufficiency of available funds to deal with such problems.

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[2] These unit costs are for MSF and RO processes. Furthermore, the size of the desalination plant causes such variation in the cost, where large plants implies less cost.

DESALINATION IN SAUDI ARABIA

Saudi Arabia is the world's leading producer of desalinated sea water. From the major 25 government-owned desalination plants, its share in the world capacity approached 25.9% in 1996[3]. These plants are operated and administered by Saline Water Conversion Corporation (SWCC) which was established in 1974 by a Royal Decree to be responsible for the production and distribution of desalinated water in Saudi Arabia. About 90% of Saudi desalination plants are MSF, while the rest are RO. The current Saudi production capacity is 2.3 mcm/day of water and 4100 MW of electricity which constitutes 25% of total electricity generated in Saudi Arabia[6].

Over the next ten years, it is planned that SWCC will increase its production capacity of water and electricity by 40% and more than 20% respectively[2]. It is noted that the actual production of desalinated water for many years was exceeding 90% of the production capacity. Table 1 shows that both the existing and projected future production and the production capacity of the desalination system in Saudi Arabia are related to domestic demand for water which currently has 10% share of the total demand for water and is expected to increase to 15% in the year 2010.

TABLE 1: Production capacity and actual production of water from the Saudi desalination plants and the domestic demand for water for the years, 1991, 1996, 2000, 2010 (MCM)

	1991	1996	2000	2010
Production capacity	730	830	975	1300
Production	670	705	910	1100
Domestic demand	1500	1700	1950	2600

Source:Annual Report, SWCC, 1996, for production capacity and production for the years 1991, 1996

As far as projections are concerned, it is assumed, in Table 1, that the desalination plants in Saudi Arabia are operating at 95% of its production capacity. The domestic demand for water, which is basically the residential demand, is assumed to grow in parallel with the economic growth rate of the country, at 3% annually[3]. In the early 1990s, it was estimated that

[3] The price of desalinated water is almost fixed in Saudi Arabia. Other factors that are affecting the demand such as population are embodied in the economic growth.

desalination satisfied 50% of the domestic demand for water. Due to population and economic growth and high level of urbanization, this percentage is expected to rise to 60% by the year 2000 and to more than 70% by 2010. This implies that more desalination plants are needed to be constructed to meet the expected increase in domestic demand for water.

Saudi planners apparently have decided to expand on desalination capacity, and to rationalize the use of available limited fresh water resources which are mainly groundwater. In 1997, it was estimated that the Saudi reserves of groundwater were about 2269bcm from shallow and deep aquifers at 300m below ground surface [4]. This amount of water is mainly for irrigation in order to meet agricultural demand, which represents an average of 90% of the total Saudi demand for water. However, expanding desalination by building new plants or upgrading the existing facilities will require vast economic costs, especially when those costs include the maintenance costs of the aging plants, that have been in use for 20 or more years, which is the average life expectancy of a desalination plant.

ECONOMIC COSTS

Saudi Arabia is an important market for desalination plants because of its large-scale desalination activity. Saudi Arabia adopts MSF, and to a less degree RO, to jointly produce water and electricity. However, the fluctuating demands for water and electricity over the seasonal cycles, as well as over the plant's life, makes it more difficult to choose the optimal mix of co-generation equipment. Given the relatively low economic value of energy and market price for water and electricity, capital cost is the most important determinant of desalination cost in Saudi Arabia. Table 2 lists past and recent average unit cost of producing desalinated water in Saudi Arabia for both MSF and RO plants as compared to world cost estimates.

TABLE 2: Unit cost of desalination in Saudi Arabia ($\$/M^3$)

Years / Plant type	1970-1985[a]	1991[b]	1995[c]	World estimates[d] 1996
MSF	1.6	1.2	0.6	0.75 - 2.5
RO	0.7	1.3	0.8	

<u>Source</u>

a) *Averaged from Ukayli and Husain (1988)*
b) *Averaged from Dabbagh et al. (1993)*
c) *Al-Mudaiheem et al. (1995)*
d) *Averaged from Bushnak (1996) where it ranges from large plants to small ones. MSF and RO large plants produce 100,000 m^3/d, and 10,000 m^3/d respectively and small plants of MSF and RO produce 10,000 m^3/d, and 1000 m^3/d respectively.*

The estimation of unit costs presented in table 2, is based on certain assumptions regarding key economic and technical parameters, such as; interest rate, plant size and configurations, life-span of the plant, and the method of financing and cost accounting. From table 2 it would noted that unit costs of desalination did not change over the past ten years for the same type of technology or plant. In Saudi Arabia, uneconomical pricing and poor water management would lead to misallocation of resources and unrealistic cost of producing water.

The present system of producing desalinated water together with electricity needs to be rationalized. One method of rationalizing the economics of desalination in a dual-purpose strategy of producing desalinated water and electricity is to seek to optimize their production. The present system is to design a dual-purpose plant to achieve minimum cost of producing desalinated water, without ignoring the gains of producing electricity. In determining the optimal capital to be invested, there is a need to define the acceptable

a) ratio of feed seawater to desalinated water
b) range of temperature at which separation of desalinated water from sea water takes place
c) dimension of the separation elements (for example, the diameter and length of the heat transfer tubes with evaporation process, the size of membranes in RO process),
d) number of effects, stages or passes in the desalination process
e) velocities of the fluid in the each element; and
f) heat to be transferred per unit area KW/m^2 in the heat exchange equipment.

CONCLUDING REMARKS

This paper has dealt on the economics of desalination to the exclusion of environmental and health issues. These issues are also important and no effort should be spared in balancing the goals of cost optimization with the desire to have a clean environment and a healthy population.

Water is needed essentially for domestic, industrial and agricultural consumption. It is true that the ground water available in Saudi Arabia is presently used mainly for irrigation. To satisfy the remaining needs for water, Saudi Arabia has relied heavily on its natural endowment of seawater. Although desalination is costly, electricity is also generated from this effort. As the technology of desalination improves, the comparative advantage of each method of desalination changes. As income from crude oil decreases, the ability to produce desalinated water without regard for economics diminishes. As a result, there is a need to conduct at regular intervals, a cost-benefit analysis of the different methods of producing desalinated water in order to know when to change from one desalination process to another, or from one source of water to another.

One main question that is yet unanswered is whether desalination is better than ground water for domestic use. At the present rate of growth, desalted water can only meet about 50% of Saudi domestic needs. But at what costs?

The Role of Water Legislation in the Management of Water Resources in the ESCWA Region

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THE ROLE OF WATER LEGISLATION IN THE MANAGEMENT OF WATER RESOURCES IN THE ESCWA REGION

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ABSTRACT

The development of water legislation has not received adequate attention in the ESCWA region. Most of the practical water legislation in the region has been based on Sharia principles, customary laws and borrowed colonial laws and regulations. During the last two decades some laws have been enacted either for surface water allocation in the agricultural sector, or groundwater development. Countries with major rivers have enacted laws for utilization of surface water and protection from pollution, while those depending on groundwater have issued laws and decrees regulating drilling activities. Accelerated development of water resources in the region has resulted in the issuing of many fragmented water decrees. Lack of enforcement of existing laws has resulted in over-development and increased groundwater mining and pollution. Broad based water legislation is needed in addressing policy formulation and implementation, guidelines for rational utilization of water resources including desalination, water use priorities, water ownership, jurisdiction of authorities responsible for controlling utilization, protection, pricing, and beneficial uses, as well as the issuance of use permits, and provisions for conflict resolution. In addition, appropriate water legislation enforcement mechanisms must be put into effect, supported by adequate manpower and financial resources, as well as public participation and education programs.

KEYWORDS: Water Legislation, Sharia Laws, Customary Laws, Colonial Laws, Enforcement

INTRODUCTION

The most fundamental element in the administration of the water sector is the availability of comprehensive legislation that can regulate and enforce optimal development, distribution, and utilization of water sources, as well as protection from pollution. Enforcement of water legislation is also a major element for achieving efficient development and management of water resources.

In the ESCWA region, many laws, decrees, and regulations have been issued to regulate water development and utilization in the water sector. Most legislative efforts have been directed towards individual laws or decrees regulating certain aspects of water resources. Lack of comprehensive water legislation in the ESCWA countries (Bahrain, Egypt, Syria, Saudi Arabia, Iraq, Jordan, Lebanon, Oman, Yemen, the United Arab Emirates, Qatar, Kuwait and the West Bank and Gaza) has contributed significantly to inefficiency of development and management of water resources in the region. In view of regional economic and social development activities within the last 20 years that have emphasized development rather than management aspects of water, existing laws and regulations which were effective a half century ago have become obsolete as competition for water utilization increases and water supplies diminish. Authorities responsible for the water sector continue to operate along traditional lines, with marginal changes brought about on an ad hoc basis.

Historically, the legal framework for water development and utilization in the Middle East, including all of the ESCWA countries, has always been receptive to water scarcity problems. This phenomenon is reflected in a number of principles that characterize the Sharia law, customary practices, and remnants of the Ottoman (Turkish) Majalla, French, and British water codes (ACSAD 1981, Caponera 1973 and 1992). The common laws prevailing in the region before the twentieth century were Ottoman Majalla code, Sharia principles and customary practices (Mallat 1993).

Water legislation of most of the ESCWA countries is still governed by Sharia principles (Saudi Arabia, U.A.E., Oman, Qatar, Bahrain, Kuwait and Yemen) and traditional practices, or a combination of Sharia law, the Majalla code (Lebanon and Syria) and some elements of modern water codes and customary laws in Oman, Jordan, Syria and Egypt (Caponera 1973, 1978 and 1992; As-Safady 1995, Al-Masri 1996, Shatanawi et al. 1997, Mallat 1995). Sharia principles governing water legislation in the region basically hold that water is a gift from God and belongs to the community as a whole, with priority being given to human requirements. However, the sale and allocation of water, particularly from surface sources, is possible under certain conditions. The historical evolution of water legislation in the ESCWA region is shown in Table (1).

STATUS OF WATER LEGISLATION

Review of the evolution of water legislation and institutional arrangements in the ESCWA region reveals that countries that depend largely on surface water have enacted individual laws designed to regulate river flow diversion and to establish water quality standards for drinking and reuse purposes, pollution control, and to some extent, water allocation guidelines. On the other hand, countries that rely mostly on groundwater have mainly issued directives or separate laws aimed at regulating groundwater development and extraction through well drilling permits for the prevention of groundwater mining and limited pollution control (ESCWA/NR 1997). This legislative effort consisted of fragmented laws and/or decrees that cannot be considered to be part of a comprehensive water code.

Surface Water

Surface water from river flow is usually state property and is subject to appropriation to different sectors. Flood water is still diverted and allocated according to Sharia law and traditional local customs in Saudi Arabia, Yemen and Oman. Regulations and allocation procedures for water irrigation from rivers, reservoir releases, and flood water in Egypt, Iraq, Syria, Lebanon and Jordan, range from simple to complex. River flow and reservoir releases are usually administered by specialized government authorities created for that purpose. Allocation regulations, carried out according to operational rules based on old practices or modern optimization criteria, are practiced in Egypt, Iraq, Syria, and to a lesser extent in Lebanon, and Jordan.

As a general rule, water infrastructure for the domestic sector is the responsibility of the state in most of the ESCWA countries. The government finances the construction, as well as operation and maintenance of water distribution systems, including all water supply activities.

Groundwater

In the countries of the Arabian Peninsula, as well as Jordan and Syria, groundwater development has largely been regulated by permits or licenses. However, these methods fall short of the needed comprehensive modern water code. There is wide variation among the member states with regard to the requirements for obtaining a permit, and regulations calling for compliance with stipulated conditions. In general, proof of land ownership is usually a prerequisite in all cases, and owners may approach the government to obtain a permit or authorization to drill a well for any purpose, subject to the terms and conditions set forth in the permit. There is usually a defined set of guidelines with respect to the manner of abstraction, well specifications, and groundwater conditions. In addition to permit specifications, water resource conditions with regard to quantity in a specific area may call for additional restrictions. These procedures are followed in Jordan, Syria, Kuwait, Qatar, Saudi Arabia, U.A.E., Oman and Yemen. Laws have been enacted in Syria, Jordan and Oman to minimize depletion of groundwater resources through protection of the area around discharging springs as well as abstraction from wells, by establishing restricted areas (Harems). Some countries have complemented drilling permit regulation by requiring the licensing or registration of professional well drilling contractors. This mechanism is being implemented in Syria, Jordan, U.A.E., Saudi Arabia, and Oman.

Recent Legislation

Most water legislation in the ESCWA region was enacted between 1967 to 1985. Some of the ESCWA countries have begun to realize the importance of comprehensive water legislation, and have consequently taken steps to update existing laws or are planning to introduce new ones to cope with development activities. During the last ten years the ESCWA member states of Egypt, Oman, Qatar, Jordan, the United Arab Emirates, and Yemen have made some effort towards revising, modernizing, or introducing new water laws, and strengthening institutional arrangements. Most of the countries of the region have enacted laws which explicitly specify that water resources are public property (Jordan, Oman and Yemen), while others imply that water is either state or publicly owned (Lebanon, Syria, U.A.E., Saudi Arabia, Kuwait, Bahrain and Qatar).

Major legislative efforts in Egypt were made in 1982 and 1984 when Laws No. 48 and 12 were enacted addressing irrigation and drainage distribution and the protection of the Nile from pollution. These laws were later amended with law 212 issued in 1994. Egypt also enacted environmental law No. 40 in 1990 that covered protection of water resources (Saad 1995, Abdulah 1996). Royal decree No. 31 was issued in Oman in 1993 to merge the Ministry of Environment with the Ministry of Municipalities, creating a single Ministry of water Resources with the authority to regulate and protect water resources, especially groundwater. In addition, decrees No. 2 and 13 issued in 1990 and 1992, respectively, address well registration and regulation of drilling permits. In Qatar, decree No. 13 was issued in 1994 amending law No. 4, which transferred the Environmental Protection

Committee to the Ministry of Municipal Affairs and Agriculture, in order to better protect water resources (Qatar Country Paper 1995). Decree No. 34 of 1980 in Saudi Arabia addressed the aspect of groundwater development. Law No. 7 issued in 1993 in the United Arab Emirates provided the foundation for the Federal Environment Agency with mandates for the protection of water resources and the establishment of standards. In Yemen, a law was enacted in April of 1995, calling for the establishment of a national water resources authority with the power to establish water policy, strategies, plans, and provide the enforcement needed for further development and management (Yemen Country Paper 1995). Many laws with limited coverage of their mandates addressing specific concerns were issued in most countries of the ESCWA region. For details of these laws, please refer to publication ESCWA.NR 1997.

Water legislation was enacted in Jordan in 1977 addressing groundwater development and protection. Other laws No. 18 and 19 were issued in 1988 to further define groundwater development and outline the means of water regulation and ownership. In Syria, during the period 1960-1973 more than 60 decrees, laws and regulations were enacted dealing with aspects of drilling, designation of prohibited zones and pollution control. Between 1971 and 1985 and additional 35 legal rules and laws were issued. Increased utilization of groundwater resources in Bahrain forced the government to enact decree No. 12 in 1980. The decree was aimed at regulating groundwater abstraction and reduce water quality deterioration. An additional ministerial decree was issued in 1982 to supplement the coverage of the previous decree and requiring farmers to install water meters. The 1980 decree was amended in 1997 to accommodate future shifts in water allocation. The features of existing legislation in selected ESCWA countries are shown in Table (2).

MODERN WATER LAW REQUIREMENTS

In the ESCWA region most member states, with the exception of Egypt, Syria and Iraq, depend mainly on groundwater resources. In addition, they share similar climates, beliefs, languages, and economic and social development objectives. Thus, it is logical that countries of the region should pursue similar water legislation and institutional frameworks. These countries should develop and implement technical and legal frameworks that encourage coordination and cooperation in the development and management of shared water resources.

It is evident from the previous discussion of existing water legislation that some of the ESCWA countries have updated existing, or are in the process of updating and formulating new water legislation, and attempted to centralise their water institutions. However, content, coverage, and jurisdiction of their water legislation may fall short of meeting the requirements necessary for implementation of an integrated approach to achieve optimal development and management of water resources. Further effort is still needed to overcome fragmented institutional arrangements, as only a few countries have actually achieved centralisation. The formulation and adoption of a comprehensive water code and mechanisms for its enforcement will achieve efficient utilisation and protection of water resources in the ESCWA region, especially the GCC countries that experience extreme natural·scarcity of water resources.

General Requirements

According to Caponera (1992-1996) when considering the drafting or the amending of water legislation, some basic requirements need to be taken into consideration in order to draft a water code that can achieve the intended objectives. The basic principles for formulating an effective water code are: simplicity, clarity with regard to legal aspects, specificity, social acceptability, and the requirement of minimal organisation for enforcement. Political, social, economic, religious and administrative implications should be given due consideration. A new law must be compatible with existing administrative, financial and judicial systems, and be able to maintain its role in achieving the objectives. In drafting water legislation, the following should be considered:

1. Availability of water at a national, basin, and sub-basin level.
2. Present and future water utilization for different purposes and different sub-sectors.
3. Order of priorities among regions, basins, sectors, areas, and users.
4. Environmental consequences of water development.
5. National development plans.
6. Existing and planned water policies, plans and strategies.
7. Function and jurisdiction of water and water-related institutions, including the private sector.
8. Ownership of water resources, water acquisition and limitations.
9. Provisions for preventing, controlling and/or mitigating the harmful effects of water such as floods or salinization.
10. Provisions for water quality control and prevention of pollution.
11. Measures to protect waterworks and structures.
12. Setting up of water rates and fees in the context of social and financial conditions.

13. Provisions for declaring special water resources development or conservation zones, as well as a mechanism for implementation and enforcement of water legislation.

In addition to the general requirements mentioned above, modern water law should address in detail the legal aspects dealing with the nature of water sources, water policy, ownership, water rights, priorities for water allocation, beneficial uses of water, provisions for groundwater sources and pollution controls.

Water Sources

In drafting legislation it is necessary to consider the nature and availability of water resources in time and space, current and future water demand, and intended purposes, over specified time horizons. Consideration should be given to the cost of water production, distribution and maintenance for different sources, as well as trends in socioeconomic and technological development. The major objective of legislative efforts should focus on achieving the most rational management of all the available water resources, including privatization of water services. A water law must include provisions for development of additional surface and groundwater sources, and distribution, the costs of which may be partially defrayed by consumers. It should also include clauses linking the financial aspects of water resource development with utilization and management. The law also may contain certain provisions governing hydraulic structures with regard to design, construction, operation and maintenance. The water code may designate agencies to be responsible for this field. The water code should establish proper legal and administrative coordination mechanisms between the water sector and other sectoral functions. The water code may also include regulations for the establishment of a protective parameter or *haram* around water works and structures to avoid pollution and/or public hazards.

Water Policy

The drafting of a new water law or updating an existing one, should allow for a range of possible scenarios for the execution of water policy within a framework of flexible directives (Caponera 1992, Burchi 1991). Water policy decisions should define food requirements, required water quality standards, improvement of health through improved water supply and sanitation, user rights, priorities according to region or use, limitations, restrictions or obligations governing users, as well as the method and magnitude of water charging. Following the concept of an integrated approach, policy decisions should also define water planning procedures, level of planning, the extent of involvement of specialists and decision makers, and relationship of water to other national resources and water sector users.

Ownership

In effective water code needs to address all possible water ownership situations in a systematic, clear and concise manner. Water ownership, in the past, has caused confusion, disputes, and kindled the implementation and enforcement of water law. A distinction needs to be made between water ownership and water rights. The distinction between water ownership and water rights has become relevant with regard to the administrative aspects of water management, especially during the implementation and enforcement of water codes. Water ownership covers different aspects of possession, transfer and utilization, including the right to use water. In general, ownership should define the right to dispose of water as a property through sale, donation, transfer, or inheritance, at the discretion of the owner. It is appropriate that any water code define the legal status of water ownership within a country, including the various types of sources under consideration. Water codes may emphasize that water be declared as state property, and therefore subject to state control, especially groundwater.

The separation of water rights from land ownership should be established in a proposed water law. With regard to the mobility of groundwater, it can be treated in a manner equivalent to property rights. Water ownership should also address exact volumes of water to allotted to property such as farmland, delimitation of sources, point extraction, location of diversion works or wells, purpose, and the location where the water is to be used. Water law must consider the interest of the public in regard to private ownership, particularly in the case of groundwater. Private ownership may be addressed in the water law or in a separate legal enactment. It is appropriate to compile a public water index registry for the purpose of administrating all types of water ownership rights. The other important element that should be addressed in any water law is the right to use water for different purposes.

Water Rights

Public water rights can be addressed through the right to use water, subject to government authorization through permits, licenses or concessions. These regulations should determine the quantity of water to be used, as well as the intended purpose. Private water may be used freely, but limitations may be imposed according to the principles governing private property rights. Any right to use water without need for administrative purposes should be clearly specified in the water legislation.

The right to use water, which differs from water ownership, can be successfully controlled through permit regulations. A permit system should apply to all types of water utilization, including municipal, industrial and agricultural effluents. Different types of water use permits should be specified in the water law. The law must make a distinction according to the type of water use: domestic, water supply, sewerage, rural, mining, industrial, commercial, irrigation, and reuse of drainage effluent. Further distinction may be established within each type of use. Water law should specify, within the permit, the limit of each type of use, discharge or category of use (Caponera 1992). The law should give emphasis to the need for detailed procedures in the granting of permits when dealing with large volumes of water use. Permit type and characteristics as contained in the law and be included in the water law. Procedures for the issuance and enforcement of permits, concessions or licenses should be established and stated in the water law.

Effective water law must deal with existing water rights, which may have been practiced over long periods of time. Existing customary water rights should be recognized, however the water law should emphasize their registration. The acknowledgement of existing water rights should be subjected to the same restrictions as rights granted under the authorization system. Another option is to consider these water rights as property rights to be handled by the owner. In the interest of the public, existing water rights (water use rights) may be reduced or modified and provisions for their administration need to be established. New water laws should limit the sale or transfer of existing water rights without the consent of the water authority. The abolition of existing water rights should be accompanied by suitable compensation to those persons who are entitled to them.

The concept of equitable water rights must be recognized as an emerging issue in the region. Equitable water rights should provide the owner with assurance of undisturbed use of water for a reasonable period of time, adequate to amortize the investment made, as well as realize appropriate investment benefits.

Priorities For Water Allocation

Priority is very important when dealing with water allocation. Depending on the status of water resources and development objectives, a state usually designates different priorities depending on use. Sometimes, for certain types of water use, priority may be established based on time, or depending on the stage of a country's economic and social development. Priority in water use should be addressed in water law. However, according to Caponera (1992,1996) the setting of water use priorities may cause some drawbacks with regard to difficulty in changing them, especially when it is expected that social, economic and technological change may take place (Caponera 1992, W 1996, Burchi 1991). This consideration should be carefully assessed and provisions should be made for future amendments, if required. The establishment of priorities in water utilization should be left to the discretion of the responsible water authority.

Water law should give priority to use for domestic purposes with emphasis on adequate water quantity and quality. The management of water resources may require that water law establishes policies and procedures for the assessment and collection of water charges and fees, according to the level of priority. In this regard the water code should consider market forces, social needs, religious reasoning, public interest, availability of water, political requirements and reimbursement policies.

Beneficial Uses of Water

Beneficial uses of water including domestic, industrial, commercial, agricultural, hydroelectric power generation, as well as recreational should be regulated through the issuance of permits or concessions specified in the drafted water law. Water legislation should regulate municipal and water disposal. Municipalities should be considered as primary users as specified in the concessions, while the public should be considered secondary users. In this way municipalities or water authorities have the right to distribute and sell water granted through concessions, to individual users. The extent, location, amount, and means of abstraction and/or diversion of water, as well as wastewater treatment and disposal of waste, should be specified in the concession.

Agricultural use of water should be addressed in water legislation as part of a concession or permit system. Specific attention should be given to the agricultural sector, since it is a major water consumer, in order to enhance water resource management. Agricultural water use should be regulated by permit for small farms and by concession for large agricultural companies. Agricultural use should be regulated by water law, subject to all requirements and procedures established within the permit or concession system. The regulating permit or concession should specify limitations and obligations needed to guarantee that the public interest is served. These mechanisms should also contain provisions concerning the use of fertilizers, pesticides and any other chemicals that are potentially hazardous to humans or the environment. Water used for industrial purposes should be brought under the water code as well as the jurisdiction of water authorities or institutions. The water law should address the subject of water pollution control, as well as water reuse and recycling. Permits or concessions for industrial uses should impose all the necessary measures to achieve property quality control.

In countries with perennial flow of rivers, the subject of construction, maintenance and operation of hydraulic works including hydroelectric power generation needs to be addressed within the water law. This topic can be addressed in terms of water allocation with regard to storage intended for this purpose. A section of the water law needs to contain permit and concession rules governing hydroelectric power production and distribution. The water law should contain regulations for plant construction, technical specifications and distribution of electricity generated from the use of water.

The water law should also include water tariffs, and recognize the precedent of previous regulations. The harmful effects of effluent disposal on water courses, including natural or man-induced actions. This issue can be handled when the water law relies permit or concession regulations. Appropriate provisions with regard to obligations and limitations can be inserted in the permit or concession to address water damage.

Provisions on Groundwater

In view of the dynamic nature of groundwater resources, it is essential that the water code in regard to water rights, specifically define water entitlements in time and space, limitations, and terms of validity. The water law may include provisions restricting the issue of water permits for groundwater use to high priority requirements such as satisfying public and domestic needs, with second priority given to industries and other users. The water code should stress basin management, with real time management of surface water through efficient allocation, and establishing allowable pumping limits for groundwater.

The water law should include provisions to provide water administrators the means to control groundwater exploitation, utilization and conservation (Burchi 1995). The water law should be subjected to a permit system for the development, monitoring and protection of groundwater sources. The rights of landowners to utilize groundwater reasonably for domestic requirements should be recognized in the water law. The restrictions and limitations imposed on surface water should also apply to groundwater sources. The water law should disregard the division between surface and groundwater. The interaction of surface and groundwater through the infiltration and recharge process, as well as groundwater discharge through springs, should be given consideration in any new water legislation. The water law should contain provisions with respect to recharging schemes from dams, diversion structures, and recharge wells. The law needs to address a means of rationing this vital source through limitation of pumping volumes or installation of meters or other measuring devices, particularly in areas considered to be at risk of depletion. All means of groundwater development should be regulated by permits and licenses according to the manner prescribed in the articles of the water code. The extraction and use of groundwater must be subjected to water use permits.

The water code must address the problem of salt-water intrusion into coastal aquifers. Restricting groundwater pumping through regulation is the classical legal system response to preventing and controlling this phenomenon (Burchi 1993). The permit requirement for exploitation of coastal aquifers must evaluate the terms and conditions in regard to the quantity, rate, location and manner of abstraction. The basic permit requirement is to maintain a balance between abstraction and the natural or artificial recharging capability of the aquifers. The water code must provide for periodic review in order to monitor the intrusion phenomenon by means of measuring devices, as well as granting policing power to the administrative authority. This legal means of enforcement should include the power of entry and inspection, suspension or cancellation of permits, identification of the nature of remedial action needed, and prosecution of criminal offences.

Pollution Control

The proposed law should include provisions addressing pollution of both surface and groundwater sources. The direct discharge of pollutants into groundwater should be forbidden, particularly if they contain hazardous substances. The water law should regulate effluent and waste discharges into water sources through the issuance of permits and monitoring, subject to established standards. Regulation can be complemented by economic incentives to comply with restrictions (Burchi 1991, Caponera 1996). The law must specify the composition and quality of effluent, and the treatment required prior to discharge. The water law must include regulations to deal with storage of pollutants, both above and below the ground surface, as well as enforcement of prevention measures to address leakage and percolation problems. The measures to combat pollution should address a variety of sources including pesticides, fertilizers and urban runoff.

Finally, a close relationship between water law and other existing legal disciplines must be established. The proposed water law must conform to the institutional laws of the concerned country, especially with regard to the legal requirements of its natural resources. The water law must consider some of the provisions included in the administrative law that regulates the relationship between public administration and society. In some countries, water ownership, use, and conservation may be included in the civil water law. It is important that the proposed water law incorporate provisions for regulating water separately from the existing civil law, especially with regard to water ownership in relation to land. A modern water law must refer to the existing provisions in penal laws addressing punishment for water and water related offences. In countries which have established natural resources and environmental laws, the proposed water law must conform to the water related provisions within these laws.

CONCLUSIONS

Formulation and implementation of comprehensive water legislation in the ESCWA countries has not received serious consideration during the last two decades. Recently, however, some countries have begun the process of updating existing water legislation, or formulating new legislation, and have attempted to centralize their water institutions. Others, however, are still applying outdated laws and regulations. Serious consideration is currently being given to drafting comprehensive water legislation in the countries of Syria, Oman and Yemen. The content, coverage, and jurisdiction of new water legislation should meet the requirements necessary for achieving effective development and management of water resources.

Broad based water legislation is needed to provide a framework for effective water policy formulation and implementation, emphasizing rational utilization of water resources including desalination, and addressing the subjects of; water use priorities, water ownership, jurisdiction of authorities responsible for distribution and utilization, protection, pricing, beneficial uses, the issuance of use permits, and provisions for conflict resolution. In addition, appropriate water legislation should include mechanisms for ensuring the most equitable economic and sustainable uses of available water resources, taking into consideration socioeconomic conditions and the need for national development.

There is a need to evaluate and learn from the experiences of both developed and developing countries, including some of the ESCWA member states, that have drafted or updated their water legislation. In addition, new concepts that focus on resource management, optimal water allocation, suitable private sector investment, and environmental concerns, need to be given due consideration in drafted legislature. Consideration should be given to the abolishment of water ownership rights that are not compatible with effective management of surface and ground water resources.

Furthermore, water resource ownership, particularly concerning groundwater, should be placed within the fold of the member state's public property (Burchi 1991). Water legislature must emphasize the concept that water belongs to the state or that the state enjoys rights of use superior to that of individuals.

Legislative efforts are needed to enact laws and regulations, and to address the integration of land resource use with water resource management. Legislation dealing with these two related subjects is important, especially with respect to agricultural development and pollution control. Legislation must address issues dealing with the discharge of waste water from the domestic and industrial sectors as well as irrigation drainage, that causes potential hazard to the productivity and sustainability of both surface and groundwater resources. New legislation must provide for monitoring and regulation as well as the placement of liability appropriate to the magnitude of damage.

In the mean time, there is a need to enact legislation addressing the enforcement of water law, including coordination and cooperation between different water agencies, as well as the delineation of their responsibilities, which will contribute significantly in the move towards integrated water resource development and management.

Appropriate water legislation enforcement mechanisms must be supported by the allocation of adequate financial resources and manpower, as well as continuous education program to encourage public participation and understanding of the critical situation of water resources. Legislation should address private sector involvement in the development and distribution of water sources by making attractive proposals to encourage participation.

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APPENDIX A

1- **Customary Laws**: The population of the ESCWA region is predominantly of the Moslem faith, with both Sunni and Shiite doctrines that emphasize Sharia principles and incorporate some customary laws as the basis for their water legislation. During the pre- and post-Islamic period in many parts of the Middle East, including most of the ESCWA countries, administration of water rights was often based on customary water practices. This practice was common prior to the introduction of written legislation, and has governed resource development and utilization to support past civilizations. Customary water law, referred to as traditional water practices, have originated from the local historical water use of a specific community and religions beliefs mainly Islam. The customary water laws addressed rights in regard to water ownership, use, and allocation. Traditional water rights were established as a result of repetition of certain actions, as well as the implementation and acceptance of binding rules set by indigenous people over many generations. In the past, customary water laws generally have not been written or registered, and have been transmitted orally from one generation to the next. During times when water was relatively abundant, traditional practices were adequate, however, as water gradually became scarcer, water use regulations became more elaborate and complicated.

Customary water laws still play an important role in water allocation, especially at the user level. In many parts of the ESCWA region, particularly Yemen, Oman and Saudi Arabia, and to a limited extent in Jordan and Syria, customary water use patterns still prevail in determining water rights

2- **Sharia Principles**: Islamic water law is based on Sharia principles, representing the most predominant legal water system in most of the ESCWA countries. The Sharia principles originate from the Holy Quoran and Hadith. Sharia principles have addressed all aspects of water resources such as development, allocation, utilization, water ownership, rights, and water conservation. The basic element of Islamic water law consisted of the belief that water belongs in principle to the community (gift of God).

A qualification of right to ownership of water may be established through value added to the water by labor, in the form of retaining water in a container and/or through distribution work (Mallat 1993). It also included a provision for water sharing principles according to local uses with acknowledgment of prior appropriation rights. The Islamic principles also included liability elements addressing withholding or misuse of water, particularly wastage and degradation of clean water. These basic elements of Sharia law were consolidated by the Ottoman Majalla Code and land laws of 1858 (Mallat 1993). Sharia principles are included in some components of water legislation that is still practiced today by the countries of the Arabian Peninsula, Jordan and Syria.

3- **Ottoman Majalla Code:** The other legal framework that influenced water legislation in some of the ESCWA countries is the Ottoman (Turkish) Majalla Code, which includes some basic concepts of Sharia law and traditional principles. Some elements of this code remain as residual legislation in Lebanon, Syria, Jordan, Palestine and Iraq. The Majalla Code also regulated water use in the past in the countries that were under the control of the Ottoman Empire, such as Egypt, Saudi Arabia, U.A.E and Yemen (Caponera 1978). Some elements of the Majalla Code (92 articles), with regard to specific water issues, may have had some impact on the Napoleonic code of water legislation used in Syria and Lebanon. For further details on the content of the Majalla articles see Caponeras in FAO publication No.2, 1973 "Water law in Moslem Countries". For further discussion on Sharia principles and customary practices see ESCWA 1997 publication.

Table (1) Historical Perspective on Water Legislation Evolution

Post Islamic - Ottoman Empire Period - 1900	Development during 1900-1950	Development during 1950 to present
a) Customary local practices	***a) Emphasis on Sharia principles***	***a) Residual of Majalla code in few countries***
b) Islamic principles - ***Quran and Hadith*** - Water, Gift of God - Free use of water - Priority to quench thirst human and animal - Concept of protective zone (Haram) - Irrigation right allocation - Discourage mis-use - Individual responsibility for maintenance work	***b) Continue application of customary practice*** ***c) Majalla and French codes*** - Majalla code practiced in most countries until 1922 - Part of French code was applied - Water is public property - Permit of uses and concessions - Affirming and elaboration of protective zone	***b) Further focus on Sharia principles*** ***c) Diminishing role of customary practices*** ***d) Introduction of water laws*** - Water as state property - Registration of wells and water rights - Development of institutions - Affirming of uses of permit to develop and utilize water - Fragmented water laws and decrees - Few comprehensive legislations - Water right attached to land
c) Majalla Code (Ottoman) - Focus of 92 articles on water issues - Further elaboration of Sharia principles - Emphasis on rights of human needs - Allowed selling of irrigation water - Establish rules for maintenance - Implicit public property	***d) Drafting of new Laws*** - Affirming state ownership - Regulation of water exploitation and use by permit - Emerging of water administration - Affirming prior water rights	- Introduction of water allocation rule for surface water - Concept of pollution control

Table (2) Legislative efforts in the water sector - selected ESCWA countries

Country	Legislation Status Past	Present	Ownership	Use	Institutions
Jordan	Residual of Majalla and few laws 1937-1988	Fragmented, most recent laws 18, 19 1988	Explicit state property	Regulation by permits for both surface and groundwater	Single, Ministry of Irrigation & Water with two water authorities 1988
Lebanon	Residual of Majalla & French code and few laws and decrees 1925-1985	Fragmented but there is a plan for a comprehensive law	Implicit Public domain	Regulation by permit & old irrigation code	Ministry of Hydraulic and Electric Work, few other ministries and many regional commissions (1966)
Oman	Sharia law, customary practices and wells & Aflaj registration laws in 1975-1988	Fragmented regulation decrees for well and Aflaj , 1995	Explicit state property	Extensive regulation by permit for development of ground water and Aflaj	Single, Ministry of Water Resources 1989
Saudi Arabia	Sharia and customary laws, water conservation regulation and many decrees 1932-1988	Planning for comprehensive law	Implicit state property	Regulation by permit System mainly ground water	Few ministries, mainly agriculture and water, other ministries: municipality, planning, saline water corporation
Syria	Residual of Majalla code Sharia law Many decrees and laws 1925-1995	Comprehensive water law under preparation	Implicit public domain	Elaborate permits regulation for both surface and ground water sources	Few ministries, mainly irrigation, 1982, others, Housing, and Agriculture, Public work and Water Resources
United Arab Emirates	Sharia and customary laws and few decrees 1980-1994	-	Implicit state property	Limit regulation by permit system for ground water	Few ministries: Agriculture and Fisheries, Electricity and Water, Municipalities and High Water Council, 1981
Yemen	Sharia and many customary laws and decrees	Drafted comprehensive water law, 1995	Explicitly state property	Regulation by permit system and old practices	National Water Resources Authority 1995

Towards Higher Efficiency in the Water and Power Utilities

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TOWARDS HIGHER EFFICIENCY IN WATER AND POWER UTILITIES

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ABSTRACT

The Gulf Cooperation Council (GCC) States are facing increasingly high demand in water and electricity supply to meet higher standard of living and developments in various economical sectors.

The GCC Governments have been able in the past to satisfy most of the demand with a high subsidy, which was affordable.

Oil income has dropped down considerably in last few years, which makes it impossible for the Governments to continue with the same trend.

Most Governments are considering various alternatives to meet the continuous demand.

This paper presents some of the major issues and suggests various approaches such as restructuring and other cost-effective measures in order to achieve higher efficiencies in water and power sectors in the GCC States. The following list the title of the topics discussed in this paper:

1. PRIVATIZATION AND INDEPENDENT AUTHORITY APPROACH TO WATER AND POWER UTILITIES
2. WATER AND ELECTRICITY SYSTEM INTEGRATION
3. INTERCONNECTION OF THE GCC STATES SYSTEMS
   a) Electrical System Interconnection
   b) Natural Gas System Interconnection
4. DEMAND SIDE MANAGEMENT
   a) Tariffs
   b) Conservation
5. TECHNOLOGY
6. TRAINING

The results of these measures if implemented will be to relieve the government budget and reduce the high subsidy cost.

INTRODUCTION

The importance of efficient water and power utilities in a modern economy is often underestimated. It is only when a problem occurs that public attention is, perforce, focused on their operations. However, their central economic roles merit more constant and focused interest from policy makers.

Throughout the Gulf Cooperation Council (GCC) States, there is a new interest in the operation of these utilities. Close attention has been made how these utilities are structured, to the role of competition in ensuring efficient operation, security of supply and to the environmental consequences of the way they are operated.

The objective of this paper is to address some of the major issues in order to achieve maximum economic benefit by improving the efficiency of the system.

Since this conference concentrate on the water aspects, I feel it is important to incorporate the power sector due to the mutual dependence between these two utilities in this part of the world.

MANAGEMENT OF THE WATER AND POWER SECTORS IN THE GCC STATES

The present management statuses of water and power utilities are as follows:

Kuwait and Bahrain are fully government managed and owned systems. Saudi Arabia, Qatar, Oman and UAE are mixture of government managed and owned systems, authorities and private companies with the government as shareholder.

All of the GCC States have attempted various methods of cost reduction programs, in addition to the transformation from government management to public authority or the path of privatization in recent years.

Most of the above measures have not proven to be effective towards efficient system due to the presence of government domination of decisions irrespective of the type of management and ownership and the lack of competitiveness and transparency.

APROACHES LEADING TOWARDS EFFICIENCY

In many industries, pressure to cut costs and maintain competitiveness will come from competition. However, the monopoly structure of the water and power industry in the GCC States means that government intervention may be required to bring about change.

This paper considers what should be the appropriate role for the government in regulating and restructuring water and power utilities.

There are two approaches, which may be adapted to ensure that water and power utilities minimize their cost of operation.

The industry may be restructured to increase competition where it is feasible and maximize transparency, where this is not possible, the government can regulate the industry to try to ensure that the costs of the monopoly operator are minimized.

A much more important potential benefit from increasing efficiency in the water and power utilities sector is the likely effect on the economy. The effect of reducing the cost of utilities will be to reduce the high cost of subsidy in GCC States. This in turn will lead to invest the achieved saving in other sectors of the economy.

A reduction in prices will also clearly convince citizens of the GCC of their governments' seriousness in reducing unnecessary financial expenditures and will, therefore, accept tariff restructure.

The following suggested approaches that might lead to more effective economical solutions to the present water and power sectors in the GCC States.

1. Privatization and Independent Authority

The results of privatization differ from place to place. In some countries, the objectives have been achieved, whereas in others they have not.

In some countries, privatization of utilities has taken longer period of time and more careful consideration. The threat of privatization has been sufficient for utilities in most countries to improve efficiency.

Authority form of management can be as effective as privatization if the authority is given full independence.

The following comparisons illustrate some of the differences between the various forms of management structure.

Factors	*Government*	*Authority*	*Private*
Efficiency	Political and Social Influence	Medium/High	High
Labor Policy	Inflexible	Flexible	Flexible
Accounting System	Government	Commercial	Commercial

As it can be seen from the above comparisons, the independent authority form of management shares most of the above factors with the private company.

Private utilities companies are run based on efficiency, therefore, the unit cost would be cheaper than that from independent authority or government managed utilities.

There are potential overall benefits to the government due to privatization, but there are also potential extra costs unless the governments' objectives and strategies are clearly identified before starting the process.

2. Integration of Water and Electricity Systems

The GCC States depends on sea water desalination to provide the bulk of its potable water requirements, in most cases these plants are linked with power production or require bulk power supply, in addition the end users for the water and electricity are common customers.

This situation makes the integration of these utilities more economical. The integration has to be more than just joint top management and accounts' services.

It has to be total system integration with common objectives and long term planning in order to maximize utilization of resources and realized the cost reduction benefits.

3. Electricity and Gas Interconnection of the GCC States Systems

A. Electrical System Interconnection

The absence of interconnection of the electricity system within the states and with other GCC States networks means that the individual systems are usually small and isolated. There is no possibility of smoothing peaks in demand by drawing electricity from neighboring systems with different load profiles and there are substantial extra costs due to the need to maintain permanent reserves in the generating system.

The integration of the GCC electric systems studies was completed in 1990. The objectives of the study were to provide for reserve sharing and generally economic and flexible operation of the networks. The year 2010 was selected as the study horizon, being the year up to which the system expansion was simulated to attain the maximum anticipated benefits associated with the interconnection.

It was agreed that the size of the interconnection to each system would be such that each system could import up to half the installed capacity of the largest generating station but no more than thirty percent of the peak load in the horizon year 2010.

Table 1 The Size of the Interconnection to Each System

System	Kuwait	Saudi Arabia	Bahrain	Qatar	UAE	Oman
Size (MW)	*1200*	*1800*	*750*	*600*	*900*	*400*

The principal economic benefits due to the interconnection arise from the sharing of reserves between the systems, consequential reduction in the installed generating capacity and associated operation and maintenance costs.

This is shown in Table 2 for the horizon year 2010.

Table 2 Capacity Benefits for year 2010

System	**Load (MW)**	**Generation (MW)**	**Reserve Without Int. (MW)**	**Reserve With Int. (MW)**	**Benefits (MW)**	**Benefits Millions of $US**
Kuwait	12 040	14 662	2622	1546	1076	873
S. Arabia	10 985	14 625	3640	2458	1182	1018
Bahrain	1 954	2 710	756	437	319	273
Qatar	2 300	3 291	991	541	450	508
UAE	5 791	7 275	1484	756	728	512
Oman	2 468	3 077	609	348	261	158

Total Capacity Benefits (Present Worth) US$ 3341 Millions

Assessment of other benefits such as spinning reserve benefits, the potential savings due to economy interchange between the systems, and benefits associated with transmission reduction and or postponement within the GCC countries indicated that such benefits would be of an order of magnitude less than those due to reserve sharing.

The total benefits are the sum of the benefits due to reserve sharing and the benefits due to reduction in spinning reserve requirements, economy energy transactions and avoided transmission construction.

These are shown in Table 3, along with the net benefits.

Table 3 Total Benefits in Millions of Dollars (Present Worth)

Benefits	**Cost in Millions US$**	
Capacity Saving	2764	
Operation and Maintenance	577	
Subtotal		3341
Spinning Reserve	26	
Energy Exchange	180	
Transmission	5	
Subtotal		211
Total Benefits		3552
Capital Cost of Interconnection		2475
Net Benefits		**1077**

Benefit/Cost Ratio 1.44

The study concluded that the interconnection project is economically viable and has a benefit to cost ratio of 1.44 using a discount rate of 6%. The analysis also showed that the cumulative present worth of the benefits, in terms of savings in generating plant investment, would exceed the capital cost of the Interconnection Project within two years after the last Phase is implemented.

The benefits of this interconnection can be summarized as follows:

- It permits a lower installed capacity on the total system
- It permits larger and more efficient generating units to be installed on the individual systems

- It enables systems to share operating (spinning) reserves
- It enables interchange of planned or incidental energy between or among utilities
- It allows for the installation of jointly owned or shared units of generation
- It permits emergency assistance between systems to mitigate the effects of unforeseen contingencies such as catastrophic multiple outages
- It permits assistance from neighboring systems to cope with unforeseen construction delays and unexpected load growth

Economy energy trading can be realized among the utilities. These benefits make the case for electrical interconnection of GCC States even more beneficial.

B. Natural Gas System Interconnection

Electricity generation is already the single largest user of primary energy, accounting for one third of the world's total energy consumption. Demand is still going up.

The situation varies widely from country to country. In the GCC States, for example, natural gas will remain the primary fuel in power generation plants. The use of natural gas as a source of energy for power generation is increasing. Today, some 28% of world gas consumption is used for power generation.

There are a number of reasons for this growing popularity, gas supplies are plentiful and growing, electricity can be generated at a competitive price from gas, and gas is kinder to the environment than other fuels.

In many areas tighter controls on the emission of combustion gases are being placed on the electricity industry. These particularly relate to concerns about "greenhouse gases" (such as carbon dioxide) and "acid rain" (sulfur dioxide and nitrogen oxide). Natural gas, in conjunction with combined cycle technology, is not only an extremely efficient way of producing electricity, but it also enables generators to reduce emission levels.

Recommendations and discussion for the establishment of a natural gas network to connect all member states has been initiated in early 1980s.

Water and power demands in the GCC States have grown significantly in recent years and forecasts indicate that this trend will continue for the years to come. Thus, low cost energy supplies constitute a major factor in ensuring economic growth and quality of life.

The utilization of common natural gas system coupled with electrical interconnection will enhance firm energy transfer to other utilities at the most economical cost. In addition, it will allow the construction of joint independent power stations with large unit sizes, which will contribute towards lower production cost of electricity and water.

4. Demand Side Management

While more and more attention is paid to demand side management in some GCC States, it is observed that in most cases it is limited to seasonal public awareness programs. Instead, it should be part of a national policy reinforced by legislation, incentives, public awareness, tariff structure and conservation, in order to direct all consumers to participate in these programs more seriously.

A. Tariffs

The governments of the GCC States have decided on various methods of oil wealth distribution. Among them was the decision to subsidize the utilities services, to the extent that some states provide these services for free, this was affordable up to a certain limit and with reasonable usage.

The level of subsidies has undergone various changes since the 70s, depending on the political, social, and the economical status of each government.

The challenges faced by the GCC States are for providing adequate supply of water and electricity services with uncontrolled demand, in an industry that requires substantial investment and high operating cost. This situation has created major financial difficulties for the GCC Governments due to the unavailability of funds to be invested at a time of declined oil prices.

The existing subsidy structure should be reconsidered urgently by all GCC Governments, in order to establish clear-cut long-term policies.

As the gap between the total costs of delivering these services to the consumers and the tariffs charged is very high, it results in massive direct and indirect subsidies.

By adopting gradual method to reduce the level of subsidy, the government will achieve:

- Conservation drive will be more effective.
- The annual demand growth will be manageable.

B. Conservation

Saving obtained from water and power conservation programs and the utilization of reclaimed water to meet nonpotable water needs will reduce the demand on very expensive potable water. This saving can be considered as a means of reducing or delaying the need for conventional additional installed capacity and thus saving on the associated operation and maintenance cost, in addition to the reduction of fuel consumption.

GCC States has done very little in this field, in fact, most of the conservation drives are a result of shortage of supply rather than long term objectives, except in some states where they implemented limited energy conservation regulation on new buildings only.

The followings are some examples of areas that require more concentrations in water and electricity conservation measures.

- Water network system leakage accounts for 15%-20%
- Domestic gardening accounts for 30%
- Toilet flushing accounts for 10%
- Air-conditioning accounts for 60%
- Lighting accounts for 15%

Government investments in water and power conservation programs have the most economic effect if the programs are well prepared and managed. Investments to reduce wastage on some of the examples mentioned above could be recovered in less than a year.

5. Technology

During the past three decades, water and power utilities markets have seen major drive to produce water and electricity at the lowest possible costs.

Factors like the oil crisis in the early seventies, the restructuring and mergers of major companies in the late eighties and emergence of stronger lobby for environment protection in the nineties etc. all have led to a continuous drive for designing plants that are more and more efficient.

Consequently, development and innovation for improvements in water and power systems efficiency and reliability had been the concern of original equipment manufacturers and owners. Indeed the 1990s may be viewed as the decade of greatest change in the world of water and power industry since its beginnings. The most noticeable innovation is the development of combined cycle that offered increases in both capacity and efficiency which has increased from 35% to about 60%.

Water desalination plants have witnessed similar major developments in capacity and efficiency. This trend will continue in the future.

The fast development in information technology applications allowed plant designers to successfully introduce process automation and control systems which give new functionality and versatility, and have resulted in accurate plant performance, increasing availability and reliability and reduce operation and maintenance costs, subsequently improving the efficiency of the plant.

6. Training

Training is the most important aspect in any utilities considering efficiency achievement.

The present training programs are mainly concentrated on the knowledge of operation and maintenance of the installed plants with no consideration given to teamwork and productivity leading to efficient utilization of all resources.

The utility should set plans to encourage employees at all levels to positive participation and suggestions in establishing new or improved operation methods and procedures, in order to promote efficiency and economy as part of the organization goal of providing high quality and reliable service at the most economical cost.

CONCLUSIONS

- The current water and power sectors' structure in the GCC States, as it has evolved over the past, is not conducive to development of competition.

- GCC States should restructure its utilities in order to achieve the higher efficiency that competition can provide, through development of framework and incentives that allow for expanded entry to independent authority structure leading to privatization.

- The involvement of variety of producers should be encouraged, especially domestic joint-investments projects.

- Total system integration of water and electricity in order to maximize cost reduction and efficiency.

- The electricity and gas system interconnection will reduce production cost and facilitate the installation of independent power stations at competitive production cost.

- Other advantages of systems interconnections such as reserve sharing and energy trading will contribute to efficiency.

- Joint efforts between GCC States in establishing long term demand side management program as part of national policy incorporating tariff and conservation.

- Water and electricity tariffs structure should be reviewed to curb wastage and make conservation programs more effective.

- Conservation programs should be introduced based on economic rates of return.

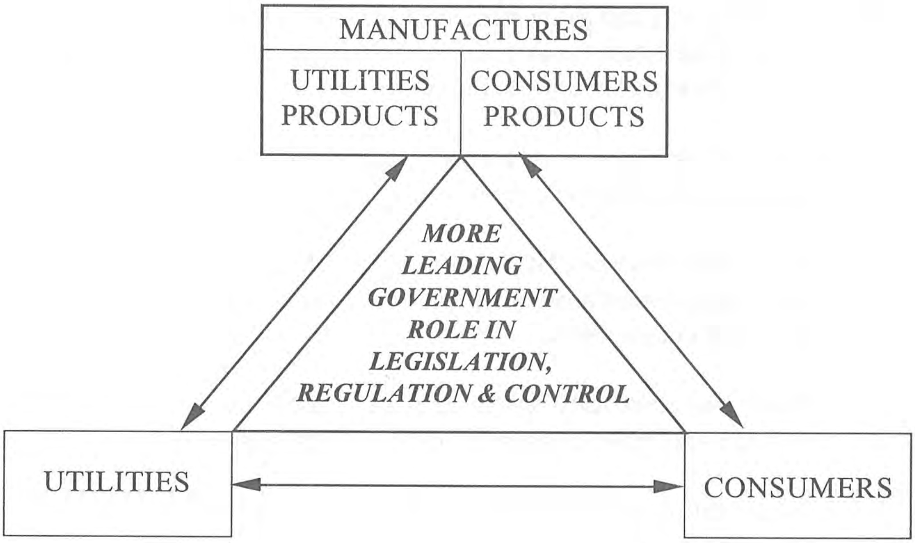
- Positive participation of GCC States with international organizations, such as utilities, manufactures and research centers in efforts leading to high technological development of advance energy and water efficient production plants and to the enhancement of consumers' end products.

- Training programs of employees at all level should incorporate and encourage economy and efficiency of the system.

- It's anticipated that water and electricity sectors in the GCC States will require an investments of more than 60 billions US $ over the next 16 years. This amount of investment warrants serious considerations by the GCC Governments to all possible efforts to reduce capital, operation, and maintenance costs and reduce fuel consumption. This can be achieved by embarking on effective measures, in order to reduce costs, which is considered substantial and possible.

- The amount that could be saved should be directed towards more useful programs to the welfare of the GCC citizens rather than to continue ignoring the unnecessary waste of our valuable resources.

- The government should take more leading role in legislation, regulation and control to enforce efficiency in water and electricity utilities and consumers' products.



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Water Resources Planning Under Unertainities

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WATER RESOURCES PLANNING UNDER UNERTAINITIES

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ABSTRACT

Increase in population as well as the rapid changes in individual consumption, social standards, industrial and agricultural needs resulted in increasing demands on available water resources in the Kingdom of Saudi Arabia. In agricultural sector, as an example, water requirements increased from 1,850 MCM in 1985 to 16,400 MCM in 1995. This leads to the need to develop and implement a management plan that is capable to optimize available water resources. Such plan can be achieved by modeling water demand-supply in a multi-objective framework. An essential element of the model is input data. Unfortunately available data are not accurate due to the inherent uncertainty associated with it. This uncertainty will generate uncertainty in model output, which affects reliability, and confidence associated with decisions. Thus, reliable planning should consider uncertainties associated with model input parameters. This paper, shows how can multi-objective modeling used to plan water resources in the Kingdom of Saudi Arabia assuming that both supply sources and demands are uncertain.

Keywords: Uncertainty, Saudi Arabia, Multi-objective Planning, Risk Analysis

INTRODUCTION

Saudi Arabia has limited water resources. Inspite of that, a substantial increase in water consumption has occurred in the past years due to increase in population, rapid developments in both agricultural and industrial sectors, and improvements in the standard of living. Table 1 summarized water demand for agricultural, domestic, industrial, and other purposes and the types of sources for several years according to the sixth development plan. As can be revealed from the table, municipal and industrial water demands increased from 510 MCM to 1,800 MCM in the fifteen years period 1980-1995 and the desalinated water increased from 50 MCM to 714 MCM in the same period. This growing demand and the limited water resources available necessitate the need to adopt a plan that is capable of making a balance between water demand and supply through a multi-objective framework. The multi-objective model should be capable of incorporating all available water resources alternatives, i.e. groundwater, desalination, surface water, treated wastewater, for allocating water for different purposes, i.e. domestic, industrial, agricultural, landscaping.

The developed multi-objective model is considered to be uncertain. Major sources of uncertainty are attributed to model formulation and model parameters. In this study the only source of uncertainty is associated with quantifying the developed multi-objective model parameters. To run the multi-objective model, values of several parameters are required. These parameters vary significantly over time. Moreover, there will be "errors" or uncertainty in estimating or quantifying the values of these input parameters which will produce uncertainty in model output. This uncertainty affects the reliability and confidence associated with decisions related to current and future water resource planning. Therefore, uncertainties associated with those parameters should be investigated and considered when implementing the developed multi-objective model. This will allow the decision maker to incorporate notions of risk and reliability in the final decision process. In this study, water supply, i.e. groundwater quantity and quality, surface water, desalination, treated wastewater; and water demand, i.e. domestic, industrial, agricultural, landscaping; are considered as the primary source of parameter uncertainty in the developed multi-objective model.

WATER RESOURCES

Groundwater

Geological and hydrological studies conclude that the groundwater is stored in more than 20 principle and secondary layered aquifers of different geological ages [3]. Groundwater resources are divided into two types: non-renewable groundwater and renewable groundwater. Non-renewable groundwater is stored in the following principle aquifers: Saq, Wajid, Tabuk, Minjur, Dhruma, Biyadh, Wasia, Dammam, Umm Er Radhma and Neogene. Renewable groundwater is stored in secondary or alluvial aquifers that can be recharged. These aquifers are located in the South-Western part of the Kingdom which include: Al-Jauf, Al-Khuff, Al-Jilh, Aruma and Basalt. Several studies have been conducted to estimate the volume stored in these principle aquifers. Table 2 shows the subjective assessments of proven, probable and possible reserves for the groundwater aquifers estimated by one of the studies. This shows the big variation or uncertainty associated with estimating both renewable and non-renewable groundwater reserves. In addition uncertainty due to amount of groundwater need to be withdrawn from groundwater aquifers must be considered when planning water resources.

Surface water

Most surface runoff generated in the southwestern and southeastern part of the Kingdom. The total runoff in the Kingdom is estimated at 2230 MCM per year. To utilize and store surface runoff the MAW constructed more than seventy-eight dams with varies capacities having a total combined storage capacity of approximately 475,000,000 m^3 [4,5].

Desalination

Due to limited ground and surface water resources in the Kingdom and to overcome water supply deficiency, the Kingdom relies heavily on large-scale desalinization plants to fulfill water demands especially for domestic purposes. Currently, there are more than 23 desalinization plants in operation with a total production capacity of about 2 MCM per day [6].

Reclaimed Wastewater

Reclaimed wastewater is currently utilized for irrigation and landscaping purposes. In the future it is expected to use treated wastewater for other purposes such as recharging groundwater, industrial cooling, car washing, fire fighting, etc. The total volume of treated wastewater utilized in 1995 is estimated at 150 MCM and is expected to reach 310 MCM in year 2000, as given in Table 1. This shows the future potential of utilizing treated wastewater in Saudi Arabia by building new wastewater treatment plants in different cities in the Kingdom.

WATER DEMAND

Domestic & Industrial Demands

Table 1 shows the actual domestic and industrial water demands. In 1980 domestic and industrial water consumption was estimated to be 510 MCM whereas in 2000 it is expected to reach 2,800 MCM. This rapid growth of water demand is attributed to the increase in population which is expected to reach 22.6 in year 2000, as shown in Table 3, and rapid development in industrial sectors in the last decade. Domestic and industrial demands are satisfied mainly through groundwater and desalination [5].

Agriculture

Agriculture requirements are met by providing water mainly from groundwater aquifers. Water demand for agriculture purposes increased from 1,850 MCM in 1980 to 16,400 in 1995. This high water consumption cause deep-aquifer mining in major aquifers enforcing the MAW to consider some control measures which help reducing agriculture water consumption to 14,700 in the six development plan as shown in Table 1 [2].

MODEL DEVELOPMENT

Demand for water increases as the population and economy grows, as a result the problem of imbalance between demand and supply will be larger and more complex. The most viable option to resolve this problem is to study all water resources alternatives in a multi-objective framework to meet demand in various sectors [4]. Multi-objective planning represents a very useful technique for planning problems that have multiple objectives and constraints. It is a systematic approach or process where trade-off is made on non-commensurate objectives (often in conflict and or competition). Thus, water resources planning is best formulated by multi-objective modeling since there exist limited water supply resources which need to meet water for various demand or objectives that are often in conflict. In this study the developed multi-objective model will be considered as stochastic model since inherent uncertainty possessed by input parameters due to its limited record or measurement errors encountered in them.

The general form and specific form of the multi-objective model is explained as follows:

Objectives

$P_1(..........)$
$P_2(..........)$
$P_3(..........)$
.
.
.
.
.
$P_n(..........)$

P_1 .... P_n represents priorities.

Specifically, the model has the following objectives.

1.To satisfy the domestic demand.
2. Meet the required domestic quality in terms of TDS.
3. Satisfy the agricultural demand.
4. Satisfy the agricultural water quality.
5. Satisfy the industrial demand.
6. Satisfy the landscaping demand.

Constraints

These constraints are as follow:

A. Quantity Constraints: The quantity constraints of the model are the finite amount of groundwater, surface water, desalinated water, and treated wastewater.

B. Demand Constraints: The demand constraints are the quantities of the demands to be satisfied such as domestic demand, landscaping and gardening demand, industrial demand, and agricultural demand.

C. Quality Constraints: The quality constraint includes the available quality of the resources such as the quality of groundwater in terms of TDS and also the quality of the surface water as well as the desalinated water source.

D. Cost Constraint: Cost of production of water for the different resources are not equivalent. For example the cost of production of groundwater, desalinated water, and treated wastewater all vary. These factors become the cost constraints. The general form of the modeling framework is shown in Table 4.

The mathematical form of the objective function with constraints, deviation variables, and priority functions are explained as below.

Priorities

The following goals, to be achieved, with priorities signified by the order in which they are stated.

- P_1 : To satisfy the domestic demand requirements of the water i.e., we minimize the negative deviation d^-_1 . This is the "achieve equal to" case.
- P_2 : To satisfy the quality of water for domestic use, i.e., we desire to achieve the required TDS value for the domestic water. Hence, we are interested in the "achieve equal to goal" (we should meet the required TDS).
- P_3 : To satisfy the demand for the agricultural use. We desire to meet the "achieve equal to goal case" (meet the demand, i.e., equal to the set requirement).
- P_4: To satisfy the quality of water for agricultural use, i.e., we desire to achieve the required TDS value for the agricultural water. Hence we are interested in the "achieve equal to goal" (we should meet the required TDS) .
- P_5 : To satisfy the demand for the industrial use. We target the "achieve equal to goal case" (meet the demand i.e., equal to the set requirement).
- P_6: To satisfy the demand for the landscaping use. We target the "achieve equal to goal case" (meet the demand i.e., equal to the set requirement).

Goals

The following goals should be satisfied for different demands:

1. Domestic demand:

In this goal we try to minimize the negative deviation variable d_1^- in the equation as shown below.

Domestic Consumption $q_{11} + q_{21} + q_{41} + d^-_5 - d^+_5 = D_D$
Where

d^-_5 is the under achievement of the satisfaction of the domestic demand.

d^+_5 is the over achievement of the satisfaction of the domestic demand.

D_D is the quantity of domestic demand.

The other terms are explained in Table 4.

2. Domestic water quality:

Quality of the water is characterized by the total dissolved solid (TDS) which needs to be satisfied according to the following equation:

$$q_{11}(T_{ng}-T_x) + q_{21}(T_{rg}-T_x)\ q_{21}(T_s-T_x) + q_{41}(T_d-T_x) + d^-_9 - d^+_9 = 0$$

Where

d^-_9 is the under achievement of the quality parameter.

d^+_9 is the over achievement of the quality parameter.

T_{rg} is the TDS of renewable groundwater.

T_{ng} is the TDS of non-renewable groundwater.

T_s is the TDS of surface water.

T_d is the TDS of desalinated water.

T_x is the required domestic water quality.

3. Agricultural demand:

Agricultural Usage $q_{14} + q_{24} + q_{34} + q_{54} + d^-_8 - d^+_8 = D_A$

Where

d^-_8 is the under achievement of the satisfaction of the agricultural demand.

d^+_8 is the over achievement of the satisfaction of the agricultural demand.

D_A is quantity of agricultural demand.

4. Agricultural water quality:

$$q_{14}(T_{ng}-T_a) + q_{24}(T_{rg}-T_a) + q_{34}(T_s-T_a) + q_{54}(T_w-T_a) + d^-_{12} - d^+_{12} = D_A$$

Where

d^-_{12} is the under achievement of the satisfaction of the agricultural water quality demand.

d^+_{12} is the over achievement of the satisfaction of the agricultural water quality demand

T_a is the required agricultural water quality.

T_s is the TDS of surface water.

T_w is the TDS of wastewater.

5. Industrial demand:

Industrial demand $q_{13} + q_{23} + q_{53} + d^-_7 - d^+_7 = D_I$

Where

d^-_7 is the under achievement of the satisfaction of the industrial demand.

d^+_7 is the over achievement of the satisfaction of the industrial demand.

D_I is the quantity of industrial demand.

6. Landscaping demand:

Landscaping and Gardening $q_{22} + q_{32} + q_{52} + d^-_6 - d^+_6 = D_L$

Where

d^-_6 is the under achievement of the satisfaction of the landscaping & gardening demand.

d^+_6 is the over achievement of the satisfaction of the landscaping & gardening.

D_L is the quantity of landscaping & gardening demand.

The developed multi-objective model were executed assuming water supply sources and water demand are uncertain. Table 5 shows the statistical characteristics and distribution of the parameters for year 1998. Based on the assumed distributions and the statistical characteristics of the uncertain parameters, random numbers or realizations were generated and used as input for the multi-objective model.

RESULT ANALYSIS

The multi-objective model were run for 40 realizations over a period of twenty years. The model executed assuming that the desalinated water quantity is unlimited. It means that the model is allowed to utilize as mush of desalinated water as it requires along with the other source (groundwater) in order to satisfy other demands.

A sample output of the multi-objective model showing the variation of agriculture water quality, expressed in terms of TDS, over time is presented in figure 1. As can be revealed from the figure TDS values, the index of water quality, increase with time indicating that water quality is deteriorating. Since the input parameters, i.e. groundwater and domestic demand, are uncertain, then the model output, i.e. agriculture water quality, will be uncertain too. This will allow the decision maker to incorporate risk, reliability and confidence in his final decision. For example, as can be revealed from figure 1, there is a reliability of 7.4% of achieving an agriculture water quality of a 3500 mg/l TDS in year 2010, or there is a risk of 92.6 of not achieving agriculture water quality of 3500 mg/l TDS in year 2010. According to this scenario, groundwater quality, which is the main source of agriculture, is deteriorating. Thus, potential control measures must be considered to stop this such as: reducing the amount of water pumped from aquifers, use treated wastewater with high quality and/or reduce the agricultural lands.

Figure 2 shows another sample output of the multi-objective model. The figure presents the variation of desalinated water consumption over time. As indicated from the figure more desalinated water is required to meet all demand requirements. According the adopted scenario, in year 2010 if the desalinated plants produces 1800 MCM, there will be 95% reliability of achieving water demands; or 5% risk of not achieving the required demand.

CONCLUSIONS

In countries where water resources are limited and faced with rapid increase in various water demands, an appropriate planning model needs to be implemented. The model should be capable for optimum allocation of water supplies (groundwater, surface water, desalinated water and treated wastewater) to various demands (domestic, agricultural, industrial and landscaping). This can be achieved by multi-objective modeling framework.

In this paper, a multi-objective model was developed and applied to the water resources in Saudi Arabia assuming model parameters (demand, supply and water quality) to be uncertain. Results show how to incorporate risk and reliability when making decisions. For example, results indicated that there is a risk of 92.6 of not achieving agricultural water quality and there is a strong need to increase the production of desalinated water in the near future to meet all demand requirements.

ACKNOWLEDGMENTS

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Table 1. Water demand and source of supply in million of cubic meters [1,2]

Water Demand	*1980*	*1985*	*1990*	*1995*	*2000*
Municipal and Industrial	510	1,200	1,650	1,800	2,800
Irrigated Agriculture	1,850	7,400	14,580	16,400	14,700
TOTAL	**2,360**	**8,600**	**16,230**	**18,200**	**17,500**
Source of Supply					
Surface Water and Re-newable Groundwater	1,140	1,850	2,100	2,500	3,000
Non-Renewable Groundwater	1,170	6,320	13,480	14,836	13,040
Desalinated Water	50	330	540	714	1,150
Reclaimed Wastewater	-	100	110	150	310
TOTAL	**2,360**	**8,600**	**16,230**	**18,200**	**17,500**

Table 2. Non-Renewable and Renewable Groundwater Reserves [3,7,8].
a. Non-Renewable Groundwater

Aquifer	**Salinity (mg/l)**	**Groundwater Reserves (MCM)**		
		Proven	**Probable**	**Possible**
Saq	300 – 3000	65,000	100,000	200,000
Wajid	500 – 1200	30,000	50,000	100,000
Minjur &Dhruma	1100 – 20000	17,500	35,000	85,000
Wasia/Biyah	900 – 10000	120,000	180,000	290,000
Umm-Er-Radhma	2500 – 5000	16,000	40,000	75,000
Dammam	2600 – 6000	5,000	25,000	18,371
Tabuk	250 – 2500	205,000	485,341	753,234
Negene	3700 – 4000	120,000	284,102	440,917
TOTAL		**778,405**	**1,199,443**	**1,962,522**

b. Renewable Groundwater

Aquifer	Salinity (mg/l)	Groundwater Reserves (MCM)		
		Proven	Probable	Possible
Khuff/Tawail	3800 – 6000	30,000	71,025	110,229
Aruma	1600 – 2000	71,000	168,094	260,876
Jauf/Sakaka	400 – 5000	100,000	236,752	367,431
Jilh	3800 – 5000	113,000	267,529	415,197
TOTAL		**314,000**	**743,400**	**1,153,733**

Table 3. Domestic Water Demand [9]

Year	Domestic Demand (MCM)	Population (10^6)
1988	619.32	14.016++
1989	669.52	14.435++
1990	677.96	14.870++
1991	771.33	15.771++
1992	855.43	16.929++
1993	877.09	17.564**
1994	931.79	18.224**
1995	946.92*	18.906**
2000	1746.00*	22.600**

*Predicted by [2]
** Population growth rate 3.75% [10]
++ The Middle East and Africa [11]

Table 4. Modeling Framework

Demand (I) / Source (J)	Domestic (1)	Landscaping & Gardening (2)	Industrial (3)	Agricultural (4)
Non-renewable Groundwater (1)	q_{11}	q_{12}	q_{13}	q_{14}
Renewable Groundwater (2)	q_{21}	q_{22}	q_{23}	q_{24}
Surface Water (3)	q_{31}	q_{32}	q_{33}	q_{34}
Desalinated Water (4)	q_{41}	q_{42}	q_{43}	q_{44}
Treated Wastewater (5)	—	q_{52}	q_{53}	q_{54}

Table 5. Statistical Characteristics of the Input Parameters

Parameter	**Type of**	**Mean (MCM) Distribution**	**Standard Deviation**
Non-renewable GW	Triangular	—	—
Renewable GW	Triangular	—	—
Surface Water	Normal	642.69	230.22
Delineated Water	Normal	607.85	102.18
Treated WW	Normal	171.00	84.73
Domestic Demand	Normal	585.11	625.48
Landscaping Demand	Normal	87.76	93.82
Industrial Demand	Normal	468.09	500.38
Agriculture Demand	Normal	11203.11	6008.7

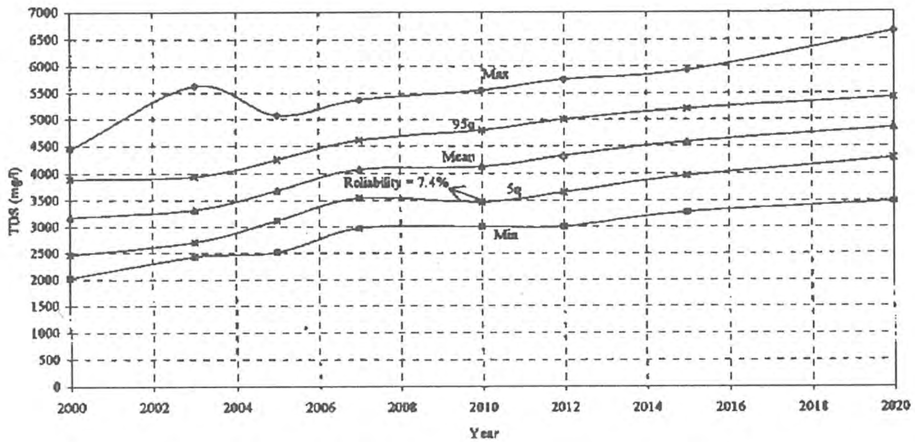

Figure 1. Agriculture Water Quality Variation

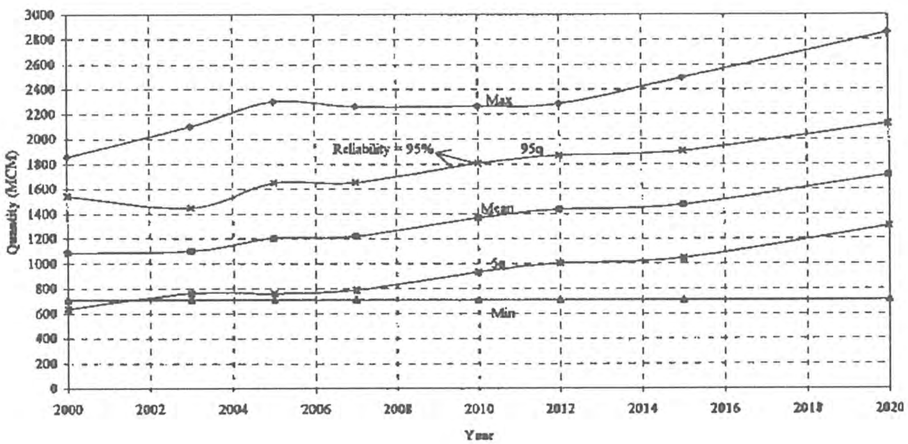

Figure 2. Desalinated Water Consumption

Future Water Supply and Demand Predictions in Saudi Arabia

Prof. Abdulaziz S. Al-Turbak

FUTURE WATER SUPPLY AND DEMAND PREDICTIONS IN SAUDI ARABIA

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ABSTRACT

Management of water resources is an essential part of any development plan in arid regions. Scarcity of water in Saudi Arabia make it essential to properly manage water resources. The agricultural sector has grown so fast during the last 20 years causing huge withdrawals from ground water. Growth of cities and industries caused domestic and industrial water consumption to increase many folds. In spite of government efforts to develop water supplies, consumption of water has reached alarming levels. In this paper, major problems facing present and future water supply and demand will be presented along with suggested solutions to meet these problems.

KEYWORDS: Water Resources, Demand, Supply, Renewable, Nonrenewable, Groundwater

INTRODUCTION

The Kingdom of Saudi Arabia has seen tremendous changes in its social and economic spheres in the last 20 to 25 years. Wealth from oil revenues made it possible for the government to develop all sectors of the economy. One major sector which has seen tremendous growth is the agricultural sector. It has grown so fast during this period causing huge withdrawals from the country's limited deep groundwater reserves. The growth of cities, increase in the population and the rise in the standards of living caused domestic and industrial water consumption to increase many folds.

The constant pressures on the country's water resources made it necessary to develop both the conventional water resources (surface and groundwater) and the unconventional ones (desalination of sea water and treated wastewater). More than 186 dams for different purposes were constructed to utilize surface water which is available in some regions of the country. The Kingdom's huge aquifers were also extensively studied and utilized for different uses. With respect to desalination of sea water, many stations were built on the Red Sea and the Gulf. Saudi Arabia is currently the world's largest producer of desalinized sea water. Desalination plants produce water for coastal urban centers and for many cities in the interior of the country including the capital city of Riyadh. Wastewater treatment plants were also constructed in many urban areas. Utilization of treated wastewater, however, is still limited.

In spite of the tremendous efforts made by the government to develop the water supplies in the country, the consumption of water in Saudi Arabia has reached alarming levels as shown by studies like Abu Rizaiza (1989) and Al-Ibrahim (1990). The objective of this paper is to discuss the major problems facing water supply and demand in Saudi Arabia in the future. This will be done after surveying present supplies and demands. Possible solutions to meet expected future water shortages will also be presented and discussed.

AVAILABLE WATER RESOURCES

Water resources in Saudi Arabia can be classified into four types: Surface water, ground water, desalinized water and treated wastewater.

Surface Water

Except for the mountainous area, in the southwestern part of Saudi Arabia, precipitation is very low and infrequent with extreme variation from one year to the next. The average rainfall for the whole country is about 90 mm per year.

Saudi Arabia has no reliable and adequate surface-water sources. It has no perennial rivers and precipitation is extremely low. Due to the desert climate, a large percentage of rainfall evaporates. According to one estimate, 20% of rainfall evaporates immediately and another 50% is evaporated through water runoff in wadis (dry water courses) (Al-Ibrahim, A.A., 1990).

In Saudi Arabia, surface runoff occasionally occurs during the rainy seasons when there are rain storms. Estimates of the amount of runoff water range between 2,000 million and 2,400 million m^3 (MCM) (Ministry of Planning, 1985) per year. Most of the runoff occurs in the coastal areas and highlands of the southwest, where rainfall is relatively abundant and regular.

The Ministry of Agriculture and Water (MAW) has constructed about 186 dams throughout the country to utilize the surface-runoff water. While these dams store runoff water and increase infiltration for recharging ground-water resources, they also prevent flash floods and irrigate adjacent agricultural lands (EL Khatib, 1980). It is expected that the efficient use of dams provided a potential surface-water supply of up to 900 MCM/year for the Kingdom in 1985 (Ministry of Planning, 1985).

Since 1985, more surface water has been utilized especially after the completion of King Fahad Dam in Bishah (capacity 325 MCM), but surface water resources in Saudi Arabia are very limited and are important only in the southwestern region of the country.

Ground Water

Al-Ibrahim (1990) presented the most concise summary of ground water resources. He stated that ground water is the most important source of water in Saudi Arabia. It comes from two types of aquifer: renewable and nonrenewable. The first type, shallow aquifers, contains a renewable water supply charged by infiltration from rainfall and surface-runoff water that flows over wadis. The renewable ground water is estimated at around 950 MCM/year. The other type, deep aquifers, contains a reservoir of water formed thousands of years ago when water was trapped in sedimentary rocks such as limestone and sandstone. These deep aquifers receive negligible or no recharge and therefore store nonrenewable and depletable ground-water resources. The depth of these aquifers ranges between 100 and 500 m and may exceed 1,000 m in some areas. Nonrenewable ground-water reserves were estimated at 500,000 million m^3, of which 67% is stored in seven major aquifers, while a series of secondary aquifers holds the rest (Ministry of Planning, 1985).

The renewable ground water resources are utilized mainly for agricultural purposes in small farms located adjacent to wadis in many areas of the country. The nonrenewable ground water has been used extensively especially since 1980 at alarming rates to provide water for irrigation in the extensive areas put under cultivation outside the traditional agricultural oases. It was estimated (Al-Turbak, 1996) that about 35% of the nonrenewable ground water resource (500,000 MCM) has been used by 1995.

Desalinized Sea Water

Due to scarcity of water resources in Saudi Arabia, desalinized sea water is extensively used as an additional source for domestic water supplies. Saudi Arabia is the largest producer of desalinated seawater in the world. The Saline Water Conversion Corporation (SWCC), which is the authority incharge of desalination, presently operates 25 desalination plants, with a total daily production capacity of about 2 MCM.

Seawater desalination is an expensive operation that requires a large amount of money to construct, operate, and maintain. In addition, the TDS level in the Red Sea and Arabian Gulf (which varies between 40,000 and 60,000 ppm) is much higher than that of other seas and oceans (Wojcik, 1981). For this reason, water desalination in Saudi Arabia is more expensive than in other countries using the same methods of desalination. Moreover, considering the fact that the operational life of a desalination plant is in the range of 15-25 years, Saudi Arabia will require large amounts of expenditure to replace worn-out plants. This will impose a heavy burden on the country's financial resources.

Treated Wastewater

In an arid country where natural water resources are limited, reclaimed wastewater can be an important potential source of water supply. In addition, the treated wastewater has several advantages over other sources of water. It is cheaper than seawater desalination; it minimizes pollution; and it is a good nutrient source for landscape and farm irrigation.

The total amount of collected wastewater in all urban centers of the Kingdom was estimated to be 1017 MCM in 1995 (Al-Turbak, 1996). Out of this amount, 418 MCM were treated using secondary treatment or better. This is expected to grow rapidly as more sewer network and more treatment plants are constructed in the future. Al-Turbak (1996) studied in details the contribution of treated wastewater in solving water shortage problems in Saudi Arabia. They predicted amounts of treated wastewater expected to be produced until the year 2025 using different alternatives of water supplies. This was also combined with alternatives of distributions of different sources among the various uses of water. The study has shown that treated wastewater will present an important opportunity in reducing water shortages in the future.

WATER DEMAND

Water demands in different sectors are met from either traditional sources (surface and ground water) or from non-traditional ones (desalination and treated wastewater) depending on the type of use. The agricultural sector uses mostly non renewable ground water with some of its demands met by surface water, renewable ground water and treated wastewater. Water for domestic use comes mainly from desalination or ground water. Industrial sector demand comes mainly from deep nonrenewable ground water.

Agricultural Sector Demand

Demand for water in the agricultural sector has grown at a very alarming rates since 1980. In that year, it was estimated at 2000 MCM. In 1985, it reached a level of 7430 MCM. The average annual growth rate for water consumption was 60%, four times greater than what was anticipated by the Third Development Plan (Ministry of Planning, 1980). By the year 1990, this demand reached 14580 MCM/year and in 1995 it was estimated at about 17814 MCM.

Domestic, Industrial and Other Uses

Domestic water demands increased many times during the last 20 years due to increase in population, rising standard of living and the immense growth of urban centers. In 1995, domestic water requirements were put at 1356 MCM. Industrial and other demands were estimated for 1995 to be 668 MCM.

NATIONAL WATER BUDGET

Table 1 shows the national water budget for Saudi Arabia for the year 1995. It shows that the total demands for all sectors were 19838 MCM, 89.9% of which was for agriculture, 6.9% for domestic uses and 3.3% for industrial and other minor uses. The table also clearly shows the sources used to meet these demands. Surface and renewable ground water satisfied 10.1% of these demands. Desalinized sea water and treated wastewater met 3.7% and 0.5% of these demands, respectively. The largest share of the 1995 demands (85.7%) came from non renewable ground water. The actual withdrawal of non renewable ground water in 1995 was about 17000 MCM; with almost 93% of this amount used for irrigation (Al-Turbak, 1996).

Table 1. National water budget, 1995

	MCM	%
Demands		
Agriculture	17,814	89.9
Domestic	1,356	6.9
Industrial + Others	668	3.2
Total	**19,838**	**100**
Resources Used		
Nonrenewable GW	17001	85.7
Renewable sources	2000	10.1
Desalinized Sea Water	730	3.7
Treated Wastewater	107	0.5
Total	**19,838**	**100**

MAJOR PROBLEMS FACING WATER SECTOR IN SAUDI ARABIA

Water supplies and demands in any developing country face many difficulties and problems. Saudi Arabia provided the water supplies with its utmost attention. However, certain problems continued to bother planners and there will be probably worse in the future if no solutions are introduced. The most serious problems are:

1. Demand for water in the agricultural sector has grown to a level much higher than the renewable resources of the country. This meant that major aquifers were mined at a very fast rate. If this trend continues in the future, nonrenewable ground water resources will be depleted soon. The government, however, has introduced some measures to reduce to some extent the excessive pumping

from ground water reserves.

2. Desalinized sea water is currently used to meet part of the ever growing domestic demands. The government, has spent billions of dollars in construction, operation and maintenance of desalination plants. But with the increase of population in urban centers, deceasing ground water supplies and lack of conservation, domestic water supplies will be in danger in the future.

3. Treated wastewater represents a very important source to be utilized for many purposes in Saudi Arabia. However, the amounts actually used now are small. This is mainly due to slowness in wastewater treatment plants construction and in providing necessary facilities to transport treated wastewater to areas where it can be efficiently used. Another problem related to wastewater is the lack of laws and regulations governing its use.

4. Surface water and renewable ground water represents the most important natural water resources for the future. In spite of this, they have not been developed properly in some parts of the country. They also suffer from neglect and inefficiencies in the areas close to wadis and in old oases.

SUGGESTED SOLUTIONS TO MEET FUTURE WATER SHORTAGES

Shortages of water in arid areas are normal and expected. However, severe shortages of water will have serious social and economic effects. They will also cause severe health problems and may result in economic collapse. To avoid the problems that will be faced by the water sector in Saudi Arabia, or at least reduce their effects, it is necessary to concentrate actions in the following areas:

1. Reduce, in a gradual manner, the consumption in the agricultural sector, to a safe level. That level should be no more than the sum of renewable surface and ground water resources and treated wastewater.

2. Conservation of water use in arid regions is of a paramount importance. Although some conservation efforts (public awareness programs, television and other public media messages etc.) were made in the past, there is urgent need to do more. Actions needed include the use of drip irrigation, increase prices for water and

require drainage water recycling.

3. Give priority in government spending to wastewater treatment plants construction and to distribution and pumping facilities for transporting treated wastewater. This will result in more treated wastewater being available for different uses. Hence, some of the demands for agriculture and industry can be met from this resource.

4. Due to possible future shortages of domestic water supplies, it is necessary to reserve parts of the areas covered by major aquifers for future domestic use. MAW has made an effort in designating few protected areas for that purpose. However, there is need to do more in this regard. The reserved areas should be large enough especially close to major urban centers with at least 1 km^2 of protected surface area per 1000 people.

5. Increase production of desalination sea water and carry on more research in the area of desalination especially on methods and materials that will help to reduce costs.

6. Develop water resources in areas adjacent to wadis and use the renewable surface and ground water in old oases in an efficient manner.

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GIS Application in Water Resources Management and Planning

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GIS APPLICATION IN WATER RESOURCES MANAGEMENT AND PLANNING

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ABSTRACT

Water is the most valuable resource on our planet. Therefore, we need to bring water management and conservation knowledge into mainstream governmental decision making. The geography of water is an important component in any governmental decision making process, and thus, requires the right tools for overall management and decision support. GIS provides one of the powerful tools to collate, manage, analyze, and present water resources information to decision-makers. Using GIS for managing our water resources should reach into every sector of water policy, from groundwater and surface water management and planning to water distribution and use/ reuse. This presentation will highlight how GIS is used in various water resources applications around the world to conserve this valuable resource.

Reallocation of the Dammam Aquifer Yield in Bahrain: A Linear Programming Approach

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REALLOCATION OF THE DAMMAM AQUIFER YIELD IN BAHRAIN: A LINEAR PROGRAMMING APPROACH

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ABSTRACT

The position with respect to the future availability of fresh groundwater supplies in Bahrain is regarded most critical. Excessive withdrawal from the Dammam aquifer has resulted in severe deterioration of groundwater quality throughout the entire island. The urgent need for planning and management of water resources in Bahrain is obvious. The success in solving the management problem depends entirely on limiting abstraction rates from the Dammam aquifer to its sustained yield and reallocation of such yield among the competing water use sectors. In this paper, linear programming is applied to explore optimal policies for reducing abstraction and reallocating the aquifer yield. A simple, yet proved to be effective, approach is introduced to describe the spatial response of the aquifer system to abstraction activities in terms of incurred groundwater quality deterioration. The generated response coefficients are used to express the gain associated with reducing abstraction in the objective function of the linear programming problem. The obtained optimal solutions reveal that the target reduction of the present abstraction and reallocation of the sustained aquifer yield will not be achieved unless pumping is stopped completely in about half of the current abstraction areas. Areas assigned to zero abstraction by the applied model indicate that about 90% of the target reduction should take place in the agriculture water use sector, whereas municipal water use and other requirements will be affected by about 10% of the total reduction. The adopted solution scheme of staged reduction succeeded in identifying potential sites and priorities for imposing control measures on abstraction. The introduced approach provides a first-step solution to the problem of reallocating aquifer yield and may serve as a background to the solution of the management problem of the aquifer system.

KEYWORDS: Bahrain, Dammam Aquifer, Sustained Aquifer yield, Management of Aquifer Systems, Reallocation of Aquifer Yield, Management Models, Linear Programming.

INTRODUCTION

As most of the Arabian Peninsula, Bahrain has an arid to extremely arid climate. The prevailing climatic conditions and catchment configuration preclude any surface water in Bahrain. The only natural source of water is groundwater from aquifers developed principally in the carbonate rocks of the Dammam formations, which extend continuously from outcrops in Saudi Arabia towards Bahrain and the Gulf. At present, groundwater abstraction from the Dammam aquifer provides over 75% of the total water consumption in Bahrain: With fast growing population and accelerated development activities, Bahrain faces a serious water crisis. The problem stems from the limited natural potential of the aquifer and the progressive groundwater overdraft to fulfil the State's increasing water consumption.

Hydrogeological studies indicate that the Dammam aquifer can potentially provide up to 100 million cubic metres (MCM) annually without affecting the aquifer dynamics [1,2]. However, such sustained yield has been violated since the early 1960's. Inventories of groundwater abstraction show a drastic annual increase from about 60 MCM in the early 1950's to over 200 MCM in the mid 1990's. Consequently, groundwater overdraft in the Dammam aquifer, particularly over the past 30 years, has resulted in severe decline in the aquifer hydraulic heads. The declining water heads have permitted saline intrusion into the aquifer. Study of spatial and temporal deterioration of groundwater quality in Bahrain [3] reveals that the major limiting factor in the future availability of fresh water supplies is the increasing contamination by saline water, due to excessive withdrawal from the aquifer system.

In view of this critical situation, unless the current levels of abstraction are brought back to the level of sustained yield, the main source of water might be completely ruined, and Bahrain could be deprived from its natural fresh water supplies shortly after the turn of the new century. Realising the seriousness of this problem and its immediate threat to the development in Bahrain, an urgent need arises for the management of groundwater resources in Bahrain. A major challenge in the management process is the reduction and reallocation of abstraction.

In this paper, linear programming (LP) is applied to explore optimal policies to reduce abstraction and reallocate aquifer yield. The introduced approach provides a first-step solution to the problem of reallocating aquifer yield and may serve as a background to the solution of the management problem of the aquifer system.

REALLOCATION OF AQUIFER YIELD

The main goal of water resources engineers or planners, who deal with groundwater systems, is the management of the system. Using the terminology of system analysis, management of a system means making various decisions aimed at modifying the state of a considered system, that is to bring it from its existing state to a more desirable one. The reason for modifying the state of a considered system is to achieve certain goals and objectives through a set of decisions related to the operation of the system. Location, rate and time of abstraction from an aquifer are examples of decision variables. Water levels and solute concentration, as functions of location and time, are examples of state variables. When each decision variable is assigned a particular value, the resulting set of decision is called a policy. In general, there will be constraints, which will limit the possible policies. A policy, which does not violate any constraint, is a feasible policy, and the subset of all feasible policies is termed the policy space. Typically, the same goal or goals can be achieved by different policies; therefore management includes selection of the best policy. The concept of a best policy implies the existence of criteria where by the effect of any feasible policy on the desirable and undesirable output from the system can be measured. This criterion is called the objective. The statement by which the output of the system can be determined is called the objective function. This process is referred to as solving the management problem of a system.

In the long run, unless it is wished to mine all or part of the volume of water in storage, the volume of water withdrawn from an aquifer cannot exceed the aquifer's replenishment. However, this is only a limiting factor to the rate of withdrawal. To conserve an aquifer, especially from the quality point of view, the yield of an aquifer can be defined as the difference between all inflows and all outflows. Based on the same approach, terms such as sustained yield or safe yield are used to describe the maximum annual abstraction, which will not produce undesired results. Since inflows and outflows can be controlled, the yield of an aquifer system is a decision variable to be determined as part of its management.

In Bahrain, abstraction from the Dammam aquifer system is taking place in the northern half of the main island through 31 abstraction areas as shown in Figure1. Since the current abstraction levels exceed the aquifer's sustained yield by one fold, reallocation of the aquifer yield essentially involves an over 50% reduction of the current abstraction, to bring it back to that of the sustained annual yield (100 MCM). Reduction of abstraction and reallocation of the aquifer yield among the competing abstraction areas is a management problem, the solution of which should be based on the system response to any proposed operation policy.

Figure 1. Location of abstraction areas

In the standard approach of solving aquifer management problems, this is normally achieved by mathematical modelling to solve first the forecasting problem. The link between the management problem and the forecasting one is then established by using the technique of influence functions [4,5]. In the absence of a flow and solute transport model to solve the forecasting problem of the Dammam aquifer in Bahrain, an alternative approach based on using historical data to generate a set of response coefficients relating abstraction rates to deterioration of groundwater quality is adopted. Such approach is intended to explore the possible optimal solutions for the management problem of aquifer yield reallocation. The approach considers the concept that quality and quantity of groundwater abstracted from a specified location (abstraction area) within an aquifer are interrelated in such manner that the value of abstraction is reduced by the incurred quality deterioration. The suggested interrelationship is a linear salinity balance equation, which for a typical abstraction area can be expressed in the form

$$S_o P_a = P_r (S_o + \Delta S)$$

or

$$P_r = P_a S_o / (S_o + \Delta S)$$

and for a unit abstraction; $P_a = 1$

hence; $P_r = S_o / (S_o + \Delta S) = C_i$

Where, P_r is the reduced value of the actual abstraction P_a, S_o is the initial or background salinity before abstraction, ΔS is the salinity increase attributed to the actual abstraction, and C_i is a discount-value coefficient of the abstraction area. The suggested discount-value relationship for different initial salinity is shown in Figure 2.

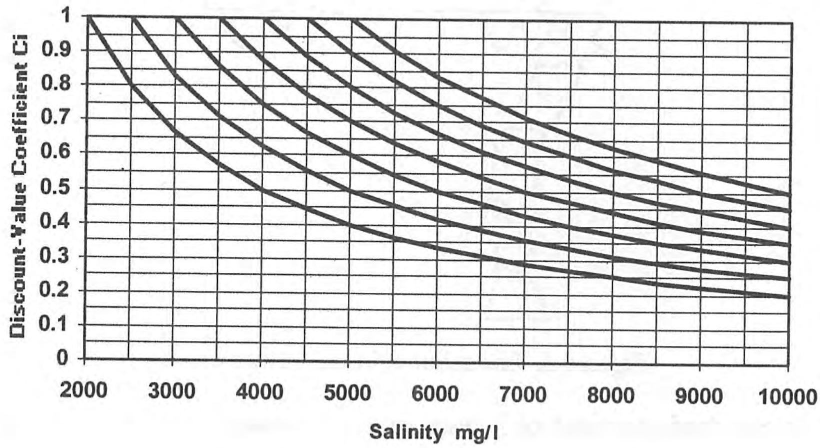

Figure 2. Discount-value relationship

The discount-value coefficients C_i represent the spatial response throughout the aquifer system to any abstraction activity in terms of quality changes. Obviously, abstraction areas with lower values of C_i contribute higher gains from reducing abstraction and vice versa. Salinity of the Dammam aquifer expressed in total dissolved solids (TDS) from the 1992 hydrochemical survey [3] is used to estimate the discount-value coefficients for the 31 abstraction areas as shown in Figure 3.

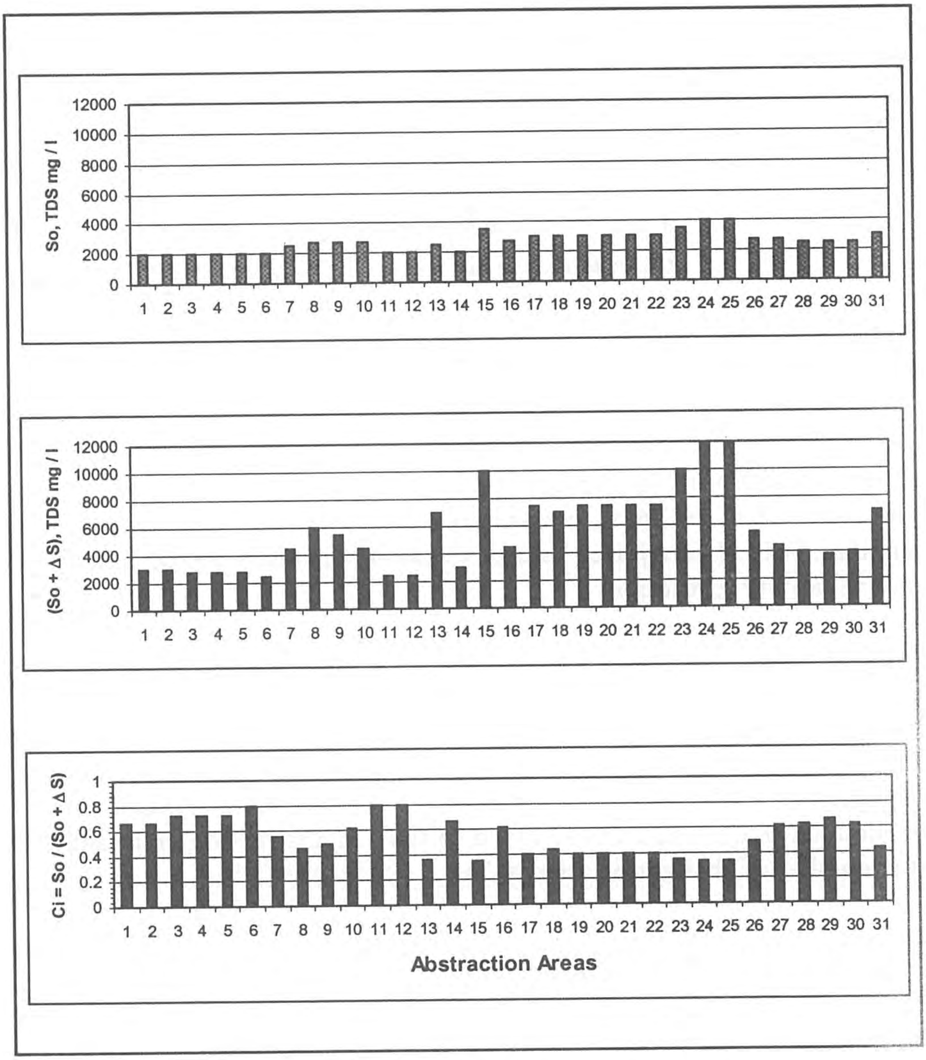

Figure 3. Discount-value coefficients C_i

STATEMENT OF THE LP PROBLEM

Linear programming (LP) is one of the powerful decisions making techniques used in solving the problem of allocating limited resources among competing users in an optimal manner. This means that among the various possible ways of allocating the given resources, the one which will optimise a specified objective function is to be selected. The objective function of such problem is normally a simple linear algebraic equation. If the constraints also can be expressed as linear algebraic equations or inequalities involving nonnegative decision variables, the result is a typical

LP problem. The principles and techniques of solving LP problems are well described in the literature, e.g. [6,7].

The LP problem at hand can be formulated as follows: the problem is to determine the values of n decisions variables P_i $(i = 1, ..., n)$ which will maximise the objective function Z

$$Z = C_1P_1 + C_2P_2 + ...+ C_nP_n$$

Subject to the m constraints

$$a_{j1}P_1 + a_{j2}P_2 + ...+ a_{jn}P_n \{\geq, =, \leq\}\ b_j \ (j = 1, ..., m)$$

Where, a_{ji} and b_j are known constants, and for each constraint only one of the signs > , = , < holds, but the sign may vary from one constraint to another. It is also required that all decision variables should satisfy the nonnegativity restriction

$$P_i \geq 0 \ , \ i = 1, ..., n$$

Where, the objective function Z is the total gain associated with reallocating the specified aquifer yield among the abstraction areas, P_i's is the annual abstraction in MCM to be allocated to the i th abstraction area, C_i's is the discount-value coefficient assigned to the i th abstraction area, and n is the number of abstraction areas = 31.

Through the imposed constraints, two main LP models are implemented to explore the possible optimal solutions. In the first model, the solution is sought for the total abstraction to be reallocated in all abstraction areas, regardless of the purpose of water use. In the second one, additional constraints are imposed to satisfy the present annual abstraction requirements (54.81 MCM) for municipal water supply. In both models, spatial distribution of demand is accounted for by limiting the maximum values of abstraction, reallocated at any of the abstraction areas, to be $\leq$ the 1990 abstraction levels [2]. The structure of the two LP models is illustrated in Tables 1 and 2.

Since the reallocation process involves significant reduction of the current abstraction levels, from the practical viewpoint, it is unlikely that such reduction could be achieved in one step. Therefore, the applied solution scheme for both models assumes that the target reduction will be staged on four phases. Accordingly, the aquifer yield constraint is set equal to 160, 140, 120, and finally 100 MCM / year, for the four phases, respectively. Obviously, the solution is implemented on four successive runs.

Table 1. Structure of LP Model 1

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31	Type	RHS bj
MAX	0.667	0.667	0.727	0.727	0.727	0.800	0.556	0.458	0.500	0.611	0.800	0.800	0.357	0.667	0.350	0.611	0.400	0.429	0.400	0.400	0.400	0.400	0.350	0.333	0.333	0.500	0.611	0.625	0.667	0.625	0.429		
j	aj1	aj2	aj3	aj4	aj5	aj6	aj7	aj8	aj9	aj10	aj11	aj12	aj13	aj14	aj15	aj16	aj17	aj18	aj19	aj20	aj21	aj22	aj23	aj24	aj25	aj26	aj27	aj28	aj29	aj30	aj31		
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	=	100
2	1																															<=	8.11
3		1																														<=	5.68
4			1																													<=	7.84
5				1																												<=	2.45
6					1																											<=	4.28
7						1																										<=	8.33
8							1																									<=	6.32
9								1																								<=	2.47
10									1																							<=	4.17
11										1																						<=	6.22
12											1																					<=	2.73
13												1																				<=	6.07
14													1																			<=	3.04
15														1																		<=	11.14
16															1																	<=	0.99
17																1																<=	17.72
18																	1															<=	2.39
19																		1														<=	6.82
20																			1													<=	9.01
21																				1												<=	5.87
22																					1											<=	11.66
23																						1										<=	5.79
24																							1									<=	3.79
25																								1								<=	7.34
26																									1							<=	2.08
27																										1						<=	8.09
28																											1					<=	7.31
29																												1				<=	2.31
30																													1			<=	6.74
31																														1		<=	6.70
32																															1	<=	1.91

Table 2. Structure of LP Model 2

	P'1	P2	P'3	P4	P'5	P'6	P7	P8	P9	P'10	P11	P12	P13	P'14	P15	P'16	P17	P18	P19	P20	P'21	P22	P23	P24	P25	P'26	P'27	P28	P'29	P'30	P31	Type	RHS bj
MAX	0.667	0.667	0.727	0.727	0.727	0.800	0.556	0.458	0.500	0.611	0.800	0.800	0.357	0.667	0.350	0.611	0.400	0.429	0.400	0.400	0.400	0.400	0.350	0.333	0.333	0.500	0.611	0.625	0.667	0.625	0.429		
j	aj1	aj2	aj3	aj4	aj5	aj6	aj7	aj8	aj9	aj10	aj11	aj12	aj13	aj14	aj15	aj16	aj17	aj18	aj19	aj20	aj21	aj22	aj23	aj24	aj25	aj26	aj27	aj28	aj29	aj30	aj31		
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	=	45.19
2	1																															<=	4.22
3		1																														<=	5.68
4			1																													<=	5.59
5				1																												<=	2.45
6					1																											<=	3.21
7						1																										<=	2.84
8							1																									<=	6.32
9								1																								<=	2.47
10									1																							<=	4.17
11										1																						<=	4.38
12											1																					<=	2.73
13												1																				<=	6.07
14													1																			<=	3.04
15														1																		<=	3.40
16															1																	<=	0.99
17																1																<=	5.87
18																	1															<=	2.39
19																		1														<=	6.82
20																			1													<=	9.01
21																				1												<=	5.87
22																					1											<=	9.09
23																						1										<=	5.79
24																							1									<=	3.79
25																								1								<=	7.34
26																									1							<=	2.08
27																										1						<=	1.54
28																											1					<=	3.10
29																												1				<=	2.31
30																													1			<=	1.96
31																														1		<=	4.13
32																															1	<=	1.91

SOLUTION OF THE LP PROBLEM

Tables 3 and 4 present the solution obtained by using one of the available PC programs for solving linear programming problems. Table 3 displays the solution of model 1 in terms of the total staged distribution of abstraction, regardless of the purpose of water use. Figure 5 illustrates the rates and pattern of abstraction achieved by the first model. The final phase solution of model 1 yields a maximum gain of 67.9, with 16 no-pumping abstraction areas and a reduction in municipal water requirements amounts to 9.12 MCM / Year. Table 4 exhibits the solution of model 2 in terms of staged distribution of abstraction after satisfying the corresponding imposed municipal water supply requirements. Abstraction rates and pattern illustrated in Figure 5 represent the optimal solution as obtained from the second model. The final phase solution of model 2 yields a maximum gain of 66.33, with 14 no-pumping abstraction areas.

Table 3. Solution of LP Model 1

Area No.	Phase I	Phase II	Phase III	Phase IV
	160 MCM	140 MCM	120 MCM	100 MCM
1	8.114	8.114	8.114	8.114
2	5.68	5.68	5.68	5.68
3	7.84	7.84	7.84	7.84
4	2.45	2.45	2.45	2.45
5	4.28	4.28	4.28	4.28
6	8.334	8.334	8.334	8.334
7	6.32	6.32	6.32	0
8	2.47	2.47	0	0
9	4.17	4.17	1.95	0
10	6.22	6.22	6.22	2.58
11	2.728	2.728	2.728	2.728
12	6.07	6.07	6.07	6.07
13	0	0	0	0
14	11.14	11.14	11.14	11.14
15	0	0	0	0
16	17.72	17.72	17.72	17.72
17	0	0	0	0
18	6.822	6.822	0	0
19	3.26	0	0	0
20	5.87	0	0	0
21	11.66	0.79	0	0
22	5.788	5.788	0	0
23	0	0	0	0
24	0	0	0	0
25	0	0	0	0
26	8.094	8.094	8.094	0
27	7.31	7.31	7.31	7.31
28	2.31	2.31	2.31	2.31
29	6.74	6.74	6.74	6.74
30	6.703	6.703	6.703	6.703
31	1.906	1.906	0	0

Table 4. Solution of LP Model 2

Area No.	Phase I	Phase II	Phase III	Phase IV	Water Supply Requirements MCM
	160 MCM	140 MCM	120 MCM	100 MCM	
1	4.22	4.22	4.22	4.22	3.89
2	5.68	5.68	5.68	5.68	
3	5.59	5.59	5.59	5.59	2.25
4	2.45	2.45	2.45	2.45	
5	3.21	3.21	3.21	3.21	1.07
6	2.84	2.84	2.84	2.84	5.49
7	6.32	6.32	6.32	0	
8	2.47	2.47	0	0	
9	4.17	4.17	0	0	
10	4.38	4.38	4.38	0	1.84
11	2.73	2.728	2.728	2.728	
12	6.07	6.07	6.07	6.07	
13	0	0	0	0	
14	3.4	3.4	3.4	3.4	7.74
15	0	0	0	0	
16	5.87	5.87	5.87	0	11.85
17	0	0	0	0	
18	6.82	6.822	0	0	
19	3.01	0	0	0	
20	5.87	0	0	0	
21	9.09	0	0	0	2.57
22	5.79	3.76	0	0	
23	0	0	0	0	
24	0	0	0	0	
25	0	0	0	0	
26	1.54	1.54	0.67	0	6.55
27	3.1	3.1	3.1	0.34	4.21
28	2.31	2.31	2.31	2.31	
29	1.96	1.96	1.96	1.96	4.78
30	4.38	4.38	4.38	4.38	2.57
31	1.91	1.906	0	0	

CONCLUSIONS AND RECOMMENDATIONS

The concept of discounting the value of abstraction by the incurred quality deterioration, as introduced in this work, provided a simple yet effective approach to describe the spatial response of the aquifer system to abstraction activities in terms of quality changes. The outcome, the so called discount-value coefficients, are then used to express the gain associated with reducing abstraction in the objective function of the linear programming problem. Optimal solutions obtained from the applied two LP models indicate that the target reduction of the present abstraction and reallocation of the sustained aquifer yield will not be achieved unless pumping is stopped completely in about half of the current abstraction areas. The adopted solution scheme of staged reduction suggests that pumping should be ceased in the first phase in six abstraction areas, namely, areas 13, 15, 17, 23, 24 and 25. The first three areas lie within the zone of saline upward flow from the deeper aquifer horizons in north-central and western Bahrain. The other three areas are situated in the aquifer zone affected by seawater intrusion in eastern Bahrain. In the second phase, abstraction areas 19 and 20 are shut down. The aquifer in these two areas is influenced by the extensive saline sabkhas south west of Bahrain. Additional eight no-pumping areas are also identified in the third and final phases. Results of both models reveal that about 90% of the target reduction in abstraction should take place in the agriculture water use sector.

The approach introduced in this work succeeded in exploring the optimal solutions for reducing abstraction and reallocating aquifer yield. However, the impacts of implementing the obtained solutions, in terms of modified state variables and aquifer recovery, cannot be assessed by this approach. This can only be achieved through simulation modelling of flow and solute transport in the aquifer system. Therefore, the development of such model for the Dammam aquifer in Bahrain is strongly recommended.

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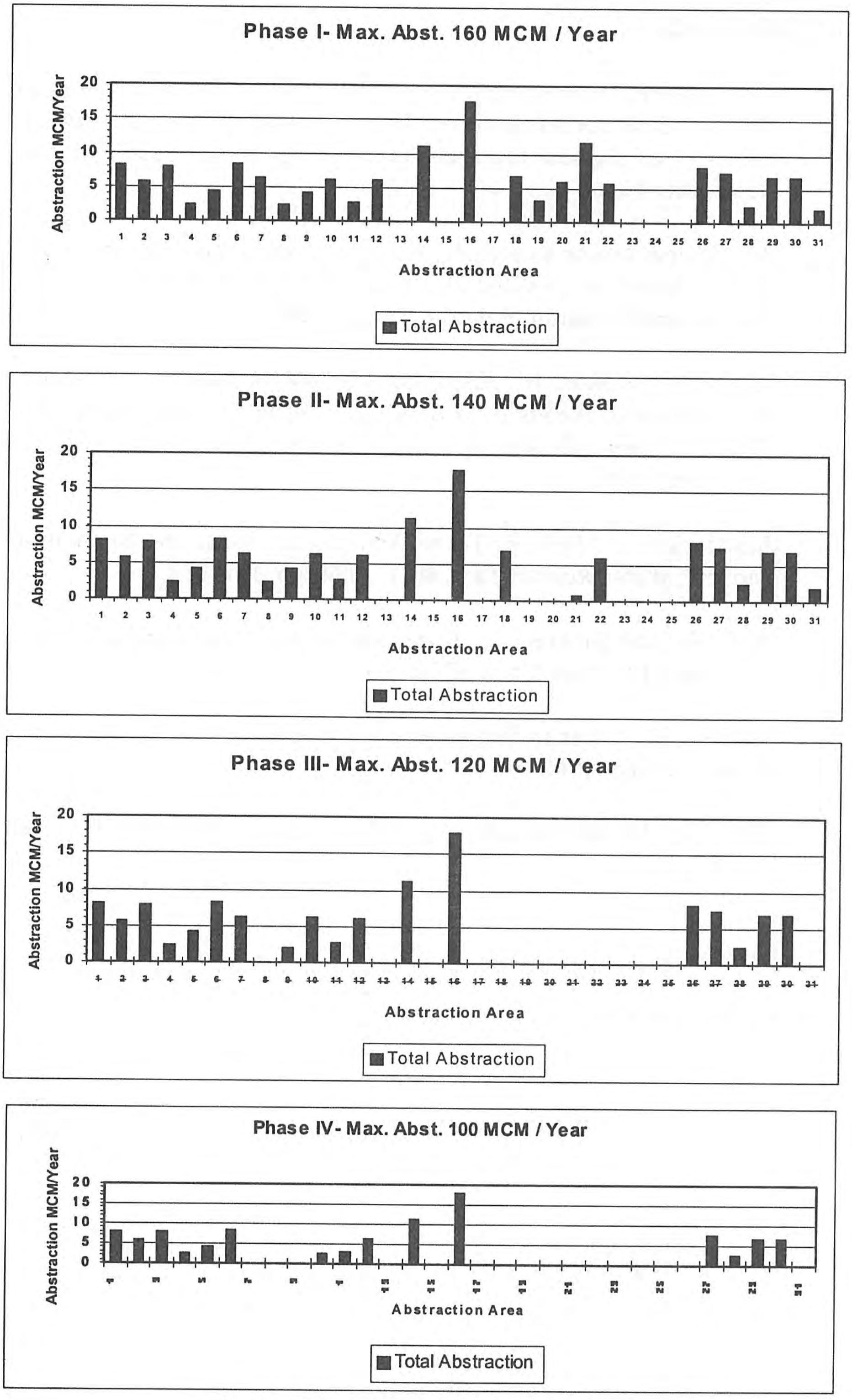

Figure 4. Solution of the LP Model 1

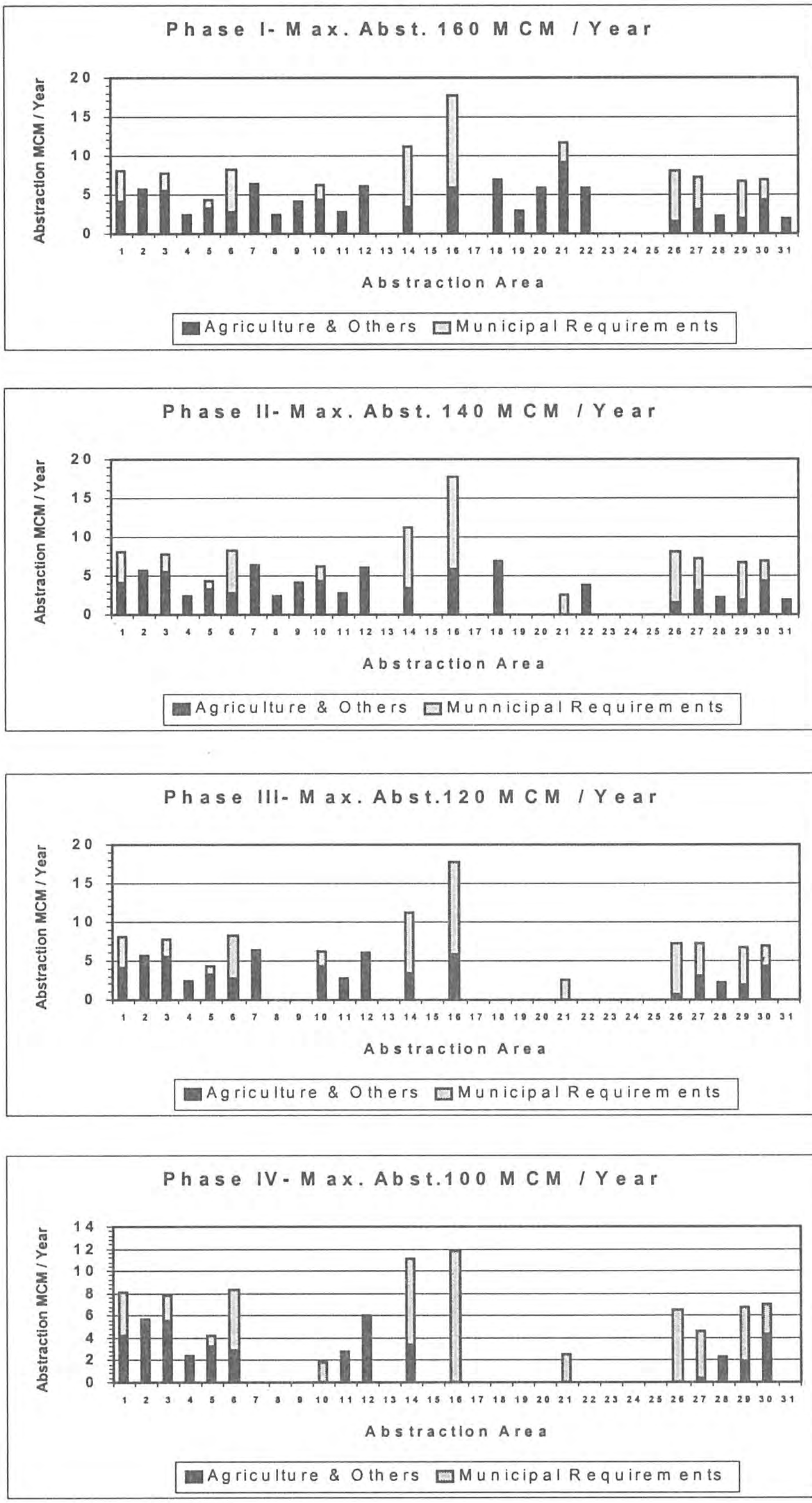

Figure 5. Solution of the LP Model 2

Cross Sectional Analysis of Residential Water Consumption in the City of Riyadh

Saud Taher and Adnan Al Saati

CROSS SECTIONAL ANALYSIS OF RESIDENTIAL WATER CONSUMPTION IN THE CITY OF RIYADH

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ABSTRACT

A cross sectional analysis for residential water demand was conducted to help understand and explain the spatial and temporal variations in per capita water use in the rapidly growing city of Riyadh, Saudi Arabia. The analysis was based on data previously collected from May 1983 to June 1984. 195 randomly selected households were distributed to three groups according to house condition, household income level, and social and cultural factors. The generated models using stepwise multiple regression indicated that plot size and number of males, females and children are the most significant independent variables. Although, coefficients of determination achieved for most of the developed models were low (0.2-0.5), the independent variables could still explain a part of the variations for such a complex social and cultural structure.

KEY WORDS: Residential water demand, Regression, Cross sectional analysis, Saudi Arabia.

INTRODUCTION

Supplying water to urban areas requires major capital investment in resource development, treatment, storage and distribution. The demand for water worldwide is enormous and will continue to grow rapidly especially in developing countries due to the increasing population and their standard of living, industrialization, urbanization and agricultural development [Kindler and Rusell, 1984]. The continuing need for upgrading and expanding the water supply systems to meet these flourishing demands dictated the necessity for accurately predicting future requirements so that maximum efficiency in funds allocation can be optimally achieved.

Forecasts of future urban water demand have traditionally been obtained by the projection of historic trends in per capita consumption and population. Such methods could be expected to give reasonably accurate predictions only while there is a steady uniform change in per capita consumption [Power, et al., 1981]. One possible way to improve prediction is to use the component model, in which water consumption is divided into its major components. Future changes in each component are predicted and then the overall results are aggregated [Parker and Penning-Rowsell, 1980]. This method, in contrast of the projection technique, is data demanding and more challenging since it attempts to explain the reason behind any changes in water consumption pattern. Therefore, factors, which are likely to influence the various components of water consumption, are identified, measured and their likely effects on future consumption are assessed.

Among the elements that contribute to the total urban water consumption – residential, industrial, commercial, public institution, and system losses – residential water use is generally the largest in terms of its quantity and size of investment. It may constitute well over half of the total municipal use in many communities [Kindler and Rusell, 1984]. In addition, it commonly requires extensive and expensive distribution network and treatment facilities that meet high quality standards. Therefore, it is essential to estimate and examine in details the factors that influence its spatial and temporal variation for a given urban area. An example of the wide variation of this estimate is given for three selected countries, Netherlands; Sweden and USA as 104, 215 and 295 liters per capita per day (lpcd) respectively which show the need for determining those variables responsible for these differences [Kindler and Rusell, 1984].

Many studies have been conducted to determine the factors that influence the level of residential water demand such as Schneider and Whitlatch [1991]; Wilson and Luke [1990]; Khadam [1985]; Grima [1985]; Weber

[1989]; Abu Rizaiza [1991] and Ayoade [1987]. Most of these studies have agreed on the fact that family size and density of occupancy in a residence are the most important ones. Khadam [1985], for instance, realized that the per capita consumption decreases with increase in the family size and thereby implying an economy of scale. He also reported that White et al., in East Africa found that the larger per capita uses were found in households with working adults. A very small consumption was observed where there was only one elderly adult and the greater the number of children the smaller is the per capita water withdrawal. In a study of residential water demand and economic development in India, it was stated that the size of a household is negatively related to the level of water consumption. Consequently, water consumption tends to decrease with the density of occupancy.

Many investigators have studied the relationship between water pricing, level of income and the amount of water consumed. It has been found that, above a minimum essential level, water is needed as an economic commodity. The effect of pricing upon water use is of basic importance to residential water management. Price setting is one of the few instrumental variables at the disposal of the management. Prices may be used to allocate resources efficiently in publicly controlled monopolies such as municipal water works. On the other hand, income level of a household is an economic factor widely accepted as a determinant of residential water use [Grima, 1972].

The consideration of metering as a significant factor influencing the quantity of water use is widely accepted and justified [Khadam, 1985]. Metering is an effective practice to discourage the excessive misuse of water because the consumer will tend to minimize his bill. Leaks from service pipes, running taps to waste, insufficient sprinkling and all other wasteful patterns of water use will be corrected promptly. Grima, [1972] found in his study on Toronto, Canada that the rate of water use for lawn sprinkling in non-metered areas is almost three times the rate of water use in metered areas on maximum day. Berry, as reported by Khadam [1985] observed that the introduction of metering in Honiara, British Solomon Islands reduced the water consumption by 50%.

The type of disposal system used for sanitary waste has also a considerable impact on the water use. In sewered areas or where dwellers are using septic tanks, it is likely that consumption will be higher than those using soakage pits, pit latrines, surface drains or similar methods.

Reduction in water use can be attained by appropriate modification of the conventional water-use appliances such as toilet flushing systems, showering and bathing facilities, hand washing sinks, dishwashers, washing machines, etc. The design and operation of these appliances could be reformed to provide acceptable services with minimum quantity of water without imparting adverse hygienic effect [Khadam, 1985].

As shown above several factors influence the quantity and pattern of residential water demand. It is the purpose of this paper to conduct a cross sectional analysis, in which a slice through customer profile at specific time frame (1983-1984) is taken, to identify user attributes that might explain the variation in consumption among users in the city of Riyadh. Several predictive models using step-wise multiple regression are formulated for three common classes of users, while taking into consideration the seasonal variations of demand. The analysis is based on field survey and measurements previously collected for 195 households from May 1983 to June 1984 by Al-Kadi [1986]. Study results are expected to explain the variation in per capita water consumption and subsequently, could be of value to consultants and planners in predicting future water demands in Riyadh.

RIYADH WATER DEMAND

Since the early seventies, the city of Riyadh, the capital of the Kingdom of Saudi Arabia, has been subjected to phenomenal growth of population and urbanization. The populated area of the city for example, has grown from less than one Km^2 in 1918 to about 1600 Km^2 in 1997. This fast growth required planning in all infrastructure systems especially water resources and water supply distribution network. Due to the lack of reliable data with respect to per capita water use in the city, water development consultants and planners, have been forced to use their experience or educated guesses in forecasting the water consumption in Riyadh. Table (1) shows an example illustrating the variation in these estimates, varying up to 50%. In addition, these values can be compared in future to the United Nations' estimate of average water consumption around the world for the years 1966 and 2000, which are 156 and 235 lpcd respectively, [IWRA, 1982]. It shows a dramatic variation from world average consumption.

Table (1): Various estimates of water demand per capita by various consultants (in liters/capita/day)

Consultant Name (year)	1965	1970	1975	1980	1985	1990	1995	2000
VBB (1964)	160	-	-	-	240	-	280	-
Sogreah (1967)	-	240	280	300	300	300	300	300
VBB (1976)	-	180	200	220	240	260	280	300
VBB (1978)	-	-	200	220	240	290	340	390
MAW, M.A. Butain (1977)	-	-	-	280	300	320	330	335
Kalthem (1978)	-	-	-	300	-	340	-	380
SWCC (VBB, 1978)	-	-	240	320	350	375	385	395
Sir MacDonald & Partners (1978)	-	-	-	-	-	-	-	400
Sogreah-Seureca (1980)	-	-	-	280	310	375	415	450
Ratio between highest and lowest estimates	-	1.33	1.40	1.36	1.46	1.44	1.48	1.50

As an attempt to come up with more accurate estimates, an extensive study was conducted by Al-Kadi [1986]. He completed a field investigation for determining the daily per capita average, maximum and minimum residential water consumption for the city of Riyadh. In addition, an attempt was also made to study the individual influence of several factors on the actual consumption from May 1983 to June 1984. 195 individual houses were randomly selected representing random samples distributed to three groups-large villa occupants, small villa occupants and apartment occupants. Variables that were considered in the study were: week days, week ends, seasons, number of males, number of females, number of children, number of residents, connection to sewers, nationality, religion, income level, house plot area, type of house, and the presence of sabeel tap (a cold water tap fixed on the boundary wall of the house to be used for drinking of pedestrians).

Although Al-Kadi's study has revealed many important conclusions, it did not, however, show any attempt to simultaneously relate residential water consumption to its explanatory variables in order to determine those key variables that could explain its variation. This fact, which was also recognized by Al-Kadi, has encouraged Quraishi et al. [1990] to develop non-linear regression models to forecast water demand for both natives and expatriates living in villas and apartments. The low values of goodness of it (0.22) for most of these generated models and the negligence of considering the seasonal effect on consumption were the initiative for this research.

DATA CHARACTERISTICS

Data involved in this study consisted of observations of relevant variables for 195 individual households as indicated previously. The variables were selected in order to reflect the social, economical, environmental and cultural characteristics that may influence water use. The selected variables can be classified into two categories: non-quantitative and quantitative variables.

The non-quantitative variables include location, type of construction, presence of swimming pools, connection to public sewerage, nationality, religion and availability of sabeel tab. The quantitative variables, on the other hand, include plot area, number of males, number of females, number of children, ground water tank volume, upper water tank volume, and monthly income level. Table (2) shows both the independent and dependent variables.

Table (2): Variables included in the analysis

Variable Number	Variable Name	Variable Description
1	LOC	Location
2	DEW	Type of dwelling
3	POOL	Presence of swimming pool
4	SEW	Connection to public sewage
5	NAT	Nationality
6	REL	Religion
7	SAB	Sabeel water
8	PA	Plot area
9	NOM	Number of males in a household
10	NOF	Number of females in a household.
11	NOC	Number of children in a household.
12	FS	Number of household members
13	TV	Total volume of ground water tank and upper water tank in m^3
14	MIL	Monthly income level: 1) less than SR 5000; 2) between SR 5000 and SR 10000 and 3) more than SR 10000.
15	Q_s	Average quantity consumed in summer season in m^3
16	Q_w	Average quantity consumed in winter season in m^3
17	Q_a	Average annual quantity consumed in m^3

The 195 samples were divided into three groups - A, B, and C based mainly on location, which might reflect their cultural behavior. Group A represents relatively high income tenants living in big villas with large landscape that mostly include swimming pools. Group B houses consisted of medium size villas with small garden areas accommodating medium income people. Finally, group C is mostly low income residence living in apartment buildings with neither gardens nor swimming pools [Al-Kadi, 1986].

THE HYPOTHESIZED MODEL

Since the pattern of water use is related to the living environment of the residents and changes in climate, the demand can then be estimated for each of the three groups of consumers by formulating predictive models that reflect annual and seasonal variations. A summer season which is assumed to extend for a duration of 8 months (Mid March thru Mid

November) and characterized by an average temperature higher than 20'C. The winter season is assumed to include the remaining four months of the year where the average temperature is lower than 20'C.

Accordingly, eighteen different predictive models were formulated estimating residential water use in liters per capita per day averaged over the (1) summer period (2) winter period and (3) whole year. These variables are used as dependent variables and they are used in turn for six groups and subgroups of water users in Riyadh. These groups are (a) group A consumers (b) group B consumers (c) group C consumers (d) consumers in all groups combined (e) consumers living in villas in all groups and (f) consumers living in buildings in all groups.

The hypothesized linear model proposed can be represented in the following form:

Q_i = F(LOC, DEW, POOL, SEW, NAT, REL, SAB, PA, NOM, NOF, NOC, FS, TV, MIL)

where:

Qi = average quantity consumed in m^3 /household for a specified period (i.e. season, or year, Q_s, Q_w or Q_a)
Other terms are as defined in Table (2)

CROSS SECTIONAL REGRESSION ANALYSIS

First order correlation matrix for all dependent variables for each user group was calculated. This correlation matrix is used to provide a basis for judging the effects of interdependency among the independent variables themselves and the dependent variables as well. A minimal interdependency among the explanatory variables was found with few exceptions. Stepwise regression was then applied to determine the best-fit models as shown in Table (3). As an attempt to improve the models prediction as indicated by the low values of R^2, regression was carried out on the logarithmically transformed data resulting in the nonlinear relationships shown in Table (4).

PROJECTING WATER USE

Table (5) represents the average seasonal and annual water use for the various groups and subgroups considered in this study. It is developed by substituting mean values of the independent variables into the corresponding best fit equation developed and presented in previous sections. Table (6) is similar to Table (5) but it is based on using the transformed equations. In general, the average predicted per capita water uses for all groups considered using the transformed equations were found lower than average values obtained when the original best fit equations are used for prediction. Based on the results of Tables (5) and (6), the average per capita water uses for consumers in group A were the highest among all groups. Similarly, the average per capita water uses for consumers living in villas for the reasons considered were found higher than corresponding values for consumers living in buildings. This is expected since consumers in villas will use more water to irrigate their gardens which are almost nonexistent for people living in building. As expected the average summer water use for each group considered was found higher than the winter water use.

Table (3): Best fit linear models

Type of Users	Regression Model	R^2
Group A Users	Q_s = 104.343 + 77.816 NOM + 0.976 PA Q_w = -6.977 + 41.243 NOM + 0.292 PA Q_a = -111.320 + 119.059 NOM + 1.269 PA	0.234 0.162 0.213
Group B Users	Q_s = -58.557 + 45.891 NOF + 0.506 PA Q_w = -7.347 + 20.908 NOF + 0.136 PA Q_a = 63.347 + 66.488 NOF + 0.639 PA	0.293 0.200 0.278
Group C Users	Q_s = 446.335 + 35.897 FS -144.728 NOC + 93.573 NOF Q_w = 100.268 + 21.131FS - 97.220 NOC + 59.009 NOF Q_a = 546.603 + 57.023 FS - 241.948 NOC + 152.582 NOF	0.484 0.499 0.470
All Groups	Q_s = -103.479 - 11.193 NOC + 62.638 NOF + 0.954 PA Q_w = -331.378 + 17.968 NOM + 25.772 NOF + 0.207 PA + 125.392 MIL Q_a = -926.652 + 61.313 FS - 70.331 NOC + 1.018 PA + 334.606 MIL	0.334 0.300 0.335
All Users Living in Villas	Q_s = -1021.47 + 108.93 NOM + 50.45 NOF + 0.65 PA + 253.12 MIL Q_w = -453.25 + 53.94 NOM + 21.07 NOF + 0.148 PA+ 130.41 MIL Q_a = -1475.76 + 162.89 NOM + 71.48 NOF + 0.8 PA + 383.98 MIL	0.297 0.211 0.273
All Users Living in Apartments	Q_s = 24.920 - 83.000 NOC + 102.861 NOF + 0.971 PA Q_w = -105.070 - 63.587 NOC + 69.091 NOF + 0.489 PA Q_a = -80.150 - 146.587 NOC + 171.951 NOF + 1.460PA	0.434 0.456 0.447

Table (4): Best fit logarithmic models

Type of Users	Regression Model	R^2
Group A Users	$log\ Q_s$ =2.4378 + 0.0275 NOM + 0.000323 PA	0.385
	$log\ Q_w$ =1.9414 + 0.0357 NOM + 0.000327 PA	0.299
	$log\ Q_a$ =2.5697+0.0299 NOM + 0.0175 NOF+0.00019 PA	0.340
Group B Users	$log\ Q_s$ =2.1105 + 0.0483 NOF + 0.000403 PA	0.278
	$log\ Q_w$ =1.7820 + 0.0435 NOF + 0.000266 PA	0.187
	$log\ Q_a$ =2.2547 + 0.0475 NOF + 0.000390 PA	0.282
Group C Users	$log\ Q_s$ =2.4670 + 0.000300 PA + 0.0109 TV	0.474
	$log\ Q_w$ =1.9654 + 0.999261 PA + 0.0153 TV	0.485
	$log\ Q_a$ =2.5405 + 0.0218 TV	0.351
All Groups	$log\ Q_s$ =2.4125- 0.0027 NOC + 0.0083 NOM+ 0.0169 NOF + 0.000316 PA	0.449
	$log\ Q_w$ =1.9555+0.0158 NOM + 0.0144 NOF + 0.000288 PA	0.395
	$log\ Q_a$ =2.3858+0.0155 NOM + 0.0143 NOF + 0.000197PA	0.396
All Users Living in Villas	$log\ Q_s$ =2.2701 + 0.0399 NOM + 0.0192 NOF + 0.000267PA	0.398
	$log\ Q_w$ =1.8504 + 0.0539 NOM + 0.000275 PA	0.296
	$log\ Q_a$ =2.2513 + 0.0473 NOM + 0.0199 NOF + 0.000153 PA + 0.0805 MIL	0.371
All Users Living in Apartments	$log\ Q_s$ =2.0370 + 0.000447 PA + 0.3295 MIL	0.498
	$log\ Q_w$ =1.6045 + 0.0124 FS - 0.0189 NOC + 0.000244PA + 0.2930MIL	0.551
	$log\ Q_a$ =2.3202 + 0.0087 FS + 0.2869 MIL	0.378

Table (5): Predicting water use from best fit equations using mean values of independent variables

	Type of cross section					
	Group (A)	**Group (B)**	**Group (C)**	**Overall**	**Villas**	**Buildings**
PA (m^3)	582	641	989	826	777	979
NOM (#)	5.8	5.0	14.0	7.6	5.0	15.8
MOF (#)	5.6	4.8	15.5	7.9	5.2	16.2
NOC (#)	4.1	1.7	11.0	5.2	3.4	42.3
FS (#)	15.5	11.4	40.1	20.6	13.6	42.3
TTV (m^3)	31.3	32.7	32.7	32.0	30.8	35.6
MIL (level)	2.66	2.10	2.00	2.33	2.47	1.89
Q_s m^3/season lpcd	1178.5 316.8	486.1 177.7	1744.2 181.2	1121.3 227.0	916.6 280.8	1745.5 171.9
Q_w m^3/season lpcd	481.0 258.6	180.2 131.7	792.8 164.8	471.9 190.0	363.1 222.5	1279.6 261.4
Q_a m^3/season lpcd	1660.4 297.6	665.4 162.1	2537.0 175.7	1591.2 214.6	1279.6 261.4	2551.0 167.7

Table (6): Predicting water use from best fit logarithmic equations log using mean values of independent variables

	Type of cross section					
	Group (A)	**Group (B)**	**Group (C)**	**Overall**	**Villas**	**Buildings**
PA (m^3)	852	641	989	826	777	979
NOM (#)	5.8	5.0	14.0	7.6	5.0	15.8
MOF (#)	5.6	4.8	15.5	7.9	5.2	16.2
NOC (#)	4.1	1.7	11.0	5.2	3.4	10.8
FS (#)	15.5	11.4	40.1	20.6	13.6	42.3
TTV (m^3)	31.1	32.7	32.7	32.0	30.8	35.6
MIL (level)	2.66	2.10	2.00	2.33	2.47	1.89
Q_s m^3/season lpcd	745.6 200.4	398.7 145.7	1318.7 137.0	717.9 145.2	598.3 183.3	1251.3 123.3
Q_w m^3/season lpcd	267.3 143.7	145.0 106.0	541.7 112.6	267.4 108.2	215.6 132.1	521.9 102.8
Q_a m^3/season lpcd	1008.9 180.8	540.4 131.7	1792.1 124.1	972.9 131.2	811.0 165.6	1700.0 111.6

RESULTS

The effect of each considered independent variable on the level of water use is presented below:

THE PLOT AREA

The developed water use prediction models indicate that the plot area (PA) is a major factor in determining water use. This was the case for groups A and B. However, for group C the plot area (PA) did not appear to be a contributing factor. This is obviously because of the absence of gardens in buildings so water is mostly used indoor.

NUMBER OF MALES

Number of males (NOM) is proven to be a significant variable in determining water use only for group A water users and also for water users living in villas.

NUMBER OF FEMALES

The number of females (NOF) was a significant variable in predicting water use for group B water users and for consumers of all groups living in villas.

NUMBER OF CHILDREN

The effect of number of children (NOC) on water consumption was found significant in predicting water use for group C users and consumers of all groups living in buildings. This result is found consistent with results of Al-Kadi [1986] which show that the average per capita water consumption decreased as the number of children in the household increased.

FAMILY SIZE

Because of the strong correlation between family size (FS) and both number of males and number of females one expects that this variable will indicate same contribution to water use level. Family size is found significant in predicting water use for group C consumers.

MONTHLY INCOME LEVEL

The monthly income level (MIL) is shown significant in predicting water use for consumers of all groups living in villas. It has positive regression coefficient in all seasons considered, indicating the increase in water use level with the increase in the values of (MIL). This result seems more sensible when compared to corresponding results derived by Al-Kadi which shows a decrease in consumption when (MIL) increased from level one to level two.

TOTAL WATER TANK VOLUME

This independent variable is proved to be significant in the transformed equations of group C water uses. However when the original best-fit equations are considered this factor proves insignificant.

CONCLUSIONS

In this study the use of linear multiple regression analysis in predicting and explaining the variations in per capita water consumption in the city of Riyadh is investigated. Eighteen prediction models were developed to represent summer, winter and annual water use variations for four cross sectional groups stratified according to aggregated economic and social factors (Groups A, B, C and overall) and according to the type of residence consumers of all groups are living in (villas and buildings). The generated models indicate that the plot area (PA), the number of males (NOM), females (NOF) and children (NOC) are the most significant variables in predicting the variation in water use for the various groups.

However, the low values of the coefficient of multiple correlation (R^2) in all models developed (0.551 for best model) one should conclude that the independent variable considered could not fully explain the variations in the level of water use. This means that other important variables were left out in the analysis. One of these variables is the water rate, which is not considered in this study. Several investigators have proven the significant impacts of water rates on level of use. It is recommended that this factor should be considered in future studies of water demand projection.

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Evaluation and Classification of Water Use Rate Policy Using the Points Credit Index

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EVALUATION AND CLASSIFICATION OF WATER USE RATE POLICY USING THE POINTS CREDIT INDEX

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ABSTRACT

In order to have clean water piped to our homes, an enormous investment, both in money and expertise is required. The typical household water consumption, industrial, commercial, government sectors and agricultural authorities are known to be of several types of country's water consumption slices (Stresses) which control the water industry of given country. In this paper a mathematical model STRESS is developed to demonstrate the relationship between various stresses with respect to consumption rate and costs, which impacts the water use economy. The method of Points Credit Index, PCI, is developed and is based on the following factors: credit, volume of consumption, and tariff systems, where the earlier accounts for both the environmental and the socio-economic norms represented by the PCI system. The model evaluates the various Stresses to determine the correct tariff with respect to the PCI concept. This method will enable the decision makers to draw a logical conclusion on how much these Stresses can change the water-use rate of a certain country.

The significance of this paper is that it is the first attempt to evaluate the water consumption by the PCI system, which controls the high consumption rate initiated by various stresses, and predicts a suitable consumption tariff for each of the different Stresses.

Key words: Consumption Slice, Mathematical Model, PCI, Stress, Tariff System.

INTRODUCTION

Due to the high population growth in the Gulf Cooperation Council (GCC), a noticeable increase in the rate of water use (consumption) occured due to the vast development and progress in the building construction, industrial and agriculture. Available data from the Secretariate General of the GCC countries and reported by Al-Megren (1992) shows that the population growth rate is between 1.8 to 4.5% per annum (Figure 1), which was accompanied by a progressive growth in the rate of water consumption. This increased consumption became a problem for the water project planners to overcome the large demand for water. In addition, although GCC countries are located in arid region, the per capita consumption rate in these countries is high where the citizen costumed the luxury and prosperous life, unaware of what he consumes of water quality.

The rate of consumption per capita is assumed to reach 300 liter/day for drinking water as indicated by the incomplete statistics. The daily rate of water consumption per capita in the GCC has exceeded the 5 milion cubic meter (MCM), except the consumption from the agricultural and industrial sectors, which are in the range of 75% of consumption rate.

Consequently, this matter has urged the GCC governments to prepare a regional water use strategy to confront the future needs. The strategic plan should also account for emergency plan, at least to ensure the basic needs of water in these countries. The cost of water production is an essential part of the water use strategic plan in the GCC countries. This should be emphasized because water resources are limited. The desalination and groundwater are the only available water resources, In addition to the limited and low rainfall rates. Therefore, the automated water demand should be planned in order to meet the increasing water production and the expected high consumption for the period 1997 to 2050.

The cost of water production, however, is dependent on the water sources which requires certain operational needs such as: treatment, operation, maintenance, fuel, storage and distribution. In Kuwait for instance, the main problem is that the production and consumption are progressively increasing with the operational costs remained at fixed rate (800 Fils/ 1000 Galon) for very long time (Table 1).

This paper emphasizes on the charges of consumption as a control tool which should be used in order to reduce the consumption, maintain the operational costs, and to test the effect of Points Credit Index System, (PCI) values on the consumption slices.

This work significantly suggests the division of the whole society into several consumption slices and then apply the PCI system to overcome any socio-economic and environmental problems that effects the supply and demand.

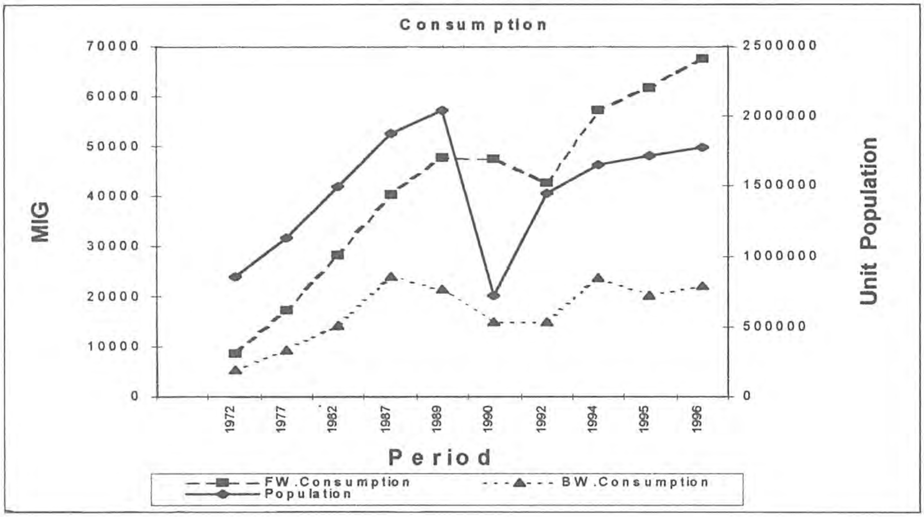

*Figure 1 **The water consumption and population increase in the GCC between (1985-1989).** (Units in thousands)*

CONSERVATION OF SUPPLIES AND METERING

Water industry in Kuwait has had its water supply metered for many years and pays for the volume of water it uses. As the price of water has been left fixed, and more importantly, as consumption has risen frequently, industry should implement a strict conservation measures to minimize wastages and water use such as recirculation and reuse before discharge. The idea is that no process should use water of a higher quality than it needs, so that water can be reused over and over again with the processes requiring the purest water using it first hand those processes where quality is least important using it last.

Table 1. The Fresh Water Operational Costs

Production Cost	1.00	KD/ 1000 Gallon
Cost of Pumping,Storage and Distribution	1.177	KD/ 1000 Gallon
Cost of Capital Consumption	0.232	KD
Operation and Maintenance	0.233	KD
Fuel	1.269	KD
Managerial Costs	0.103	KD

Data compiled from Ministry of Electricity and Water (ME&W).

Unlike industry, the private consumer has always seen water as a right, and one that should essentially be free (Gray, 1994).

Since the formation of the regional water authority represented by Ministry of Water and Electricity, (ME&W), in 1943, the idea of metering water supplied to homes and charging for what had been used rather than having a fixed charge has gradually become established. The prime motivation for the introduction of meters was really to conserve supplies and make consumers more responsible in their daily use of water. The charges have been kept fixed at 800 Fils/1000 Gallon as stated earlier, the argument that householders would be unresponsive to price changes and so unlikely to make economies was valid.

Metering is a method of making people more aware of their use of water and rewarding them for using water wisely. The fact that those who use more water pay more will help to achieve the water conservation objective. Water charging methods are currently under review by the consumers department at ME&W. The average household bill for water supply has increased by 84% since 1989-95 from 40 KD to 100 KD per month. However, in addition to the volume charge there are fixed charges for the entire consumers slices and not for the sizes of meter.

Each consumption slice should use on an average each day 20 gallons for flushing the toilet, 20 gallons for washing clothes and 50 gallons in kitchen uses. This type of water usage is not controlled and should be organized through the implementation of new roles and regulations. Saving water is not a valid excuse for poor hygiene (Gary,1994), and for an arid environment such as Kuwait, so how can consumers realistically save water?.

An attempt has been made by the Saudi Arabian Government to apply the monthly consumption cost per consumption slice (Table 2). The method is actually divide the whole country in to several consumption slices or stresses, with different charges, rather than a single consumer based program. Consequently, those consumers responsible for high water-use rate will be identified clearly which again will guide the monitoring of consumption policy in the country. As the water supply is known as the main component of the hydrologic cycle; however, water demand is thought of as societal. Hence it was suggested by ME&W to divide the consumers of fresh water in Kuwait accordingly into four components as follow:

1- Industrial and production establishments

2- Commercial and investing houses

3- Household and social sectors and

4- Governmental sector.

Table 2. Monthly calculated consumption slices and costs.

Consumption Slices	Consumption Volume (Galons)	Cost of Consumption (Rials)	Total Cost (Rials)
1	11×10^3	0.10	5
2	11×10^3	0.15	7.5
3	22×10^3	2.00	200
4	22×10^3	4.00	400
5	13×10^3	6.00	360

MODELING APPROACH

Consumption Slices

The water use rate policy is dependent largely on the size of population and to greater extent on the degree of awareness of citizens. The matter of awareness actually follows certain climatic norms particularly in the GCC countries, where temperature is the key factor controlling many activities.

For instance, in the moderate climate of UK, the typical household water consumption, typical here meaning a family of two adults and two children, is 104 galons per day (gl/d). This is equivalent to a per capita water consumption rate of 30 gl/d. Toilet flushing is the single major use of water at 32% of the consumption per person per day, followed by bathing and showering at 17%, then washing clothes at 12%. The previous norms are followed here in the GCC countries, but with typical family size of two adults and four children. Therefore, the water policy should be planned according to the concept of consumption slices. Table (3) illustrates the daily use of water supplied by the Severn Trent Water Authority during the 1984-5 (Gray,1994). The type of use defines number of consumption slices.

In Kuwait, however, consumers are divided into four stresses or slices. Consequently, the model is designed to have by default a maximum number of seven usage types or slices (stresses) and are given in Table (4). It is recommended that the more slices involved during evaluation, the better defined the causes of high consumption of fresh water.

Table 3. Estimated daily usage of water. (After: Archibald,1986; Seven Trent Water Authority; and Gray,1994).

Type of use	Amount used (gl/d)	Purpose	Amount used (gl/d)
Domestic	185×10^6	-Basic -Toilet flushing -Bathing -Washing machine -External use -Luxury application	63×10^6 53×10^6 34×10^6 25×10^6 6×10^6 3×10^6
Industrial and Commercial	116×10^6	-Processing -Domestic -Cooling:direct -Cooling:recycled	56×10^6 33×10^6 17×10^6 10×10^6
Agricultural	11×10^6	-Livestock -Domestic -Protected crops -Outdoor irrigation	8×10^6 2.2×10^6 $.66 \times 10^6$ $.44 \times 10^6$
Unaccounted for	115×10^6	-Distribution system -Consumers service pipes -Trunk mains -Service reservoirs	56×10^6 36×10^6 11×10^6 3.5×10^6
Total	428×10^6		

Table 4. The default consumption slices suggested by the model.

Consumption slices	**Symbols**	**Number**
Station filling	STAFIL	CS-1
Social and Environmental	SANDE	CS-2
Commercial	COMIND	CS-3
Government sector	GOVRM	CS-4
Industrial	PINDUST	CS-5
Household	RHH	CS-6
Others	OTHR	CS-7

Points Credit Index System, (PCI)

The correct selection of water consumption slices which will be considered for supply purposes is important. The wider the range of slices, the clearer the problem, and hence more realistic decision making and planning could be taken. The main parameters of concern to the water industry are:

1. Consumers

2. Water demand

3. Charges.

In order to impose a control on the demand (consumption) and consumers, it is important to follow a standard system or a scale which exerts certain extra charges on the bill. This system should work as a pointer or " index" that gives both consumers and water supply authorities a clearer picture of the problem and enhance the economic system of the country through the collection of the imposed charges on the extra water consumption.

This pointer, called Points Credit Index (PCI) is actually an arbitrary scale divided into ten points. Each point is given an arbitrary PRICE value equals 20 Fils. In this work the PCI scale is divided into three levels 1,2, and 3. This classification is done to demonstrate the scale of severity of high consumption problem as follow: P1= 10 points , P2= 7 points and P3= 5 points. The program STRESS will first search for the previous consumption readings for each consumption slice and then will asign a proper group value to each slice. For instance, the highest of all consumption will be assigned as P1 and the least consumption will be assigned as P3. Each of the consumption slices will be consequently given new charges according to the following equations:

$$CS_x = Pn\ [points]\ X\ PRICE\ [\ Fils]\ \ldots\ldots (1)$$

$$NEW\ CHARGE = CS_x\ X\ CS_{x\ CONSUMPTION\ (t-1)}\ [Fils/gll]\ \ldots\ldots (2)$$

where, x is the consumption slice (CS) number, n is the PCI group number, Consumption (t-1) is the previous consumption reading for CSx.

Model Structure

The model is named STRESS with respect to its main component consumption slices. Consumption is known to act as a stress on the economy with respect to its fluctuations. Therefore, the STRESS model is physically based in the sense that the tariff system is modeled by certain options (Fig 1) such as:

1. A proper Pn group

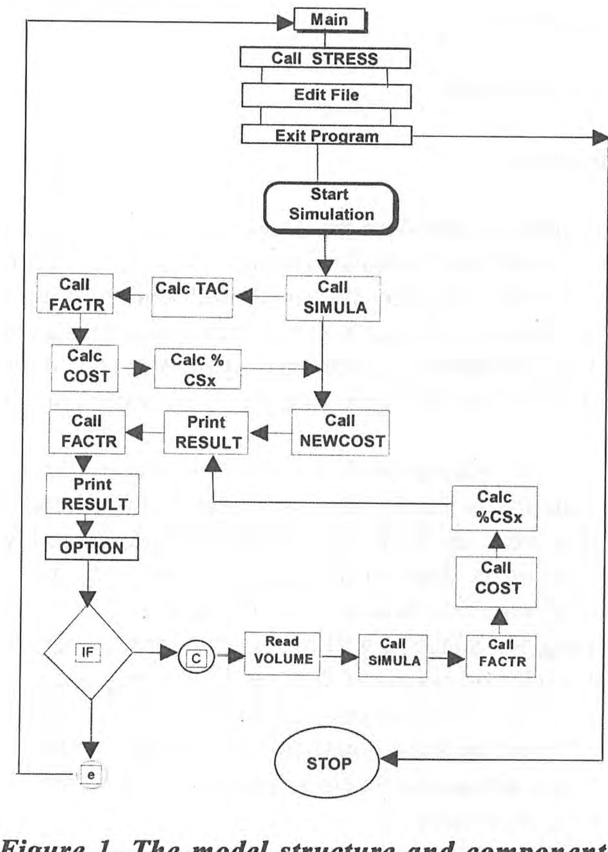

Figure 1. The model structure and components.

Where, TAC	is a subroutine which reads the total consumption at time (t)
FACTOR	is a subroutine which determines the proper Pn group
SIMULA	is the simulation module
COST	is the subroutine which calculates the tariff rate
VOLUME	is a subroutine which calculates the per capita per slice

2. Number of consumption slices

3. Tariff rate per capita per consumption slice.

In water resources projects the level of complexity at which modeling can be carried out varies according to data availability, type of problem, scale of operation, required accuracy, computer facilities and, of course, economic considerations (Abbott, et al, 1986). The STRESS is therefore, designed as a flexible modeling system where the simplicity is achieved through its empirical equations and options of simulation.

Parameter and Data Requirements

Application of a consumption related, physically-based model such as STRESS requires a large amount of parametric and input data (Table 5). In principle the model doesn't need calibration, where the aim is to determine the tariff system per consumption slice based on the arbitrary PCI value. The available data was restricted to a number of seven consumer slices (selected on the basis of actual consumer whose name is on the bill, rate of production, and rate of consumption both recently and previously.

CASE STUDY

The aim of this study case is to run and test the model in examining a particular tariff system based on the PCI system with respect to the number of consumption slices and the relevant supply and demand policy. It is evidently noticed from the examples of the years 1993 and 1996 (Table 6), that there is a great deal of inconsistency on who will be the main consumer of the year. This will consequently impact the planning for next year supply and demand schemes.

It was noticed that the household water consumption is the main high consumption slice (Figures 2a and 2b). This might not be realistic due to the conditions on which these subdivisions of consumption slices were based as they may not be exactly known. The results of STRESS model show evidently that the house-hold slice is the major consumer and the others are known as secondary consumers. This distribution is more convenient if a plan for demand and supply control is to be attempted.

CONCLUSION

The cost of fresh water consumption must be reviewed from time to time in accordance with the population growth. The charging system should be based on the consumption slice. It is noticed that the consumption slice is very much accurate in the determination of the type of water usage that is responsible for high consumption rates.

Table 5. The default input parameters.

Input and Parameter	Values	Units
Old Consumption Price	0.800	Fils
New Consumption Price	0.600	Fils
Gross Fresh water Production	53284.00	MIG
Gross Fresh water Consumption	517555.500	MIG
Net Fresh water Consumption	51595.00	MIG
Rate of Consumption	206364.200	MIG
Total Consumption	21929.500	MIG
Revenues	10360326.00	K.D
Household	12938.88	MIG
Social and Environmental	23146.00	MIG
Commercial	51755.500	MIG
Government sector	17251.800	MIG
Industrial	440.0	MIG
Station filling	515469.00	MIG
Network Consumption	87164.00	MIG
Others	-	MIG

Table 6. The default input data used in the Case-Study. (Source: ME&W)

Consumption slices	1993		1996	
	Supply MIG	Demand MIG	Supply MIG	Demand MIG
Household		948528	8687110	6949688
Social and Environmental			2546111	2036888
Commercial		25852		
Government sector			30	24
Industrial		25852	199784	159827

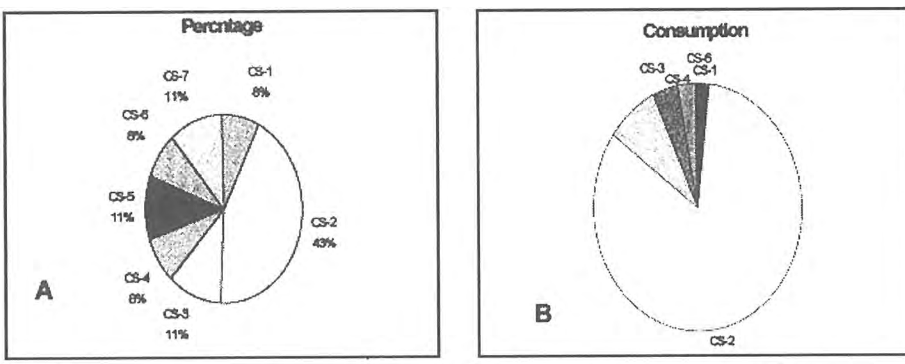

Figure 2. Model outputs A) Consumption percentage, B) consumption rates.

The PCI technique should be followed to control the increasing water consumption rates. The PCI system considers both the soci-economic and the environmental norms, while calculating the new charges per consumption slices. The model STRESS should be applied in a mini project to test and plan a new metering and charging system. However, in practice a certain amount of verification is likely to be required. This can be achieved by normally having the simulated consumptions below the actual one with the modification of tariff rate per volume of fresh water such as 500 Fils/ 700 gall or 800 / 1000 gall.

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BAS Experience in Condensate Water Utilization

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BAS EXPERIENCE IN CONDENSATE WATER UTILIZATION

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ABSTRACT

This paper presents Bahrain Airport Services (BAS) experience in collecting and recycling Air Conditioners condensate water in meeting most of its non-drinking water demands. BAS Catering Department utilizes about 8700 m^3 annually for its non-drinking operations (washing and toilet flushing). This water is supplied by the Civil Aviation Affairs (CAA), which is produced by pumping the over-exploited Dammam aquifer in Bahrain. A scheme that consists of a condensate collection from an open-system Air Conditioning, anti-corrosion treatment, and recycling into the company's non-drinking water network was implemented in mid-1996. The execution of this scheme has resulted in an annual water saving of about 95% in 1997, which costs BAS about BD5,150, in addition to reduction in groundwater abstraction. At present, during the months from April-November, a surplus of about 29,000 l/d is available. It is planned that this condensate surplus be utilized in BAS headquarters, which has a summer average demand of about 21,000 l/d, used in landscaping. It is recommended that this scheme be adopted by companies who have similar cooling system and utilization, especially hotels and commercial centers, in order to reduce the total commercial/industrial/tourism water demands in Bahrain.

KEYWORDS: Bahrain, Commercial/Industrial water consumption, Condensate Water Collection and Utilization.

INTRODUCTION

Bahrain, like most of the Arabian Gulf Countries, suffers from water shortage, where water demands are higher than available water supplies. Due to desalination plants' limited capacity, the country's water deficit has been met essentially by groundwater abstraction, which has reached levels beyond the safe yield of the aquifers in Bahrain. Consequently, groundwater over-exploitation has resulted in water levels drop and quality deterioration, where, at present, half of the original aquifer in Bahrain has been lost to pollution by invasion of seawater and deep connate water. If groundwater abstraction will continue to be used in meeting the country's ever-increasing water demands, the whole of the groundwater resource will be lost (Zubari et al., 1993).

Therefore, one of the greatest challenges faced by the water authority in Bahrain is the provision of fresh water supply to meet the agricultural, domestic, and industrial sectors' demands to promote their further development, and at the same time to control and lower these sectors water demands to reduce their negative impacts on the country's limited water resources. However, these governmental efforts will not be successful unless aided by public awareness and supported by consumers' participation. Therefore, consumer participation and initiation is an essential part in the field of water conservation in Bahrain water resources management, and solutions at the consumer level can lead to a better situation with respect to the total conservation efforts in the country.

As a water consumer in the commercial/industrial sector in Bahrain and as part of its efforts in alleviating the country's water problem and contributing to conserving its water resources, Bahrain Airport Services (BAS) developed an innovative water collection and utilization scheme. The designed scheme constitutes of collecting and recycling air conditioners (A/C) condensate water in meeting most of its non-drinking water demands.

This paper presents BAS experience in collecting and recycling air conditioners condensate water in meeting parts of its non-drinking water demands. The paper illustrates the advantages and benefits of the developed scheme in terms of money and groundwater saving. Furthermore, potential water savings in the case of scheme implementation in the commercial/ industrial sector in Bahrain are discussed.

BAS WATER DEMANDS AND SUPPLY

(BAS) is such a commercial activity that requires waters for many purposes, such as drinking, non-drinking (toilet flushing, washing), landscape irrigation, car and aircraft washing. Table (1) displays BAS water requirements by department for the year 1995, the source of water, and the type of utilization in each department. BAS annual total water requirements are about 111,390 m^3, with only small percentage of these waters are directed towards drinking purposes, while the rest are used for non-drinking purposes (e.g. Headquarters, Catering, Ground and Ramp Engineering Departments).

Prior to 1996, water used by different departments at BAS was provided by the Civil Aviation Affairs, which are divided into two types of water. The first is raw groundwater pumped directly from the Dammam aquifer and supplied to the Catering Department and BAS headquarters (landscaping) at a rate of about 20,750 m^3 annually, representing about 19% of the total water supplied. The rest of the departments are supplied by desalinated water produced from a desalination plant that uses water abstracted from the Dammam aquifer in Muharraq Island as its feed water. Groundwater input to the desalination plant is about 57 m^3/hr (0.5 Mm^3/y), and outputs about 35 m^3/hr, of desalinated fresh water.

Table 1. BAS departments water requirements and their type of utilization

Department	m^3/year	Type of utilization
Cargo (desalinated)	9,767	Washing and drinking
Catering (desalinated)	57,271	Drinking, cooking and dish-washing
Catering (groundwater)	**8,694**	**Washing, toilet and urinals flushing**
Headquarters (groundwater)	12,052	Landscape irrigation
Headquarters (desalinated)	11,558	Drinking and non-drinking
Ground Engineering (desal.)	8,759	Drinking, toilet flushing and car washing
Ramp Engineering (desal.)	3,291	Drinking, non-drinking, and aircraft washing
Total	**111,392**	

BAS WATER COLLECTION AND UTILIZATION PROJECT

The designed scheme consists of a condensate collection network from 14 A/C units, which diverts the old drainage system of the condensate to a 1,000 liter water tank (Figure 1). The cold water is pumped into two tanks with a total capacity of 27,000 liters. In its way to the roof tanks, the water is filtered through a polyporpylene grade 10 (75 micron), to get rid of the suspended particles. In the roof tanks the condensate water is treated by an anti-corrosion, anti-scale chemical, a polyphosphate reagent (BetzDearborn Flogard 558). The chemicals are injected into the roof tanks continuously by a feed pump at a rate of 1.5 l/d. This dosage is designed for a consumption rate between 100 and 110 m^3/d. The roof tanks are then connected to the non-drinking water network, which supplies floor washing and toilet flushing.

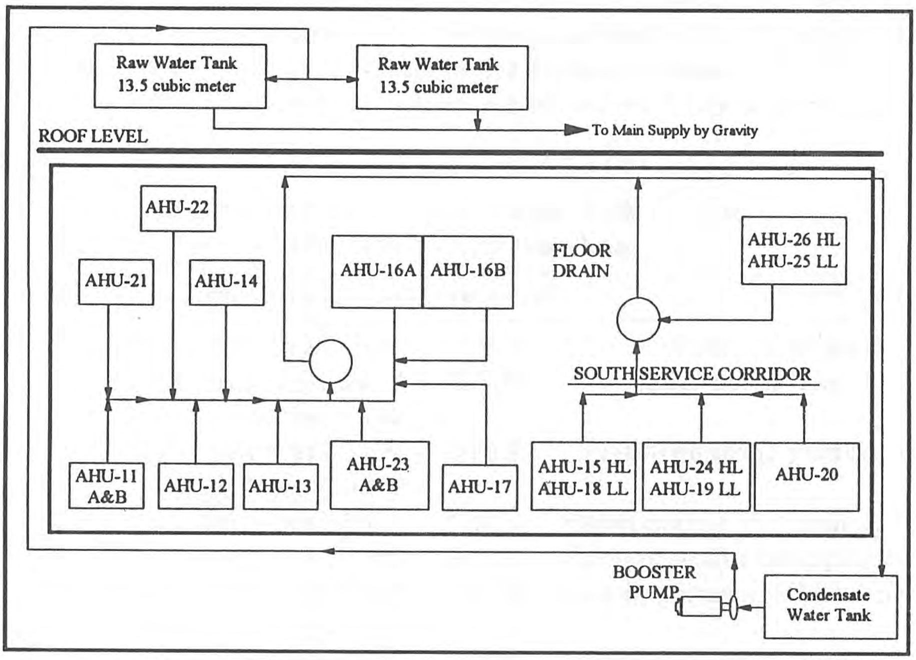

Figure 1. Schematic diagram of the condensate collection and treatment project

The total cost of the construction of the collection and utilization scheme has reached about 1,250 Bahraini Dinars (BD). The material and labor cost are summarized in Table (2). The cost of treatment, that is applying the polyphosphate reagent, which is added daily to the collected condensate water, is about 0.120 BD/day (45 BD per year).

Table 2. Water collection and utilization Project cost

Item	Cost, BD
20 numbers PVC pipes (600cmx4cm)	88.000
1,000 liters Fiber Glass Water Tank (1)	120.000
13,000 liters Fiber Glass Water Tank (1)	700.000
Industrial Type Pump (1)	300.000
Labor (3 workers x 16 hours)	38.000
Total	**1,246.000**

Prior to its full implementation, the designed system was pilot-tested for a period of two months (June-July, 1996). The pilot testing was carried out to assess the efficiency and the feasibility of the scheme. The results of this preliminary testing were that quantities of collected condensate water were ranging between 21,600 to 10,800 l/d, and that variation in the collected amounts depended on temperature, relative humidity, and wind speed.

Furthermore, chemical analyses of the collected condensate water were conducted to evaluate its quality and suitability for the proposed non-drinking uses and to anticipate future water quality problems. Table (3) displays the chemical analysis results for the condensate water and the pumped ground

Table 3. groundwater and condensate Chemical analysis

Constituent	Groundwater	Condensate
TDS, mg/L	3683	18-21
Alkalinity (CaCO3), mg/L	178	<2-15
Hardness (CaCO3), mg/L	1312	128-148
pH @ 27°C	6.9	6.0-6.8
Sodium, mg/L	870	ND
Chloride, mg/L	1631	<1.0-1.0
Calcium, mg/L	268	148?
Sulfate, mg/L	568	ND
Magnesium, mg/L	117	ND
Potassium, mg/L	36	ND
Bicarbonate, mg/L	183	ND
Iron, mg/L	0.1	0.02-0.05
Zinc, mg/L	0.02	0.09-0.28
Nitrite, mg/L	10	7.0

ND = not determined

which was utilized before the implementation of the project. By comparing the chemical constituents of the condensate water with those of groundwater, it was found that the condensate water quality far exceeds that of the groundwater. However, the condensate was found more acidic (pH=6.0-6.8) than groundwater (pH=6.9), i.e. more corrosive. This problem was solved by adding to the condensate an anti-corrosion, anti-scale chemical (polyphosphate reagent).

Comparison between the average BAS Catering Department non-drinking water needs in terms of quality and quantity, which is about 24,750 l/d for the two months, with the collected quantities (21,600-10,800 l/d) has indicated that large percentage of these water needs could be satisfied by the collected condensate. Based on these preliminary results, a full implementation of the scheme was made in August, 1996.

RESULTS

Table (4) and Figure (2) illustrate BAS Catering Department water consumption for the period from 1995 to 1998. The year 1995 to May, 1996 represents the period prior to the implementation of the scheme, and illustrates the water consumption reference levels in the Catering Department. The period from June-July, 1996 represents the pilot testing and experimenting stage, while the period from August 1996 to June 1998, represents the period where a full implementation of the scheme was made.

Table 4. Groundwater consumption for BAS Catering Department, 1995-1998

Year	**1995**		**1996**		**1997**		**1998**	
Month	**m^3**	**BD**	**m^3**	**BD**	**m^3**	**BD**	**m^3**	**BD**
January	882	529.2	107	244.2	0	0.0	0	0.0
February	793	475.8	489	293.4	208	74.9	0	0.0
March	770	467.4	866	519.0	160	57.6	0	0.0
April	884	506.4	1,219	731.4	76	27.4	0	0.0
May	765	459.0	690	414.0	0	0.0	0	0.0
June	1485	891.0	32	19.2	0	0.0	0	0.0
July	725	435.0	0	0.0	0	0.0	0	0.0
August	635	381.0	0	0.0	0	0.0	-	0.0
September	518	310.0	0	0.0	0	0.0	-	0.0
October	513	307.0	0	0.0	0	0.0	-	0.0
November	396	237.7	0	0.0	0	0.0	-	0.0
December	248	148.8	0	0.0	0	0.0	-	0.0
Total	8,614	5,148.3	3,403	2,221.2	444	159.9	-	0.0

Prior to the implementation of the scheme in 1995, desalinated water consumption (supplied by CAA) was about 8,700 m^3. During the year 1996, when the condensate water collection and recycling scheme was pilot-tested during the months of June/July and was fully implemented in August 1996, desalinated water consumption was reduced to about 3,400 m^3 (61% reduction). In 1997, desalinated water consumption was reduced to about 444 m^3 (95% reduction), while in the first half of 1998 desalinated water consumption was reduced to zero (100% reduction).

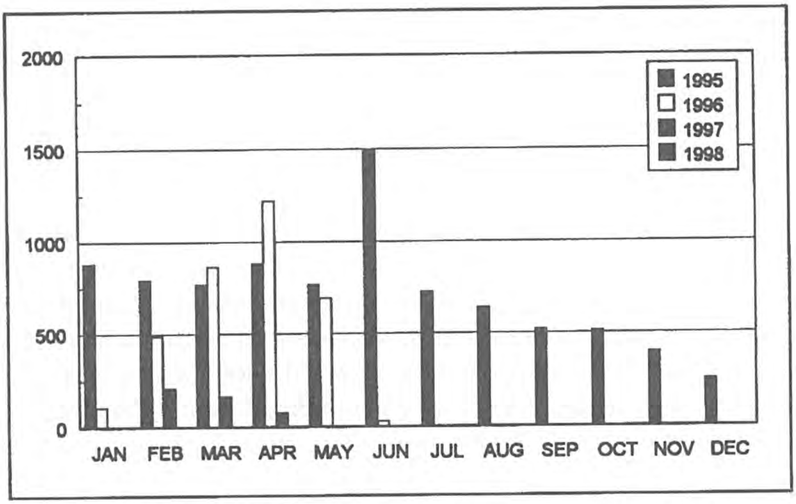

Figure 2. Groundwater consumption for BAS Catering Department in cubic meters, 1995-1998

In terms of water cost, in 1995, BAS paid about 5,150 BD (Table 3) to the Water Supply Directorate. In 1996, when the scheme was partially implemented, it paid about 2,200 BD (57% saving), mainly for the first half of the year (Table 3). In 1997, when the scheme was fully implemented, it paid about 160 BD (97% saving), while in the first half of 1998, no groundwater water was used from the CAA, as the collected condensate satisfied all the water needs of the Catering Department. The cost of treatment (daily application of polyphosphate reagent to the collected condensate) remains, more or less, constant at about 45 BD per year.

Furthermore, during the months from April to November 1997, it has been observed that a condensate surplus, averaging about 29,000 l/d, is available. It is planned that this surplus of collected condensate water be utilized in BAS headquarters, which has a summer average water demand of about 21,000 liter/day, used mainly for landscaping. The expansion in the utilization of the condensate for these purposes would further increase money and groundwater saving.

DISCUSSION

The benefits achieved from the implementation of the condensate collection and recycling project can be divided into two main points:

1) The creation of a new source of water that is practically free and renewable resulting in tremendous money saving for the company, particularly on the long run; and

2) The saved water amounts (about 8,600 m^3/year) has resulted in a reduction of abstraction from the Dammam aquifer by the same. Groundwater in Bahrain in general, and Muharraq in particular, is under crucial conditions, where seawater intrusion is occurring in the aquifer as a direct consequence of over abstraction. Therefore, reduction of aquifer abstraction would help in combating aquifer salinization.

While most of the industrial sector consumption of water in Bahrain is well known, the commercial and tourism sectors total water consumption are not well defined, and the two sectors consumption is lumped with the domestic sector. At present, Bahrain represents a tourist attraction point for the Gulf States, and has over 60 registered hotels with a total capacity of 6,000 rooms. Furthermore, many commercial centers and malls have been created. It is believed that water consumption by these two sectors is large and would represent a considerable percentage of the domestic water consumption in the country. Most of the hotels and commercial centers in Bahrain have A/C systems and water utilization types that are very similar to those of BAS Catering Department. Therefore, an adaptation and implementation of the condensate collection and recycling scheme would result in a considerable money saving by these hotels and commercial centers, and more importantly, reduction of domestic water demands in Bahrain, which will help in alleviating groundwater stresses and the water problem in Bahrain.

CONCLUSION AND RECOMMENDATIONS

The implementation of BAS condensate collection and recycling scheme has resulted in an annual water saving of about 95% (1997) of the average water demand of 8,700 m^3, utilized by the Catering Department for non-drinking purposes (washing and toilet flushing). In terms of money, a 97% saving has been achieved. Further expansion in condensate utilization is planned in BAS headquarters landscaping during the summer months utilizing condensate surpluses. This will result in further reduction of groundwater abstraction and money saving for the company.

Benefits achieved from the implementation of the project are: 1) creation of new, cost free renewable source of water resulting in money saving for the company; and 2) reduction of groundwater abstraction used previously to meet the Catering Department demands.

It is recommended that this scheme be adopted by companies who have similar cooling system and water utilization, especially hotels, commercial centers, etc., in order to reduce the total commercial/industrial water demands in Bahrain, and help alleviate the water problem in Bahrain.

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ACKNOWLEDGEMENT

... would like to thank ... continued support and encouragement ... Agriculture, Engineering Department ... material and facilities for ... staff and colleagues at BAS ... the execution of this ...

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Groundwater Resources

An Overview of Nuclear Science and Technology in Groundwater Assessment/Management and IAEA Activities in the Gulf Region

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AN OVERVIEW OF NUCLEAR SCIENCE AND TECHNOLOGY IN GROUNDWATER ASSESSMENT / MANAGEMENT AND IAEA ACTIVITIES IN THE GULF REGION

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ABSTRACT

Methodologies based on the use of isotopes as tracers and particularly of naturally existing isotopic species of Oxygen, Hydrogen and Carbon, are presently employed as an integral part of the investigations related to water resources assessment and management. The scientific discipline often referred to as "Isotope Hydrology" deals with identification of the genesis of water, study of the processes involved in the occurrence/circulation of water and enables independent estimates of the relevant physical parameters of the hydrological system. Applications based on the temporal/ spatial variations of naturally existing isotopes (Environmental Isotopes), particularly in groundwater studies, have the distinct advantage of providing time/space integrated information on the origin of water and its flow/mixing dynamics even for large scale systems. The paper provides an overview of the basic concepts and methodologies of isotope techniques in groundwater resources of arid regions. The International Atomic Energy Agency (IAEA) has been actively involved in isotope applications in hydrology, and substantial amount of isotope data and experience has been acquired in this specific field throughout the activities undertaken over the last four decades. Typical examples of field applications and results obtained in Gulf region are included in the paper.

KEY WORDS: isotopes, basic data for Gulf region, applications in arid zone hydrology.

INTRODUCTION

Methodologies based on the use of isotopes in a wide spectrum of hydrological problems encountered in water resources assessment, development and management activities are already an established scientific discipline recognized as "Isotope Hydrology", and proven methods are presently employed as an integral part of water resources investigations, particularly in groundwater systems.

During last four decades, the International Atomic Energy Agency (IAEA) has been directly involved in efforts directed towards research and development of nuclear techniques in water sciences, their actual field applications, and acted as an international scale focal point for dissemination of information and promoting their wider scale use, within the framework of its activities related to peaceful nuclear applications.

ROLE OF ISOTOPE APPLICATIONS IN WATER RESOURCES

Use of isotopes in water sciences essentially stem from the general **"Tracing"** concept. Potential role and contributions of isotope methods in water resources can be grouped into following general categories:

- determination of **physical parameters related to flow, its dynamics** and **structure** of the hydrological system,

- delineation of processes involved in circulation of water and mass transport characteristics,
  (Process Tracing),

- study of **origin** (genesis) of water,

- determination of mixing dynamics of component flows
  (Component Tracing),

- study of **"Time-scale"** of events.

Applications of isotope hydrology in problems often encountered in groundwater systems are summarized in **Table-1**. Use of naturally occurring isotopes often referred to as "Environmental Isotope Methodologies" have distinct advantage of facilitating study of water movement in much larger temporal and spatial scales than possible with intentionally injected tracers, which are often used for site-specific local scale engineering and geo-technical problems. The production and temporal/spatial variations of environmental isotopes in the hydrological cycle can not be controlled by the investigator, and they are result of different natural processes. However, hydrological inferences can be made in all of the above cited type of applications, through observations to be made of their concentration distributions in a given hydrological system. Therefore, environmental isotope methodologies are quite commonly employed in regional scale studies in water resources, and particularly in groundwater systems.

ENVIRONMENTAL ISOTOPES

Environmental **stable isotopes** of potential use in hydrology are listed in **Table-2**, where specific application areas are also indicated. The most commonly employed natural isotopes of Oxygen and Hydrogen **(Table-2)** have the advantage of being ideal tracers for water. They exhibit temporal and spatial variations due to isotopic fractionation occurring during phase changes, i.e. evaporation and condensation, which is mainly a temperature dependent phenomena. The isotopic changes thus induced, is a conservative property of the water during its transport, and it is a finger-print of the history of the processes involved in its formation and circulation. Characteristic relationship of Oxygen-18 and H-2 isotopes for different hydrological processes are shown in **Figure-1**, which provides the basis for the above cited applications.

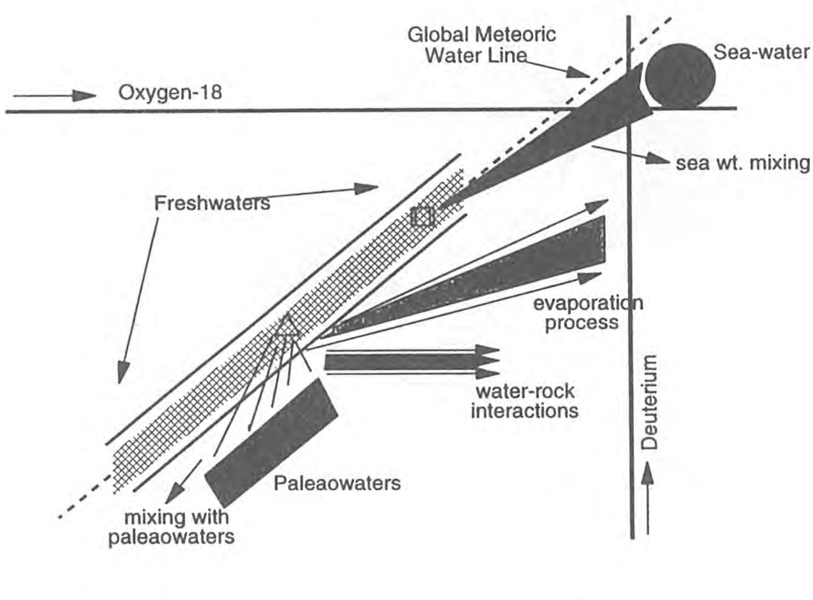


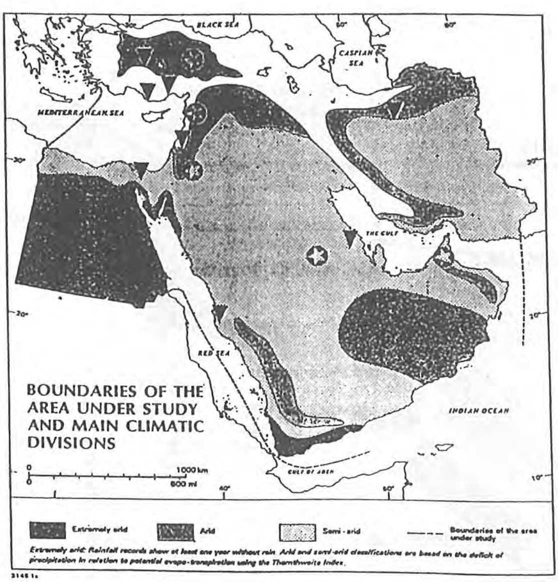
Figure 1: Stable isotopic evolution of water during different natural processes

Natural radioactive isotopes often used in groundwater studies are listed in **Table-3**. Among them, H-3 (Tritium), with a half-life of 12.43 years; and C-14, with a half-life of 5730 years are the most frequently employed isotopic species for study of water movement in "Time" domain, and also providing "dating" method for determination of the age of groundwater. The unique decay property of environmental radioactive isotopes enable to infer characteristic time parameters (travel time or transit time) of water transport through a time scale of thousands of years.

Substantial amount of background data and experience have been acquired in the applications of environmental isotopes in hydrological sciences so as to understand the cause/effect relationships of their occurrence and distribution, and to develop sound evaluation methodologies [1,2,3,4,5,6,7,8,9,10,11,12,13]. Characteristic features of the isotope-input concentrations into the hydrological cycle have been mainly derived from systematic data collected from monitoring undertaken by the IAEA from a global network of isotopes in precipitation (GNIP) [7].

BASIC ISOTOPE DATA AVAILABLE IN GULF REGION

The stations cooperating in GNIP located in and around Gulf region are shown in **Figure-2**.



▼ Stations in the IAEA\WMO Global Network

✪ Stations within national monitoring network

Figure 2: Precipitation stations in and around Gulf region for isotope monitoring

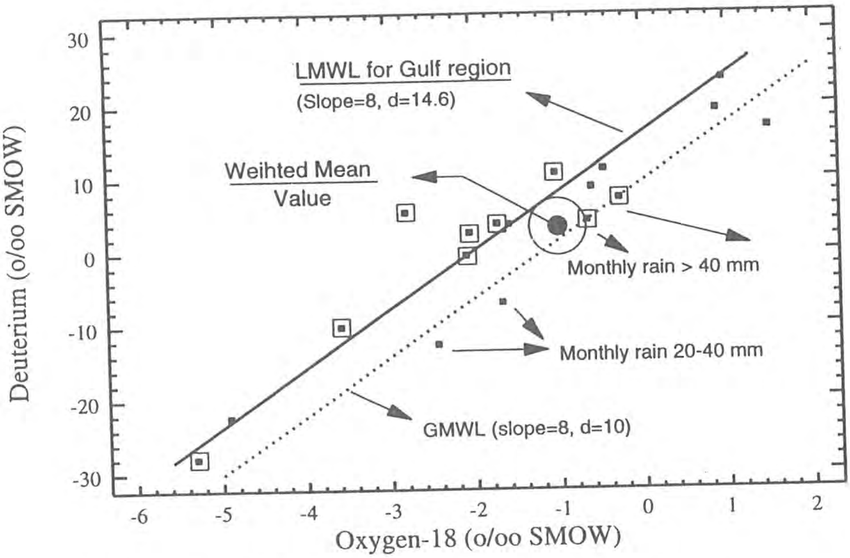


Figure 3: Stable isotope composition of precipitation at Bahrain station

One of the stations in GNIP representative of the Gulf region is located at Bahrain, which has a regular isotope data collected during the period of 1961-1987 [7]. Analyses of the stable isotope data of monthly precipitation from this station is shown in Figure-3, in the form of $^{18}O - ^{2}H$ relationship. Considering the data for months having significant rainfall amount, the relationship given (Figure-3) provides the base-line stable isotope characteristics for the Gulf region under present climatic conditions, and signifies the expected stable isotope composition of groundwater derived from recent precipitation. The earlier mentioned temperature dependence of the stable isotopic (^{18}O and ^{2}H) content of precipitation, provides also basis for inferences to be made of palaeo-temperatures through investigation of stable isotope composition of groundwater, deep ice-cores and lake sediments as palaeoclimatic archives.

The long term variations of tritium concentration of precipitation at Bahrain station, as a basis for defining the tritium-input concentration into the hydrological systems in the Gulf region, is shown in **Figure-4**, together with similar data from selected two long-term stations (Ottawa/Canada and Vienna/Austria). The transient nature of the tritium input **(Figure-4)** observed since 1953, superimposed on the steady-state natural production, offers effective means of studying the transit time of the water for rather fast circulating hydrological systems. The presence of tritium in the groundwater signifies the occurrence of recent recharge. In this context it is often also employed as a means of assessing the vulnerability of the aquifers to pollution.

RADIOISOTOPES AS TRACERS

Artificial tracer applications in hydrology involves injection of a minor quantity of radioactive isotope to trace water movement, and this has distinct advantage in some cases due to very high sensitivity of detection. Typical applications include, investigation of seepage and leakage from reservoirs, in-situ study of sediment transport (both bed-load and suspended sediment) at coastal sites and estuaries, in-situ direct measurement of groundwater filtration velocity in bore-holes (single well dilution methods), measurement

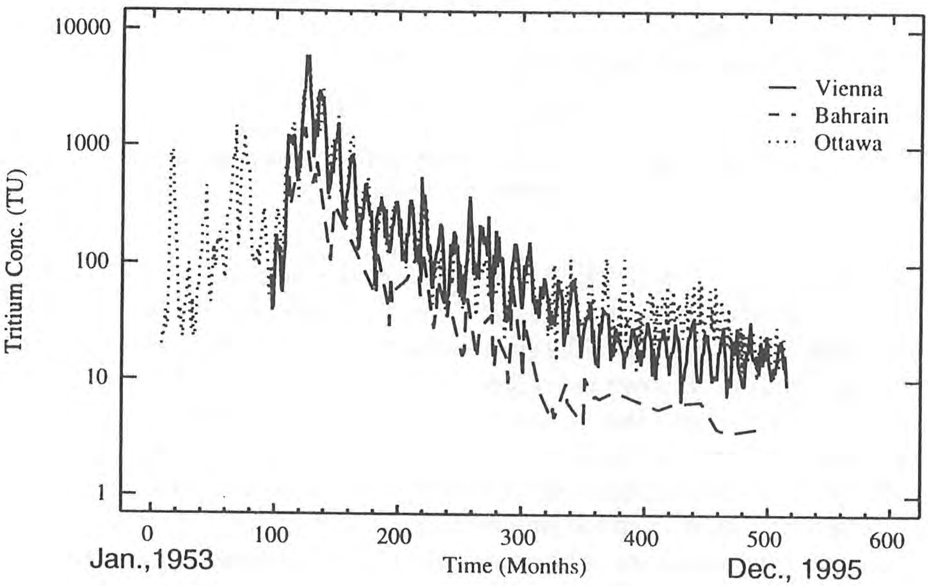


Figure 4: Long-term tritium data for precipitation at Bahrain

of aquifer parameters and dispersion characteristics (multi-well techniques). Commonly used isotopes for hydrological purposes are ^{3}H (Tritium) with a half-life of 12.43 years, ^{51}Cr with a half-life of 27.8 days, ^{82}Br with a half-life of 35.7 hours, ^{131}I with a half-life of 8.05 days and ^{198}Au with a half-life of 64.8 hours. It should be stated, however, that the use of radioactive isotopes are often restricted to some very specific cases, where the engineering and economic implications of the problem involved and the type of quantitative information required would justify the use of a radioactive tracer as compared to conventional tracers.

OVERVIEW OF IAEA's ACTIVITIES AND EXAMPLES OF RESULTS FROM ISOTOPE APPLICATIONS IN GULF REGION

There has been number of earlier isotope investigations conducted in the regional aquifer systems of the countries in the Gulf region, results of which have been already published. The Agency has implemented a regional technical cooperation project entitled "Isotope Hydrology in the Middle East"-(RER/8/002) in which eight countries have actively taken part (Islamic Republic of Iran, Jordan, Kuwait, Lebanon, Saudi Arabia, Syria, Turkey and United Arab Emirates) [14]. The project involved applied isotope field investigations in the selected aquifer systems of each country. At the present, a follow-up technical cooperation project in the West Asia region entitled "Isotope techniques in water resources management-(RAW/8/002)" is in progress.

Characteristic stable isotope composition of some of the major aquifer systems in the Gulf region is shown in **Figure-5**. As can be seen from Figure-5, some of the regional aquifer systems, such as Umm Er Rhaduma and Neogene aquifers as well as Dammam aquifer in Kuwait contain palaeo-waters, as also confirmed by the radiometric dating indicating the waters to be replenished during Pleistocene.

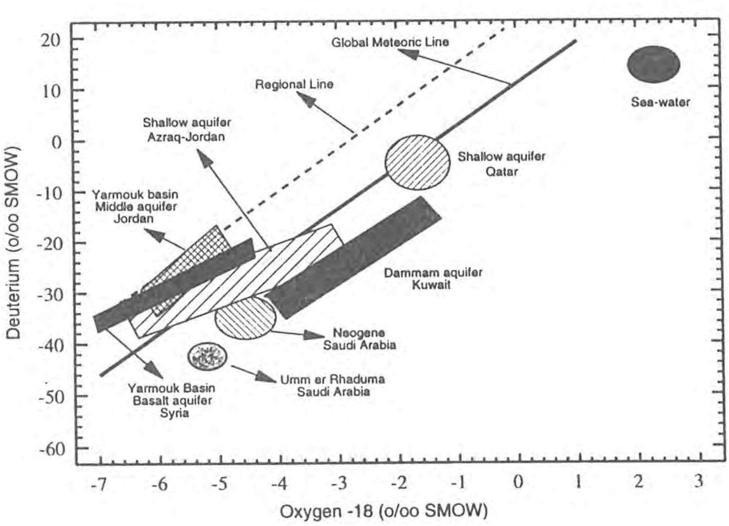


Figure 5: Stable isotope characteristics of some major aquifers in the Middle East

The isotopic chracteristics of the steppe and desert plateaus of Al Badiyeh and Hamad regions also indicate fossil groundwaters related to Pleistocene recharge and groundwater with recent recharge [15, 16], as shown in **Figure-6**.

In an earlier study conducted by the IAEA in Qatar, the origin and replenishment of groundwater in shallow aquifer, and its hydraulic interconnection to deeper confined aquifer system were investigated [16,17], **(Figure-7)**. The cause of salinity increase in the shallow groundwater of southern Qatar, was delineated to be mainly due to upward leakage from underlying confined aquifer of Umm er Rhaduma and also partly due to sea water intrusion. The results of tritium monitoring of wells in the upper shallow limestone aquifer indicated areas where the groundwater was being effectively replenished by the direct rainfall. An average replenishment rate in the range of 7-24 million cubic meters per annum (3-11 mm per year) was estimated for the northern part of the aquifer based on tritium results.

Most of other isotope studies presently being undertaken in the major groundwater aquifer systems of the countries in Gulf region, within the framework of the Agency's above cited ongoing regional technical cooperation project are still in progress and the results and findings of these studies will be published by the IAEA upon completion of these studies.

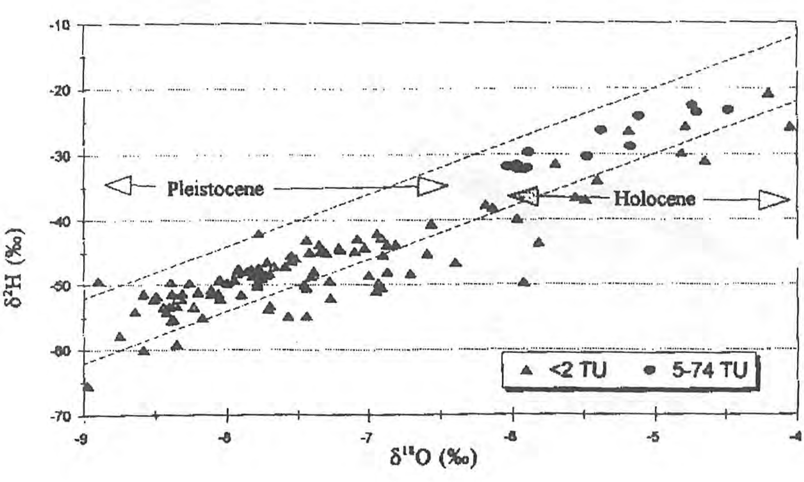


Figure 6: Isotopic characteristics of the aquifers in Al Badiyeh and Hamad regions

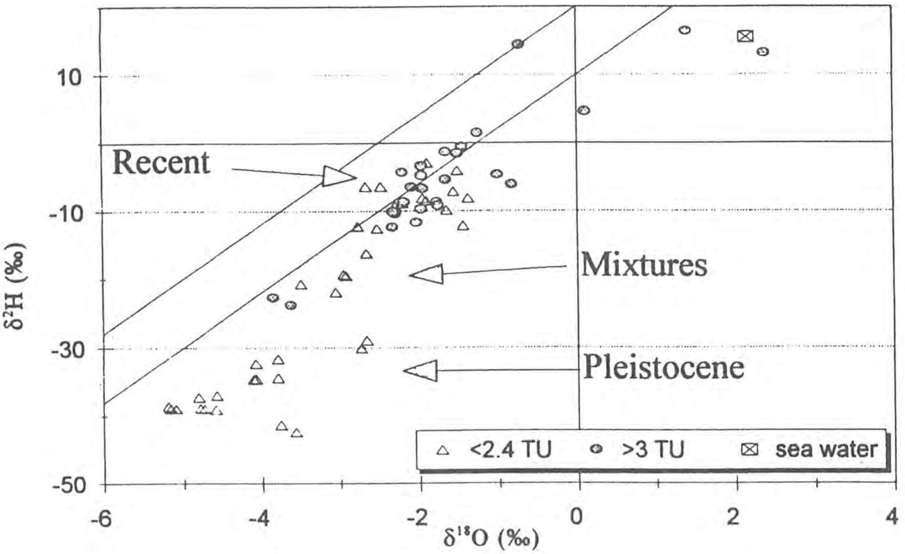


Figure 7: Stable isotope data of groundwater in Qatar

CONCLUSIVE REMARKS

Methodologies based on the environmental isotope applications in hydrology are rather well established. The basic input data required for applications of environmental isotopes in the Gulf region are already available from network stations of the IAEA in the region, and more detailed similar long-term data will be available in the future from national networks recently initiated in some countries. The analytical facilities necessary for undertaking isotope analyses of water samples are also available in the region, such as the Isotope Hydrology Laboratory of the Water Authority of Jordan, which is fully equipped to provide analyses for all of the commonly used isotopes (O-18, H-2, H-3, C-14 and C-13).

The Agency's earlier completed and ongoing regional technical cooperation projects aims at transfer of the technology and know-how in the field of the isotope applications in hydrology, and it is expected that, there will be a core of well trained local staff in most of the countries in the region, who are fully capable of planning, implementing and evaluating results of isotope field applications for future studies within their national programmes related to water resources assessment, development and management.

Isotope data collected within the framework of hydrogeological applications substantially contribute to improved understanding of the processes involved in the occurrence and transport of water and for quantitative evaluations relevant to transport processes within the context of system identification. They should be considered to be an integral part of hydrogeological investigations related to assessment, development and management of groundwater resources and the cost of undertaking isotope studies are very small fraction of the overall costs involved.

Table 1. Applications and contributions of isotopes in groundwater systems

	TECHNIQUES			
PROBLEMS	**STABLE ISOTOPES**	**RADIOACTIVE ENVIRONMENTAL ISOTOPES**	**ARTIFICIAL TRACERS**	**MATHEMATICAL MODELS**
GROUNDWATER ORIGIN AND DYNAMICS				
Hydraulic parameters and aquifer characteristics	XXXX	XXXXXXXXX	XXXXX	XXXXXXXX
Groundwater dating		XXXXXXXXX		XXXXXXXX
Sources and vulnerability to pollution	XXXX	XXXXXXXXX		
Dispersion and mixing	XXXX		XXXXX	XXXXXXXX
Groundwater salinization	XXXX			XXXXXXXX
UNSATURATED ZONE				
Water and pollutant transport	XXXX	XXXXXXXXX	XXXXX	XXXXXXXX
Recharge - infiltration rates		XXXXXXXXX	XXXXX	XXXXXXXX
GROUNDWATER-SURFACE WATER INTERACTIONS	XXXX	XXXXXXXXX	XXXXX	XXXXXXXX

Table-2. Stable isotopes commonly used in water resources investigations

Isotope(s)	Substance	Potential/common applications
Oxygen-18 (^{18}O) **Deuterium (^{2}H)**	H_2O	Origin of water Identification of recharge areas Hydraulic connections, aquifer leakage Identification of paleowaters Interconnection with surface waters Salinization mechanisms, Recycling of irrigation water Geothermal activity
Carbon-13 (^{13}C)	HCO_3^- and CH_4	Origin of carbon compounds Identification of paleowaters Groundwater dynamics Identification of methane sources
Sulphur-34 (^{34}S) **and** **Oxygen-18 (^{18}O)**	$SO_4^{=}$	Identification of sources of pollution Acidification, acid mine drainage Groundwater flow in geothermal systems
Nitrogen-15 (^{15}N) **and** **Oxygen-18 (^{18}O)**	NO_3^-, $NH4_4^+$ N_2	Origin of nitrates, Sources of pollution, Microbial denitrification processes
Boron-11 (^{11}B)	$B(OH)_4^-$ $B(OH)_3^-$	Identification of pollution sources (sewage effluents)
Chlorine-37 (^{37}Cl)	Cl^- Chlorinated hydro-carbons	Identification of pollution sources Sources of salinity

Table-3 Environmental radioactive isotopes commonly used in water resources investigations

Isotope	Half-life (years)	Common applications
Krypton-85 (^{85}Kr)	10.8	Transport mechanisms: fissure flow Delineation of protection zones
Tritium (^{3}H)	12.43	Identification of recent recharge Water transport in the unsaturated zone
Silicon-32 (^{32}Si)	100	Dating shallow groundwater Exposure ages, weathering rates
Argon-39 (^{39}Ar)	269	Groundwater dating
Carbon-14 (^{14}C)	5730	Groundwater dynamics Identification of paleowaters
Krypton-81 (^{81}Kr)	210,000	Dating of old groundwater
Uranium-234 (^{234}U)	250,000	Dating of old groundwater Rock-water interaction
Chlorine-36 (^{36}Cl)	306,000	Rock-water interaction, dating

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Hydrogeological Conditions of Paleogene Aquifer in the ESCWA Region

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HYDROGEOLOGICAL CONDITIONS OF PALEOGENE AQUIFER IN THE ESCWA REGION

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ABSTRACT

The paper is based on published information and will review briefly on regional hydrogeologic, gehydraulic and hydrochemical caracteristics of the aquiferous Palegene formations.

Paleogene aquifers extend over wide areas in the eastern part of the Arabian Peninsula and provide a large groundwater storage volume. However, present-day recharge in the Paleogene aquifers in the ESCWA region is, according to the climate conditions, in general very limited and principally restricted to areas with relatively favorable rainfall and / or infiltration conditions. In most of the arid zones groundwater in Paleogene aquifers is fossil with estimated groundwater ages between 10,000 and 30,000 years. Aquifer transmissivity and well yields are generally low to moderate in the Paleogene aquifers of the North Arabian Platform. Groundwater salinity distribution reflects, to a large extent, the pattern of modern recharge: Fresh water occurs in Paleogene aquifers in the sub-humid to semi-arid northwestern part of the ESCWA region and, in the arid zones, under open karst surfaces and along major wadi courses. Brackish groundwater is contained in wide ranges of the Paleogene aquifers in the arid areas. Groundwater movement is directed, in general, from outcrop areas of Paleogene or overlying formations to areas of groundwater discharge in springs or sabkhas. Groundwater exploitation from Paleogene aquifers in ESCWA countries faces particular limitations of water resources availability:

- limited permeability and aquifer thickness in the northwestern ESCWA region,
- very low recharge and limited occurrence of groundwater with low to moderate salinity in the arid Arabian Peninsula.

Intensive exploitation of Paleogene aquifers mainly for irrigation has caused significant declines of piezometric levels and subsequent increase of the salinity of the extracted groundwater in many areas.

Under these conditions, beneficial groundwater exploitation on longer term needs an adequate groundwater management which is based on an assessment of available renewable and stored groundwater resources.

1. GENERAL HYDROGEOLOGIC BACKGROUND

Aquiferous Paleogene formations constitute part of a sequence of Mesozoic to Tertiary carbonate rocks which extend over wide parts of the geological province of the Arabian Shelf. The carbonate sequence, comprising predominantly limestones, dolomites, chalks, marly limestones and marls, was deposited during a long period of submersion of the Arabian Shelf under the sea, which lasted from the Middle Cretaceous until the Eocene. The carbonate sequence includes two important aquifer complexes:

- Cretaceous limestones and dolomites with major outcrops in the sub-humid northwestern part of the ESCWA region,
- Paleogene deposits which extend over part of
  - the semi-arid to sub-humid region in Syria, Lebanon and West Bank,
  - the steppe (Badiyeh) and the Hamad area in Syria, Jordan, Iraq and northwestern Saudi Arabia,
  - southern Iraq, eastern and southeastern Saudi Arabia and adjoining areas on the Gulf, southwestern Oman and southeastern Yemen.

The Paleogene deposits of the Arabian Shelf comprise prevailingly carbonate rocks: limestone, chalk, dolomite, with intercalations of marls and of chert layers or nodules. The occurrence of sandstones is restricted to limited stratigraphic stages and marginal parts of the basin of Paleogene sedimentation.

A rather uniform classification of Paleogene sedimentary rocks into **stratigraphic units** is found on geological maps of the Arabian Peninsula and southern Iraq, where the sequence is generally known as Hasa Group and sub-divided into Umm er Radhuma, Rus and Dammam Formations.

The Paleogene formations in the northwestern part of the ESCWA region constitute deposits of a marine transgression of the Mediterranean Sea and are separated from the Paleogene of the Gulf Basin by the Hail - Rutbah uplift structure. They can be divided into the following general units:

Paleocene - Lower Eocene marls and chalky marls,

Lower (-Middle) Eocene limestone - chert alternations,

Middle Eocene chalk and limestone,

Upper Eocene and Oligocene (mainly in Syria).

Although the lithological sequence of the Paleogene in the studied region is rather uniform, in general, considerable variations occur in the lithologic composition of rocks of the Paleogene stratigraphic units over the large area of the Arabian Shelf. Major trends of subregional lithologic variations are:

- The base of the Paleogene (Paleocene - Lower Eocene) is represented by prevailingly argillaceous sediments in the northwest (Syria, Jordan) and by carbonate rocks (Umm er Radhuma Formation) in most of the Arabian Peninsula.
- The upper part of the Lower Eocene comprises carbonate rocks with abundant chert components in the northwest and gypsiferous sediments in parts of the Arabian Peninsula (Rus Formation).
- Limestones with varying portions of chalk and marl extend over most of the Middle Eocene and, in some areas, the upper part of the Lower Eocene.
- Sediments of Upper Eocene and Oligocene age are restricted mainly to the northern part of the region.

According to the regional geologic and hydrogeologic conditions, the Paleogene aquifer system of the Arabian Shelf can be divided into four **hydrogeologic sub-regions**:

- the North Arabian Platform covering parts of Syria, Jordan southwestern Iraq and northwestern Saudi Arabia,
- isolated Paleogene aquifers west of the rift zone in Palestine, Lebanon and Syria,
- the Euphrates - Gulf Basin extending over parts of Saudi Arabia, southern Iraq and including Kuwait, Bahrain and Qatar,
- the Rub al Khali Basin covering the Rub al Khali desert and its surroundings in Yemen, Oman and the UAE.

Main Paleogene aquifers are:

- on the North Arabian Platform and the adjoining western mountains and highlands:

chalky and nummulitic limestones, chalks and cherts of prevailingly Eocene age,

- on the Arabian Peninsula and in southern Iraq:

  limestones and dolomites of the Umm er Radhuma and Dammam Formations (Paleocene -middle Eocene).

On the **North Arabian Platform**, an aquitard of sub-regional extent, composed of marls and chalky marls of Upper Cretaceous (Maastrichtian) - Paleocene age, separates the Paleogene chalk - limestone aquifer from the underlying Upper Cretaceous (Cenomanian - Turonian - Campanian) limestone and dolomite aquifer. Towards structurally high zones - uplifts of the rift zone in the west and the Rutbah uplift in the southeast - the marl aquitard wedges out or grades into carbonate facies and groundwater from the Paleogene aquifer into the deeper Upper Cretaceous aquifer.

The Palmyrean mountain chains separate the Paleogene aquifer system of the North Arabian Platform into a northern and southern block:

- the Aleppo - Hama area in northern Syria,
- the Hamad - Wadi Sirhan area (southern Syria, eastern Jordan, southwestern Iraq, northwestern Saudi Arabia).

The Paleogene of the North Arabian Platform comprises, in general, a single aquifer which may be locally subdivided by low permeability layers. Present-day recharge is significant in the northwestern parts of the sub-province with average annual rainfall of 300 - 400 mm. In the dry southern and eastern parts, recharge is restricted mainly to infiltration of sporadic wadi runoff.

In the area west of the rift zone Paleogene aquifers of limited extent occur in synclinal structures of the Ansariyeh, Lebanon and Judean mountain belts.

The **Euphrates - Gulf - Rub el Khali Basin** comprises a huge, partly artesian hydrogeologic basin, in which Paleogene carbonates of the Umm er Radhuma and Dammam Formations constitute a major middle to upper aquifer within a multi-layer aquifer system.

Paleogene aquifers of the Euphrates - Gulf Basin constitute part of a complex regional aquifer system, including:

- a deep sandstone aquifer (Wasyah Formation),

- a middle aquifer: Aruma and Umm er Radhuma Formations (Upper Cretaceous, Paleocene),
- an upper aquifer: Paleogene Dammam (Khobar and Alat) Formation and Neogene to Quaternary formations.

The middle and upper aquifers appear, on sub- regional scale, hydraulically connected.

Karstified sections of the Umm er Radhuma and Dammam Formations provide, in some areas, aquifers with high productivity.

The Rub al Khali Basin adjoins the Euphrates - Gulf Basin to the south without strict separation and comprises a complex aquifer system similar to the Euphrates - Gulf Basin. The Umm ar Radhuma aquifer appears, however, to be situated at considerable depth in wide parts of the basin. The Paleogene is, to a large extent, covered by the Rub al Khali sand seas.

Paleogene aquifers extend over wide areas in the eastern part of the Arabian Peninsula and provide a large groundwater storage volume. The stored groundwater resources are, however, to a large extent fossil and receive very limited replenishment under present climate conditions.

Hydraulic connections of Paleogene aquifers with overlying and deeper aquifers are observed in several areas: In parts of all four sub-provinces, the Paleogene formations are covered by thick Neogene - Quaternary sedimentary or volcanic rocks, e.g. in the Ad Daw and Wadi Sirhan basins, the Euphrates depression, the Dibdiba Basin and the Jebel Aarab basalt field. In many areas, Paleogene and overlying formations constitute hydraulically connected multi-aquifer systems. Hydraulic connections to aquifers underlying the Paleogene occur in particular on the North Arabian Platform, where the most productive aquifers are Mesozoic karstic or fissured carbonate rocks. In the Arabian Peninsula, only limited hydraulic connections appear to exist between Paleogene aquifers and deeper sandstone aquifers.

Aquifer transmissivity and well yields are generally low to moderate in the Paleogene aquifers of the North Arabian Platform, which are composed mainly of chalks, chalky limestones and cherts of limited thickness. Fissure or karstified limestones and dolomites of the Umm er Radhuma and Dammam Formation provide prevailingly moderate transmissivities in the saturated aquifers of most of the Euphrates - Gulf Basin. High transmissivities occur in particular in karstified parts of the Umm er Radhuma aquifer near the Gulf coast of eastern Saudi Arabia. Information on hydraulic parameters of Paleogene aquifers of the Rub al Khali Basin are scarce. In the Najd of southern Oman, karstified sections in the Umm er Radhuma aquifer have generally moderate transmissivities.

2. RENEWABLE GROUNDWATER RESOURCES AND GROUNDWATER SALINITY DISTRIBUTION

The outcrop belt of Paleogene carbonate formations in the ESCWA countries extends from the sub-humid zone in the northwest to the eastern and southern parts of the Arabian Peninsula with prevailing arid climate. Precipitation events are dominated by the movement of air masses from the eastern Mediterranean Sea, from where low pressure systems enter into western Asia during winter and produce precipitation over the areas adjoining the Mediterranean Sea. The precipitation pattern is strongly influenced by the mountain chains running sub-parallel to the Mediterranean Sea coast, which create a pronounced lee effect with, on average, rapidly decreasing rainfall towards east.

On the Arabian Peninsula, occasional rains in winter and early spring are produced by

- Mediterranean cold fronts,
- advection of cold air from central Asia to the Arabian Peninsula (northeast monsoon),
- easterly winds from the Indian Ocean and atmospheric depressions in the Gulf area.

Monsoonal rainfall which occurs in the southern parts of the Arabian Peninsula during summer does generally not affect the Paleogene outcrop areas.

The rainfall variability in time and space is extremely high in the arid areas. Long dry periods are common in the whole region. Even in the area with sub-humid climate in the northwestern ESCWA countries, the dry season without precipitation extends over 5 to 6 months. Potential evaporation in most of the Paleogene outcrop areas is in the range of 1.5 - 3 m/year with very high values of up to 4.5 m in some desert areas.

Present-day **recharge** in the Paleogene aquifers in the ESCWA region is, according to the climate conditions, in general very limited and principally restricted to areas with relatively favorable rainfall and / or infiltration conditions. Recharge can be expected to occur mainly

- in the northwestern part of the ESCWA region with relatively high rainfall on outcrops of Paleogene chalks and limestones,
- in dry zones on karstic surfaces of outcrops of Paleogene limestones and dolomites,
- on pervious surfaces of Neogene - Quaternary sediments or volcanics overlying Paleogene aquifers,
- in wadi beds where surface runoff infiltrates into Paleogene aquifers or overlying formations.

Limited contributions to the groundwater regime in the Paleogene aquifers may derive from recharge to overlying sand dunes and from present-day or previous recharge in outcrops of sandstone aquifers in upstream areas.

A major source of artificial recharge is irrigation return flow in some agricultural areas.

Reported estimates of mean recharge rates on outcrops of of Paleogene aquifers or overlying Neogene sediments in arid zones of the Arabian Shelf vary generally from 0.6 to 18 mm/year or 1 to 30 percent of mean annual rainfall. Relatively high recharge rates are estimated for areas, where surface runoff collects locally in morphological depressions and infiltrates into sand dunes (Faulkner 1994) or karst openings, e.g. in As Sulb Plateau in Saudi Arabia (Hoetzl 1996) or in Qatar (Harhash & Yusif 1985, Lloyd et al. 1987).

An evaluation of existing **isotope data** reveals the general distribution of recently recharged and of fossil groundwater in Paleogene aquifers on the Arabian Shelf. The isotopic composition of groundwater indicates regimes related to present-day recharge in unconfined Paleogene aquifers of the Qalamoun area (between Antilebanon and Palmyrean Mountains north of Damascus), the Aleppo area, limited ranges along wadi courses in the Hamad (southern Syria, southwestern Iraq, northeastern Jordan), karstified Paleogene outcrops of Qatar and Bahrain and wadis of the Dhofar Mountains. Groundwater in Paleogene aquifers in most of the arid zones is fossil with estimated groundwater ages between 10,000 and 30,000 years.

The fossil groundwaters, recharged during the Pleistocene, are generally characterized, apart from low ^{14}C values, by values of stable isotopes of oxygen and hydrogen which differ significantly from values of present rainfall and indicate more humid and cooler climate during the Pleistocene.

Isotope data indicate that recent recharge from flood flow infiltration in shallow wadi aquifers in arid areas, e.g. in Kuwait and central Oman, has no significant impact on the groundwater of underlying Paleogene aquifers.

Groundwater salinity distribution reflects, to a large extent, the pattern of modern recharge: Fresh water occurs in Paleogene aquifers in the sub-humid to semi-arid northwestern part of the ESCWA region and, in the arid zones, under open karst surfaces and along major wadi courses. Brackish groundwater is contained in wide ranges of the Paleogene aquifers in the arid areas and comprises SO_4 and Cl type waters. The elevated SO_4 concentrations in the brackish groundwater originate mainly from dissolution of sulphate from evaporites deposited on the surface or interlayered in Paleogene formations, in particular the Rus Formation.

Elevated Cl concentrations in the brackish water may be related to

- mixing with deep saline water,
- previous marine intrusions,
- recent sea water intrusion,
- evaporative enrichment.

The sources of elevated groundwater salinity - evaporative enrichment, inflow of deeper groundwater, salt water intrusion, dissolution of evaporite layers - have been determined in some areas through detailed hydrochemical and isotope hydrologic studies, e.g. in Qatar.

Saline Cl water extends under sabkha areas and along the Gulf coast.

3. GROUNDWATER MOVEMENT AND DISCHARGE

Groundwater movement is directed, in general, from outcrop areas of Paleogene or overlying formations to areas of groundwater discharge in springs or sabkhas. Main discharge areas are:

- closed basins on the North Arabian Platform: Jaboul, Matah, Azraq,
- the Orontes and Euphrates Valleys in northern Syria, where groundwater discharges from multi-aquifer systems,
- oases, sabkhas and the sea shore in the Gulf coast area,
- sabkha areas within the Rub al Khali desert and on the Gulf coast of Abu Dhabi north of Rub al Khali.

Quantities of groundwater discharge from Paleogene aquifers or from multi-aquifer systems combining Paleogene and Neogene aquifers are reported from several areas of the Arabian Peninsula.

The following examples illustrate the order of magnitude of groundwater discharge (in million m³/year:)

Discharge from main springs in the Euphrates Valley (1979/1980)	35
Groundwater extraction from well fields in Kuwait (1993)	120
Evaporation from sabkhas in the eastern province of Saudi Arabia	1000
Direct transpiration of groundwater by vegetation in the coastal strip of Saudi Arabia, Tarut Island, Jabrin and Bahrain Islands Extraction from wells	158
Alat aquifer, coastal belt of the Gulf in Saudi Arabia (1990)	101
Khobar aquifer, coastal belt of the Gulf in Saudi Arabia (1990)	326
Umm er Radhuma aquifer, Greater Dhahran (1990)	685
Alat aquifer, Wadi el Miyah (1994)	133
Khobar aquifer, Wadi el Miyah (1994)	408
Umm er Radhuma aquifer, Haradh (1988)	90
Neogene, springs and shallow wells Al Hasa (1990)	608
Dammam, boreholes Al Hasa (1994)	5
Umm er Radhuma, boreholes Al Hasa (1994)	20
Dammam aquifer, Bahrain (1994)	218
Umm er Radhuma aquifer, Bahrain (1994)	24
Rus-Umm er Radhuma aquifer, Qatar (1996)	220

According to Bakiewicz et al. (1982), the total volume of groundwater circulation in Paleogene and Neogene aquifers in the eastern province of Saudi Arabia and Bahrain is under natural conditions in the order of 1300 million m³/year.

At the present stage, artificial groundwater extraction from Paleogene aquifers exceeds the natural discharge in most areas.

Groundwater movement in Paleogene aquifers over national boundaries is known or may be assumed to occur

- on the North Arabian Platform: in the Hamad area, in an aquifer system connecting Paleogene formations and overlying basalt in the Jebel el Arab - Azraq area, and in the Wadi Sirhan catchment,
- in the Euphrates - northern Gulf Basin: from recharge zones in karstified outcrops of the Umm er Radhuma Formation in Saudi Arabia and the Dammam Formation in Iraq to zones of exploitation or natural

discharge in Iraq and Kuwait,

- from eastern Saudi Arabia into Bahrain and Qatar,
- from the southern margin of the Rub al Khali Basin in eastern Yemen and southern Oman into the Rub al Khali desert of Saudi Arabia,
- from the Rub al Khali desert in Saudi Arabia into the Abu Dhabi Emirate.

All known trans-boundary movements of groundwater in the Paleogene aquifers involve low quantities of groundwater flow or are related to flow of fossil groundwater with retention periods of more than 10,000 years up to more than 30,000 years.

4. TRENDS IN GROUNDWATER LEVELS AND QUALITY

The upper aquifer system in the **Aleppo - Hama area** is heavily exploited for domestic supply and irrigation. Construction of irrigation wells has increased dramatically since around 1985 (Ward & Smith 1994). Consequently, water levels are declining at rates of 1 - 2 m per year in many areas. Because of the limited thickness of the saturated aquifer, this leads to reduction of well yields and eventually to a local depletion of the aquifer. The following decline of water levels has been observed:

- 30 m between 1967 and 1995 at some locations in northwestern Syria (Ward & Smith 1994),
- 17 m between 1983 and 1996 at Tel Hadya (mean of 3 boreholes at ICARDA station Tel Hadya),
- around 4 m between 1993 and 1996 in 5 observation wells west of Aleppo.

The electrical conductivity of the groundwater in Tel Hadya increased from 600 μS/cm in 1987 to 1000 μS/cm in 1995. The salinity increase may reflect an increase of groundwater salinity with depth within the aquifer or an impact of irrigation return flow.

In **Kuwait** a general decline of piezometric levels in well fields was observed between pre-development stage in 1960 and levels in 1990, with lowering of water levels of 40 to 60 m in the cones of depression. The decline of piezometric levels is accompanied by a significant increase of the salinity of the extracted groundwater in some well fields.

Water levels in the Umm er Radhuma and Dammam aquifers in the **eastern province of Saudi Arabia** show a general decline in the past 20 years.

Prior to the development of the Umm er Radhuma and Dammam aquifers in the area, the system is believed to have been in a steady, or quasi-steady state, with a balance between recharged water at the outcrop areas in the west and natural discharge in springs and sabkhas. Major development started in many areas in the mid nineteenseventies with increasing abstraction from the aquifers by wells in rates considerably exceeding the natural recharge of the system. Water is taken from the aquifer storage and general groundwater level declines are observed.

The following trends of water levels and groundwater salinity are reported:

- Well fields exploiting Umm er Radhuma aquifer in Greater Dhahran area: water level decline from +11.42 m to +7.79 m asl. and increase of average salinity from 2750 to 3545 mg/l TDS between 1978 and 1982;
- Al Hasa oasis, Neogene - Paleogene aquifer: net water level decline between 1978 and 1984: 40 m in Al-Ghwaibah area, 30 m in southwestern part of Al-Hasa oasis, 5 m in the southern part of the oasis;
- Al Hasa oasis, Neogene - Paleogene aquifer: average salinity increase from 1414 mg/l to 1737 mg/l TDS between 1976 and 1987;
- Wadi Al-Miyah, Dammam aquifer: no significant changes between 1967 and 1980.

In **Bahrain** the piezometric surface of the Dammam aquifer dropped between 1925 (pre-development stage) and 1991 by 2 to 5 m, on average by 4 m. In **Qatar** water level declines in the Rus-Umm er Radhuma aquifer declined between 1971 and 1982 by 3 to 4 m in the northern zone, where groundwater is extracted intensively for irrigation. In the Dammam aquifer in the southwestern corner of Qatar, a maximum water level decline of 3 m was observed between 1971 and 1982.

5. WATER RESOURCES ASSESSMENT AND GROUNDWATER MANAGEMENT

Groundwater exploitation from Paleogene aquifers in ESCWA countries faces particular limitations of water resources availability:

- limited permeability and aquifer thickness in the northwestern ESCWA region,
- very low recharge and limited occurrence of groundwater with low to moderate salinity in the arid Arabian Peninsula.

Intensive exploitation of Paleogene aquifers mainly for irrigation has caused significant declines of piezometric levels and subsequent increase of the salinity of the extracted groundwater in many areas.

Under these conditions, beneficial groundwater exploitation on longer term needs an adequate groundwater management which is based on an assessment of available renewable and stored groundwater resources. Major parameters to be identified for the water resources assessment are:

- Hydraulic aquifer properties: permeability, saturated thickness, storativity, hydraulic gradient;
- Recharge rates;
- Discharge volumes;
- Water salinity distribution.

Paleogene aquifers in the **sub-humid areas of northwestern Syria, Lebanon and West Bank** with mean annual rainfall of more than 300 mm are characterized by the following hydrogeologic conditions:

- Present-day recharge on outcropping aquiferous formations is significant, probably in the order of some tens of mm per year;
- Fresh groundwater occurs over extensive areas,
- Permeability and saturated thickness of the aquifer (transmissivity) is relatively low;
- The generally shallow aquifers are vulnerable to contamination from the surface.

Beneficial and cost efficient groundwater exploitation can be achieved under these conditions if the extracted volume of groundwater is adjusted to the renewable resources. Groundwater exploitation in excess of groundwater recharge will lead to fast decline of water levels and to hazards of aquifer depletion.

For the development of management strategies of the mainly shallow aquifers, situated in a range of 0 to 200 m below land surface, an assessment of renewable and stored water resources for individual catchment areas appears appropriate. Relevant information can be obtained through an evaluation of water level contour maps, data of aquifer transmissivity and storativity, natural and artificial groundwater discharge and of water level fluctuations in relationship to precipitation and groundwater extraction.

The Paleogene aquifer in the area around Aleppo - Idleb - Hama - Salamiyeh in northwestern Syria, apparently provides a relatively high, but already intensively used potential for groundwater exploitation. Information required for water resources assessment and management for that area may be obtained through field surveys of the numerous existing wells, in addition to evaluation of available reports on previous hydrogeologic studies. Establishment of groundwater management plans may be supported by application of mathematical groundwater models for individual catchment areas. Where groundwater from the shallow aquifer system is used for domestic supply, measures for groundwater quality protection have to be introduced, considering in particular hazards of contamination from unsewered sanitation and from irrigation return flow.

In Paleogene aquifers in **semi-arid to arid areas of central Syria, the Hamad and the Jordanian limestone plateau**, groundwater recharge rates and aquifer transmissivities are, in general, low. Groundwater is brackish in most parts of the sub-region, fresh water lenses are restricted to major wadi systems.

Groundwater is used mainly for local water supplies, watering stations for nomadic activities and, in few areas, for irrigation. The potential for groundwater exploitation is generally restricted to extraction of limited quantities of fresh to brackish groundwater at few locations. Exploration of groundwater for additional water supplies may be considered mainly on a local scale, including exploration of the potential of underlying Mesozoic carbonate aquifers.

Approaches to groundwater resources assessment and management are reported for several areas of the **Euphrates - Gulf Basin**: The order of magnitude of total discharge and subsurface outflow from the Umm er Radhuma and Dammam aquifers in the Salman zone in **southern Iraq** has been assessed as 250 million m^3/year (Al Mashadani 1995). Main input components of the groundwater balance are:

- groundwater recharge over the catchment area comprising a total of 35,183 km^2,
- subsurface inflow in the Euphrates Valley.

Mathematical groundwater models were applied to predict the impact of increased groundwater extraction for agricultural development in the South Nukhaib area, Hwara - Manneyah zone, in southern Iraq (Al-Ansari et al. 1995). The simulations considered extraction from the Upper Cretaceous Hartha and Tayarat aquifers and from the Paleogene Umm er Radhuma aquifer over an area of 15,000 km^2. According to the simulation results, the extensive aquifer system can sustain abstraction rates of around 15 m^3/s with a cumulative drawdown of 2 to 9.2 m over 20 years. To avoid interference of drawdown between neighboring wells, distances of at least 0.5 km between production wells were suggested.

Hydraulic properties of the Dammam aquifer in **Kuwait** are relatively well known. Brackish groundwater is extracted from well fields under the responsibility of the Ministry of Electricity and Water, based on long term exploitation policies.

Groundwater reserves in the Umm er Radhuma and Dammam aquifers in the **eastern province of Saudi Arabia** were estimated as follows (Sadiq & Hussain 1997):

Aquifer	Salinity (mg/l TDS)	Groundwater reserves (million m^3)		
		proven	probable	possible
Umm er Radhuma	2500-5000	16,000	40,000	75,000
Dammam	2600-6000	5,000	25,000	

If the present abstraction rates of about 1,500 million m^3 annually are compared with the amount of recharge received by these aquifers (1070 million m^3/y), then the Paleogene aquifers are being over-drafted by about 430 million m^3/y. In other words, the proven reserves for the Paleogene aquifers are being depleted in a rate of about 2% annually, while the probable reserves are being depleted by about 0.7% annually as a minimum.

Dabbagh & Abderrahman (1997) report the following figures for groundwater resources and extraction in Paleogene aquifers and the eastern region of Saudi Arabia:
Estimated groundwater reserves to a depth of 300 m bls:

- Umm er Radhuma: reserve 190×10^9 m^3, recharge $406\times10^6 m^3/year$, salinity 2-5 g/l,
- Dammam: reserve $45\times10^9 m^3$, recharge $200\times10^6 m^3/year$, salinity 2.6-6 g/l,

Irrigation water consumption on 58,000 hectares in the eastern region from Umm er Radhuma, Dammam and Neogene aquifers 1992: $1.2\times10^9 m^3/year$.

Numerical modeling techniques were used to assess the impact of groundwater pumping practices in parts of the Eastern Province of Saudi Arabia and of possibilities of developing adequate groundwater management and conservation schemes (Abderrahman et al. 1995). The study focussed on the Dhahran - Al Hasa area, which comprises three main aquifers separated by semi-confining beds: Umm er Radhuma aquifer, Khobar and Alat (Dammam) aquifer, Neogene aquifer. Total groundwater withdrawal from these aquifers in the Eastern Province was around $1.2\times10^9 m^3$/year in 1992. Based on available data from various hydrogeological and numerical modeling studies, drawdown contour maps were constructed for the different aquifers and declines of the potentiometric surface between the years 1987 and 2000 were simulated. Under present extraction conditions, waster level declines of 3 to 14 m are expected, and up to 40 m in areas with low aquifer transmissivity. Groundwater salinities in all aquifers are expected to increase significantly if present groundwater extraction rates are maintained, e.g. from 3500 mg/l TDS in the Umm er Radhuma aquifer of Dhahran area in 1990 to 4000 mg/l in the year 2000.

In **Qatar**, the reserve of fresh water in the Rus - Umm er Radhuma aquifer (TDS <2000 mg/l) were given as 2500 million m^3 (Parker & Pike 1976). The present (1996) abstraction rate from the aquifer in Qatar is about 220 million m^3/year, while the average annual recharge for the aquifer is calculated at about 45 million m^3 for the period 1972-1983 (Harhash & Yousif 1985). These figures suggest an annual depletion of the fresh water resources by about 175 million m^3 or 7% of the reserves.

The present groundwater discharge of 125 million m^3/year of artificial groundwater abstraction and 4 million m^3/year outflow to the sea exceeds the recharge from rainfall and irrigation return flow by around 74 million m^3/year. The cumulative depletion of the fresh water resources from 1960 to 1995 is estimated at 1311 million m^3 of original 1800 million m^3. Further salinity increase is expected in most of the domestic supply well fields even if groundwater extraction for irrigation is kept at the 1990 rate of 120 million m^3/year (Joudeh 1994).

Field trials to study the **feasibility of artificial recharge** in Paleogene carbonate aquifers have been performed in Kuwait and Qatar. In Kuwait, experiments of artificial recharge of desalinated sea water into the Dammam brackish water aquifer were carried out in the Sulaibya area west of Kuwait City with the following results:

- very little geochemical compatibility problems are expected during injection of desalinated water into the Dammam aquifer,
- recovery efficiency of water with <1500 mg/l TDS ranges from 10 to 20 %.

It is planned to make use of surplus capacity of desalination plants for storage of fresh water in the Dammam aquifer. The preliminary design proposes injection of a total of 82 million m^3 over 5 to 10 years with injection rates of 665 - 1310 m^3/day in 35 - 40 injection wells (Al-Awadi et al. 1995).

Similar studies of artificial recharge in the Rus and Umm er Radhuma aquifers in Qatar indicate an overall recovery efficiency of 17 - 70 % of the injected water (Ruskin et al. 1995).

One of the measures implemented in Qatar for groundwater management is a groundwater recharge scheme where runoff collected in depressions is diverted to a large number of recharge wells to facilitate the transfer of flood water into the Rus and Umm er Radhuma aquifers. The scheme started in 1987 with five recharge wells and was later expanded to include 140 recharge wells. Water level monitoring during 1977-1988 indicated that the recharge volume was increased through these schemes by 30%. Construction of several hundred recharge wells is planned (Abdulrazzaq 1997).

The following **management strategies** for sustainable extraction of groundwater with moderate salinity Paleogene aquifers in the **Gulf area** of eastern Saudi Arabia, Kuwait, Bahrain and Qatar have been proposed or introduced:

- Improvement of the design of well fields affected by over-exploitation:
  - relocation of production wells and change from dense well clustering to adequate spacing of wells,
  - planning of well field design according to detailed hydrogeologic investigations and use of numerical simulation and optimization techniques;
- Maintaining groundwater withdrawal from existing wells at present or reduced levels through
  - implementation of effective water conservation schemes and introduction of water saving measures,
  - replacing part of the groundwater abstraction by use of treated waste water and / or establishment of additional desalination plants;
- Artificial recharge using treated waste water, surplus capacity of desalination plants or rain water collection;
- Hydraulically balanced extraction of water from lenses with fresh

water or slightly brackish water and of underlying water with higher salinity which may be used to feed brackish water desalination plants.

The objective of these measures is to extend the long-term productivity of aquifers and to help stabilize the quality of groundwater.

The potential of exploitation of the **Umm er Radhuma aquifer in the Najd** in southern Oman has been studied and a plan for pilot agricultural development of 2500 hectares within a total survey area of 11,000 km^2 is considered (Al-Harthy et al. 1995). Proposed well field abstraction from the C aquifer (lower Umm er Radhuma Formation) of 38 million m^3/year will be derived mainly from fossil groundwater storage. Abstractions are equivalent to 1200 l/s while aquifer throughflow sustained by recent recharge is estimated at 400 - 500 l/s. The main conclusions derived from the model calculations are:

- For immediate development of 1000 ha, the model predicts a total drawdown in the aquifer C piezometry between 104 and 121 m at two well fields after 30 years of operation and a regional drawdown between 14 and 35 m;
- Most of the drawdown within the well field will occur during the first year of operation.

Sub-models investigated the effects of different well densities. Further model verifications are envisaged in a "develop and monitor" approach with initial cropping of limited areas and minimum well field and infrastructure investments. The decision to proceed to full development can then be based on a validated model, incorporating new hydrogeologic information and a reassessment of farm economics.

6. PROPOSED FURTHER WORK PROGRAM

The report compiled contains the results of evaluations of published information on Paleogene aquifers in the region and is intended to be a first stage of a cooperative study between ESCWA and the member countries. The following additional evaluations maytaken into consideration:

- Statistical evaluation of hydrochemical data with a view to define relationships between hydrochemical groundwater composition and main processes of salinization;
- Two-dimensional modeling of groundwater movement in Paleogene aquifers along selected sections to define probable relationships

between groundwater movement and past or present groundwater recharge.

Subsequent joint activities may comprise:

- an updating of the information on hydrogeologic conditions and state of development of Paleogene aquifers,
- the formulation of general policies for sustainable groundwater management based on experience of the member countries.

Joint studies of selected areas involving two or more member states may be considered as well as application of mathematical methods to simulate sub-regional groundwater regimes and application of isotope methods to identify long-term and short-term hydrological processes in sub-regional aquifer systems.

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Appendix 1: Estimates of groundwater recharge in the area of extent of Paleogene aquifers

Area	Aquifer	Infiltration conditions	Mean annual precipitation (mm/year)	Estimated mean recharge rate		Investigation method	Observation period	Reference
				mm/year	% of precipitation			
Salman zone, southern Iraq	Umm er Radhuma + Dammam		94-140	6-7.5	5-6	water level fluctuation		Al Mashadani 1995
W.Batin basin, southern Iraq	Dibdiba sand +gravel		94-110	4.05-9.72	3.8-14.3	water level fluctuation		Al Mashadani 1995
W.Batin basin, southern iraq	Dibdiba sandstone		94-110	2.5-12	4.85-8	water level fluctuation		Al Mashadani 1995
Eastern province of Saudi Arabia	Neogene - Paleogene	ponding in wadi areas	60	2.6	4	climatologic analysis	1952-78	Faulkner 1994
		ponding adjacent to sand dunes		17.8	30			
		direct infiltration in sand dunes		3.8	6			
		direct infiltration in Neogene sediments		0.6	1			

As Sulb	Umm er	open karst	90	44	47	field tests	Hötzl 1994	
Plateau	Radhuma	surface						
Qasim area		sand dunes	100	2-2.3	2-2.3	natural tracers	Dincer et al. 1974	
Qasim area		sand dunes	100	0-30	0-30	natural tracers	Al Saghabi & Muallem 1996	
Qasim area		sand dunes	89-231		5-15	soil mopisture modeling	Al-Turbal et al. 1996	
Qasim area		sand dunes	120	14	12		Caro & Eagleson 1981	
			80	6	7.5			
Bahrain	Rus	karst surface		3.5		modeling of climate and soil data	GDC 1980	
				5-20			Wright et al. 1983	
Qatar	Rus- Umm er Radhuma	karst surface	75	7.5	10		Harhash & Yusif 1985	
					10-12	runoff analysis	Lloyd et al. 1987	
Najd	Umm er Radhuma			16.25			Al Harthy et al. 1995	

Application of Natural Isotopes for Hydrogeologic Investigations in United Arab Emirates

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APPLICATION OF NATURAL ISOTOPES FOR HYDROGEOLOGIC INVESTIGATIONS IN UNITED ARAB EMIRATES

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ABSTRACT

The natural, stable, deuterium and oxygen-18, and radioactive isotopes, tritium and carbon-14, in rain and groundwater are used to characterize precipitation and determine origin, evolution and age of groundwater in the UAE.

The meteoric water line for the present-day precipitation in UAE has an average $\delta^{18}O$ = 0.8 ‰, an average $\delta^{2}H$ = 12.4 ‰ and a deuterium excess (d) = 15, suggesting two sources of precipitation; the Mediterranean Sea in winter and Indian Ocean in summer. The average ^{3}H content in rainfall for the period 1984-1987 was 4.7 Tritium Units.

The depleted stable isotopes in groundwater of Wadi Al Bih Permian limestone aquifer, eastern Quaternary gravel aquifer and easternmost parts of the western gravel aquifer show the effect of recent recharge at high altitudes, Ru'us Al Jibal (1,050-2,090 meters) in the north and Oman Mountains (≈ 650 meters) in the east. The parallel increase of salinity and $\delta^{18}O$ indicates sea-water intrusion in the western Quaternary gravel aquifer, whereas the increase of salinity and constancy of $\delta^{18}O$ in Wadi Al Bih and Liwa aquifers indicate dissolution of salts from the aquifer matrix. Stable isotopes in groundwater of the western gravel aquifer and Liwa sand aquifer are distinctly different. Enrichment of stable isotopes in the Liwa aquifer indicates evaporation prior to infiltration. However, the projection of stable isotopes in both areas on the Local Meteoric Water Line indicates a common, high elevation recharge source (the northern Oman Mountains). Groundwater of the northern and eastern parts of the UAE has high tritium and carbon-14 activities, indicating ages from modern to 5,000 years old, while the groundwater in the western and southwestern parts has low tritium and carbon-14 activities, indicating ages of 15,000 years or older.

Interpretation of stable isotope data in light of geochemical modeling suggests the source of saline water in the Wadi Al Bih aquifer is not from sea water intrusion, but most likely from mixing of a deep circulating component that has undergone water-rock reactions with evaporites or mixing with brine from lower stratigraphic units.

Stable isotopes, deuterium and oxygen-18, within oil-field brine and the Liwa aquifer from the Bu Hasa area are distinctly different and do not suggest mixing of oil-field water injected in the Miocene clastic aquifer with the shallow, fresh Liwa aquifer.

KEYWORDS: isotopes, United Arab Emirates, groundwater

INTRODUCTION

A large number of water samples was collected in the United Arab Emirates by the Ministry of Electricity and Water (MEW) during the period 1984-1990. Stable isotopes, deuterium (^{2}H) and oxygen-18 (^{18}O), and radioisotopes, tritium (^{3}H) and carbon-14 (^{14}C), were measured and complete chemical analyses were conducted in the laboratories of the MEW. Between 1993 and 1996, the authors collected 150 groundwater samples from the Wadi Al Bih Permian limestone aquifer, Jabal Hafit Dammam limestone aquifer, western Quaternary gravel aquifer, eastern Quaternary gravel aquifer, Al Ain falajes, and Liwa Quaternary sand aquifer, at Liwa and Bu Hasa areas (Figure 1). Samples were analyzed for ^{2}H, ^{18}O and ^{3}H, and complete chemical analyses of the samples were carried out in the UAE University, Al Ain.

The common stable isotopes, ^{2}H and ^{18}O, show temporal and spatial variations due to isotopic fractionation occurring during phase changes, i.e. evaporation and condensation. This isotopic change is a conservative property of water during its transport, and is a fingerprint of the history of the processes involved in its origin and circulation (Yurtsever, 1996). In the UAE, large differences in the ^{2}H and ^{18}O content were observed in the groundwater as a result of various processes and mechanisms occurring before, during, and after groundwater recharge such as evaporation before infiltration, mixing between different waters in the aquifer, or dissolution of salts from the aquifer matrix.

Among the radioactive isotopes, ^{3}H with half-life of 12.43 years, and ^{14}C, with half-life of 5,730 years, are the most frequently employed isotopic species for studying water flow in the time domain and for providing dating tools for determination of groundwater age. Observed ^{3}H content in precipitation since the 1950's offers an effective mean for studying the transit time of water and its distribution through aquifers. Tritium is also employed as a means of identifying the existence of recent natural replenishment of aquifer systems (Yurtsever, 1996). Because of the steady-state input of ^{14}C, this isotope offers a unique opportunity for dating groundwater covering a time span of about 40,000 years.

The objectives of this study are to employ the natural isotopes of hydrogen and oxygen to characterize winter and summer rains in UAE and determine the source and age of groundwater in different aquifers. Isotopes are also used to identify the source of increasing groundwater salinity in Wadi Al Bih Permian limestone aquifer, Ras Al Khaimah

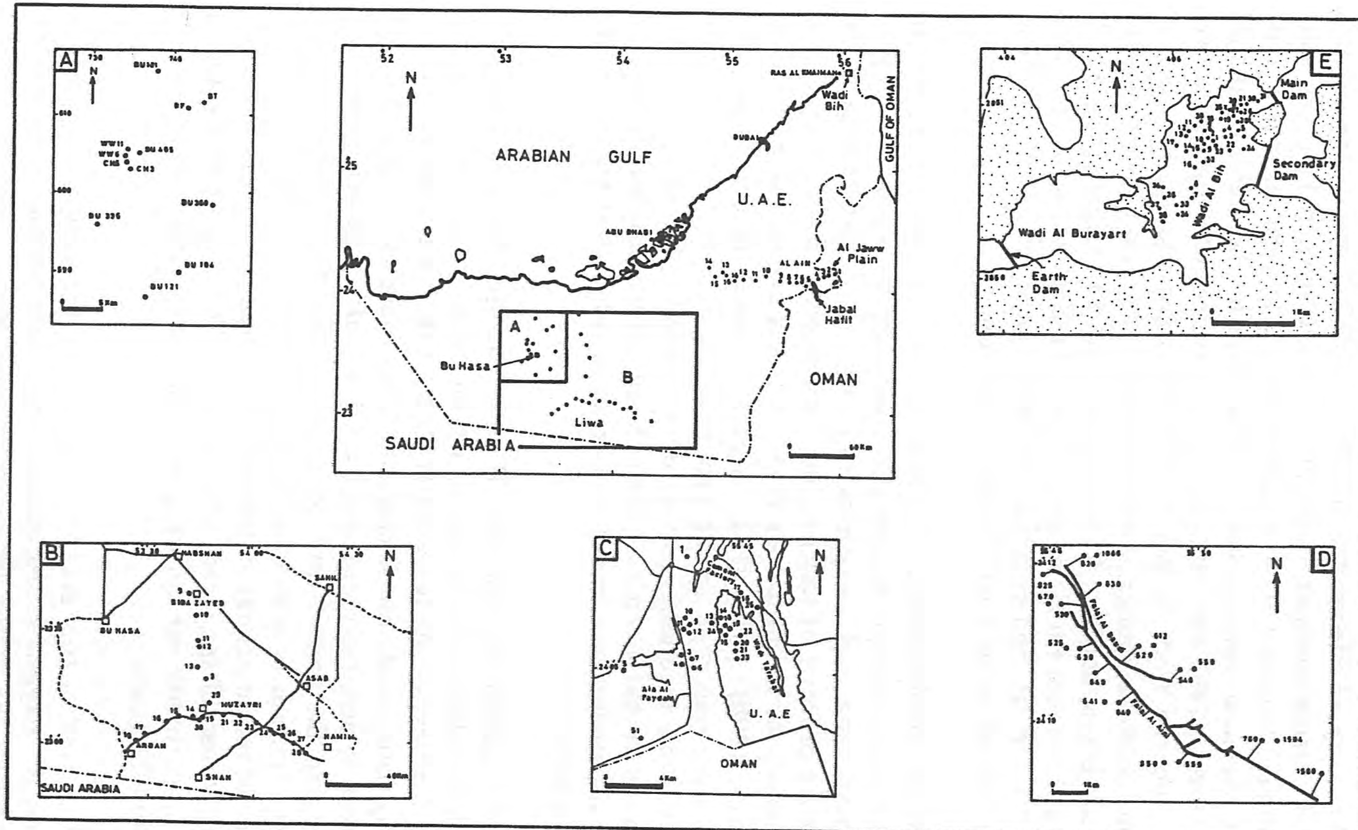

Figure 1. Location map of the study areas in UAE; (A) Bu Hasa, (B) Liwa, (C) Jabal Hafit, (D) Al Ain falajes, and (E) Wadi Al Bih. Black circles represent data points.

area, and assess groundwater pollution of the Liwa Quaternary sand aquifer associated with the oil industry, Bu Hasa area.

ISOTOPIC COMPOSITION OF UAE PRECIPITATION

A plot of ^{18}O versus ^{2}H contents in 52 samples of UAE rainwater collected by the MEW during 1985-1991 period shows that the average values of $\delta^{18}O$ = 0.8 ‰ and $\delta^{2}H$ = 12.4 ‰. The regression line of best fit to all data points can be described by the equation: $\delta D = 4.26\ \delta^{18}O + 9.23$ (Figure 2). However, the line best defining the ^{18}O versus ^{2}H, for months having more than 20 mm rain, has a slope of 8 and an intercept (d or deuterium excess) of 15. This relationship is the best estimate of the stable isotope composition for groundwater of meteoric origin being replenished from precipitation under the present-day climatic conditions in UAE. The tritium (^{3}H) contents in rainfall events for the 1984-1987 averages about 4.7 Tritium Units (TU), which corresponds to present rainfall.

To compare the UAE precipitation with similar areas in the Gulf region, local data was plotted with those of Bahrain and Oman (Clark, 1984). The isotopic composition of rainfall in Bahrain, the nearest long-term station to the UAE, has been monitored for the period 1963-1993 within the scope of the International Atomic Energy Agency/World Meteorological Organization global survey. The stable isotope data available from this station was used to provide basic characteristics of the stable isotopic composition of the present-day meteoric water, especially in the coastal areas of UAE. Stable isotope data of the Al Buraimi area, Oman, was also used to characterize precipitation of the eastern mountainous area of UAE (Figure 3). This figure shows that Oman rain has the most depleted stable isotopes and falls on the Mediterranean Meteoric Water Line (MMWL) of $\delta D = 8\ \delta^{18}O + 20$. Stable isotopes of Bahrain rain lies mostly between the MMWL and the Global Meteoric Water Line (GMWL) of $\delta D = 8\ \delta^{18}O + 10$. In the UAE, the winter precipitation falls on the MMWL and the summer rain, relatively enriched in stable isotopes, falls on the GMWL. This suggest that there are two sources of precipitation in UAE; the Mediterranean Sea and the Indian Ocean. Akiti and others (1988) and Kulaib (1991) came to the same conclusion. The scatter of stable isotope data points suggests that the raindrops are affected by evaporation during the fall of the droplets (Yurtsever, 1992). The maximum, minimum and average values of deuterium (‰) and oxygen-18 (‰) in rainwater of UAE are listed in Table 1.

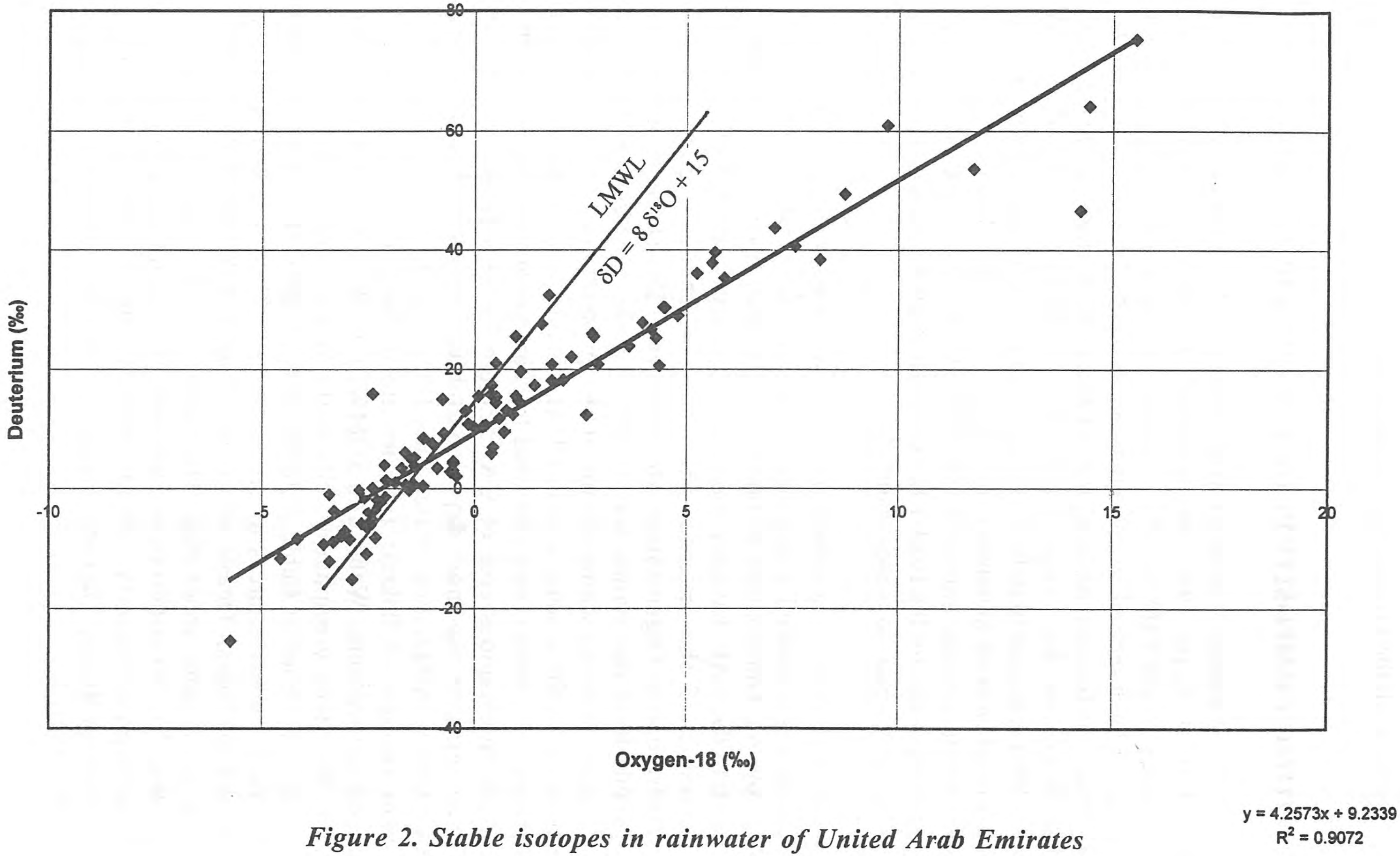

Figure 2. Stable isotopes in rainwater of United Arab Emirates

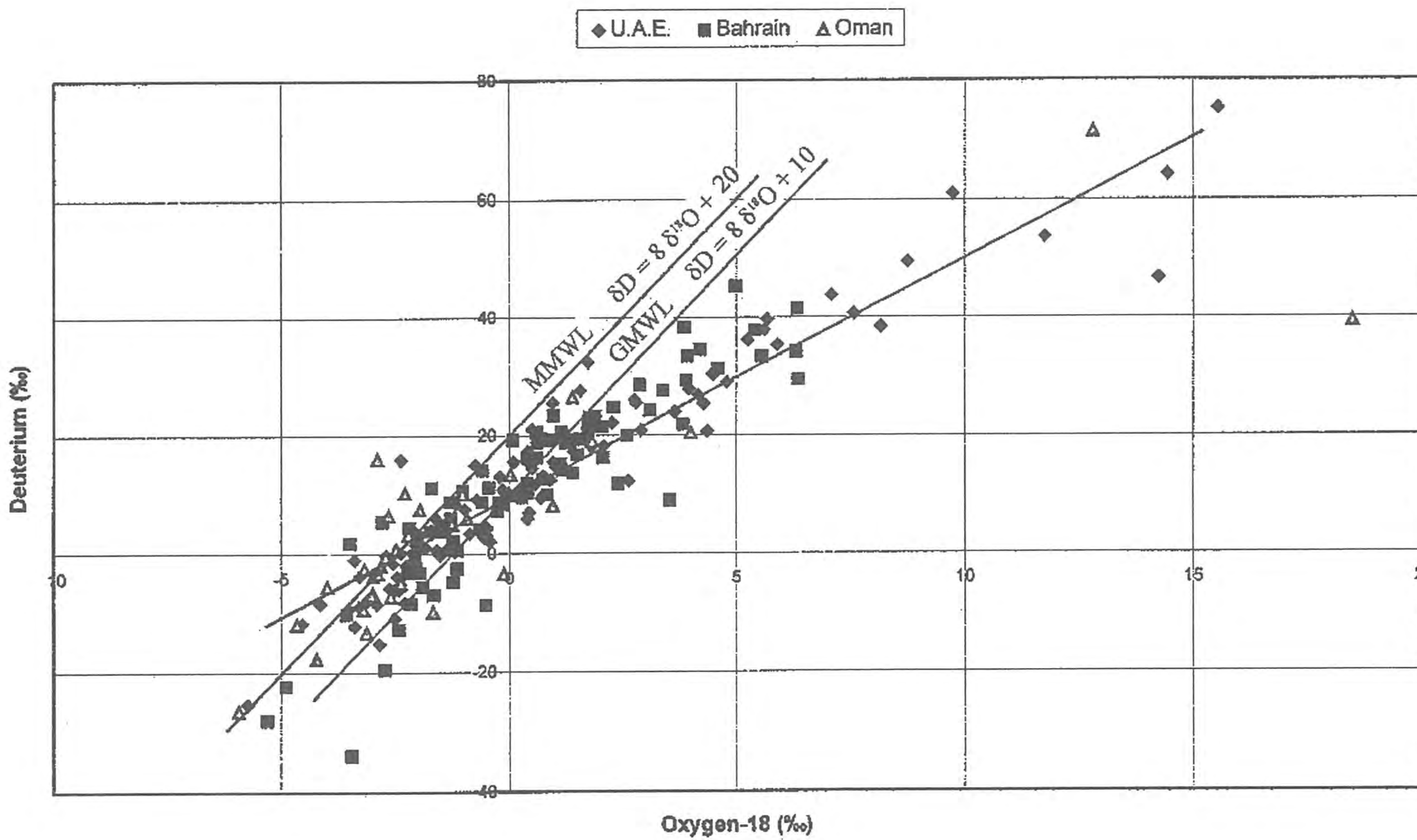

Figure 3. Stable isotopes in rainwater of United Arab Emirates, Bahrain and Sultanate of Oman.

Table 1. The maximum, minimum and average values of stable isotopes of hydrogen and oxygen in rainwater of Bahrain, Oman and UAE.

Isotope	δ Deuterium (‰)			δ Oxygen-18 (‰)		
Country	Max.	Min.	Ave.	Max.	Min.	Ave.
Bahrain	45.3	-69.1	11.64	6.3	-10.1	0.4
UAE	75.2	-25.4	12.4	15.5	-5.7	0.8
Oman	71.4	-26.5	3.3	18.4	-5.9	-1.0

ORIGIN AND AGE OF GROUNDWATER

Figure 4 shows relations between ^{2}H and ^{18}O for different processes, which form the basis of process identification through the use of these isotopes. The study of stable and radioisotopes in UAE groundwater, confirms the presence of different flow systems proposed by Rizk and El-Etr (1994). A summary of the general chemical and isotopic features of these systems is given in Table 2 and illustrated in Figure 5.

Table 2. Summary of chemical and isotopic characters of groundwater flow systems in the U.A.E. (Modified from Al Sharhan et al., 1998).

Parameter	Unit	Flow system		
		Local	Intermediate	Regional
TDS	mg/l	500-1500	1500-10000	>10000
Water type		HCO_3^-	SO_4^{2-}	Cl^-
Dominant cation		Mg^{2+}	Ca^{2+}	Na^+
Major dissolved salt		$Mg(HCO_3)_2$	$CaSO_4$	NaCl
Tritium (^{3}H)	TU	>10	>5-<10	<5
^{14}C activity	%PMC	>50	50-10	<10
^{14}C age	Year	<5000	5000-15000	>15000

Because of the variable geomorphological setting and hydrogeological characteristics of different aquifers in UAE, striking differences were also observed in isotopic contents of groundwater in various aquifers (Figure 6). Superposition of Figure 6 on Figure 5 indicates that the Wadi Al Bih aquifer, the eastern gravel aquifer and a part of the western gravel aquifer discharge the local groundwater-flow system and receive present-day recharge. This recharge occurs under favorable infiltration conditions from sporadic storm events, by infiltration of Wadi runoff, and by rainfall on exposed karst aquifers. The following is a summary of the isotopic characters of UAE aquifers.

WADI AL BIH PERMIAN LIMESTONE AQUIFER

Investigation of groundwater resources of Wadi Al Bih and Al Burayrat fields was carried out by Gonfiantini (1992). The study was based on the results of isotope analysis of a large number of water samples collected from the basin during the period 1984-1992. He attributed the origin of groundwater salinity to the dissolution of salt present in the aquifer materials and sea-water intrusion from the Arabian Gulf. He also indicated the presence of mixing between old groundwater and modern water in the study area.

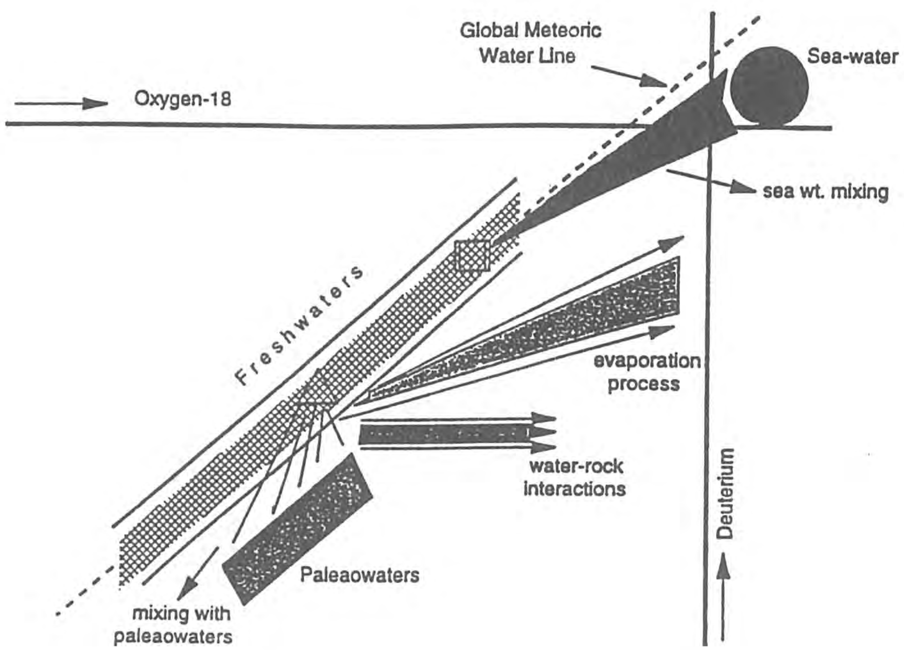

Figure 4. Evolution of stable isotopes ^{18}O and ^{2}H, during different processes (Yurtsever, 1996)

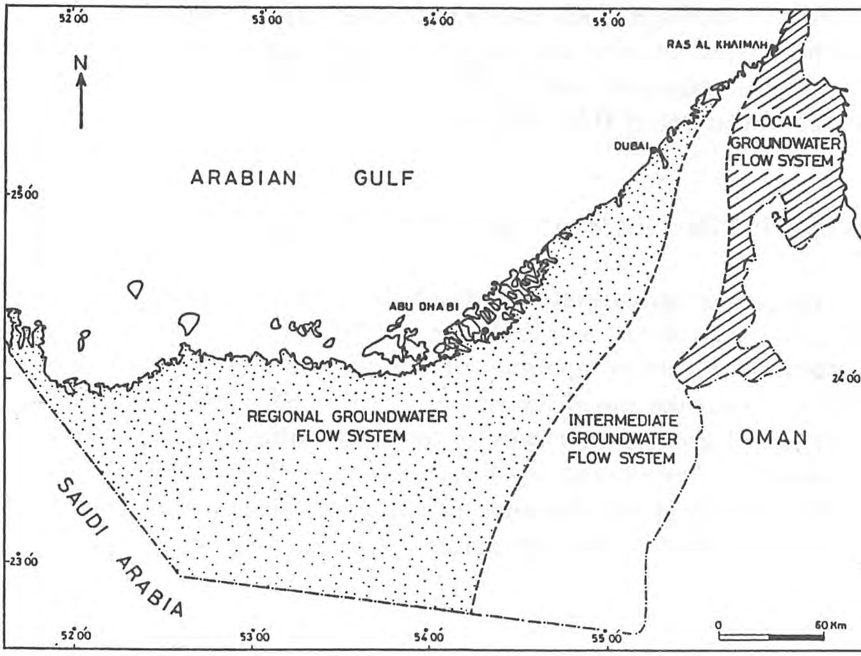

Figure 5. Approximate distribution of local, intermediate and regional groundwater systems in UAE (from Alsharhan et al., 1998)

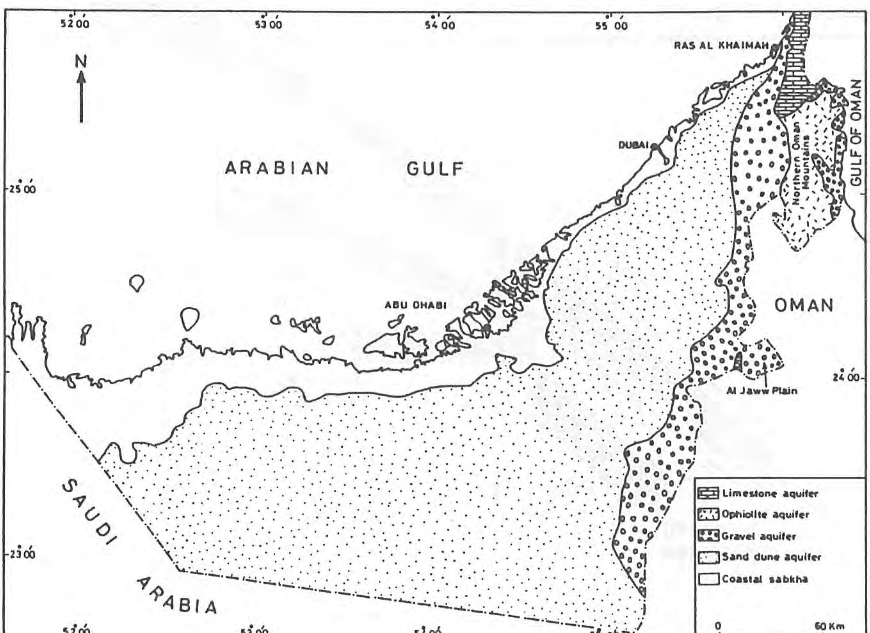

Figure 6. The main water-bearing units (aquifer) in UAE (modified from Rizk et al., 1997)

The aquifer contains groundwater with an isotopic composition more depleted than the average values of the stable isotopic composition of the atmosphere (Figure 7; Table 3), proving that the possible source of moisture in this area is the Mediterranean Sea which recharges groundwater at high elevations (Akiti et al., 1992).

Most of groundwater in this aquifer plots close to the LMWL, with a deuterium excess (d) of + 20, showing that the aquifer is receiving present-day recharge. A few groundwater samples plot to the right of the LMWL, reflecting the effect of evaporation, mixing of different waters or salt-water intrusion from the Arabian Gulf.

The parallel increase of EC and $\delta^{18}O$ from 3,200 mg/l and -3.54‰ in 1985 to 15,070 mg/l and -2.89‰ in 1986 at Wadi Sahawat shows the effect of mixing between sea water and groundwater. It was also noted that the ^{3}H content also decreased from 6.7 to 3.7 TU. In Dohreen, the increase of EC from 2,400 mg/l in 1984 to 6,000 mg/l in 1986 while the $\delta^{18}O$ remained constant around -3.50‰, suggests the dissolution of salt in the soil during groundwater infiltration. These two processes led to the deterioration of groundwater quality. Excessive groundwater pumping from the aquifer during the last two decades at an annual average rate of 11 million m^3 added to the problem. The source of increasing groundwater salinity in the aquifer will be addressed later in this paper.

JABAL HAFIT DAMMAM LIMESTONE AQUIFER

The origin of high temperature (40-50°C), radium-226 (^{226}Ra), Radon-222 (^{222}Ra) in brackish water of the Jabal Hafit Dammam limestone aquifer was studied by Khalifa (1997). The results indicate that deep fractures may act as conduits which bring old, thermal, saline water close to the surface where it is mixed with cool, shallow, fresh water and become diluted, producing the observed brackish water (3,900-6,900 mg/l) of the aquifer. This model is supported by the fact that the ^{2}H and ^{18}O isotopes are lighter than the surrounding areas, suggesting the presence of a local recharge component from the rain falling on Jabal Hafit itself. The ^{3}H levels, while relatively low (average = 1.5 TU), still indicate the presence of some younger water which supports Khalifa's (1997) mixing model.

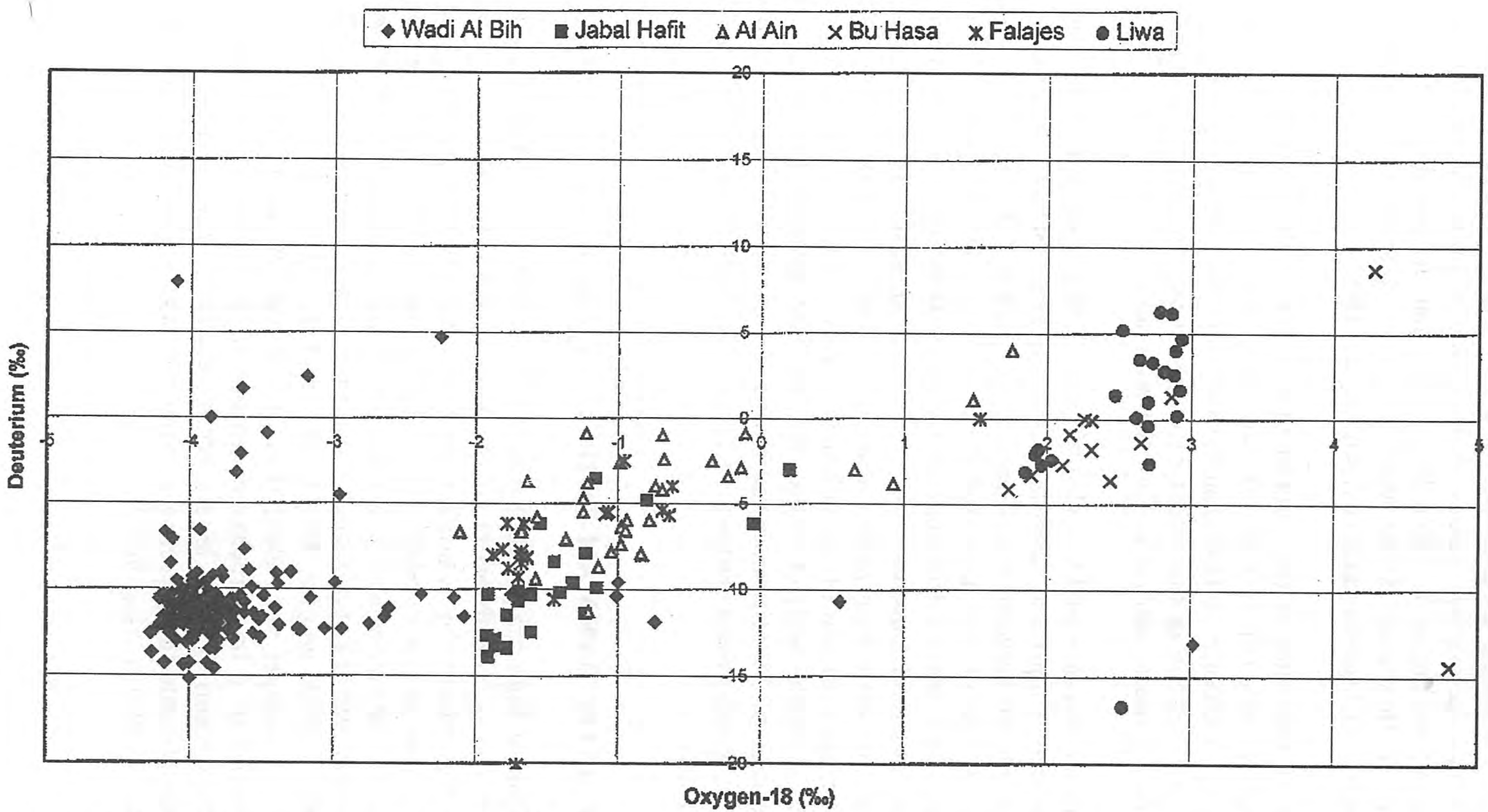

Figure 7. Stable isotopes of Wadi Al Bih Permian limestone aquifer, Jabal Hafit Dammam limestone aquifer, Western Quaternary gravel aquifer (Al Ain), Al Ain falajes, and Liwa Quaternary sand aquifer

The isotopic composition of the Jabal Hafit aquifer is distinctly different from that of Wadi Al Bih aquifer, reflecting recharge from different elevations (Figure 8). While Ru'us Al Jibal (1,050-2,090 m) is the main recharge area of Wadi Al Bih aquifer, the Oman Mountains (≈ 650 m) is the main recharge source of Jabla Hafit aquifer.

Table 3. The maximum, minimum and average values stable isotopes of hydrogen and oxygen in groundwater of UAE

Isotope	Deuterium (‰)			Oxygen-18 (‰)		
Aquifer	Max.	Min.	Ave.	Max.	Min.	Ave.
Wadi Al Bih limestone aquifer	7.9	-15.2	-10.8	3.0	-4.3	-3.7
Jabal Hafit limestone aquifer	-3.0	-9.7	-3.0	0.2	-1.9	-1.4
Western gravel aquifer	19.2	-17.2	-4.2	2.3	-1.9	-0.7
Eastern gravel aquifer	-3.6	-9.5	-6.1	-2.1	-3.0	-2.5
Liwa sand aquifer at Liwa Crescent	43.1	-16.7	2.4	10.5	1.9	2.9
Liwa aquifer at Bu Hasa area	-14.4	8.7	-1.1	6.0	1.7	2.9
Al Ain falajes	0.0	-20.1	-7.3	1.5	-1.9	-1.3

WESTERN QUATERNARY GRAVEL AQUIFER

The western gravel aquifer forms the piedmont plain which extends between the Oman Mountains in the east and the sand dune fields in the west. The groundwater in the easternmost part of this aquifer is depleted in stable isotopes. The samples collected from this aquifer plot on both sides of the meteoric water line, indicating progressive enrichment of stable isotopes from east to west, which could come about by the long residence of water in the aquifer. The clay in alluvium will not permit rapid infiltration and therefore can causes enrichment as the infiltration water moves downward through the aquifer.

The presence of highly enriched stable isotopes can be also explained by interception of deep, old groundwater in the cone-of-depression of various well fields discharging the aquifer in the eastern region. Enrichment of stable isotopes in the aquifer increases from the east towards the west, in the direction of groundwater flow. Figure 9 shows that the ^{18}O increases form -1.25‰ at Al Jaww plain in the east to 1.48‰ at Al Khaznah in the west. This enrichment occurs as the groundwater moves from recharge area towards the Arabian Gulf. The accompanied increase in Electrical Conductivity (EC) from 408 mg/l

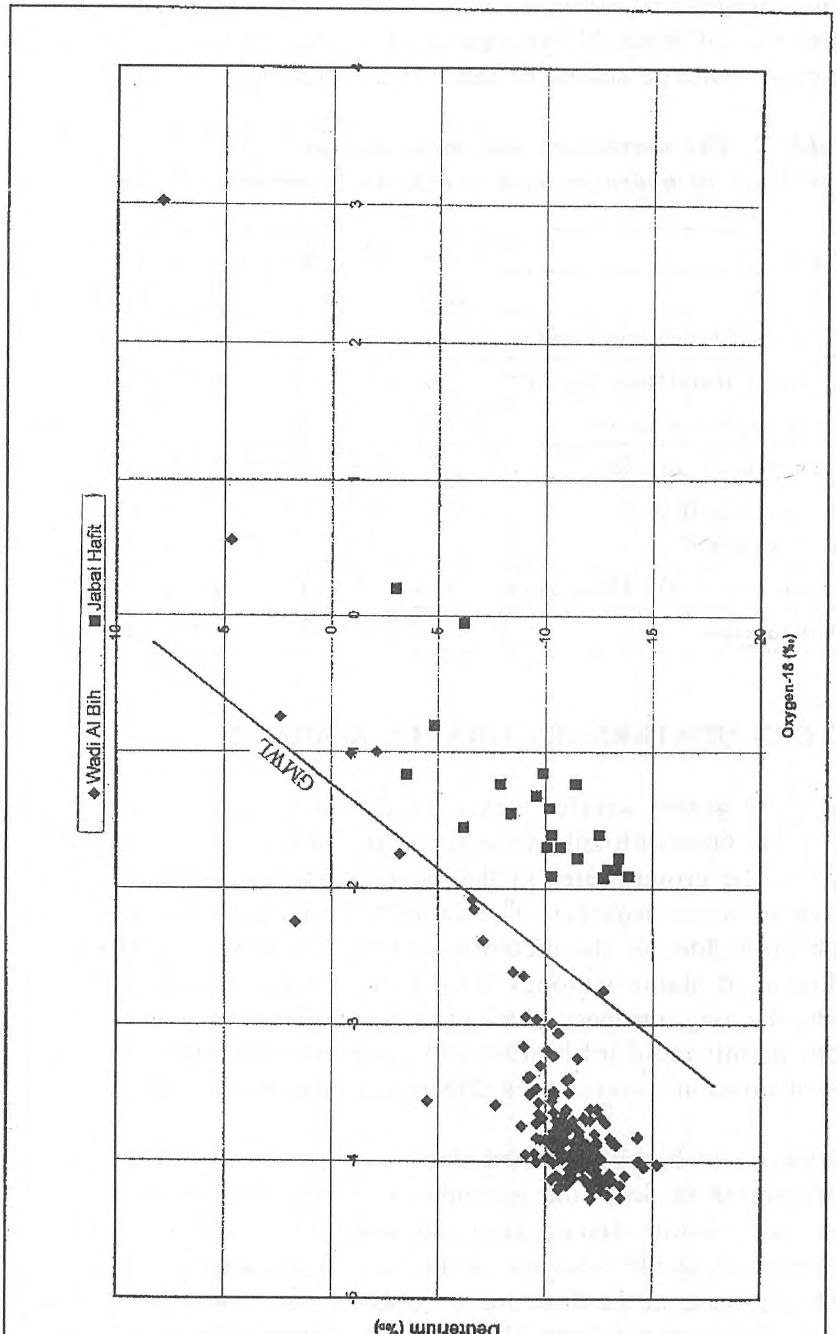

Figure 8. Stable isotopes of Wadi Al Bih Permian limestone aquifer and Jabal Hafit Dammam limestone aquifer

in the east to 14,810 mg/l in the west confirms the movement of groundwater in that direction.

We believe that the inability of the small volumes of flood water to wash out clay particles from the gravel aquifers in UAE increases the water residence time, salinity and isotope contents. Infiltration measurements by Rizk et al. (1996) showed that the infiltration rates of the sand dunes around Al Ain area are three to six times those of the gravel aquifer on the Al Jaww plain.

The high chloride content and enriched stable isotopes confirms the effect of groundwater flow and its dissolution of salts as it moves. Evaporation from groundwater lowers the value of the deuterium excess. However, this is unlikely to occur because the depth to water in the aquifer averages 50 m below the ground surface. It is also possible that the western gravel aquifer receive old water which mixes with infiltrating rain water falling directly on aquifer outcrops.

Present-day recharge is restricted to the areas adjacent to the mountains. A general increase in groundwater age is observed in the western gravel aquifer, suggesting the reduction of hydraulic conductivity as water moves towards the Quaternary Liwa sand aquifer. At the gravel-sand dune boundary, ^{3}H content can be highly variable, suggesting that the communication between the western gravel aquifer and Liwa sand aquifer can be slow or fast depending on the prevailing flow routes (Akiti et al., 1992).

It is possible that there is a flow in the alluvium to the sand dunes or that the recharge events occurred by way of ancient wadis (Figure 10). The aquifer recharge is lower than the discharge rates. This point must be considered for water-resources planning purposes.

Wells at the western edge of the western gravel aquifer contain little or no tritium. The activities in ^{14}C of the Total Dissolved Inorganic Carbon (TDIC) are very low, suggesting old-age groundwater. The ^{14}C age of groundwater in the Abu Dhabi Emirate ranges from modern in the east to 15,000 years old in the western region (Figure 5).

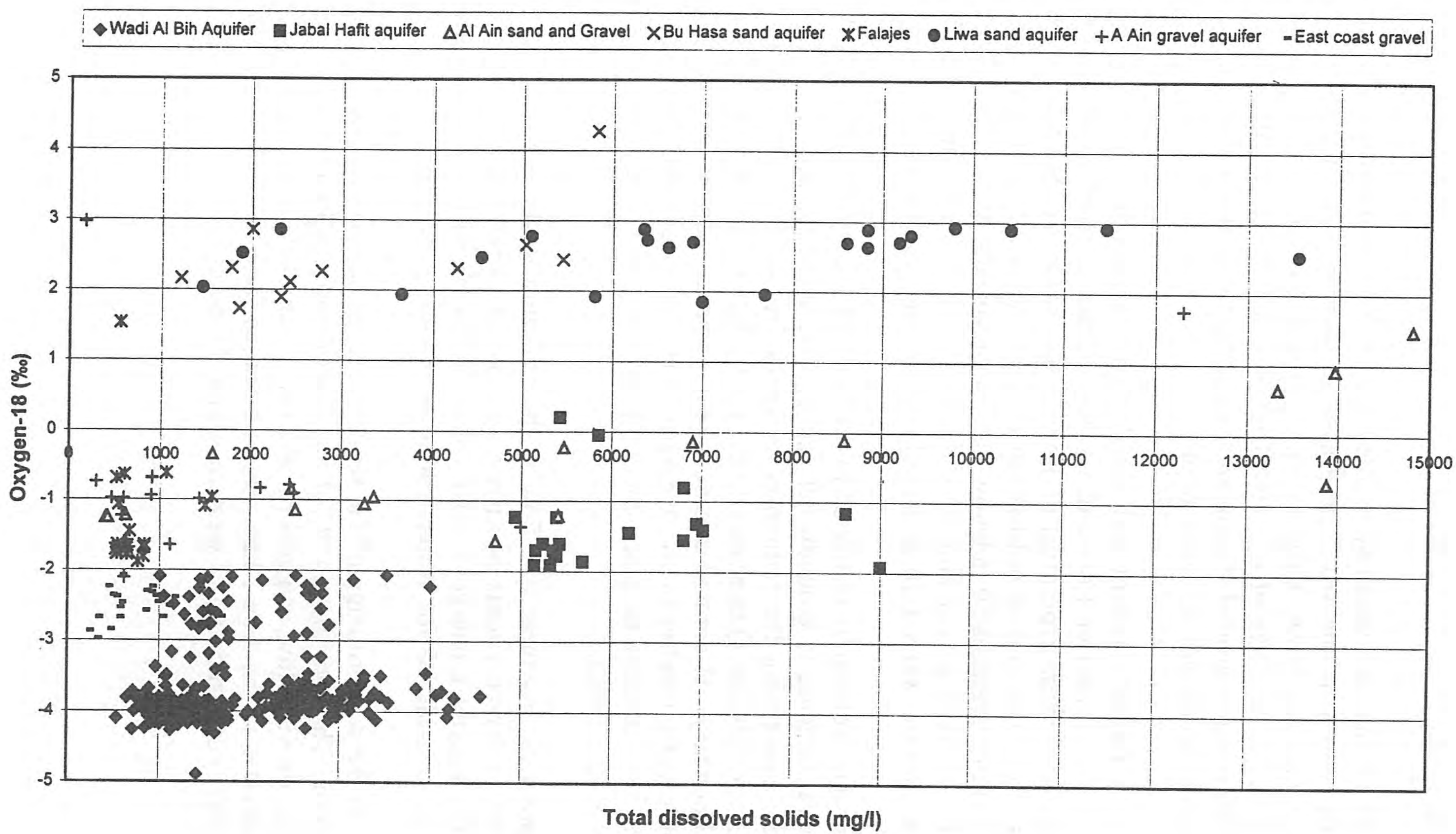

Figure 9. Oxygen-18 (‰) versus Total Dissolved Solids (TDS in mg/l) in UAE groundwater.

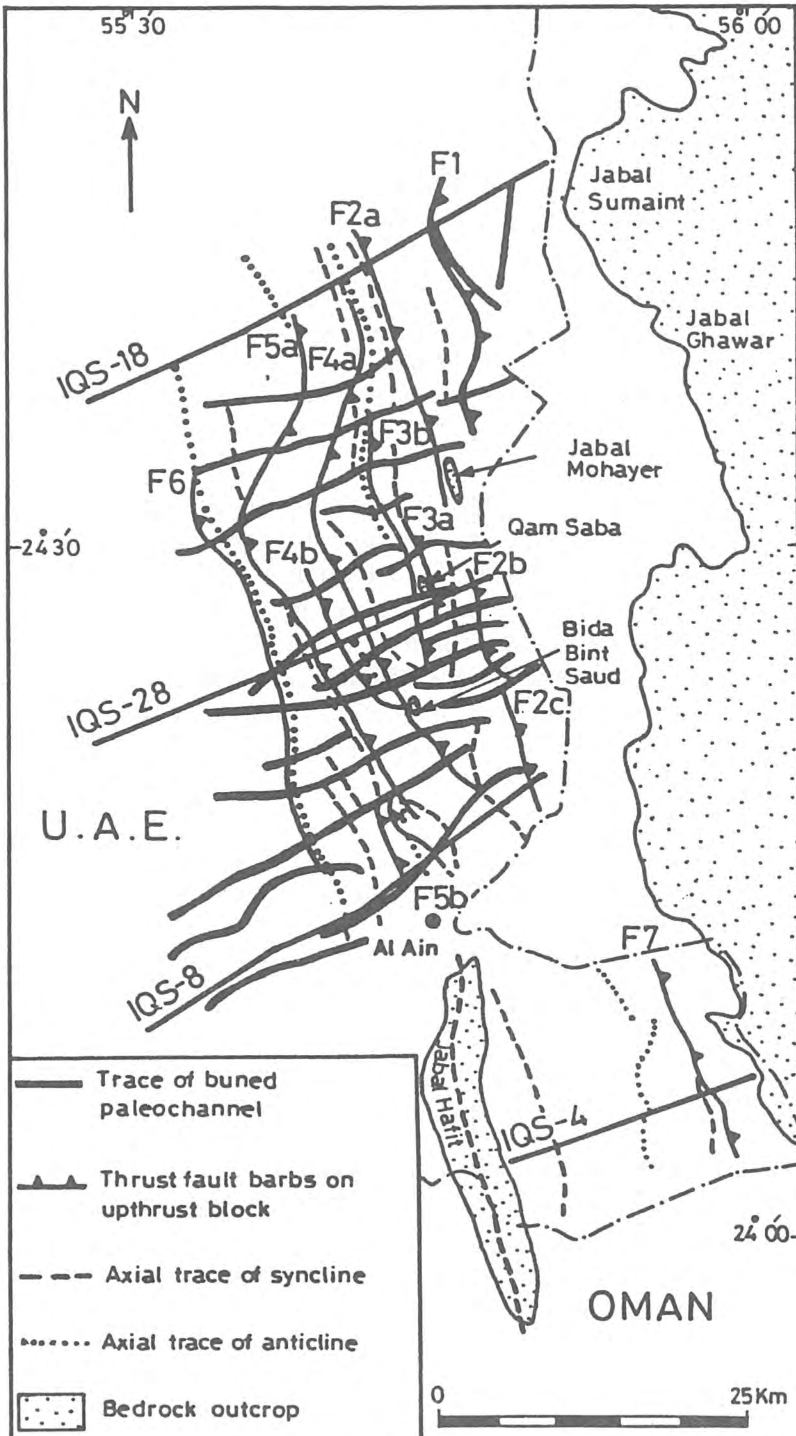

Figure 10. Generalized shallow structural features of Al Ain area, showing trace of buried paleochannels (Woodword, 1994)

EASTERN QUATERNARY GRAVEL AQUIFER

Groundwater in this aquifer plot on the meteoric water line. However, few wells show the effect of evaporative enrichment. The low chloride concentrations (average 300 mg/l) suggest younger water in hydrogeological terms. This would mean the sampled wells discharge from a local groundwater flow system (Figure 5).

The stable isotope contents are relatively depleted compared with the western gravel aquifer. The deuterium excess 13.6 suggests that this region is, in part, receiving recharge from two air masses; the winter precipitation from the Mediterranean Sea and the Monsoon rain from the Indian Ocean.

The tritium content in groundwater of the eastern gravel aquifer is higher than those in the present-day rainfall (Figures 11). It seems that this water was recharged after 1972 (which was an exceptionally wet year) and decayed in time during groundwater circulation. Groundwater in this aquifer contains the highest activities in ^{14}C of Total Dissolved Inorganic Carbon (TDIC) in UAE (Figure 5). The ^{14}C ages of groundwater range from modern to 7,000 years B. P. This agrees with the high ^{3}H content in the aquifer and confirms that this aquifer is receiving modern recharge.

LIWA QUATERNARY SAND AQUIFER

The groundwater in sand dune aquifer plots very far from the GMWL, indicating enrichment before and/or during groundwater recharge. According to Akiti (1988), the low salinity of water in the sand dunes of the Liwa area suggests the possible recharge by way of an ancient wadi. However, this possibility needs further investigations.

The tritium values measured in 1996 range from 0.1 to 3.4 TU, with an average of 0.6. These values are low but does not rule out the possibility of recharge which can occur in association with exceptionally heavy rain storms which occasionally may affect this extremely arid region.

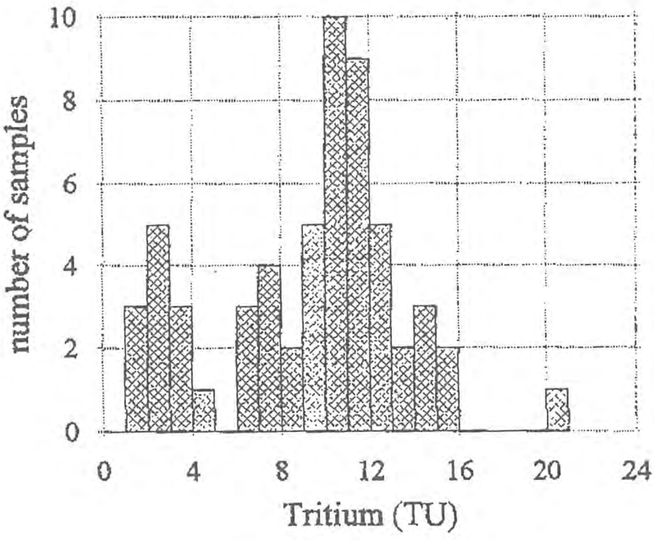

Figure 11. Frequency distribution of tritium values of groundwater samples from the eastern gravel aquifer of UAE (Wagner, 1997)

The wells tapping groundwater in sand dunes contain practically no detectable tritium. However, some of the samples analyzed in 1996 contain up to 3.4 TU, proving the possibility of present-day recharge. However, this assumption needs further investigation and more ^{14}C measurements.

The lowest ^{14}C activities are found in the Quaternary Liwa sand aquifer. These low activities are accompanied by low Cl^- and TDS contents, because the aquifer is mainly composed of sands which usually has low salt contents.

SOURCE OF GROUNDWATER SALINITY

Gonfiantini (1992) made a preliminary analysis of isotope data from Wadi Al Bih Permian limestone aquifer and concluded that salt-water intrusion is an ongoing process, causing the observed rise in groundwater salinity (Figure 12). Rizk et al. (1998) re-evaluated this data to investigate the source of salinity in the aquifer and assess the impact of the Wadi Al Bih dam on groundwater recharge. The LMWL for UAE has a lower slope than the GMWL, indicating evaporation of precipitation (Figure 2). The groundwater samples, on the other hand, are clustered in a narrow range of more depleted values (Figure 13). The narrow distribution of the data suggests that either evaporation or

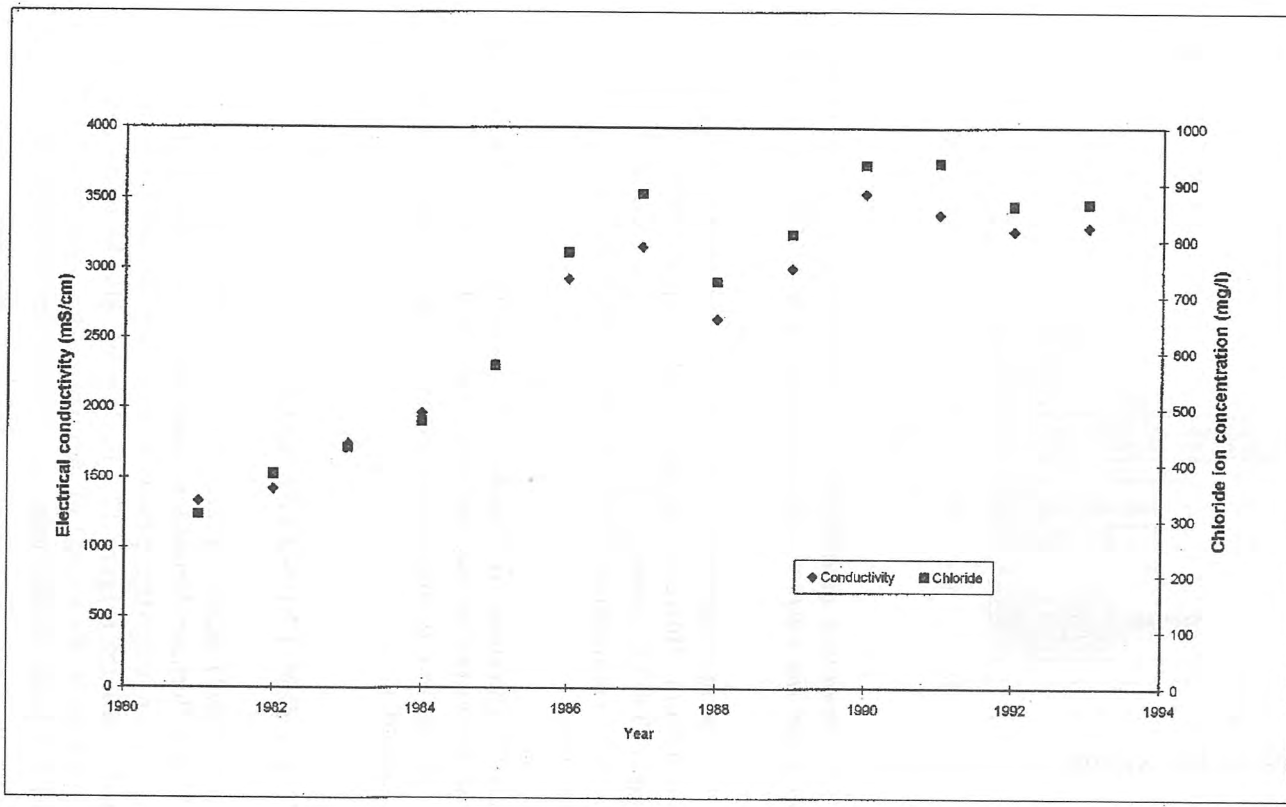

Figure 12. Electrical conductivity ($\mu S/cm$) versus chloride-ion concentration (mg/l) in Wadi Al Bih Permian limestone aquifer for the period 1980-1994)

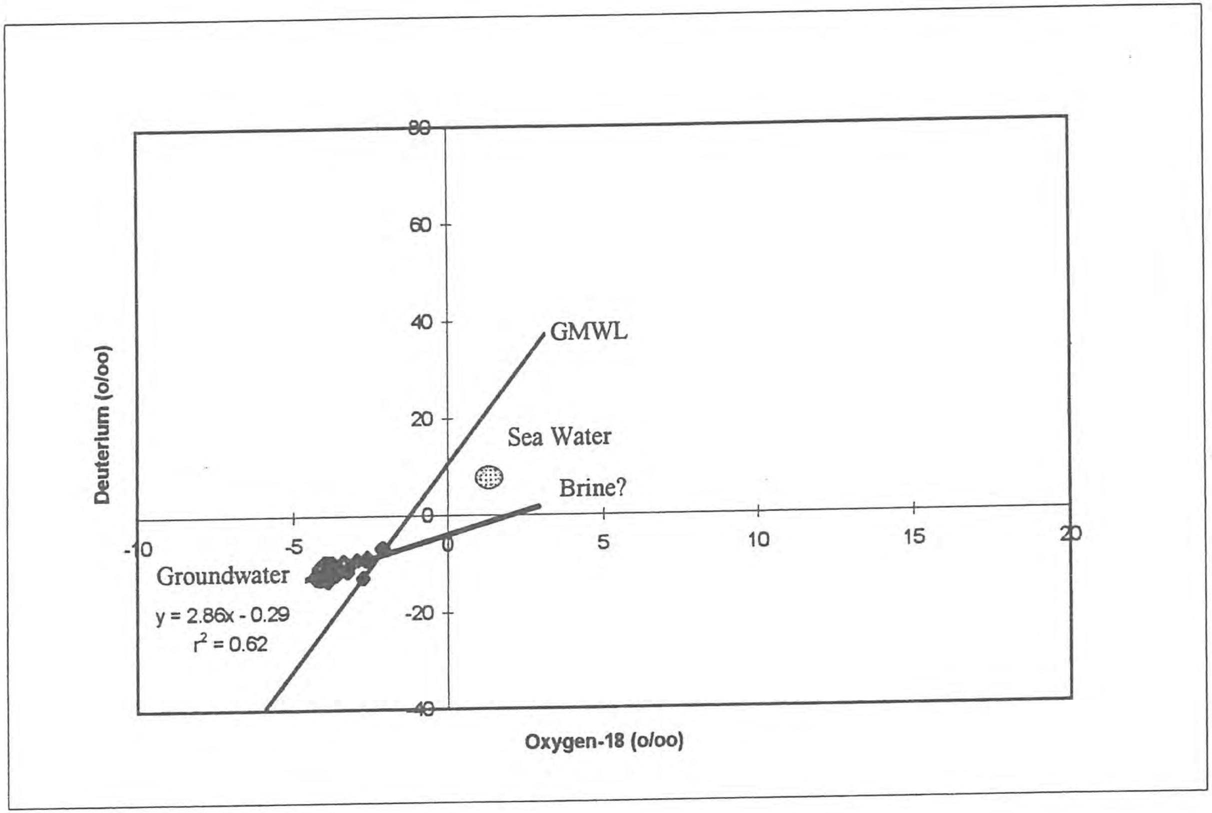

Figure 13. Stable isotopic composition of groundwater in Wadi Al Bih Permian limestone aquifer (from Rizk et al., 1998)

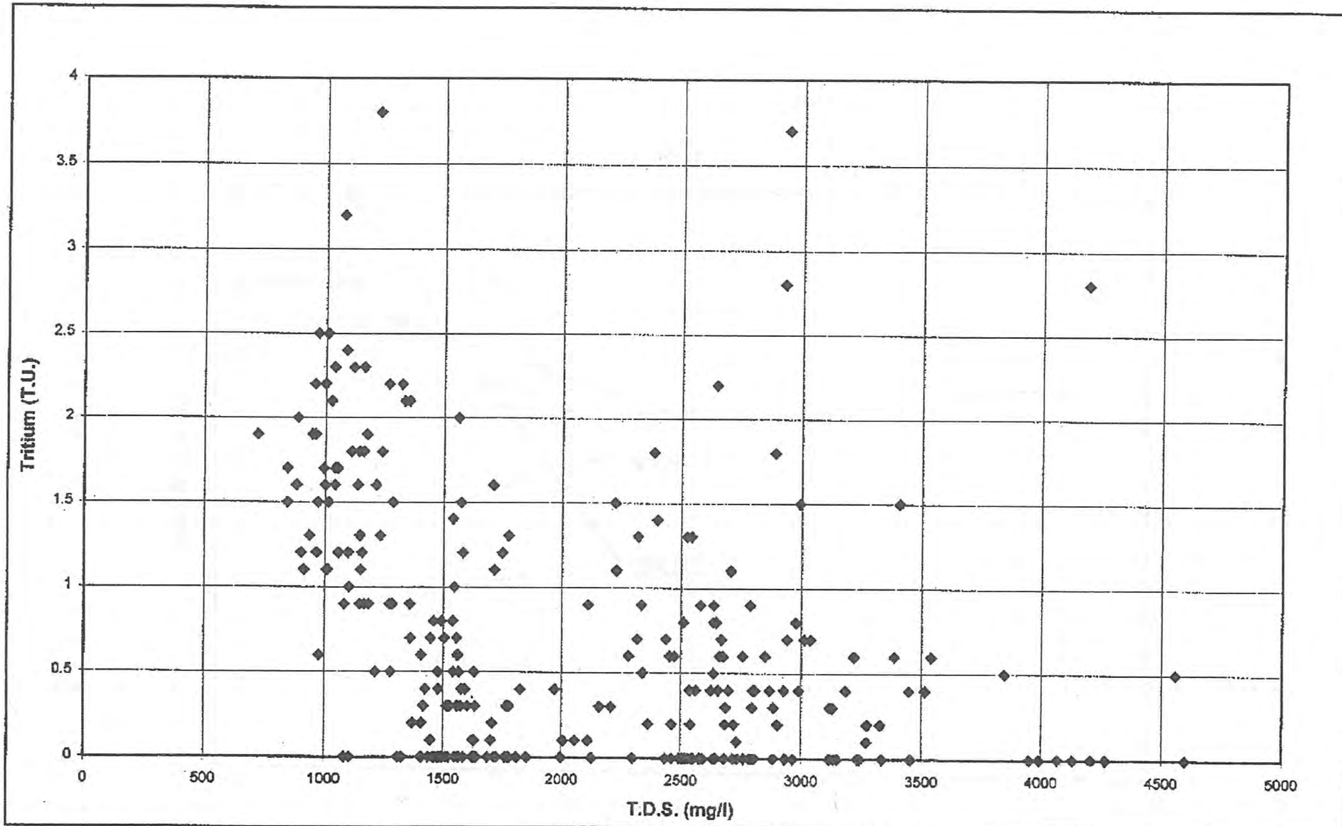

Figure 14. Tritium (TU) versus Total Dissolved Solids (TDS in mg/l) in Wadi Al Bih Permian limesone aquifer

mixing processes do not have pronounced affects on the stable isotopic composition of groundwater. A weak best-fit trend through the data (r^2=0.6) suggests a small component of either evaporation or of mixing with an unknown source of water, probably not sea water. As calculated with NETPATH (Plummer et al., 1991), a range of sea water mixing values (up to 35%) are needed to reproduce the observed salinity in Wadi Al Bih groundwater, yet the isotope data does not strongly follow this trend. Therefore, it is possible that highly saline water or brine may exist in lower stratigraphic units. A much small component of mixing would be required to produce the observed change in salinity with a less pronounced affect on the isotopic composition of groundwater. This unknown component may only represent a deeper groundwater flow path for the Wadi Al Bih system which undergoes water-rock reactions with evaporite minerals at depth. This hypothesis is supported by the relationship between salinity and higher-temperature water in the northeastern section (Figure 12) and by the relationship between tritium and salinity (Figure 14). The tritium (^3H) content of Wadi Al Bih groundwater is < 4 tritium units (TU) whereas precipitation during the period ranges between 5 and 10 TU (IAEA Global Precipitation Network station at Bahrain). This supports the hypothesis that groundwater in the Wadi Al Bih aquifer system is a mixture of older (possibly deep flow) and younger (karstic flow) groundwater, both from the same recharge area (Figure 15). It is interesting to note that, though there is a slight evaporative trend in the stable isotope data, the data do not suggest a large component of recharge induced by the Wadi Al Bih dam (which would have a strong evaporative signature).

The steady increase of groundwater temperature in Wadi Al Bih basin towards the northwest may indicate a source of water from deeper horizons entering the aquifer. Evaluation of the chemistry of the water, in particular the Ca^{2+}/Mg^{2+} and the Cl^-/SO_4^{2-} suggests the end-member mixing source for Cl^- and SO_4^{2-} is not modern sea water (Hounslow, 1995), rather a variable degree of water-rock reactions with NaCl rich evaporite minerals or a brine (Figures 13 and 16). The source of SO_4^{2-} in the Wadi al Bih aquifer system should be investigated using stable S isotope.

The depleted isotopic composition of groundwater with respect to local precipitation suggest the recharge zone is at a higher elevation. Rizk et al. (1998) estimated the average elevation of recharge. They used a mean $\delta^{18}O$= -3‰ for groundwater, a mean $\delta^{18}O$= -1.1‰ for measured rainfall near the GMWL, and the arid zone adiabatic change in $\delta^{18}O$ of 0.2‰ per a 100 m increase in altitude (Erikson 1983). The average elevation of recharge calculated in this way would be 1,050 m. The elevation of the

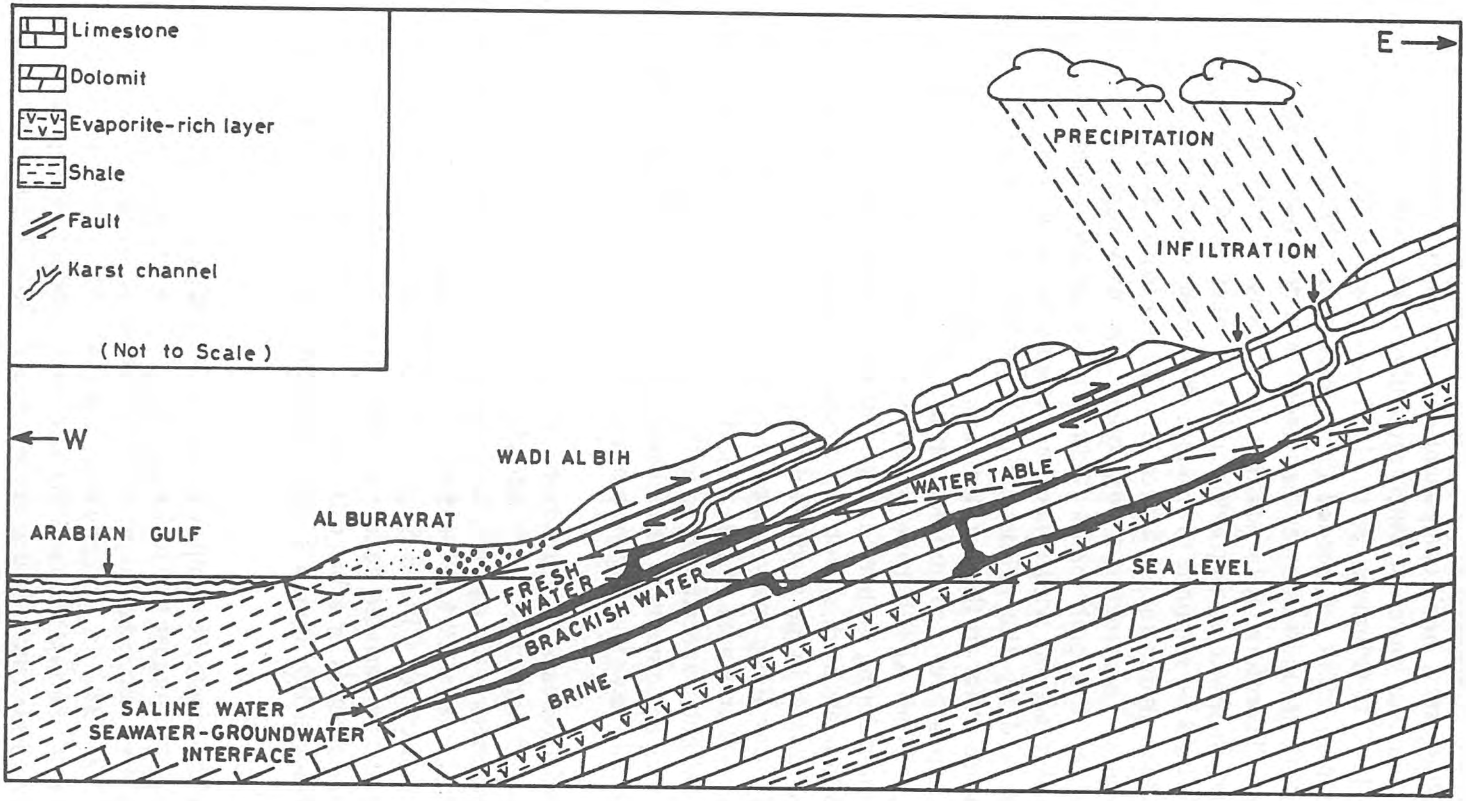

Figure 15. Schematic diagram illustrating the hydrogeologic condition of Wadi Al Bih Permian limestone aquifer

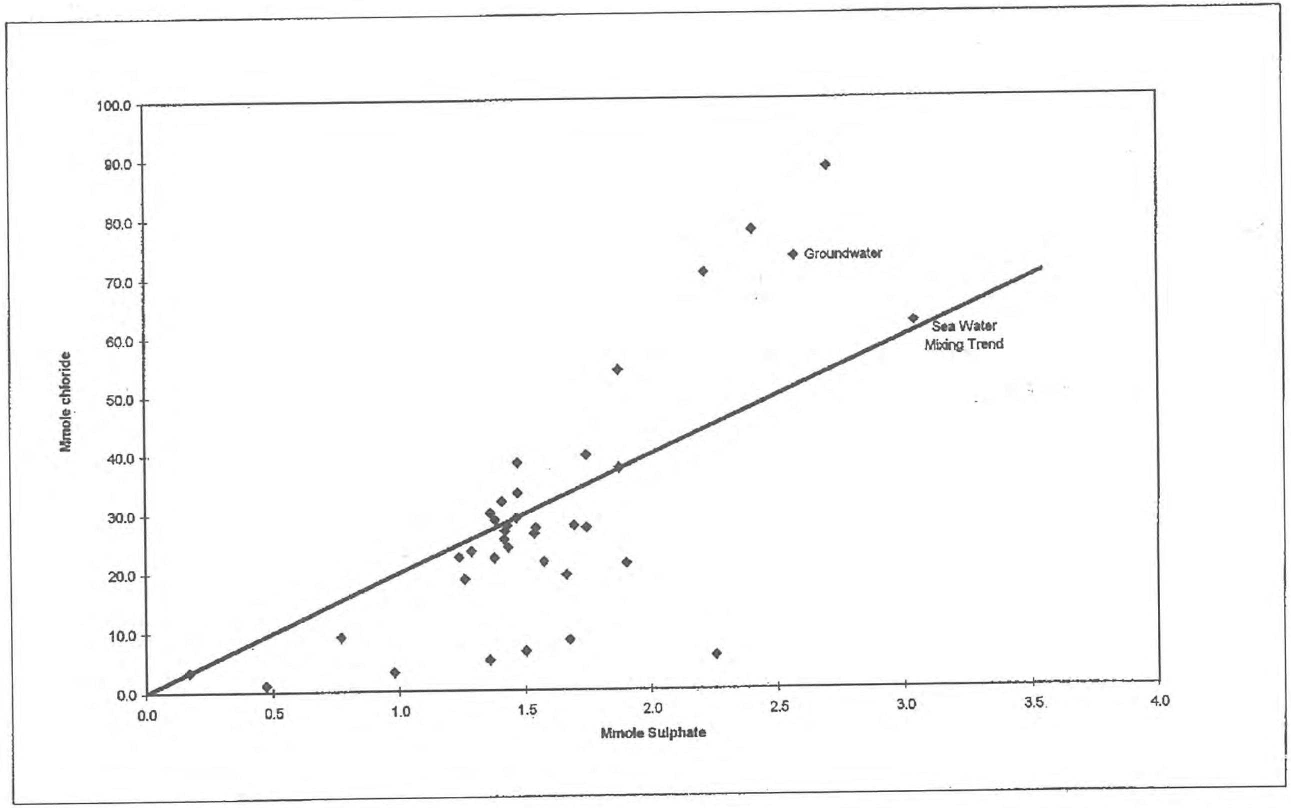

Figure 16. Chloride versus sulphate concentrations (mg/l) in Wadi Al Bih Permian limestone aquifer, illustrating sea water mixing trend

peaks in the Ru'us Al Jibal mountains which surrounds the aquifer varies between 1,050 and 2,090 m. Therefore, it seems logical to conclude the main recharge area for the Wadi Al Bih aquifer system is at high elevation in the surrounding mountains, or the recharge water is largely derived from runoff and wadi infiltration at higher elevations. This again indicates that the influence of the Wadi Al Bih dam on groundwater recharge has been minimal.

ASSESSMENT OF GROUNDWATER POLLUTION

Figure 17 is a plot of ^{2}H versus ^{18}O in several water samples from the Quaternary Liwa sand aquifer in the Bu Hasa area and an oil-field water sample which is currently disposed in the Miocene clastic aquifer. The plot suggests that the stable isotopic composition of oil-field water and water of the Quaternary Liwa aquifer at the Bu Hasa area are distinctly different. This points out to the effectiveness of the Lower Miocene Fars Formation as a good seal, preventing oil-field water from moving upward into the fresh Liwa aquifer. In contrast, groundwater in the Bu Hasa area seems to have isotopic composition identical to that of groundwater in the Liwa Crescent area in the southeast, suggesting a single common source of groundwater in both areas.

Figure 18 illustrates a comparison of stable isotopes in UAE groundwater with those in groundwater of the Arabian Gulf and Middle East regions. While groundwater in Wadi Al Bih Permian limestone aquifer lies on the regional meteoric line, groundwater in the Liwa Quaternary sand aquifer exhibits the most isotopically enriched aquifer in the whole region. One hypothesis is that the Liwa area was occupied by a lake from which excessive evaporation might have occurred leading to high enrichment of stable isotopes before water moves downward recharging the aquifer. Wet pluvial periods of 12,000 and 22,000 years ago were indicated by analysis of lacustrine deposits from the Liwa area (Wood, 1996). These periods may represent the pluvial intervals during which the recharge of isotopically enriched water occurred. Stable isotopes of the Quaternary gravel aquifers plot on both sides of the GMWL. Groundwater in the eastern gravel aquifer has depleted stable isotopes, high tritium (average 7 TU) and ^{14}C activities and receive present-day recharge from the northern Oman Mountains. Stable isotopes in groundwater of the western gravel aquifer varies from depleted values in the east to highly-enriched values in the west. The tritium content ranges from 0.1 to 8.7 TU with an average of 2.5 in the eastern part of the aquifer to virtually no tritium in the western part. Jabal Hafit Dammam limestone aquifer contain enriched isotopes,

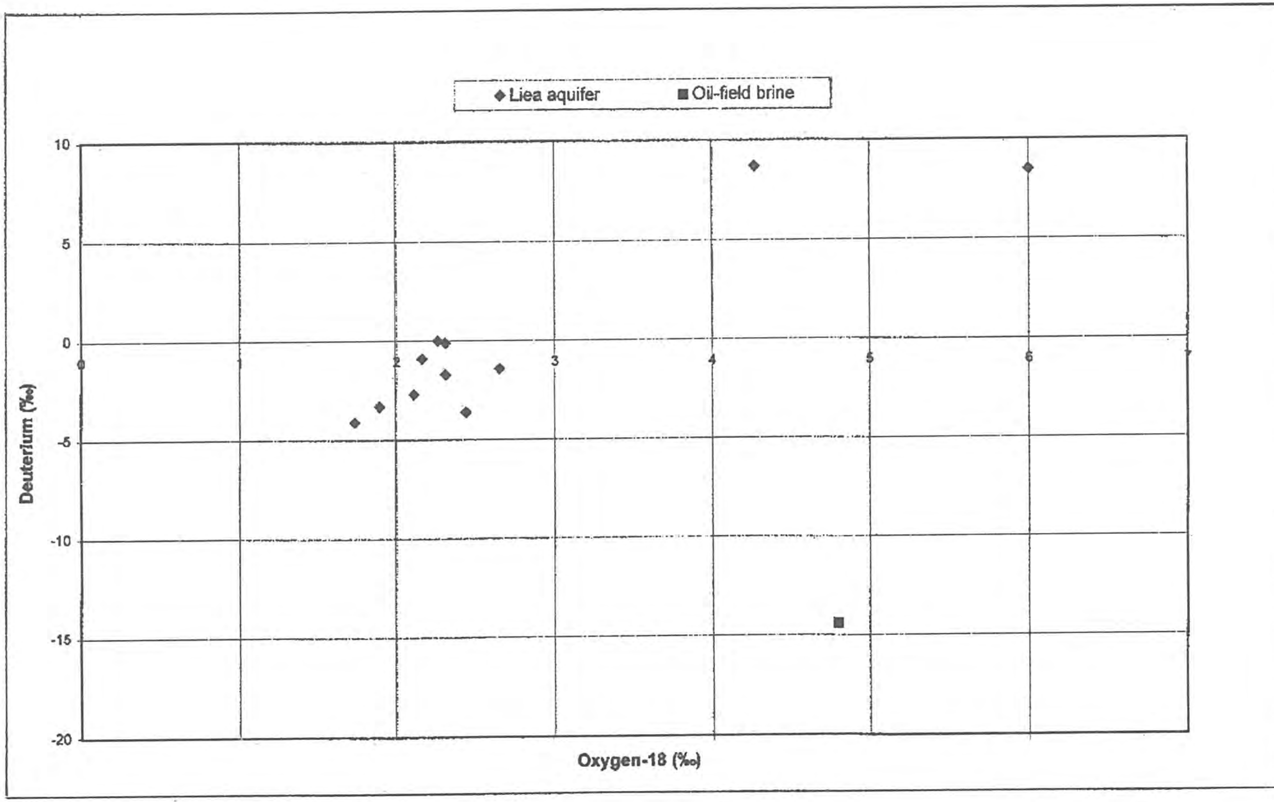

Figure 17. Stable isotopes in the Liwa Quaternary sand aquifer and oil-filed brine disposed in the Miocene clastics at the Bu Hasa area

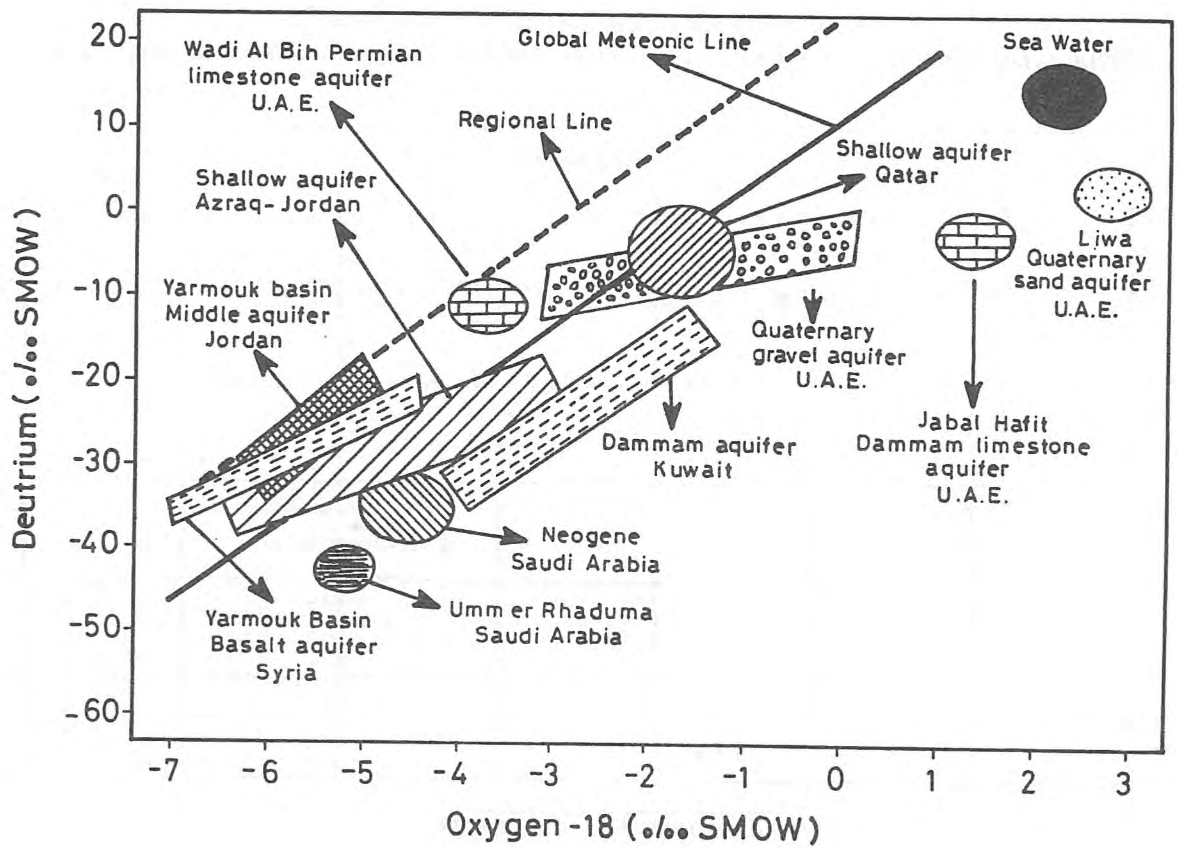

Figure 18. Characteristic stable isotope concentrations of some major aquifer in the Gulf region and Middle East

reflecting old-age groundwater. The overall setting of UAE groundwater in Figure 18 shows a pronounced evaporation trend between the highly-depleted groundwater of Wadi Al Bih limestone aquifer and the extremely enriched groundwater of the Liwa sand aquifer.

CONCLUSIONS

The meteoric water line for the present-day precipitation in UAE has a mean $\delta^{18}O$ of -1.99‰, mean $\delta^{2}H$ of -0.4‰ and deuterium excess (d) = 16, suggesting two sources of moisture; the Mediterranean Sea in winter and Indian Ocean in summer. The depleted winter precipitation falls on the MMWL and the enriched summer rain falls on the GMWL. The scatter of some stable isotope data suggests that the raindrops are affected by evaporation during the fall of the droplets. The average ^{3}H content in rainfall is 4.7 Tritium Units (TU).

Ru'us Al Jibal and the northern Oman Mountains are the main recharge areas for groundwater in UAE. Wadi Al Bih Permian limestone aquifer is receiving recent recharge at high altitude from Ru'us Al Jibal area (1,050-2,090 m). This recharge is indicated by seasonal variations in groundwater temperature and salinity, high ^{14}C activity and high ^{3}H content (4 TU). The eastern Quaternary gravel aquifer is recharged from the northern Oman Mountains (650 m) as indicated by low salinity (800 mg/l), high ^{3}H content (7 TU) and depleted stable isotopes of hydrogen and oxygen (^{2}H = -6‰ and ^{18}O = -2.5‰). The eastern part of the western Quaternary gravel aquifer is presently recharged as shown by low salinity (408 mg/l), high tritium content (2.5 TU) and high ^{14}C activity. Groundwater in the Jabal Hafit Dammam limestone aquifer, most parts of the western Quaternary gravel aquifer, and Liwa Quaternary sand aquifer is old and does not seem to receive significant recent recharge. Water in these aquifers is characterized by high salinity, absence or low ^{3}H, low ^{14}C activity and highly-enriched ^{2}H and ^{18}O values. The parallel increase of EC and $\delta^{18}O$ indicates salt-water intrusion in the western Quaternary gravel aquifer, whereas the increase of salinity and constancy of $\delta^{18}O$ in Wadi Al Bih and Liwa aquifers indicate dissolution of salts from the aquifer matrix. Stable isotopes in groundwater of the western Quaternary gravel aquifer and Liwa Quaternary sand aquifer are distinctly different. Enrichment of stable isotopes in the Liwa aquifer indicates evaporation prior infiltration. However, the projection of stable isotopes in both areas on the Local Meteoric Water Line (LMWL) indicates a common, high elevation recharge source (the northern Oman Mountains). Groundwater of the northern and eastern parts of UAE has high ^{3}H and ^{14}C activities, indicating ages from modern to 5,000 years old, while the groundwater in the western and southwestern parts has low ^3H and ^{14}C activities, indicating ages of 15,000 years or older.

Geochemical modeling of Wadi Al Bih Permian limestone aquifer revealed that the source of increasing groundwater salinity, from 812 mg/l in 1980 to 2113 mg/l in 1994, is a result of water-rock reactions with sedimentary rocks including evaporites and or mixing with a Low-SO_4^{2-} brine potentially found in lower stratigraphic units. This conclusion is supported by re-evaluation of stable isotope and tritium data that suggest groundwater in the Wadi Al Bih limestone aquifer system is a mixture of older (possibly deep flow) and younger (karstic flow) groundwater, both from the same recharge area.

Stable isotopes (^2H and ^{18}O) of oil-field brine and Liwa aquifer from the Bu Hasa area are distinctly different and does not suggest mixing of oil-field water injected in the Miocene clastic aquifer with the shallow, fresh Liwa aquifer.

Present isotope investigations involve the use of ^{34}S to differentiate between the salinity form brine and sea-water intrusion, and ^{15}N and ^{18}O in (NO_3^-) to determine the source of high of nitrate ion in shallow groundwater.

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Changes in Ground-Water Quality Related to Agricultural Development in the Liwa Crescent Area, Abu Dhabi Emirate

Ismail Al Bady

CHANGES IN GROUND-WATER QUALITY RELATED TO AGRICULTURAL DEVELOPMENT IN THE LIWA CRESCENT AREA, ABU DHABI EMIRATE

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ABSTRACT

In 1996, the Ground-Water Research Program began to investigate environmental concerns and document changes in ground-water quality in agricultural areas in Abu Dhabi Emirate. One phase of this reconnaissance study concentrated in the Liwa Crescent area in the western region. This paper discusses the results of sampling in the Liwa Crescent area where hundreds of farm wells have been constructed since 1990.

The Liwa Crescent area is located in the south central part of Abu Dhabi Emirate. It is an interdunal area about 160-km long by 2-km wide, which contains at least 57 natural oases. The usable ground water is shallow and salinity generally increases with depth.

The study consisted of general screening of water quality and drilling observation wells. Nitrate and conductivity analyses were used as a rapid, inexpensive, and effective screening technique for the water quality. This screening took two forms: sampling two or more times to measure changes with time and sampling once white taking the age of farms into consideration. In 1991, many wells in the Liwa Crescent area were sampled for conductivity. In 1996, some of these wells were resampled for conductivity and nitrate. In 1998, wells in a farming strip 1-kilometer wide by 15 kilometers long were sampled for conductivity and nitrate. This area consisted of farms ranging from less than one year old to seven years old. To ensure continued monitoring of the effects of agricultural activities on the ground water, the Program established a network of observation wells in selected agricultural areas.

The study indicates a direct relation between increasing agricultural activity and degradation of ground-water quality between 1991 and 1996. Nitrate concentrations are substantially higher in the ground water from farm areas compared with uncultivated areas. Conductivity and nitrate increases are

proportional to the ages of farms, indicating that the older the farm the higher the conductivity and nitrate concentration in the ground water.

Keywords: Abu Dhabi Emirate, agriculture, conductivity, ground water, Liwa, nitrate.

INTRODUCTION

The Ground-Water Research Program (GWRP) has been conducted since 1988 by the National Drilling Company of Abu Dhabi Emirate and the United States Geological Survey to evaluate the ground-water resources of the Emirate. Before 1996, information about the chemical quality of ground water was obtained primarily to define the extent of fresh and brackish water. In 1996 a program was initiated to investigate environmental concerns and document water quality problems in the Emirate.

Ground water is a precious commodity and is the only fresh natural water resource in the Emirate. Almost all of the fresh ground water is contained in shallow aquifers ranging from about 20 to 100 meters deep. This makes it highly susceptible to contamination from land surface activities such as farming and industrial practices.

The purpose of this report is to summarize ground-water quality changes in the Liwa Crescent area between 1991 and 1996 and compare the changes with agricultural development. Analyses of specific electrical conductance, or conductivity, and nitrate concentration were used as rapid, inexpensive, and effective screening techniques for ground-water quality. Areal distributions of these water-quality parameters were mapped and temporal changes were evaluated.

Location of the Study Area

The Liwa Crescent area is located in the south-central part of Abu Dhabi Emirate about 100 km south of the Arabian Gulf (fig. 1). The Liwa Crescent is a 160-km long by 2-km wide are of sand-dune desert area that forms the northern rim of the empty quarter of the Arabian desert. It contains at least 57 small oases, both natural and manmade. Hundreds of farm wells have been drilled along the Crescent since 1990.

Hydrogeologic Setting

The aquifer in the Liwa Crescent area is composed of homogeneous eolian sand contained within sand dunes, interdunal areas, and sabkhas. Ground water in the Liwa Crescent area is a fossil water that has been age dated between 6 and 10 thousand years before present (Imes and others, 1994). There is little or no natural recharge to the ground-water system, primarily because of the desert climate with average rainfall of only 10 centimeters and the thick unsaturated zone of about 35 meters between ground surface and the water table. The natural ground-water discharge is through evaporation, mainly in sabkha areas north and south of the Crescent.

Figure 2 shows that fresh ground water in the Liwa Crescent area occurs north of the Crescent and occupies an area of about 2,400 km^2(Imes and others, 1994). The fresh water occurs in a lens about 25 meters thick that is surrounded and underlain by brackish and saline water. Because water salinity increases with depth, most wells penetrate the upper part of the aquifer. In this situation, where the lens of fresh water floats on brackish water, there is a high probability that ground-water quality will deteriorate as the brackish water moves upward to replace fresh water withdrawn for irrigation, municipal supply, or other use.

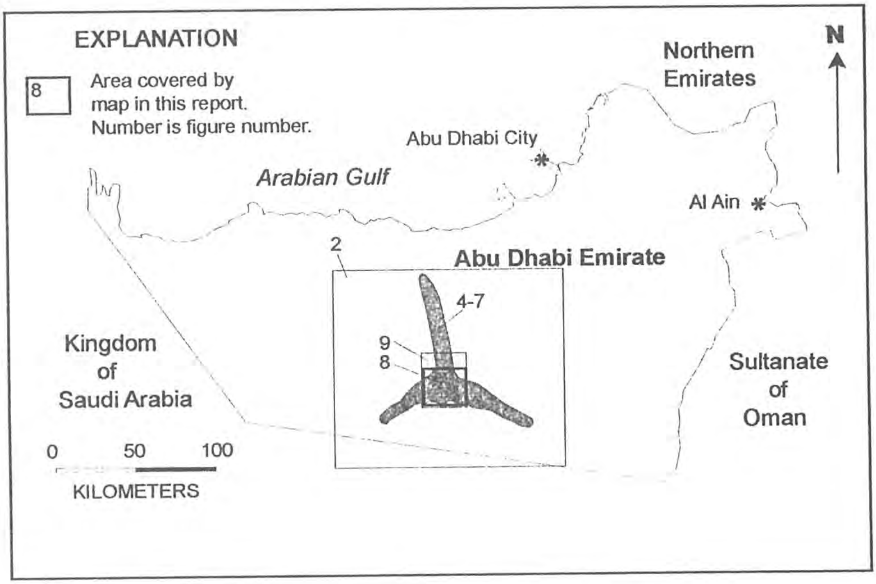


Figure 1 Location of the Liwa Crescent area.

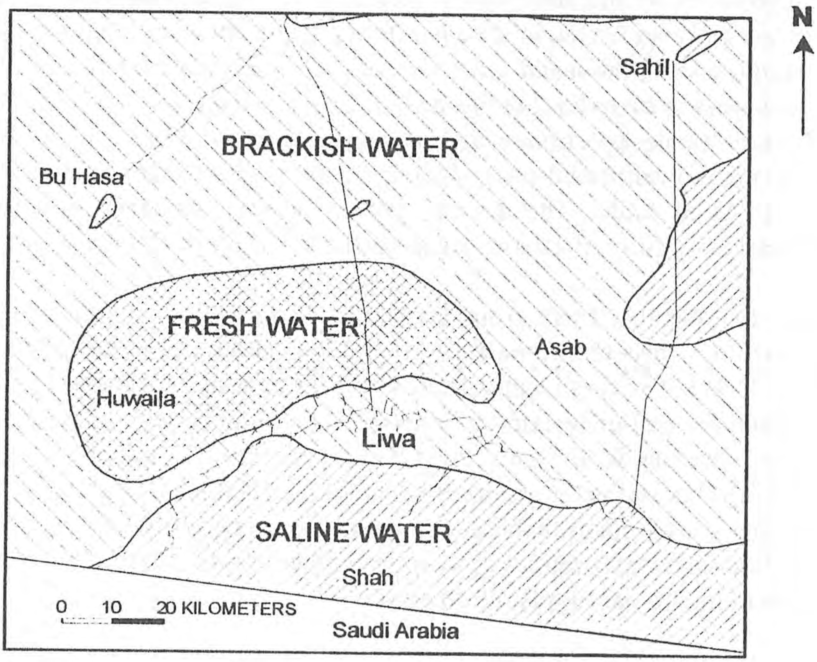


Figure 2 Location of fresh ground water in the Liwa Cresecent area.

METHODS OF STUDY

This study assesses specific ground-water quality concerns in the Liwa Crescent area including:

- differences in water quality among farm forest, and municipal wells,
- 1991 and 1996 conductivity of shallow ground water;
- 1996 nitrate concentrations in shallow ground water,
- areas under cultivation in 1987 and 1996, and;
- relation between farm age and ground-water quality degradation.

Conductivity (measured as specific electrical conductance in microsiemens per centimeter, µS/cm) may increase in irrigated farm and forest areas as irrigation water dissolves applied chemicals or natural salts in the soil. Excess water then percolates downward transporting these salts to the water table. Increases in conductivity of ground water may also result from upcoming of deeper brackish or saline water beneath pumping centers. In the Liwa Crescent area, salinity, or total dissolved-solids (TDS) concentration, can be estimated by multiplying conductivity by 0.72 (Imes and others, 1994).

Nitrate concentrations were monitored because of potential health implications and because elevated nitrate may be an indication of more serious contamination problems. Large nitrate concentrations in drinking water may cause methemoglobinemia in small children. This condition occurs when nitrate oxidizes the iron in hemoglobin, thus reducing the oxygen carrying capacity of the blood. In adults, excessive nitrate may be associated with certain forms of cancer. In this study, nitrate is expresses as milligrams per liter (mg/L) as nitrogen (nitrate-N). The World Health Organization (WHO) recommends 10 mg/L of nitrate-N as the maximum limit in drinking water.

In 1991, about 170 drilled and dug wells in the Liwa Crescent area were sampled for conductivity. In 1996, 117 selected wells were resampled; 81 farm wells, 20 forest wells, and 16 either municipal wells or wells in uncultivated areas. In 1996, samples were also analyzed to determine nitrate concentrations. In 1998, 30 wells in an agricultural area were sampled for conductivity and nitrate. This area consisted of farms that range in age between less than one year old and seven years old. Each sample was collected directly from the well (not from a reservoir or tank) to ensure that a representative sample was obtained. The samples were analyzed for conductivity and nitrate within 12 hours of the collection time. Conductivity was measured using an Orion meter; nitrate was analyzed using a HACH 2000 spectrophotometer.

To ensure the continuation of the agricultural sampling, the GRWP drilled wells in selected agriculture sites. The wells were drilled upgradient, downgradient, and near the center of the farms. The locations of these wells were selected to enable the comparison of water quality before, during, and after it passes under the farm area. In addition, these wells can be used to assess the effects of farming activates on ground-water levels. The wells were constructed with plastic well screens between depths of about 30 and 75 meters.

Satellite image maps for 1987 and 1996 were inspected to evaluate agriculture development in the Liwa Crescent area. Field checks were also made to compile the ages of selected farms established between these dates.

RESULTS

Water-Quality Changes

Figure 3 illustrates the conductivity relation between well-water samples in 1991 and again in 1996. Of the 117 wells sampled, conductivity increased in 100 wells, most of which were farm wells. Samples from forest and municipal wells showed little or no increase in conductivity.

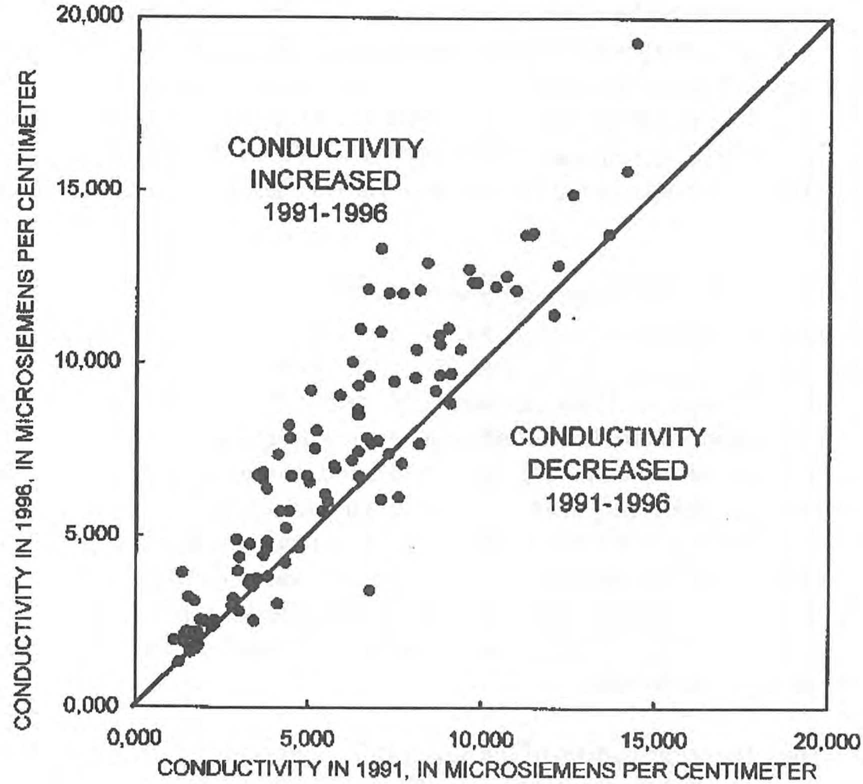


Figure 3. Ground-water conductivity in 1991 and 1996.

Maps showing the areal distributions of conductivity were drawn for 1991 and 1996. The conductivity map for 1991 (fig. 4) shows a relatively large area of fresh (less than 2,250 µS/cm) and slightly brackish (2,250 to 5,000 µS/cm) water along and north of the Liwa Crescent. Three small areas on the map indicate highly brackish water with conductivity greater than 10,000 µS/cm.

By 1996 (fig. 5) the areas of fresh and slightly brackish water had decreased while the area of highly brackish water increased significantly along the entire Liwa Crescent. In addition, the 1996 map shows two areas with conductivity greater than 15,000 µS/cm. Figure 6 shows the changes in ground-water conductivity between 1991 and 1996. Large areas had increases of more than 2,000 µS/cm. Most of these increases were in farm wells along the Liwa Crescent. The smallest increases in conductivity, generally less than 500 µS/cm occurred north of the Liwa Crescent where most of the sampled wells are forest or municipal wells.

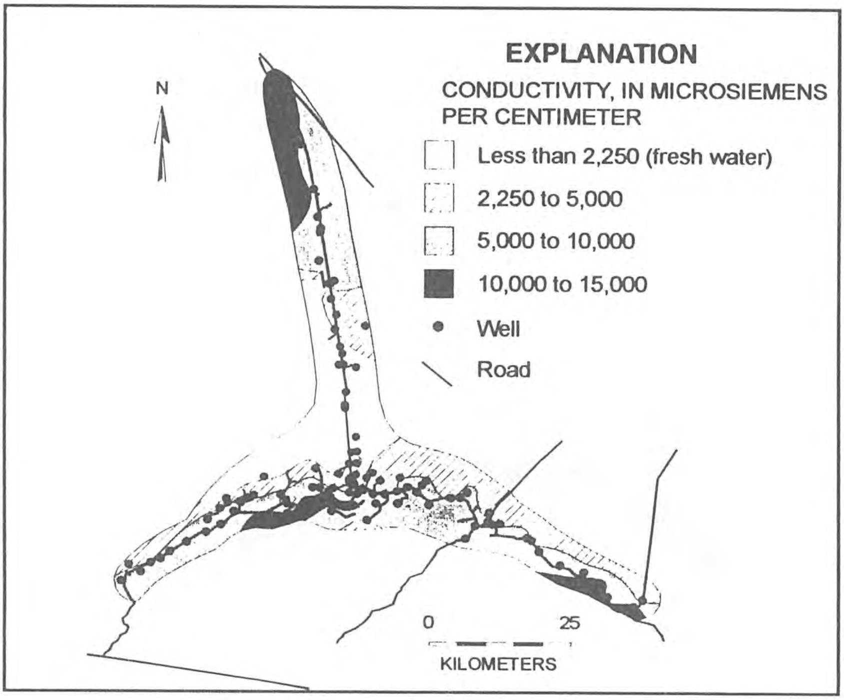


Figure 4. Conductivity of ground water in 1991

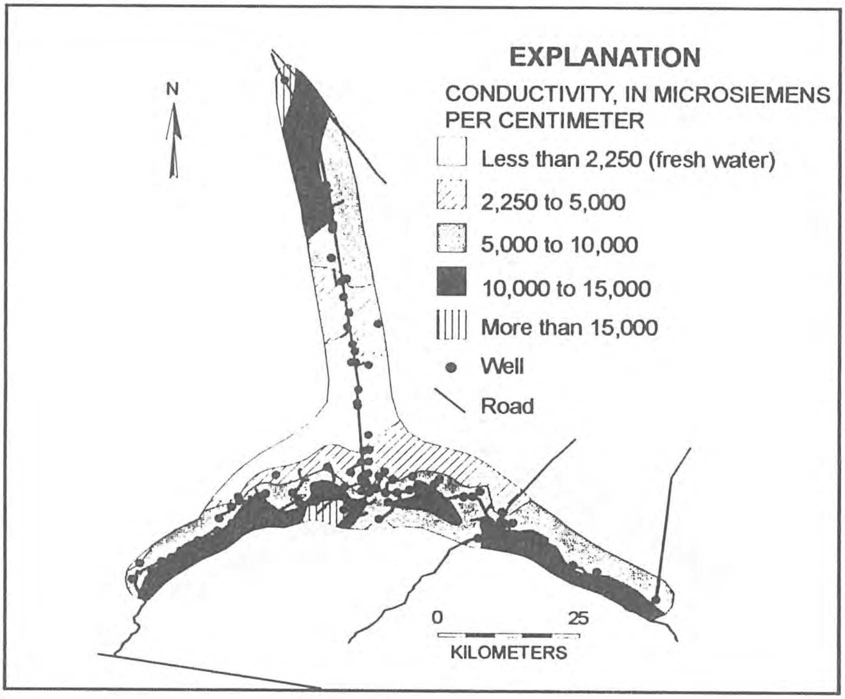


Figure 5. Conductivity of ground water in 1996

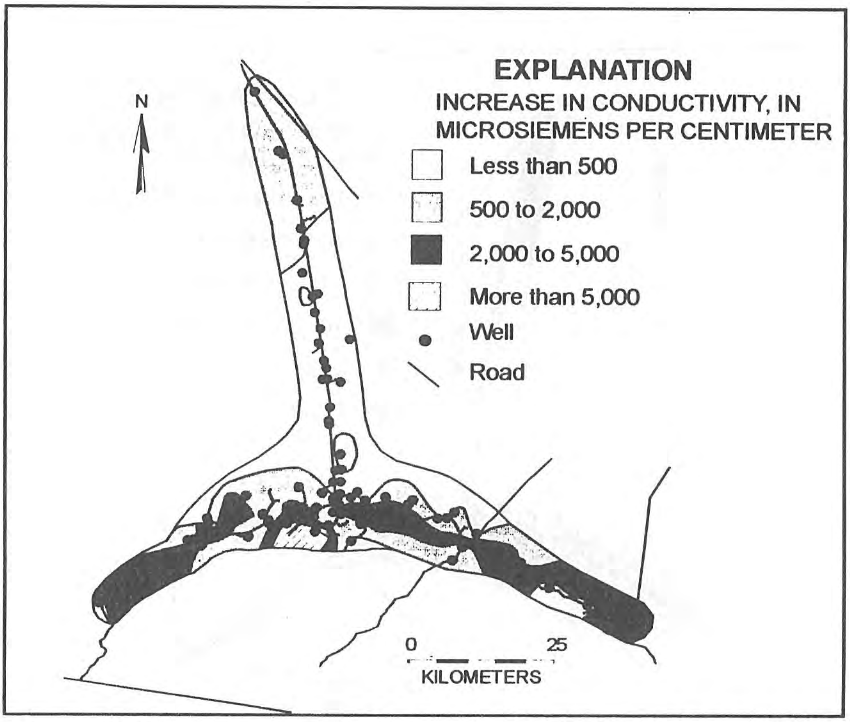


Figure 6. Change in conductivity of ground water, 1991-1996.

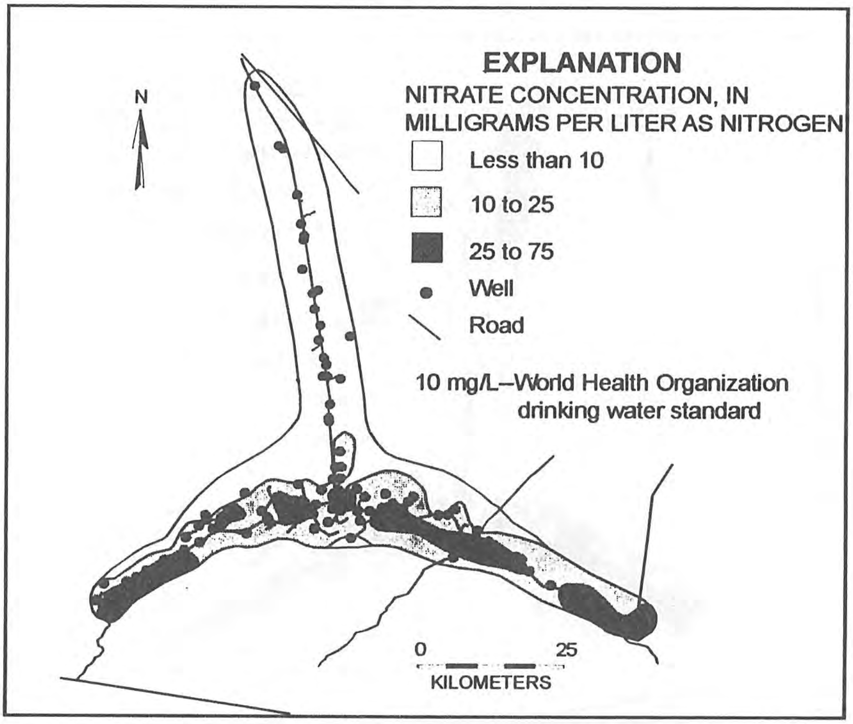


Figure 7. Nitrate in ground water in 1996

Figure 7 shows nitrate concentrations in water from the wells sampled in 1996. Nitrate concentrations ranged from 5 to 75 mg/L. Historical information for the Liwa Crescent area indicates that natural nitrate concentrations range between about 5 and 10 mg/L (Al Bady and Al Aidrous, 1997). In 1996, nitrate concentrations were less than 10 mg/L in forest and municipal wells north of the Liwa Crescent, indicating near-natural concentrations. However, nitrate concentrations were more than 25 mg/L in farm wells along the Liwa Crescent where large conductivity increases were also observed.

Land Use Changes

Figures 8a and 8b show satellite images of part of the Liwa Crescent area. The images show the extent of irrigation in 1987 and 1996 and the dramatic increase in irrigated area between 1987 and 1996. Analysis of the entire Liwa Crescent area indicates that agriculture area increased from 1,000 hectares in 1987 to 4,500 hectares (10 to 45 km^2) in 1996. Forest area increased from 5,000 to 8,000 hectares (50 to 80 km^2). If farms are truly the cause of increasing salinity and nitrate concentration in ground water, future sampling should indicate higher levels at existing sites and more widespread contamination proportionate with the increase in agriculture development.

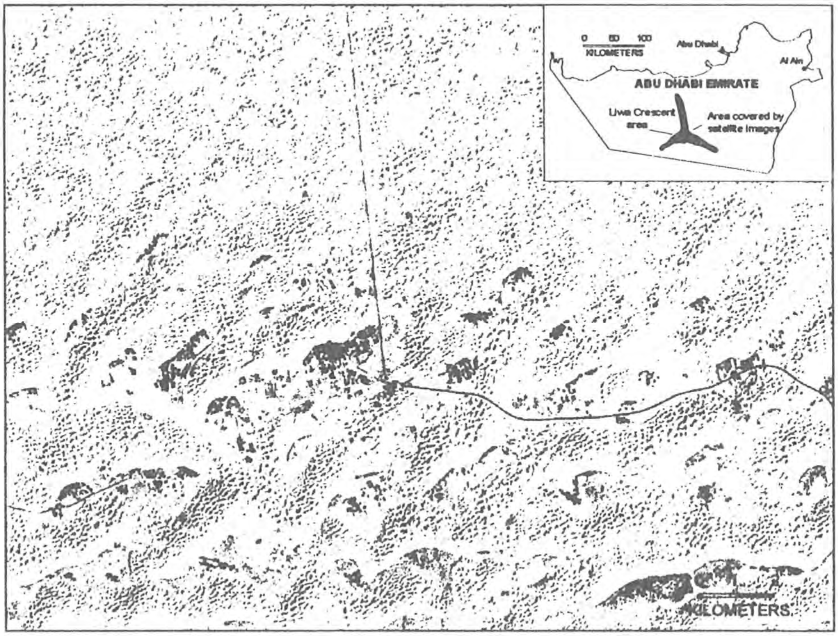
Effects of Farm Age on Water Quality

Because of the general increase in conductivity and nitrate in the Liwa Crescent area, the GWRP selected specific benchmark-farm areas for detailed studies of the effects of agricultural practices on ground-water quality. A monitoring network was established whereby ground-water levels and quality could be measured periodically to document changing conditions. Because of the ongoing agricultural development in the Liwa Crescent area, many sites were available for this type of detailed study.

One benchmark-farm area, approximately one kilometer wide by 15 kilometers long, is located just to the north of the Crescent (fig.9). Four 75-meter-deep monitoring wells were drilled adjacent to and on both sides of the farm area (fig 9). The lithology encountered in these wells was almost entirely dune sand, and the depth to water was about 40 to 50 meters, deeper than many areas in the Liwa Crescent area.

The earliest farms in this area were established around 1991. Since then, the number of farms constructed has increased each year, and in 1998 more land was being leveled to construct more farms. Each farm has two or three wells that pump approximately 300 liters per hour for at least 8 hours per day. The main crops cultivated in this area are vegetables, especially tomatoes in winter, and melons in summer. Other widely cultivated crops include potatoes, onions, cabbage, and eggplant. Fertilizer and agriculture chemicals are applied during planting and generally also through a drip irrigation system on a nearly continuos basis. This area appears to be for monitoring groundwater quality degradation and declines in ground-water levels resulting from agriculture practices. Through a program of periodic monitoring, it should be possible to verify the speed of the effects of the agriculture activities on the ground water.

In 1998, water samples were collected from 34 farm wells in the benchmark-farm area and were analyzed for nitrate and conductivity. The results of the analyses are summarized in table 1. In this area background (or pre-development) concentrations of nitrate are approximately 6 mg/L and conductivity values are about 1,300 μS/cm. Increases in both nitrate and conductivity were detected at farms during the first year of cultivation. At 2-year-old farms, water in some wells was brackish and nitrate concentrations exceeded the WHO standard for drinking water. At 7-year-old farms, water in all wells was brackish. Nitrate concentrations were as much as 70 mg/L, or about ten times the natural background level and 7 times greater than the WHO standard for water. Two older wells in this area have been monitored for water quality since 1991 (fig. 9). The two wells, located near the farms, are pumped daily to fill water trucks, yet conductivity values and nitrate concentrations have remained near background levels.



a. 1987

b. 1996

Figure 8. Landsat satellite images of the Liwa Cresecent area, 1987 and 1996.

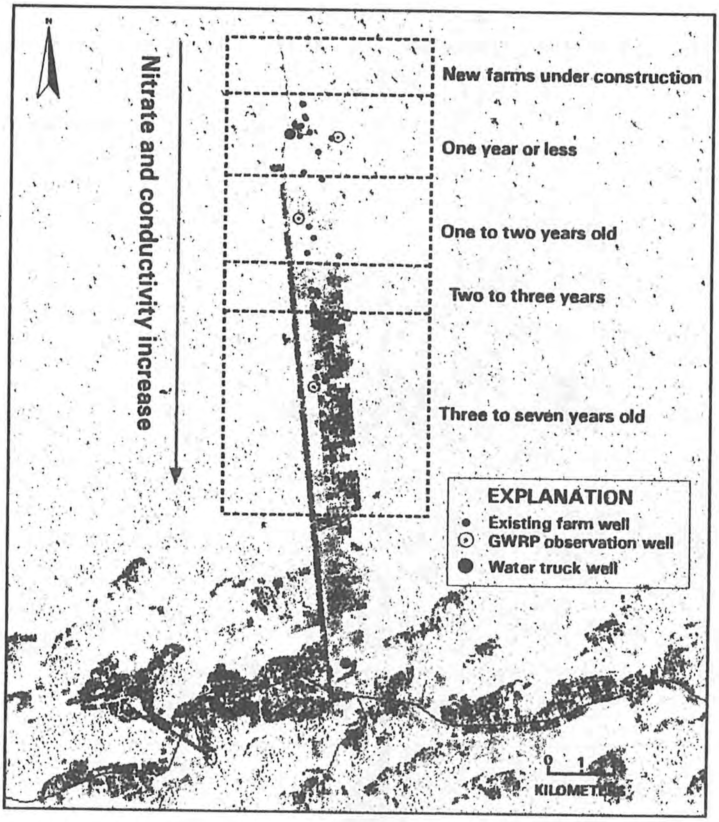


Figure 9. Relation between farm age and ground-water quality degradation

Table 1 Farm age and ground-water quality.

[(μS/cm), microsiemens per centimeter; mg/L, milligrams per liter]

Age of farm (years)	Maximum ground-water conductivity (μS/cm)	Conductivity increase above background (μS/cm)	Maximum nitrate concentration	Nitrate increase above background (μg/L)
< 1	1,900	600	9	3
1 - 2	2,600	1,300	14	8
2 - 3	3,300	2,000	21	15
3 - 7	4,900	3,600	71	65

Background conductivity of ground water = 1,300 μS/cm

Background nitrate concentration in ground water = 6 mg/L

CONCLUSIONS

Agricultural expansion in the Liwa Crescent area has resulted in an increase in the volume of the ground water extracted from the surficial aquifer and an increase in the amount of applied fertilizers and other agricultural chemicals. The increase in conductivity and elevated nitrate concentration occur mostly in farm areas. Forest and municipal wells produce water with conductivity and nitrate concentrations close to the natural background levels of the area. From these facts, conclusions can be drawn concerning ground-water quality in the Liwa Crescent area:

- Conductivity increases in the Liwa Crescent area are due to agricultural activities. Conductivity may increase when irrigation water dissolves farm chemicals and percolates downward to the ground-water reservoir. Conductivity of ground water may also increase when a well pumping from the surficial freshwater lens draws the underlying brackish water upward. Determining whether one or both of these processes contribute to these conductivity increases will require further study.

- The high nitrate concentrations in the Liwa Crescent area are most likely related to the amount of fertilizer applied to farm areas.

- Increases in conductivity and nitrate were noted after less than one year of cultivation, indicating the rapid impact of farming on the quality of ground water.

Water-quality problems in the Liwa Crescent area may be alleviated by:

- Managing pumping rates to minimize upconing of underlying brackish water.

- Managing the use of irrigation water to minimize the amount of excess water that returns to the aquifer

- Managing the application of fertilizers and agricultural chemicals to minimize the amount of chemicals that are leached below the rooting depth of crops.

- Planting crops that require low quantities of water and fertilizer.

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Temporal Variation of Groundwater Chemistry in SAQ Aquifer, Qassim Region, Saudi Arabia

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TEMPORAL VARIATION OF GROUNDWATER CHEMISTRY IN SAQ AQUIFER, QASSIM REGION, SAUDI ARABIA

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ABSTRACT

Assessment and future prediction of water chemistry in Saq aquifer in central Qassim was investigated using two patches of data sets with different sampling times. A comparison of old data (BRGM, 1985) and recent data collected for this study by KACST staff in 1996 in terms of chemical composition has revealed salinity increase and nitrate reduction with time. The salinity in the study area has presently increased 21 % (170 mgl^{-1}) of the average salinity of 1985 in last decade. The nitrate composition has decreased from 70.5mgl^{-1} in 1985 to 9.2mgl^{-1} in 1996. This could be a result of reduction of nitrogen fertilizer usage in the region. The type of water of Saq aquifer in the study area was found to be as a NaCL water type. This shows that the water quality in Saq aquifer in the study area is deteriorating with time, which is attributed to heavy agricultural pumping from the aquifer. Local spatial variation of TDS in aquifer water, some areas with poor quality water, is also common in the study area. Therefore, special attention and proper management is required to reduce the risk of water quality deterioration.

KEYWORDS: total dissolved solids, water quality, deterioration and pumping.

INTRODUCTION

Most of the Kingdom of Saudi Arabia is considered arid land and annual average rainfall varies between 50mm in the Eastern Region and 600mm in the southwestern region. The evaporation exceeds 3000mm per year (Sharaf & Hussien, 1996). The study area is located in Qassim region, Northwest of Riyadh (Fig. 1) and depicted between Latitude 26^0 and 27^0 N and Longitude 43^{0}40' and 44 ^{0} 40' E. The physiography of the study area is characterized by hills and depressions.

The aridity of the region has made groundwater very valuable and important in the Kingdom of Saudi Arabia and hence the efficient use of groundwater for domestic, agriculture and other purposes is a matter of great concern. Groundwater chemistry is, therefore, essential to verify the quality, evolution and existence of groundwater contaminants in the water bearing systems. The objectives of this paper are to investigate chemical composition and temporal variation of groundwater chemistry in Saq aquifer in central Qassim, Saudi Arabia, and discuss the future trend of chemical composition with time.

HYDROGEOLOGICAL SETTING

The Saq formation (Cambo-Ordovician age) is one of the main producing aquifers in the Kingdom of Saudi Arabia, dips towards the Arabian Gulf and rests directly on the crystalline rocks of the Precambrian basement. This formation crops out in the southwest of the study area (Fig. 2) where recharge of the aquifer is assumed to take place. The Saq formation comprises of coarse, medium and fine-grained sandstone. Sandstone facies are generally constant throughout the extension of the formation but thin shaley layers occur in the upper part of the formation (Edgell, 1989).

Previous studies (M. A. W., 1984; Lloyd and Pim, 1990) proved significant volume of water ($280*10^9m^3$) is stored in Saq aquifer. The aquifer water was dated and found be 10 to 30 thousand years old (Sharaf & Hussien, 1996). Individual researchers and groups (Watban, 1976; BRGM, 1985; Jerais, 1986; Edgell, 1989; Segar, 1988; Sowayan & ALLayla, 1989; Hussein et. al., 1992 and Alsagaby & Moallim, 1996) have conducted other studies on groundwater occurrence, movement, chemistry, water level, and potentiality of the Saq aquifer. All these studies have proved the presence of huge volume of water, water level fluctuation and chemical variation with variability of water quality in Saq aquifer. This aquifer was and still the main source of water for Qassim, Tabuk, Hail and As-sir regions and has been pumped heavily since 1970s for agriculture consumption.

MATERIAL AND METHODS

To achieve the objectives of the study, one part of the samples representing the groundwater of Saq aquifer in the study area were taken from the study conducted by Bureau De Recherché Geologiques et Minieres (BRGM) for the Ministry of Agriculture and Water, where the data were collected in 1984. The other part of the data used for this study were collected randomly by the staff of King Abdul Aziz City for Sciences and Technology (KACST) in the period from 23-27 February 1996. These samples were collected from the running wells used by inhabitants of the area for different purposes. The sensitive parameters such as pH, temperature and electric conductivity were measured in the field using a portable instrument called Electrochemistry made by CIBA-CORNING Company.

Chemical analyses were performed for major ions content using standard methods. The major ions analyzed chemically include Na^+, Mg^{+2}, Ca^{+2}, K^+, Cl^-, SO_4^{-2}, HCO_3^-, CO_3^{-2} and NO_3^- . The concentrations of Na^+ and K^+ were measured by using flame photometer and Ca^{+2} and Mg^{+2} by titration method. Similarly, the concentration of different anions was measured, for Cl^- by Titration with Silver nitrate (Argentometri Method), $SO4^{-2}$ by Turbidity (Spectrophotometer), NO_3^- by colorimteric method and alkalinity, carbonate and bicarbonate by using electrometric titration. Hydrowin program (Lukas, 1993) was used for cation\anion balance and the accuracy of complete chemical analysis for water samples was less than 5 % which is tolerable for the interpretation of results.

RESULTS AND DISCUSSION

The results of the field measurements and chemical analysis are presented in Table 1, which provide a general picture of the characteristics of water chemistry for the two sets of samples (BRGM, and KACST).

The sequence of both cations and anions in the analyzed water samples has generally the following order: Na > Ca > K and Cl > SO4 > HCO3 and the majority of the groundwater samples in the investigated area have similar salt pattern except the range varies with time. The composition of groundwater in Saq aquifer in the study area is generally not homogeneous because of residence time of water in the aquifer. This can be observed from the total dissolved solids, which range between 500 mgl^{-1} in the Southwest at Mulayda (Fig. 3a), near the recharge area, and 1800 mgl^{-1} in the north and northeast part of the study area, at the deeper part of the aquifer (BGRM Data, 1984), while the TDS for the data collected by KACST staff after 13 years (1996 data) range between 500mgl^{-1} and ~ 3200mgl^{-1}

in the same trend with the previous direction (Fig. 3b). Local variations in total dissolved solids are common in both patches of data. Exceptional case of high total dissolved solids was observed in the wells of Rowed Al-Jaw village in both sets of data. The increase could be a result of structural phenomena, which reduces the movement of water along the flow path and in turn increase the residence time of water causing an increase in total dissolved solids. Generally, the increase of total dissolved solids in both sampled data coincides with the general trend of groundwater flow direction.

The change in chemical composition of Saq water with time in the study area was indicated by the total dissolved solids and is shown in figure 4. The difference between the average total dissolved solids of both patches of samples (1984 and 1996) has been calculated and found to be about 170 mgl^{-1}. This shows the increase of total dissolved solids with time, indicating that the salinity in the study area has presently increased 21 % of the total salinity of 1984 (12 years period). Furthermore, this temporal variation in salinity in Saq aquifer might be accelerated with frequent use of the aquifer and, therefore, special attention and proper management is required to be taken in the future in order to reduce the risk of water quality deterioration.

Chemical composition of groundwater in the investigated area has also indicated a significant decrease of nitrate concentration. The lowest nitrate concentration in the water samples collected in 1996 was 0.1mgl^{-1} and the highest was 9.2mgl^{-1} while the average concentration was 2.3mgl^{-1}. For the water samples collected in 1984, the lowest nitrate concentration was 0.6mgl^{-1} and highest was 70.5mgl^{-1} while the average was 15.1mgl^{-1}. The highest nitrate concentration in both sample sets was encountered in AL-Bukayriyah well. The decrease of nitrate concentration in the water samples with time could be a result of reduction of agricultural practice in the region and less excess of nitrified mineral fertilizers like ammonia (NH_3) and Nitrate (NO_3) used by the farmers of the region.

The relationship between the total dissolved solids and electric conductivity, which both increase with the concentration of ions, has been expressed by Hem (1970) as TDS (mgl^{-1}) = A*EC (μmohos cm^{-1}), where A is a conversion factor. Hem (1970) reported that nearly all natural waters lie between 0.55 to 0.75. The range between 0.5 to 0.65 includes NaCL water type only while the range between 0.65 to 0.75 is a mixture of water types represented by NaCL, $CaSO_4$ and $NaSO_4$ (Sen and Dakheel, 1986). Figure 5 shows the relationship between EC and TDS from the Saq aquifer in central Qassim.The coexistence of a good relationship is evident from the correlation coefficients (R^2 = 1 and 0.83) for both sampling sets. The conversion factors (0.60 & 0.64) for both sampling fall in the middle of range designated for NaCL water type by Hem (1970). Therefore, the dominant water in the study area is a NaCL type.

Plot of chemical analysis data on the trilinear diamond diagram (Piper Diagram, 1944) was used in order to classify the nature of groundwater in the wells throughout the study area. The chemical data indicate that all water samples are located along the right hand side of the diamond shape field which in turn reflects the amount of total dissolved solids and type of water (the overall composition of the water samples). Therefore, the type of water involved in the aquifer is mainly chloride facies and sodic facies. It was also noticed that, on a relative basis, the contents of chloride were above 90% whereas the contents of sodium were between 80 to 90% (Fig. 6). Thus, this indicates the presence of a salt formation which might have resulted from high evaporation originally and dissolved by the interactions between the water and host rocks.

CONCLUSION

Assessment and future forecast of water quality in Saq aquifer in central Qassim was made using two patches of data sets with different sampling times. A comparison of old data and recent data in terms of chemical composition has indicated salinity increase and nitrate reduction with time. Salinity of the aquifer in the study area was increased with time to about 21% in the last decade (from 1985 to 1996). This might indicate that the water quality in Saq aquifer in the study area is deteriorating with time. Local spatial variation of TDS, some areas with poor quality water, is also common in the study area. Therefore, attention should be paid to the use of the aquifer. The type of water of Saq aquifer in the study area was found to be as a NaCL water type.

ACKNOWLEDGMENT

The authors would like to thank King Abdul Aziz City for Sciences and Technology for continuous support. Special thanks are also due to the staff of Natural Resources and Environment Research Institute Laboratory for sample analyses.

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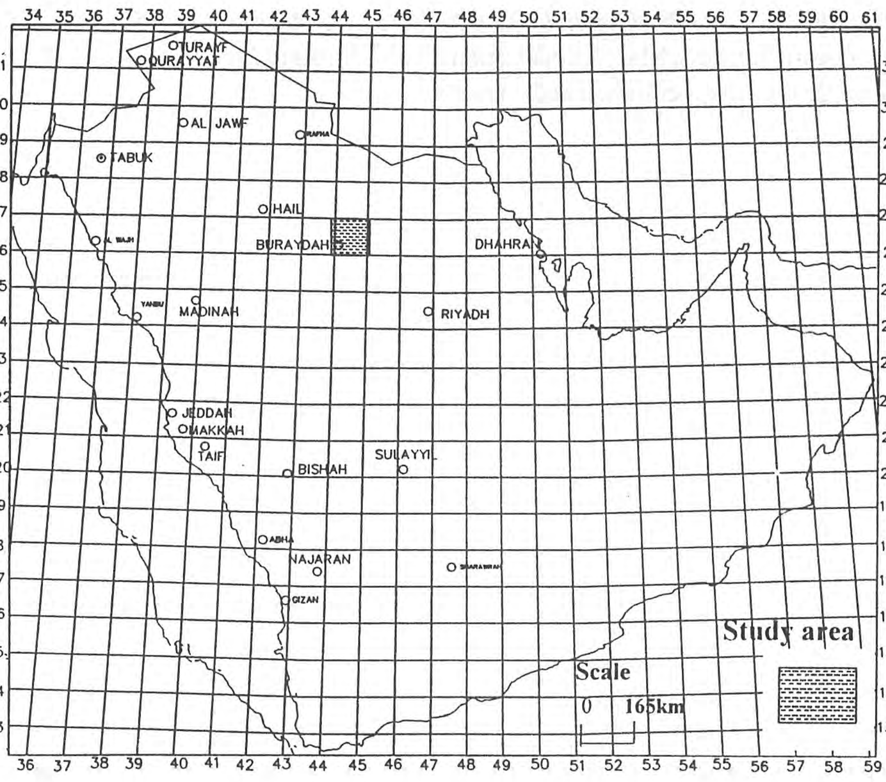


Figure 1: Location Map of the study area

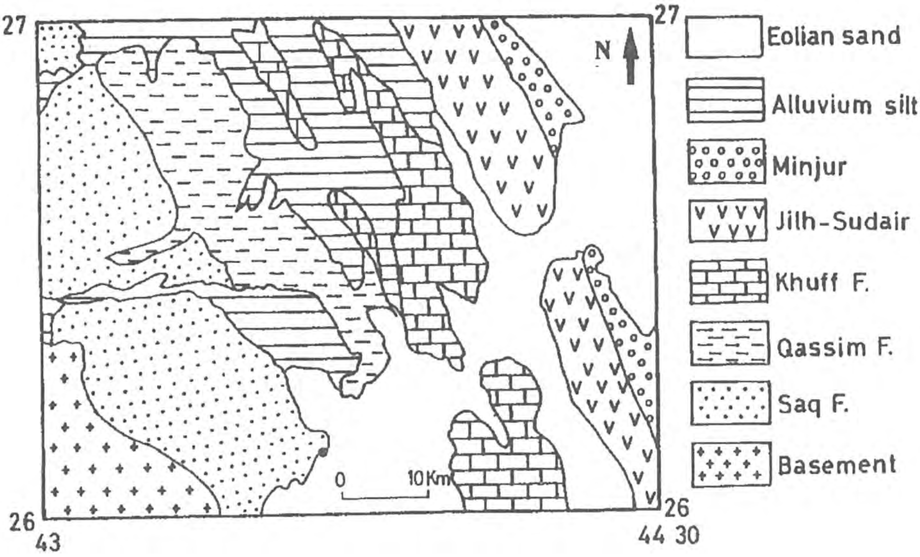


Figure 2: Geological map of the study area (modified from BRGM, 1985)

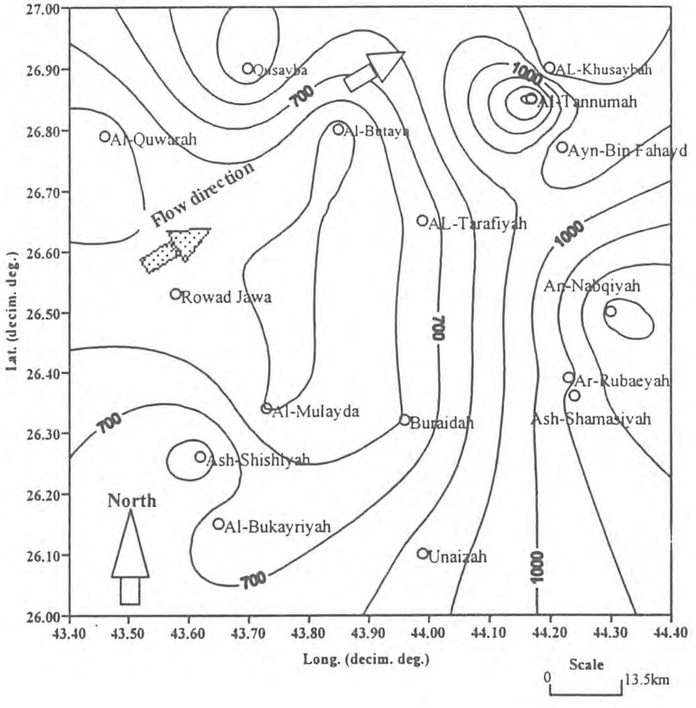


Figure 3a: TDS distribution in Saq aquifer, central Qassim, Saudi Arabia (BRGM, 1985)

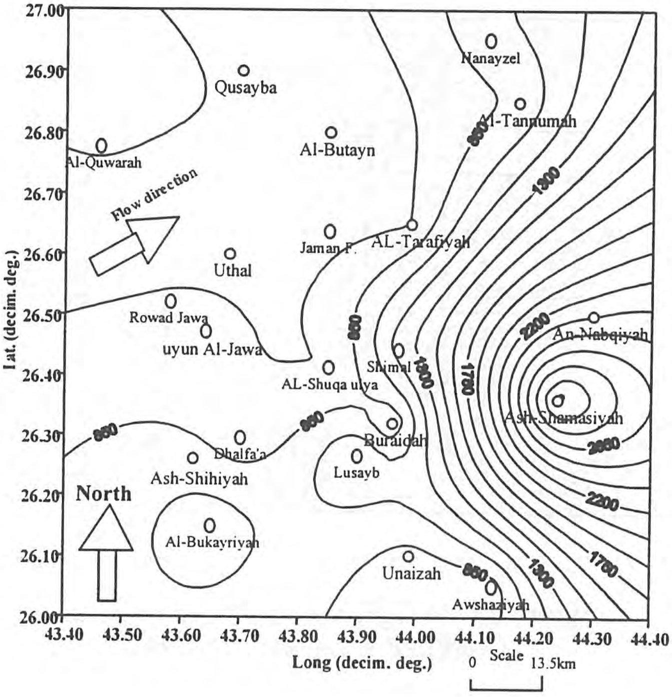


Figure 3b: TDS distribution in Saq aquifer, central Qassim, Saudi Arabia (KACST, 1996)

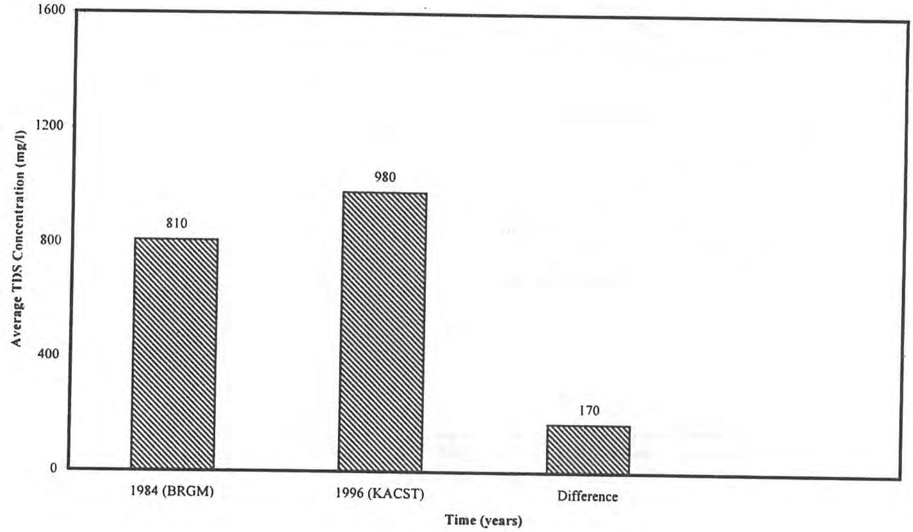
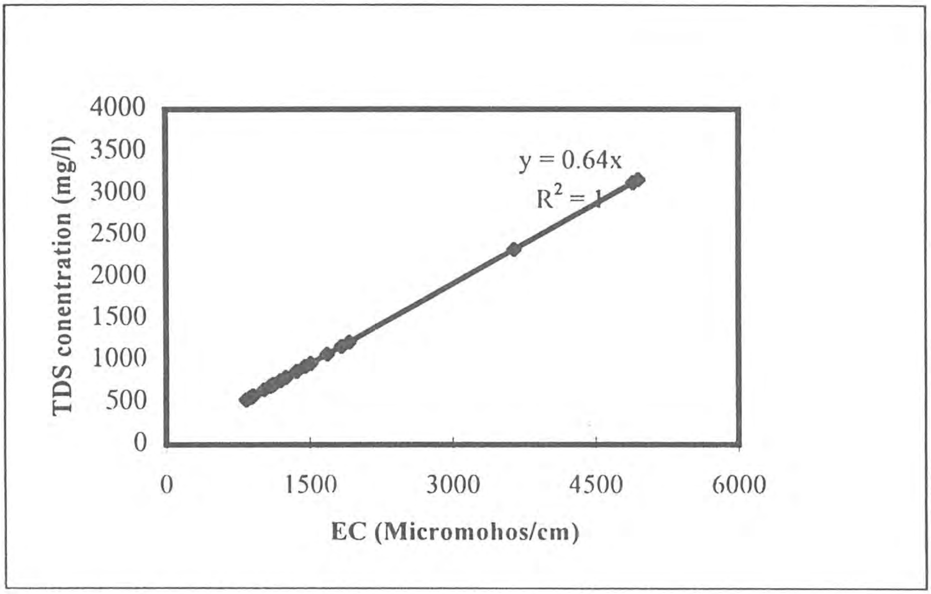
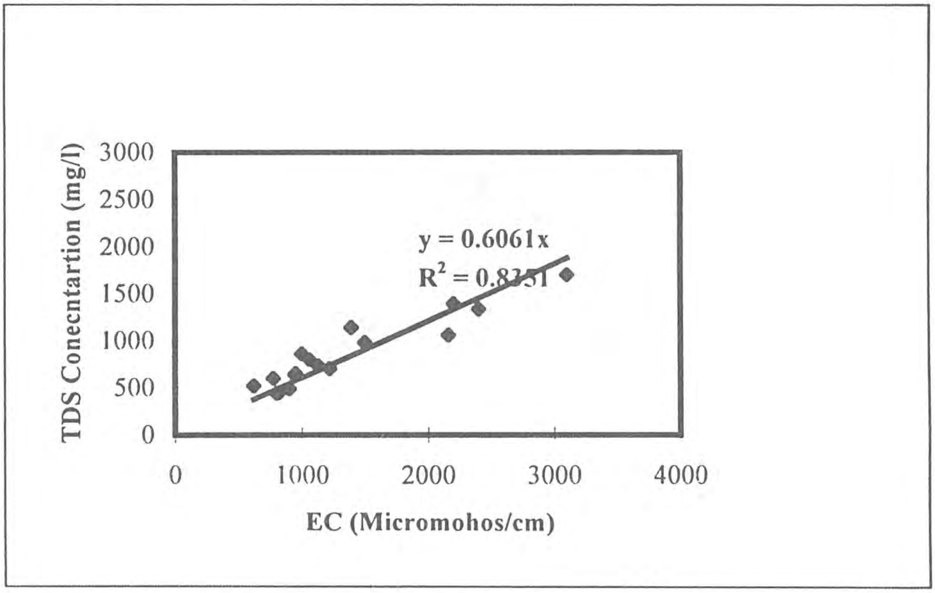


Figure 4: Temporal Variation in TDS Concentration in the Study Area

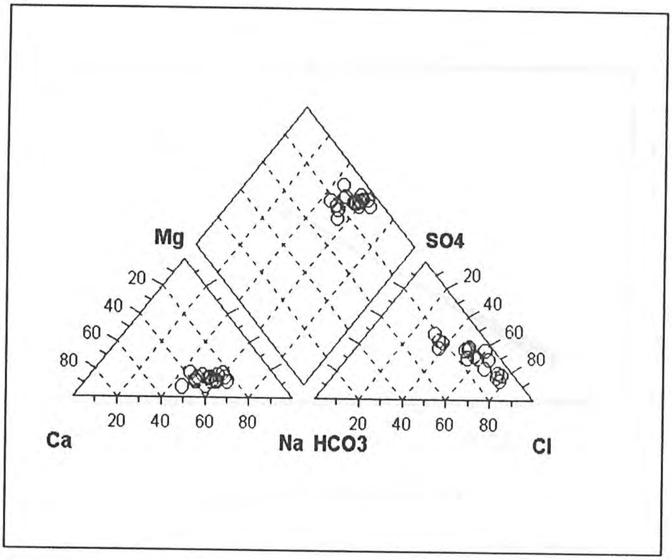


A. BRGM Data (1984)

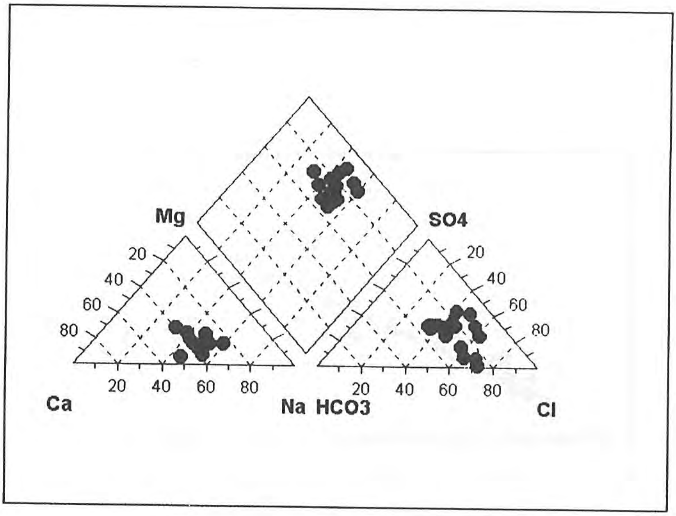


B. KACST Data (1996)

Figure 5 : Regressional analysis of the two sampling sets



A. BRGM Sampling



B. KACST Sampling

Figure 6: Piper Diagram showing chemical facies for the two period sampling sets

Table 1: Chemical data collected from the wells in the study area (mg/l)

KACST#	Location Name	Depth (m)	Ph	EC (mmohos/cm)	TDS	Na	K	Mg	Ca	Cl	So4	Hco3	No3
mc1	Lusayb	650	7.06	1834	1174	135	27.2	35.3	83.4	419	225	165	0.1
mc2	Al-Bukayriyah	200	7.11	1684	1078	163	7.6	12	153.2	280	325	101	9.2
mc3	Shihiyah	218	7.29	1455	931	168	5.4	12.5	103	266	208	103	8.4
mc4	DHalfa'a	250	7.73	1126	720	120	5.8	20.3	82	177.5	192	154	5
mc5	Oyun Al-Jawa	450	7.01	890	750	105	7.2	18.4	54.5	107	120	171	3.5
mc6	Rawd Al-Jawa	300	6.96	1110	710	123	7.8	17.8	74.6	156	133	164	4.9
mc7	Quwarah	450	7.27	836	535	95	9.9	12	61	107	139.5	171	1.7
mc8	Qusayba	864	6.98	880	563	83	20.8	15.5	60	107	136.6	181	nil
mc9	Al-Butayn	1250	7.44	909	582	98	22.4	16	50.5	128	150	168	0.5
mc10	Shimal Factory	850	7.15	1914	1225	190	22.6	43	143	270	388	170	0.2
mc11	Buraidah (No.23)	650	6.95	1442	923	120	32	19.5	80.2	320	135	59.5	0
mc12	Tarafiyah	1100	6.9	1083	693	90	24.8	21	48.1	177.5	30	145	0.4
mc13	Unaizah	600	7.03	1251	801	103	9.3	26.1	80.2	177.5	166.7	140	4.5
mc14	Awahaziyzh	750	6.99	1191	762	75	15	36.3	82	170.4	173.4	184	0.1
mc15	Shamasiyah	1000	6.93	4950	3168	725	35.8	57.6	153.2	1228	287	174	0.4
mc16	Nabgiyah	1460	7.03	3650	2336	290	37	51	208.1	951	30	195	0.7
mc17	Tannumah	1542	6.98	1360	871	103	29.6	17	68.2	252	33.3	156	0.5
mc18	Hunayzel	1600	7.02	1509	966	128	33.4	21.3	64	295	6.7	188	0.3
mc19	Al-Jama'an F	1600	7.06	1022	654	83	21.2	22.3	43.3	160	60	129	0.4
mc20	Al-Shuga Al-Ulya	600	6.88	1102	705	78	18.2	26.2	64	160	116.7	176	0.2
mc21	Awthal	650	6.9	900	576	95	9.9	17.9	56.1	142	373	172	0.2
BRGM#													
1q10	Ar-Rubai'yah	1140	7.3	2160	1065	216	34.7	27.2	110	497	115	91.5	0.6
1q11	Al-Tannumah	1542	7.6	2200	1398	329	34.7	29	108	635	192	81.7	0.6
1q26	Unaizh	600	7.3	1130	841	150	7.4	18	100	226	221	101	16.7
1q30	Buraidah	650	7.2	775	601	127	29.3	17	60	190	177	74.4	0.6
1q54	Rwad Al-Jawa	300	6.8	620	523	113	6.6	18.5	63.2	95.8	198	115	27.7
1q71	Ayn Bin Fahayd	1500	7.6	1060	802	158	30.4	16.6	75.6	305	139	85.4	0.6
1q79	Al-Quwarah	430	6.5	800	443	86.9	9.8	17.9	64	99	162	104	3.1
1q140	Shamasiyah	1000	7.2	1390	1147	246	49.1	36.6	97.8	536	149	107	32.2
1q161	Bukayriyah	200	7.4	950	658	123	5.1	11.4	110	170	160	57.3	70.5
201	An-Nabaqiyah	1460	7.8	2400	1340	276	54.2	28.8	118	579	202	90.3	0.6
220	Al-Khusaybah	1600	8	1220	707	139	26.5	17.3	67.6	224	163	76.9	0.6
240	Al-Tarafiyah	1100	7.2	945	640	114	22.2	17.3	72	192	144	92.7	3.7
535	Al-Butayn	1250	7	820	451	92	21.2	12.6	61.1	99.4	144	132	20.5
683	Ash-Shihiyah	218	6.8	1000	863	182	4.3	13.2	100	326	195	41.3	42
735	Qusayba	1000	6.9	1500	986	306	19.1	38.6	103	453	365	56.7	0.6
3824	Al-Mulayda	450	6.9	900	493	121	5.5	15.8	62.2	112	145	126	32.2

The Impact of Aquifer Materials on Groundwater Quality in the Umm Gudair Area, Kuwait

Dr. Khaled M.B. Hadi

THE IMPACT OF AQUIFER MATERIALS ON GROUNDWATER QUALITY IN THE UMM GUDAIR AREA, KUWAIT

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ABSTRACT

The results of initial laboratory and field analysis of 41 production wells were used to determine the hydrochemical properties of ground water for both the Dammam Limestone aquifer and the clastic Kuwait Group aquifer in the Umm Gudair area at the western part of Kuwait state. The core samples of these wells have been collected and analyzed in order to determine the hydrogeological properties of the same aquifers in the Umm Gudair area.

Hydrochemical data of these aquifers have been analyzed using various methods, which facilitate the description of relations between hydrochemically distinct bodies of water, and elucidate links between hydrochemical data and hydrogeological parameters. During this study the Expanded Durov diagram has been simplified and linked with Sulin classification method in order to give more interpretation values. The result shows that the aquifer materials influence the quality of ground water in each aquifer. The Kuwait Group aquifer water is characterized by Cl-Mg and Cl-Ca genetic water types with average TDS of 4008 mg/l and belongs to chloride water type. The Dammam Limestone aquifer water characterized by Na-SO_4 and Cl-Mg genetic type with average TDS of 3480 mg/l and belongs to sulphate type.

INTRODUCTION

The State of Kuwait adjoins the northwestern part of the Arabian Gulf, at the northeastern corner of the Arabian Peninsula. This location is classified as an arid region, which is marked by very scarce rainfall, high temperatures and evaporation rates, and a lack of perennial surface waters. The demand of water in Kuwait is met from three different sources. These are desalination plants (53%), brackish groundwater (37%), and treated wastewater (10%) (Akkad, 1990).

The Umm Gudair well field is one of the major brackish groundwater well fields in Kuwait (Fig. 1). It is located in the southwest corner of the country, near the border with Saudi Arabia and occupies an area of about 450 km^2. The hydrochemistry of the groundwater in the well field and its interrelation with the aquifer geology is the subject of this study.

The Kuwait Group and underlying Dammam Limestone form the principal aquifer system in the Umm Gudair area. These aquifers are separated by a continuous karst zone ranging in thickness between 7 and 30 m in the study area. This zone is formed from karstification of the upper part of the Dammam Formation and the lower part of the Kuwait Group.

In the Umm Gudair area the Kuwait Group is represented by siliciclastic sediments, which range from uncemented sands to completely cemented calcarous sandstone. The Kuwait Group varies in thickness from 150 meters to 230 meters and the thickness generally decreases from southwest to northeast direction. Core samples show no significant lateral or vertical variations in lithology in the cored intervals, except for a basal clay layer, which ranges in thickness from 3 to 9 meters. This clay layer has a significant hydraulic role (combined with the Upper Karst Unit of the Karst Zone) and acts as an aquitard, hydraulically separating the two main aquifers in the area (i.e. the Kuwait Group and Dammam Limestone aquifers).

Dammam Formation has carbonate rock sequences of: mainly massive chalky dolomite as the upper member; fossiliferous laminated limestone and dolomicrite with lignitic seams as the middle member; and nummulitic limestone as the lower member. The thickness of the Dammam Formation increases from south to north and ranges from 122 to 300 meters. The depth of this formation also increases from south to north and ranges from near surface to a maximum of 550 meters at the north-east of the country.

The Ministry of Electricity and Water (MEW) completed 41 dual completion production wells in the Umm Gudair well field in October, 1986. Both the Kuwait Group aquifer and the Dammam Limestone aquifer are open to production in these wells, and the total production capacity of the well field is $1.14x10^5$ m^3/d.

During well field construction both the Kuwait Group and Dammam Limestone aquifers have been hydraulically tested separately. Also water samples from both aquifers have been collected and chemically analyzed by MEW in order to identify the major cations and anions. The results have been utilized in this study in order to determine the hydrochemical properties of the main aquifers in the Umm Gudair area.

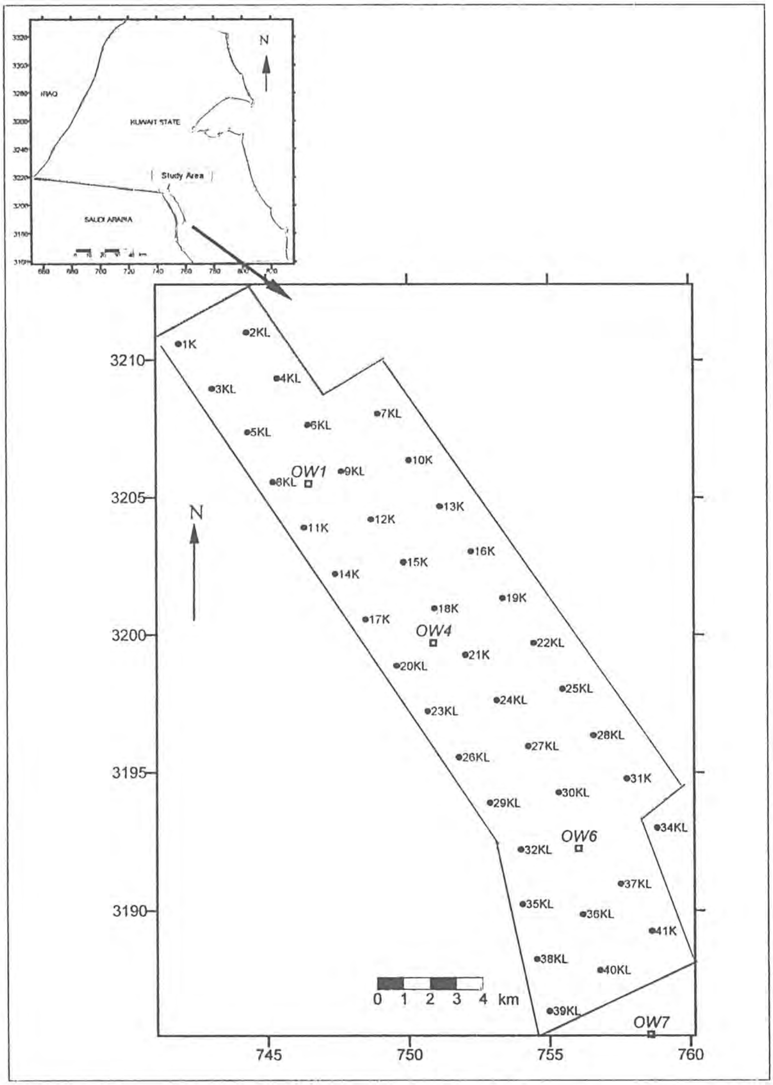

Fig. 1. The locations of the production wells in the Umm Gudair water.

AQUIFER SYSTEM

The Kuwait Group aquifer extends from the Dahna area in the central part of Saudi Arabia to the Arabian Gulf coasts. The piezometric level of this aquifer in the study area, ranges between 87 to 103 meters above mean sea level (M.S.L.). Abu Hijleh (1988) collected and analyzed the pumping test data of the Umm Gudair production wells, in order to identify the hydraulic properties of the Kuwait Group and Dammam aquifers. According to his results, 33 wells were fitted according to Walton's (1962) pumping test methods in the Kuwait Group aquifer. The results of this analysis suggest that the aquifer acts as a semi-confined one with transmissivity ranging between 90 and 382 m^2/d with an average of 212 m^2/d. The effective permeability (K) range between 0.9 and 3 m/d with an average value of 2 m/d. On the other hand, the pumping test results show that the Dammam Limestone is considered to be a semi-confined to confined aquifer. The effective permeability of the Dammam Limestone aquifer range between 0.3 to 11.2 m/d, with an average value of 2.5 m/d, while average transmissivity value is 328 m^2/d.

The recharge areas of the aquifer systems in Kuwait are located at the outcrop of the aquifer formations in Saudi Arabia in the south and southwest of the Umm Gudair area. These recharge areas provide the aquifers in Kuwait by lateral flow from areas receiving infiltrating rainwater. The quantity of this lateral flow depends on the hydraulic properties of these aquifers. The flow direction has been recognized since the 1950's to be from the main recharge area to the main discharge area in the Arabian Gulf and Shatt Al-Arab in a northeasterly direction, in all aquifer systems in Kuwait.

METHODS OF INVESTIGATION

The initial chemical data of the Umm Gudair well field were collected from MEW (Table 1 and 2) in order to evaluate the Kuwait Group and Dammam Limestone aquifers chemically and determine the main hydrochemical properties. Two different data presentation methods have been used for this purpose and to facilitate the groundwater classification in the study area. These methods are the expanded Durov diagram (Fig. 2) and Sulin classification system. In addition, a representative water sample from the recharge area was used in the study to investigate the change in groundwater chemistry area during lateral flow from the recharge area.

EXPANDED DUROV DIAGRAM

The anions HCO_3, SO_4 and Cl are the most mobile constituents of groundwater. They are considered to be the most satisfactory for a basis of classification especially when investigating the genesis and metasomatism of groundwater (Burdon, 1958), whereas, cations Ca, Mg and (Na + K) are considered secondary. Thus, groundwater samples can be primarily classified on the basis of percentages of anions present. The cation contents may be used as secondary criteria. Burdon and Mazloum (1958) recognized four groups of groundwater as follows:

1. Bicarbonate Group where HCO_3>50% of total anions.

2. Sulphate Group where SO_4>50% of total anions.

3. Chloride Group where Cl>50% of total anions.

4. Mixed Group where there are no dominant anions.

The expanded Durov diagram (Fig. 2), which have been developed by Burdon and Mazloum (1958), was designed to demonstrate the relationship between these different groups of water and the trend in which the diagenetic process allows water to change from one group to another. In addition the lines of "chemical diagenesis" or evolution of groundwater can be illustrated in this diagram where the major evolution line is from bicarbonate water to chloride water following the order of:

$$HCO_3 \rightarrow HCO_3>Cl \rightarrow Cl>HCO_3 \rightarrow Cl$$

and the minor evolution line is from bicarbonate water to sulphate water following the order of:

$$HCO_3 \rightarrow HCO_3>SO_4 \rightarrow SO_4>HCO_3 \rightarrow SO_4$$

Table 1: Initial chemical data of the Kuwait Group aquifer in the Umm Gudair well field.

SITE	COND	TDS	pH	Na	K	Ca	Mg	Cl	SO4	HCO3	SiO2	NO3	F	B
01K	5910	4790	7.7	710	16	533	113	1617	1230	61	25.75	94	1.7	1.65
02K	5198	4251	7.6	565	14	638	98	1264	1125	73.2	28.8	72	1.2	1.25
03K	5700	4486	7.9	520	15	503	112	1299	1080	73	29.25	67	1.55	0.925
04K	4859	4122	8			474	119	1232	1140	62	28.4	1.5		0.8
05K	4740	3643	7.4	500	14	401	102	992	1065	85	26.4	62.4	1.7	0.7
06K	5029	3850	7.95	580	13	460.5	105	1200	1023	60	28.2	71	1.6	1.9
07K	6610	4674	7.6	640	16.5	593	143	1700	1065	70	27	125.1	1.56	1.75
08K	4803	3887	7.6	620	14	444	102	1088	1050	78.5	27.2	70	1.5	0.95
09K	5311	4083	7.7	560	15	509	113	1160	1230	76	28	72	1.5	1.1
10K	5610	4379	7.7	680	15	534	115	1454	1014	85	26.9	110	1.45	2
11K	5085	4356	7.8	625	15	540	120	1280	1109	60	27	77	1.5	1.4
12K	6572	4281	7.45	650	16	486	108	1365	941	69.2	19.1	54.6	1.5	1.4
13K	5690	4447	7.6	630	16	494	134	1464	990	64.9	25	111.6	1.4	2
14K	5594	4391	7.45	650	17	569	129	1424	1248	69	27	82	1.5	0.9
15K	4900	3637	7.5	625	15	480	108	1238	1010	70	28	60	1.4	1.7
16K	6080	4686	7.5	700	18.5	551	135	1719	1044	80	25.75	126	1.4	1.85
17K	5198	3825	7.85	610	14	492	104	1221	1134	70	28	34	1.65	0.95
18K	6480	4618	7.5	640	18	599	132	1436	1208	71	28	69.6	1.6	1.45
19K	6000	4493	7.65	650	20	540	135	1485	1020	70	23	114.4	1.56	1.65
20K	5290	3943	7.6	610	17	501	120	1122	1208	77	27.6	72	1.6	1.6
21K	6120	4140	7.5	600	15	500	120	1400	1205	85	27	63.5	1.5	1.4
22K	5290	4231	7.55	465	19	465	120	1327	1050	69	25.5	102.72	1.4	2.35
23K	4720	3792	7.95	540	16	413	90	1024	1020	63	26.25	75.2	1.55	1.5
24K	4750	3642	7.5	510	16	435	113	1032	1020	78	25	75	1.65	0.8
25K	4720	3791	7.7	620	23	330	113	1141	900	83	27.5	95.22	2.1	1.37
26K	4370	3502	7.65	500	14	413	98	968	1050	67	25	78.4	1.66	0.67
27K	4600	3647	7.8	525	20	394	105	944	1065	64	26	75.2	1.53	1.48
28K	5280	4091	7.5	540	17	461	128	1239	1140	72	26.75	95.34	2.2	2.1
29K	3890	3130	7.7	455	13.5	345	80	792	930	74.7	25.5	53.4	1.9	1.7
30K	4600	3685	7.65	520	15	412.5	105	1011	960	69.3	24.75	72	1.8	1.75
31K	5640	4540	7.6	620	18	533	128	1388	1110	66	26.55	102	1.6	1.55
32K	4450	3488	7.8	540	14	405	105	972	1050	80.5	26.5	74.2	1.95	1.05
33K	4630	3450	7.7	580	15	383	101	883	1215	72.1	25.6	82.04	1.67	1.25
36K	5220	3981	7.65	530	17.5	450	120	1185	1035	71	25.75	87.39	2.07	2.2
37K	4970	3696	7.5	515	16	450	105	1101	960	63	25.25	79	1.9	1
38K	4360	3410	7.65	470	14	383	105	921	1050	73	25.5	75.9	1.5	0.65
39K	4520	3372	7.65	470	14	396	112	947	1065	69	24.25	75.91	1.88	0.35
40K	5110	4003	7.55	600	17.5	461	135	1149	1080	75	26.25	78.26	1.98	1.32
41K	5060	3909	7.8	530	15.5	495	158	1191	960	69.3	28	88.8	1.68	1.95

Table 2: Initial chemical data of the Dammam Limestone aquifer in the Umm Gudair well field.

SITE	COND	TDS	pH	Na	K	Ca	Mg	Cl	SO4	HCO3	SiO2	NO3	F	B
1L	3720	2945	8	440	15	293	105	588	1260	136	24.75	6.5	2.3	1.3
2L	3670	2861	7.9	370	12	300	120	500	1230	151.3	27.5	9	2.05	1.1
3L	3640	2882	8	410	14	248	112	544	1110	148	26.5	2.75	2	1.15
4L	3503	2903	7.85	370	13	324	112	552	1284	155	24	8.4	2.2	1.3
5L	3730	2822	7.9	370	13	278	110	520	1080	153.2	24.2	6.8	1.7	1.1
6L	3560	2856	7.5	425	12	307.5	114	584	1043	151.7	25.8	8.8	1.85	1.35
7L	3970	3343	7.2	425	14.5	375	158	728	1260	232	22	10.1	1.77	1.15
8L	3390	2990	8.15	450	14	302	122	536	1140	130.8	25.2	2.1	1.7	1
9L	3729	2881	7.65	380	14	309	120	560	1212	157	24	7	2.3	1.2
10L	4880	3712	6.7	450	14	443	170	967	1170	240	22.7	27.2	1.4	2.3
11L	3505	2798	7.9	410	12	303	108	528	1069	122	25.6	13	1.9	1.3
12L	4191	2898	7.95	420	14	320	96	615	1056	138.1	22.5	16.7	1.8	1
13L	4490	3730	7.3	450	17	494	104	939	1272	207	22.3	23.2	2.3	1.3
15L	3955	3060	7.7	440	13	330	122	627	1116	128	26	29	1.75	1.45
16L	4530	3690	6.95	450	15.5	529	158	991	1245	173.7	22.5	44.7	1.85	1.5
17L	3785	3127	7.8	430	14	341	131	640	1230	147	26	17.6	2.1	1.2
18L	4270	3297	7.45	435	18	407	144	710	1313	137	27.2	2.8	1.8	1.25
19L	4140	3278	7.3	425	16	375	135	780	1140	192	24	31.3	1.8	1.25
20L	4390	3630	7.35	425	14	432	158	809	1135	281	28	9.2	2	1.1
21L	4530	3744	7.45	410	19	450	150	752	1500	149	28.25	21.6	2.2	1.4
22L	4030	3396	7.6	370	17	540	143	804	1290	185	25.5	23.21	1.75	1.25
23L	4410	3779	7.95	430	17	413	143	776	1320	111	21	18.2	2.3	1.25
24L	4210	3838	7.05	450	15	450	173	736	1380	151	24	25.8	2.2	1.25
25L	4410	3675	7.95	450	19	443	173	753	1275	180	21.5	14.78	2.7	1.55
26L	4690	3811	7.45	415	18	465	165	781	1485	166	22.25	8.6	2.12	1.8
27L	4320	3727	7.75	400	17	405	161	723	1350	140	22.75	10	2.02	1.3
28L	4760	3884	7.7	470	20	454	188	871	1320	171	22.25	19.66	3.1	1.6
29L	4170	3323	7.2	490	17	390	150	730	1280	152.3	23.25	4.25	2.12	1.2
30L	4260	3650	7.3	410	18	412.5	157.5	776	1182	157.1	22	16.75	2.31	1.45
31L	4930	4084	7.45	430	17	488	193	1082	1260	203	14.5	41.85	1.45	0.85
32L	4340	3400	7.1	410	17	405	165	777	1230	191	22.35	6.9	2.1	1.3
34L	6250	5534	6.75	590	19	623	218	1627	1200	137	22.75	56.4	1.6	1.62
35L	4340	3304	7.8	410	17	450	158	692	1200	158	21	9.7	1.73	1.23
36L	4220	3484	7.15	435	18.5	383	225	779	1260	184	22.75	10.22	2.2	1.5
37L	4270	3487	7.5	380	18	390	165	731	1170	149.3	23	4.05	2.55	1.2
38L	4090	3176	7.25	370	16	360	150	664	1350	167	22.6	2.7	1.92	1.05
39L	6370	5107	8.15	550	18	623	210	1671	1020	124	24.5	58.4	2.2	2.6
40L	4440	3504	7.4	440	19	383	173	740	1380	178	23.25	6.17	2.85	1.25
41L	5050	4141	7	440	18	503	203	1056	1260	186.4	26	16.6	2.12	1.4

Normally the two lines are mixed, to form a mixed line of evolution order:

$$HCO_3 \rightarrow HCO_3 > SO_4 > Cl \rightarrow SO_4 > HCO_3 > Cl \rightarrow$$

$$SO_4 > Cl > HCO_3 \rightarrow Cl > SO_4 > HCO_3$$

These evolution lines are very dependent on the nature of the porosity, permeability and temperature of the rock type involved (Lloyd, 1965).

SULIN'S CLASSIFICATION SYSTEM

Sulin (1946) proposed a genetic classification system based upon various combinations of dissolved ions in saline and brackish groundwater. This system is widely used, especially in oil-field hydrogeology. In this system major cations and anions are expressed in percentage of milliequivalents/

litre (meq/l), taking the sum of cations and anions as 100%. Na/Cl, (Na-Cl)/SO_4, and (Cl-Na)/Mg coefficients are calculated (Na generally refers to (Na+K) in practice) to determine genetic type. Four different water types are identified according to this classification system. These are:

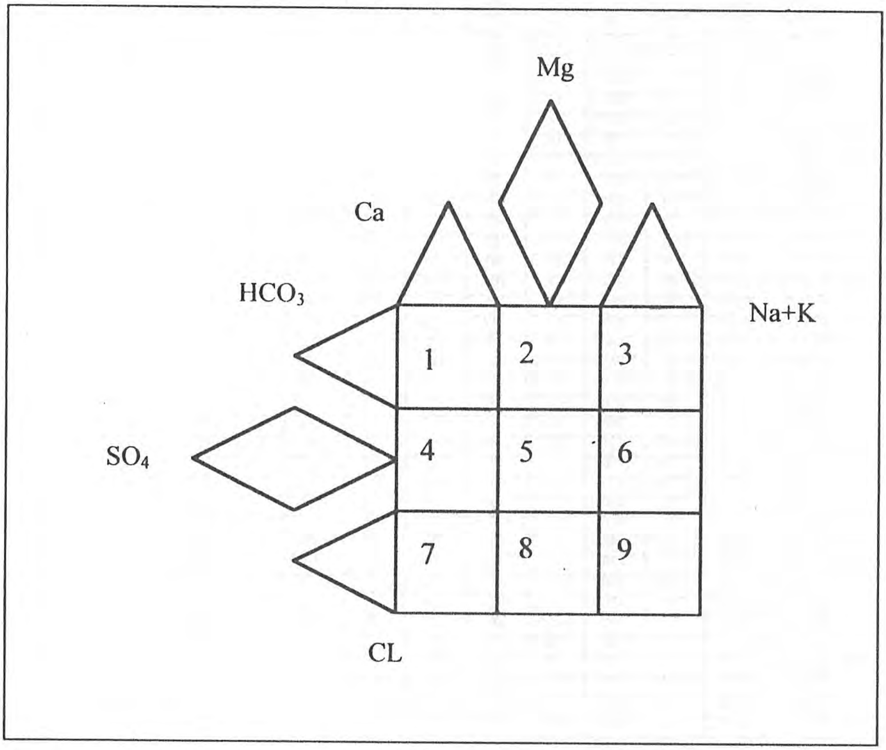

Fig. 2. Expanded Durov diagram with sub-square numbers.

1. Sulphate-Sodium. This type of water is of meteoric water associations with the soluble sulphates are supposedly derived from terrestrial conditions.

2. Bicarbonate-Sodium. This type of water also reflects meteoric associations, and the bicarbonates are supplied by continental conditions.

3. Chloride-Magnesium. This water is indicative of marine environments and evaporite sequences.

4. Chloride-Calcium. This is associated with less mobile subsurface water bodies (perhaps non-meteoric).

The calculated coefficients are used to differentiate between these genetic types as demonstrated in Table (3). The Na/Cl ratio separates the water into two groups: the sodium group (when combined with sulphate (sodium-sulphate type) or bicarbonate (sodium-bicarbonate type) if the Na/Cl >1), and the chloride group (when combined with magnesium (chloride-magnesium type) or calcium (chloride-calcium type) if the Na/Cl<1). The (Na-Cl)/SO_4 coefficient is used to indicate the genetic water type within the sodium group, where (Na-Cl)/SO_4 value is greater than one for sodium-bicarbonate and less than one for sodium-sulphate. Similarly in the chloride group, the value of (Cl-Na)/Mg is less than one in the chloride-magnesium water type and greater than one in chloride-calcium.

Table 3: Water genetic types classification according to Sulin system

Type of water	**Na/Cl**	**(Na-Cl)/$(SO)_4$**	**(Cl-Na)/Mg**
Chloride - Calcium	<1	<0	>1
Chloride - Magnesium	<1	<0	<1
Sodium - Bicarbonate	>1	>1	<0
Sodium - Dulfate	>1	<1	<0

RESULTS AND DISCUSSION

Chemistry of the Kuwait Group aquifer

The groundwater of the Kuwait Group aquifer in the Umm Gudair area is of brackish type with total dissolved solids ranging from 3130 mg/l at well number 29 to 4790 mg/l at well number 1, while the average value is 4008 mg/l.

The Kuwait Group aquifer is characterised by a high chloride ion content, which is the dominant anion. Its concentration ranges between 792 and 1719 mg/l. The second most dominant anion is sulphate with concentration ranging from 900 to 1248 mg/l. Both chloride and sulphate ions (as well as total dissolved solids) generally increase from south-west to north-east direction in the study area, down the hydraulic gradient.

The bicarbonate ion concentration is relatively low compared with chloride and sulphate ion concentrations, (range: 60 to 85 mg/l). The predominant anion trend in the Kuwait Group aquifer water is Cl >SO_4>HCO_3 all over the Umm Gudair well-field.

Sodium is the dominant cation in the Kuwait Group aquifer. Its concentration ranges between 455 and 710 mg/l. Calcium is the second most dominant cation and its concentration ranges from 330 to 638 mg/l. Both sodium and calcium ions generally increase in the same direction as total dissolved solids and main anions (i.e. down hydraulic gradient). The magnesium ion concentration is generally low compared to the sodium and calcium concentrations, and falls in the range of 80 to 158 mg/l. The presence of calcium and magnesium in these concentrations causes the water to be very hard, with total hardness in the range of 1190 to 2068 (with an average of 1655) all in mg/l as $CaCO_3$. In general Na>Ca>Mg is the predominant cation distribution all over the study area.

The expanded Durov diagram in figure (3) indicates that all samples which have been collected from the Kuwait Group aquifer are classified as chloride water type with no cation dominance as they are located in sub-square No. 8, (except well No. 25 which has a sodium dominant cation as it is located in sub-square No. 9). The representative recharge water sample is located in sub-square No. 5, reflecting that the water originated as a sulphate water in the recharge area. As the water flowing to the discharge area through the clastic sediments the water type changed to a chloride water type following a minor descent line starting with $SO_4 > Cl > HCO_3$ order and finishing with $Cl > SO_4 > HCO_3$ order. This anion order indicates that the chloride concentration of this aquifer water has been increased, either by natural halite dissolution during travelling from the recharge area, or by encroachment of more saline waters. In the latter case, reverse cation exchange may have occurred in the aquifer.

According to Sulin classification system all Kuwait Group aquifer samples are located in the upper quadrant of Sulin's diagram (Fig. 4), and characterized by Cl-Mg and Cl-Ca genetic water types. The Cl-Mg type is located in the western part of the Umm Gudair area parallel to the Kuwait - Saudi Arabia border, where the flushing process partially occur in this area by meteoric continental recharge water.

This process becomes less influential in the north-east direction, where the groundwater becomes more saline and the Cl-Ca genetic type is more dominant in the eastern part of the study area (Fig. 5).

CHEMISTRY OF THE DAMMAM LIMESTONE AQUIFER

The salinity of the Dammam Limestone aquifer is more variable than that of the Kuwait Group aquifer in the Umm Gudair area and lower on average. Total dissolved solids range from 2798 to 5534 mg/l with an average of 3480 mg/l.

In general the Umm Gudair area can be divided into three zones (north, central, and south) according to the concentration of total dissolved solids. The northern zone has the lowest mineralized water, where the total dissolved solids concentration are less than 3000 mg/l, while the central zone acts as a transitional belt between the northern zone and the southern zone, with the concentration of total dissolved solids ranging from 3000 to 4000 mg/l.

The southern zone is the most saline area in the Dammam Limestone aquifer in the Umm Gudair area, where the total dissolved solids concentration are more than 4000 mg/l and reach more than 5000 mg/l on some occasions (as in well number 39). All the wells that are adjacent to the Saudi border in the west have the lowest mineralized waters in all zones, since the recharge water flows from this direction.

Anion concentrations in the Dammam Limestone aquifer vary through the area. Sulphate is the dominant anion in the area having a concentration range between 1500 and 2020 mg/l, with the central zone showing highest concentrations. Chloride concentrations generally increase from northwest to southeast in the area, with a concentration range from 500 to 1671 mg/l, where the northern zone has the lowest.

Bicarbonate has the lowest major anion concentration in the area and ranges from 111 to 281 mg/l. (Compared with the Kuwait Group aquifer, this range is still relatively high). Anion distribution all over the Umm Gudair mainly show SO_4>Cl>HCO_3 order, except for the eastern and southern well lines which follow Cl>SO_4>HCO_3.

Turning to cations, calcium and sodium occur in similar concentrations in the Dammam Limestone aquifer in the Umm Gudair area. Sodium concentrations range from 370 to 590 mg/l with no coherent spatial trend. Calcium concentrations range between 248 and 623 mg/l, generally increasing from northwest to southeast. Magnesium ions in the Dammam Limestone aquifer are higher than in the Kuwait Group aquifer (96 to 225 mg/l) with an average of 150 mg/l. Due to that fact the water has a high hardness value, which ranges between 1079 and 2451 mg/l as $CaCO_3$ (with an average of 1625 mg/l as $CaCO_3$). The predominant order of cations is Na>Ca>Mg at the northern part of Umm Gudair area and Ca>Na>Mg at the southern part.

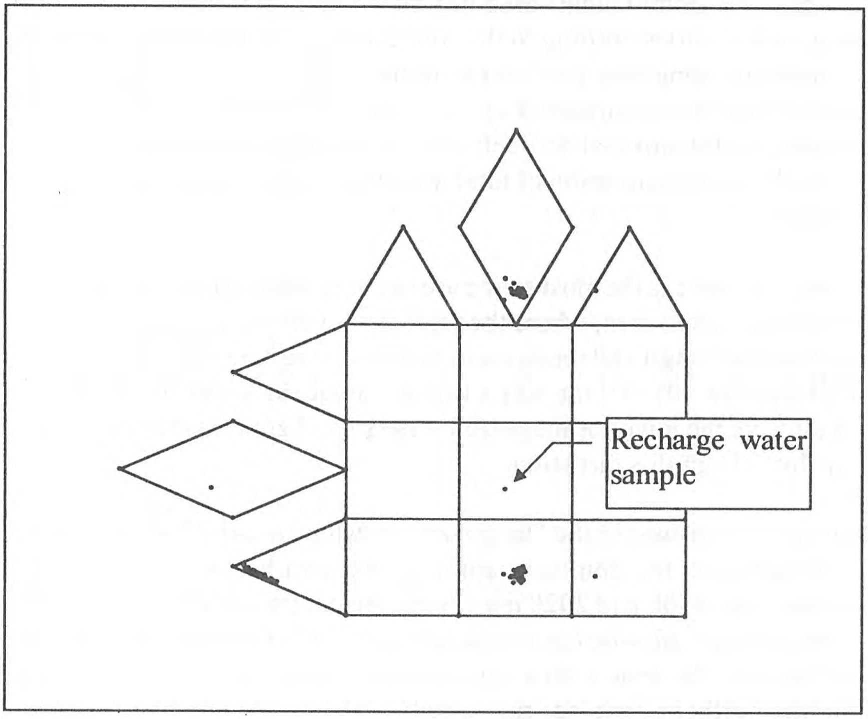

Fig. 3. Distribution of the Kuwait Group aquifer samples on the expanded Durov diagram.

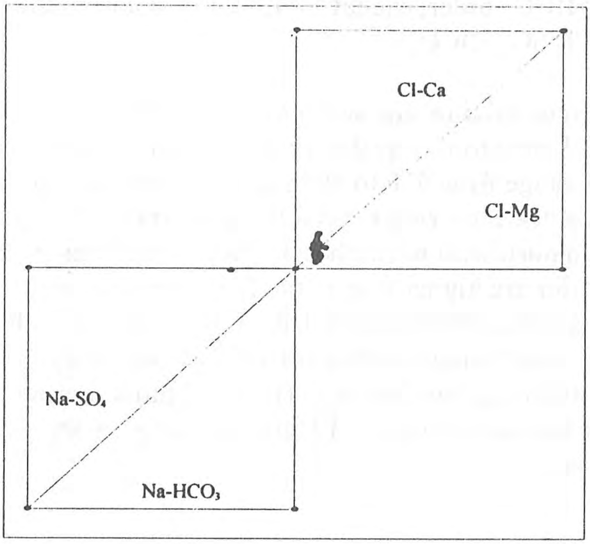

Fig. 4. Sulin diagram shows genetic types of waters in the Kuwait Group aquifer in the Umm Gudair area.

In the expanded Durov diagram, the main location of the samples collected from the Dammam limestone aquifer is in sub-square No. 5. This location indicates that the quality of this water is a result of simple dissolution of aquifer materials which may be composed of gypsum (or anhydrite), or pyrite, causing the water to become a sulphate group water type according to Burdon and Mazloum's (1958) classification. As the aquifer water, which originated in carbonate strata in the recharge area, flowed towards the study area, the chemical composition altered from a sulphate water type with calcium as the dominant cation, to the mixed water type following a minor descent line showing the increase of the chloride and sodium ions in the water (Fig. 6). The samples from only four wells showed different trends, and these were well Nos. 31, 34, 39 and 41, which are located in the southern part of the study area. These wells showed a chloride water type and are located in sub-square No. 8, which may be a result of vertical leakage from the lower evaportic aquifer (Rus Formation).

The genetic type groundwater of the Dammam Limestone aquifer in the Umm Gudair area is mainly Na-SO_4 of meteoric origin in the northern zone, and Cl-Mg of marine association in the southern and eastern zones (Fig. 7). Only well numbers 34 and 39 reflect the old stagnant original water of Cl-Ca genetic type in this aquifer.

Figure 8 presents the distribution of water of different genetic types in the study area, which is clearly controlled by flushing process of old stagnant saline water by fresh water of meteoric origin. It is also clear that the flushing direction in both the Kuwait Group aquifer and Dammam Limestone aquifer is from southwest to northeast, which is the flow direction of groundwater. The flushing process depends mainly on porosity and permeability of the aquifers.

CONCLUSIONS

A study was carried out to classify groundwater of the Umm Gudair area of Kuwait based on its geochemistry. The average TDS in the Kuwait Group is 4008 mg/l and in the Dammam Limestone aquifer the average is 3480 mg/l. Sulin's (1946) classification system demonstrates that the Kuwait Group aquifer is characterized by Cl-Mg and Cl-Ca genetic types, with the Cl-Mg genetic type occurring in the western part of the study area. This classification system also demonstrates that the Dammam Limestone aquifer water is characterized by Na-SO_4 genetic type in the northern zone of the study area, and by the Cl-Mg genetic type in the southern zone of the study area.

The expanded Durov diagram shows that the Kuwait Group aquifer water originates as a sulphate water type in the recharge area and reaches the study area as a chloride water type, following a minor descent line starting with $SO_4^{2-} > Cl^- > HCO_3^-$ order and finishing with $Cl^- > SO_4^{2-} > HCO_3^-$ order. This is due to halite dissolution or reverse cation exchange, or both. In the Dammam Limestone aquifer water, the expanded Durov diagram indicates that the water originated in the recharge area as a sulphate type, with calcium as the dominant cation, and ended with the same type of water but with no cation dominance. However, four samples showed a chloride water type, which indicate that an upward vertical leakage from the underlying Rus Formation may occur at that particular location.

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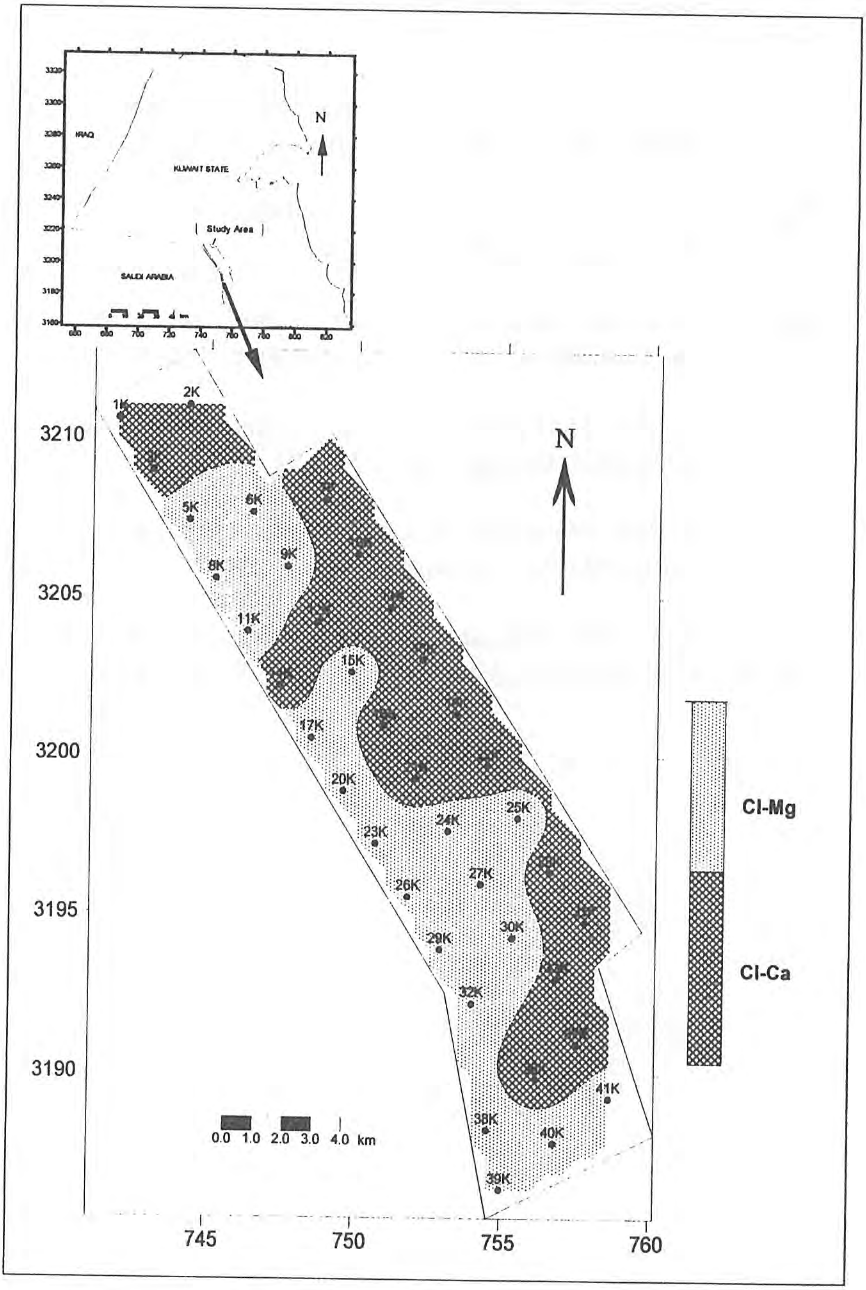

Fig. 5. Water genetic type distribution in the Kuwait Group aquifer in the Umm Gudair area

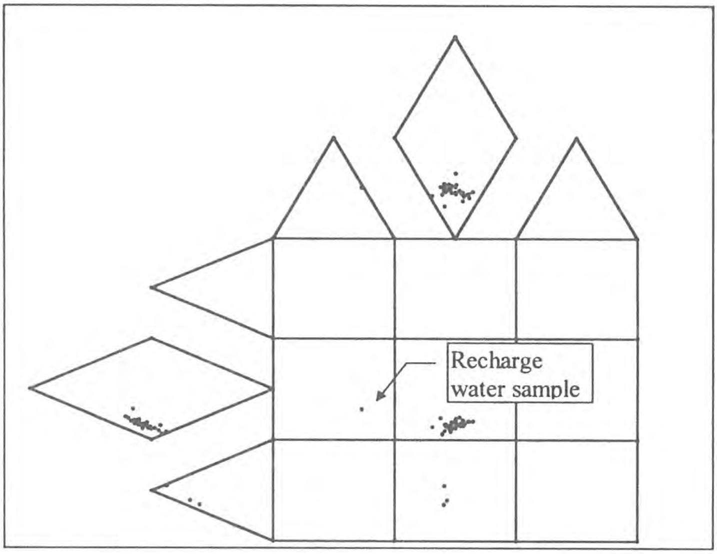

Fig. 6. Distribution of the Dammam Limestone aquifer samples on the expanded Durov diagram

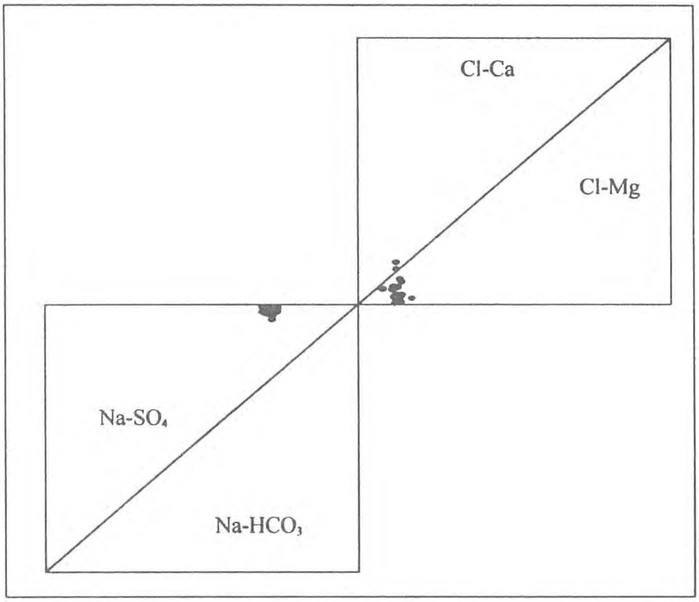

Fig. 7. Sulin diagram shows genetic types of waters in the Dammam Limestone aquifer in the Umm Gudair area.

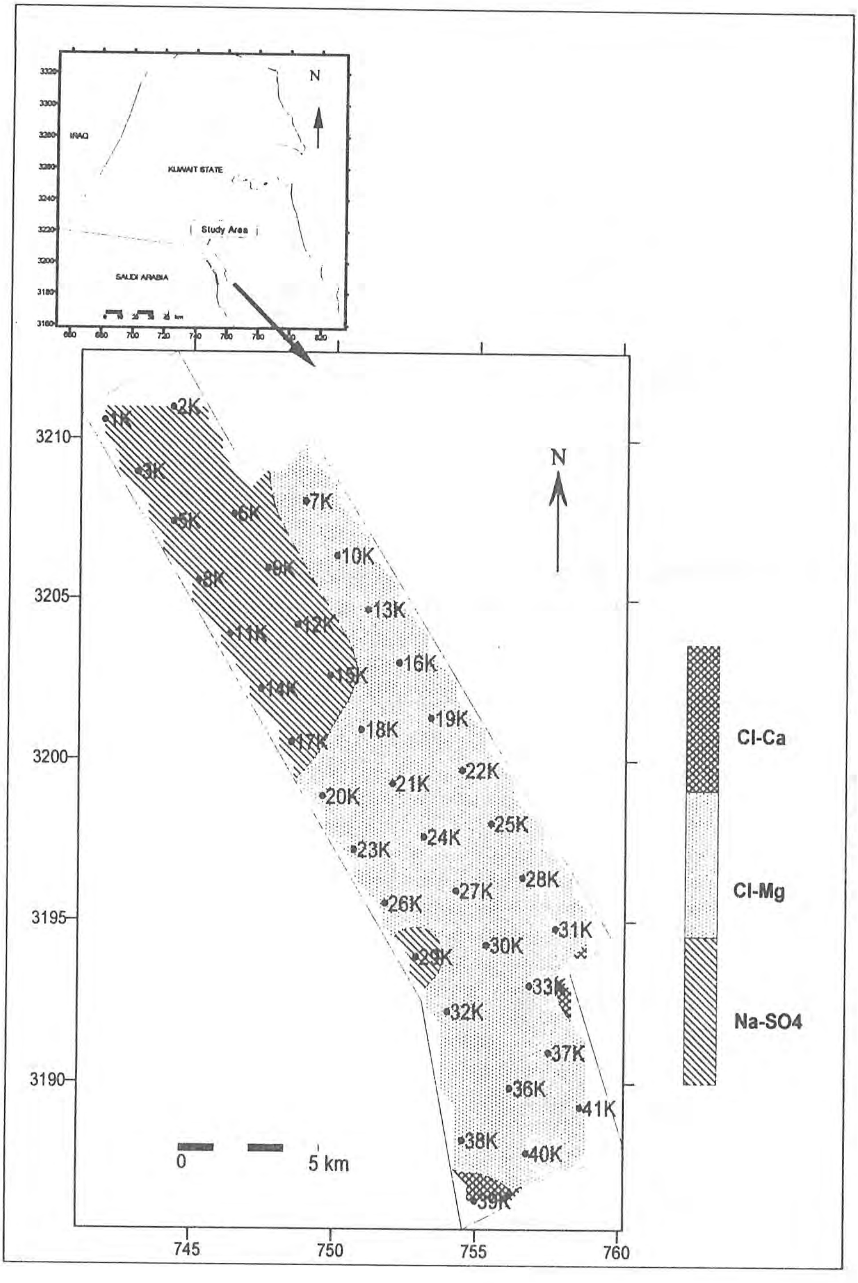

Fig. 8 Water genetic type distribution in the Dammam Limestone aquifer in the Umm Gudair area

Spatial Design and Optimization of Groundwater Salinity Observation Network in Bahrain

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SPATIAL DESIGN AND OPTIMIZATION OF GROUNDWATER SALINITY OBSERVATION NETWORK IN BAHRAIN

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ABSTRACT

Groundwater resources development and management relies essentially on the qualitative and quantitative monitoring of these resources. Information obtained from monitoring networks of a given groundwater resource are used as significant indicators for the status of that resource, and subsequently management schemes are made in order to develop and utilize this resource on a sustainable basis. In this paper, the Dammam aquifer salinity observation network in Bahrain was designed and optimized using the geostatistical method of kriging. The methodology consisted of conducting a structural analysis on the salinity of a group of wells that are regularly monitored, where the construction and interpretation of sample variogram and the selection of model variogram to best fit the structure of the log transformed salinity was carried out. The model variogram was then used in the kriging analysis to estimate the spatial average value of the salinity and the associated error of the estimation. The error in the estimation was then modified by a weighting function, which accounted for the salinity distribution in the aquifer and the distance from wells directly used for domestic supply in Bahrain. The produced weighted error was used in indicating the aquifer areas where monitoring is needed. After adding wells to the network, the procedure is repeated until no significant reduction in the maximum and average error are observed. The final designed network utilizes all the regularly monitored domestic supply wellfields as an essential part of the designed network. Furthermore, all the new proposed locations of the network utilizes the existing farmers abstraction wells.

KEYWORDS: Bahrain, Dammam aquifer, Salinity Monitoring Network, Design and Optimization, Geostatistics, Kriging.

INTRODUCTION

The State of Bahrain depends primarily on the Alat and the Khobar aquifer for its agricultural, municipal, and industrial fresh water supply. The two aquifers are termed collectively as the Dammam aquifer, and are considered as one aquifer system in Bahrain. The total withdrawal from the Dammam aquifer system is about 218 million cubic meters per year (Mm^3/y), while its suggested safe yield is about 112 Mm^3/y (Al-Noaimi, 1993). The aquifer over-exploitation has lead to continuous sharp decline in the aquifer water levels, and more dangerously, rapid deterioration of its quality by saline and brackish waters invasion (Zubari et al, 1997).

Groundwater resources development and management relies essentially on the qualitative and quantitative monitoring of these resources and is one of the basic activities in the process of groundwater protection. Information obtained from monitoring networks of a given groundwater resource are used as significant indicators for the status of that resource, and subsequently management schemes are made in order to develop and utilize this resource on a sustainable basis. Furthermore, monitoring information can be used to evaluate and assess the effectiveness of implemented management schemes.

In Bahrain, the Water Resources Directorate (WRD), Ministry of Works & Agriculture (MWA), has a water-level groundwater monitoring network that consists of 47 boreholes in the Dammam aquifer. Most of these observation wells have extensive continuous water level data, which have started in 1980. However, salinity data from these boreholes are very limited and groundwater quality monitoring is not carried out on regular basis. Furthermore, the Water Supply Directorate (WSD), Ministry of Electricity & Water (MEW), has been regularly monitoring groundwater quality from its production wellfields (about 25 wellfields), which are located and clustered mainly in the northern parts of Bahrain.

Groundwater quality monitoring for the Dammam aquifer in Bahrain has been carried out in the form of major country-wide surveys. In the past 25 years, three comprehensive groundwater quality surveys were conducted. These were made in 1970 (Italconsult, 1971), 1979 (GDC, 1980), and 1991/92 (Al-Noaimi, 1993), i.e., about every 10 years, and included most of the producing wells in Bahrain. Although very expensive, these surveys provided comprehensive information on the quality of groundwater in Bahrain, which were essential for the early assessment and evaluation processes of groundwater resources in Bahrain, and for detecting major changes and trends in groundwater quality. However, with the increasing over-abstraction trend in Bahrain and its associated rapid groundwater quality changes, these country-wide surveys for monitoring groundwater quality can not be relied upon in making adequate management decisions for protecting the aquifer over short periods of times.

Therefore, there is a need to design and optimize a regular observation network to monitor the salinity of the Dammam aquifer in Bahrain. This network should be designed in such a way that they would give sufficient spatial and temporal information on the aquifer salinity status, and more importantly, indicate any significant changes in the aquifer salinity that would arise from over-exploitation. Furthermore, the designed network should utilize the WSD regularly monitored wellfields, and include it as part of the network.

The aim of this study is to spatially optimize the setting up of a salinity monitoring network for the Dammam aquifer in Bahrain. A geostatistical approach, particularly the geostatistical mapping method of Kriging, was used to design and optimize the observation network. The approach is based on augmenting the existing WSD wellfields network by a statistically based process of variance reduction, where the error of the estimation is utilized in indicating the aquifer areas where monitoring is needed.

METHODOLOGY

Variance-based approaches have been established for the problem of groundwater quality monitoring network augmentation in local-scale settings (e.g. Rouhani, 1985; Loaiciga, 1989; Graham and McLauglin, 1989a, b). In this approach, the estimation variance and/or a weighted measure of estimation variance are used as a criteria in the design process, and variance reduction is used as a measure of network performance. Variance reduction involves a methodical search for the number and locations of sampling sites that minimize the variance of estimation error of contaminant(s) concentration in the aquifer.

In summary the steps involved in implementing the variance reduction approach in designing the salinity monitoring network for the Dammam aquifer in Bahrain are (figure 1):

1) Preparation of the regularly monitored wells of WSD data (location and average TDS of 1996), which are considered as an existing network in the Dammam aquifer.

2) Conducting structural analysis on the WSD data (Experimental variogram, model variogram, and cross-validation of model variogram) using software GEOEAS (EPA, 1997).

3) Kriging the Dammam aquifer salinity using the WSD wells' salinity and the constructed model variogram, and calculating the associated error of estimation.

4) Construction of error weighting function to signify sampling sites importance, multiplying it by the calculated error of estimation to generate a weighted error map.

5) Observing the maximum weighted error and calculating the average error.

6) Adding locations of monitoring wells based on the maximum weighted error and the availability of production wells by utilizing the WRD production wells database.

7) Kriging the Dammam aquifer salinity using the WSD wells and the newly added wells, and calculating the associated error of estimation.

8) Multiplying the error weighting function by the calculated error of estimation to generate a weighted error map.

9) Repeating steps 5 to 8 until no significant reduction in the error is observed.

RESULTS AND DISCUSSION

Data Preparation and Basic Statistical Analyses

The location and salinity (1996) data for the Dammam aquifer regularly monitored wells obtained from WSD are plotted in Figure 2. The WSD data set consists of 86 wells constituting 25 WSD wellfields, which are monitored on monthly basis. However, the TDS data used in this study are selected for only those points which are regularly pumped in order to guarantee a sampling point. Therefore, the data set was reduced to 17 monitoring points as indicated in Figure 2. The TDS of the wells are reported in milligram per liter (mg/L), and for the year 1996 they ranged from about 2,400 and 8,750 mg/L, with the higher salinity located in the east coast (seawater intrusion) and central region (brackish water up-flow), and the south-west region (sabkha water intrusion). The low salinity is located in the west, north-west, and north coast regions, where the Dammam aquifer is recharged by underflow from the equivalent aquifer in Eastern Saudi Arabia.

Table 1 summarizes statistics of the TDS data for the Dammam aquifer obtained from the WSD wells. The TDS of the 17 WSD wells has a large variance about the mean, and are moderately skewed to the right, as can be seen from the histogram plot of the data illustrated in Figure 3a. The TDS histogram plot indicates a marked asymmetry (skewness=2.42), with tails towards the higher values of TDS suggesting a long-normal distribution. This TDS behavior is attributed to that the aquifer original waters are intruded by saline waters.

Table 1. Summary statistics for the TDS in WSD wells producing from the Dammam aquifer.

Parameter	Value
N	17
Mean	3570
Variance	2357099
Standard Deviation	1535.28
Minimum	2408
Maximum	8749
Skewness	2.42
Kurtosis	8.75

In such cases, it is preferable to take the logarithm of the data before making the geostatistical analysis and estimation (Delhomme, 1979; Neuman, 1982). This is done because the structure of the TDS is much better (i.e. the variogram shows a better correlation) if the log of the variable is used instead of its raw value (Matheron, 1971). Moreover, kriged estimation of the variable provides better estimation if the data used are normally distributed (Ahmed et al., 1988). Figure 3b displays the distribution histogram of the log transformed TDS data for the Dammam aquifer, which is close to normal.

STRUCTURAL ANALYSIS ***(Experimental and Model Variograms and X-Validation)***

In practical geostatistics, there are several methods that have been developed for the computation of the experimental variogram. Among these: the "classical" or traditional estimator (Matheron, 1963), the Cressi-Hawkins estimator (Cressie and Hawkins, 1980), the squared median of the absolute deviation (SMAD) estimator (Dowd, 1984), and Omre estimator (Omre, 1984). In this study, the classical estimator was adopted in calculating the experimental variogram.

The classical estimator equation is (Matheron, 1963):

$$\gamma(h) = \left[\frac{1}{2n(h)}\right] \sum_{i=1}^{n(h)} \left[Z(x_i + h) - Z(x_i)\right]^2 \qquad (1)$$

where the estimator $\gamma(h)$ is the calculated experimental variogram, $n(h)$ is the number of data pairs separated by the vector, or lag distance, h, and $Z(x_i)$ are measured values of ln(TDS) at coordinates x_i. Figure 3c shows the computed experimental variogram of ln(TDS). The computation of the experimental variogram used a lag distance of 2500 m and included 98 pairs. The experimental variogram shows a clear sill and the presence of spatial correlation at the shortest lag.

An appropriate theoretical model must be fitted to the experimental variogram computed. Several theoretical mathematical models could be fitted to the experimental variogram, which include the spherical, exponential, power, Gaussian, and cubic (Marsily, 1986). However, the spherical model has been found to be more applicable to the variables under consideration.

The spherical model is transitive; it consists of two separate functions, with a discontinuity. The model equations are (Henley, 1981):

$$\gamma(h) = C_0 + C\left[\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] \qquad \text{for } h < a$$
$$\gamma(h) = C_0 + C \qquad \text{for } h \geq a \qquad (2)$$

where a is the range of influence, C_0 is the nugget variance, and C_0+C the sill. C_0 and C represents the random and spatial components of variation, respectively. The fitted model variogram for ln(TDS) data is displayed in Figure 3c. The fitted model has a nugget variance of 0.0, a sill of 0.12, and a radius of influence of 6000.

Cross validation, or x-validation, is used to check the reliability and effectiveness of the calculated model variogram in estimating the ln(TDS) fields in the Dammam aquifer. In x-validation, an estimation of each observed data is made by utilizing the model variogram and the rest of the data set. At the end of this process, a comparison is made between the estimated values and the observed ones. Figure 3d shows a scatter plot for the estimated values and the observed values, resulting from the x-validation. The plot shows that, except for one point, the calculated model variogram is capable in estimating the observed points, and thus, is used in estimating the ln(TDS) distribution in the aquifer.

KRIGING

Kriging is performed to estimate the ln(TDS) values at unknown location in the Dammam aquifer. The regularly monitored WSD ln(TDS) data and the structural model given by equation (2), were used in the estimation of the ln(TDS) function distribution in the aquifer. The kriging equations are (Marsily, 1986):

$$\sum_{i=1}^{n} \lambda_o^j \gamma(x_i - x_j) + \gamma = \gamma(x_i - x_o) \qquad i = 1,...n$$

$$\sum_{i=1}^{n} \lambda_o^i = 1 \qquad (3)$$

where λ_o^j is the weighting function of each point j to be used in the estimation of point x_o, $\gamma(x_i - x_j)$ the variogram value for the distance between x_i and x_j, and μ is the Lagrange multiplier. The variance of the error of estimation for point x_o is given as

$$\sigma_{x_o}^2 = \sum_{i=1}^{n} \lambda_o^i \gamma(x_i - x_o) + \mu \qquad (4)$$

ERROR COMPUTATION AND ERROR WEIGHTING FUNCTION

After using kriging in the estimation of the ln(TDS) fields in the Dammam aquifer (using the regularly monitored WSD wells and the model variogram), the associated standard deviation of estimation were generated. Figure 4 illustrates the prepared error (raw) distribution map in the Dammam aquifer associated with the estimation of ln(TDS) values. As expected, low variances were found around the control points, which are located at the areas of WSD wellfields, and highest degrees of uncertainty were found in areas where control points are fewest or absent. The standard deviation in ln(TDS) estimation ranged from 0.0766 to 0.286.

The raw error map has to be modified to represent the importance of the area to be monitored. The importance of a given site within the monitoring network can be identified by two factors. The first factor is the TDS level in the site, which indicates a contamination and salinization source that needs to be monitored. For example, sites at northwestern Bahrain have TDS values of about 2,500 mg/L representing the best waters in Bahrain and would not require extensive monitoring, while sites located at and near the east coast of Bahrain have high TDS values due to seawater intrusion, and therefore, their monitoring is more important. In this respect, the TDS distribution field for the year 1992 in the Dammam aquifer (Al-Noaimi, 1994) is used as a multiplication factor for the raw error.

The second factor is the distance of a given site from the WSD wellfields that directly used for domestic supply without blending with desalinated water. The closer the site to these wellfields, the more important the site would be, as it will give early warning of contamination. In this respect, the inverse distance to the wellfields is used as a multiplication factor for the raw error.

Figure 5 shows the resulted weighted error by multiplying the raw error by the constructed weighting function (concentration/distance, or 'c/d'). The resulted weighted error ranged from 0.0125 to 0.827. The high errors occurring along the eastern coast of Bahrain are due to the high TDS values resulting from seawater intrusion. In the central areas of Bahrain, the highest weighted errors occur. This is due to the elevated salinity by the brackish water up-flow and the close distance to the WSD domestic supply wells.

MONITORING WELLS PLACEMENT

The weighted error maps were used to place new monitoring wells based on the maximum weighted error and the availability of production wells by utilizing the WRD agricultural production wells database. A total of 16 wells were placed to augment the 17 WSD at this stage in order to reduce the weighted error. The location of these wells is indicated in Figure 5.

After adding the locations of the new monitoring wells defined above (16 wells) to the data set of the monitoring network, the new data set was kriged and an estimation error map was prepared (Figure 6). The estimated standard deviation ranged from 0.0765 to 0.351, i.e, the maximum error is reduced from 0.386 to 0.351. This error map was multiplied by the weighting function 'c/d' and the weighted error map was generated and is shown in Figure 7. In this stage the maximum weighted error is reduced to 0.639 as compared with stage 1, which was at 0.827.

As done above, new monitoring wells are added to the monitoring network data set based on the maximum weighted error and availability of wells. In this stage 14 additional monitoring wells were added to the network and are shown in Figure 7.

The newly placed wells (14) were added to the data set and kriged, and an estimation error map was prepared (Figure 8). The estimated standard deviations ranged from 0.0765 to 0.347, i.e. further reduction in the error is made. The weighted error map was generated by multiplying the raw error map by the weighting function 'c/d' (Figure 9). The maximum weighted error is reduced to 0.506 as compared to the previous stage, which was at 0.639.

At this stage, it was decided that the 30 additional wells and the 17 WSD wells constituting the monitoring network are enough to cover the TDS of the Dammam aquifer in Bahrain. This is based on the analyses of raw error and the weighted error reduction obtained in the three stages as shown in figure 10. The error figures indicate that adding more wells will not significantly enhance the monitoring network performance.

Figure 11 displays the location of the suggested wells to be used as for salinity monitoring network for the Dammam aquifer in Bahrain. The network consists of 47 wells with 17 of these are regularly monitored by WSD.

CONCLUSION AND RECOMMENDATIONS

A salinity monitoring network has been spatially designed for the Dammam aquifer in Bahrain based on a variance reduction approach. The geostatistical method of kriging and its associated estimation error influenced by a weighting function (consisting of the aquifer TDS and the distance from wells directly used for domestic supply) are used as a criteria in the design process and as a measure of the network performance. The design methodology consisted of augmenting a pre-existing regularly monitored wells (17) with available production wells (30) by a systematic search for the location of sampling sites that minimize the variance estimation error of the aquifer TDS concentration.

It is recommended that the proposed salinity monitoring network be adopted and utilized in:

a) Provide information to aid in the planing and management decision making (e.g. selected artificial recharge areas, augmenting domestic water supply by desalination water, augmenting irrigation water by treated wastewater, etc.).

b) To assess groundwater quality and delineate horizontal extent of contamination and salinization to the Dammam aquifer.

c) To determine temporal trends in selected water quality parameters.

d) To evaluate the effectiveness of management schemes.

e) To give an early warning of contamination to the domestic water supply wells.

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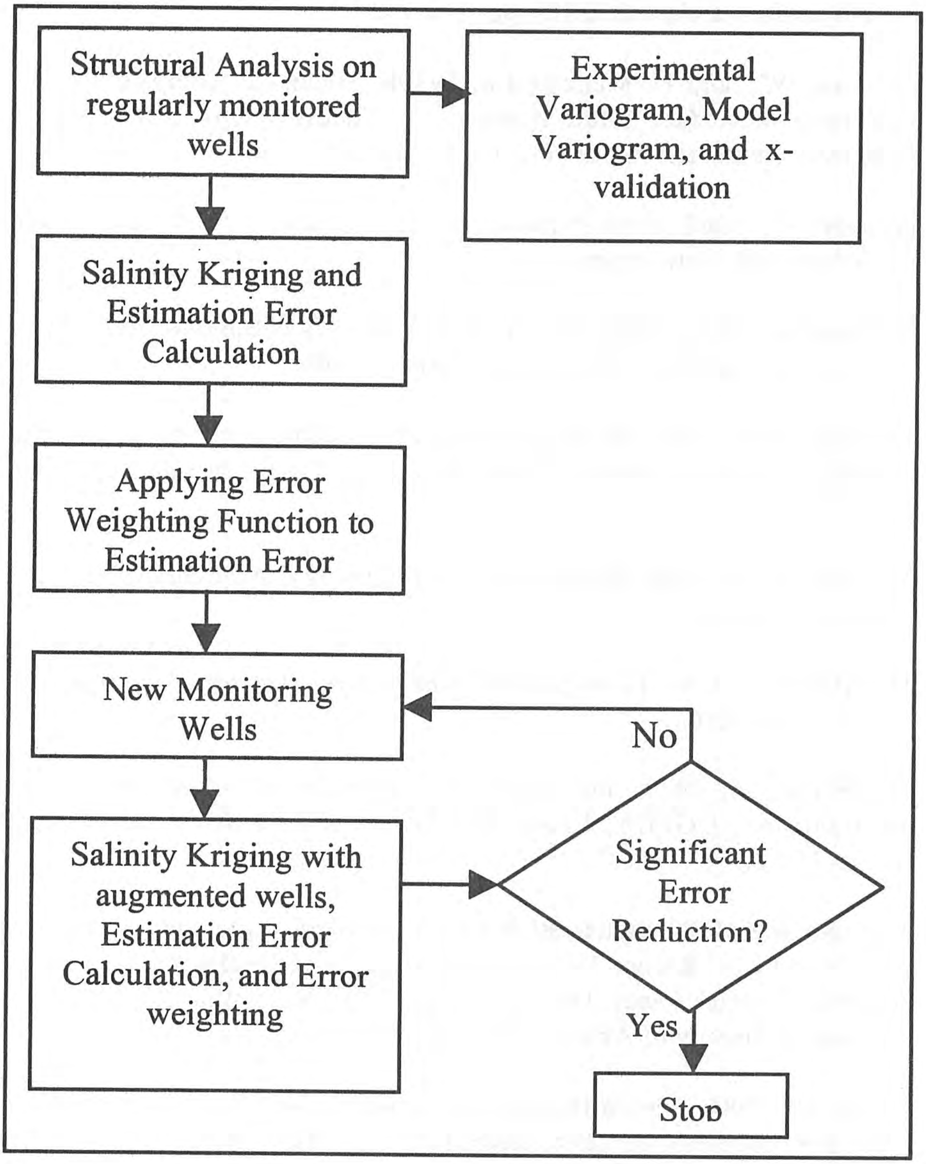

Figure 1: Procedures for monitoring network design.

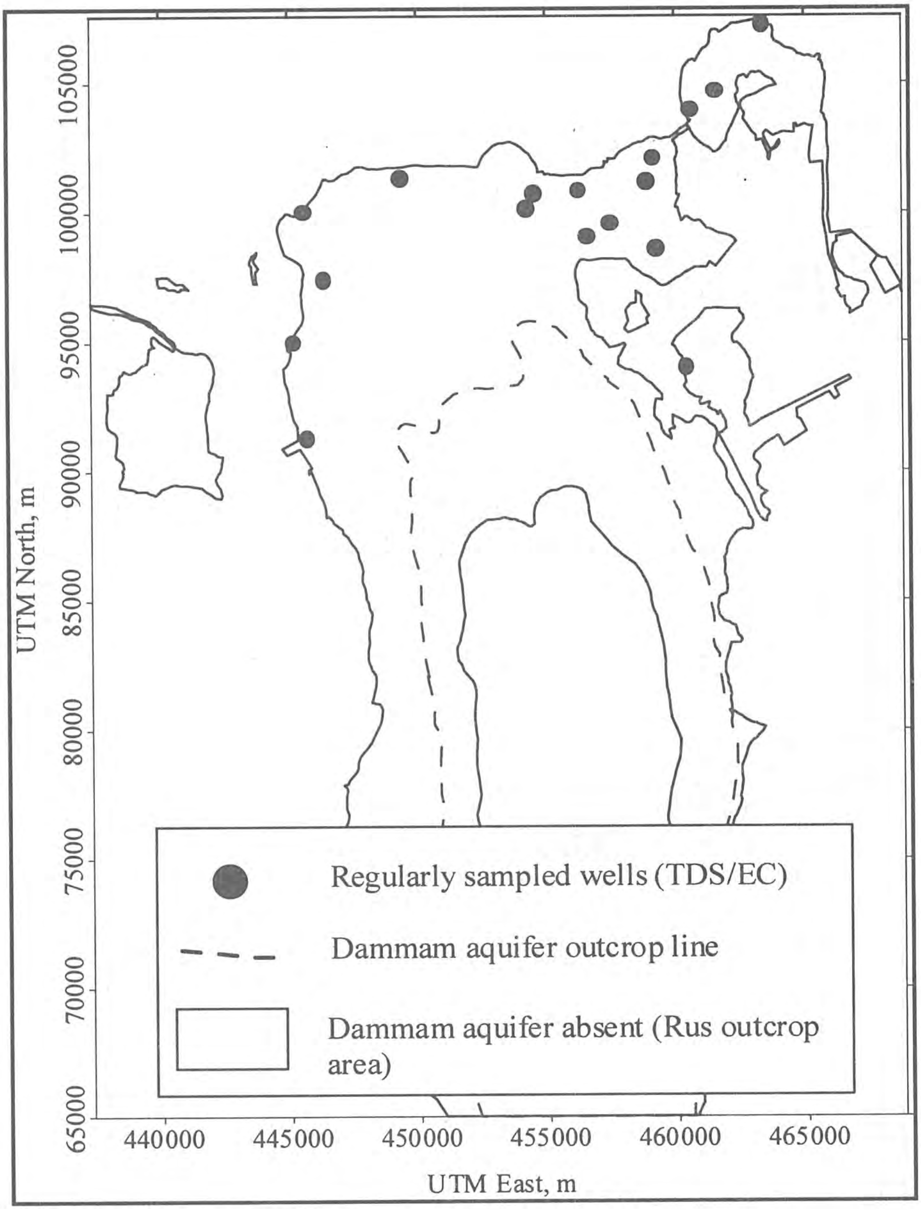

Figure 2: Location map of WSD regularly monitored wells.

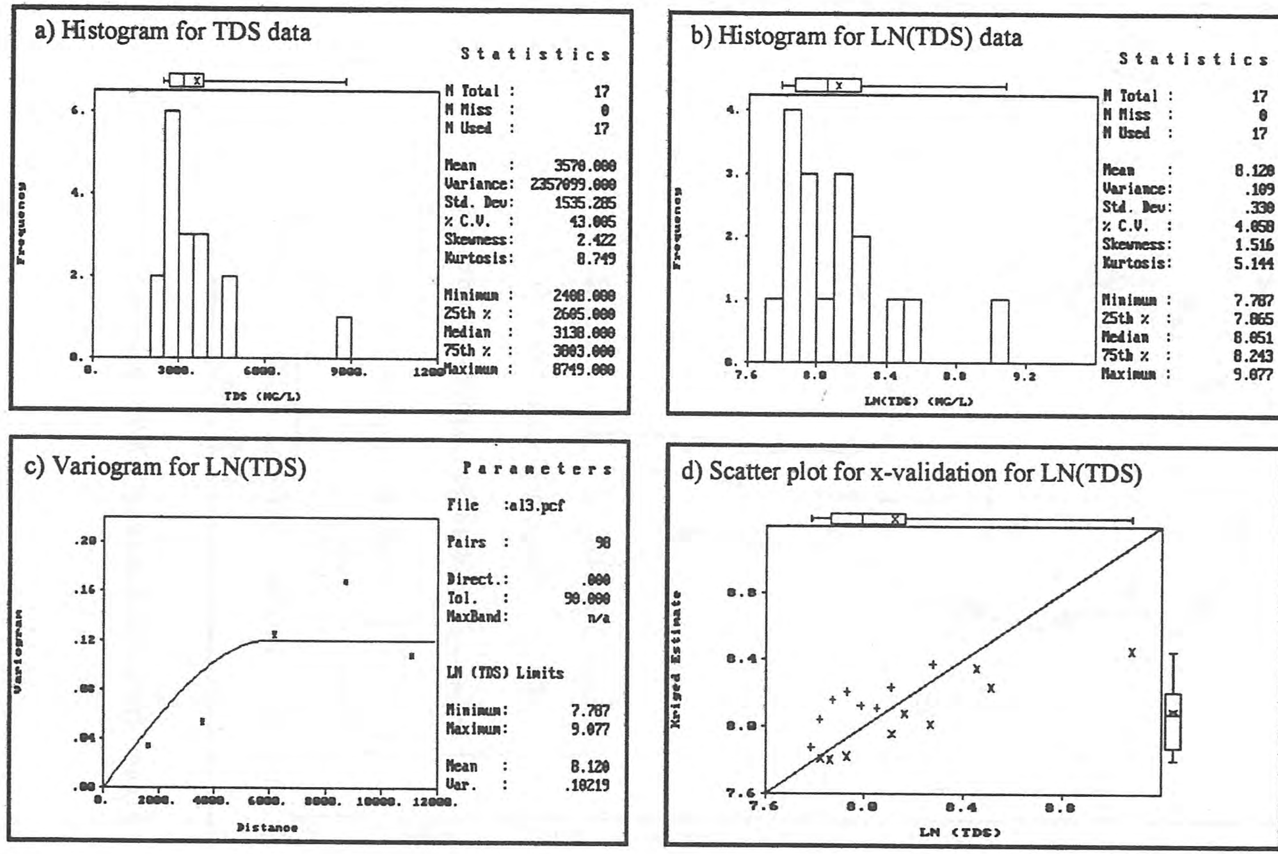

Figure 3: Structural analysis of the regularly monitored WSD wells

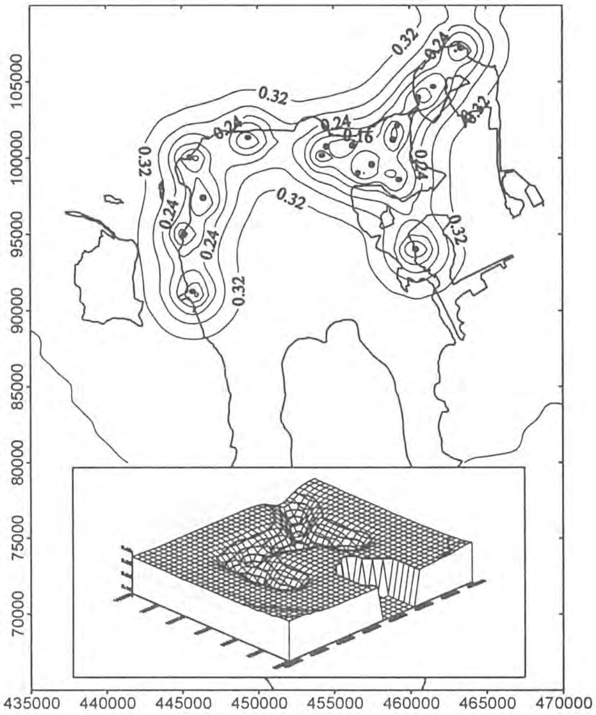

Figure 4: Raw Error – Stage 1.

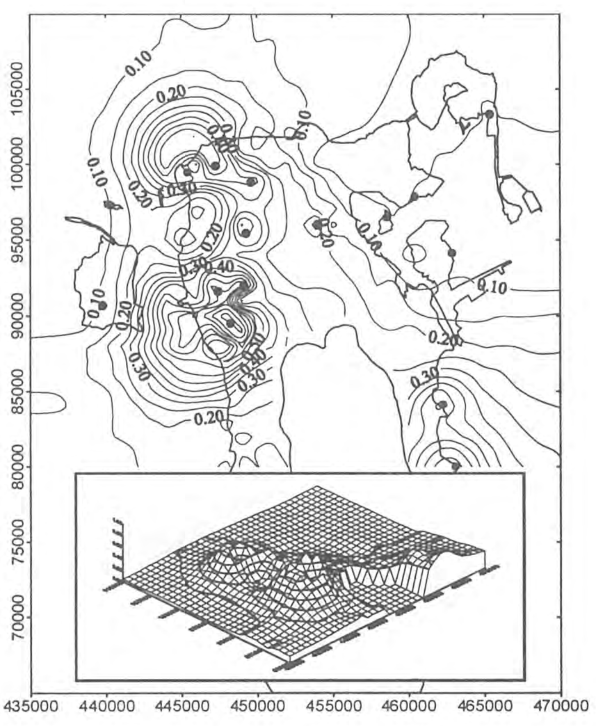

Figure 5: Weighted Error – Stage 1

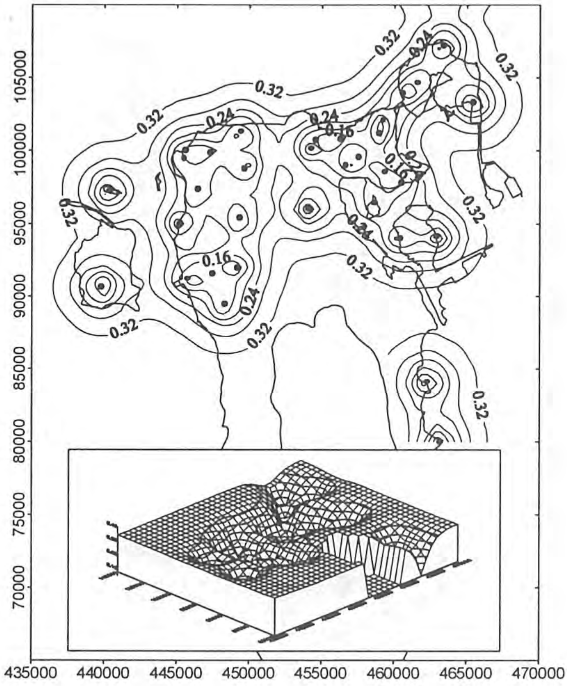

Figure 6: Raw Error – Stage 2

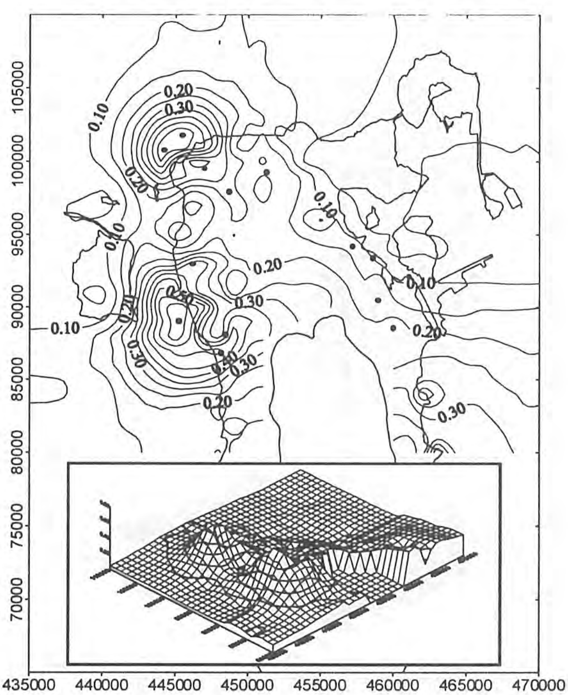

Figure 7: Weighted Error – Stage 2

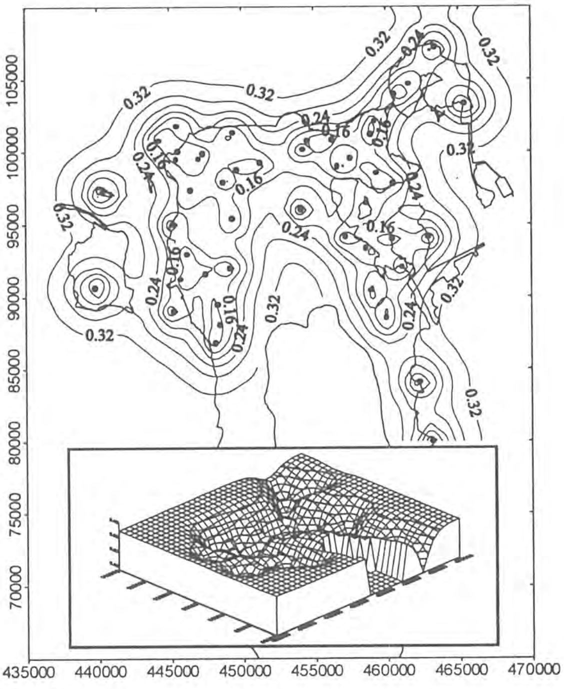

Figure 8: Raw Error – Stage 3

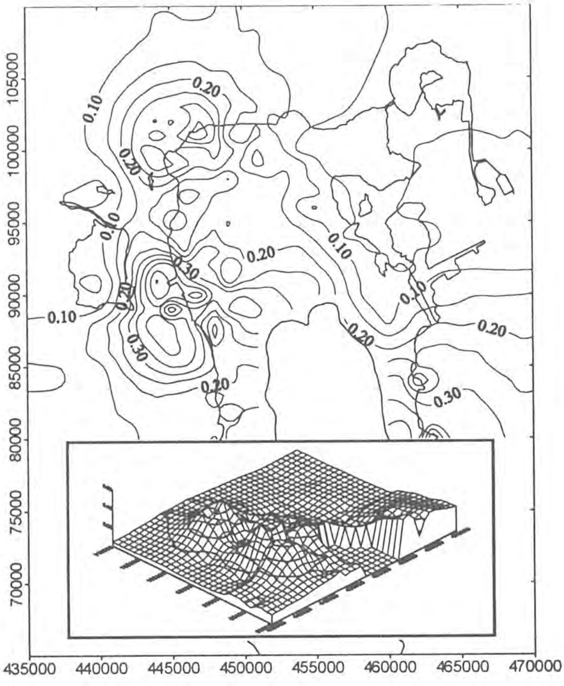

Figure 9: Weighted Error – Stage 3

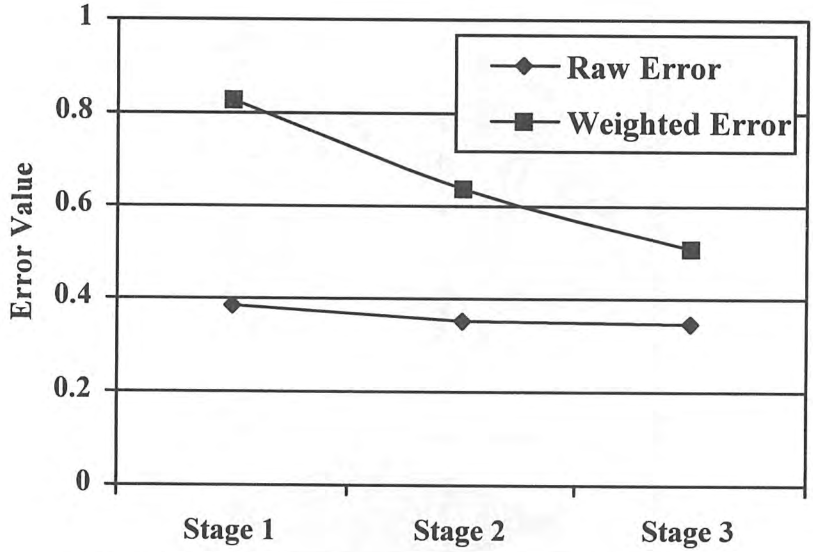

Figure 10: Maximum raw and weighted errors for stages 1, 2, and 3

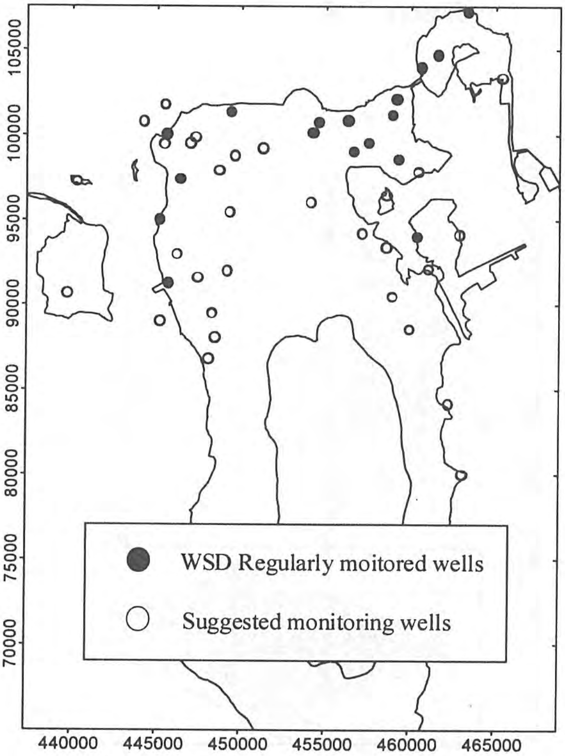

Figure 11: Location of wells suggested for Dammam aquifer salinity monitoring network

Options for Aquifers Storage and Recovery in Kuwait

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OPTIONS FOR AQUIFERS STORAGE AND RECOVERY IN KUWAIT

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ABSTRACT

Artificial recharge of groundwater could be a viable management option for Kuwait as an arid country. This was found to be a beneficial technique in solving the main deficiencies of water resources utilization in Kuwait. Among the important problems are; (1) Overdraft of the aquifers which lowered groundwater levels and escalated the deterioration of their quality; (2) High dependence (about 90 %) on desalination plants on producing potable water. These plants may be subjected to stoppage due to any accidental reason which would cause a water crisis; and (3) Poor operation efficiency of desalination plants due to seasonal fluctuation in water demand.

Two possible practices of freshwater injection-recovery were found feasible to encounter the above problems. First, through seasonal cycles of water injection-recovery, desalination plants can operate at their optimum capacity all over the year irrespective of seasonal fluctuations in domestic water demand. Aquifers yield can also be increased through using this type of storages. Second, using a long-term storage, where surplus of desalinated water can be stored in aquifers to meet expected demand of potable water during emergency conditions. Numerical modeling was used to predict the system response quantitatively and qualitatively during the practice of freshwater injection and recovery. Thus, the feasibility of using these aquifers as underground storages for huge amounts of potable water was investigated.

Keywords: numerical models, artificial recharge, water management, desalination, seawater intrusion.

INTRODUCTION

Artificial groundwater recharge has been practiced for scores of years throughout the World. The purpose of artificial recharge is to increase the rate at which water enters aquifers in order to supplement the quantity of groundwater storage. Hence, artificial groundwater recharge can be an important element of a fully developed water management system, in which aquifers can be used as underground storages. As surface storage of water becomes less available and as over-consumption of groundwater resources leads to saline water intrusion and land subsidence, the need for such a technique that will enhance and supplement the natural recharge, and increase the utilization of aquifer for storage, will become more vital. Generally, artificial recharge has many advantages and potential uses. In addition to its use in increasing the groundwater storage in the aquifer, it can also be used in creating a hydraulic barrier to prevent or reduce saline water encroachment.

The purposes of artificial recharge vary in general from one place to another and from one period to another. In Arid and Semi-arid regions, number of artificial recharge purposes were identified from literature, including:

1. Making use of aquifer storage and increasing the yield of a resource system;
2. Seasonal storage adjustment aimed at increasing the supply capacity during the summer months of peak demand;
3. The build-up of hydraulic barriers and replenishment of depleted aquifers for the prevention of sea water intrusion, and to avoid quality deterioration due to upward leakage or upconing of saline waters;
4. Improving the quality of wastewater during infiltration through the soil and/or the zone of aeration;
5. Disposing of chemically or thermally polluted liquids;

It is important to carefully consider the range of recharge objectives for any proposed project and to select and prioritize those that are applicable. This begins first with identifying the actual need for applying the artificial groundwater recharge technique.

ARTIFICIAL RECHARGE NECESSITY

Based on the hydrological conditions, water system operation, and water demand in Kuwait, three major issues were identified as follows:

1. For potable water supply, there is an extreme dependency on seawater

desalination. There is a danger that the desalination plants will lose part or all of their capacity in event of emergency conditions resulting, for example, from sea water pollution (e.g., with crude oil) or accidental/intentional breakdown of desalinated plants

2. Operating desalination plants at poor efficiency. Most of the urban potable water comes from sea water desalination plants. These plants have fixed optimal operational capacities. Operation of desalination plants at other outputs results in sub-optimal efficiencies. Water demand, however, varies significantly on a seasonal basis, high in summer and low in winter. Hence, most of the year, desalination plants are operating at poor or low efficiency.

3. Subjecting the aquifers to overpumping is creating a sharp decline in their potentiometric heads. This decline is inducing sea water intrusion and upward leakage of the deep saline water, leading to a deterioration of the groundwater quality.

The above problems can be solved using two types of storage. First, through short-term storage, seasonal water demand fluctuations could be overcome, where the excess desalinated water during winter is stored to be used later during the water peak demand in summer. Second, through long-term storage, part of desalinated water surplus could be placed in the aquifer to face water demand under emergency conditions.

Since Kuwait is an arid country, with no rivers, canals or lakes to be used as natural storage, aquifers could provide the needed storage. Underground storage of freshwater in brackish aquifers by artificial recharge may be used as an alternative to a surface reservoir. Such a process would typically involve injection of freshwater, storage until needed and subsequent abstraction from the same well. Storing water underground has the advantages of: (I) being economically more feasible than surface storage because of the low cost of construction and maintenance; (ii) minimizing evapo-transpiration losses; and (iii) being relatively safe from pollution threats.

METHODOLOGY

To assess the feasibility of using the aquifers in Kuwait as underground natural storages, three 3-D numerical groundwater flow and transport models (regional, sub-regional, and single-well) were used. All these models are two-layered consisting of the Kuwait Group and Dammam Formation aquifers. The regional domain was discretized using a square mesh consisting of 73 x 70 cells with irregular grid spacing. A finer grid spacing ($\Delta x = \Delta y$) of 2 km was assigned at the locations of wellfields to represent the expected steepness in the hydraulic gradient resulting from groundwater abstraction. The domain of the sub-regional model was discretized using a rectangular mesh consisting of 80 x 176 cells with a uniform grid spacing, where ($\Delta x = \Delta y = 500$ m). On the other hand, the single-well domain was discretized using a square mesh consisting of 55x55 cells with irregular grid spacing. A very fine cell (0.5 x 0.5 m) was used at the center of the model, to represent the location of the well. Away from this node, the grid spacing was gradually increased in all directions using an expansion factor of 1.2. A distance of 409 m between the well node and the boundary node in the x and y directions was modeled, where Δx set equal to Δy. The boundary nodes had the largest nodal spacing of 68.7 m.

The MODFLOW groundwater flow modeling package (McDonald and Harbaugh, 1988), and the three-dimensional transport code MT3D (Zheng, 1990) were used to solve these models. Density variation between the injected freshwater (with a TDS of 300mg/l) and the native groundwater (with a TDS of 4500 mg/l) is insignificant. Thus, its effect on the groundwater flow was ignored.

The models were calibrated for both the steady and transient conditions. They were then used to simulate the hydraulic and transport responses of the aquifers to various scenarios of water injection and recovery at some selected sites. The regional model was used to identify the optimum locations to store freshwater, while the sub-regional model was used to determine the optimum management variables to inject and recover freshwater at the selected sites. These variables include: number and geometry of injection/ recovery wells, injection/recovery rates, duration of injection required to create the intended quantity and quality of freshwater. The single-well model was used to identify the aquifer dispersivity, rate of well-face clogging during water injection, and the recovery efficiency for water injection/ recovery experiments which conducted for the Dammam and Kuwait Group aquifers (Mukhopadhyay et al, 1994). The Dammam Limestone is considered to be the most appropriate aquifer for water injection. The possibility of clogging at the interface between injected wells and aquifer formation are much more less in fissured formations than in granular media. This was proved by the water injection/recovery tests carried out for the Kuwait Group and Dammam Formation aquifers.

Seasonal Storage

The current and proposed groundwater abstraction from the aquifers in Kuwait, as indicated by the simulation flow model are seriously exposed to miss-managed development, where the groundwater is abstracted (or may be mined) regardless of the aquifer's safe yield. Because the salinity of the groundwater in the utilized aquifers is already high (ranges from 3000 to 6000 mg/l), any further deterioration will make these aquifers less usable in the future. By that time, any remedy will be impossible.

On the other hand, urban demand for freshwater varies considerably between summer and winter months resulting in operating the desalination plants under sub-optimal conditions. It was found that if integrating the aquifers and the desalinated water production together practices the artificial groundwater recharge, the desalination plants can operate with their optimum capacity, irrespective of demands for freshwater, while the aquifer yield can be restored. Two benefits follow from this practice:

1. Operating Desalination Plants at Optimum Capacity: This can be done through a seasonal cyclic storage and recovery of desalinated water. It is possible to store the excess desalinated water during winter months, and recover the stored water later during the summer to meet peak water demand. In addition, using the aquifers as a standby storage to meet the peak water demand, the establishment of new desalination plants can be postponed depending on the aquifer storage capacity and the number and capacity of injection/recovery wells. The optimum site to be used as a seasonal storage was found to the Shigaya-B wellfield (Fig. 1). The main reasons for selecting this site are: (1) its capacity to store and recover large volumes of water within a short period of time; and (2) its location in a highly depleted area, thus, the aquifer head can be restored and the undesirable effects affecting groundwater quality can be reduced. The number of wells required to make the desalination plants operate at their optimum capacity year-round are 20 wells, where their theoretical optimum injection (during the injection cycles) and pumping (during the recovery cycles) rates are 7000 m^3/d per well. The initial recovery efficiency was found to be improved with the increasing number of injection/recovery cycles from 12% to about 48% obtained after 10 cycles, where each cycle is 6 months length.

2. Increasing the Aquifer Yield: At the same time, the depleted aquifer heads are restored to a certain degree using the cycle of water injection/

recovery. For example, recharging the Shigaya-D wellfield (Fig. 1) at a rate of 1840 m^3/d per well using 24 wells on a seasonal basis was found to raise the Dammam aquifer heads at the major cones of depression by 80, 20, 10, and 7 m at the recharged site, Shigaya-B, Umm Gudair, and the Sulaibiya wellfields, respectively. Thus, the aquifer yield at the wellfields is increased, and the possibility of groundwater quality deterioration due to sea water intrusion or upward leakage of saline water from underlying layers is reduced.

In general, it was found that, to maximize the benefits from artificial groundwater recharge in increasing the aquifer yield, it should be practiced in conjunction with groundwater abstraction.

Long-Term Strategic Storage

Storage and recovery of a sufficient volume of freshwater is a feasible option to meet the shortage in freshwater supply that may occur during emergency conditions. The Shigaya-A wellfield (Fig. 1) was found to be the optimum site to be used as a long-term underground strategic reserve. This is mainly due to its high recovery efficiency, and the sufficient depth of the aquifer potentiometric head at this site, which allows the buildup in water head inside the injection well if it is clogged. Emergency conditions were assumed to persist for 270 days, which is the required duration to build a new desalination unit. Three different scenarios for the emergency to occur were assumed in this study. They are classified according to the degree of severity, ranging from a limited deficit in freshwater resulting from a limited failure of one or two desalination plants, to a total loss of the desalination plant's capacity and of the surface reservoir capacity. The optimum management variables required to store a sufficient volume of freshwater to fulfill the shortage in freshwater supply during each scenario were separately identified as follows:

Scenario A: Very limited mechanical failure in one or two desalination plants was assumed. Under this scenario, the available storage and the capacity of desalination plants would be adequate to replace the lost portion of freshwater, and there was no need for artificial underground freshwater storage in this case. However, under the other two scenarios, underground artificial storage was necessary.

Scenario B: Total loss of desalination plants assumed to occur, but the surface reservoirs were still available. Under this scenario, a volume of 53.2 Mm^3 of freshwater had to be injected into the aquifer to be able to recover 9.7 Mm^3 (which is the freshwater demand during emergency conditions). This means that the recovery efficiency is 18.2%. This was done using 20 wells with an injection rate of 1750 m^3/d per well for about 4.16 year. The optimum spacing of the wells, under which the maximum injection rate and maximum recovery efficiency can be obtained, was found to be 1000 m.

Scenario C: Total loss of the desalination plant's capacity and of the surface reservoir capacity assumed to occur. Under this scenario, where freshwater supply was completely lost, more water had to be stored (about 115.32 Mm^3) to recover 21.9 Mm^3 of freshwater to meet freshwater demand during the period of the emergency. This involves the use of 40 injection wells with a rate of 1500 m^3/d per well over 5.26 years. The optimum spacing for these wells was found to be 1500 m.

CONCLUSION AND RECOMMENDATIONS

Artificial groundwater recharge was found to be a very beneficial management alternative for Kuwait; to improve its water system efficiency, increase the aquifer yield, and to create a strategic reserve for emergency use. Two alternatives for injecting, storing, and recovering freshwater were found to be feasible. Through seasonal cyclic of injection/recovery of water, it will be possible to operate the desalination plants year-around at their optimum capacity, while the aquifer yield can be increased. Also, through long-term storage, a sufficient volume of freshwater could be stored in the aquifer for later use during water crisis. To increase the efficiency of recovering stored water from aquifers, two main points should be considered in practicing artificial groundwater recharge under the Kuwaiti hydrological conditions, these are as follows:

1. For the purpose of creating a long-term freshwater strategic reserve for emergency use, the proposed site for this purpose is recommended to be used initially as a seasonal cyclic storage (for about 3-5 years). This will help in improving the recovery efficiency at this site with the successive cycles of water injection/recovery. Consequently, the volume of freshwater, which needs to be injected in order to create the required freshwater storage for emergency use, will be less.

2. Recharge wells should be constructed as Aquifer Storage Recovery (ASR) wells to permit them to be used for dual purpose (i.e. for abstraction as well as recharge). This design will also help in developing the injection wells (if they became clogged) from time to time without much effort and loss of time.

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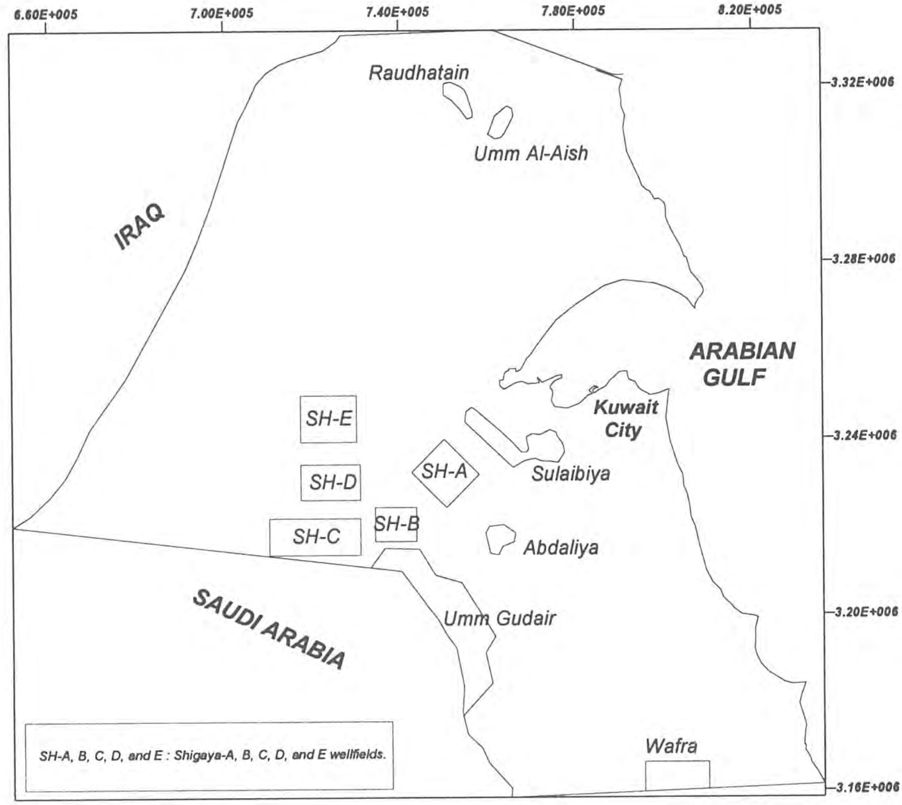

Fig. 1: Location of the existing water wellfields in Kuwait

Digital Simulations of Ground-Water Salvage in Northeastern Abu Dhabi Emirate

Eric Silva and Fatima Al Nuaimi

DIGITAL SIMULATION OF GROUND-WATER SALVAGE IN NORTHEASTERN ABU DHABI EMIRATE

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ABSTRACT

The surficial aquifer system in a 1,200-square-kilometer area of northeastern Abu Dhabi Emirate conveys fresh ground water from a recharge area along the Oman mountain front to an area containing brackish water. Numerous wells extract fresh water from the surficial aquifer system, however, about 70,000 cubic meters per day moves downgradient beyond the intercepting wells. This water reaches the brackish-water area through a 22-kilometer-long section and becomes unusable as a drinking water supply.

A ground-water model was developed to assess historical and future hydrologic conditions in the surficial aquifer system. Model input parameters were estimated by analyses of well logs to define lithology and thickness of the surficial aquifer system, analyses of long-term pumping records from existing well fields, and construction of water-level maps. Long-term rates of inflow from mountain front recharge areas were estimated from water-table gradients and aquifer properties.

The ground-water model was used to simulate future changes in the flow system and to evaluate a number of strategies to salvage throughflow. The simulations indicated that if 1995 pumping rates continue, several areas will be depleted of ground water within 20 years. This depletion could be alleviated by strategic placement of additional wells to capture about 35,000 cubic meters per day of throughflow that would normally be lost to the desert beyond the model boundary. Model simulations also indicate that throughflow could be effectively salvaged and stored in the ground-water reservoir behind a 17-kilometer-long subsurface dam. The model can be used to evaluate many other water-management scenarios.

Keywords: Abu Dhabi Emirate, ground-water model, MODFLOW, water management

INTRODUCTION

In 1988 the National Drilling Company of Abu Dhabi, in cooperation with the United States Geological Survey, initiated a Ground-Water Research Program (GWRP) to evaluate the water resources of the Emirate. One aspect of that study was to assess hydrogeologic conditions in the largest and most prolific alluvial deposit in the Emirate. This deposit occurs within the surficial aquifer system in a 1,200-square-kilometer area in northeastern Abu Dhabi Emirate about 50 kilometers north of the oasis city of Al Ain (fig. 1). Heavy pumpage from the surficial aquifer system has resulted in ground-water level declines of 9 meters in parts of the area. Some fresh ground water moving westward with the regional flow regime escapes the pumping and is wasted to evaporation in inland sabkhas.

The primary objectives of this study were to understand the hydrologic conditions in the surficial aquifer system and to evaluate alternatives for alleviating the declining ground-water conditions. The study included interpretation of geophysical surveys, exploration drilling, aquifer testing, water-level and water-quality monitoring, and ground-water modeling. This paper, focuses on the modeling aspects of the study. Strategies considered were installing pumping wells in the downgradient area to capture throughflow, a reduction of present pumping rates, and the creation of a physical underground barrier across a section of aquifer.

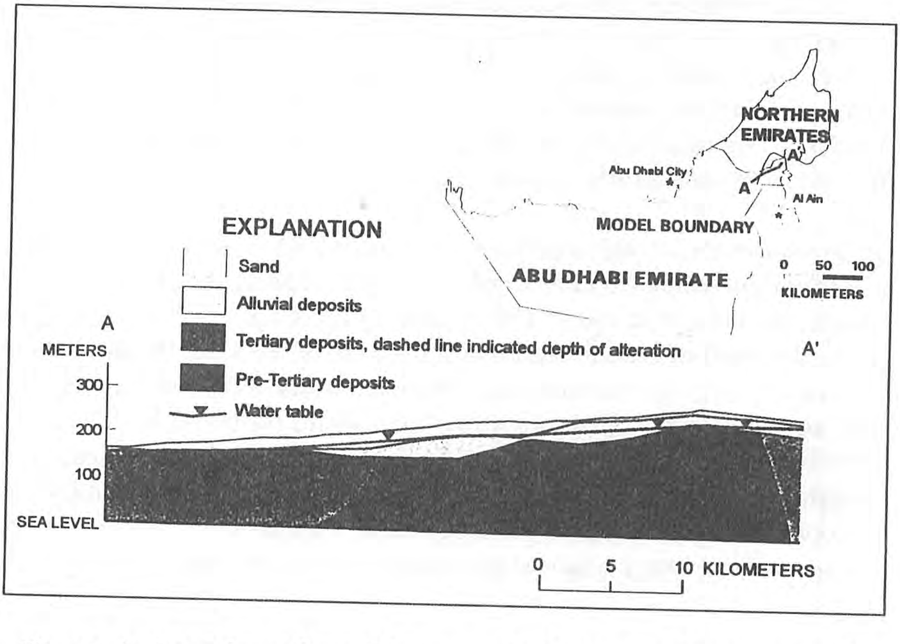

Figure 1. Location of model area and diagrammatic cross section in northeastern Abu Dhabi Emirate

HYDROGEOLOGIC CONDITIONS

The surficial aquifer system is composed of a number of hydrogeologic units. The units include alluvium of Quaternary age, altered Late Tertiary rocks composed of clastic and non clastic sediments and evaporites, and Tertiary and Cretaceous limestones that contain secondary fractures and solution cavities (Bright and Silva, 1998). The major aquifer in the region is the alluvium deposited by Quaternary-age fluvial systems, which carried sediment westward from the Oman Mountains. The saturated alluvium generally is a gravel zone that is variably cemented and differentially dissolved by ground-water related processes. The differential solution of carbonate cement that binds the formation has resulted in permeable channels within the unit. The areal distribution of these permeable zones has been defined by geophysical methods and regional investigations (Al Za'afarani and Al Kamali, 1995; and Bright and Silva, 1998).

Ground water enters the surficial aquifer system at the base of the Oman Mountains as subsurface inflow in buried alluvial channels and as recharge along wadi beds. The northwestern part of the study area borders the gravel plain of Wadi Sumaini, which flows north along the mountain front during periods of heavy rainfall (fig. 2). The 5- to 10-kilometer-wide gravel plain on which Wadi Sumaini flows is the major recharge area for the northern part of the study area. The southern part of the study area borders a gravel plain on which Wadi Mashiq, Wadi Safwan, and Wadi Athamiya flow during periods of runoff. These wadis flow from east to west across the gravel plain and into dunes.

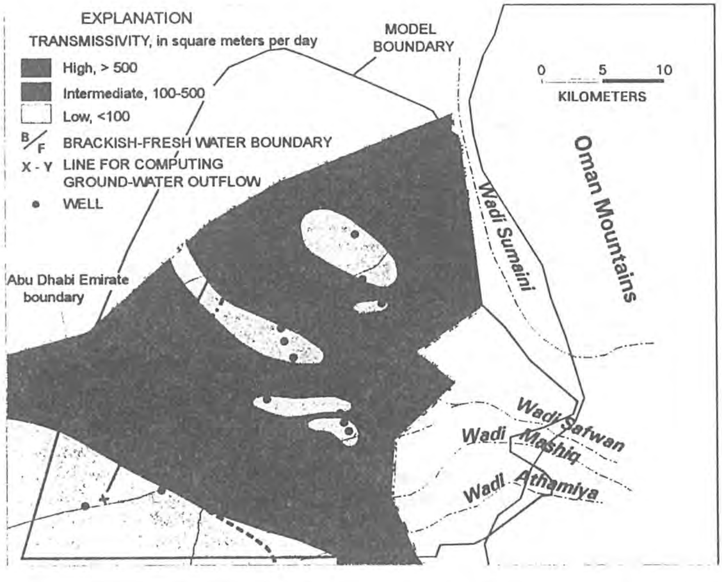

Figure 2. Transmissivity of the surficial aquifer system

The depth to water in wells varies depending on the distance from the mountains and on whether the wells are located on or between dunes. The water level near the Mountains is about 15 m below land surface. Ground-water levels in the dune areas range between 15 and 60 meters below land surface. Predevelopment and 1995 hydraulic potential maps are shown in figure 3 (Maddy, 1993; and Hutchinson, 1996). Predevelopment water levels were estimated from well construction records provided by public agencies (Maddy, 1993). The 1995 map was based on wells drilled and inventoried by the GWRP (Hutchinson, 1996) The maps indicate that hydraulic continuity exists among the members, which suggests that the members can be considered as a single aquifer. The predevelopment head slopes to the west with a gradient of 0.004 (line AB in fig. 3a). The 1995 surface shows a lesser gradient of about 0.003 for the same line, which reflects the effect of ground-water withdrawal (line A'B' in fig. 3b). Both the predevelopment and 1995 surfaces indicate east-west aligned flow direction. Water levels in the western part of the study area have not been appreciably affected by pumping, primarily because the ground water in this area is brackish and generally unusable.

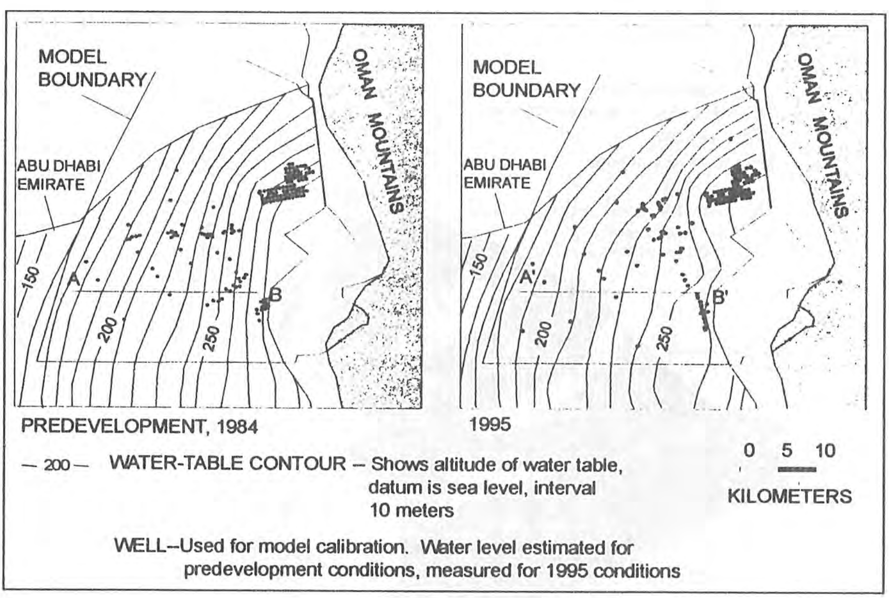

Figure 3. Predevelopment and 1995 ground-water levels.

Hydraulic Properties

Aquifer tests in the 1970's indicated that transmissivity of the alluvium ranges between 200 and 1,400 square meters per day and storage coefficient between 0.005 and 0.1 (Gibb and others, 1974). Transmissivity calculated from 60 single-well tests of the surficial aquifer system conducted by the GWRP ranges between about 10 and 7,500 square meters per day. Transmissivity is lowest where the aquifer is composed of Tertiary claystone and highest where it is karstic limestone (Bright and Silva, 1998). The distribution of transmissivity was found to be related to resistivity contrasts observed in surface geophysical surveys and variations in water quality (fig. 2). Transmissivity was mapped as high, (>500 m^2/day) medium, (between 100 and 500 m^2/day) and low, (<100 m^2/day). The higher transmissivity zones extend as alluvial paleochannels and are bordered by medium and low transmissive zones (fig. 2). The westward bulge of fresh ground water is associated with the zone of high transmissivity. The storage coefficient of the alluvium, calculated from aquifer tests, ranges between 0.003 and 0. 15 (Turner and others, 1986; and Silva, 1997). The storage coefficient for the surficial aquifer system, based on interpretation of geophysical logs, ranges between 0.07 and 0.29 (Al Aidrous, 1995). Subsequent tests conducted by the GWRP indicate that the storage coefficient is near the lower value of 0.07. Tests conducted with observation wells in the shallow limestones and Tertiary deposits yielded storage coefficients varying from confined to semi-confined figures depending on the locality of the water bearing layer in the multilayered sequence. The uppermost productive layer, which is directly linked with the alluvium, shows near unconfined values varying from 0.08 to 0.12. Based on these analyses, a storage coefficient of 0.1 was considered to be representative of the surficial aquifer system.

Aquifer Recharge

Linear studies were conducted by the Oman government from the mountain valleys westward into the sand dunes near the Abu Dhabi Emirate border to evaluate the potential for various water development programs. Steady-state ground-water flow through a 7-kilometer-wide section of Wadi Safwan was estimated to be about 3,200 cubic meters per day per kilometer of aquifer width (Turner and others, 1986). For modeling purposes, it was assumed that the Wadi Safwan benchmark recharge value could be applied to the other wadi systems that flow into northeastern Abu Dhabi Emirate.

A study by Rizk and others (1998) indicated that annual rainfail should exceed 140 millimeters in order to contribute significantly to ground-water recharge in dune areas. Records from the Al Ain Agriculture and Animal Production Department indicate that rainfail exceeded 140 millimeters in 8 of the 27 years of record collected from 1971 to 1997. Moreover, rainfall intensity perhaps is more important than rainfall total when considering mechanisms for recharge. The GWRP meteorological data indicates that during the 1993-1997 period, heavy rainfall of more than 40 millimeters occurred on 5 days. For modeling purposes, the long-term average areal recharge by infiltration of rainfail was considered to be 3 millimeters per year.

Aquifer Discharge

Major outflow from the surficial aquifer system includes pumpage from wells and subsurface ground-water outflow. Ground-water levels declined 1 to 9 meters during the period 1985-1995, in and around pumping centers. Because the aquifer thickness rarely exceeds 20 meters, it is probable that wells in some areas will become dry in the near future unless discharge is, reduced or the aquifer system is recharged artificially. It was estimated that in 1995 about 22 and 9 million cubic meters were pumped by municipal and agricultural wells, respectively (Kendy and others, 1996). The withdrawal of water from storage is a localized phenomenon related to pumping rates and aquifer characteristics.

Natural ground-water outflow was estimated by applying the Darcy flow equation, $Q = KIA$, or hydraulic conductivity x hydraulic gradient x cross-sectional area, along the western boundary of the model. A calculated 70,000 cubic meters per day leaves the study area as lateral ground-water outflow along a 22-kilometer-long section (line XY in fig. 2). This outflow enters a brackish-water area and is considered to be lost ground water that could be salvaged.

GROUND-WATER MODEL

The ground-water system in northeastern Abu Dhabi Emirate was characterized using the U.S. Geological Survey digital ground-water model, MODFLOW (McDonald and Harbaugh, 1988). The model simulates ground-water levels and movement based on estimated aquifer properties and stresses. The area of interest was subdivided into a series of grid blocks, each with representative hydraulic conductivity, storage coefficient, recharge, and pumpage. The simulation period of the model was then divided into time steps, over which these representative conditions were allowed to change. Calculations were made to solve a set of simultaneous equations using finite-difference approximation methods. Model output was as waterlevel maps, drawdown maps, hydrographs, and water budgets showing inflows and outflows at the end of each tirne step.

Model Boundaries and Assumptions

The modeled area comprises a single layer of 8,272 grid blocks, each 500 meters square and between 40 and 100 meters thick. Seventy grid blocks face the recharge area from the east. The model was aligned with the general east-west direction of flow. The simulation period of the model was from 1984 to 2015. The model is bounded by a flow boundary at the mountain front on the east, a constant-head boundary in the dunes on the west, and no-flow boundaries on the north and south (fig. 2). The aquifer was simulated as a single layer with a free water table. It was assumed that the higher transmissive channels of the study area extend eastward to the mountains and the medium transmissive channels extend to the north boundary of the model area (fig. 2).

Recharge was applied along the mountain front at various rates required to satisfy the result of the Wadi Safwan study that an average flow of 3,200 cubic meters per day passes through 1 kilometer of aquifer. Areal recharge was applied at the rate of 3 meters per year. Recharge was assumed to remain constant over the simulation period from 1984 to 2015. Pumpage calculated for 1995 was also considered to be a constant for the 1995 to 2015 period. Evaporation from the water table was ignored due to the relatively thick unsaturated zone (more than 15 m). Pumpage was estimated from maps, reports, and files provided by the Al Ain Water and Electricity Department and the Department of Agriculture and Animal Resources. Water levels estimated for 1984 and measured in 1995 and the subsurface outflow for 1995 calculated by the Darcy equation were the calibration targets.

Model Results and Discussion

Figure 4a shows a good correlation between the predevelopment water levels calculated by the model for the given hydrogeological parameters and the estimated water levels. Reasonable correlation was also noted for the water levels calculated by the model for 1995 and field measurements made in 1995 (fig. 4b). Figures 5 and 6 illustrate simulated water levels under various conditions. Each simulation is represented by a cross section and map. The cross sections show the simulated water table along a flow line and the maps show the changes of the water table relative to the predevelopment water table. The cross section shown in figure 5a represents the simulated water level in the aquifer in 1995 and conveys the idea that the aquifer is very thin and is being affected by pumping. The map in figure 5a shows the location of row 66 and the simulated drawdown that has resulted from pumping for municipal and agricultural supplies during the period 1984-1995. Figure 5b shows the simulated status of the aquifer in 2015 if 1995 pumping rates continue. The model indicates that some grid blocks will be dry in the central regions where drawdown is 16 to 20 meters. Figure 5c illustrates the water level in the aquifer in 2015 if 50 percent of the out flow (35,000 cubic meters per day) is captured by weils installed in the western part of the area. The pumping from the downgradient wells would produce a cone of depression that would accelerate water-level declines. However, if the 1995 rates of pumping were reduced by half from 1998 to 2015, water-level declines would be reduced (fig 5d).

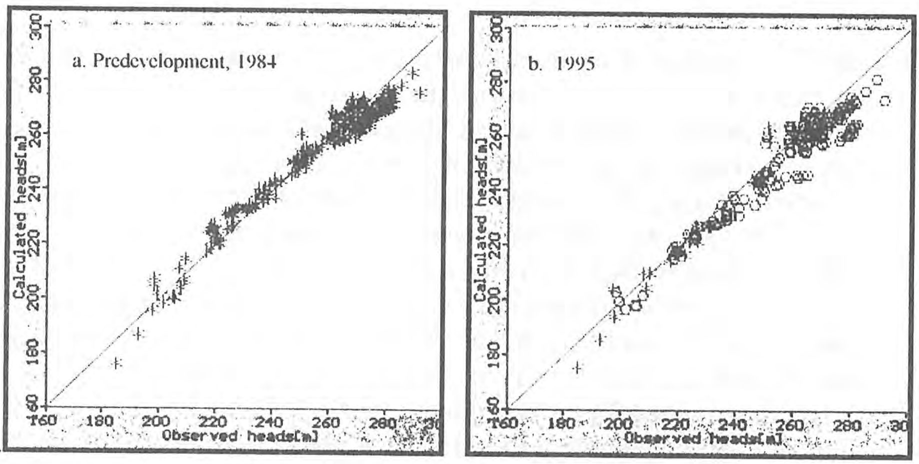

Figure 4. Model calculated versus observed heads

Figure 6a shows simulated ground-water levels in the year 2015 if the outflow at the west boundary is barred by an underground dam beginning in 1997. The simulated dam is about 17 kilometers long and about 80 meters deep. The location and alignment of the axis were selected to dam the most transmissive ground water channels in the study area. Rises in water levels between 1 and 20 meters would occur in a wide area of over 150 square kilometers. Constructing such underground dams to capture flow is possible. In 1994, on the basis of field studies, the Cosmo Oil Company proposed a plan to construct a dam more than 40 kilometers long, in another area of the northeastern Emirate (Cosmo, 1994).

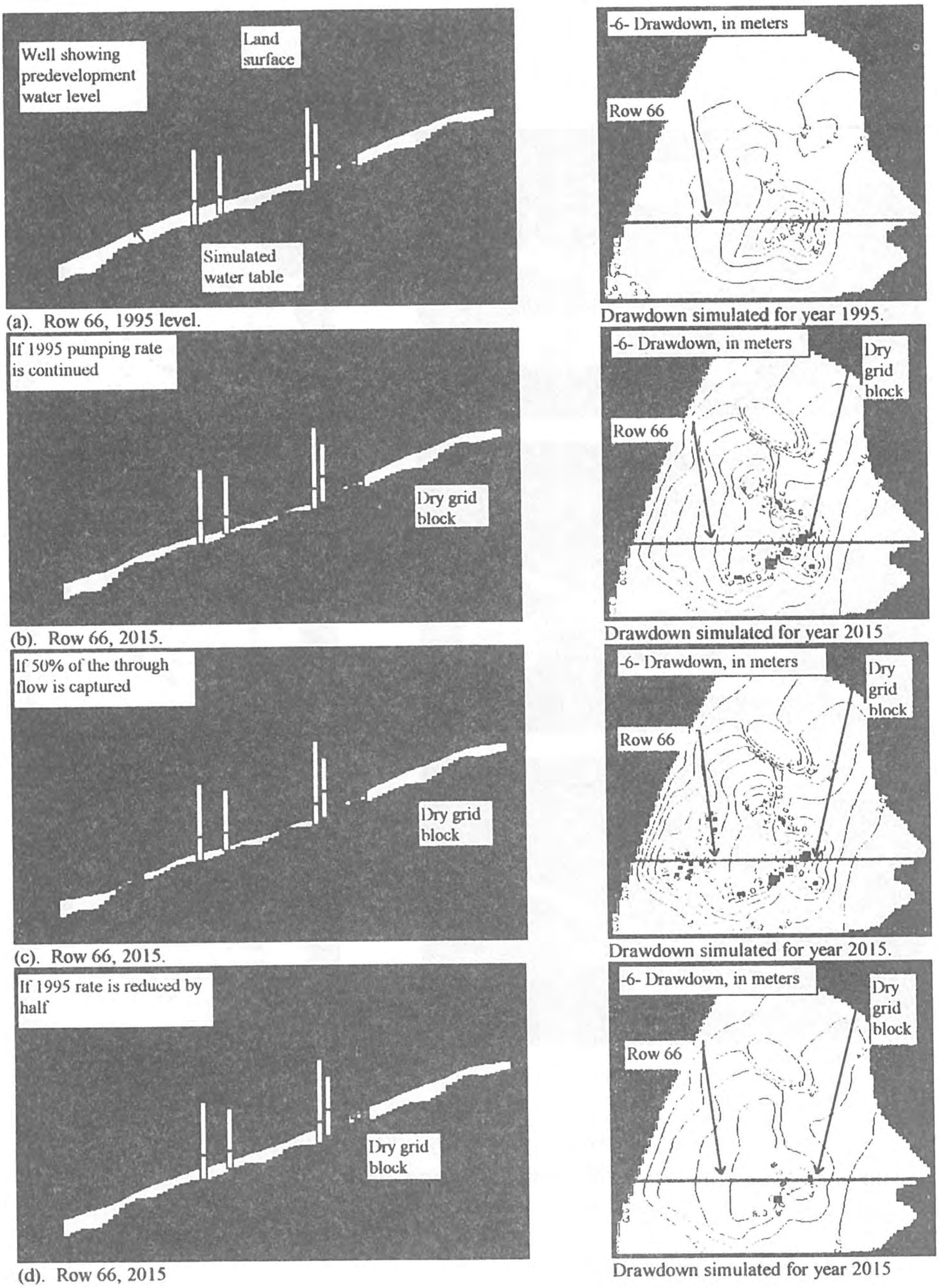

Figure 5. Model simulations of water-management scenarios

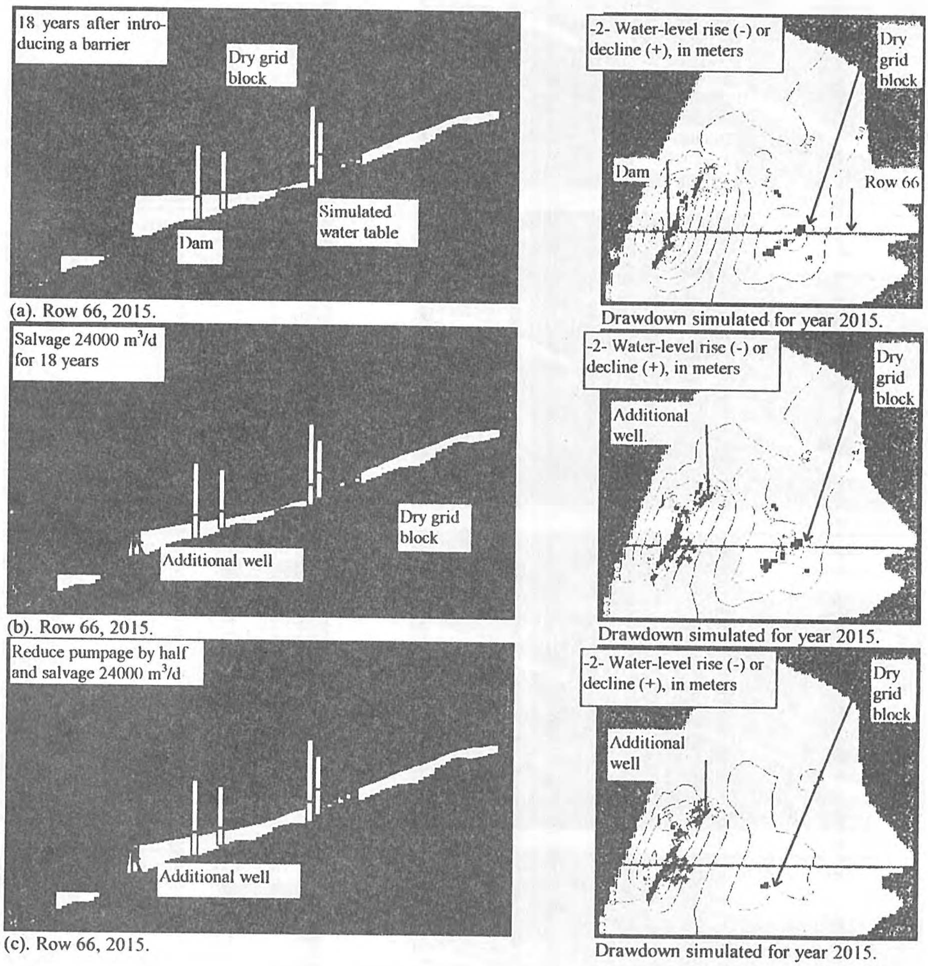

Figure 6. Model simulations of ground-water salvage with a subsurface dam.

Additional pumping wells in the dammed area were simulated to capture 24,000 cubic meters per day, or about 35 percent of the flow that is barred by the 17-kilometer-long dam. Simulated water levels remained above the aquifer bottom for 18 years under this scenario (fig. 6b). Captured water could be supplied to the declining well fields in the east or elsewhere. Figure 6c shows the effect of the additions wells behind the dam combined with a 50-percent reduction in pumping from existing well fields.

The effect of the different strategies on the aquifer can be understood further by studying the major components of the water budget calculated by the model for the above simulations (table 1). The decrease in constant-head outflow from 105,000 cubic meters per day in 1995 to 77,000 cubic meters per day in 2015 indicates that pumping captured 28,000 cubic meters per day. The decrease of well discharge from 84,000 to 74,000 cubic meters per day indicates that pumpage was shut off in some grid blocks when they became dry. The reduction of constant-head outflow from about 105,000 to 55,000 cubic meters per day indicates the capture of the ground-water flow by the dam. The positive impact of the dam on the hydraulic status of the aquifer can be understood by the decrease in the constant-head outflow and storage change. It is important to note that the differences in hydraulic properties between the alluvium and the overlying dune sands would have an effect on water levels rise into the currently unsaturated dunes.

Table 1. Water budgets for modeling scenarios.

[R, recharge; CHO, constant-head outflow; P, pumpage; ΔS, storag e change; m^3/d, cubic meters per day, rounded]

Simulation		R	CHO	P	ΔS
Period	Strategy	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)
1984	Predevelopment, no pumping	111,000	111,000	0	0
1984-1995	Pumping variable	111,000	105,000	84,000	-78,000
1995-2015	Pumping at 1995 rate	111,000	77,000	74,000	-40,000
1995-2015	Pumping at 1/2 of 1995 rate	111,000	83,000	41,000	-13,000
1995-2015	Pumping + capture 35000	111,000	66,000	79,000	-34,000
1995-2015	Pumping + dam	111,000	55,000	75,000	-19,000
1995-2015	Pumping + dam + capture 24000	111,000	55,000	99,000	-43,000
1995-2012	pumping + dam + capt 24000	111,000	58,000	65,000	-12,000

The water budget equation: $R-(CHO+P)= \Delta S$

CONCLUSIONS

Between 1984 and 1995, water levels in the surficial aquifer system in northeastem Abu Dhabi Emirate declined as much as 9 meters. A model study conducted by the National Drug Company's Ground-Water Research Program indicates that some wells could go dry before the year 2015 if withdrawals continue at 1995 rates. Model simulations indicate the possibility of decreasing the decline rate by reducing pumpage, strategic placement of wells to salvage ground-water outflow to the desert, or redistributing captured throughflow that would accumulate behind an artificiel barrier. A 50-percent réduction of 1995 pumpage would reduce water-level declines to some extent. Strategic placement of wells could conceivably salvage about 35,000 cubic meters per day. Constructing a 17-kilometer-long subsurface dain to capture throughflow would result in a rise in water levels and produce a ground-water reservoir that could serve as a source of water.

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Simulated Impacts of Pumping from Well Fields Near Umm Ghafa, Eastern Abu Dhabi Emirate

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SIMULATED IMPACTS OF PUMPING FROM WELL FIELDS NEAR UMM GHAFA, EASTERN ABU DHABI EMIRATE

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ABSTRACT

Pumping from wells near Umm Ghafa in eastern Abu Dhabi Emirate has resulted in significant declines in ground-water levels since 1982 when the first public-supply wells were installed. In 1995, pumpage exceeded recharge in a 342-square-kilometer area that contains about 400 water-supply wells. The 80-meter thick surficial aquifer system has been affected most severely in the pumping center at Mezyad where the ground-water level declined about 12 meters between 1989 and 1995.

The United States Geological Survey ground-water model, MODFLOW, was used to simulate hydrologic conditions in the Umm Ghafa area. 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 representative of pre-1982. A transient calibration was achieved by introducing annual pumpage and adjusting porosity and recharge until simulated water levels matched those measured in observation wells between 1989 and 1995. A predictive model simulation assumed that 1995 pumping rates would continue to the year 2005. This simulation indicated that water-level declines would accelerate as the aquifer is dewatered. By 2005, ground-water levels could decline as much as 25 meters below 1995 levels in heavily pumped areas.

The model was used to demonstrate the severity of water-level declines caused by pumping and that the sustainable yield of the aquifer has been exceeded. The simulation for 1995 indicated that about 12,600 cubic meters were withdrawn in excess of salvaged subsurface outflow and induced subsurface inflow. Use of this model as a management tool is recommended for considering ways to alleviate the observed water-level declines, site new well fields, evaluate the need for abandonnent of old well fields, and optimize water production from the area.

KEYWORDS: Abu Dhabi Emirate, ground-water model, MODFLOW, water budget.

INTRODUCTION

Long-term ground-water withdrawals from the surficial aquifer system for municipal and agricultural use have caused water-level declines between 1982 and 1995 in Umm Ghafa area in eastern Abu Dhabi Emirate (figure 1). Due to the good water quality, anticipated increasing demand for municipal supplies will stress the ground-water system to a greater extent. Pumping results in a lowering of the water levels, which in turn, increases the potential for upward leakage of brackish water contained in deep aquifers into the fresh-water aquifer.

The overall objective of this study is to improve understanding of the shallow ground-water flow system in the Umm Ghafa area. The purpose of the report is to describe the development of a ground-water model of the Umm Ghafa area. It explains how the model was used to simulate predevelopment conditions in the surficial aquifer system and simulate the aquifer system's response to pumping. The model is based on estimates of hydraulic properties of the aquifer system and recharge and discharge rates. Calibration is achieved when computed water levels match observed water levels in selected wells. The calibrated model can be used to predict the impact of future ground-water withdrawals.

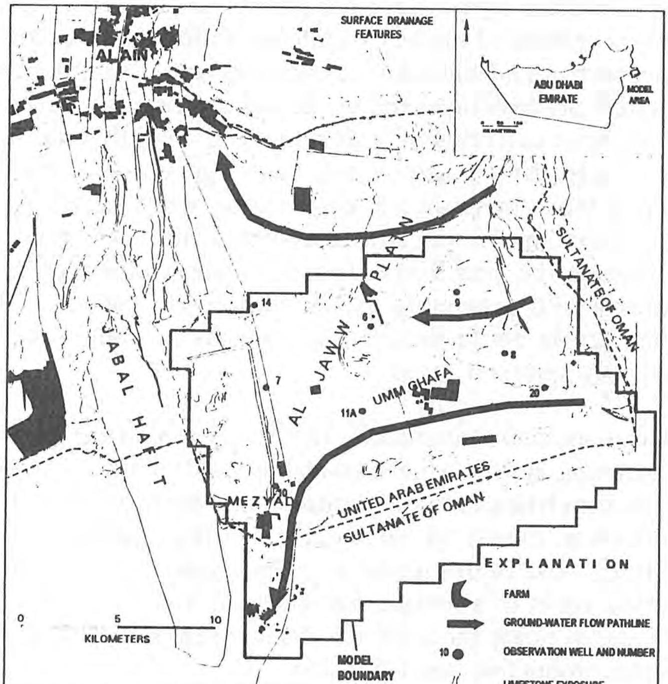


Figure 1. Umm Ghafa area, model boundary, and observation wells

HYDROGEOLOGIC FRAME WORK

Umm Ghafa area occupies the southern half of Al Jaww Plain within eastem Abu Dhabi Emirate. The Plain is a gently sloping area, which is bounded by Jabal Hafit on the west and by the Oman Mountains on the east (fig.1). All the major wadis crossing Al Jaww Plain originate from the Oman Mountains, which form the major catchment and recharge area of the region under study. The catchment area is composed of barren high mountains and hills that are relatively impervious. Narrow valleys filled with alluvium and intermontane flat areas drain the mountain area and discharge to the gravel plain. Jabal Hafit, a Tertiary limestone anticline, rises to an elevation of 1,160 meters above sea level, or 800 meters above the surrounding plain, and effectively impedes the westward flow of ground and surface waters.

The surficial aquifer system in the Umm Ghafa study area is composed mainly of Quaternary alluvium that is underlain in places by altered Tertiary deposits (Bright and Silva, 1998). The alluvium consists of sand and gravel with interbeds of silt and clay. The alluvium is underlain by calcareous claystone and mudstone; where altered by dissolution and weathering, these underlying deposits form the basal unit of the surficial aquifer system. The saturated thickness of the aquifer ranges from about 80 meters near the foothills of the Oman Mountains on the east, thins in the middle of the Plain to about 70 meters, and thickens to about 100 meters near Jabal Hafit in the west.

The permeability boundary that defines the base of the surficial aquifer system corresponds to an unconformity where the base of the alluvial deposits, sharply contrasting difference in permeability, and a well-defined lithologic boundary are all coincident. However, in parts of the study area, the base of the surficial aquifer does not conform with formation boundaries. At some locations, the uppermost part of the Lower Fars Formation is moderately permeable and yields water to wells. The base of the surficial aquifer is defined as the depth at which the intrinsic permeability is less than 1,000 millidarcies (md, equivalent to a hydraulic conductivity of 0.8 meter/day). Estimates of intrinsic permeability are calculated from geophysical logs using a method described by Jorgensen and Petricola (1994). The 1,000-md value represents an approximate lower permeability limit for low-yield aquifer material such as silty and clayey sand.

GROUND-WATER-FLOW SYSTEM

Predevelopment hydrologic conditions existed prior to man's influence on the system. Predevelopment water levels (Maddy, 1993) indicate that fresh water recharge occurs in the east and ground-water moves to the west. There is a surface-water divide in the Plain near Umm Ghafa. North of Umm Ghafa the wadis originating from Oman Mountains turn toward Al Ain after entering the Plain. In the southern part of the Plain the wadis flow in the opposite direction across the Oman border. The major wadis have streambed patterns that are similar to the major flow path lines of the ground water system. Prior to the establishment of municipal well fields, the discharge of the ground water from the study area paralleled the two main directions of surface drainage (fig. 1).

Ground-water inflow from the east is derived primarily as subsurface flow in alluvial material channeled through intermontane gaps. Small amounts of recharge are also derived from seepage along wadi beds and as leakage from fractured bedrock along the entire mountain front. The surficial aquifer system also receives recharge in the area of Jabal Hafit. Evidence for such recharge includes wadi surface drainage, ground-water head conditions, and environmental isotopes (Maddy, 1993, p. 205). The amount of recharge from Jabal Hafit was estimated as 10 percent of the total recharge to the area.

Ground-water levels in the study area declined between 1982 and 1995 as a result of groundwater development. During this period, well fields were established at Mezyad and Umm Ghafa for public supply and irrigation wells were constructed in new farm and forestry areas. Between 1989, when the GWRP began its data-collection program, and 1995, ground-water levels declined 4 meters at Umm Ghafa and 12 meters at Mezyad.

HYDRAULIC PROPERTIES

The hydraulic properties of the surficial aquifer were estimated from aquifer tests and geophysical logs. The range of hydraulic conductivity is 1.6-9.6 m/d. High hydraulic conductivity values (6 - 9.6 m/d) were estimated for the east near Jabal Hafit. Low hydraulic conductivity (1.6 m/d) was estimated for the southern part of the study area near the Oman boundary. Specific yield was estimated to range between 1 and 8 percent.

RECHARGE AND DISCHARGE

The recharge areas are mainly located along the eastern border of the model in gaps between the mountains, where subsurface water flows into the area. The recharge volumes were estimated using techniques developed by Osterkamp and others (1991). Recharge varies from year to year according to rainfall in the Oman Mountains, however, for the model the estimated long-term average recharge rate is 15,900 cubic meters per day. It is recognized that recharge occurs as seepage along the numerous wadi beds incised in Al Jaww Plain and as leakage from bedrock along the entire Oman Mountain front. However, this recharge is estimated to be small compared to the subsurface inflow.

Ground-water discharge occurs as pumpage from approximately 400 wells and as subsurface outflow at the western edge of Al Jaww Plain north and south of Jabal Hafit. Discharge was equal to recharge under predevelopment conditions. Public well fields began pumping in 1982. Some farm wells existed prior to this date, however, withdrawals prior to 1982 are considered to be insignificant. Public well fields and farm wells withdrew about 17,800 *m3/d* in 1995. This withdrawal resulted in some reduction of subsurface outflow, a slight increase in inflow, and a large withdrawal from aquifer storage.

GROUND-WATER MODEL

The ground-water system in Umm Ghafa area was characterized using the U.S. Geological Survey digital ground-water model, MODFLOW (McDonald and Harbaugh, 1988). The model simulates ground-water levels and movement based on estimated aquifer properties and stresses. The area of interest was subdivided into a series of grid blocks, each with representative hydraulic conductivity, storage coefficient, recharge, and pumpage. The simulation period of the model was then divided into time steps, over which these representative conditions were allowed to change. Calculations were made to solve a set of simultaneous equations using finite-difference approximation methods. Model output was as water-level maps and hydrographs, and water budgets showing inflows and outflows at the end of each time step.

MODEL GRID AND BOUNDARY CONDITIONS

The model grid contains 342 cells of constant dimensions, each 1-kilometer square. The grid parallels flow pathlines north and south of the study area to permit simulation of no-flow boundaries. Recharge was simulated as subsurface inflow through 6 cells that coincide with mountain gaps on the eastem boundary of the model. Discharge was simulated as subsurface outflow at one cell in the southwestern corner towards Oman and two cells in the northwest corner toward Al Ain and around the northern end of Jabal Hafit. It was estimated that two thirds of the ground-water

Figure 2. Observed and model-simulated water levels under predevelopment conditions with no pumping

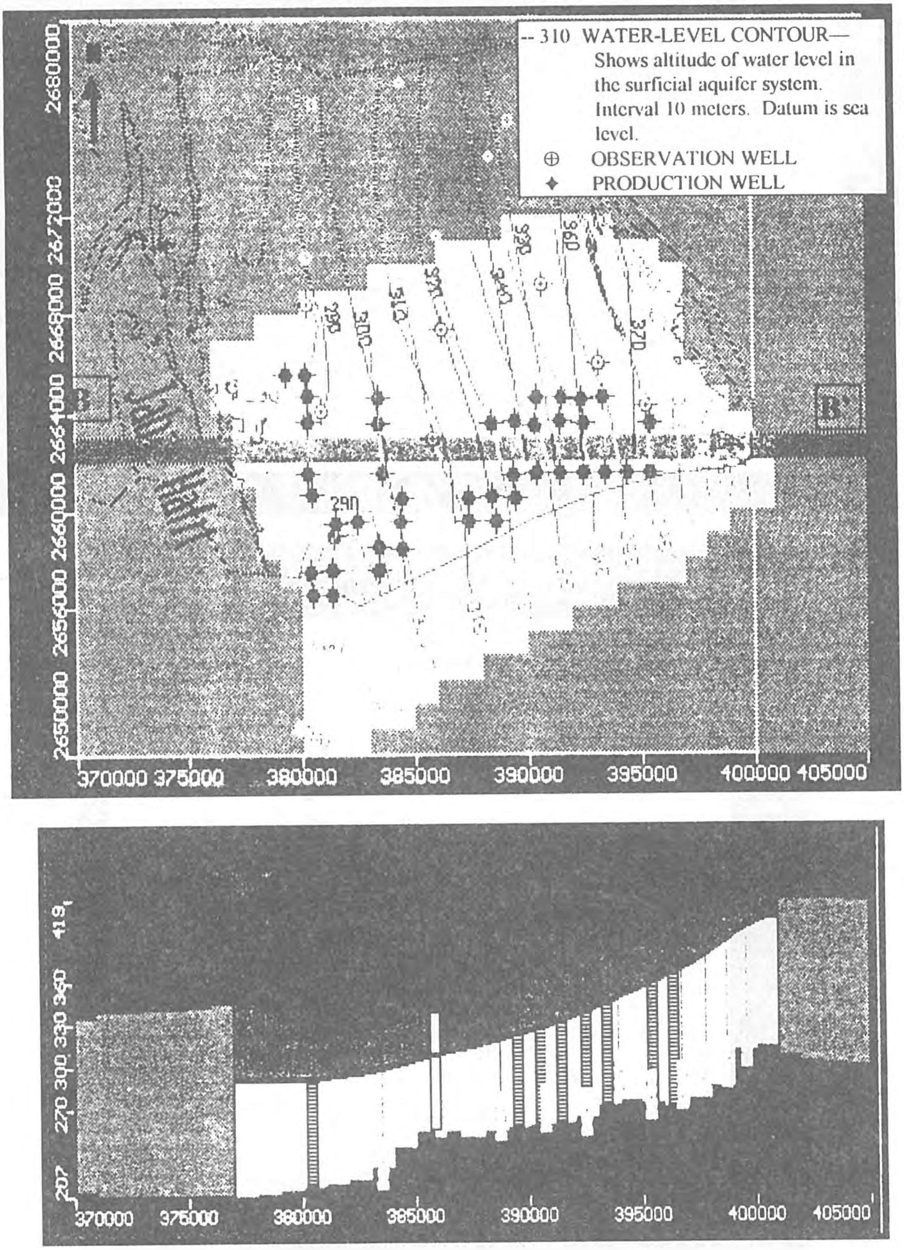


Figure 3. Observed and model-simulated water levels under 1995 conditions with no pumping

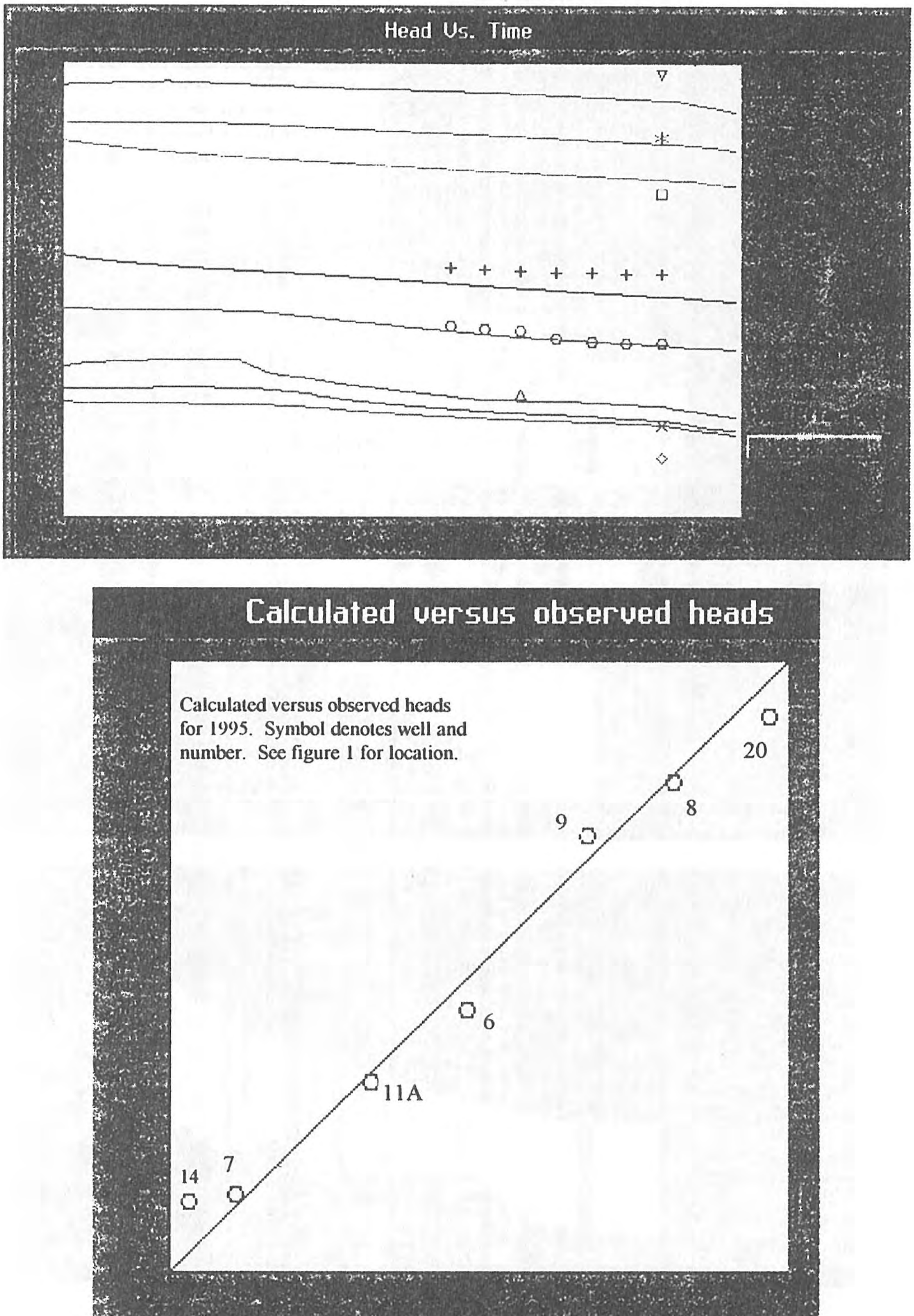


Figure 4. Observed and simulated water levels in observation wells, 1989-1995

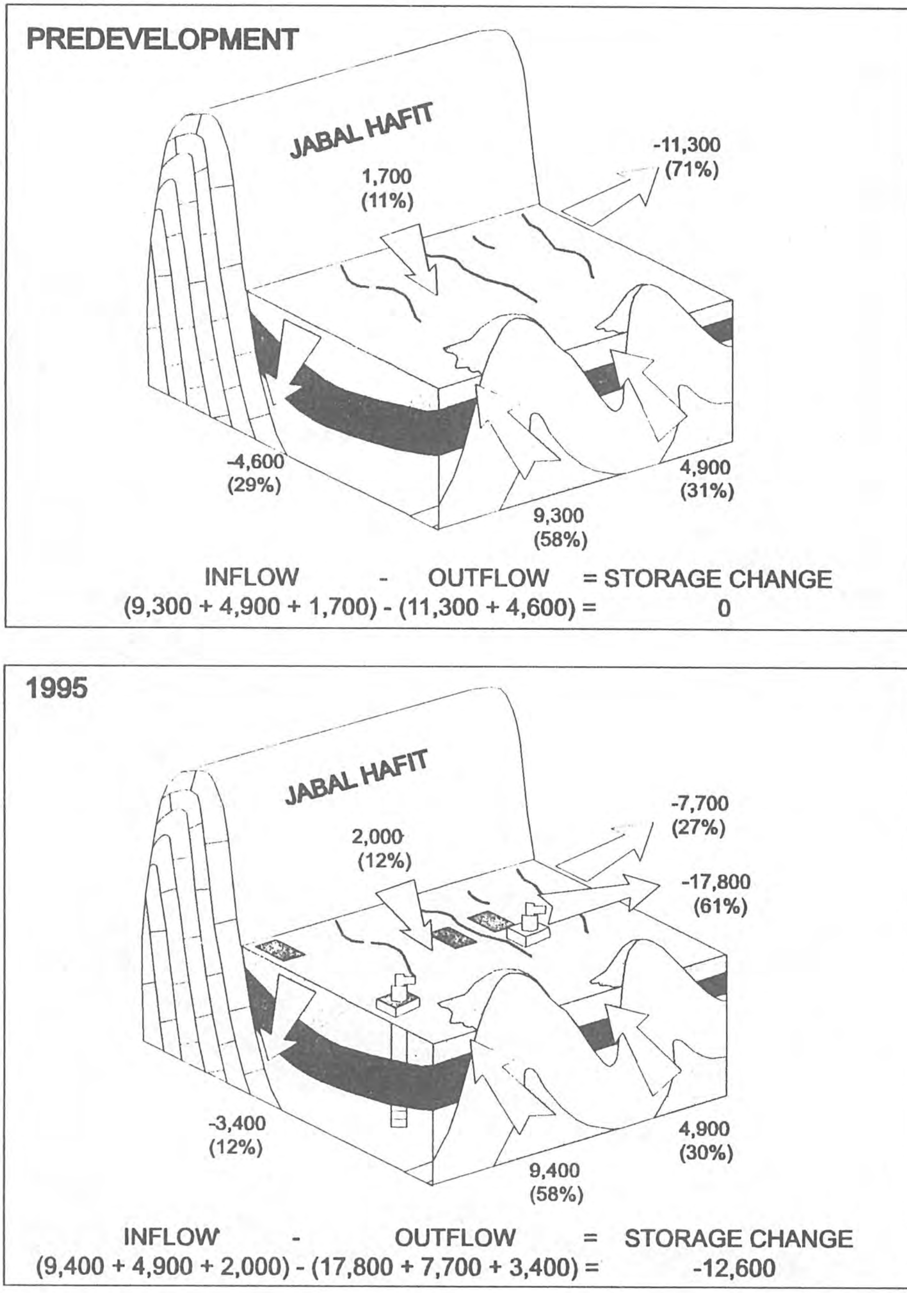
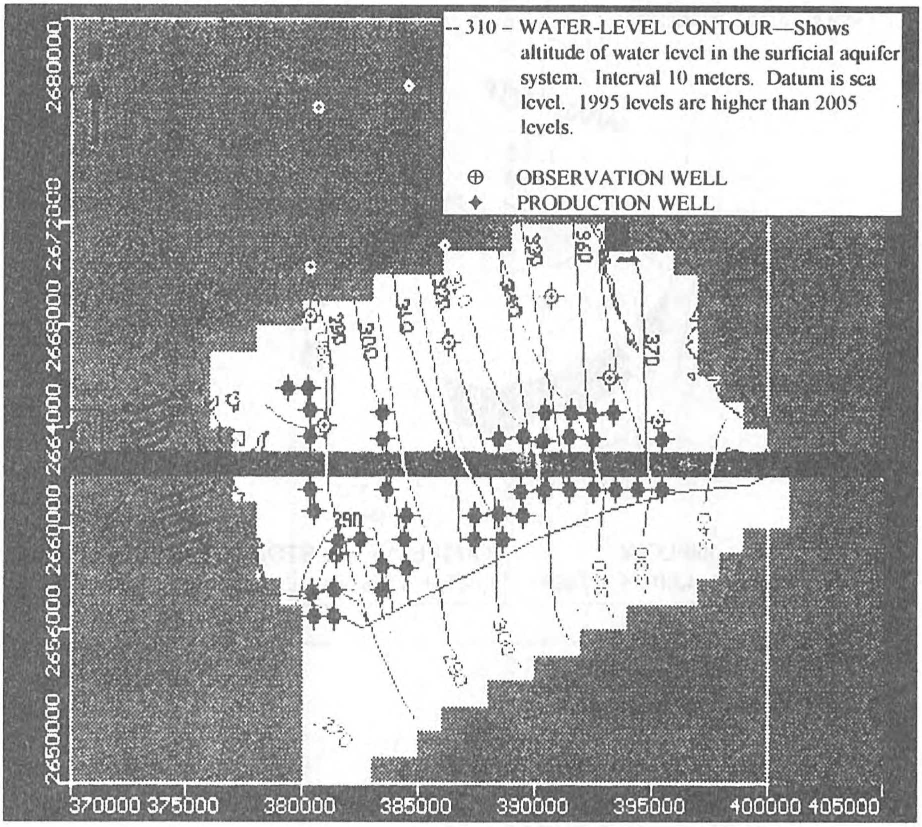


Figure 5. Ground-water budgets under predevelopment and 1995 conditions (values are in cubic meters per day).



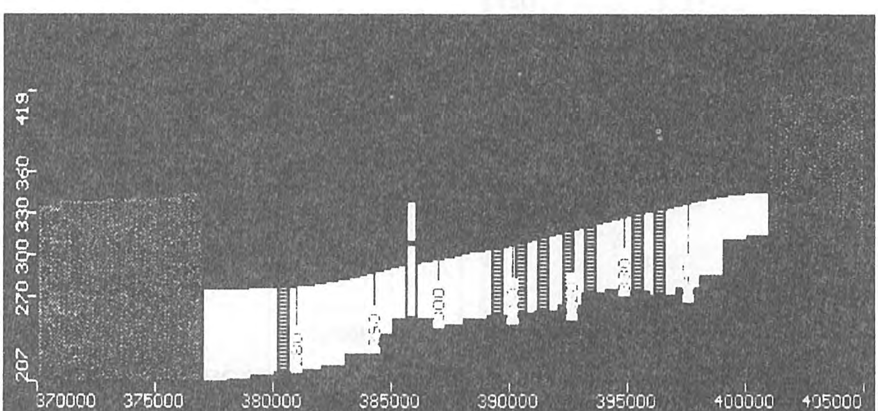


Figure 6. Model-simulated water levels in the year 2005 and water levels observed in the year 1995

discharge occurred in the northwest corner. Constant-head boundaries were used to simulate ground-water recharge and discharge. The active model grid comprises 333 cells for simulation of head and 342 cells for simulation of flow.

CALIBRATION

Ground-water flow simulations were conducted for steady-state predevelopment conditions and for transient pumping conditions. Ground-water flow models are calibrated by minimizing the differences between simulated and measured hydraulic heads (and flow volumes) through a process of adjusting hydraulic properties used in the model. Successful calibration of the model demonstrates the reasonableness of the conceptual model of the flow system. The calibration process serves to define areas where the conceptual model could be refined.

Calibration targets were as foflows:

1. Recharge from Jabal Hafit is equal to or greater than 10 percent of the total recharge of the area.
2. Recharge from Oman Mountains is estimated to be 30 percent at the northern gap and 60 percent at the southern gap.
3. Rate of discharge through the northwestem corner to discharge through southwestern corner is 2/3 : 1/3 ratio.
4. The range of difference between observed and simulated water levels is ±5 meters.

Ground-water levels for steady state predevelopment conditions were simulated for the 333 active cells of the model area. A comparison of simulated and mapped water levels is presented in figure 2. Simulated water levels averaged less than 5 meters above or below the observed levels, which are based on contours using 9 observation wells.

The model was run under transient conditions to simulate the water-level changes resulting from pumping. The transient simulation period was from 1982, when the first public wells began pumping, to 1995. The measured and model-simulated water levels at the end of 1995 are compared in figure 3. Figure 4 compares hydrographs of simulated and observed water levels in selected wells. Figure 5 compares the ground-water budgets under predevelopment conditions with no pumping and 1995 conditions with purnping.

FUTURE PREDICTION

The model was used to simulate water-level conditions 10 years beyond 1995, for the year 2005 (figure 6). Pumpage was assumed to remain at the 1995 rate. The simulation indicated continuing water-level declines to about 25 meters below 1995 levels at Mezyad and about 15 meters below 1995 levels at Umm Ghafa. One cell in the north east corner of the model was completely dry, which indicates the potential for dewatering of the aquifer system.

CONCLUSIONS

Continuous pumping from the surficial aquifer system in Umm Ghafa area between 1982 and 1995 has resulted in as much as 12 meters of decline in ground-water levels. A numerical model was developed for a 342-square-kilometer area to evaluate hydrologic conditions in the surficial aquifer system. Calibration of the model using plausible ranges of input variables confirms the conceptual interpretations of the aquifer system.

Based on the transient calibration, it is concluded that pumping in 1995 exceeded the sustainable yield of the aquifer system. The simulation for 1995 indicated that about 12,600 cubic meters were withdrawn in excess of salvaged subsurface outflow and induced subsurface inflow. The modeling exercise emphasized the need for collection of wadi flow and infiltration data. Until such data become available, the model simulations can be considered to represent worst-case scenarios wherein there is no recharge by infiltration from land surface.

The model was used as a predictive tool for the future, by projecting 1995 pumping rate of 17,900 cubic meters per day 10 years into the future. The simulation indicated that continuing to pump at the 1995 rate could accelerate water-level declines. Ground-water levels could decline as much as 25 meters below 1995 levels and complete dewatering of the aquifer could occur in some areas.

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Groundwater Resources/Salinity Modelling of the Tripoli Aquifer, Libya

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GROUNDWATER RESOURCE/SALINITY MODELLING OF THE TRIPOLI AQUIFER, LIBYA

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ABSTRACT

Over-abstraction of groundwater resources near coastal regions can lead to long term problems of salinity intrusions. This paper describes a modelling study of the coastal Gefara Plain aquifer near Tripoli, where extensive demands are placed on a shallow aquifer for agricultural and domestic purposes. Field data and the modelling study confirmed the effects of seawater intrusion. The model study investigates future water management strategies and demonstrates that the aquifer will take many years to recover to freshwater conditions.

INTRODUCTION

The Gefara Plain, located in the north western part of Libya, is an important agricultural and populated coastal area, with Tripoli as the principal city with 30% of Libya's 5.6 million population. Increased use of the Upper aquifer below the Gefara Plain for both municipal and agricultural purposes has led to severe depletion of the aquifer and the region has now been subject to several studies that seek to identify the most appropriate water resources strategies. A major consideration of these strategies is the Great Man Made River project (GMMR), a major development to bring groundwater from sources in the central regions of Libya to the more densely populated coastal regions in the north.

This paper describes the application of a new 2D Groundwater model to the Upper aquifer to the Tripoli aquifer, a 300km^2 area of the Gefara Plain and the upper aquifer. The study considers the long-term implications for aquifer recovery following the implementation of different water management strategies in the region. Water level and saline intrusion effects in the aquifer for different abstraction profiles are considered.

GEOHYDROGEOLOGY

The geology/hydrogeology for Northern Libya is complex. Two studies, (GEFLI, 1972 and Krummenacher, 1982), provide the most detailed accounts of the aquifer systems in the region. In summary several East-west faults run across the northern part of the country with the Nafusa fault and escarpment dominating the southernmost part of the Gefara Plain (figure 1). The topography of the region rises from sea level to the north to 200m above sea level, 50km to the south.

The principal aquifer used by the population in the Gefara Plain and Tripoli area is the Upper Aquifer, which occur under unconfined conditions, and consists of Quaternary mainly sandstones and riverine sediments underlain by Miocene sandstone with clay lenses located near the base. The thickness of the aquifer is variable, but is typically 150m thick, lying immediately below the surface.

Groundwater level is generally between 20-60m below ground surface, making it a readily available source for economical exploitation. The deterioration in groundwater quality in the immediate vicinity of the coast in recent years provides evidence that seawater intrusion is occurring along the northern coast.

WATER RESOURCES

The water balance of the Tripoli aquifer system, in terms of recharge and demand is critical in ensuring a sustainable use of any aquifer system. This is especially true of aquifers vulnerable to seawater intrusion such as the Upper Aquifer, the subject of this study.

RAINFALL

Average annual rainfall varies between 144mm to 595mm pa, but is typically 300-350mm per annum (pa). Much of this is lost to evaporation and evapotranspiration, with most studies (Pencol, 1978; Krummenacher, 1982) of the region estimating the recharge function to be between 5-15% of the rainfall, depending largely on soil moisture deficit for the prevailing year. For this study 37mm (10%) of rainfall has been considered as recharge (10.36Mm^3/yr). Recharge from river systems (or Wadis) is not considered to be significant in the Tripoli catchment, although in the wider Gefara Plain Upper aquifer, some recharge is known to take place.

GROUNDWATER ABSTRACTION

Water is used extensively in the Tripoli region for both domestic supply and agricultural irrigation. Most of this demand has been met until recently by the Upper aquifer, although some abstraction from lower aquifers is taking place. Demand has dramatically increased over the past 30 years and is expected to continue with population growth and agricultural development. The abstraction has been significantly reduced in the past year because of the GMMR project providing 91Mm3/yr with the possibility of increasing this to 116Mm3/yr. As this new supply is made available, less demand has been placed on the Upper aquifer. Table 1 illustrates the substantial increase in water demand.

Generally, about 45% of the water demand is for domestic supply, and given the current sewerage infrastructure for Tripoli, it is estimated that 25% of this water is returned to the aquifer via leakage and effluent seepage. The other 55% of demand is for irrigation, with 10% considered to be lost to the aquifer (FAO, 1979;Krummenacher, 1982). After 1996 the water demands from the aquifer has been considerably reduced because of the supplies from the GMMR project, yet recharge continue, because water demand has not been reduced.

THE MODEL SYSTEM

Several Models (Berney, 1980; Krummenacher,1982; and NCB and MM, 1994) have been developed in the past for the Gefara and Gefara aquifer systems. These have considered the overall water balance of the system in terms of demand recharge and subsequent behaviour of saline intrusion along the northern boundary of the models.

For the purposes of this study looking at the Tripoli aquifer, a new 2D horizontal finite difference model was developed. The model was developed generally so that the description of any 2D aquifer system including boundary conditions could be defined by the data input files alone. An indicator system was deployed to determine whether cells were confined/unconfined, constant head cells or no flow cells. A separate datafile describe the hyrogeologic features of the aquifer, abstraction locations and flows and recharge levels. A forward time (explicit), but spatially centred, finite difference scheme was used for both the flow and solute equations (Wen-sen and Willis, 1985; Zaho, and Valliappan, 1994). The model employs the Gauss-Seidal interative method for the flow equation, and upwind differencing for the advective components of the solute scheme. While dispersion is included, its effect was secondary to the predominant advection terms. A variable cell size feature that would give more detailed resolution in the region of the model closer to the coastal boundary is also included. The final grid designed for the aquifer simulation was 200m by 1000m cell size with 24 columns and 72 rows as shown in Figure 2. The timestep for the model was determined using normal stability criteria:

$$\Delta t \subseteq .5 * \frac{S}{T} * \left(\frac{\Delta x^2 * \Delta y^2}{\Delta x^2 + \Delta y^2} \right)$$

where, S is the storativity, and T is the transmissivity.

The model was rigorously tested for stability and accuracy for grids of varying sizes, ensuring the mass balance of flow and concentration remained conserved to less than 1% of the total mass of flow and solute.

Some concern might be expressed at the suitability of a depth averaged 2D grid for simulating saline intrusion, which is governed not only by aquifer hydraulic gradients, but also by the density gradients as described (Reilly and Goodman, 1985; Emliki et al, 1996). Indeed the approach here is a simplification of the 3D processes involved. The argument for the approach taken is that reliable data on salinity with depth is lacking because, first many of the boreholes with reported levels of salinity pumping from different levels within the aquifer, and, secondly the upper aquifer itself is a relatively shallow system 150 m compared with the modelled grid dimensions of 21km by 14km.

MODEL CALIBRATION

The northern boundary cells of the model maintained a constant head at sea level, while the eastern, western and southern boundaries were chosen as no-flow boundaries. This assumption was based on groundwater levels data assessed and analysed by (Pencol,1978).

The hydraulic conductivity was calibrated as 1.35m/day, which is within other estimates of hydraulic conductivity (Anderson and Woessner 1992) and was found by the researchers (Berney, 1980; Krummenacher,1982; ; NCB and MM, 1994) to give drawdown profiles in keeping with field data. The transmissivity T=KB where K = hydraulic conductivity and B is the depth of flow in the aquifer. For the study area, the depth of water flow in the aquifer, of typical thickness 150m, reduces to 20m or less and therefore any variation in water table level will have a significant effect on the value of Transmissivity. The model recalculates the value of transmissivity at every timestep. Storativity was taken as 0.1, based on previous studies and Porosity as 0.3.

Abstraction was modelled at the cells shown on Figure 2 at locations where much of the region's abstraction takes place.

PREDICTIVE SIMULATION

The purpose of the study is to examine the long-term implications for water quality in the aquifer for particular abstraction scenarios. Three modelled scenarios are made, with all assume population will continue to rise at 1% from 1996 onwards (NCB and MM, 1994). The three scenarios are:

Scenario 1 - Abstraction continues for both municipal and agricultural supplies at early 1990 levels, based on the principal supply of water coming from the Upper Aquifer but supported by some lower aquifer supplies.

Scenario 2 - Abstraction for municipal supplies has effectively ceased in 1996 as a result of the GMMR project meeting domestic demands by supplying 91Mm^3/yr. Under this condition, demand from the aquifer is assumed to drop by the equivalent amount while losses to the aquifer were maintained at 25% of the total water demand.

Scenario 3 - Extends the GMMR capacity yet further to 116Mm^3/yr. Reducing the demand on the aquifer further, while maintaining the replenishment levels.Each simulation starts in 1930 when demand on the aquifer was less than total recharge, giving the model the opportunity to establish groundwater level and flow conditions to more representative levels than the initial assumption of 5m below the ground as an initial start up condition.

GROUNDWATER LEVELS

Early years show a groundwater profile with flow in a northerly direction towards the coast. No sea water intrusion was reported in these early years. By 1960, the groundwater levels begin to slope in a southerly direction, giving rise to the start of model predictions of salinity in the northernmost cells. Drawdown in the region for the 1980s was widely reported as 4-5m per annum, broadly similar to the model predictions for the same period.

The comparison of groundwater levels at cell (36,12) in the middle of the model is shown on Figure 3. Here the relative effects of each of the three abstraction and demand scenarios is shown. Scenario 1 with continued high level abstraction continues to show a lowering of groundwater levels, and, in some places, predicted aquifer drying. In reality abstraction would tend to fall off as the cost of abstraction from deeper groundwater levels and poorer quality groundwater became unsuitable for use. What is clear is that, from a water balance view, the continued use of the aquifer at 1996 levels is unsustainable. On the other hand, Scenario 2 shows recovery of the aquifer water levels. While Scenario 3 shows even further improvements in groundwater level recovery.

Figures 4 and 5 further illustrate this recovery. By 1990 the groundwater levels have fallen to 60m below sea level. However, for Scenario 3 in the year 2050, the ground water level is almost leveled with that of the sea, indicating that at this time onwards the levels will reverse saline intrusion. In fact saline intrusion will require greater gradients towards the coast in order to reduce the freshwater displacement caused by the vertical distribution of the more dense saltwater.

SALINITY PROFILES

The salinity profiles predicted by the model over the 150 year period simulated by the model is shown on Figures 6 and 7 for Scenarios 2 and 3. Scenario 1 could not be shown because of extremely low water level predictions from 2000 onwards. For 1990 the model predicts concentrations of salinity greater than 5g/l at 300m from the coast. For Scenario 2, the region affected by concentrations greater than 5m extends 1km inshore by 2080, although the rate of progress has almost ceased by 2080. For Scenario 3 the saline intrusion is shown to recede, indicating the aquifer is beginning to recover by 2050.

CONCLUSIONS

The study has shown that aquifers in arid and semi-arid regions where recharge is small will take many years to recover, even if alternative supplies can be found as is the case for Tripoli. While groundwater levels may indeed return to some degree of normality after say 30 years or so, the problems of high salinity will persist for many years after, simply because the resources have been severely depleted and the recharge is insufficient.

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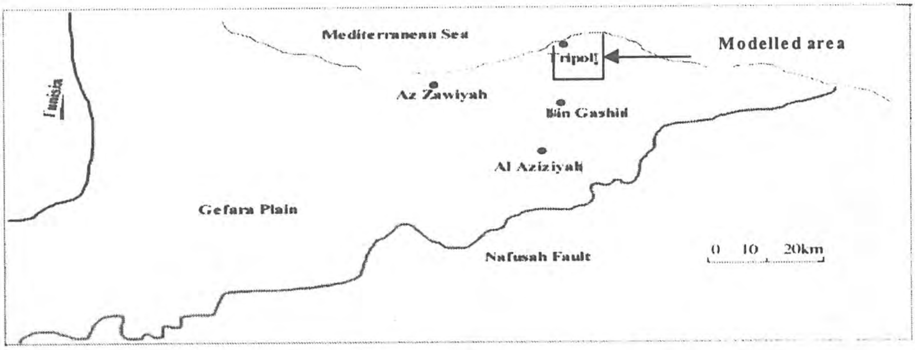

Figure 1: Northern Libya and Tripoli Area

Table 1 Water Balance for Tripoli Aquifer

Year	Total demand (Mm^3/yr) [1]	Total Abstracted from Upper aquifer (Mm^3/yr) [1]	Returned to aquifer (Mm^3/yr) [2]
1930	6	6	1
1960	25	15	4.3
1980	140	94	15.5
1990	150	94	17.75

1.Estimated from available data

2.Based on recharge of 10% of rainfall (i.e. 37mm per year).

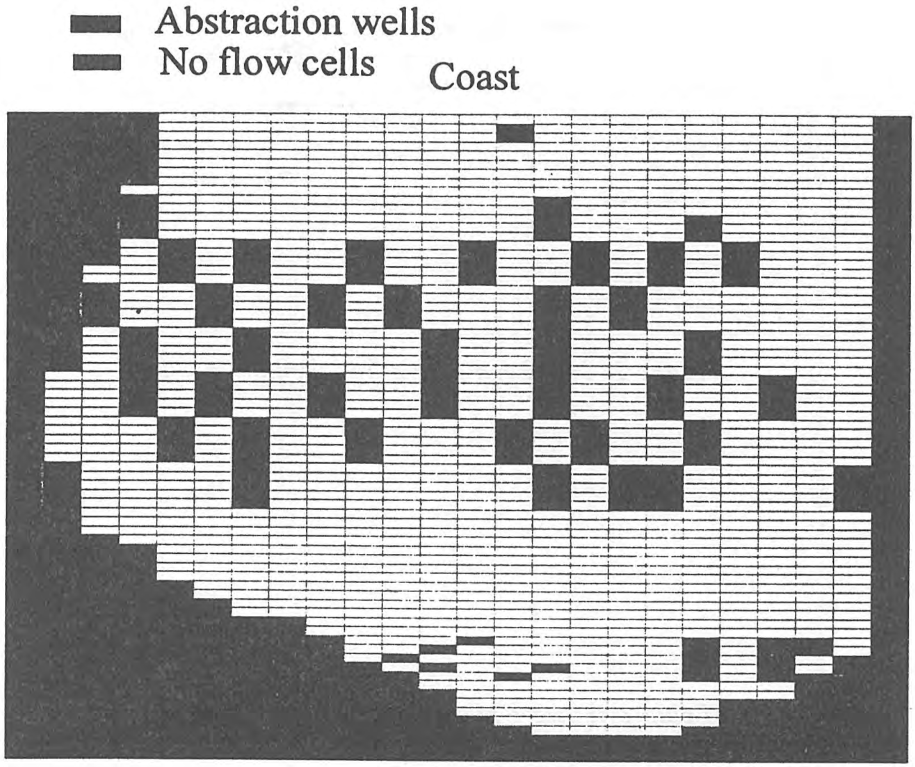

Figure 2: Model Grid

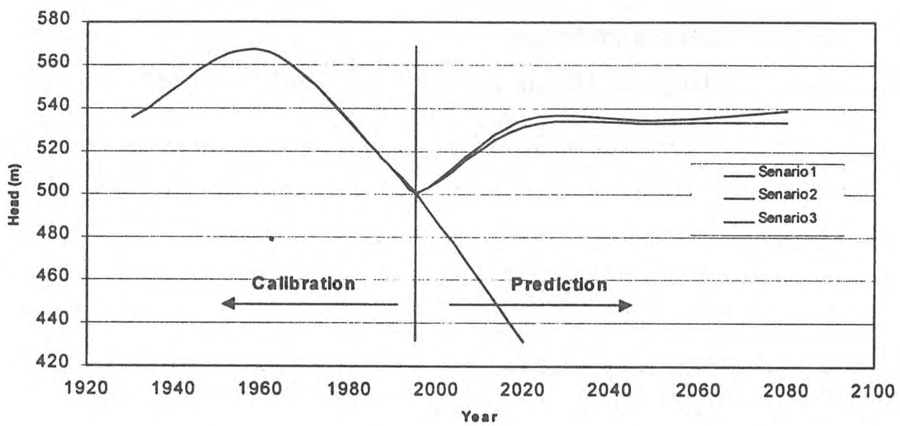

Figure 3: Groundwater levels predictions 7km from coast

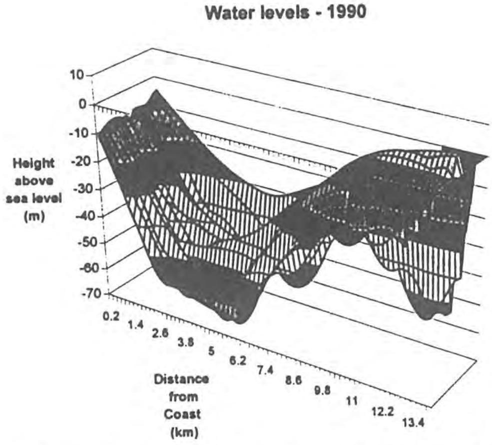

Figure 4 : Groundwater levels for 1990

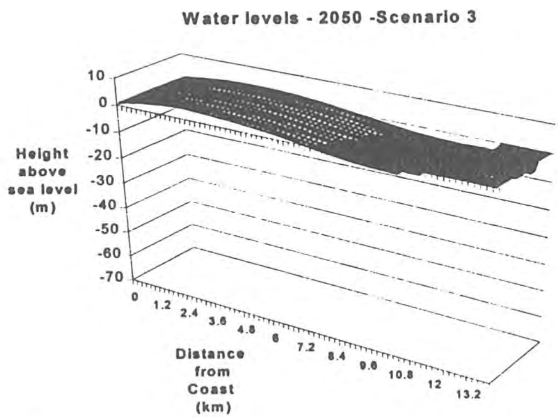

Figure 5 : Groundwater levels for 2050

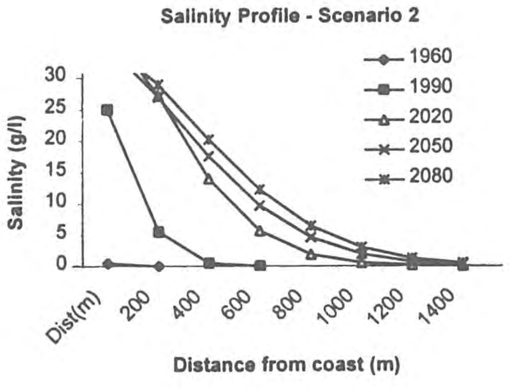

Figure 6 : Salinity profile development - Scenario 2

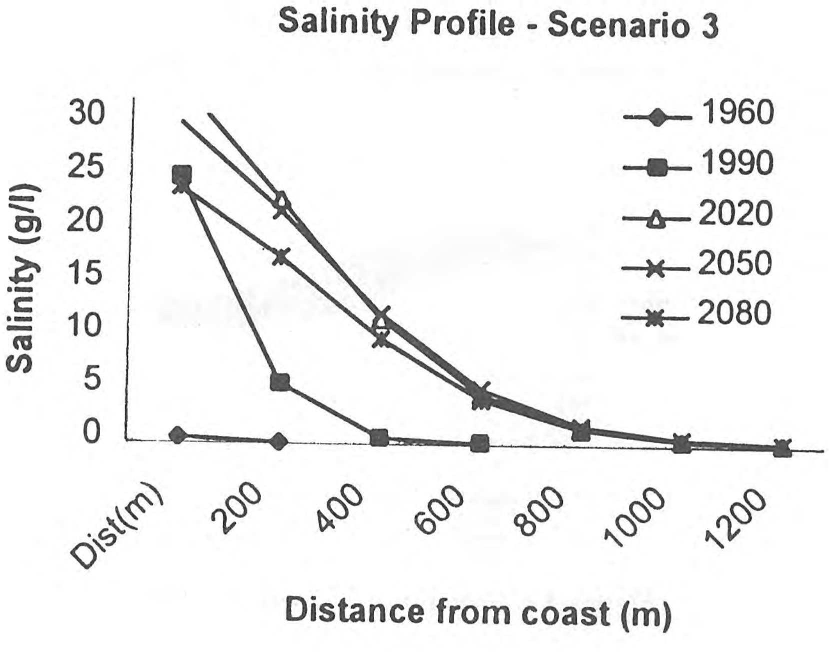

Figure 7 : Salinity profile development - Scenario 3

Assessment of the Side Effects of Groundwater Development in the West Nile Delta Region

Akram Fekry, Maha Abdel Salam and Ebel Smidt

ASSESSMENT OF THE SIDE EFFECTS OF GROUNDWATER DEVELOPMENT IN THE WEST NILE DELTA REGION

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ABSTRACT

In the west Nile Delta Region intensive land reclamation activities took place during the last 40 years. In parallel new cities were founded (viz. Sadat City and 6th of October City). Most of these development activities are based on groundwater, as the only available source. Starting from 1990, several groundwater development scenarios have been proposed and evaluated with relation to the expected drawdown and the change in groundwater quality. These two factors are considered to be crucial for a successful sustainable development. The drawdown will affect the economy of the extractions while deterioration of the groundwater quality may ultimately end the suitability of the resource. The accepted scenario is the 'restricted use' of groundwater scenario. The implementation of this scenario has been made possible by the combination of applied research leading to groundwater potentiality maps, the setting up of a licensing system, and regular monitoring of abstraction rates, groundwater levels and quality. The well inventory of 1995 shows that the total extraction for the area was within the limits of the 'restricted use' scenario. In some sub-areas the allowed extraction was exceeded, which has been compensated for in other sub-areas. Groundwater level drawdown was slightly less than predicted by the models. Locally observed groundwater deterioration is threatening the sustainability of the developments. These results of the monitoring efforts has accelerated the research into the possibility of artificially recharging the regional aquifer by treated sewage water and or Nile water originating from floods. The results of these studies will be of great benefit in updating and implementing the development scenario and fits into the general Egyptian policy of implementation of groundwater protection measures.

Keywords: Groundwater development, groundwater potentiality, well licensing system, salinization of aquifers, groundwater protection

GENERAL OUTLINE

The West Nile Delta Region is located north-west of Cairo between the Rosetta Branch in the east and 29° longitude in the west. Most of the region is occupied by barren desert and was uninhabited for centuries. Due to its fertile soils and strategic location between Egypt's main cities, Cairo and Alexandria, new reclamation activities had already started during the construction of the High Aswan Dam in the sixties. Population increased rapidly in the rural communities and more recently also in new cities like Sadat City and 6th of October City.

Nowadays, the Western Nile Delta Area is characterised by a rapid development in land reclamation both with surface water and groundwater projects (Figure 1). Extensive land reclamation using surface water from Nubariya canal system started in the sixties and covered 400,000 feddans in 1990. Reclamation of another 100,000 feddans is under execution or is planned. Reclamation projects depending on groundwater are mainly carried out by the private sector and located to the area to the south and east of Wadi El Natrun, mainly along the Cairo-Alexandria Desert Road. The present cultivated area based on groundwater reach about 70,000 feddan. The total groundwater extraction for the purpose of land reclamation increases continuously, from 460 million m^3/year in 1990 to about 760 million m^3/year in 1995. Groundwater extraction for domestic and industrial purposes is small in comparison to agricultural use. The main city in the area, Sadat City, uses about 15 million m^3/year.

HYDROGEOLOGY

The study area is covered by sedimentary rocks belonging to the Quaternary and Late Tertiary. The main aquifer systems are represented by the Nile Delta aquifer system and the Moghra aquifer system. Other local aquifer systems are found but are of local nature such as the Mediterranean Coastal aquifer and the Wadi El Natrun aquifer. In the following an overview about the hydrogeological characteristics of the area will be given:

- **The Nile Delta Aquifer System** covers the greater portion of the study area in the north and north-east sides. It consists of Pleistocene sand and gravel changing into fine and clayey facies in the north. The aquifer is generally underlain by Pliocene marine clay, except in the northern part where it is underlain by Pliocene and Pleistocene sandy limestone. The aquifer is semi-confined in the Delta and El Nubariya areas. In the rest of the area the aquifer is phreatic. The aquifer thickness reaches 300 m and decreases westwards and northwards.

- **The Moghra Aquifer System** represents the main aquifer system in the southern and the western portions of the study area and extends westward to the Qattara depression. It is composed of Lower Miocene sands and sandstone with some clay intercalations. The aquifer is underlain by Oligocene basalt or shales. The aquifer is confined by Pliocene and Pleistocene siliceous limestone at Wadi El Natrun and north-west of Wadi El Natrun respectively. In the rest of the area the Moghra aquifer is exposed at the surface, but show some confinement due to interbedded clay layers. The thickness of the aquifer varies from 150 m near Wadi El Farigh to 600 m west of Wadi El Natrun.

Due to the complex geological structure and the lateral change of facies these systems are in hydraulic connection and will therefore be considered as one aquifer system (Figure 2). The main groundwater flow and quality characteristics of the system are:

- The general groundwater flow pattern is from east to west. The piezometric level decreases from 14 +MSL near Rosetta Branch in the eastern side to about 10 -MSL near Wadi El Natrun to the west (Figure 3).

- The quantity of groundwater recharging the aquifer system from the Nile along the eastern boundary amounts to 84-100 million m^3/year. In addition about 100 million m^3/year is recharging the aquifer system in the north-west due to excessive irrigation in the past. The quantity of irrigation return flow in the area is unknown so far, but might add up to another 100 million m^3/year as input to the system. The discharge of the aquifer system is taking place artificially through the extraction from wells, which reaches about 785 million m^3/year in the recent years and also naturally through the evaporation and evapotranspiration amongst others in the Wadi Natrun depression (estimated as 73 million m^3/year).

The salinity of the groundwater in the study area varies from less than 300 ppm to more than 2,000 ppm. The groundwater in the eastern part (near Rosetta Branch) is characterised by low salinity, less than 500 ppm and the water type is $CaHCO_3$ - $MgCO_3$. Anomalies with high salinity water are found and can be due to the overpumping and /or to the poor drainage of agricultural land. The groundwater in the middle of the area is characterised also by low salinity, the water of Na HCO_3 type. The north-western part of the area (close to Wadi El Natrun) is characterised by groundwater of high salinity (more than 1000 ppm) and the water is of NaCl type.

GROUNDWATER RELATED CONSTRAINTS TO DEVELOPMENT IN THE WEST NILE DELTA REGION AND THEIR SOLUTIONS

Three groundwater related processes have already affected or may further affect the development process in the region:

Water logging and salinization

Water logging and salinization problems are restricted to the El Nubariya area in the north of the study area, where all agricultural activities are based on surface water from El Nubariya and El Nasr canals. In these areas the groundwater level has risen due to the downward seepage of excess irrigation water (as the basin irrigation system is predominant) and leakage from irrigation canals. Groundwater mounds of 20 m have been developed during the sixties and seventies. The heterogeneous hydrogeological characteristics of the existing aquifer in these areas are the main reason that some areas are more effected than others.

The implementation of drainage systems was the main solution for the problems of water logging and salinization. After 1974, drainage systems were installed in most of the water logged areas, while in the new reclamation projects more efficient irrigation systems (drip, central pivot irrigation) were introduced and lined irrigation canals were constructed. All these measures served in decreasing /stabilising the groundwater mounds in the northern part of the region (El Nubariya). But still the groundwater movement in radial flow towards the Mediterranean Sea (to the north) and towards the desert areas to the south (near Wadi El Natrun) (Attia et al. 1998).

Drawdown of groundwater levels

Drawdown of the groundwater level occurs mainly in the southern part of the region, near the Cairo-Alexandria desert road, where extensive groundwater exploitation has resulted a noticeable drawdown in the groundwater level. On the long term, this can lead to aquifer depletion, while in the short and medium term a large part of the existing wells will fall dry. The drilling of new wells with greater depths will effect the economic viability of the development projects.

The solution for this specific problem is based on proper groundwater planning and management including aspects of preventive and remedial (corrective) groundwater protection measures.

Deterioration of groundwater quality

Deterioration of groundwater quality is observed in many cases simultaneously to the noticeable drawdown. The groundwater deterioration is presented by increasing of the salinity as in some areas near El Khatatba and the desert road. The main processes which are causing this phenomenon are: upconing of deeper brackish to salt water, irrigation return flow, use of fertilisers and leaching of salts from clayey lenses. The absence of the top clay layer and the existence of sandy soil increase the infiltration rate of the low water quality.

The solutions for this phenomenon are identical as those mentioned for the drawdown phenomenon and are the subject of this paper.

GROUNDWATER MANAGEMENT

The first groundwater development plan for the West Nile Delta region (1990) was drafted with the help of a numerical groundwater flow model (TRIWACO package). The model has been calibrated according to the recorded hydrogeological situation of 1960 (pre-development situation, as non of the reclamation projects existed yet) and the subsequent changes in groundwater conditions (unsteady state) in the period 1960-1990.

The proposed groundwater management was based on the evaluation of several alternative scenarios for the period 1990 – 2000. These scenarios were:

1. no new groundwater developments allowed after 1990;
2. uncontrolled, full development of the groundwater resources;
3. controlled and restricted development; and
4. controlled development of groundwater resources with additional surface water imported in the area.

The responsible authorities of the Ministry of Public Works and Water Resources in close co-operation with the RIGW, have selected the third scenario as the base for the development plan.

The main constraint was considered to be the lowering of the groundwater level. According to this scenario groundwater extraction for agricultural use will reach 770 million m^3/year by the year 2000. The representative cultivated area would increase from 70,000 feddan to about 130,000 feddan. This plan was supposed to be revised and updated each 10 years which is represented in Figure 4, showing the planning cycle in the West Nile Delta Region.

The implementation of the plan was guaranteed by the establishment of a well licensing system and a regular monitoring programme for groundwater levels, quality and extraction rates.

During the first year of the implementation it was observed that the groundwater extraction exceeded already the allowed extractions for the year 2000, viz. in the areas East Wadi El Farigh and Khatatba (see Figure 5). This was a real warning to make new decisions to enforce the control of groundwater extraction. In the example of Wadi El Farigh no further developments in the east were allowed and were reallocated to the western part of Wadi El Farigh, which also showed a higher potential than previously estimated. The updated plan was presented in 1991.

RESULTS OF MONITORING AND COMPARISON WITH THE MODEL RESULTS

The lowering of groundwater levels during the period 1991-1995 is presented in Figure 6. From this figure it appears that groundwater levels in areas like Wadi el-Natrun, Dina Farm and the areas along the Cairo-Alexandria desert Road (south of the Dina farm) are declining at – still - moderate rates (less than 1 m/year).

In the continuous process of planning the calibrated model has been updated recently according to the last well inventory in 1995. At present, the total amount of extracted groundwater is about 800 million m^3 /year while it was

640 million m³/year in 1991. This means that there is an increase in the amount of extracted groundwater by 20% during 1991-1995. The model simulation has been executed with this gradual (annual) increase of extracted groundwater between 1991 and 2000, equally distributed over the concerned development areas. Figure (7.a, 7.b and 7.c) represent the simulated hydrographs for three representative locations in the distinctive development areas (Wadi El Natrun, Dina Farm and El-Khatatba Road respectively). The three hydrographs show a more or less linear decrease of the groundwater table with time period (1990-2040). This reconfirms the mining of groundwater, where the maximum drawdown in Wadi El Natrun will reach about 25 m, and will reach about 11 m in both Dina and El Khatatba road. Comparison between the observed groundwater levels and the calculated ones in the Khatatba area shows that the present drawdown corresponds well to the expected drawdown in the 'restricted development scenario'. The fact that the model calculates slightly higher drawdowns might be caused by underestimating the inflow from the northern groundwater mound. The collected data will serve the further optimisation of the model.

As mentioned above, the extensive groundwater extraction is in many cases accompanied by an increase in groundwater salinity. Comparing the measured groundwater salinity in some selected locations (1995) with the groundwater salinity map of 1990, it becomes clear that there is an increase in groundwater salinity in areas which suffering from groundwater level drawdown and in which groundwater is the only source (Figure 9).

A noticeable high increase in groundwater salinity is also found in the areas where both groundwater and surface water are used (conjunctive use), these areas are located to the east (near Rosetta Branch) and to the north and north-west of the region.

GROUNDWATER PROTECTION MEASURES IN THE WEST NILE DELTA REGION

Preventive Measures

Legislation and Enforcement

There are several existing laws which prohibited the direct and indirect pollution of groundwater, but these laws need reinforcement to be implemented.

The initialisation of the well licensing system can be considered as a preventive measure. The implementation of this system started in 1990, and is mainly base on the potentiality maps. These maps are based on integration of several factors like: productivity and saturated thickness of the aquifer, rate of recharge and the depth to water table. The groundwater potentiality also takes into consideration the groundwater quality characteristics. Figure 10 shows the effect of the implementation of well licensing system on the control of groundwater extraction.

Public Awareness

Public awareness is an effective tool to protect groundwater, as human activities form the main threat of polluting groundwater. The pollutant can originate from agricultural, industrial and domestic activities. Disseminating of educational and oriental measures about the role of the people in the protection of groundwater has been started during the recent years in Egypt. The participation of the stakeholder and users in the early stage of the planning is also extremely important. Many development planners have discovered through learning experiences that without stakeholder participation effective realisation of development goals can not be achieved. A direct and quick step towards technical engineering solutions while neglecting the crucial role of users and beneficiaries, will result a very negative consequences.

Remedial Measures

Artificial Recharge is one of the most important tools in augmentation of the depleted aquifers within the Nile Delta region. A pilot experiment has been executed by RIWG in two areas, El Bustan Extension and Burg El Arab area. The selection of the specific sites within these areas is based on intensive hydrogeological investigation. The results of the experiments are promising with respect to its technical feasibility (Attia et al., 1998).

A pilot experiment of using of the treated sewage water in artificial recharge is under implementation. Preliminary selection indicated feasible areas along the Cairo-Alexandria desert and the southern part of the West Nile Delta region, where the existing Oligo-Miocene aquifer contains low groundwater quality.

CONCLUSIONS AND RECOMMENDATIONS

Groundwater modelling proved to be a powerful tool in the set up of an effective groundwater management plan. The implementation of the management plan has been made possible by the introduction of a well licensing system and regular monitoring programmes. The outcome of the monitoring programmes again serve in the optimisation of the groundwater models. It is recommended to include the groundwater quality aspects in future modelling efforts.

Control measures should be further implemented to protect the water resources in the area. Such measures essentially include rationalisation of water use, minimising losses, quality protection, and improving the potentiality of aquifer systems through artificial recharge of treated sewage water, as a non-traditional water resource.

Water users play a dual role in water resources planning: they are not only the ultimate beneficiaries, but also managers at a local scale. User involvement is desirable from the early stage of preparation of groundwater management plans.

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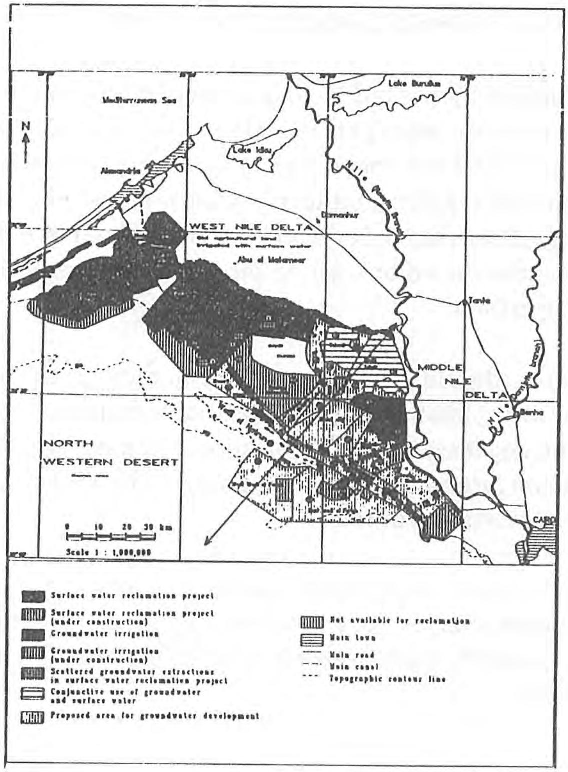

Figure 1. Land Use Map of The West Nile Delta Region

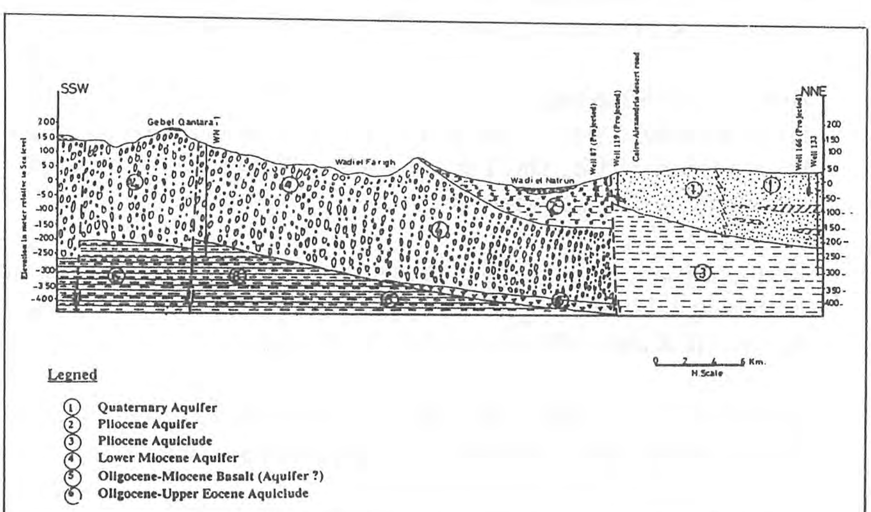

Figure 2. Hydrogeological Cross Section Through The Study Area

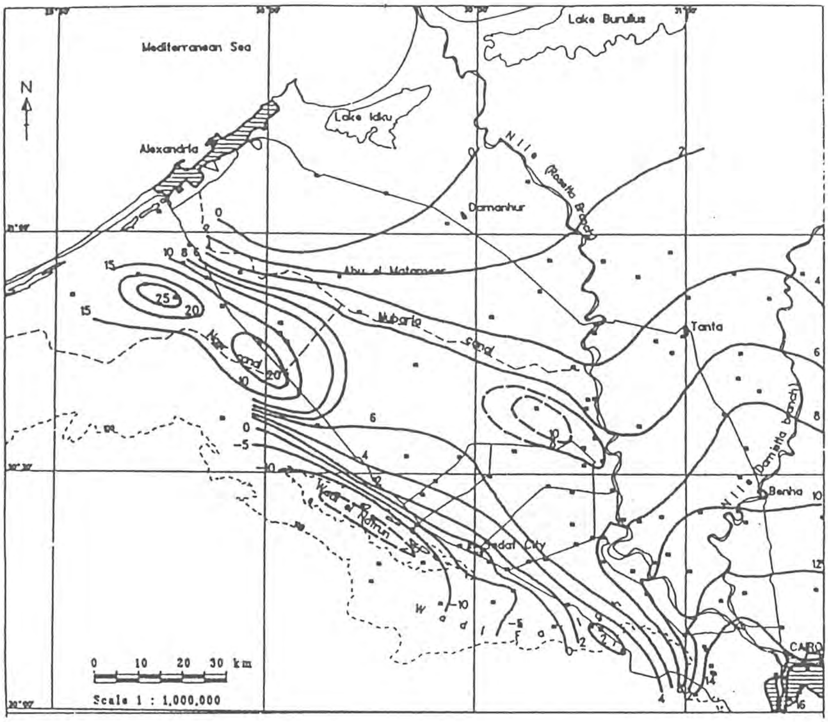

Figure 3. Piezometric Contour Map of The Nile Delta Region

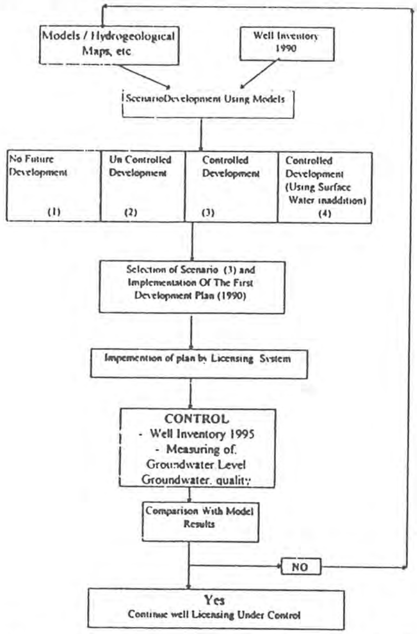

Figure 4. Planning Cycle in The West Nile Delta Region

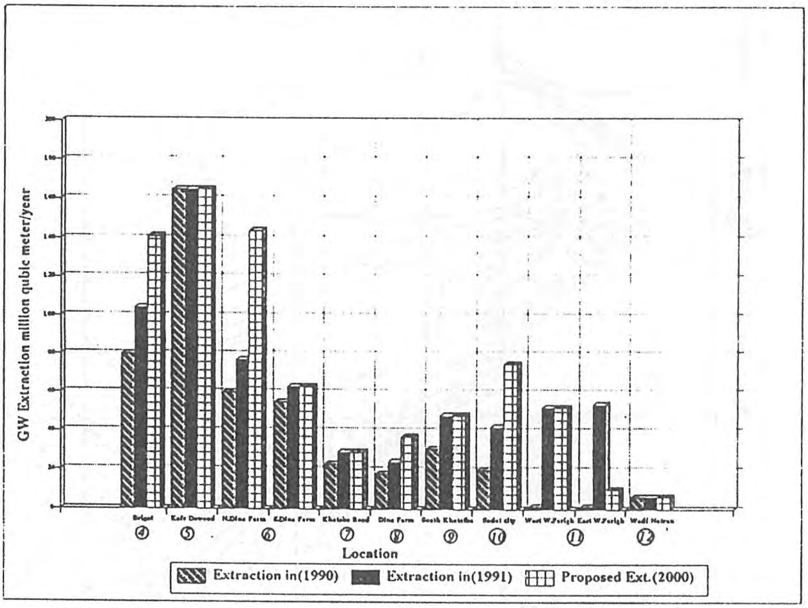

Figure 5. Groundwater Extraction in 1991 Compared with the groundwater development Plan (1990-2000)

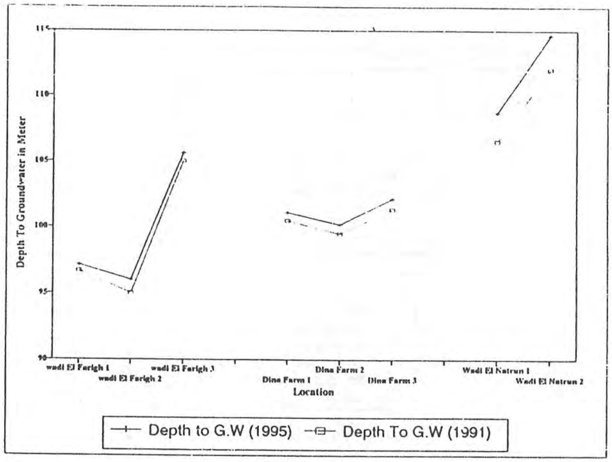

Figure 6. Change in the Depth to Groundwater in Some Selected Areas

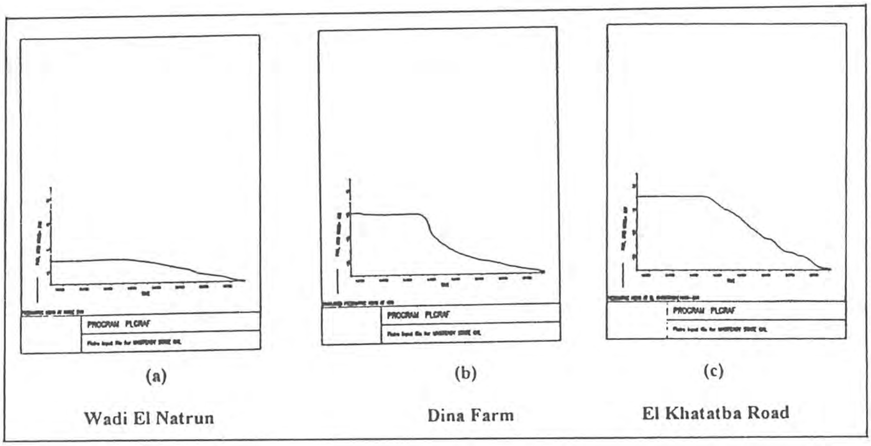

Figure 7. Predicted Change in Groundwater Level in Some Selected Areas (1990 - 2040)

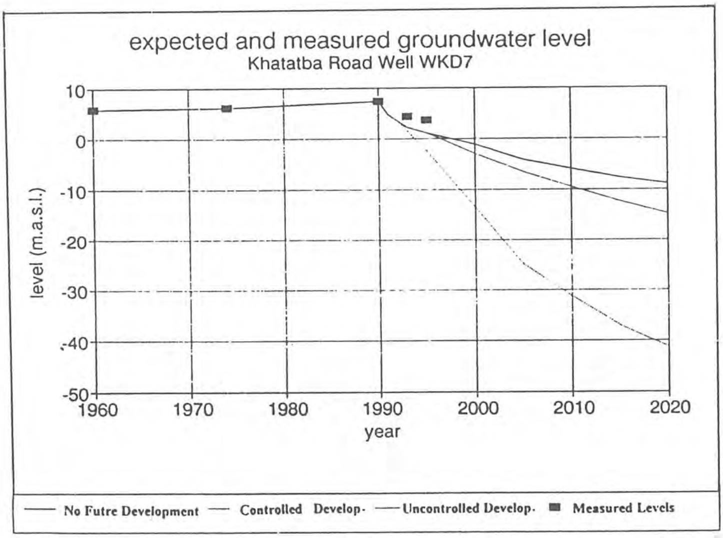

Figure 8. Comparison between observed and predicted groundwater levels (Khatatba)

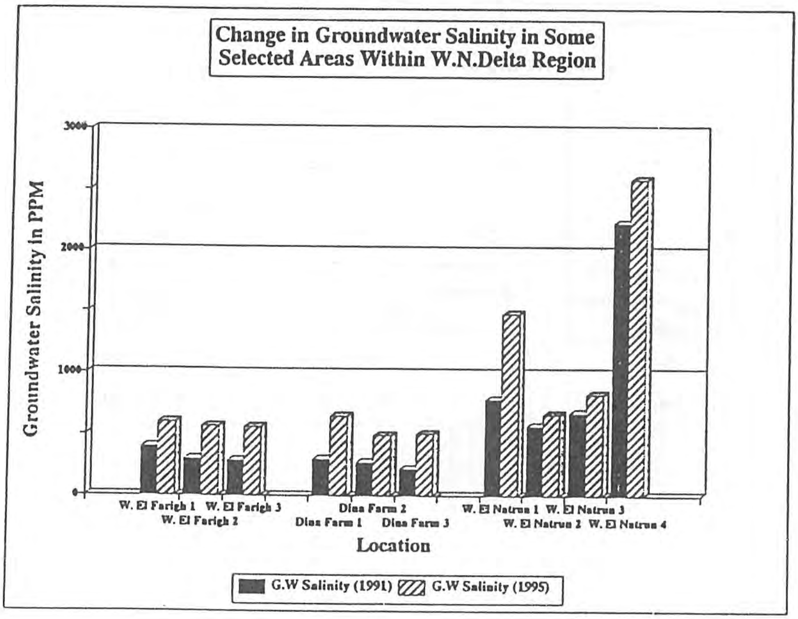

Figure 9. Increase in Groundwater Salinity in Some Selected Areas

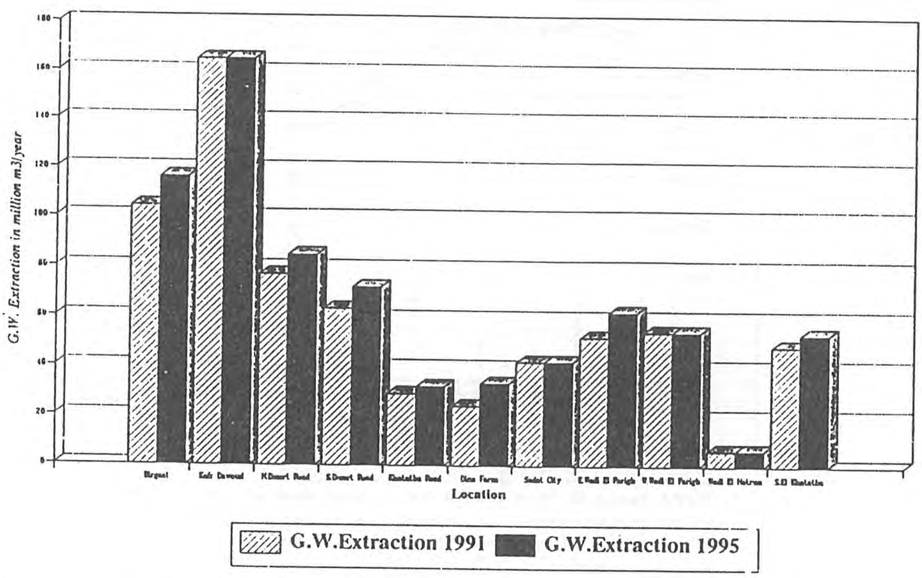

Figure 10. Groundwater Extraction Increase Between 1991 - 1995

Application of a Geographic Information System to the Hydrology of Abu Dhabi Emirate

Juanito M. Tamayo and Khalid Al Junabi

APPLICATION OF A GEOGRAPHIC INFORMATION SYSTEM TO THE HYDROLOGY OF ABU DHABI EMIRATE

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ABSTRACT

Geographic Information System (GIS) technology is an important aspect of modern-day hydrologic studies in Abu Dhabi Emirate by the National Drilling Company Ground-Water Research Program. It is used for scientific investigations, resource evaluation, and planning. Accurate maps are essential for locating existing wells; selecting future drilling sites; and relating and displaying geographic, geologic, chemical, and hydrologic data. Features such as agricultural areas, surficial geologic contacts, roads, and coastlines were digitized from satellite-image maps and entered into a computer based GIS. Other data entered into the GIS include well locations and associated information such as ground-water levels and quality.

The GIS software includes ARC/INFO and ERDAS-Imagine. ARC/INFO consists of two modules-Arctools and Arcpress. Arctools is used to process maps at various scales. Arcpress is used to make high-quality prints of the processed maps. ERDAS-Imagine is used to process, manipulate, enhance, and georeference the satellite images.

A GIS can be used to combine different maps to convey information more effectively. For example, images from different times can be overlain to delineate land-use changes. The major advantage of a GIS is that it allows the user to understand the spatial relationships between map features. It also stores data from which the user can create the desired view.

A GIS has been used by the Ground-Water Research Program for database management, spatial analysis, and cartographic presentation. Studies have been conducted on the coastal sabkhas, agricultural contamination, delineation of fresh water areas, and geologic mapping. Its main benefits are the visual portrayal of satellite images and graphic overlays. Its main drawbacks are the simplistic text editor and file limitations.

* Former employee

Keywords: Abu Dhabi Emirate, Geographic Information System, hydrology.

INTRODUCTION

Since 1988, the National Drilling Company of Abu Dhabi has conducted a Ground-Water Research Program (GWRP) to assess the Emirate's ground-water resources. The investigation utilized a wide range of technologies and realized the advantages and benefits of using a Geographic Information System (GIS) for interpretation and presentation of map data. GIS is defined as an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, analyze, and display all forms of geographically referenced information." In a GIS, the primary requisite for mapping is that the locations of data points are known. Location is usually as Universal Transverse Mercator coordinates or as degrees of latitude and longitude. Coordinates are used to represent points, lines (arcs), and polygons. At these spatial coordinates, values can be assigned for desired parameters such as elevation, chemical concentration, or hydrologic property. Any variable that can be located spatially can be fed into a GIS. Data must be in a format that the computer can recognize. The data can be captured into the computer by digitizing or by scanning.

The GIS software used by the GWRP includes ARC/INFO and ERDAS-Imagine. ARC/INFO contains two critical modules–Arctools and Arcpress. Maps were generated using the Arctools module. Arcpress was used to create a "printer-level language" for rapidly making high-quality prints, especially when using images as layers. ERDAS-Imagine is used to georeference the raw data from Landsat satellite images. The images for a desired area of interest were enhanced and sometimes manipulated by changing color-band combinations to highlight certain objects such as sabkha and agricultural areas. These images were converted to a format called "tiff", which is compatible with Arctools. Arctools is used to build a "view" and a "layout." The view consists of thematic coverages, or data layers, such as roads, wells, and farms which may be combined with the satellite image. The layout consists of up to 63 objects including one or more views, text items, scale, or other map feature. The layout can be converted to a graphics file, which Arcpress reads for printing.

Hardware[1] used in the GWRP consists of a Sun Enterprise 3000 file server, Sun Sparc workstations, Tektronix graphics terminal, Altek Datatab AC40

[1]Any use of trade, product or firm names is for descriptive purposes only and does not imply endorsement by the National Drilling Company.

digitizing table, and a Hewlett Packard UP750C color plotter. GIS is run under a Unix operating system.

The GWRP acquired digital files of Landsat Thematic Mapper images for September 1987 and April 1996. Each file contains 9 scenes, each approximately 180-kilometers square and with a pixel resolution of 30 meters by 30 meters. The images were provided in seven spectral bands including blue, green, red, near-infrared, short-wave infrared I, short-wave infrared II, and thermal-infrared. The images are available commercially at a cost of about $4,400 per scene.

In addition to the digital images, resolution-enhanced satellite-image maps were prepared by the U.S. Geological Survey Earth Resources Observation Systems (EROS) Data Center in the United States. Enhancements included adjustments to spectral bands 2, 4, and 7 of the 1987 Landsat images and merging with 1986 SPOT data–high-resolution panchromatic images from the French "System Probatoire d'Observation de la Terre". The resulting maps at scales of 1:20,000 and 1:50,000 were used to digitize road networks, agricultural areas, physiography, and geologic features.

GIS APPLICATIONS

One of the first GIS applications was to combine 9 scenes for 1987 to provide a seamless satellite-image mosaic for the entire area of the United Arab Emirates at a scale of 1:250,000 (U.S. Geological Survey, 1991). The resulting map was used to discern physiographic divisions within the UAE. Also, roads, agricultural areas, and offshore shoals were plainly visible. Hundreds more GIS applications have been made over the 11-year span of the Ground-Water Research Program. Methods used in a few cases will be discussed briefly to summarize the capabilities of GIS and its applicability to hydrologic problems. Locations of four selected study areas are shown in figure 1.

Study of Agricultural Contamination

The eastern part of Abu Dhabi Emirate is underlain by fresh ground water. Many farms tap the surficial aquifer system for irrigation supplies. Also, because the desert soil has a deficiency of nutrients, much fertilizer is applied to grow luxuriant crops such as fodder, tomatoes, cabbage, and corn. Results of high fertilization and flooding to flush salt buildup in the soil has led to contamination of the surficial aquifer system. Background levels of nitrate are generally less than 1 milligram per liter and the World Health Organization

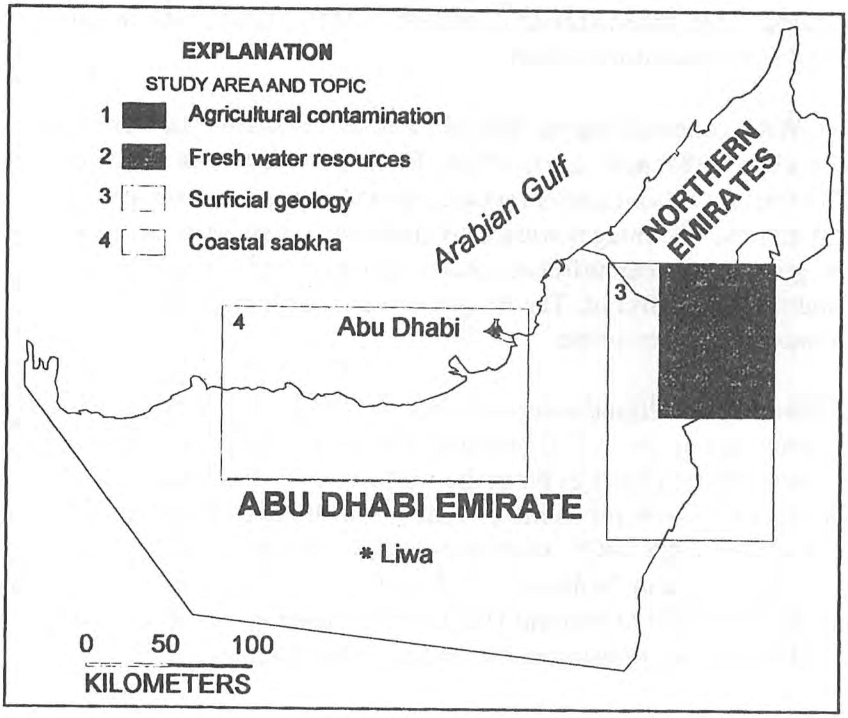


Figure 1. GIS applications described in this report.

standard for potable water is 10 milligrams per liter. Levels measured in the farm areas have been as high as 120 milligrams per liter.

Satellite images and a GIS were used successfully to define a study area where nitrate contamination is likely to occur. Images for 1987 were used to delineate "old" farms and images for 1996 were used to confirm their continued existence. The "bird's-eye view" offered by the satellite images allowed definition of areas where agriculture was concentrated over a long time period, and thus, where to focus sampling efforts.

Results of the investigation are illustrated in figure 2. ERDAS-Imagine was used to examine satellite images and compile images of the selected agricultural area for 1987 and 1996. The images were converted to tiff files, which were imported to Arctools for annotation and plotting. Arctools was also used to create the block diagram that illustrates nitrate contamination of the ground-water system.

Study of Fresh Water Area near Al Ain

Approximately 200 wells in northeastern Abu Dhabi Emirate, near the City of Al Ain, were sampled between 1990 and 1996 for analysis of ground-water quality. A base map was partitioned from the 1996 satellite image using ERDAS-Image and the wells were plotted with accompanying total dissolved-solids concentrations. The boundary between fresh and brackish water was defined and digitized. A thematic coverage of polygons was generated and superimposed on the satellite image (fig. 3). Recharge areas, mainly within the banks of intermittently flowing wadis, were also superimposed on this map to define areas where the surficial aquifer is vulnerable to contamination from surface spills. Arctools was used to produce maps at various scales. The maps are being used by the Al Ain Town Planning Department to evaluate potential environmental impacts on the ground-water prior to permitting certain types of land use.

Study of Surficial Geology

The main fresh-water-bearing geological strata near Al Ain include carbonate rocks of Eocene to Miocene age and unconsolidated fluvial alluvium and eolian deposits of Quaternary age. These deposits generally occur within about 100 meters of land surface. The surficial geology and structural geology of the Emirate define the areal extent of the aquifer systems and patterns of ground-water flow. The mineral composition of bedrock and unconsolidated surficial deposits largely determines the chemical quality of the ground water and the hydraulic properties of the aquifer. Knowledge of geological relations is essential for locating well fields for development of ground-water supplies.

Figure 4 shows a map of the surficial geology that was prepared using a GIS (Hadley, 1995). The map is based on compilation of existing data and interpretation of satellite images, aerial photographs, and field surveys. The 1:20,000-scale satellite-image maps were examined to define and digitize geologic features, thereby creating a thematic coverage (polygons) of different geologic units. Symbols were assigned to each unit and added to an attribute table of GIS items. Field surveys were conducted to verify geologic contacts that seemed uncertain during the digitizing process. Mapping of bedrock was difficult because of the limited exposure of geologic units in the generally low-relief sand-covered terrain. Drilling logs were used to confirm the geology.

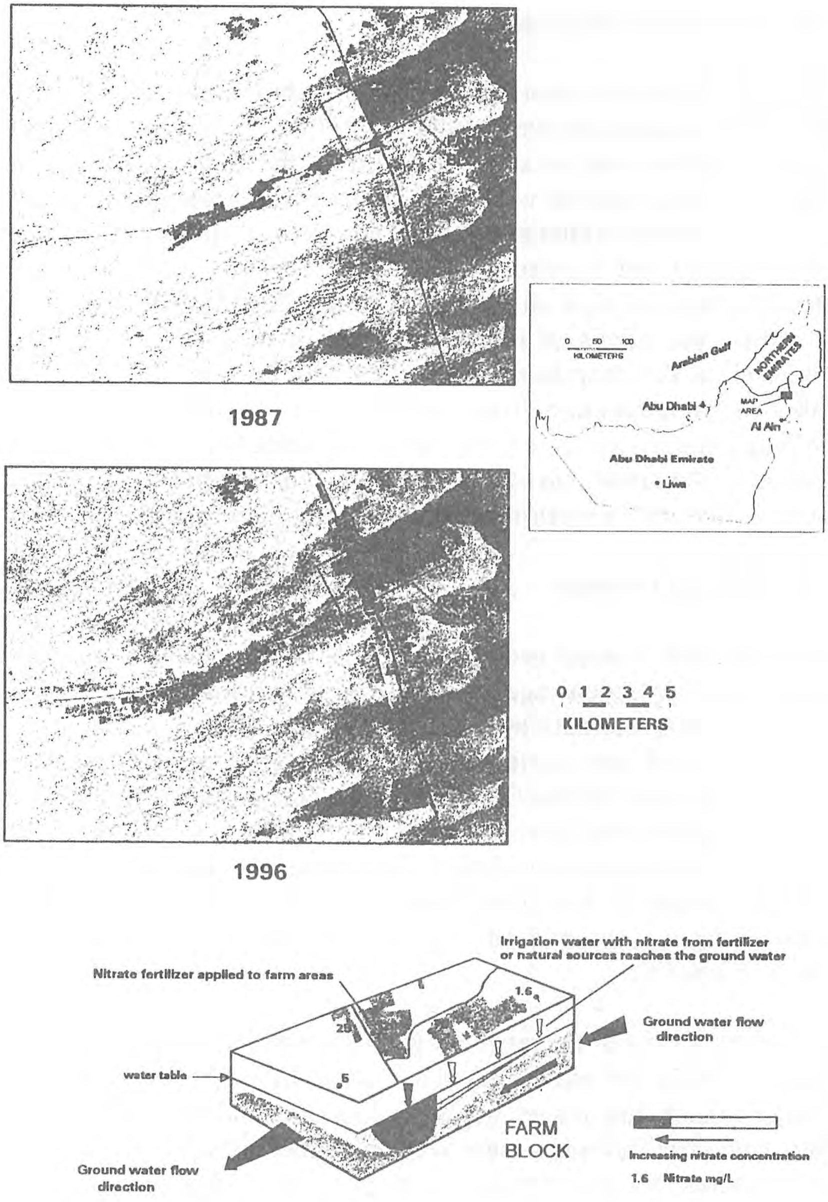


Figure 2. Satellite images and diagram prepared with a GIS to display agricultural change and nitrate contamination of ground water.

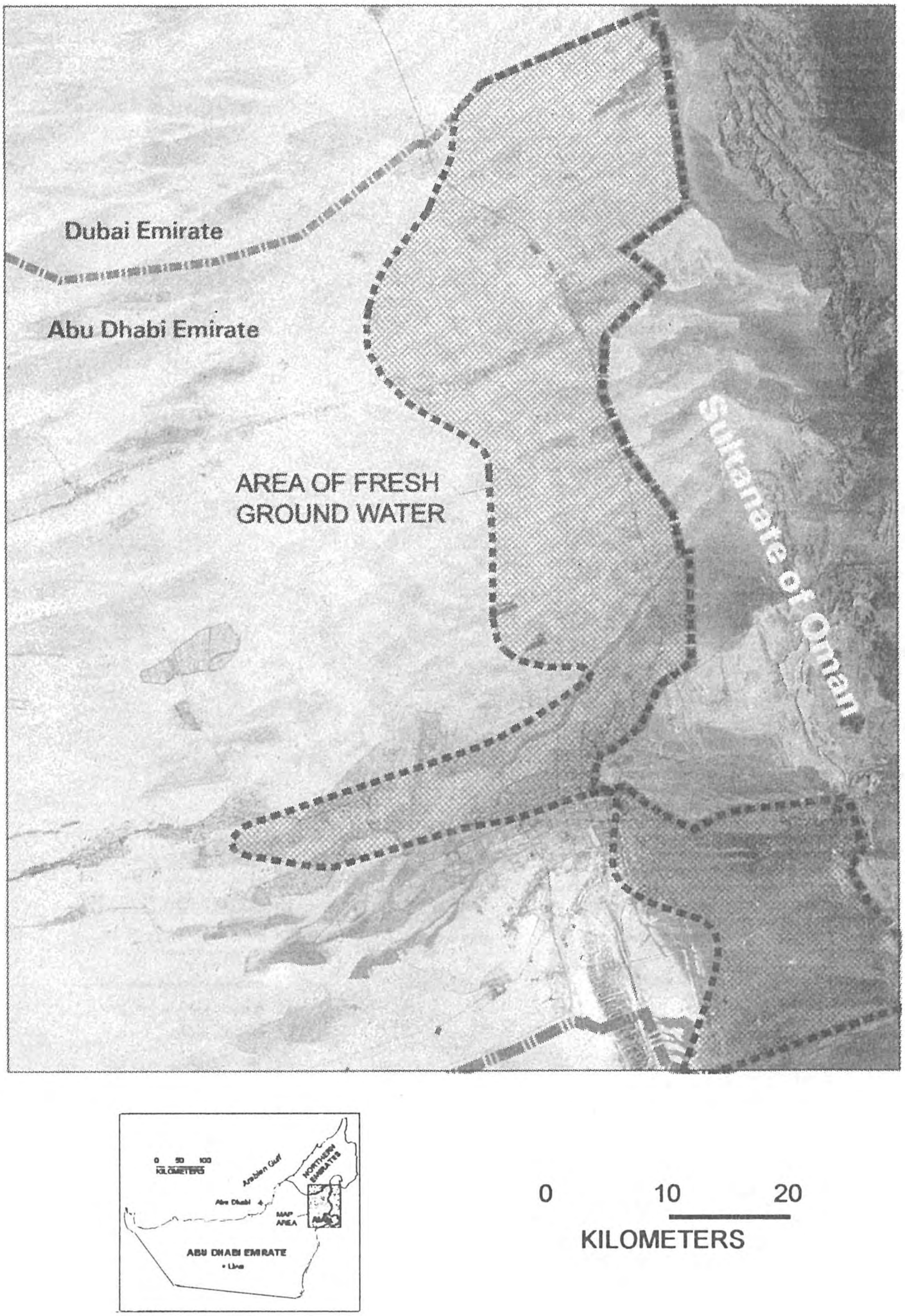


Figure 3 GIS map depicting areas underlain by fresh ground water in northeastern Abu Dhabi Emirate

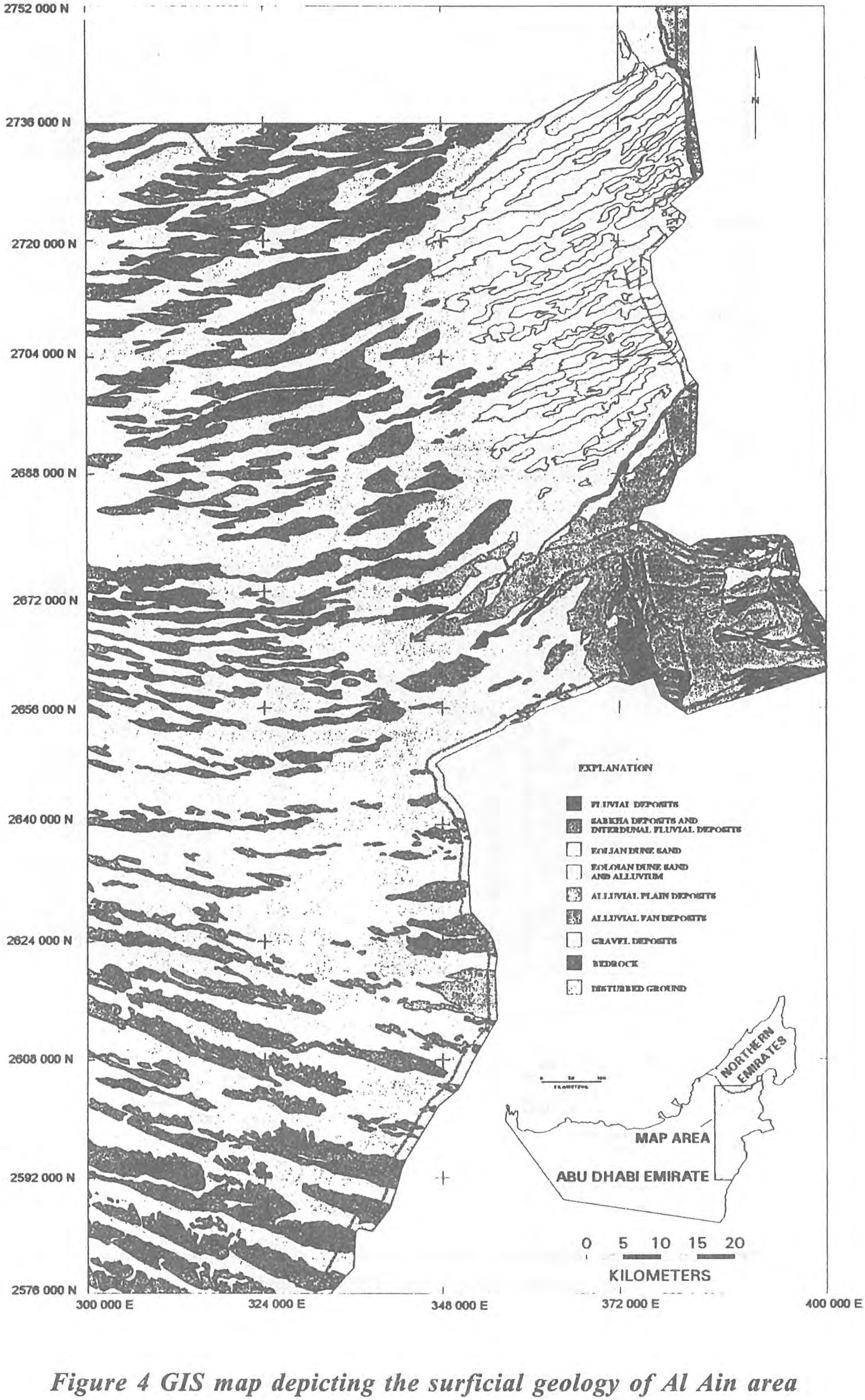


Figure 4 GIS map depicting the surficial geology of Al Ain area

Study of Coastal Sabkhas

In 1998, an investigation was undertaken to evaluate geochemical processes in the world renowned coastal sabkhas of Abu Dhabi Emirate. The sabkha is restricted to the coastal plain just above high-tide level. In Abu Dhabi Emirate, the sabkha is about 350 kilometers long and is between 10 and 50 kilometers in width. One aspect of the research has been the estimation of lateral ground-water flow toward the coast and discharge by upward seepage. The relation between sabkha deposition and tidal flooding has been described in classical studies, however, the contribution from ground water has been largely ignored (Wood and Imes, 1995).

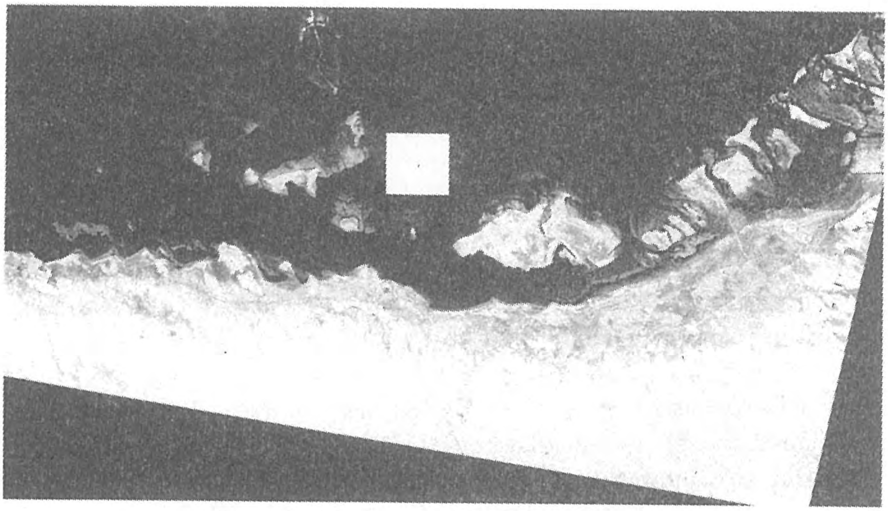
The coastal sabkhas consist of thinly-bedded layers of sand, silt, and evaporite that occur in supratidal mudflats. Incoming water is largely seawater, but upwelling of deep ground water may contribute to the inflow. Brine with 4 to 6 times the dissolved-solids concentration of seawater is nearly always round at depths between 1 and 2 meters below the sabkha surface. Evaporation of capillary water during dry periods concentrates and precipitates various salts to form a hard crust or cementing agent in near-surface sand and silt layers. Standing water from rainfall and tidal invasion provides some recharge and evaporation concentrates the salt. The ratios of certain trace elements cannot be explained by simple evaporation models and this has led to the study of upwelling ground water. The sabkha surface generally is light tan to white in color, largely due to the presence of gypsum and other evaporite minerals.

Satellite-image maps composed with the ERDAS-Imagine software were interpreted to delineate the areal extent of the coastal sabkhas. The images were enhanced and stretched to portray better color and resolution. The three color bands visible to the naked eye were manipulated by changing the combinations to highlight the sabkha features. The satellite image with an original true color combination of 7-4-2 (green-blue-red) was changed to 2-7-4 (red-green-blue) to enhance the sabkha features. After changing the band combinations, the images were converted into another format compatible with ARC/INFO. Maps were produced at various scales using the Arctools module (fig. 5).

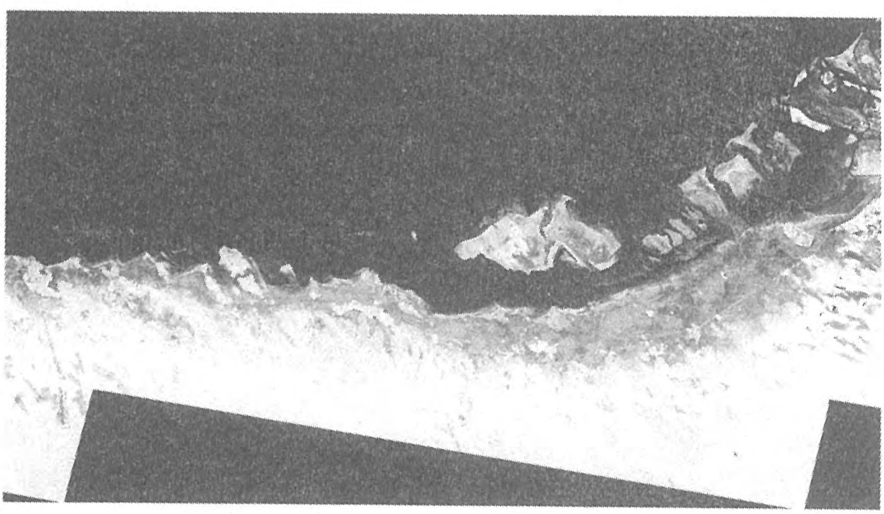
BENEFITS AND DRAWBACKS OF A GIS

A GIS is increasingly being used to produce graphics to convey the results of studies by the GWRP. The main benefit of a GIS is its ability to portray satellite images that can be used to visualize and thereby understand the results of scientific studies. A GIS can be, used to overlay satellite images with point coverages such as wells, line coverages such as roads, and polygon coverages such as geological features or areas of fresh water. Once the data has been delineated, maps can be produced at convenient scales. A GIS stores data from which a user can create some desired view drawn to suit a particular purpose. A GIS serves several functions including database management, spatial analysis, and cartographic presentation.

A GIS is not without drawbacks. The text generator in Arctools is unwieldy. For example, the positioning of on-screen text does not always print in the same position on paper. For this reason, we have round that it is simpler to create ascii text files with a word-processing program and import them into Arctools for placement and layout. Another drawback is that only 63 objects can be defined in a layout. This deficiency is particularly evident, for example, if 64 views, text items, or other objects need to be displayed in a layout. In this case, an extra view would have to be created to portray the information. File management and editing can be problematic when a map (such as shown in fig. 4) contains as many as 300 objects.



a. Green-blue-red color-band combination.



b. Red-green-blue color-band combination.

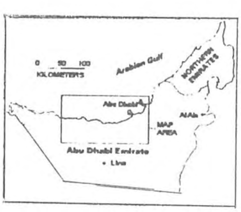


Figure 5 Satellites images of the Abu Dhabi coastal Sabkha prepared with a GIS using different color-band combinations

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Visualizations of Abu-Jarjor Wellfield Boreholes Data Using GIS

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VISUALIZATION OF ABU-JARJOR WELLFIELD BOREHOLES DATA USING GIS

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ABSTRACT

Geographical Information System (GIS) has been widely used to visualize and analyze spatial information of geologic, hydrologic, and hydrogeologic data. This study illustrates building a GIS system for 15 groundwater production boreholes, constituting a wellfield feeding the Abu-Jarjur Reverse Osmosis Desalination Plant in Bahrain. A 13-year attribute data of major-cations, major-anions, and TDS of these boreholes has been integrated along with spatial data of the wellfield area. The end product is a user-friendly and simple, and can be used by both technicians and decision-makers easily. The customization of its graphical user interface (GUI) is clear and uncluttered, and the users have the capability to navigate through the system without any difficulty. The constructed GIS system can be used to analyze, explore, and visualize changes in the chemical constituents, which makes it an efficient tool for monitoring and predicting the trends of the quality of the groundwater fed into the desalination plant.

KEYWORDS: Geographical Information Systems (GIS), Visualization, Graphical User Interface (GUI)

INTRODUCTION

In Bahrain, brackish groundwater occurring as a large lens in the Rus and Umm Er Radhuma (UER) formations is utilized for desalination (Figure 1). Since 1984, this brackish water has been abstracted at about 25 million cubic meters per year (Mm^3/y) by a wellfield, located at Abu-Jarjur area at the East Coast of Bahrain. The pumped water is fed to a reverse osmosis (RO) desalination plant with a maximum output capacity of about 17 Mm^3/y.

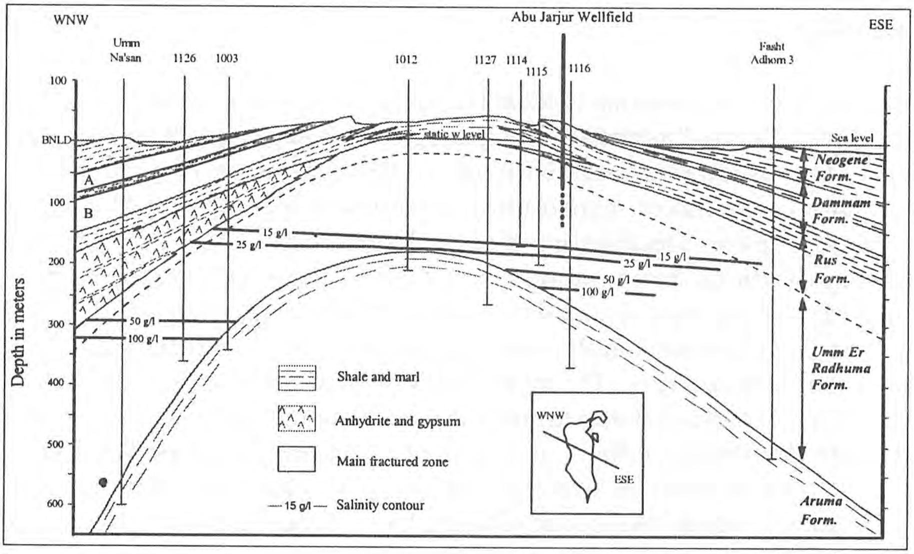

Figure 1: Hydrogeological cross section showing the C aquifer geometry (modified after GDC)

The utilization of the aquifer in feeding the desalination plant will continue as long as the produced water salinity does not increase to concentrations comparable to seawater, which will be caused by the upward migration of the underlying brine zone (>100 g/L) as a result of water levels drop and coning under the wellfield. There are a number of proposed management schemes, such as augmenting the aquifer storage by artificial recharge and modification of the present wellfield design, to maximize and prolong the aquifer future availability in feeding the desalination plant. Therefore, monitoring and prediction of the quality of the produced groundwater is an important task in the utilization process and also during the implementation of the proposed management schemes to evaluate their effectiveness.

Due to the extensive quantity of borehole data, there is a need to input, manipulate, display and develop integrated solution through an automated electronic medium. GIS provides a combination of spatial database management and cartographic modeling capabilities (Star and Estes, 1990), which are ideally suited for groundwater resources information management and monitoring. In essence, GIS can be viewed as an enhanced information system that aids decision-making by referencing data to spatial or geographic coordinates. If designed correctly, a GIS system can be used to monitor, analyze, and understand the problems affecting groundwater quantity and quality, and evaluate the impact of man activities on aquifers.

In this study, a GIS system is constructed to monitor and help in detecting trends in the chemical constituents of the produced groundwater by the 15 production boreholes of the Abu-Jarjur wellfield (Figure 2). The constructed system can be used to display, explore, and analyze boreholdes data using visualization techniques.

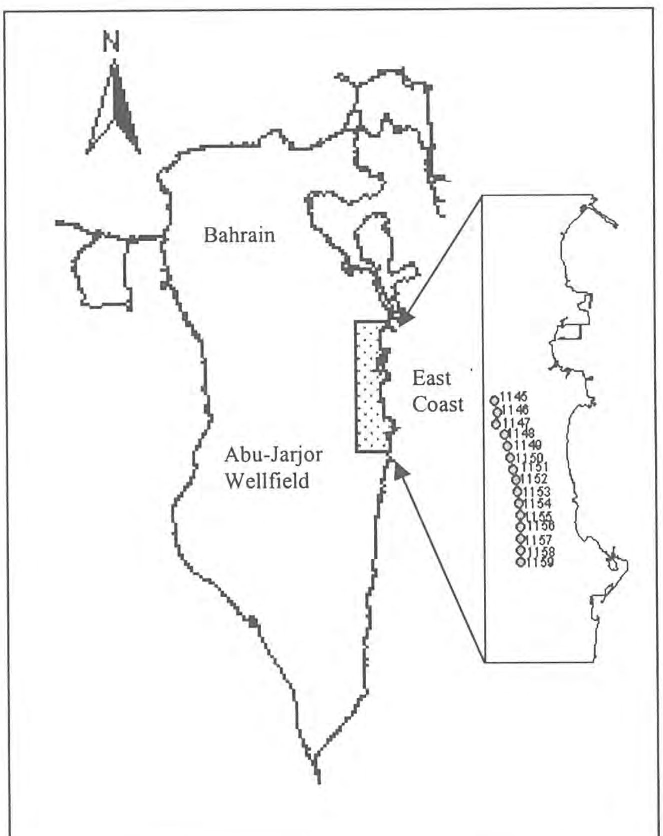

Figure 2: The study area and the 15 Production Boreholes

DATA SOURCES AND INTEGRATION

Data used in this study are classified into two categories, spatial and aspatial (attribute). Table (1) summarizes the data sources and the methods employed in integrating these data into the GIS system.

Table 1. Spatial and Aspatial (Attribute) data sources

Description	Source Format
Spatial Data	
Bahrain Map, Scale : 1:50,000	ArcInfo export files (.e00)
Study Area Map, Scale: 1:10,000	ArcInfo export files (.e00)
Observation Wells-Location	ArcInfo export files (.pts file)
Abstraction Wells-Location	ArcInfo export files (.pts file)
Aspatial Data	
Salinity as TDS Major Cations (Na, Ca, Mg, K) Major Anions (Cl, SO_4, HCO_3)	Microsoft Excel spreadsheets containing water sample data for the 15 production wells from 1986-1998. All files are saved as .txt (ArcInfo readable format), and as .dbf (ArcView readable format)
Photographs	Desalination plant unit image, saved as JFIF-JPG
Schematic Diagram	The aquifer cross-section scanned and saved as JFIF- JPG

These different types of data are integrated into the GIS system in a number of steps. These included digitizing, scanning, and building the aspatial data (Figure 3). The following is a brief description for each step

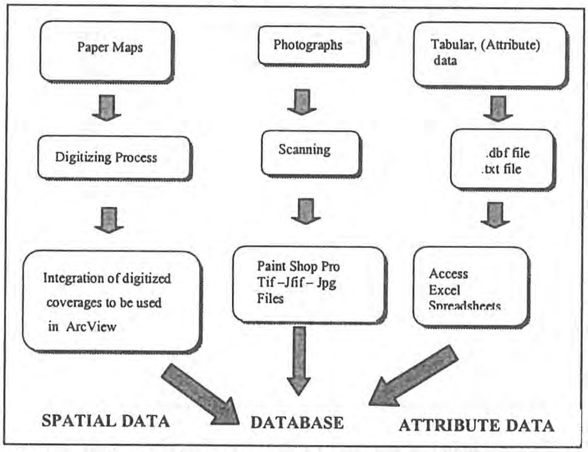

Figure 3: Data Integration from different sources

Digitizing and Integration of Spatial Data into Arc/Info

Digitizing converts the spatial features on a map into digital format. Bahrain coastal boundary, Geology, and municipal boundaries were derived by digitizing Bahrain paper map of a scale 1:50,000. A more detailed map (1:10,000) was used to obtain the location of the 15 production boreholes and other features of the study area.

Scanning Images

In order to simplify the GIS system to its users, some images have been incorporated into the system. These include Bahrain Geographic Map, Bahrain National Flag, some of the Desalination Plant Units (DPU), and the hydrogeological cross-section shown in Figure 1.

Building Aspatial (Attribute) Data in Excel

Chemical data for the 15 production boreholes are available since 1986, and chemical analysis is conducted every six months for 29 parameters. These data were available on hardcopy in a chemical lab report format. Eight selected parameters, Table (2), were chosen for the analysis of the water quality of the boreholes, and were re-input in an electronic spreadsheet (Excel) for the period from 1986–1998 (13 years).

Table 2. Cations, Anions, and Total Dissolved Solids in 1986.

Absloc_id	TDS 86	NA 86	CA 86	MG 86	K 86	CL 86	HCO3 86	SO4 86
1145	13040	2128	605	307	102	6984	191	581
1146	12396	1969	646	264	95	6736	188	585
1147	12680	2023	528	296	98	6736	188	588
1148	13131	2082	632	308	96	6748	197	558
1149	13926	2200	639	304	102	7409	197	565
1150	13557	2136	646	308	100	7196	205	552
1151	13209	2120	644	319	100	7090	217	524
1152	12981	2137	642	294	103	7019	225	506
1153	12750	2088	630	209	98	6842	205	548
1154	12998	2125	648	287	102	7019	215	546
1155	13040	2128	605	307	102	6984	191	581
1156	13319	2214	610	310	103	7161	220	539
1157	13431	2178	610	310	102	7161	214	545
1158	12118	2037	586	305	97	6665	193	568
1159	12303	2030	590	300	94	6594	192	562

GRAPHICAL USER INTERFACE (GUI)

Both Dialog Designer and Menu bar customization were used in constructing the GUI. Figure 4 shows the introductory view of the system, using Dialog Designer. The constructed GUI is practical and user-friendly that enables the user to navigate, explore, query, and obtain information from the data through visualization.

In the second GUI view (Figure 5), the user can navigate to query and analyze then visualize all the chemical parameters. The Menu bar customization is chosen for this view because it is more suitable, as more than one option is offered to the user facilitating information about the chemical parameters. Figure 6 illustrates the flowchart for the main different choices available to the user under this GUI.

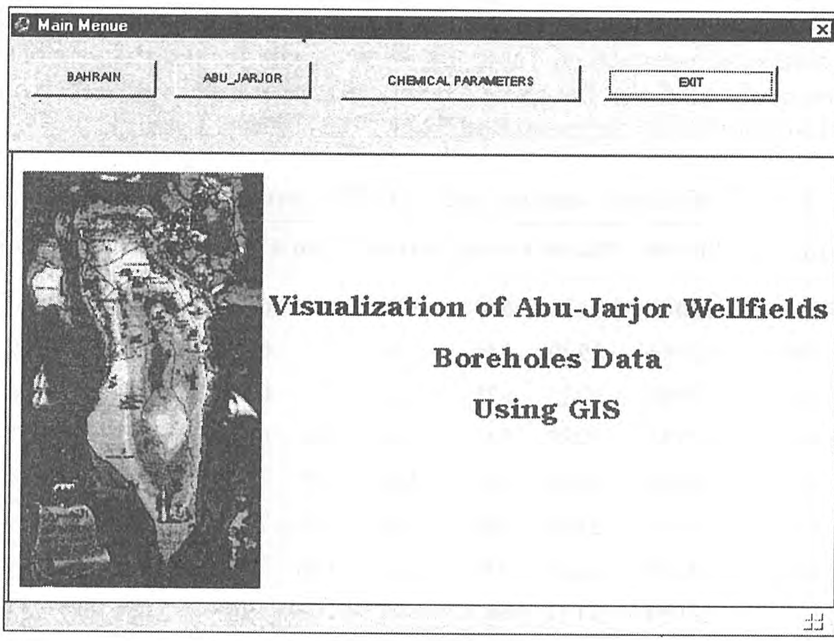

Figure 4: The introductory view of the Building System

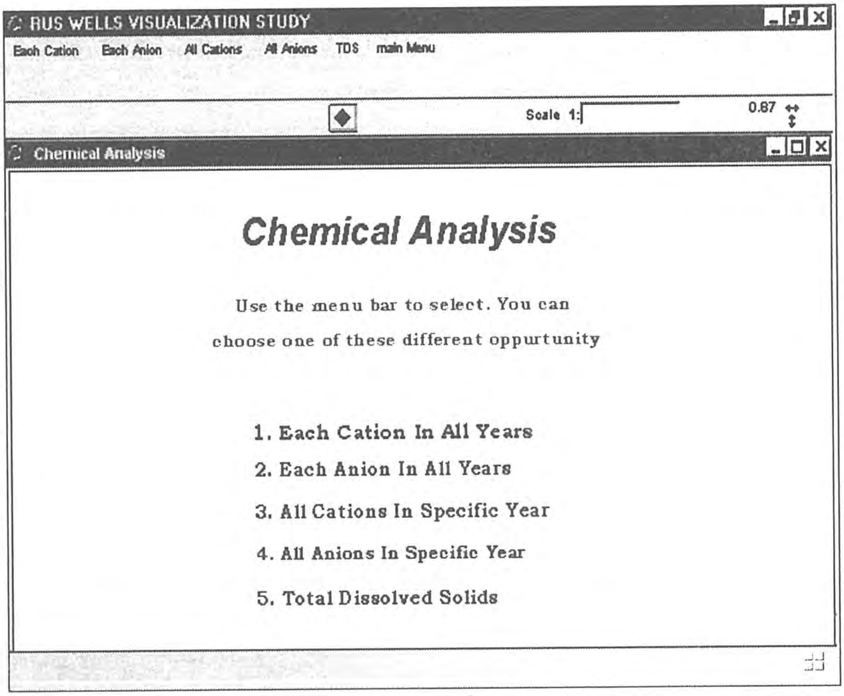

Figure 5: The introductory view of the chemical parameters

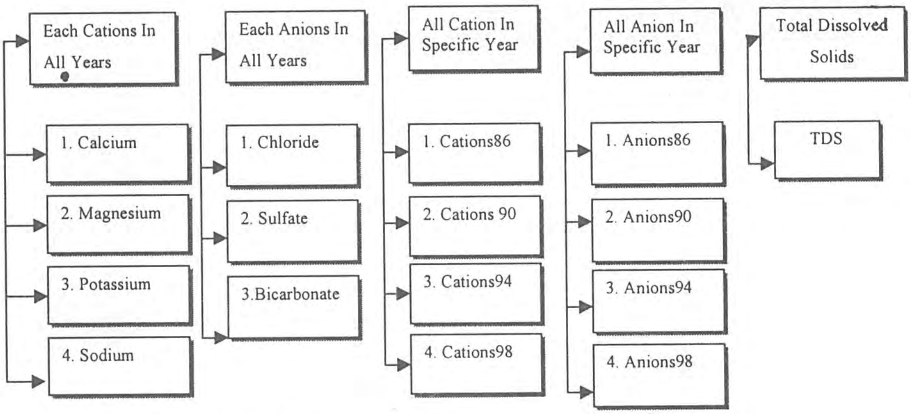

Figure 6: Flowchart introduces the structure of the chemical parameters (GUI)

DATA VISUALIZATION

The main purpose of the constructed GIS is to be able to monitor and observe temporal trends in the concentration of the chemical constituents of groundwater produced by the 15 boreholes of Abu-Jarjur wellfield. In other words, the user should be able to use the system to query, explore, analyze and predict, by visualization, the changes in the quality of groundwater fed into the desalination plant.

For this purpose, a number of visualization options can performed to know the conditions, trends and pattern of the chemical constituents monitored. The followings are some examples:

- If the user needs to know the wells that have a given chemical parameter enclosed within a certain concentration range, or if it has reached above or below a certain concentration limit in any of the production boreholes, then he can use the query option (Figure 7). In this option, the user can specify a concentration range or limit, and the boreholes that satisfy the concentration condition will be listed and their concentration chart will be displayed.

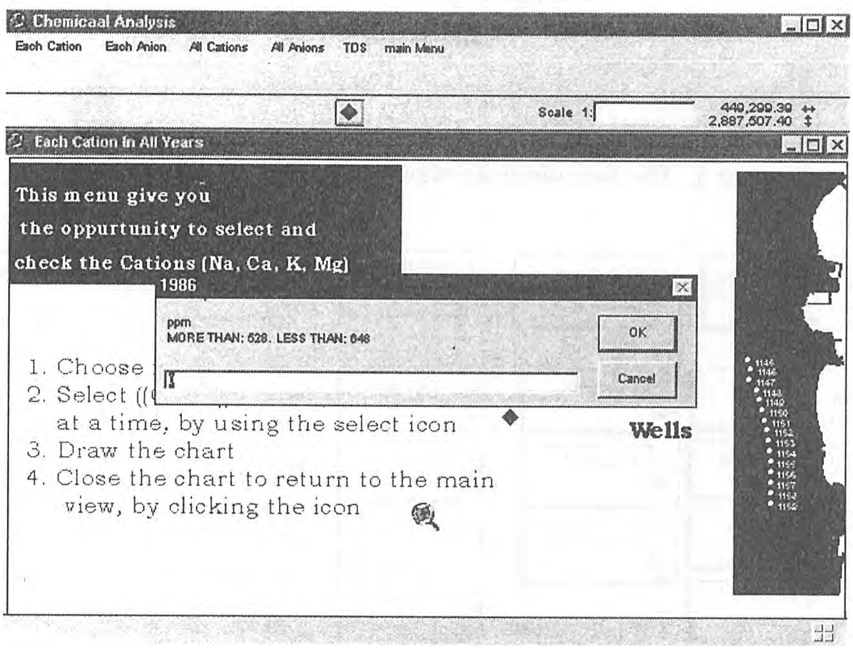

Figure 7: Query Box

- If the user wants to see if there are any anomalies in the concentration of a given chemical constituent, or wants to analyze its temporal variations, the chart option can be used. Figure 8 shows an example of Na and TDS charts produced for 8 production wells for the period 1986-1997.

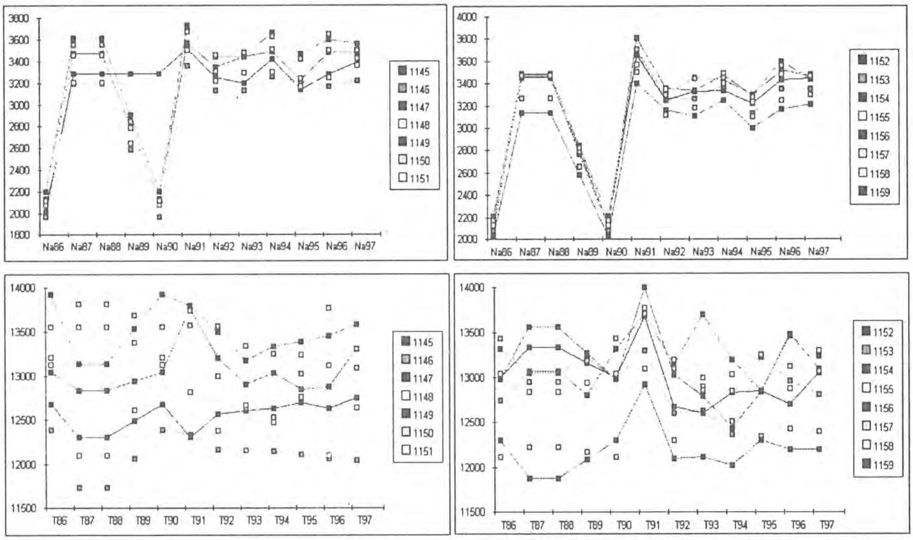

Figure 8: An example of Na and TDS charts

CONCLUSION & RECOMMENDATION

This study illustrates the building of a GIS for 15 groundwater production boreholes, feeding the Abu-Jarjur Reverse Osmosis Desalination Plant in Bahrain. A 13-year attribute data of major-cations, major-anions, and TDS of the boreholes has been integrated along with spatial data of the wellfield area. GIS is considered to be a fundamental tool for visualizing and handling information of groundwater data. A GUI was built to facilitate the manipulation, display, analysis, and visualization of the boreholes data. This customized GUI allows the display of all the data related to the study area of Abu-Jarjor wellfield, and the Desalination Plant Units, and to select a query and draw a chart to explore the changes in water quality associated with the 15 production boreholes. The system provides a facility for generating a yearly analysis report from 1986 to 1998.

The end product is a user-friendly and simple, and can be used by both technicians and decision-makers easily, and the users have the capability to navigate through the system without any difficulty. The constructed GIS system can be used to analyze, explore, and visualize changes in the chemical constituents, which makes it an efficient tool for monitoring and predicting the trends of the quality of the groundwater fed into the Geographical Information System.

This study can be considered as a pilot project due to the small number of attribute data selected. To further improve the system, all the 29 chemical parameters measured at Abu-Jarjor Desalination Plant should be entered as well as the data for the coming years. This will enhance temporal changes analysis of the produced water by the wellfield. Moreover, building a suitable database will provide a valuable information for determining and analyzing any changes occurring in the aquifer. However, as the reserves of the brackish aquifer are being reduced due to its utilization, salinity increase is expected to start taking place. Therefore, monitoring of the wellfield boreholes, presently carried out every six months, should be carried out on a quarterly or monthly basis to provide an early warning system.

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DATABASE SOFTWARE APPLICATIONS FOR HYDROLOGIC STUDIES IN ABU DHABI EMIRATE

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ABSTRACT

The Ground Water Research Program is being conducted by the National Drilling Company to evaluate the ground water resources of Abu Dhabi Emirate. Data collection platforms are used to monitor hydrological and meteorological parameters at selected sites in the eastem and western regions of the Emirate. The network provides information on water-level fluctuations and meteorological conditions. Manual measurements are also made in selected wells to monitor long-term changes in water levels and water quality. Data received from the DCP network and manual measurements are loaded into a database system to facilitate retrieval and analysis.

The Ground-Water Research Program database system includes many software applications that allow users to retrieve data in useful formats such as reports, tables, and graphs. The applications running under Oracle, version 7.2.3, have been designed by specialists to meet the project requirements and needs. Tables of data include a well-schedule table that contains all information for wells; data-collection platforms table; water-level and water-quality tables that enter, modify, and auto correct data received from data-collection platforms; a geology table that describes lithology and seismic lines; a falaj table that contains discharge information; and a sabkha table that contains hydrologic information about sabkha areas in Abu Dhabi Emirate. All of the tables are accessible for data selection through Oracle programs such as SQL*PLUS for data retrieval and updating, Developer/2000 Graphics 2.5, and Developer/2000 Report 2.5 for data listing, organization, and drafting. The database holds long-term records for hundreds of sites and can be used to evaluate the status of the Emirate's water resources and uses.

KEYWORDS : Abu Dhabi Emirate, database, ground water, Oracle.

INTRODUCTION

The National Drilling Company of Abu Dhabi and the United States Geological Survey have established an integrated computer database as part of the cooperative Ground-Water Research Program (GWRP) to investigate and evaluate the water resources of Abu Dhabi Emirate. Since the inception of the GWRP in 1988, approximately 300 boreholes have been drilled, logged, tested, and measured, and thousands of records and bits of information have been collected, compiled, checked, and stored in a relational database (Moreland, 1998). The database represents a permanent archive and provides historical records that can be used to evaluate hydrologic trends in Abu Dhabi Emirate.

A vital component of any large scientific agency is the organization, storage, and retrieval of scientific data. These tasks are best accomplished using a relational computer database system. A relational database has numerous advantages. Data redundancies and inconsistencies can be avoided, data can be shared among many users and locations, data is secure and controlled, and data reporting can be enforced. When coupled with effective quality control procedures, the use of the relational database can provide an organized, reliable, and comprehensive repository of scientific information (Campbell, 1998).

This report briefly describes the structure and use of the GWRP database. It lists 18 tables that comprise the database, and provides examples that demonstrate its use. The report is intended for those interested in the type and extent of data that it contains and how it is used for hydrological applications.

DATABASE COMPONENTS

The database used by the GWRP is a relational database management system called Oracle[1] (Version 7.2.3). The GWRP accesses and manipulates the Oracle database using several software tools (Table 1). In addition to internal manipulation through Oracle tools, data can be downloaded to Windows-based software programs such as Microsoft Excel for viewing, analysis of statistics, reporting, and graphing.

[1]Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the National Drilling Company

Table 1. Software tools and functions used to access the relational database, Oracle

Tool (Software)	Functionality
SQL *PLUS 3.3	A programming language to retrieve, tabulate, manage, and update data for existing tables.
Discoverer/2000 Browser 2.0	Intuitive "point-and-click" software that allow users to retrieve and print data using few SQL commands. Browser may also be used for statistical analyses.
Developer/2000 Forms 4.5	A software to be used by Oracle programmers and developers to create forms for different applications.
Developer/2000 Reports 2.5	A software that enables presentation of database information, images, and other report elements.
Developer/2000 Graphics 2.5	A software that is used to build customized graphical forms that plot data in a number of styles including x-y, pie, or bar charts (fig. 1).

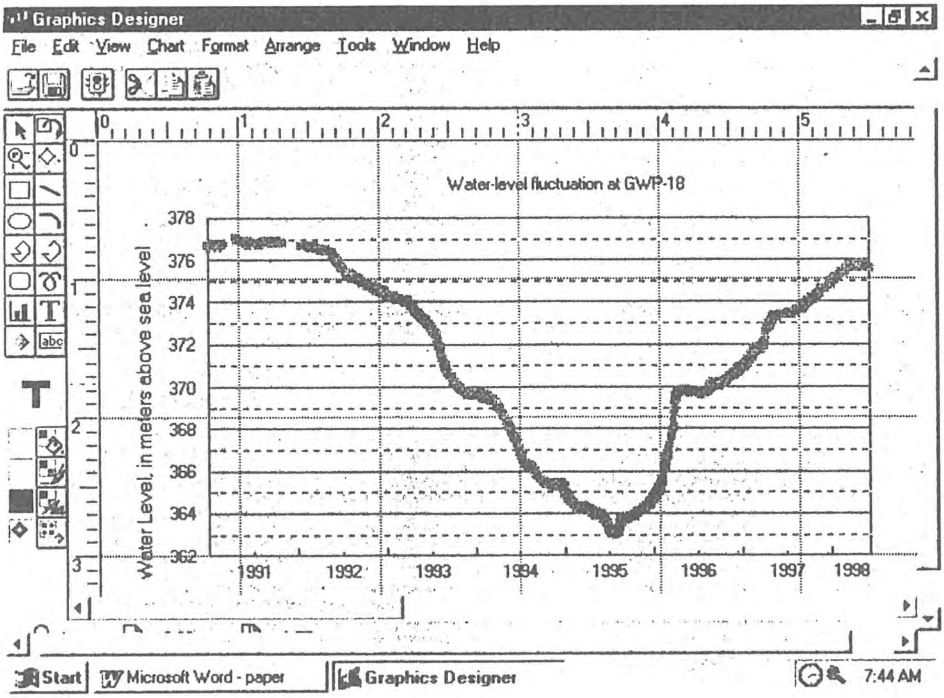

Figure 1. Hydrograph plotted on computer screen using Oracle Developer/2000 Graphics 2.5

STRUCTURE OF THE GWRP DATABASE

The GWRP database contains 15 tables of scientific information (table 2). This information represents the bulk of data collected by GWRP staff since 1988, and small amounts of data collected by other agencies since the 1960's. These data include well construction details, and geologic, hydrologic, and chemical information collected in Abu Dhabi Emirate. The database contains raw data (and in limited instances calculated or processed data - aquifer transmissivity, for example). The data in one table may be correlated to data in other tables by the well name (for well-related data) or by a site identifier (SID) that is unique for each sample or well location. Each table consists of several columns of related data. Each column comprises a particular data type (for example, numbers, characters, or date).

Temporary tables were created to store inconsistant data and raw data imported from other agencies. Data in the temporary tables is evaluated and adjusted before entering into the program database. To ensure the quality control of the database, systematic checking procedures were established for all data tables.

Table 2. Types and names qf technical data tables in the GWRP database

Data category	Table name
well construction details:	
• name, location, construction details, and other basic well information	WELL_SCHEDULE
• measuring-point altitudes for wells	MP_ALTITUDE
• name, site or sample type, location, and other basic information pertaining to sabkha investigations	SABKHA
geologic information:	
• general lithology	GENLITH
• detailed lithology	LITH
• seismic-log line locations	SEISMICLINES
• geophysical-log line locations	GEOPHYSLINES
• borehole geophysical log comments	GEOLOG
hydrologic information:	
• aquifer tests, raw data	AQTEST_RAW
• aquifer tests, results	AQTEST_RESULTS
• automatic data-collection platform data (holds final DCP data after their reformatting in a temporary table called DAILYTEMP_DCP)	DCP
• information about the automatic data-collection equipment	DCPINFO
• manual water-level measurements	MANUALWL
• falaj discharge measurements	FALAJ
chemical information:	
• water-chemistry analyses, analyzed in USGS laboratory, USA or Water and Electricity Department laboratory, UAE	CHEM

REPORTING FROM THE DATABASE

Data retrieved and selected from the GWRP database tables can be presented and reported in different formats using the Oracle tools listed in table 1. The data may be reported using "structured query language," or SQL, statements and Browser 2.0 (table 3 and fig. 2). Another advantage of Oracle Developer/2000 is Reports 2.5, which allows users to build a detailed master report of graphics and illustrations. The programs can be run on a personal computer and linked to other Windows-based software programs such as Microsoft Excel for statistical analysis.

Table 3. ***SQL statement querying water-level data in a well for a specific time period.***

```
SQL> SELECT WELL,MEASDATE,SWLEVEL
     FROM MANUALWL
     WHERE WELL = 'GWP-19'
     AND MEASDATE BETWEEN '01-JAN-98'AND '31-MAR-98'
     ORDER BY MEASDATE;
```

The result of the query after the execution will appear as following:

WELL	MEASDATE	SWLEVEL
GWP-19	02-FEB-98	301.75
GWP-19	03-MAR-98	301.78
GWP-19	26-APR-98	301.71

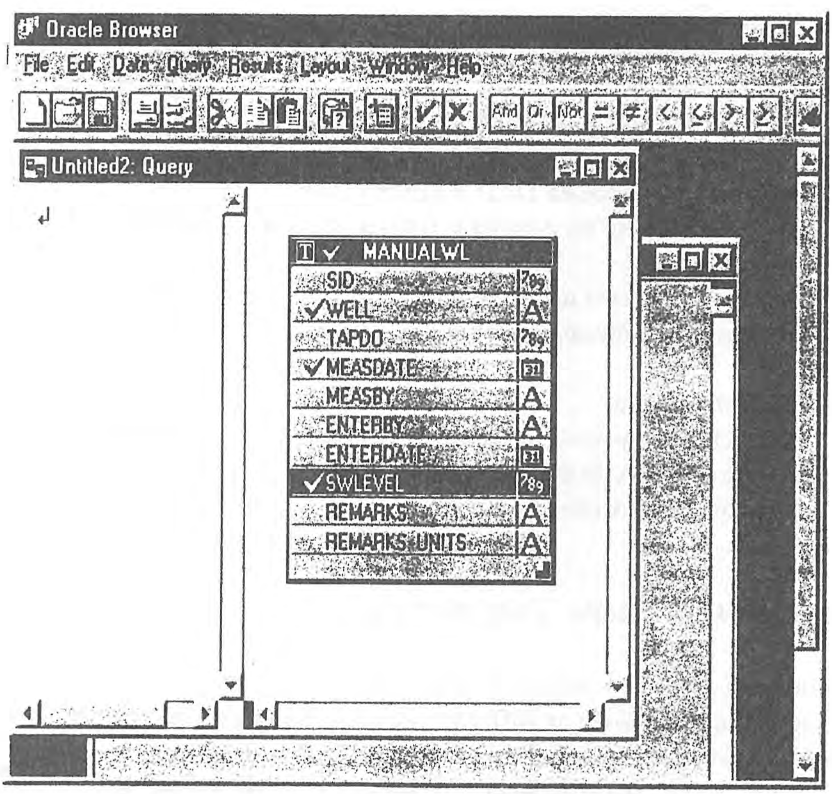

Figure 2. Browser 2.0 screen demonstrating point-and-click procedures instead of SQL statements listed in table 3.

OTHER COMPONENTS RELATED TO THE GWRP DATABASE

The project used a Geographical Information System to store, process, retrieve, and map areal information including surficial geology, roads, boundaries, irrigated areas, wellfields, and well locations. Used in combination with the GMRP database, the Geographical Information System was useful in preparing maps of water-level contours, water-quality conditions, aquifer characteristics, and other topics of interest. More importantly, the system could be used to overlay maps containing various kinds of information to prepare interpretive products. For example, a map that combined geologic and water-quality information was prepared to delineate areas where fresh ground-water supplies are vulnerable to contamination from landuse activities (Tamayo, 1997). Other technical and scientific software being used for groundwater analysis such as Ground-Water for Windows can interact with the Oracle database for data selection and utilisation.

CONCLUSIONS

The Ground-Water Research Program developed a computerized ground-water database to store, process, and retrieve information concerning ground-water resources. Information stored in the GMRP database includes geologic and lithologic data from Program test holes, hydraulic data collected during aquifer tests, water-level data from observation wells, water chemistry data from Program and Water and Electricity Department wells, locations of geophysical surveys, and other ancillary data of relevance to ground-water investigations. The database system can be used to selectively retrieve information based on user-specified criteria, process data to obtain statistical information or calculate variables, plot data on graphs and charts, and prepare tables of data in various formats. The GWRP database contains information for more than 1,500 wells, 59 water-level recorders with daily records for selected periods between 1989 and 1998, and 365 surface geophysical measurement sites. About 59,000 daily water-level records and 13,000 periodic water-level measurements are on file. Water-quality analyses of samples from more than 500 wells are also available as well as meteorological data recorded during the Program study term.

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GPS Surveying Techniques Applied to Ground-Water Exploration in Abu Dhabi Emirate

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GPS SURVEYING TECHNIQUES APPLIED TO GROUND-WATER EXPLORATION IN ABU DHABI EMIRATE

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ABSTRACT

A new era in surveying technology began with the inception in the early 1980's of the Global Positioning System (GPS). Until now, surveying has consisted mainly of measuring angles and distances between points and using these measurements to compute geometrical positions. Now in GPS surveying, two or more GPS receivers placed at two or more points simultaneously receive signals from orbiting GPS satellites. This data is then analyzed and used to calculate the baseline vector on a three-dimensional geocentric coordinate system. With this information, accurate positions can be determined anywhere in the world at any time of the day with centimeter accuracy. Continued technological advances in equipment design, field observation techniques and data post-processing contributed to the rapid development of GPS. This has made a significant impact on a wide range of surveying applications related to ground-water exploration. The National Drug Company foresaw the benefits of the GPS and has utilized the system since 1991 for hydrologic investigations. GPS has been used to accurately survey positions of wells and test holes, locate geodetic benchmarks and surveyed points, establish ground control for surface geophysics Fines and water-supply well fields, map outcrop and geological boundaries, and navigate to and from work sites in remote areas. GPS data can be easily incorporated into geographic information systems to provide accurate maps of all surveyed information. GPS surveying is more advantageous compared to conventional methods in terms of costs, accuracy, time and manpower requirements. Two types of GPS measurement are employed—the static method used for single-point positioning and the dynamic method used in navigation and other surveying applications. Differential GPS (DGPS) techniques are applied to achieve a higher degree of accuracy required in, establishing the location and elevation of points. Post-processed results are converted to various file formats for export to geographic information system or computer applications.

Disclaimer:

Any use of trade, product, or firm names in this report is for descriptive purposes only. Trademarks used belong to the respective manufacturers. GPS receiver specifications and prices are for information only and are subject to change without notice. For specific and current information, GPS receiver manufacturers should be contacted. No endorsement is hereby intended or implied by the National Drilling Company.

Keywords: Global Positioning System surveying, navigation, hydrologic investigations,ground water.

INTRODUCTIONS

Land surveyors have used a variety of instruments and techniques to locate and mark their position on the surface of the earth. Advances in technology have brought about significant changes in equipment and methods, thus improving the accuracy and case of performing surveys. The development of the Global Positioning System (GPS) in the last decade and its full deployment in the early 1990's has made it possible for a user to obtain accurate three dimensional position in virtually all parts of the world. The complete satellite constellation, improved models and reduced costs of receivers have extended GPS positioning capability to centimeter range with a 24-hour coverage period. Thus enhanced performance allows for measurements over long distances and collection of precise position data, once attainable only by executing arduous and time-consuming conventional surveying techniques.

This paper briefly reviews the fundamental principles and history of GPS, and the benefits of using GPS equipment in ground-water exploration. It describes the capabilities, installation and operation of GPS receivers used in various survey applications. Field procedures for data collection and post-processing operation are also discussed.

History and Principles of GPS

The NAVSTAR Global Positioning System is a satellite-based navigation network that was developed and deployed by the United States Department of Defense. It consists of three major segments: the space, the control system and the users. The space segment is a constellation of 24 satellites orbiting the earth twice a day at an altitude of about 20,000 km. GPS satellites, equipped with powerful radio transmitters and highly stable atomic clocks, are constantly transmitting time and position information 24 hours a day. The satellites are arrayed in six orbital planes inclined at 60 degrees from the equator (fig. 1). Each satellite broadcasts over two radio frequencies; L 1 band called Standard Positioning Service (SPS) at 1575.42MHz, and L 2 band or Precise Positioning Service (PPS) at 1227.60 MHz. There are two codes, the C/A (coarse acquisition) code intended for civilian use, and the P (precise) code reserved for military users (Scherrer and Fricker, 1985). By measuring the travel time of signals transmitted from either three or four satellites, a GPS receiver can calculate its distance from those satellites, determine its position, and provide precise time and frequency.

The first operational prototype (Block I) GPS satellite was launched in 1978,. By 1990, the Block I constellation was composed of six functioning satellites launched between 1978 and 1985 (Dixon, 1991). In February 1989, the first Block II satellite with many improvements on board was put in orbit. By late 1992, there were 21 Block II satellites in operation, enabling simultaneous observation of four or more GPS satellites worldwide. Although the system has been in use since 1978, the signal's availability period (window) to civilians was limited to just a few hours a day at first, increasing gradually until GPS was declared fully operational in December 1994 after the completion of the 24 satellite constellation (Ouellete, 1995).

The control system consists of five monitoring stations, spaced almost evenly around the world at Diego Garcia, Ascension Island, Kwajalein Atoll, Hawaii, and a master control station at the Consolidated Space Operations Center at Colorado Springs, Colorado, USA. The purpose of the control system is to update and maintain the operation (health) of the satellites, determine their orbits and the behavior of their atomic clocks, and inject the broadcast message into the satellite (Wells and others, 1987).

The user segment consists of all military and civilian users. GPS provides open access and is freely available to all users. Originally conceived as a targeting control for military weapon systems, its use has been extended to civilian and commercial applications, ranging from navigation and surveying to exploration and tracking. Technological advances in the microchip industry helped reduced the size and cost of GPS receivers. The first GPS receiver for- civilian use, available in 1984, retailed for $150,000 and required two men to carry the equipment to the field. The first hand-held units appeared in 1989, priced at around $3,000. This price dropped to approximately $200 per unit by 1995 (Ouellette, 1995).

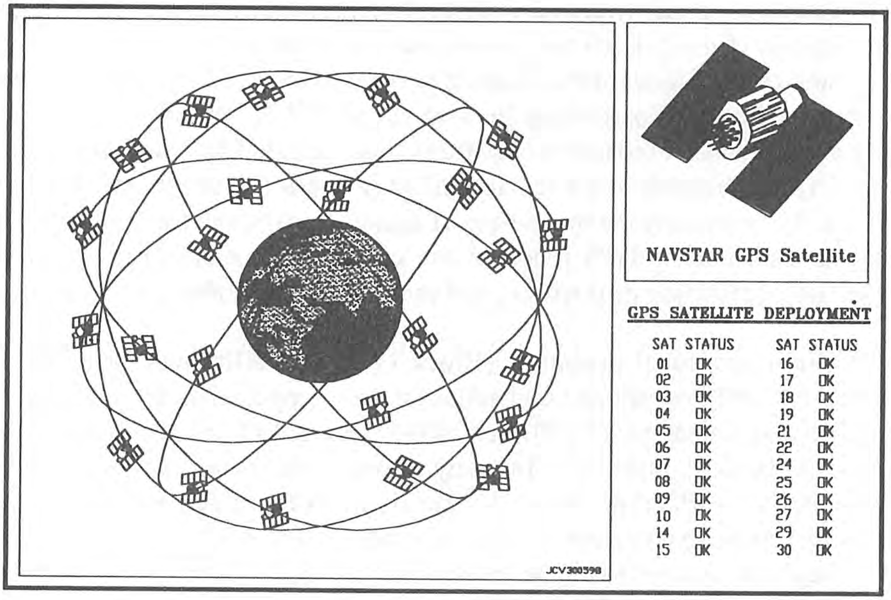

Figure 1. GPS satellite constellation

Methods of Measurement

The two main methods of GPS measurement are dynamic or kinematic and static positioning. In the static method, the receiver is stationary and the time needed to obtain measurement is of secondary importance; in the dynamic method, the receiver moves and in this case, it is important to determine the position in real time. These methods are further classified into whether the position is to be computed in an absolute global coordinates system (autonomous positioning), or merely relative to another point (differential positioning).

In surveying, static positioning is used, since in this case accuracy takes precedence over time. The absolute determination of a point within a global coordinates system is known as single point positioning. For geodetic applications, relative or differential positioning is used wherein satellite signals must be received simultaneously by at least two receivers. In Differential GPS (DGPS), one of the receivers is stationed at a known reference point (base station) and the remote receiver, the rover, at the point where the position is to be determined. The rover may be stationary or dynamic. The base and the rover need to be looking about the same view of the sky so that differential corrections made at the base will also be valid at the rover (Gann, 1993). Dynamic GPS requires that a continuos satellite connections called lock is maintained when roving between survey points. A new method, called real time kinematic (RTK) GPS, uses radiomodem repeaters to broadcast a correction message from the base station to the roving receiver. The rover processes the information in real-time to solve an accurate position relative to the reference station with an accuracy of 1-2cm (Sumpter and Asher, 1994).

Precision and Accuracy

From its inception, GPS has been able to pinpoint autonomous locations to within 100 meters using the civilian frequency C/A code (SPS). This has now unproved to 15 meters for civilian users even with the use of hand-held receivers. The development of the differential GPS (DGPS) technique which uses ground stations as additional reference points, together with refined post-processing solutions can provide accuracies in the centimeter range at present. From time to time in order to maintain military security, the U.S. Government activates Selective Availability (SA), a program which inserts random errors into the data transmitted in the SPS code, thus reducing accuracy to around 100 meters. DGPS cancers the effect of SA and other random errors caused by the Earth's atmosphere.

The accuracy of GPS determined positions depends on two factors: the satellite configuration geometry, and the measurement accuracy (Wells and others, 1987). Position Dilution of Precision (PDOP) is a measure of the possible position error related to geometric quality or the strength of the satellite configuration. The lower the PDOP, the higher is the accuracy of the observed position (fix). GPS measurements are subjected to systematic and random errors resulting from variable, uncontrollable observing conditions. Systematic errors are minimized by designing a good satellite network and observation schedule while various post-processing techniques are used to reduce random errors by correcting or eating bad observations (Ikehara, 1992).

GPS positioning accuracy is dependent on the type of receiver and method of measurement being used. Static DGPS using refined carrier phase measurement and double differenced post-processing technique can produce horizontal positioning accuracies in the millimeter range (Ouellette, 1995). This is achieved by using expansive receivers with extremely accurate, stable quartz oscillators. Dual-frequency receivers use a squaring technique to reconstruct carrier signals, making it easier to track the signal and reacquire it rapidly after interruption. This is important in RTK system GPS where several points are to be surveyed with centimeter accuracy in a movmg enviroment.

Advantages of using GPS

GPS surveying, with careful planning and execution produces accurately measured points and offers the following advantages compared with conventional surveying methods:

1 . Visual communication (intervisibility) between points on the ground is not necessary, thus saving time and money on reconnaissance. Points can be surveyed where they are needed and need no longer be placed on high ground to ensure a clear line of sight. There is also no limit on the distance between receivers, depending on the type being used, but shorter baselines should be maintained for greater accuracy.

2. GPS is not affected by weather conditions and is now available around the clock at any part of the world making it very useful in land, air and marine navigation.

3. In DGPS technique, position accuracy is identical for each point surveyed, and unlike in traverse, there is no propagation of error. A reference azimuth is not required to obtain a relative three-dimensional position in a very short period of time.

4. A geodetic control network is no longer required although available bench marks at the site should be observed to verify the operational capability of the receiver.

5. Position and height of each point are determined by a combined three-dimensional equation and computed in a universal coordinate system. Resulting values can be displayed in any local datum or grid coordinates, facilitating the creation and transfer of data files in any information system.

6. Equipment and operating costs are reduced by using GPS to establish control points at remote areas where survey is to be done, thus eliminating long traverse work.

GPS IN ABU DHABI

The Ground-Water Research Program (GWRP) is being conducted by the National Drilling Company (NDC) of Abu Dhabi Emirate to evaluate the ground-water resources of the Emirate. The main objective of the GWRP is to evaluate ground-water quality and well yields. This involved the drilling, logging, testing, and sampling of over 250 wells since 1989 (fig. 2).

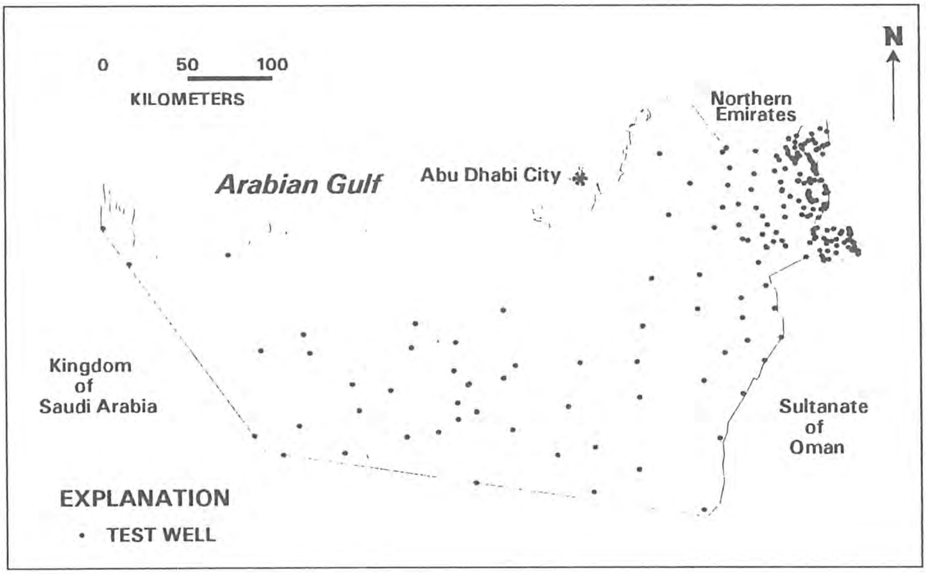

Figure 2. GWRP wells in Abu Dhabi Emirate

Survey Personnel and Equipment

Two 3-man survey teams were carrying out survey works with the GWRP using conventional equipment such as Theodolite and Electronic Distance Meter (EDM) during the early stage of the Program. However, surveying with conventional equipment was found to be costly in terms of time and manpower. When GPS equipment was utilized in 1991, a two-man survey team was formed to conduct survey tasks using the new equipment. With the GPS system, the survey crew could determine well coordinates and elevation with high accuracy using the DGPS technique, locate well sites and geodetic bench marks, and measure long distances without worrying about inaccessible terrain or doing multiple instrument setups as had been the case when running a traverse using conventional methods.

GPS Receivers

The GWRP operates two kinds of SPS-type GPS receivers, the Motorola Eagle and the Magellan NAV and ProMARK systems. The Motorola Eagle Mini-Ranger GPS receiver is intended to be used in land, air and sea navigation or survey system. It is capable of providing either autonomous or real-time differential positioning data when used in static, kinematic and relative positioning applications. The receiver can also be integrated in a geodetic system to survey fixed points, achieving relative accuracy in the centimeter range and post-processed results in the order of 1:100,000. The hardware provided with the system is composed of several components including the antenna/preamplifier, Eagle receiver, and a laptop computer as the system controller (Motorola, 1988).

The GWRP uses different models of Magellan GPS receivers. The NAV 1000 PRO is a single-channel GPS receiver and has accuracies ranging from 3 to 25 meters Root-Mean-Square (RMS) depending on the operating mode being used. Accuracies of 25-30 meters RMS in horizontal are attainable in a single fix mode, 15 meters RMS (2-D) and 20 meters RMS (3-D) in averaging mode, and up to 3 meters RMS in differential mode. In DGPS, it requires the use of two units, the control unit positioned over a known point serves as the reference station to develop correction data for the remote unit, taking out errors induced by SA and ionospheric and tropospheric distortions. A newer version, the NAV 5000 PRO, uses five channels working simultaneously to track and collect data from GPS satellites. Data collected from satellites is processed immediately to compute the current position, altitude, velocity, and navigation data in less than 1 minute. It is capable of 12 meters RMS horizontal accuracy in autonomous operation without SA, 5 meters RMS using field differential (without post-processing) and 3 meters RMS with post-processed differential. The NAV 5000 PRO can be set to different modes to determine positions. Three satellites are needed to obtain a position fix in 2-D mode and a minimum of four satellites to determine position in 3-D mode. In the automatic mode, the unit uses 3-D when four satellites are present and automatically switches to 2-D when only three satellites are available.

The ProMARK X-CP, one of the latest Magellan receivers capable of submeter accuracy, is a rugged hand-held 10-channel SPS code and carrier phase code receiver designed to collect pseudorange and carrier phase data. The Pro, was developed primarily for land use in marking and locating geographical sites requiring high level of accuracy. With its position averaging and differential functions, it can be used in third-order surveys ideally for GIS data collection, positioning, and navigation. The unit has a large memory capacity of up to 25 hours of data storage at 1 fix/second or 9 hour's worth of field data. It can store up to 500 waypoints and as many as 10 routes of up to 20 legs each. The operation can be set to 2-D, 3D or automatic mode. The Pro is capable of 12 meters RMS horizontal accuracy in autonomous position with the absence of SA. This can be improved by using the Magellan post-processing software for differential calculations which can achieve 3 meters RMS horizontal accuracy. A submeter accuracy of 0.9 meter RMS can be obtained using the carrier phase module and a multipath antenna making it one of the lowest cost solution for submeter applications. Data output can also be converted to any GIS format (Magellan, 1995).

A new, improved version of Magellan's professional GPS receiver, the ProMARK X-CM is capable of obtaining centimeter accuracies of 15mm +/-3ppm in conjunction with the MSTAR Professional GPS Software. With enhanced 10 parallel channels and a large data storage capacity, the ProMARK X-CM speeds up data collection, simplifies field operations and provides multiple DGPS applications (Magellan, 1997a and 1997b).

GPS Survey Applications

GPS data acquisition and analysis has brought a wide range of surveying applications related to oil, gas and mineral exploration; seismic, magnetic and geochemical surveying and survey quality control; precise positioning of unique rock outcroppings, formations, and sample sites; mapping and reconnaissance of exploration areas; as well as navigation to and from sites. GPS has been used primarily to survey the position of wells and test holes drilled by NDC for its hydrologic investigation. Selected government-owned and privately-owned wells were also surveyed to form an inventory of wells in the Emirate. Most of these wells were constructed or drilled in remote areas several kilometers from survey control networks. GPS could determine highly accurate horizontal positions and altitudes of these wells using differential positioning with submeter capability. Furthermore, GPS is also used in establishing ground control for surveying surface geophysics Fines and water-supply well fields. With its navigation mode, it can locate geodetic bench marks and set-out proposed drilling sites that have been predetermined from aerial photograph or satellite-image maps. Using its mobile differential function, surveyors could easily produce location maps and update land features such as tracks, newly-built roads, farms and other important features otherwise not shown in old base maps. These GPS acquired data were then processed and reformatted for use with other software like databases, spreadsheets, GIS or AutoCAD formats for mapping updates and location drawings.

Field Procedures

Session planning and data collection are two important tasks that surveyors do when surveying with GPS. High degrees of accuracy are not achieved without detailed preplanning and quality control in the field. A GPS receiver tracks all satellites that are above the horizon, however, data collection sites may not provide a clear or unobstructed view of the sky. Before going to the field, the survey crew runs the GPS PC-based post-processing software's session planning function to check the availability of satellites that are visible to the planned survey site. The crew would then select time windows for satellite sets that provide the best PDOP or satellite geometry. Both control and remote receivers are then programmed to collect data from the same satellite set. The software computes as many as four satellite sets and their projected PDOPs for each interval over a 24-hour period. If carrier phase module (for submeter accuracy) has been installed and session planning is done in 3-D operation, the software will project satellite sets based on CPDOPs (Carrier Phase Dilution of Precision). These reports are saved as file PDOPS.OUT or CPDOPS.OUT and can be printed.

After session planning, the crew are then set for data collection in the planned site. Most GPS surveys done by the GWRP involve two units of receivers for carrier phase differential positioning to achieve submeter accuracy. For example, a GPS receiver with a multipath-resistant antenna is positioned at each data collection site. Multipathing occurs when the same signal is detected several times at the receiver's antenna after being reflected. Carrier phase data can be collected only by using a multipath-resistant antenna (fig. 3). Potential satellite sets with optimal satellite geometry taken from a CPDOP report are used to collect data. Control and remote units are set to the same parameters and data collection should be within the same time period. Both units must be set to 3-D operation and use the same mask angle, raw data sample rate of 1, time format and almanac age. All units must be operating continuously during a collection session.

Field activity coordination must be observed. Start time of data collection may not be exactly the same at all units but must be close. Only overlapping data are used in the software computations so the time that data collection will begin and end should be determined. Matching datasets of less than 20 minutes overlay will be proportionately less accurate than a longer observation time especially for widely separated units. Processing requires control and remote files to be matched (synchronized in time and by satellite) so more data must be collected if the first few minutes of data were not matched. Post-processing software calculates a solution with the maximum matched data collected (Magellan, 1995).

Another common GPS operation in the field by surveyors and other users is navigation. The need for a precise navigational system introduced the development of GPS navigational functions. The use of GPS as a navigation and guidance tool is but one application of many that are being used in exploration. In the GWRP, the GPS navigation function is often used to locate drilling sites, inventory wells, geodetic bench marks, and traveling to and from work sites where there are no access roads or tracks. In navigation, waypoints are needed to set routes and routes are needed to navigate.

Figure 3. GPS data collection

A waypoint is a position's coordinates that have been saved or coordinates that have been scaled from a map or taken from other sources. It can be stored in alphanumeric order on a GPS receiver and can be viewed, deleted, and renamed. A route is a planned course of travel from one place to another and can be divided into several legs. Waypoints are used as the start and destination of each leg. A route can be defined as a series of waypoints, with the destination of one leg being the start of the next leg. It cannot be created unless waypoints are already stored in the receiver's memory.

After a route has been activated, navigation information such as bearing, distance, and direction of travel will then relate the user's progress along the courseline to the destination of the current leg. When navigating on a route, messages are displayed to indicate how close is the user to his destination, or if he has arrived or completed the course. A reverse route function allows the user to reverse the waypoint order of any route to bring him back to his starting point (Magellan, 1995).

Post-Processing

Post-processing provides statistical analysis and differential processing of positioning data collected by GPS receivers. Static differential is a process by which a dataset or subset obtained from one or more stationary remote positions is compared with a dataset obtained from a control (known) position, and then applies a correction to the data obtained at the remote (unknown) position. This process can produce accuracies of up to 2 meters RMS, depending on satellite geometry and type of processing used. For example, the Magellan post-processing software can process either the double-differenced pseudorange or carrier phase data. Of the two, carrier phase is generally used in GWRP well location surveys due to its high degree of accuracy (fig.4). With its carrier phase module of the submeter kit, carrier phase differential is accurate to 0.9 meter RMS or better.

CARRIER PHASE DIFFERENTIAL SOLUTION SUMMARY

CONTROLPOSITION		SESSION INFORMATION	
Northing	: 2680940.26 N	Satellites Used	: 29 01 25 21 15 31 03
Easting	: 40 369566.65		
Altitude	: 276.90 M	Start Date/Time(UTC)	: 6:06 11/09/1997
		Week/Sec (GPS)	: 931 22011
Ephemeris File	: GW1109A0.CAR	Duration of Session	: 44 Min 25 Sec
Control File	: GW1109A0.CAR	# Measurements	: 2662
Remote File	: GW1109A1.CAR	CPDOP for Session	1.8
Output File	: GWP-XXX.DIF		

Corrected Remote Antenna Location			CORRECTIONS	BASELINE
Northing	: 2661976.65 N	North (Y)	: 56.09 M	-18728.91 M
Easting	: 40 399034.97	East (X)	: 51.17 M	29630.00 M
Altitude	: 420.92 M	Height (Z)	: 44.32 M	144.71 M
		Length (2D)	:	35052.95 M
		Length (3D)	:	35053.25 M

Descriptor : WADI SAA
Attribute : GWP WELL
Antenna Offsets (C/R) : 0.14/1.40 M

Processing Status : >>> RUN COMPLETED <<<

Figure 4. Carrier phase post-processed differential result

The post-processing software can also perform mobile differential. Mobile point positioning is the least accurate method of differential where the control unit is stationary and the remote (rover) unit is moving during data collection. The control unit collects and stores data at the base (reference) station while the remote unit collects data at different locations, calculates fixes at 1 second update rate and stores the fixes in its buffer memory. Both datasets are synchronized and error over time is computed from the comparison made on the calculated position to the true control position. Correction is then applied to each matched position in the remote file (Magellan, 1995).

For the GWRP, mobile differential is used mainly when updating map features on a drilling site and its vicinity for producing location maps and GIS mapping requirements. An example of a mobile differential plot is shown in figure 5. A location map was required for five GWP wells at sites 2, 3, 4, 5 and 6 located on the same well field. This was accomplished by mobile differential positioning using two Magellan ProMARK X-CP GPS receivers. The control unit was set at a known base station while the remote receiver was positioned inside a car with an external antenna mounted on the roof. The car originating from point 'A' along the main road moved eastward towards a road junction (roundabout), then traveled along the tracks leading to the well sites ending northeast of the starting point at site 6. The collected data was post processed and then converted to a DXF file for export to AutoCAD where text and other details were added. Enlarged views of sites 1 and 2 show dots representing satellite position fixes along the course of roads and tracks taken white the car was moving. This continuous stream of dots or position fixes was plotted from the post-processed mobile differential result.

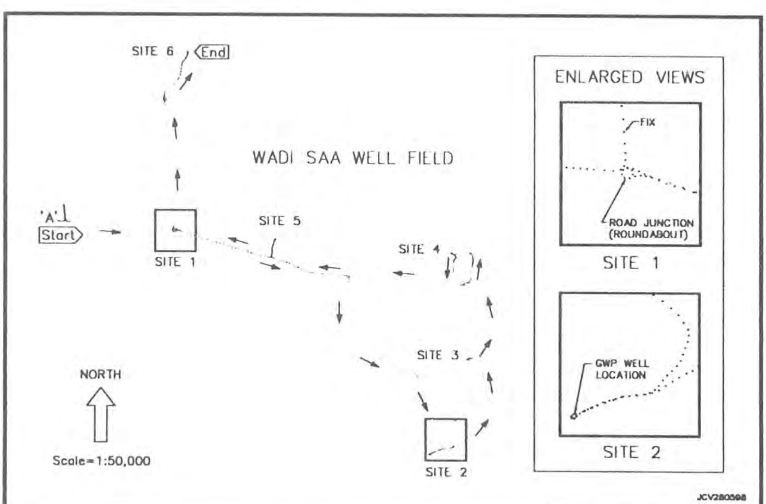

Figure 5. Mobile differential plot

Data Export and File Formats

In most GPS post-processing software, data files can be translated and exported to other various formats using the software's convert function. It translates any files from post-processing software that are in a proprietary format. The files must be converted before they can be exported to other systems. Some of the commonly used file formats that GPS data can be converted into are ASCII, SGIF, ARCINFO, DXF and RINEX. For the GWRP, GPS data files are converted to ARCINFO which is a widely accepted format used in GIS for mapping applications. Data files are also converted to DXF format if they are used when producing location maps with AutoCAD (fig. 6).

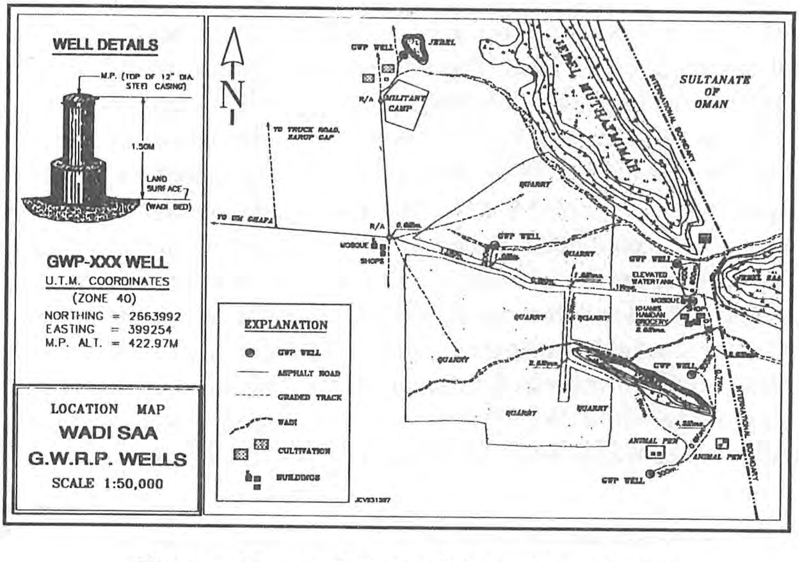

Figure 6. AutoCAD well location drawing

CONCLUSIONS

GPS has become an indispensable, highly efficient tool in providing continuous accessibility for navigation and positioning tasks in ground-water exploration. As accuracy improves with the development of new receivers and faster data post-processing software, GPS application has been extended to various surveying activities. Accurate well-head altitudes can now be measured rapidly and provide accurate estimates of ground-water levels. Work output is also increased and operational costs are reduced. The use of GPS is more productive than conventional methods in terms of the number of points that can be measured in a given time, and requires less personnel to complete the survey. Its primary advantage is being able to tie together points that are great distances apart without resorting to time-consuming old survey field techniques.

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Using Geophysical Logs to Evaluate Internal Circulation in Wells, Northeastern Abu Dhabi Emirate

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USING GEOPHYSICAL LOGS TO EVALUATE INTERNAL CIRCULATION IN WELLS, NORTHEASTERN ABU DHABI EMIRATE

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ABSTRACT

Ground water in northeastern Abu Dhabi Emirate occurs in the 100-meter thick surficial aquifer system which is composed of interbedded alluvial and marine deposits. The aquifer system contains localized permeable zones with characteristic water-level and quality. Some zones produce either fresh or brackish water. Salinity generally increases with depth.

Water wells screened in multiple permeable zones need to be carefully constructed to eliminate adverse effects that may arise when an intervening confining layer is breached and permeable zones containing different water quality are connected. Seepage from a saline zone might contaminate the fresh water zone under nonpumping conditions. Fresh water may also be lost through the well or borehole to other unusable zones. Geophysical logs, especially fluid specific conductance and fluid temperature, provide useful tools to evaluate whether a well is experiencing internal flow. For uncased boreholes, these logs may help identify internal circulation between permeable zones and lead to correct well design.

In 1997, the Ground-Water Research Program of Abu Dhabi Emirate logged 16 wells under nonpumping conditions to obtain specific conductance and temperature profiles. The logs indicated that some wells experience internal circulation. The logs are also useful for determining depths such wells should be plugged. Post-plugging specific conductance and temperature logs can be used to evaluate the integrity of the plugging operation. That several wells experienced problems of internal circulation suggests this problem could be widespread because hundreds of wells with unknown construction are located in northeastern Abu Dhabi Emirate.

Keywords: Abu Dhabi Emirate, geophysical logs, internal circulation, well plugging.

INTRODUCTION

Since 1989, the National Drilling Company Ground-Water Research Program (GWRP) has studied hydrologic conditions in Abu Dhabi Emirate. Much of this study has focused on the surficial aquifer system in a 2,400-square-kilometer area in the north eastern part of the Emirate where a reservoir of fresh and slightly-brackish ground water is located (fig. 1). This reservoir is tapped by hundreds of wells that withdraw water for agricultural and municipal supplies. In addition, more than 100 test wells were constructed, logged, tested, and sampled by the GWRP (Bright and Silva, 1998).

The surficial aquifer system is composed of a 100-meter-thick section of eolian sand; alluvial gravel; altered Tertiary deposits consisting of claystone, mudstone, and siltstone; and karstic limestone. A basal confining unit of unaltered Tertiary deposits separates the surficial aquifer system from deep aquifers with characteristically high head and usually saline water. The hydraulic conductivity of the various units ranges between less than 1 and more than 100 meters per day and the total dissolved-solids concentration of the ground water ranges between 200 and about 5,000 milligrams per liter.

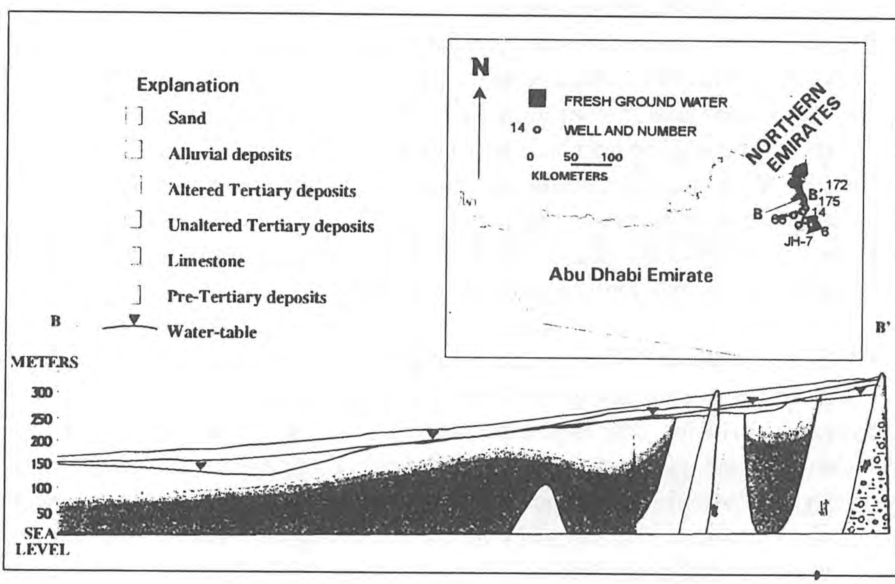

Figure 1. Generalized hydrogeologic section and locations of multizone test wells in northeastern Abu Dhabi Emirate

The surficial aquifer system is composed of interbedded sediments characterized by localized zones of high and low permeability. Some wells are constructed with shallow screens in multiple permeable zones. Through such wells there is a high probability for cross-contamination by internal flow within the well under nonpumping conditions. Depending upon head relations, saline water could move upward from the deeper zone and out into the shallower zone, or fresh water could move downward from the shallower zone to the deeper zone. Water could also move vertically in the annulus between the casing and borehole wall or through the gravel pack.

Borehole geophysical logs, especially fluid specific conductance and temperature, were used to evaluate vertical movement between deep and shallow zones connected by multizone wells. Plugging or sealing the lower zone often may eliminate contamination of or loss of water from the fresh zone.

WELL CONSTRUCTIONS PROBLEMS

Many wells in eastern Abu Dhabi Emirate may be improperly constructed. For example, water-level and water quality (as represented by specific conductance) data from the multiple screened well in figure 2 indicates a water-level decline of about 20 meters and specific conductance change from 1,000 to 1,600 microsiemens per centimeter (μS/cm) over a 2-year period. If this well had been completed with only the upper screened interval, water-quality change may not have occurred.

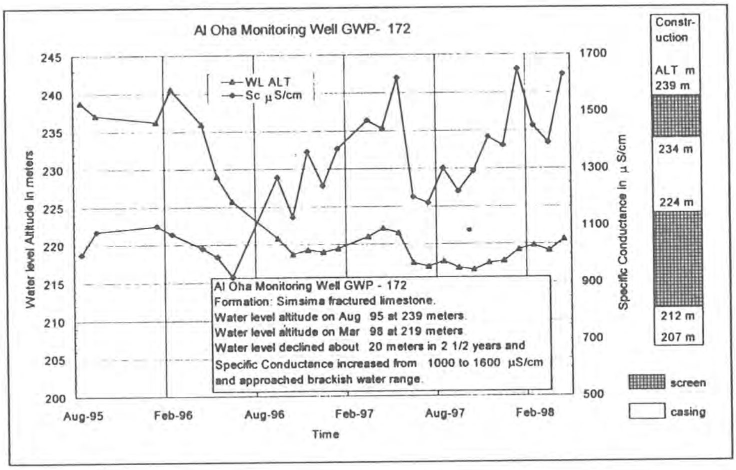

Figure 2. Water-level and specific conductance changes in a multizone well.

A second example that demonstrates the problem of constructing wells in an aquifer system with multiple permeable zones is shown in figure 3. The well was drilled and screened in fractured limestone and siltstone formations. The underlying shale formation was left as an open hole in what was thought to be an impermeable formation.

Because of the excessive pumping from nearby wells, the water level declined and the specific conductance of water continually increased. The problem was investigated by logging the well manually using specific conductance and temperature probes and taking point measurements down the well at one-meter intervals. The resulting log indicated that specific conductance increased from 2,410 (μS/cm) at a depth of 30 meters to 31,200 μS/cm at a depth of 90 meters. It was determined that saline water had moved upward from the shale through the bottom of the open casing. The well was plugged, pumped, and relogged to indicate uniform water quality with depth based on specific conductance measurements between 1,895 and 2,040 μS/cm.

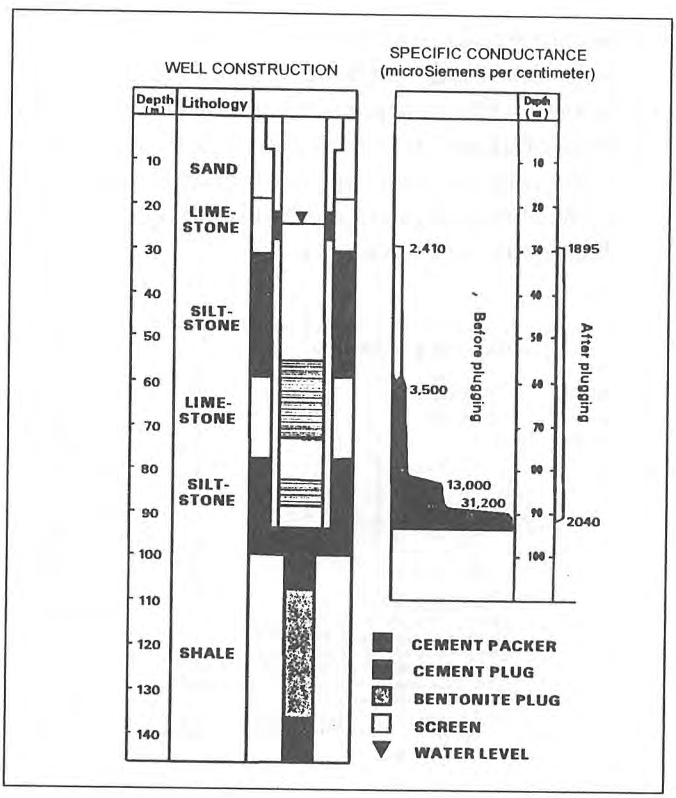

Figure 3. Construction and specific conductance logs before and after plugging a well completed in multiple zones.

Geophysical Logging Principles

Specific conductance and temperature logs are valuable geophysical tools for assessment of the flow regime in a well or open borehole. This information can be used to identify the producing and receiving zones. If wells are completed in multiple aquifers, the casino between multiple screens column serves as conduit between the aquifers. Water will flow upward or downward to the aquifer with low hydraulic head. Fluid movement could occur under pumping and nonpumping conditions as illustrated in figure 4.

Logging wells for specific conductance and temperature for the purpose of studying the flow system in the well is preferred when the well has not been used for a considerable time. This will allow the borehole fluid to be in equilibrium with respect to specific conductance and temperature. It is preferable to run these logs at the beginning of logging operations to run them in the downward direction to avoid disturbance of the borehole fluid column. However, if logs are run before, during, and after a pumping test, a series of time-lapse profiles can at least be used to indicate the base of the lowest producing zone.

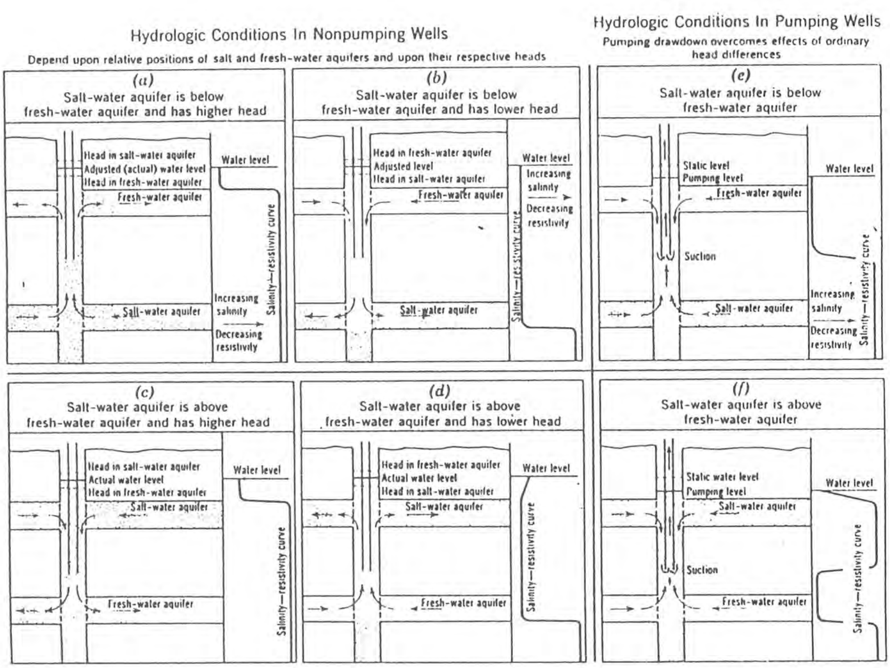

Figure 4. Hydrologic conditions and resistivity curves for wells penetrating two aquifers, under nonpumping and pumping conditions (Todd, 1980, p. 445).

The temperature log provides a vertical profile of ground-water temperature. When there is no internal circulation in the well or borehole, the temperature log is usually a straight line of increasing temperature that indicates the geothermal gradient. Typically, the geothermal gradient ranges between 1 and 1.3 degrees Fahrenheit per 100 feet (°F/100-ft) as reported by Keys and MacCary (1971, p. 99).

A differential temperature log (DT) can be processed from the original temperature log. It is a continuous record of the difference between measured new temperature and the previous measurement on a constant time interval. It is a record of the rate of change in the geothermal gradient curve. A DT log is more sensitive than the temperature log and anomalies of the log can be readily observed and compared.

Temperature logs can also be used to provide information about hydrogeologic conditions and internal water circulation in a well. Any departure from the slope of the normal geothermal gradient may indicate the vertical movement of water in a well or open borehole. Anomalies in the temperature log may also be used to identify direction of internal flow.

LOG INTERPRETATION AND APPLICATION

In 1997, the Ground-Water Research Program logged 16 wells under nonpumping conditions to obtain specific conductance and temperature profiles. Four cases were selected to demonstrate how geophysical logs are being used to evaluate internal circulation within well casings or open boreholes. The locations of the sites are numbered in figure 1.

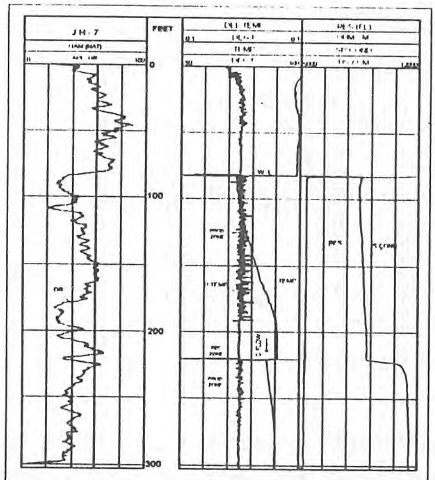

Figure 5 Geophysical logs for well at site JH-7

At site JH-7, a well is completed with an open hole in karstic and fractured limestone. Specific conductance and temperature logs shown in figure 5 were used to define a producing interval between the water table at 83 feet and a depth of 193 feet. This producing interval is indicated by the increase of the temperature log slope and by anomalies of DT log. Between 193 and 223 feet, the temperature log is constant due to the cooling effect of the upper water that is moving downward. The sharp deflections on the specific conductance and temperature logs at 233 feet indicate that a cavity or fracture is accepting the downward flowing cool water. The temperature log follows the geothermal gradient below a depth of 233 feet, which indicates no internal circulation below this depth.

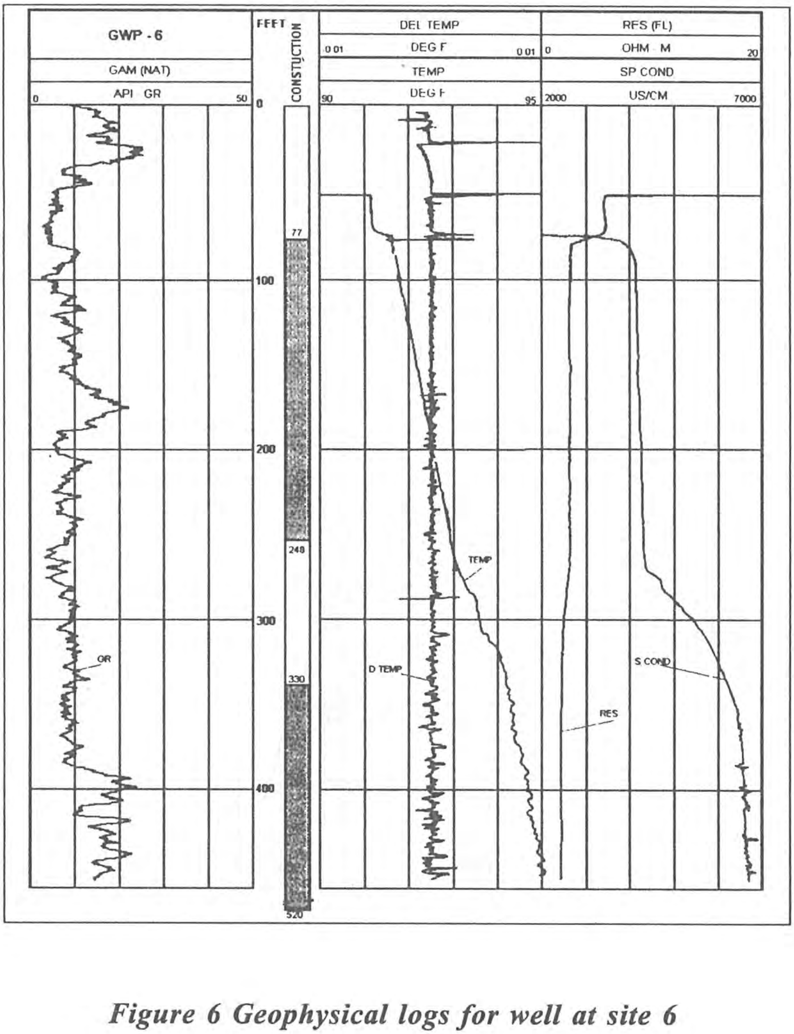

Figure 6 Geophysical logs for well at site 6

At site 6, a well was completed with screened depths from 77 to 248 and 330 to 520 feet, cased depths were 0 to 77 feet and 248 to 330 feet. The well was logged in July 1997, eight years after construction. The upper screened zone contains water with a specific conductance of 4,000 µS/cm. Below 330 feet, the water is more saline, with a specific conductance of about 6,000 µS/cm. Specific conductance increases downward within the cased interval between the screens. This likely indicates that the salinity increase is due to molecular diffusion or thermal convection rather than internal flow between the upper and lower screens. The steadily increasing temperature follows the geothermal gradient and supports the conclusion that there is no internal flow. Sealing the bottom screened section would result in a significant improvement in well-water quality.

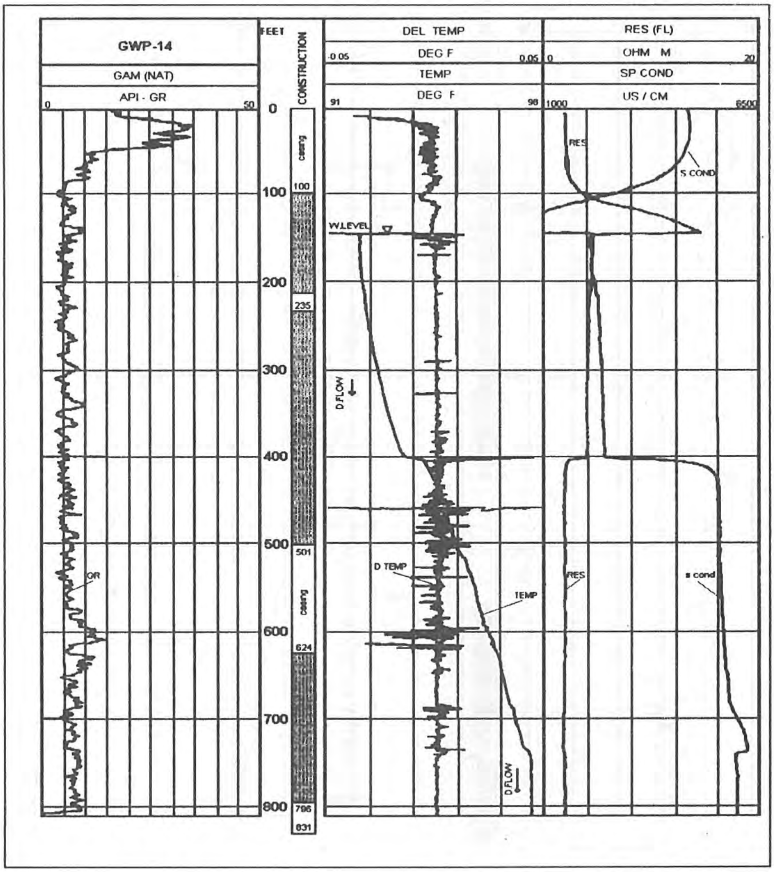

Figure 7 Geophysical logs for well at site 14

The well at site 14 is completed in multiple zones with screen at depths from 100 to 214, 235 to 501, and 624 to 796 feet (fig. 7) Geophysical logs were run in the well eight years after construction. Depth to water was 145 feet. The logs indicate two water-quality zones. The upper zone is composed of alluvial sediments and contains water with a specific conductance of about 2,300 μS/cm. The lower zone is composed of interbedded sand, silt, and limestone containing more saline water with a specific conductance of about 5,500 μS/cm. The two zones are separated by a marl layer between 405 and 425 feet. The temperature gradient in the upper zone is 0.7°F/100-ft, or about half the normal geothermal gradient and the temperature gradient in the lower zone is about 1°F/100-ft. A third shift in the temperature gradient is evident below a depth of 735 feet. Anomalies in the specific conductance and temperature logs at 400 feet and 735 feet indicate internal circulation within the well. Internal flow would cease and quality of water would improve if the well was sealed below 400 feet.

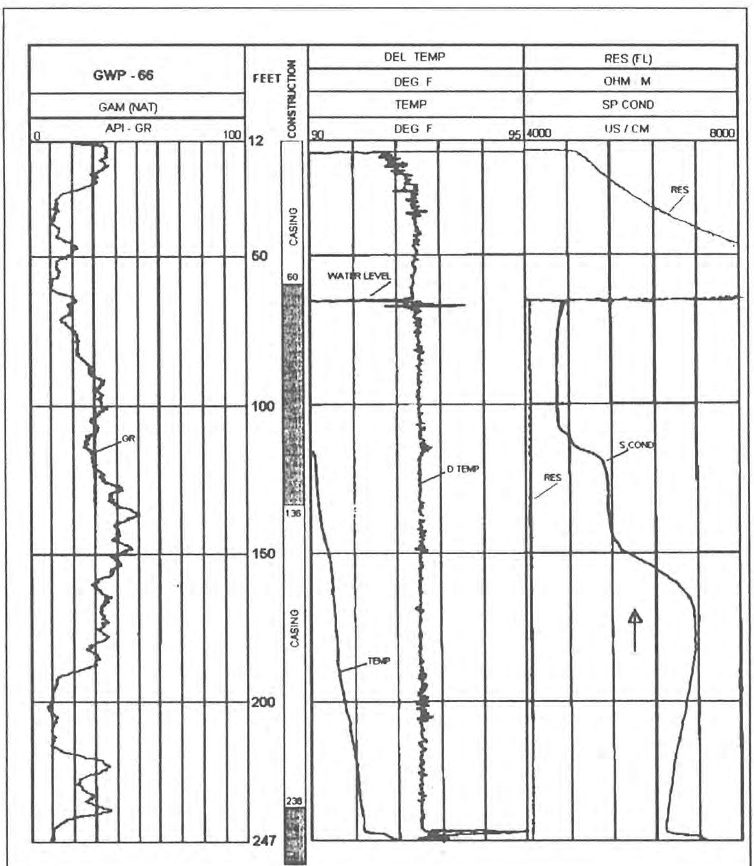

Figure 8 Geophysical logs for well at site 66

The well at site 66 is completed in multiple zones with screen at depths from 60 to 136, and 238 to 257 feet (fig. 8). Geophysical logs were run in the well six years after construction. Depth to water was 65 feet. The thermal gradient averages 1°F/100-ft between depths of 120 and 240 feet, although small changes are evident within this interval. An obvious break in the thermal gradient occurs at a depth of 245 feet. The rapid increase in temperature is accompanied by a deflection in the specific conductance from 6,600 to 7,400 μS/cm. By relating well construction to the logs, it is apparent that the well breaches a confining unit and connects two permeable zones. Saline water moves upward to, the upper screen and is contaminating the bottom half of the upper permeable zone.

CONCLUSIONS

Specific conductance and temperature logs are useful tools for identifying causes of salinity increases and internal flow in wells. However, such indirect methods for analysis of well construction problems is subject to error. It is recommended to support and confirm log interpretations with flow meter surveys that measure the direction and rate of vertical flow. These logs should always be run prior to conducting well-plugging programs.

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Surface Water

Rainfall-Runoff Relationships in an Arid Area
Case Study, Wadi Ahin-Oman

Aisha Al-Qurashi and Dr. G. Herbertson

RAINFALL-RUNOFF RELATIONSHIPS IN AN ARID AREA CASE STUDY, WADI AHIN-OMAN

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ABSTRACT

A study was undertaken of the rainfall-runoff relationship for Wadi Ahin in the Sultanate of Oman. As is typical of arid regions the amount and quality of data for such a study was very limited due to the short period of data collection and the infrequency of rainfall-runoff events. Despite this, trends and the most significant parameters were identified. This will provide a firm basis for gauge network improvement and for planning of further studies.

The rainfall-runoff relationships were found to vary from summer to winter, with summer events yielding a greater percentage of runoff. The relationships show that losses are generally high with initial losses varying from under 8 mm to around 20 mm. Continuous losses such as those due to evapotranspiration and transmission were also found to be significant but again were found to vary considerably from event to event. Despite this a very strong correlation was found between transmission loss and the flow volume passing the upstream station.

KEY WORDS: rainfall-runoff, arid areas, transmission losses, evapotranspiration, Wadi Ahin.

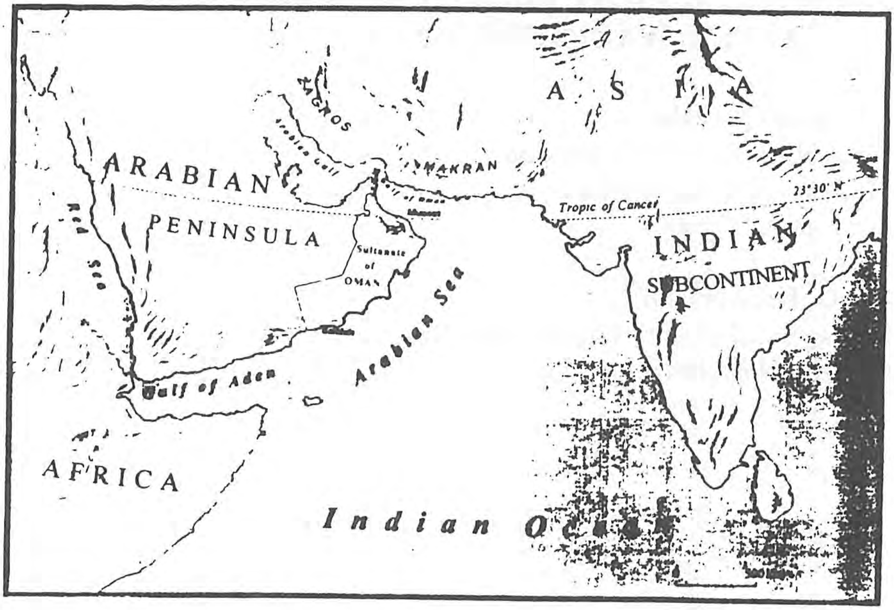

Figure 1.1: Sultanate of Oman - geographical location

1. INTRODUCTION

The rainfall-runoff relationship is one of the most important aspects of hydrology. Many studies of the relationship have been made but most of these have been concerned with humid areas. Very little attention has been given to arid areas. The present study seeks to some extent to address this deficiency.

Arid areas have many distinctive features and these require different modelling approaches from those appropriate to humid areas. In particular in arid areas there is an absence of base flow, sparsity of plant cover, greater temporal and spacial variation of rainfall, and transmission losses are of critical importance. In addition there are differences in runoff producing storms, in evaporation and evapotranspiration, in rapidity of surface ponding and in the climatology in general. Hydrographs are flashy with steep rising and falling limbs. The quality of data in many arid areas is poor due to the sparse rainfall and runoff coverage, isolation of recording stations, difficulties of access in rainy periods, the high variability and irregular occurrence of flow, the lack of suitable natural control sections in streams with movable beds, difficulties of current metering with high sediment and debris loads, and the harsh climatological and physical conditions, El Hames et. al. (1994). In carrying out studies in arid areas, it is important that all these features be borne in mind.

The Sultanate of Oman is an arid area with average annual rainfall amounts varying from 50 mm in central Oman to 300 mm in the mountain areas in the north. The rainfall also varies greatly from one year to another. The geographical location of Oman, as Fig. 1.1 shows, has a large influence on its climate. It is located in a zone where different weather systems are dominant in different seasons. The seasons in Oman can be divided into two: summer, from April to October, and winter, from November to March. In recent years, hydrology has received high priority from the Government with the formation of a new ministry, Ministry of Water Resources (MWR). MWR is the authority responsible for carrying out all studies dealing with water resources and hydrology. It is also responsible for collecting of rainfall, runoff and falaj data as well as for monitoring ground water levels.

This paper examines the adequacy of the rainfall and stream flow network to establish a simple rainfall-runoff relationship and to make an initial assessment of loss components. Wadi Ahin catchment was chosen for the study.

2. SITE DESCRIPTION

Wadi Ahin is located in the North Al Batinah region lying between longitude of 0420 to 0490E and latitude of 2640 to 2700N, and extending from the mountain area to the coast (Fig. 2.1). This catchment was chosen because of its simple geology, its manageable size of about 900 km^2 and because of its reasonable quality data and length of record. The catchment is located in a frontal mountain area, consisting mostly of opholites. The drainage pattern is of a typical dentric pattern with a fairly uniform wadi density and the stream frequency over the mountain area. The cross-sectional profile is generally of v-shape for high order streams, except where the wadi bed is wide such as upstream of Al Hayl and around Haybi and Al Qufays.

The catchment has four wadi flow gauges, Al Hayl and Majis Kabirah inland and another two gauges near the coast on left and right channels near the highway. There are no tributaries between Hayl and Majis Kabirah, hence this section is good for estimating channel transmission losses. There are five rainfall stations, Wuqbah, Qufays, Haybi, Hayl Ashkharyin and Ghuzayfah.

The Hayl flow station represents the mountain area as it is located upwadi

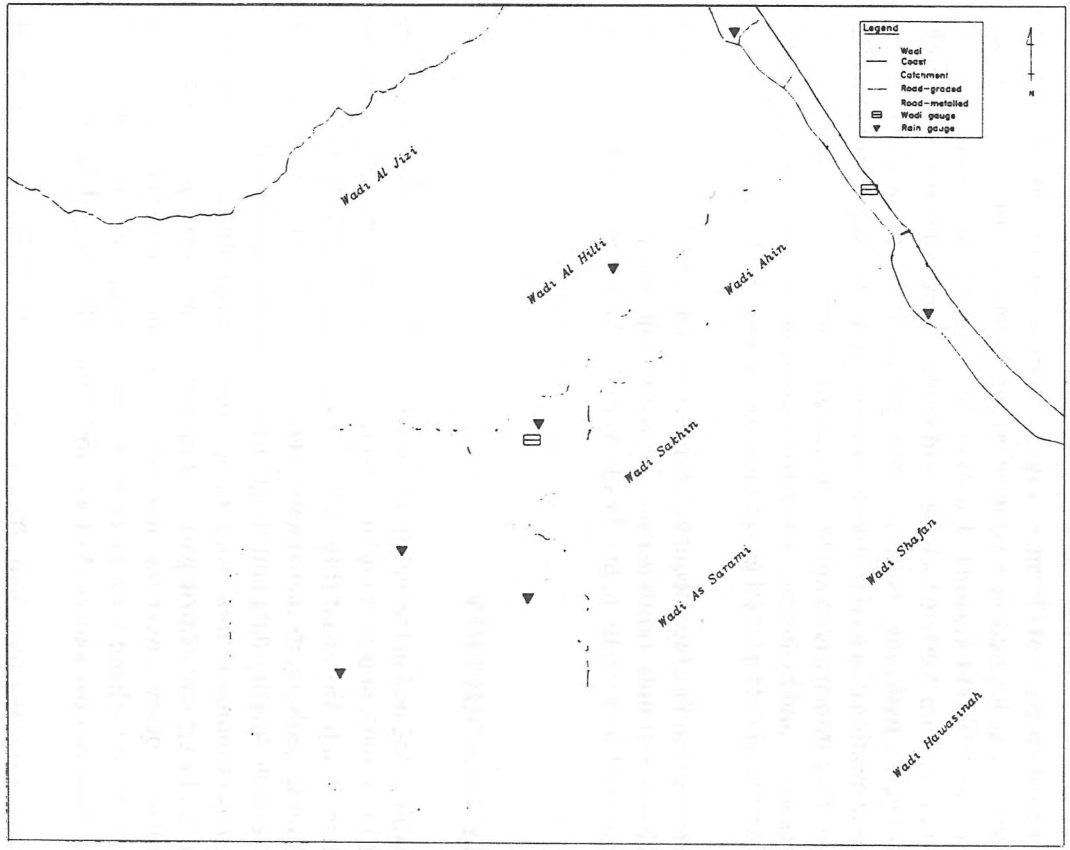

Figure 2.1: Location of rainfall and flow recording gauges

in a gorge in the foothills. Majis Kabirah is located out in the Batinah plain near the coast. Both stations use Omnidata, Model II Datapod gauge instruments.

3. DATA ANALYSIS

The analysis of the rainfall-runoff data was carried out using a primary input of daily rainfall in mm and the daily runoff volume in cubic metres for the hydrologic years 1987 to 1995. For the purpose of this study, a simple regression relationship was attempted between rainfall and runoff for selected events. Primary checks on initial losses, evapotranspiration, and transmission losses were also made and the results compared with those of previous studies in other parts of Oman or in other arid countries.

3.1 Rainfall

Table 3.1 shows the details of the five rainfall stations within the catchment area. These stations are all located in the mountain area and therefore, three rainfall stations from the neighbouring catchments (Dhoharat, Sohar, Saham) were added to the analysis to represent the plain area. Automatic gauges were chosen as far as possible, the exception being at Haybi where only a standard gauge was available.

The average rainfall depth was determined using Thiessen polygons, as using isohyets was thought unlikely to give better results with the present coverage of long term rainfall gauges.

Table 3.1: Rainfall stations details

Station Name	Station I. D	Wadi Basin	UTM Coord.	Elevation (m)	Type of Gauge	Period of Operation
Wuqbah	DM339923AF	Ahin	0439200E 2639300N	750	AUT	1983-
Qufays	DM444945AF	Ahin	0444400E 2649500N	570	AUT	1983-
Haybi	DM545506AF	Ahin	0455000E 2645600N	540	STD	1974-
Hayl Ashk-haryin	DM565082AF	Ahin	0455862E 2660102N	300	AUT	1983-
Dhoharat	DM672387AF	Hilti	0462094E 2673060N	160	AUT	1984-
Sohar	DM792227AF	Hilti	0472200E 2692700N	15	AUT	1977-
Saham	DM868954AF	Sarami	0488500E 2669400N	10	AUT	1983-

3.2 Runoff

The daily runoff was calculated in mm for each selected event. Only high events which reached the downstream station were selected. The quality of the recorded data for the selected events was also checked to give confidence in the results.

The downstream station (Majis Kabirah) is located about 42 km from Hayl wadi flow station. Table 3.2 gives details of the two wadi gauges.

Table 3.2: Wadi stations details

Station Name	Station I. D Basin	Wadi Coord.	UTM (m)	Elevation Area	Drainage Gauge	Type of Operation	Period of
Ahin nr Hayl	DB554869AD	Ahin	0454600E 2658800N	300	734	-water stage recorder -crest-stage gauge	1983-
Ahin nr Majis Kabirah	DB872977AD	Ahin	482809E 2679706N	9	879	-water stage recorder -crest-stage gauge	1985 -

3.3 Rainfall-runoff relationships

Rainfall and the corresponding runoff was determined for the selected events. Analysis of these showed a distinction between summer and winter events. Some of the differences can be seen in Tables 3.3A and 3.3B and in Figs 3.3.1A and 3.3.1B, 3.3.2A and 3.3.2B).

Table 3.3A: Hayl Station, rainfall-runoff relationships, 1987-95

Event	*Rainfall (mm)*	*Runoff (mm)*	*Runoff Coeff.*	*Season*
21-24 Feb 87	21.77	1.57	0.07	Winter
07-10 Apr 87	23.60	1.66	0.07	Summer
17-20 Feb. 88	48.10	1.62	0.03	Winter
16-19 Dec 89	12.31	1.03	0.08	Winter
07-18 Feb. 90 (*)	53.10	11.36	0.21	Winter
02-06 Apr 92	49.10	6.08	0.12	Summer
20-22 Jul. 92	9.40	3.98	0.42	Summer
09-14 Aug. 92	6.90	2.89	0.42	Summer
02-04 Apr 93	2.21	0.36	0.16	Summer
08-10 May 93	19.28	1.71	0.09	Summer
08-10 Aug 93	7.45	1.55	0.21	Summer
25-27 Dec 93	0.13	0.07	0.54	Winter
04-05 May 94	3.98	0.84	0.21	Summer
21-25 Jul 95	106.01	9.68	0.09	Summer

(*): estimated flood volume

Table 3.3B: MK Station, rainfall-runoff relationships, 1987-95

Event	*Rainfall (mm)*	*Runoff (mm)*	*Runoff Coeff.*	*Season*
20-21 Feb 87	22.91	0.002	8.73E-05	Winter
07 Apr 87	21.086	0.074	0.004	Summer
18-19 Feb 88	55.74	0.681	0.012	Winter
16-17 Dec 89	16.79	0.106	0.006	Winter
11-12 Feb 90	52.78	0.313	0.006	Winter
04-05 Apr 92	46.99	0.516	0.011	Summer
22-23 Jul 92	8.39	0.36	0.043	Summer
11-12 Aug 92	5.8	0.079	0.014	Summer
02-04 Apr 93	3.82	0.14	0.037	Summer
08-10 May 93	17.91	0.31	0.017	Summer
08-10 Aug 93	6.22	0.14	0.023	Summer
25-27 Dec 93	2.43	0.23	0.095	Winter
04-05 May 94	3.5	0.16	0.046	Summer
*21-25 Jul 95**	102.36	3.42	0.033	Summer

Note: (*): A dam started to operate between Hayl and MK, therefore runoff coefficient for this event can't be used.

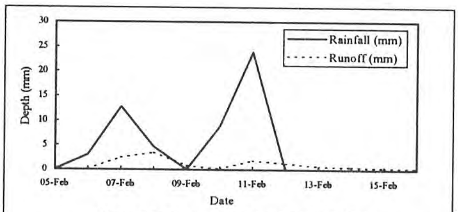

Figure 3.3.1A: 11-15 Feb 1990 Flood at Hayl

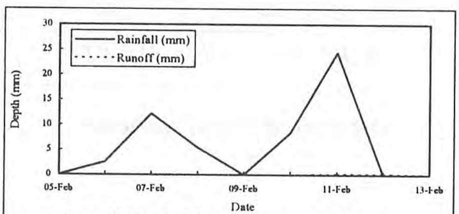

Figure 3.3.1B: 11-12 Feb 1990 Flood at Majis Kabirah

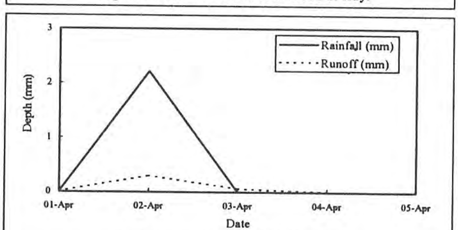

Figure 3.3.2A: Apr 1993 Flood at Hayl

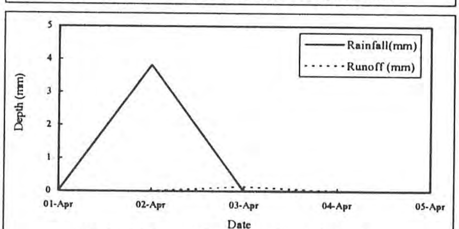

Figure 3.3.2B: Apr 1993 Flood at Majis Kabirah

RAINFALL-RUNOFF HYDROGRAPHS

Linear regression correlation was tried for the summer and winter events for both stations but the correlation obtained was poor. The summer results are plotted in Figs 3.3.3A and Figs 3.3.3B. The regression value r was 0.85 and 0.50 for Hayl and MK respectively. The best fit equations for Hayl and MK respectively are:

$$Runoff = 0.082*Rainfall + 1.111 \quad (1)$$

$$Runoff = 0.008*Rainfall + 0.115 \quad (2)$$

The winter events, as shown in Figs 3.3.4.A and Figs 3.3.4B show regression values of r = 0.46 and 0.74 for Hayl and MK respectively. The best fit equations for Hayl and MK respectively are:

$$Runoff = 0.173*Rainfall - 2.005 \quad (3)$$

$$Runoff = 0.128*Rainfall - 0.199 \quad (4)$$

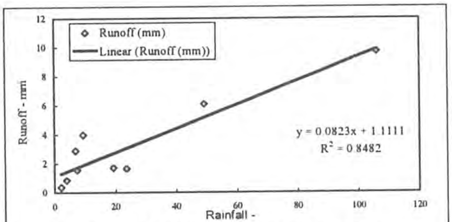

Figure 3.3.3A: Summer Events at Hayl, 1987-95

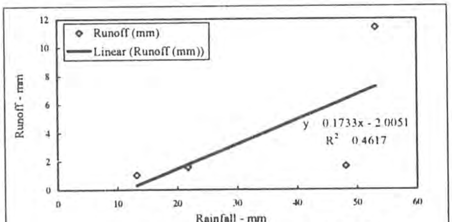

Figure 3.3.4A: Winter Events at Hayl, 1987-95

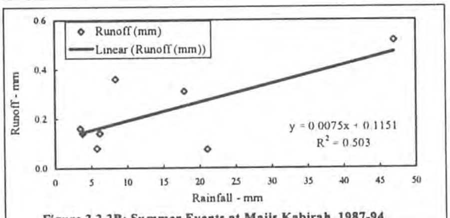

Figure 3.3.3B: Summer Events at Majis Kabirah, 1987-94

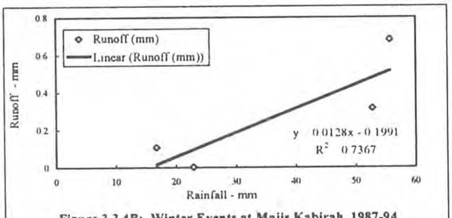

Figure 3.3.4B: Winter Events at Majis Kabirah, 1987-94

RAINFALL-RUNOFF CORRELATIONS

3.4 Initial and continuous losses

The relationships between rainfall and runoff show that a large amount of rainfall is lost. The losses include initial losses, evapotranspiration, infiltration, and transmission losses. An hourly analysis of rainfall and runoff was carried out for two events (July and August 1992 events) to estimate the range of initial and depression storage losses. The lag time between the occurrence of rainfall and runoff was variable making it difficult to quantify the losses. However, an attempt was made and values ranging from less than 8 mm to around 20 mm were obtained. Further study is required to properly quantify this parameter. Attempt was also made to quantify the infiltration values but unfortunately there wasn't enough data available and the values obtained from the site varies widely from one location to another. Infiltration is affected by the soil type, soil moisture, wet period,...etc.. Further investigation is necessary to quantify such an important parameter.

There is some sparse vegetation over the catchment as well as some farms on the channel bank, so it was thought relevant to calculate the evapotranspiration for the rainy days. This was done using the modified Penman-Monteith method, (FAO, 1990):

$$ET_o = ET_{rad} + ET_{aero} \tag{5}$$

where:

$$ET_{rad} = \frac{0.408\,\Delta\,(R_n - G)}{\Delta + \gamma\,(1 + 0.34\,U_2)} \tag{6}$$

and

$$ET_{aero} = \frac{\gamma}{\Delta + \gamma\,(1 + 0.34\,U_2)} * \frac{900}{(T + 273)} * U_2\,(e_a - e_d) \tag{7}$$

where:

ET_o	:	reference evapotranspiration of standard crop canopy [mm/day]
ET_{rad}	:	radiation term [mm/day]
ET_{aero}	:	aerodynamic term [mm/day]
Δ	:	slope vapour pressure curve [$kPa°C^{-1}$]
R_n	:	net radiation flux at surface [$kJm^{-2}s^{-1}$]
G	:	soil heat flux [$kJm^{-2}s^{-1}$]
γ	:	psychrometric constant [$kPa°C^{-1}$]
U_2	:	wind speed measurement at 2 m height [$m\ s^{-1}$]
T	:	air temperature [°C]
$e_a - e_d$	:	vapour pressure deficit [kPa]

As stated previously the values of evapotranspiration were calculated only for rainy days. As anticipated the evapotranspiration was found to be greater in the summer with values between 2.2 mm and 6.9 mm for the April 1992 event. Winter evapotranspiration was 1.7 mm in February 1988 and 5.0 mm in December 1989.

High transmission losses are a particular feature of arid areas and in this case the transmission losses were calculated between Hayl and MK. The total volume of losses between the two stations was found to be in the range of 88 - 95% for high floods and up to 100% for small floods. The two stations are 42 km apart and unfortunately there are no stations between them so detailed analysis of the losses is not possible. Fig 3.4.1 shows the losses between Al Hayl and MK and from this the relationship between the total volume of the losses and the volume passing the upstream station was found. The best fit equation is:

$$T.L = 1.0013 * V_A - 201075 \tag{8}$$

where:

$T.L$: the total transmission loss.

V_A : upstream station volume.

The correlation between the total losses and upstream volume is strong with r=0.999. To standardise the data, the losses for the first mile for each event were calculated using Jordan's (1977) equation. The same equation was used by Walter (1990). The equation is:

$$V_1 = V_A \left(1 - \left(\frac{V_x}{V_A} \right)^{1/x} \right)$$

Where

V_1 : the loss in the first mile

V_A : the flow volume at the upper station

V_x : the volume of flow at distance x respectively

The values obtained are listed in Table 5. The calculated average loss per mile, *T.L*, was then plotted against the upstream volume, Fig 3.4.2. The best fit equation is:

$$T.L = 0.0383 * V_A - 6.3407 \tag{10}$$

Table 5: Transmission loss data

Date	U/S Flow, Hayl	D/S Flow, MK	T.L	W. Length	Avg Loss	Loss in first mile
	(V_A)	(V_X)		(X)	per mile	(V_{II})
	acre-ft	acre-ft	acre-ft	mile		acre-ft
07-10 Apr 87	998	53	945	26.15	36.14	106.05
16-19 Dec-89	611	76	535	26.15	20	47
07-18 Feb-90	6,763	224	6,539	26.15	250	827
02-06 Apr-92	3,623	368	3,255	26.15	124	303
20-22 Jul-92	2,402	257	2,114	26.15	81	197
09-14 Aug-92	9,858	56	9,801	26.15	375	1,767
02-04 Apr-93	213	101	113	26.15	4	6
08-10 May-93	1,020	221	799	26.15	31	58
08-10 Aug-93	9,195	102	9,094	26.15	348	1,455
04-05 May-94	496	113	383	26.15	15	27

Note: 1km=0.6214 mile, 1acre-ft=1233.5m³

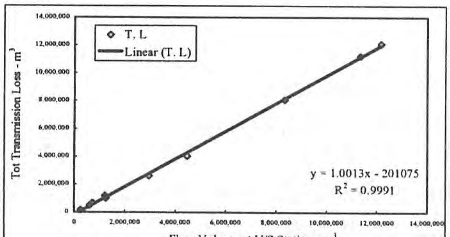

FIG. 3.4.1: Relation of Total Transmission Losses to U/S Station Volume

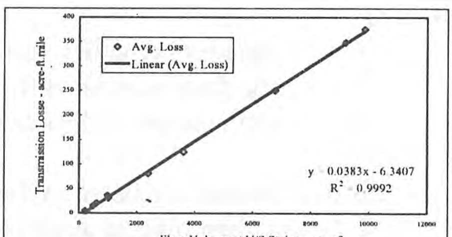

FIG. 3.4.2: Average Transmission Loss per mile & U/S Station Volume

TRANSMISSION LOSSES BETWEEN WADI GAUGES

4. DISCUSSION OF RESULTS

The results of this study show clearly that, the characteristics of the rainfall-runoff relationships are different from those in humid areas. Agreement is good with similar studies in the other arid areas. Rainfall-runoff plots show a high degree of scatter. The scatter could be due to spatial and temporal variations as suggested by Rodier (1985), and Wheater (1991a), but the short period of records and the sparse rainfall network make this difficult to ascertain. This is a particular problem in arid areas where rainfall and runoff events are very infrequent and even long periods of records may only contain very few flood events as indicated by El Hames (1994).

The effect of seasonality is also clear from the analysis, This effect was also noted in studies by Rodier (1985), JICA (1986), Wheater (1991) and El Hames (1994). The summer floods have higher runoff values for the same amount of rainfall compared with winter events and they have steeper rising and falling limbs due to the high rainfall intensities and the negligible interception capacities.

The runoff coefficients were determined for each summer event and for each winter event for each station. The summer coefficients at Hayl varied from 0.09 to 0.42 and from 0.003 to 0.046 at Majis Kabirah. The winter coefficients varied from 0.03 to 0.21 at Hayl and <0.0001 to 0.01 at Majis Kabirah. The runoff coefficients decrease as the catchment size increases. This agrees with the findings of Cordery and Pilgrim (1983). The large variability of these values is reflected in other studies. Gibb (1976) found that the typical range of runoff coefficients for monthly rainfall data was 0.017 to 0.20. These increased to 0.25 to 0.35 in a hard rock area. Wheater and Bell (1981) obtained values of 0.0001 to 0.0121 in the North of Oman and Sorman and Abdulrazzak (1993) obtained 0.01 to 0.07. The general conclusion is that more studies are required to identify the reasons for this large range of variations.

The regression equation derived for the rainfall-runoff relationship for combined summer and winter events shows poor results. However, when the summer and winter events are considered separately the correlations are better, thus confirming the seasonal effect. Unfortunately the short period of records and the very few events make the regression equations statistically invalid and should be considered as simply indicative of possible trends.

Previous studies have given a range of predicted values for initial losses. Cordery (1983) suggested a value smaller than 2.5 mm for small watersheds, while Gibb (1976) and Bell (1981) used values of 8 mm. In their study in Saudi Arabia, Wheater and Bell (1987) obtained values of 20 mm. In the present study some events produced values as high as 20 mm, but in other cases runoff resulted from rainfalls of less than 8 mm. In order to explain this variation, a more detailed investigation is required which would include factors such as basin geomorphology, but first considerable improvements would have to be made in the density and coverage of the gauge network.

In previous studies opinion has varied on whether or not to include the effects of evaporation and evapotranspiration losses in rainfall-runoff relationships. Wheater and Parisspoulos (1992) consider that they could be ignored in the case of flashy floods with high velocities and short durations. In the present study of Wadi Ahin, the calculated values of evapotranspiration were in the range of 1.71 to 4.97 mm for winter days and 2.18 to 6.89 mm for summer days. These amounts are comparable with those obtained by Mott MacDonald (1991). It should be noted that these values were calculated only for rainy days. Values on normal (dry) days are likely to be greater. It is thought that in the case of Wadi Ahin, particularly at Hayl, the effects of evapotranpiration should be included because floods have a relatively long duration and base flow is present.

Transmission losses are very important in arid regions. This is confirmed by the large number of studies dealing with them, e.g. Sharp and Saxton (1962), Jordan (1977), Cordery (1983), Walter (1990). Transmission losses are very high and like all parameters in arid regions are very variable. Sharp and Saxton (1962) reported values as high as 150,000 m^3/km. The present study shows a range of 16,000 to 29,000 m^3/km. Much of the variation can be accounted for by the fact that transmission losses depend on the catchment characteristics.

The correlation obtained in the present study was very strong, r=0.999. Thus despite the very limited data set a usable relationship was produced linking flow at the upstream, Hayl, and downstream, Majis Kabirah, stations.

5. CONCLUSIONS

(i) The study confirmed that the characteristics of rainfall-runoff relationships in arid areas are significantly different from those in humid areas. The results show very considerable scatter due to large temporal and spatial variations in rainfall over the area, the short period of the records and the relatively poor quality of the data and of the gauge network cover.

(ii) Despite the large scatter the effect of seasonality on the rainfall-runoff relationships is apparent. Summer events have higher runoff coefficients than winter events principally because in summer the rainfall is more intense and has shorter duration and smaller areal extent. More data and further study are required to confirm and quantify these trends.

(iii) The rainfall-runoff relationships show that losses are generally high but appear to vary very considerably from one event to another and from one season to another. The uniform value of 8 mm for initial losses recommended by Gibb (1976) and Wheater and Bell (1981) was found inappropriate, with values ranging from under

8 mm to 20 mm. Again further data are required to confirm these results.

(iv) Seasonal trends are also apparent in the calculated values of evapotranspiration. The summer values are higher than the winter values. Amounts are significant in the Wadi Ahin catchment and cannot, as has been suggested in some previous studies, be ignored in the overall assessment of losses.

(V) Transmission losses were determined between Hayl and Majis Kabirah. The losses are significant and the analysis shows a strong relationship between the transmission loss and the volume passing upstream station. The regression equation derived has an r value of 0.999 and is considered adequate for estimating the flow volume when a record is missing at any one of the two stations in this study area.

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Description of Cloud Seeding Experiment in North Libya

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DESCRIPTION OF CLOUD SEEDING EXPERIMENT IN NORTH LIBYA

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INTRODUCTION

The lack of fresh water for human consumption, agricultural purposes, and variety of industrial uses increasingly becoming a problem throughout the world. The calculations at the last few years indicate that the consumption of fresh water rate in all over the world increased by 4%, and it is now about 3.300.00 m^3 for person per year.

Shortages arise in highly developed areas (e.g. the southwestern United States) as well as in areas lacking the sources to attempt costly remedies for the lack of water (e.g. north central Africa). Shortages arise because of over utilization of existing ground water or because of a lack of replenishment of the ground water due to short-term or long-term decreases in precipitation.

Traditional solutions to the problem have been to better utilize surface runoff with dams and altered cropping practices, to consider limiting or moving population, and to initiate rainfall augmentation programs to modify the clouds to increase its ability to give amounts of rain more than the normal case.

In this paper we present an interesting typical case study of cloud seeding experiment conducted over Tripoli on 24 January 1990 using silver iodide (AgI) nucleating crystals as an example of the weather modification and precipitation enhancement work being carried out in Libya.

CLOUDS

The cloud formation (condensation) which is considered as one of the important meteorological variables occurs when air is cooled below its dew point, thereby creating a slight supersaturation, which activates as Cloud Condensation Nuclei (CCN) some tens or hundreds of the most suitable particles present in each cubic centimeter of air. The cloud type, thickness and microstructure depend upon meteorological conditions, including temperature and humidity fields in 3 dimensions, the cooling mechanism and the population of small particles present.

The first published classification of clouds was that of the French naturalist (Jean Babtiste Lamarck) in 1802, in which a limited number of interesting cloud forms were identified and named (in French). Although Lamarck's names were never adopted, his method of dividing the regions where clouds form in to three layers is used in modified forms in the present international classification of clouds ("International Cloud Atlas" World Meteorological Organization 1956). The basis of the international classification of clouds is the system proposed by the English meteorologist (Luke Howard) in 1803 who used the four Latin names *cumulus* (a heap or pile) for convective clouds, *stratus* (a layer) for layer clouds, *cirrus* (a filament of hair) for fibrous clouds, and *nimbus* for rain clouds. In general clouds are divided or classified in to three types which are low, middle, and high.

Cold Clouds

Cold clouds are those clouds in which "ice" plays a dominant role in the precipitation physics. In most temperate and continental regions of the world, the precipitation that falls to earth in the form of rain, originated at the upper regions of the clouds as ice crystals which grew and eventually melted during their fall to earth. These "cold" clouds do not rain if they do not grow tall enough or live long enough, to allow the formation of ice crystals of precipitation size.

Warm Clouds

Warm clouds are those clouds in which the ice phase does not play a significant role in the formation of precipitation. Although the cloud tops of these clouds may extend higher than the freezing level, the collision and coalescence process involving water droplets is the dominant precipitation mechanism. Thus, the warm - rain process involves only liquid droplets and is generally associated with tropical and subtropical regions which are sufficiently warm to allow clouds to form with substantial cloud depth warmer than freezing.

CLOUDS IN NORTH AFRICA AND MEDITERRANEAN

One of the most notable features of the Mediterranean cloud cover is that the area is nearly cloudless during the Summer and about 50 % overcast during the Winter. From November to February, the central regions, including Italy, Greece and the Aegean sea are 50-60 % covered and eastern Spain and Egypt are 35 % covered. In Spring, the cloud area gradually retreats northward, and in May a mean cloudiness of 50 % is found only over northern Italy and north of northern Greece. During the Summer, northern Italy retains a 40 % cloud cover, while all other sections enjoy nearly cloudless skies. In September, the overcast begins to increase again, but is not appreciable until October. In that month, a 50 % cover will be found over Italy and Sicily, while eastern Spain and Egypt are still clear. The wedge of cloudiness, which has spread south, then extends itself east and west in returning to Winter conditions. The distribution of mountain ranges, the changes of air-mass characteristics determine which cloud types will form.

Air moving over the Mediterranean from North Africa is warmer than the sea at all seasons, especially in Winter, whereas air reaching it from the North eastern Atlantic is cooler at all seasons, but especially in the Summer. Continental air reaching the Mediterranean from Europe is heated from below in the Winter, but cooled in Summer.

Studies of cloud formation and lifetime in the Mediterranean indicates that the length of cloud bands in the region is between 3000 to 10000 Km, with a width ranges from 600 to 1400 Km, it's lifetime is between one day to 11 days, and in some rare cases it can survive up to 19 days. The mean lifetime of these bands for the whole year is 5.4 days and the highest mean for a month is 6.2 days which occurs in March, and the lowest one is 3.5 days which occurs in June (H.M. Zohdy).

WEATHER MODIFICATION AND CLOUD SEEDING

The first carefully observed experiments, which opened the way to cloud modification research, were carried out by (Vincent J. Schaefer) at the General Electric Laboratory in July 1946. He observed the dramatic effect of dropping a bit of dry ice (solid CO_2) in to a supercooled laboratory cloud, thereby producing some 10^8 ice crystals in a volume of about 0.13 m^3. Dry ice, whose temperature is -78.5 øC , cools the nearby air thus producing very high supersaturation and leading to production of many ice crystals by homogeneous nucleation. Subsequently, field observations demonstrated that dry ice dropped into supercooled layer clouds can convert large volumes of the clouds in to glaciated clouds. In some cases precipitation fell, leaving clear air surrounded by cloud. Ice crystal clouds also have been formed by dropping dry ice into air which is saturated with respect to ice but not with respect to water.

Soon after Schaefer's demonstration of the effect of dry ice on supercooled cloud (Bernard Vonnegut) in the General Electric Laboratory discovered that silver iodide crystals are effective in producing ice crystals in water clouds at temperatures below -4 ºC. Subsequently, silver iodide was shown to be effective in modifying natural clouds.

The importance of Vonnegut's discovery was that, although silver iodide is somewhat less effective than dry ice in nucleating ice crystals, it can be introduced into the atmosphere upwind of the target area and perhaps at the ground, where the temperature may be above 0ºC, and can then be carried into supercooled clouds by natural air currents. Also whereas dry ice creates ice crystals in large concentrations and therefore tends to overseed in the region of seeding, silver iodide concentrations of ice nuclei (of the order of 10 per liter) may be possible.

At present, silver iodide (AgI) appears as the most suitable glaciogenic seeding agent, one difficulty with using it is that the number of active ice nuclei among a population of AgI crystals increases by about one order of magnitude for each 4ºC drop in temperature down to near -20ºC, Figure 1. This means that larger amounts of AgI may be required to seed cloud with top temperatures a few degrees below 0ºC than to seed larger clouds with colder tops. However, there is little point in searching for seeding agents able to cause freezing at temperatures very close to 0ºC, say at -1 to -2 ºC, because the growth rate of ice crystals surrounded by supercooled water goes to zero when temperature is 0ºC.

PRECIPITATION ENHANCEMENT BY CLOUD SEEDING

Field experiments in the early 1950's in the United States and Australia showed that seeding of Winter supercooled orographic clouds (produced by airflow over mountains) seemed to result in average increases in precipitation of 10 % - 15 %, somewhat less than the year to year variability of natural precipitation, but still an economically significant increment.

Although a great deal has been learned about cloud physics in the years since these early experiment, evaluations of the most carefully conducted programs carried out in recent years in the United States and (the middle east) indicate that seeding may result in increase or in decrease in Winter orographic precipitation, but that the average increase over a season is still limited to about 10 % - 15 %.

Results of seeding cumulus clouds have varied widely, some series of experiments have resulted in precipitation decrease while others have resulted in increase. The most encouraging results have been reported from a series of experiments carried out since 1968 in Florida by the United States National Oceanic and Atmospheric Administration (NOAA). In these experiments isolated cumulus clouds seeded were reported to produce about twice as much precipitation as the unseeded clouds used as statistical control.

Another experiment was carried out in the Pune region in India during the 9-summer monsoon seasons (June -Sept) of 1973-74,1976,1979-84. The results of the rainfall experiment (Murty et al., 1985 a) indicated increase in rainfall (13 to 55 %) during 6-monsoon seasons (1973-74,1976,1979,1982 and 1984), decrease in rainfall (6 to 22 %) during 2-monsoon seasons (1981 and 1983) and no change in rainfall during the monsoon season of 1980.

The cumulative result in Pune cloud modification experiment indicated an increase in rainfall of 5%.

Seeding Procedure

Silver iodide is delivered to the appropriate storm location using flares with nucleation effectiveness of approximately 2×10^{13} ice nuclei per gram of AgI at cloud temperatures between -10°C and -15°C. There are two types of flares, droppable silver iodide flares, and wing-mounted end-burning flares. The end-burning flares contain 150 gm of AgI and burn for approximately 4 minutes. The AgI formulation is the same in both the wing-mounted and droppable flares namely NEI-TB1. These flares are used for cloud base seeding, they are commonly referred to as (cloud base flares). Similarly, the 20 gm droppable flares are used for cloud top seeding, they are commonly referred to as (cloud top flares). The cloud seeding rate is 150 gm flare burning for 4 min. or 37.5 gm per min.

Seeding Techniques

Seeding of cold topped cumulus clouds involves locating updrafts in clouds and releasing carefully-gauged small amounts of seeding material therein. Seeding is based on visual observations of the clouds, interpretation of the airflow in and around the clouds, and placement of seeding charges, so that the processes causing cloud growth are enhanced. Timing and restraint are important and necessary to preclude too rapid localized growth, which causes spindly towers to break off at mid cloud level and also to prevent overseeding to such an extent that an outflow shield develops.

The most productive technique is to cause neighboring turrets to join in a cloud and then to cause neighboring clouds to join, thereby increasing the area extent while confining vertical growth to no more than 28,000 or 30,000 feet of altitude. As such complexes develop, new turrents appear, especially upwind, or upshear, and on the flanks of the mass, which are ideal candidates for further treatment.

The procedure of seeding updrafts of clouds minimizes the energy dissipated in turbulence, and in changing momentum, so that only delicate treatment is necessary. It is unproductive of rain to seed the whole cloud top because such overseeding induces too rapid growth which results in disturbing the internal organization of the cloud and the air currents sustaining it. The most striking aspect of a successfully seeded cloud is, not its vertical growth or rapidity of development, but its general increase in overall bulk.

CLOUD SEEDING PROJECT IN LIBYA

The climate of northern Libya is typically Mediterranean, with hot, dry summers and mid-winter rainfall maximum. This maximum decrease in intensity quite rapidly as one moves south toward Libya's interior Figure 2. Rainfall in this arid interior is quite variable and far too low to support any significant agricultural development. Thus, virtually all of Libya's agricultural areas lies along a narrow coastal strip which is under the influence of the Mediterranean moisture source.

It is clear, then, that any increase in the frequency and total amount of rainfall, which might result in a widening of the agricultural coastal strip, would be extremely beneficial to the entire Libya. Before the project gets under way, however, some significant questions had to be answered. With the limited climatological data available in Libya, and since no weather modification had ever been undertaken there, would cloud seeding to be feasible in such an area? There was also very little practical information available on just what would be the economic impact of a project in rainfall simulation.

It was for these reasons that the approach decided upon would be scientific rather than operational. In other words, the first year would be classified as an experiment. In October 1971, Sierra Research Corporation (U.S.A.) signed a contract with the Ministry of Agriculture and Agrarian Reform to conduct seeding experimentation over selected areas of Northern Libya, which begun actually in November 1971.

The results of this experiment concluded that the cloud seeding increased rainfall in the tested clouds by using randomized tested data for 55 cloud areas, which proves the technical feasibility of seeding clouds over coastal areas of Libya on selected days. The results indicated that the cloud-group which were seeded showed the duration increasing by a factor of 2, the intensity by a factor of 4, and the volume by a factor of 12.

The estimated cost for producing additional rain along the coastal areas is very low on a "per 1000 gallon" basis, when compared to alternative sources such as desalinization water. During the start-up period and the 1972 period of operations abóut 465,000 Libyan Dinars were spent, the rain in seeded areas during that period exceeded the total rain in the control areas by $1.893 \times 10^8\ m^3$ (5.00×10^{10} gal). From statistical tests it was concluded this was probably due to the seeding operations. Therefore, we can estimate the cost of this additional rain water as follows:

$$\text{water cost} : \frac{4.65 \times 10^5 \text{ Dinars}}{5.00 \times 10^{10} \text{ gal}}$$

$$= 0.009 \text{ dinars} / 1000 \text{ gal}$$

This can be compared to water obtained from desalinization at about 0.3 Dinars per 1000 gallons. So it seems clear that cloud seeding is very economical in Northern Libya.

Depending upon this fact, the operations of cloud seeding experiment conducted since November 19, 1980 in Tripoli at the North of Libya, then it extended in 1981 to Sirte and El-Marje sites to cover all the coastal North area of the country.

Case Study of Seeding Operation over Tripoli

Tripoli is situated in a low coastal plain with an elevation of approximately 80 m. A range of low mountains roughly parallel the coast at a distance of about 80 km to the south. The average monthly temperature is about 12°C in January and 27°C in August. The region typically receives about 20 cm of rainfall annually with less than 1 cm falling in each of the months April through September (Wernstedt 1972).

The Tripoli site is equipped with a Mitsubishi C - band radar mounted on a 30 m tower, complete with Plan Position Indicator (PPI) which displays the horizontal plan view of the precipitation echoes and is used to determine the location of the clouds relative to the radar site, thus their location can be verified relative to the target area. With this display, we can determine the location of the cloud areas as well as their movement through measurement of sequential positions, and with Range Height Indicator (RHI) which displays a vertical crossection of precipitation echoes at selected azimuth.

The daily routine work in the site begin with the mounting of a radar watch, if appropriate. The project meteorologists proceed to the weather forecasting office at the airport to check and obtain copies of the latest available data, usually the 0000 GMT upper-air charts (850 - 700 - 500 mb) and 0000 GMT, 0600 GMT surface charts. The latest satellite imagery was also examined. With these information the project meteorologists return to the site to plot the 0000 GMT sounding estimating the Lifting Condensation Level (LCL), Convective Condensation Level (CCL), Free Condensation Level (FCL), and Convective Temperature (Tv), then they consult the radar operators to determine the status for the day according to the criteria prepared (Table 1) and start the daily briefing to the pilots and all the project staff of the weather situation and status for operations.

The general weather situation of 24 January 1990 as appears in the surface synoptic 0000 GMT chart in Figure 3 shows that Tripoli is affected by a trough of low pressure situated at the south of Libya, expanding towards the north, and a high pressure situated over the Atlantic and moving to the east towards west Libya, advecting cold air from north west Europe to the northern region of Africa.

The weather reports indicated that Cu, Sc, Ac, and As clouds were observed with showers over some places (Table 2 represents rainfall records on 24 Jan 90, climate dept.), surface wind blows from east and north east with 10 gusting to 20 knots. The maximum surface temperature was expected to record 16ºC, while the estimated convective temperature from the sounding was 13ºC, which gives a possibility to build up cumuliform clouds after the maximum heating after midday.

In the upper air, there is an intense low pressure over south western Libya as appears in the 500 mb chart at 0000 GMT in Figure 4, associated with a cold air mass (T = -23ºC over Tripoli). The temperature moisture and wind sounding of 24 Jan 90 is shown in Figure 5. Between 700-500 mb winds are backing with height indicating cold air advection. The sounding is quite moist up to 400 mb level, the height of freezing level (T = 0ºC) is 7500 ft, -05ºC level is 9500 ft, and -10ºC level is 12000 ft.

According to this situation the status of seeding was 2 to 3 , therefore two missions were launched on this day. The first originated at 0925 and ended at 1010, 14 flares were dropped into clouds west and south of the radar site. The second mission started at 1527 and ended at 1620, 19 flares were dropped with an additional base flare, into cloud cells east of the radar site, Figure 6 represents the flight track of the two missions relative to the radar site.

From tables 3 and 5 which represent the pilot report during the seeding operations, we can see that the heights of the cloud tops in the first mission which was in the morning ranged between 15000 and 19000 ft, with -10øC temperature and the flight level was 14000 ft. But in the second mission, the height of the cloud tops was 20000 ft with -15øC temperature, and the flight level was 17000 ft, only one base flare was released at 12000 ft. We note that the clouds developed and expanded in height after the maximum heating and its temperature cooled and decreased.

Tables 4 and 6 show a selected rainfall recording stations in the area located where the seeding operations were carried (Target Area), we can see that some of it recorded a good amounts of rainfall reached 45.0 mm. Also the rainfall distribution and analysis chart Figure 7 shows a concentration of rainfall in the seeded areas according to the flight track Figure 6.

CONCLUSION

The design of weather modification experiments has developed according to a standard fashion and was directed to significantly increase annual or seasonal rainfall. In all designs statistical evaluation was stressed and reference was made that the use of physical factors as co-varieties could improve the statistical evaluation.

With very few exceptions this approach has not been satisfactory because such experiments require about fifteen years for completion in order to obtain sufficient numbers of seeded and unseeded experimental units, another difficulty has always been the measurements of rainfall and cloud physics parameters.

The main reasons for this unsatisfactory situation were scientific and financial limitations. Part of the stagnation may also have been the lack of ideas and technology.

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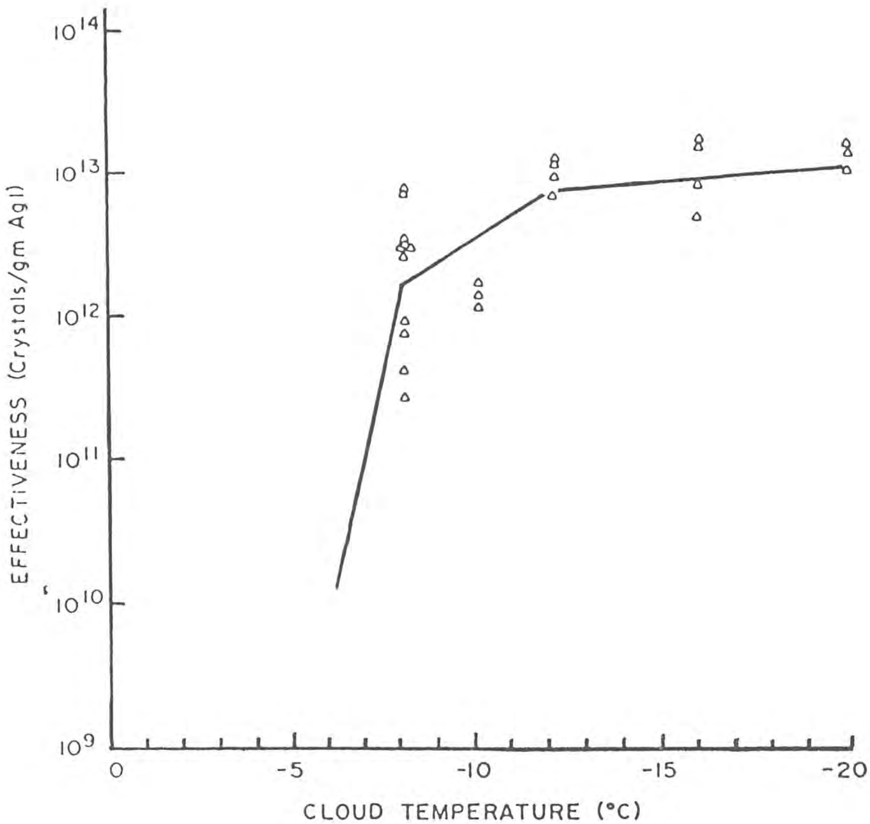

Figure 1: Nucleation effectiveness for AgI NEI TB-1 Pyrotechnics

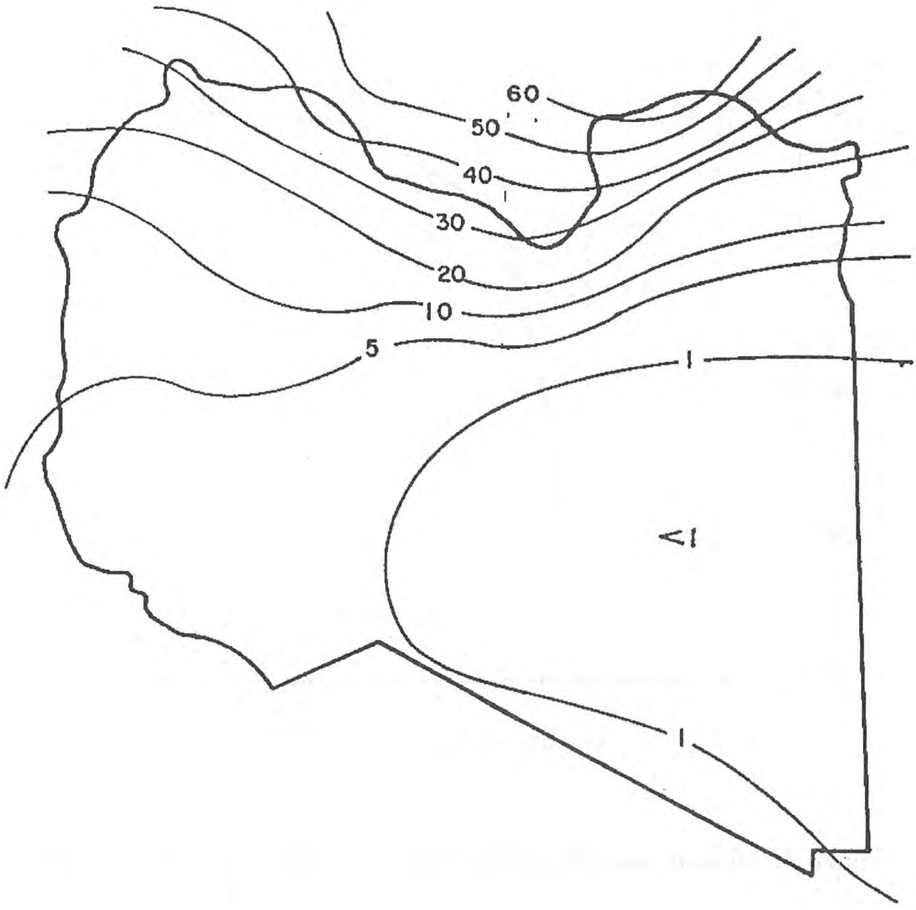

Figure 2: Average annual number of days with ≥ 1mm. Precipitation for Libya

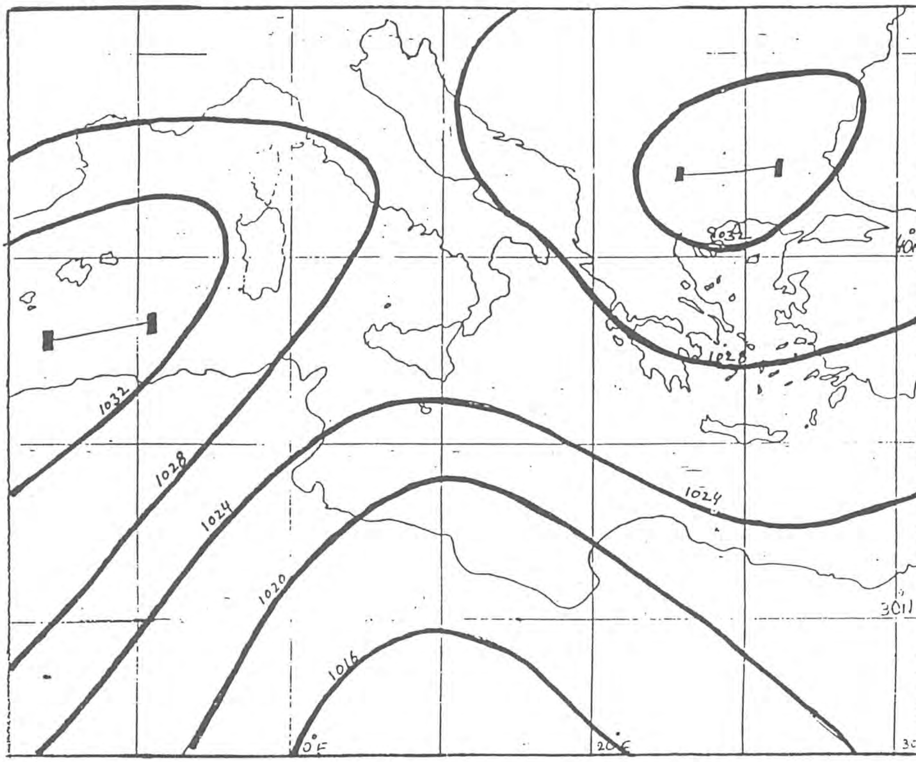

Figure 3: Surface Chart, 0000 GMT, 24 Jan. 1990

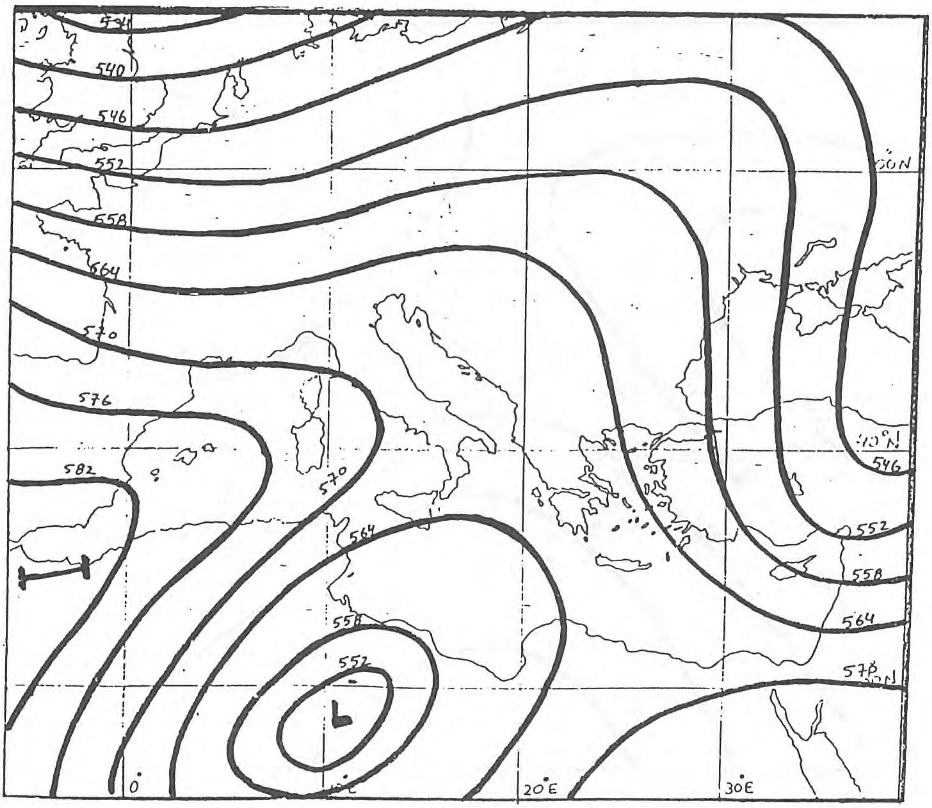

Figure 4: 500mb Chart, at 0000 GMT, 24 Jan. 1990

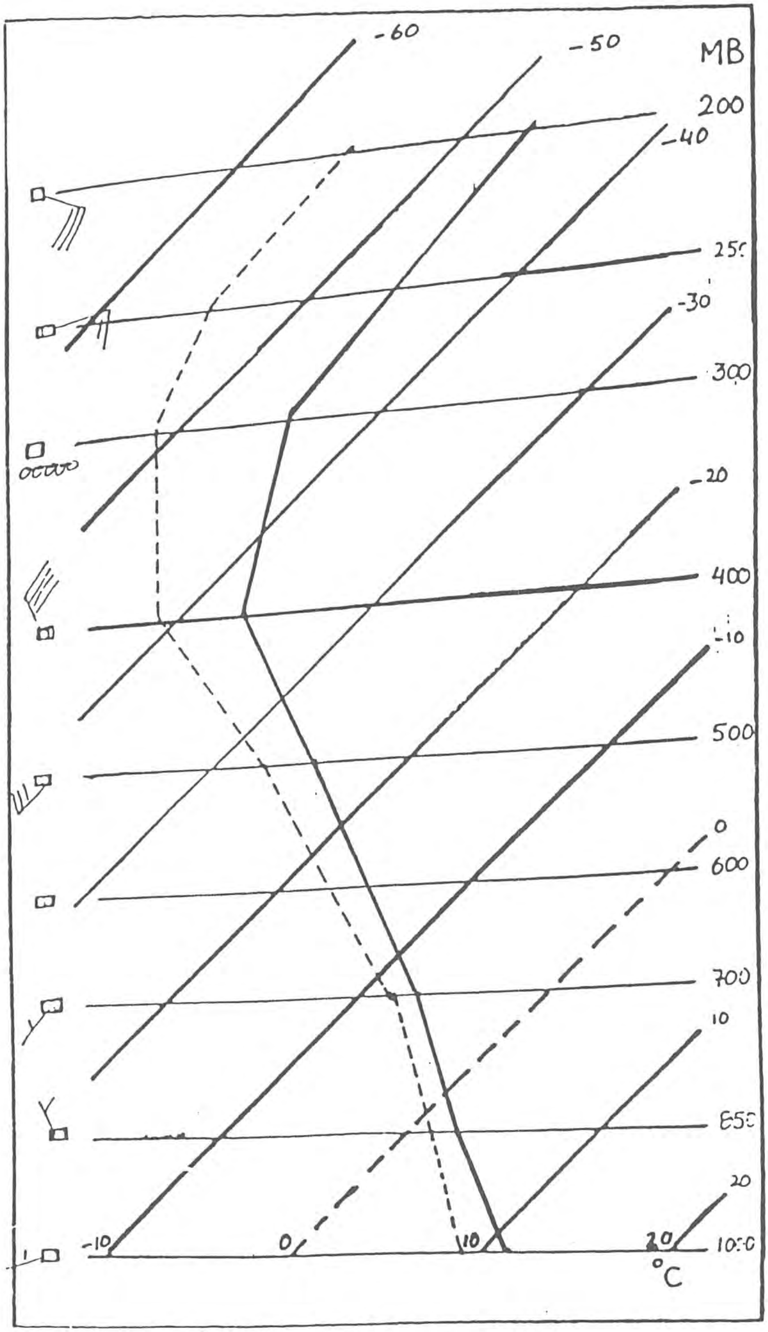

Figure 5: Tripoli Sounding, 1200 GMT, 24 Jan. 1990

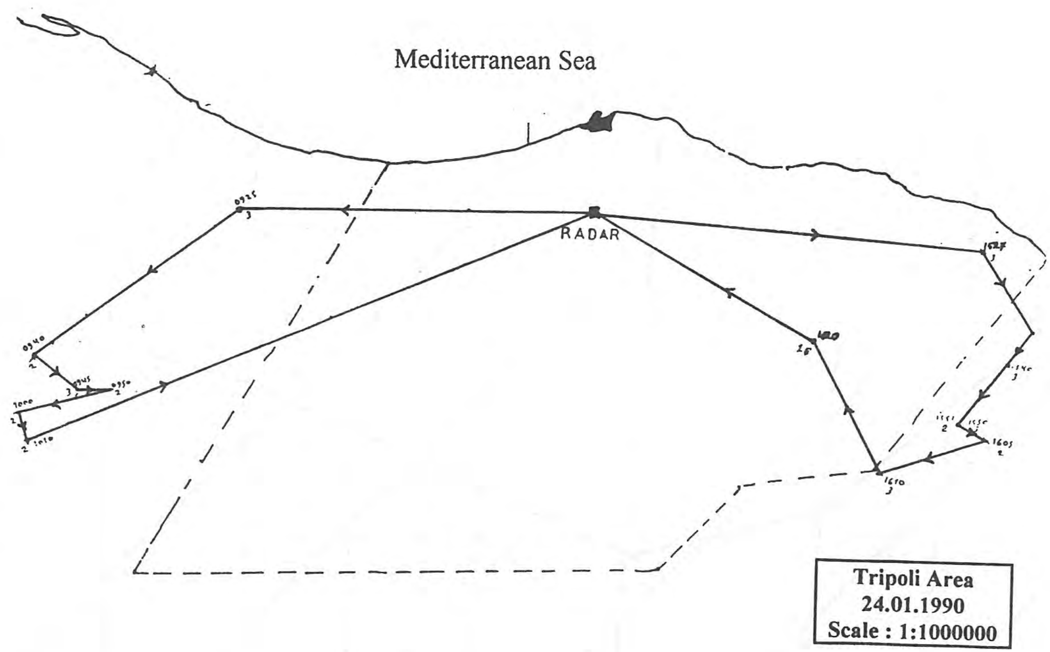

Figure 6: Flight Track, Tripoli Area 24 Jan. 1990

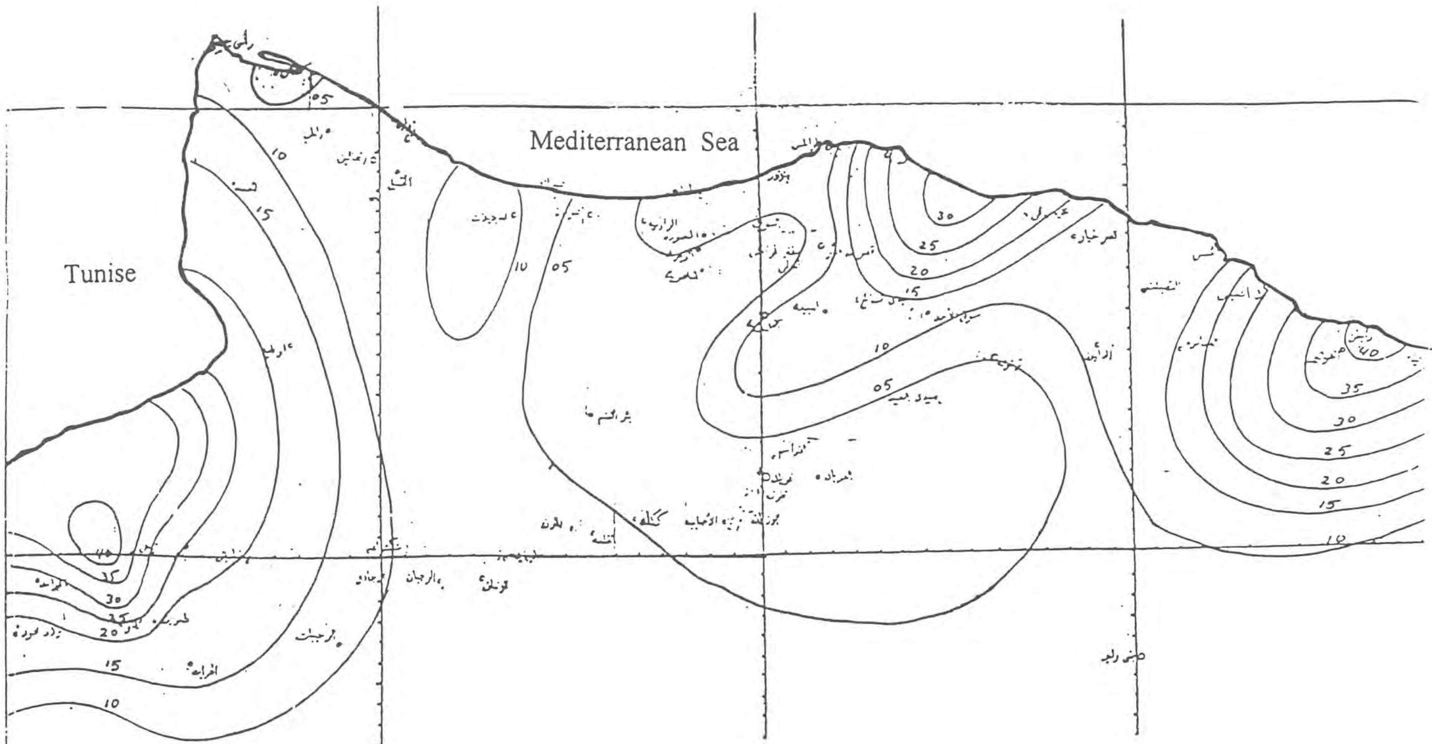

Figure 7: Rainfall Distribution and Analysis, 24 Jan. 1990 Tripoli Area

Table 1: Daily Status Predection Table

Daily Status	Actual Sky Observation	Weather Forecast	Synoptic Brief Description
0	Sky clear or high clouds	Sky clear or high clouds	Flat pressure distribution or high pressure over the area or stable dry ascent
1	Ac, As or Sc, Cu of fair weather clouds or clear sky	Ac, As or Sc, Cu of fair weather clouds. (PATROL FLIGHT AS NEEDED FROM RESEARCH UNIT)	Ahead of through of depression or on the right side of high pressure or thermal inversion at low altitude
2	Ac, As, Cu with embedded cumuliform clouds or just strati-form clouds or showers	Expected cumuliform clouds with a good thickness for showers (PATROL ON REQ. FROM RADAR OR RESEARCH UNIT)	Trough or weak cold front with a little cold advection or stable at high altitude or-05 C level higher than expected cloud tops
3	Showers from Cu clouds on project area or sky partly cloudy.	Expected seedable cumuliform clouds (SEEDING)	Remarkable trough, remarkable cold front, convergence area or good convection (Tc <= Tf) or cold advection
4	Sky partly cloudy to cloudy	Very good chance for thick cumuliform clouds (SEEDING)	A good cold advection with remarkable thermal contrast unstable ascent, convergence convection, trough & cold wave
5	Sky cloudy, showers lightening and thunder	Very active situation, Cu, Cb lightening and thunder, hail or snow. (SEEDING)	Very remarkable cold advection Very active cold front Trough or moist ascent

Air Crew Status

0 = Free	1 = Standby by telephone	2 = Standby in airport
3 = Operation	4 = Operation	5 = Operation

Prepared by : Meteorology Unit, Cloud Seeding Project

Table (2) Rainfall, Jan 24, 1990 - Tripoli Area, Libya

RAIN STATION	RAINFALL (mm)	RAIN STATION	RAINFALL (mm)
RAS GHEDIR	05.0	HAI AL ANDALOUS	10.0
ABOU KAMASH	03.0	MINA TARABOLOUS	05.0
RAGHDALIN	09.0	TARABOLOUS ALMADINA	08.3
ZWARA	06.0	TAGOURA	23.0
AL ASSAH	12.0	TAGOURA AL BOHOUT	10.5
OGHBAA BEN NAFAA	06.0	SOUK AL JOMHA	09.0
E GMAILE	09.5	AL HADBA AL KHADRA	10.0
MASHTEL HEILFIA	15.0	GASER BEN GHESHIR	04.5
EGDIDAH GHRBIA	12.5	MATAR TARABOLOUS	05.0
AL AGILAT	14.0	AL ALOUS	19.0
SABRATA	01.0	GASER KHIAR	11.0
SOUL ALALKAH	10.0	MSILATAH	20.0
SORMAN ERSSAD	08.5	AL AMAMRAH	17.0
SORMAN MARKZ	15.0	AL KHOMS AL MRKZ	13.0
SORMAN MARKZ GHABAT	07.0	SOUK AL KHAMIS	30.0
AL MATHRAD	08.5	WADI KAAM	44.0
BIR TERFAS	05.0	SOUK AL AHAD	11.0
ZAWIA ERSSAD	05.8	TARHONAH	05.0
GODAIEM	05.9	TARHONAL AL BOHOUT	07.0
EZAHRAA	05.0	AL DAOWWN	14.0
AL NASSERIAH	02.0	SOUK ALJOMHA ZLLITIN	45.0
AL MAMOURAH	05.0	ZILITIN	40.0
BIR AL GHANM	01.0	SOUK ALTHOLATA AL FWATIR	36.0
AL AZIZIAH	12.0	AL DAFNIAH	37.0
SENAOWN	03.0	ZAWIAT AL MAHGOUB	22.5
NALOUT	23.7	MISRATAH	26.3
AWLAD MAHMMOUD	14.0	GASER AHMAD	33.0
AL HAWAMED	19.0	AL KRARIEM	19.0
KABAOW	40.0	THOMINAH	16.0
TANDEMIRAH	14.0	TAWERGHA	12.0
AL ROWISE	03.0	MARAAI AL HISHA	06.5
TAKOUT	02.0	AL HISHA	03.0
AL GHAZAIAH	16.0	AL WASHKAH	09.5
THOMZIN	15.5	SIRTE 50 KM WEST	06.5
TALAT	20.0	SIRTE 30 KM WEST	05.0
AL MGHABRAH	22.0	SIRTE 17 KM WEST	14.0
TIGI	25.0	AL GHRBIAT	15.0
BADR	10.0	SIRTE	22.6
AL FIASLAH	10.0	AL SEDADAH	08.3
FARZOWGHAH	10.0	ABOU HADI	06.0
GHADO	12.0	HRAWAH	02.5
AL ROGBAN ERSSAD	06.4	AL NOFELIAH	04.2
AL ROGBAN ALMRKZ	06.5	MARAAI BEN GHAWAD	13.0
AL ZENTAN ALMARKZ	06.7	BEN GHAWAD	06.0
MAZRAT SHOFIETH	05.0	GHADAMMES	01.0
KEKLAH	04.5	AL GHRIATE	06.0
AL ASABAH	04.5	AL FATAIAH AL ZIRAEIAH	01.8
TEGHRENAH	02.0	OM E RZEM	02.5
GHERIAN	03.9	ABIAR MIGI	06.0
AL KOUASSEM	03.0	EL GHOUSH	15.0
AL SWANI	01.0	AL ZAWIA AL MARKZ	06.0

Table (3) Cloud Seeding Experiment, Tripoli First Mission 24, January 1990

TIME	DIRECTION (DEG)	DISTANCE (MIL)	FLARES No.	CLOUD TOP HIGHT (FT)	0 C LEVEL	FLIGHT LEVEL(FL)	TEMP AT (FL)
0925	270	55	3	15000 FT	7500 FT	14000 FT	- 10 C
0940	255	90	2	19000 FT	7500 FT	14000 FT	- 10 C
0945	250	85	3	16000 FT	7500 FT	14000 FT	- 10 C
0950	249	80	2	15000 FT	7500 FT	14000 FT	- 10 C
1000	250	95	2	15000 FT	7500 FT	14000 FT	- 10 C
1010	247	95	2	15000 FT	7500 FT	14000 FT	- 10 C

Table No. (4)

Direction (DEG)	Distance (MIL)	Flares	Stations	Rainfall (mm)
270	55	3	Mshtel Halfaia	15.0
			Sorman El Markz	15.0
			Al Agilat	14.0
			Souk Al Alalgah	10.0
			E Gemaail	09.5
255	90	2	Egdidah Ghrbiah	12.5
			Al Wttiah	06.0
249-250	80-85	5	Tigi	25.0
			El Ghoush	15.0
			Bader	10.0
			Bir Elghanam	01.0
247	95	2	Thomzin	15.5
			Kabaow	40.0
			Ghado	12.0
250	95	2	Al Hawamed	19.0
			Tandmirah	14.0
			Awlad Mahmmoud	14.0

Table (5) Cloud Seeding Experiment,
Tripoli Second Mission 24 January 1990

TIME	DIRECTION (DEG)	DISTANCE (MIL)	FLARES No.	CLOUD TOP HIGHT (FT)	0 C LEVEL	FLIGHT LEVEL(FL)	TEMP AT (FL)
1527	095	60	3	20000 FT	7500 FT	17000 FT	-15 C
1535	105	70	3	20000 FT	7500 FT	17000 FT	-15 C
1540	110	68	3	20000 FT	7500 FT	17000 FT	-15 C
1550	120	70	3	20000 FT	7500 FT	17000 FT	-15 C
1551	120	70	2	20000 FT	7500 FT	17000 FT	-15 C
1605	120	65	2	20000 FT	7500 FT	17000 FT	-15 C
1610	132	60	3	20000 FT	7500 FT	17000 FT	-15 C
1620	120	39	1 BASE	20000 FT	7500 FT	17000 FT	-15 C

Table No. 6

Direction (DEG)	Distance (MIL)	Flares	Stations	Rainfall (mm)
095	60	3	Souk Jomha Zlitin Zilitin Souk Al Khamies Msilatah Al Amamrah Al Kḥoms Almrkz	45.0 40.0 30.0 20.0 17.0 13.0
105	70	3	Wadi Kaam Souk Alahad	44.0 11.0
110	68	3	Al Dafniah Al Fouatier Zawiat Al Mahgoub Al Krariem Thominah Tawerghah	37.0 36.0 22.0 19.0 16.0 12.0
120	70	5	Maraai Ben Gawad Al Washkah Marai Al Hishah Al Hishah	13.0 09.0 06.5 03.0
120	39	1 Base Flare	Al Dawoon Trhouna Al Bohout Trhouna	14.0 07.0 05.0

Umm Al-Nar Hydraulic Laboratory

An Asset to Gulf Water and Marine Researchers, Designers & Policy Makers

Khaled S. Al-Amri and Rashed A.H.A. Thabet

UMM AL-NAR HYDRAULIC LABORATORY
AN ASSET TO GULF WATER AND MARINE RESEARCHERS, DESIGNERS & POLICY MAKERS

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ABSTRACT

In 1994, the ADWEA decided to convert an existing tidal model into a modern facility for marine hydraulic applied research. Besides studying the interaction between existing and future desalination plants in the area with the marine environment, the facilities are also to serve other governmental and non-governmental bodies in the UAE who may wish to have tidal hydraulics and related support for their design and/or management requirements in any of the areas modeled. Supported by DELFT HYDRAULICS, an international lead hydraulics institute, a hybrid modeling approach was adopted in creating suitable applied research facilities. These comprise:

- A suite of numerical 2D tidal and wind-driven flows models: This suite includes the Arabian Gulf model and a series of nested models, including the regional UAE model, the local Abu Dhabi model and the detailed Umm Al Nar model. In another nesting line, the detailed Taweelah area model was also developed.

- Two tidal scale models: The Umm Al Nar scale model, the result of upgrading and modernizing the original Umm Al Nar model, covering an area of 560 sq. Km around the Island of Abu Dhabi, and the Taweelah tidal scale model, covering an area of 10x5 Km around the Taweelah Power & Desalination Plant. Both models are operated by boundary conditions derived from the respective numerical models.

The paper describes above facilities and discusses their present and potential applications in service of Abu Dhabi and envisaged benefits to the UAE and other Gulf countries.

Keywords:
- tidal hydraulics
- numerical tidal models
- tidal scale models
- hybrid modeling

INTRODUCTION

The Abu Dhabi Water & Electricity Authority (formerly the Water & Electricity Department WED) of the Government of Abu Dhabi has built in the eighties a large tidal scale model, reproducing the tidal streams around Abu Dhabi Island and a part of the Arabian Gulf. The model was completed in 1987 and has subsequently operated for some 4 years.

In 1994, the WED decided to convert this model, which is housed in a large hall, 108x70 m^2, into a modern facility for marine hydraulics applied research. A primary goal of the facility is to study the interaction between existing, and possibly future, power and desalination plants in the area with the marine environment, thus providing engineering design support to (modifications to) these plants on the one hand, and on the other hand a means to assess their impact on the marine environment. This is particularly important since most plants are located in a complex inner lagoon around Abu Dhabi Island, that is connected to the sea through a few tidal channels. Careful management of the lagoon system is therefore essential to avoid possible adverse effects on the environment and/or on the operational efficiency of the plants themselves.

The available facilities were also to serve other governmental and non-governmental bodies in the UAE which may wish to have tidal hydraulics and related investigations to support their design and/or management requirements in any of the areas modeled.

To enable this ambitious goal, WED contracted DELFT HYDRAULICS, an international lead hydraulics institute, specialized amongst others in marine hydraulic research, to provide scientific, technical and operational support. The support was provided for three and a half years, from October 1994 to April 1998.

At the end of this period, the the Abu Dhabi Water & Electricity Authority has at its disposal the *Umm Al Nar Hydraulic Laboratory*, located inside Umm Al Nar Power & Desalination Plant on Umm Al Nar Island just outside Abu Dhabi City.

After a brief description of the marine coastal area of the UAE, the paper describes in detail the present configuration of the Hydraulic Laboratory and discusses its present and potential applications in service of UAE and other Gulf water and marine researchers, designers & policy makers.

BRIEF DESCRIPTION OF THE GULF MARINE COASTAL AREA OF THE UAE

The Gulf marine coastal area of the UAE covers the south-eastern coast of the Arabian Gulf. Starting east of the Qatari Peninsula, the coastline runs roughly in a west-east direction for some 250 Km and then changes direction to run in a nearly south west-north east direction for another 300 Km (see Figure 1). This coast is composed of a chain of bays, Wadi mouths and small or large lagoons, in particular at its central part where the orientation of the coast changes direction. Most of the recent developments in the country have taken place in this central part, which includes the cities of Abu Dhabi, Dubai, Sharjah and Ajman, all being connected in some way or another with above mentioned natural marine systems. The same applies for presently developing areas, such as Taweelah, Sadiyat and Mussafah.

The city of Abu Dhabi is mainly built on Abu Dhabi Island, which is located within a copmlex lagoon system (see Figure 2). The inner tidal waters around Abu Dhabi Island are fed from the Arabian Gulf (sea) through two main channels, the North Lagoon Channel, passing Mina Zayed, and the South Peripheral Channel. They are inter-connected through the Maqta Channel. This system is further interconnected to the Khor Faridah Lagoon in the north east and to the South Lagoon in the south west (see Figure 2).

The tidal wave at that part of the Arabian Gulf is of the mixed, predominantly semi-diurnal type but with a significant diurnal component. Its direction of propagation along the coast is from north east to south west. It first enters into the Khor Faridah Lagoon, a few minutes later into the North Lagoon (the Channel at Mina Zayed) and another few minutes later into the South Peripheral Channel and South Lagoon, successively.

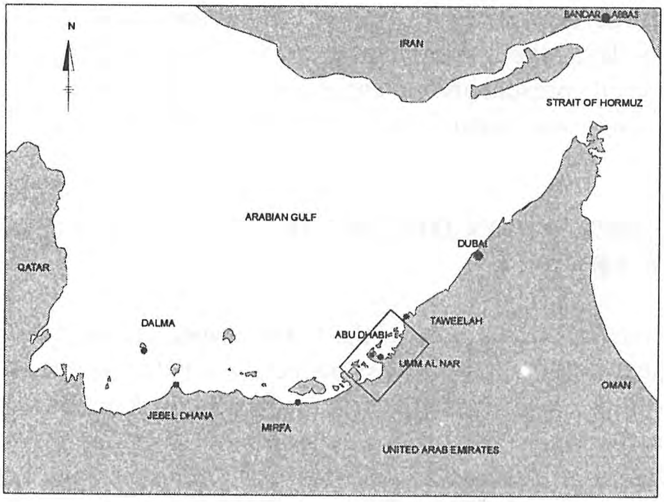


Figure 1: The Gulf marine coastal area of the UAE

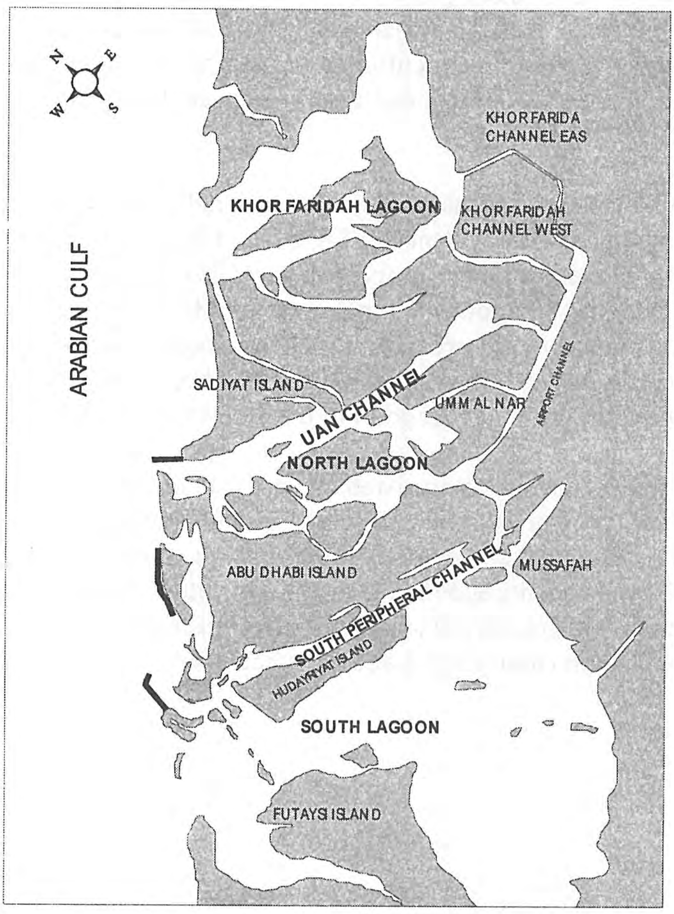


Figure 2: Complex lagoon system around Abu Dhabi Island

Inside each of these systems, the tidal wave propagates and deforms at rates which are governed by the geometry (length, cross-section, inter-tidal areas and bed roughness) of the channel(s) of the Lagoon system.

The meeting point of the two tidal waves, approaching through the Channel at Mina Zayed and the Southern Peripheral Channel, lies in the area near Umm Al Nar. The location of this meeting point, the deformation of the tidal wave in both systems and the interaction with the Khor Faridah and South Lagoon systems are the factors governing the generation of residual flow and hence the long-term water circulation and dispersion patterns within the lagoons and to/from the sea.

Any significant change in the geometry of (a channel of) the Northern or Southern Lagoon systems will effect the propagation of the tidal wave and hence the mutual effect of interconnecting lagoons, location of the meeting point(s) and long-term (residual flow) circulations.

Similar, but less complex, tidal systems occur at the other development centres in the UAE, such as Taweelah, Dubai, Sharjah, etc. They all have in common that the long-term water circulation and dispersion patterns are governed by possible changes in the geometry of these tidal systems, e.g. as caused by development works in their water areas. In order to safeguard the quality of these tidal waters and their aquatic environment, it is therefore essential to dispose of modeling possibilities to simulate the tidal and wind-driven flows and related phenomena in these areas. This requirement emphasizes the need for and underlines the establishment of Umm Al Nar Hydraulic Laboratory as a research centre for tidal hydraulic studies in UAE and the Gulf area.

MAIN COMPONENTS OF THE HYDRAULIC LABORATORY

In the year 1994 it was only logic to adopt a *hybrid modeling approach* for the update of the model complex. The term hybrid modeling is used here in the meaning of *conjunctive, off-line, application of both numerical and scale models reproducing specific areas*. The numerical model essentially covers a larger area than the scale model. It serves to:

(1) Provide mutually consistent boundary conditions at the locations of the control boundaries of the scale model under the different and varying geometrical and bathymetric conditions. Such input would facilitate the operation of the scale model and increase its reliability and accuracy.

(2) Perform hydraulic studies directly and independently from the scale model or as preliminary studies prior to studies in the scale model. In the latter case to reduce the duration of studies and to avoid unnecessary break-off and rebuilding work in the scale model.

The Umm Al Nar Hydraulic Laboratory now comprises the following modeling facilities:

- A suite of numerical 2D tidal and wind-driven flows models [1]: This suite includes the Arabian Gulf model, covering the entire Arabian Gulf and a part of the Gulf of Oman. A series of nested models have been developed, including the regional UAE model, the local Abu Dhabi model and the detailed Umm Al Nar model. In another nesting lines, the detailed Taweelah area model and the detailed Mirfaa area model were also developed (see Figure 3).

  Two tidal scale models: The Umm Al Nar scale model, the result of upgrading and modernizing the original Umm Al Nar model [2], and the Taweelah tidal scale model, covering an area of 10x5 Km^2 around the Taweelah Power & Desalination Plant [3]. Both models are operated by boundary conditions derived from the respective numerical models.

In addition, a network of automatic tide gauges has been established, providing long-term water level observations, in particular around Abu Dhabi Island and in the Taweelah area. The results enable tidal studies and reliable tidal analyses and predictions.

THE SUITE OF NUMERICAL TIDAL MODELS

As part of the update of the model complex, four numerical models were developed on the basis of DELFT3D, DELFT HYDRAULICS' simulation program for hydrodynamic flows and transport [4]. These are the Regional UAE model, the Abu Dhabi model, the Umm al Nar Detail Model (UAN), and the Taweelah model, see Figure 3.

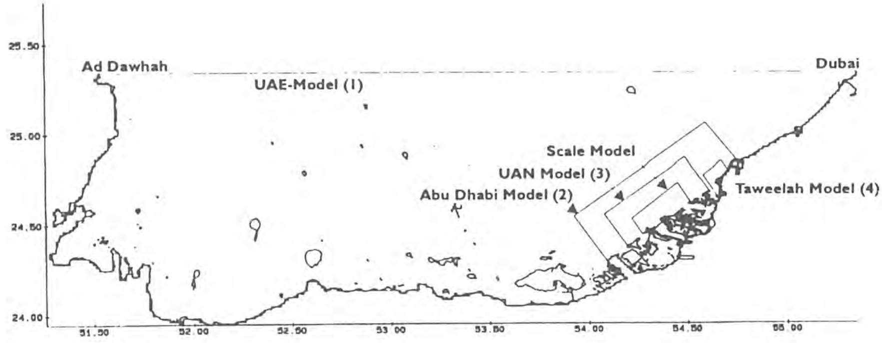


Figure 3: Suite of 2D numerical tidal models in relation to UAN scale model

The Regional UAE model covers the southern coast of the Arabian Gulf between Dubai and Ad Dawhah. It uses spherical coordinates and has been nested in DELFT HYDRAULICS' overall Arabian Gulf model, which is three times coarser than the UAE Model. The grid size of the model varies with latitude between 1683 and 1696 m, and equals about 1846 m for all longitudes.

The UAE model generates boundary conditions for the Abu Dhabi model, which in turn provides the boundary conditions to operate the detail UAN model. The latter two cover the islands and inner lagoon systems in the (wider) area around Abu Dhabi Island, as well as a larger or smaller part of the sea. They both employ curvilinear coordinates which allows refinement of the grid cells in areas of interest. The grid size varies from about 2000 m at the open boundaries to about 100 m, respectively 70 m, in the narrow channels around Abu Dhabi Island. Islands are schematized partly by defining the computation area which follows the land boundary (of coast and islands), completed by the definition of "thin dams" (block the flow in the direction perpendicular to the thin dams) and 'dry points' (points that do not participate in the hydrodynamic computation).

In the same way, the Taweelah numerical and scale model are interconnected and jointly operated.

The Umm Al Nar numerical model has been calibrated on base of a comprehensive hydrometric field data campaign which was carried out in the summer of 1997. The location and type of measurements carried out (water level, current velocity & direction and cross-sectional discharge) are shown in Figure 4. In the same way a comprehensive field campaign in the summer of 1996 provided tidal field data for the set-up and calibration of the numerical Taweelah model.

The UAN and Taweelah models have been schematized in accordance with recent or recently updated geometry/bathymetry data of the areas concerned.

The grid configuration of the Umm Al Nar numerical model is shown in Figure 5. The dimension of the model amounts 160x225 gridcells. Compared to the dimension of the Abu Dhabi model (146 x 77), the Umm al Nar model is about three times finer.

The tidal dynamics of the model are driven by prescribing tidal water level variations and current variations along the open sea boundaries with tidal constituents. Amongst the 17 constituents applied, the 10 main constituents are: Q1, O1, K1, P1, (diurnal) N2, NU2, M2, L2, S2, K2 (semi-diurnal).

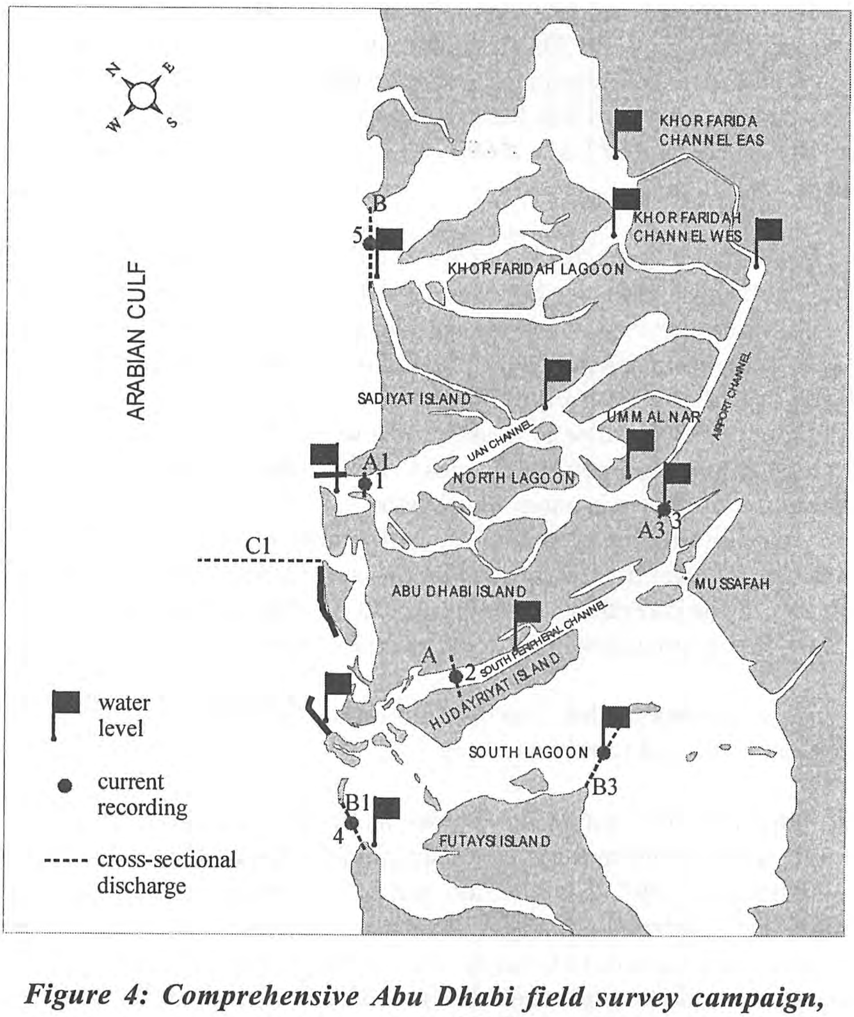


Figure 4: Comprehensive Abu Dhabi field survey campaign, summer 1997

The calibration and verification of the model took place simultaneously, covering about 4 days under spring tide conditions and 4 days under neap tide conditions. In this way optimum use is made of the available field measurements, without sacrificing on the accuracy and reliability of the model and its predictive ability. An example of the calibration results of the numerical Umm Al Nar detail model is shown in Figure 6.

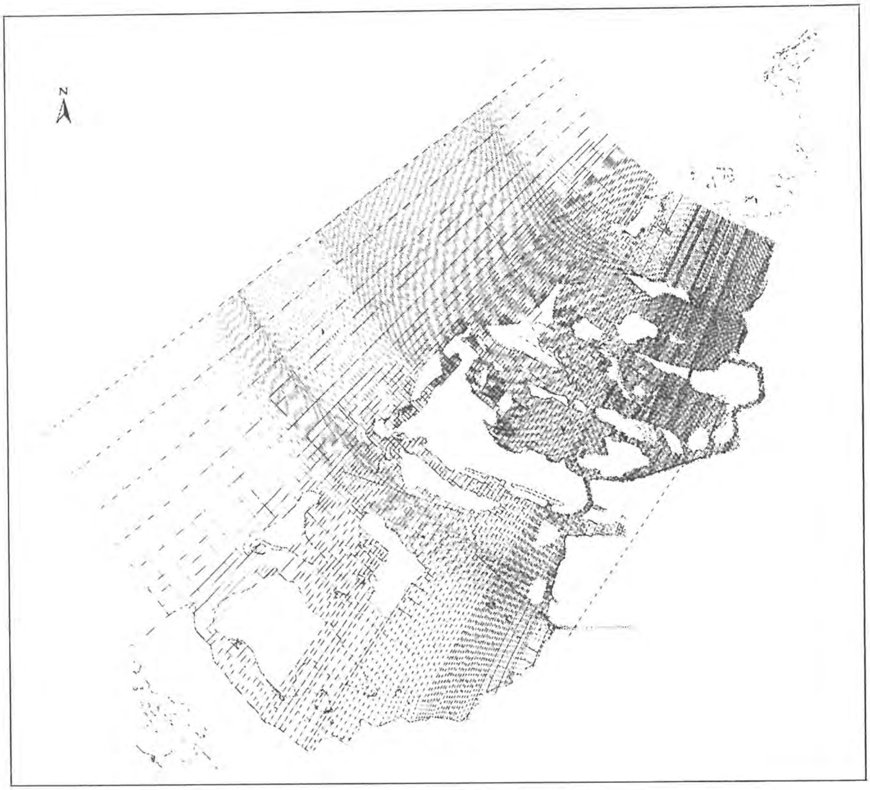


Figure 5: Computational grid, Umm Al Nar numerical model

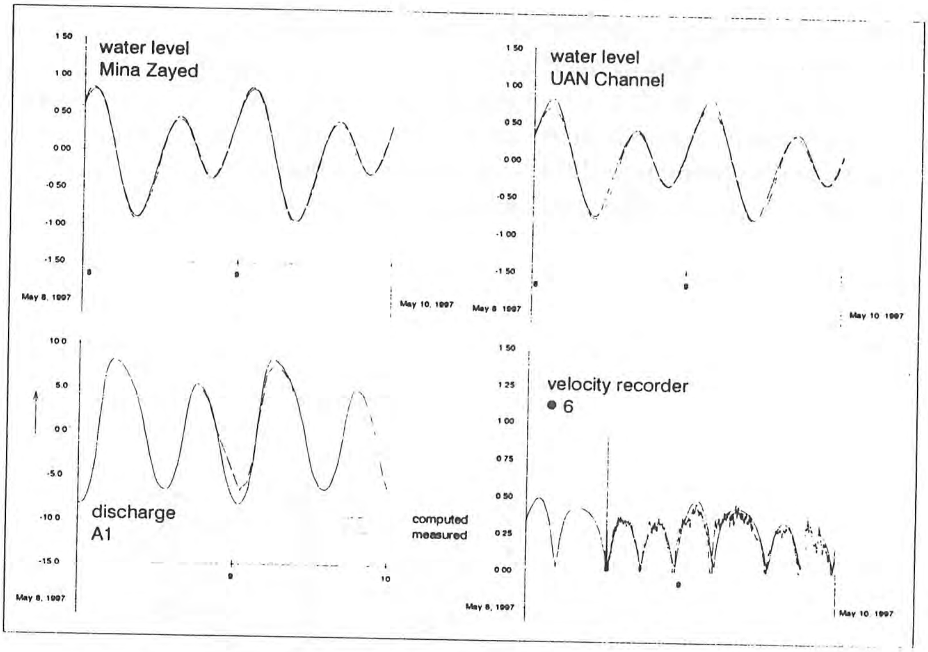


Figure 6: Example of calibration results of UAN numerical detail model

UMM AL NAR AND TAWEELAH TIDAL SCALE MODELS

The model hall now encompasses two tidal scale models, the UAN and Taweelah models. Their location in the laboratory hall (108x70 m^2) is shown in Figure 7. Photograph 1 gives an overview of the laboratory hall looking from the south-western sea side of Umm Al Nar model.

The Umm Al Nar tidal scale model, which was built in the mid-eighties, covers an area of 560 sq. Km, reproducing the Island of Abu Dhabi and the lagoon systems directly around it, as well as an adjacent part of the Arabian Gulf offshore the Island. The model scales are:

Horizontal scale	1 : 375
Vertical scale	1 : 60

The distortion factor of 6.25 is on the high side but is just suitable for this type of models.

As part of the update of the hydraulic laboratory, the UAN model has been extended to reproduce some additional areas where future developments are envisaged. In addition, the model control system has been revised and improved. The tidal motion in the model is now simulated through 6 *Boundary Control Units*. The location of these units is shown in Figure 8.

The tide at sea is in principle generated at the boundaries N and S1. They control the tidal discharge Q(t) and water level h(t), respectively. Such a mixed Q(t)-h(t) control system is needed for a short reach (relative to the length of the tidal wave) as the one under discussion, to ensure accuracy and repeatability of the tide generated in the model. Earlier studies [6] have shown that if the same parameter, h(t) or Q(t), is being regulated at both boundaries, inevitable small inaccuracies in the model regulation system would produce much larger inaccuracies within the model, as these inaccuracies do not amplify and even are reduced in case of a mixed control system.

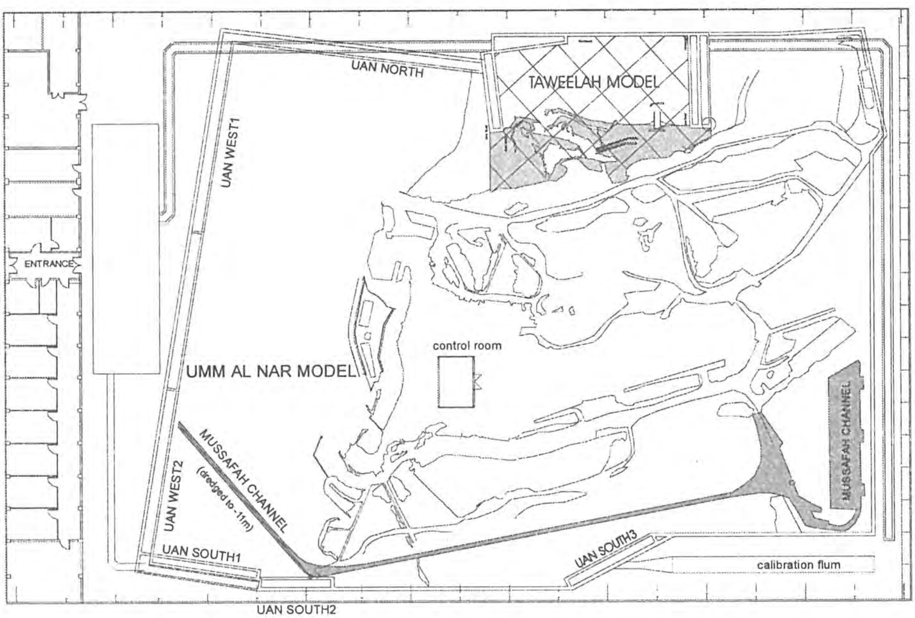
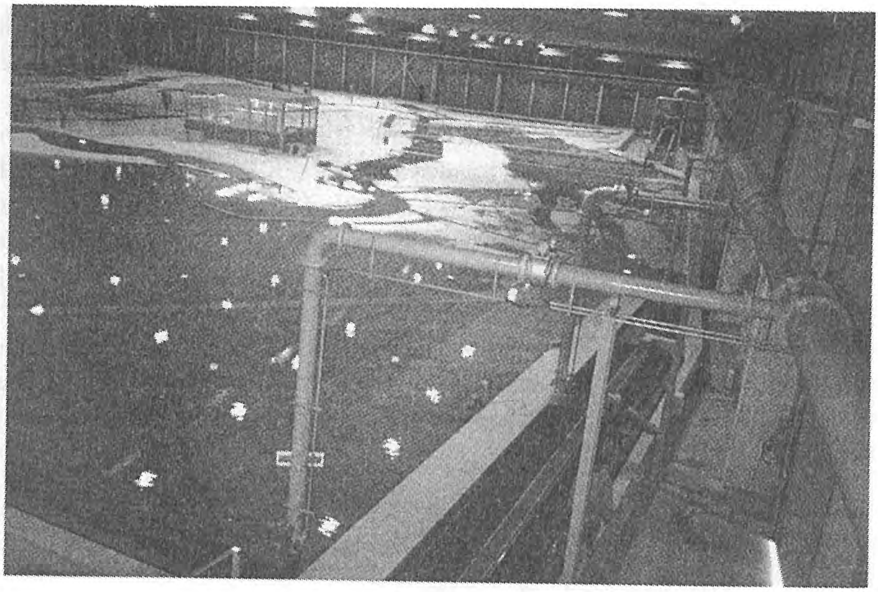


Figure 7: The layout of the laboratory hall and location of the scale models



Photograph 1: Overview of the laboratory hall

In the original model, the boundary parallel to the coast was a closed one, based on the assumption that the tidal *flow* in the sea area is predominantly parallel to the coast. However, it was soon realized that additional control at (some parts of) this boundary was needed to account for the strong flow components perpendicular to the coast. In the recent update, the control system at sea has been profoundly modified.

In preparation of the extension/upgrading of the scale model, a study was carried out in the UAN numerical detail model to determine the most appropriate *location and type* of the boundary controls of the scale model and thus enable optimization of the model control system. A number of computational runs was carried out, making mainly use of the facility "thin dams" [4]. A thin dam is actually an "internal boundary condition"; it does not occupy a space but only blocks the flow in the direction perpendicular to it.

This was particularly applied to determine which part of the west boundary (parallel to the coast) should be kept close and which other parts should be equipped with a boundary control unit, and of which type. In this way, possible solutions for location and type of boundary control units of the scale model were studied *within* the numerical detail model. The results of the solutions studied are reported in [7], the optimized boundary control system is shown in Figure 8.

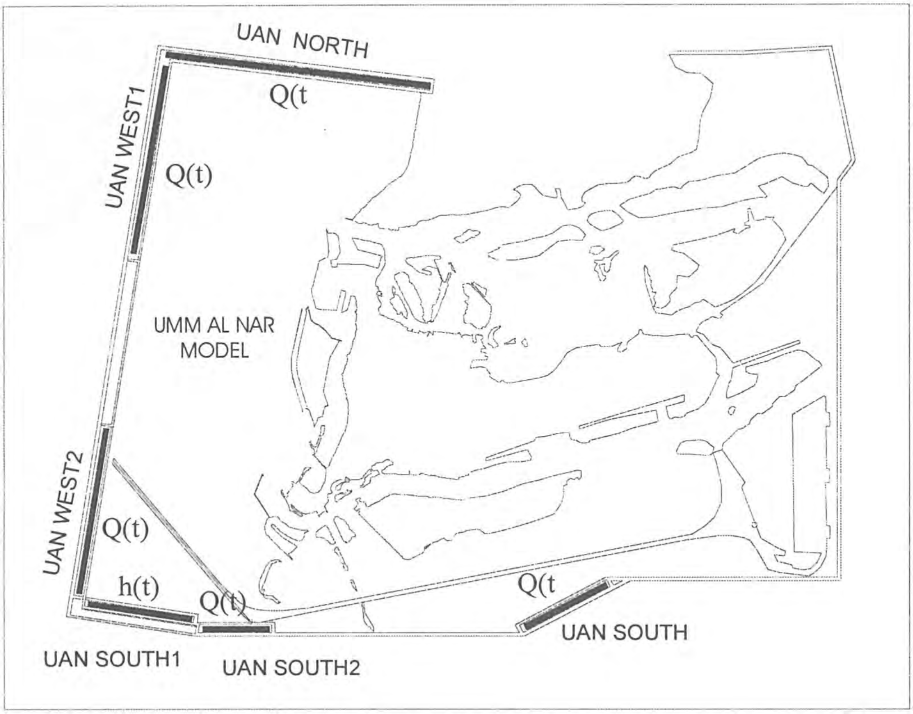


Figure 8: Upgraded boundary control system for Umm Al Nar tidal scale model

The water circulation system of the tidal model is shown schematically in Figure 9. The two types of boundary control applied, the water level control h(t) and the tidal discharge control Q(t) are illustrated in Figures 10 and 11, respectively.

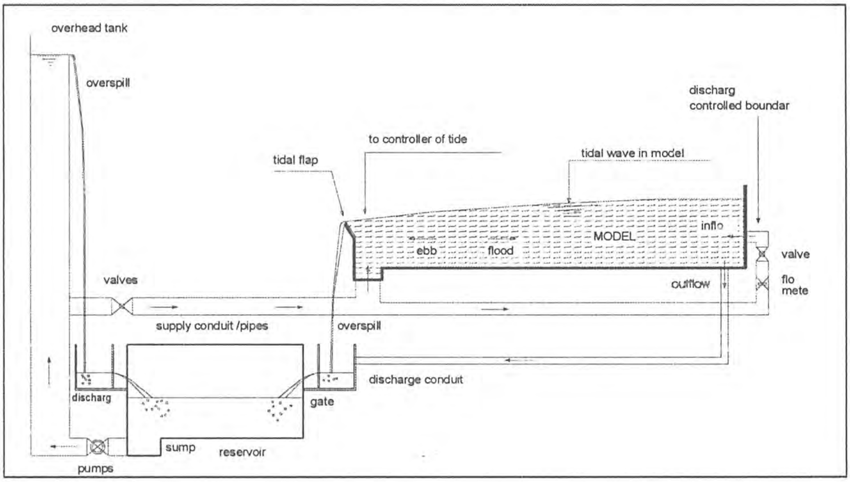


Figure 9: Schematic presentation of water circulation system

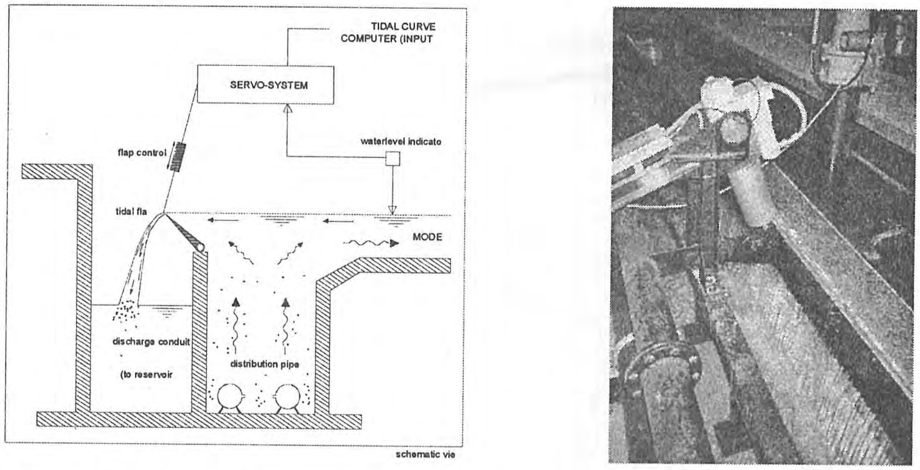


Figure 10: Water level control boundary h(t)

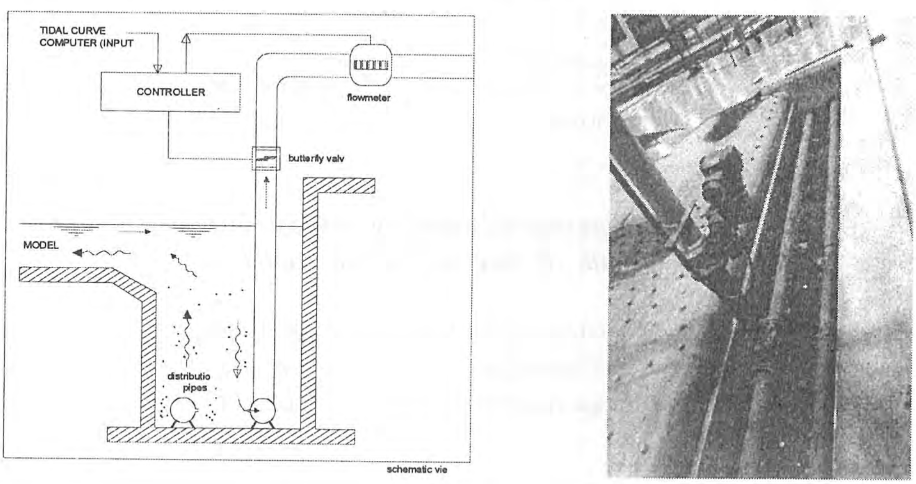


Figure 11: Tidal discharge control boundary Q(t)

The UAN scale model is currently being re-calibrated. The re-calibration is to take place on base of the comprehensive 1997 field data, supplemented by additional data from the numerical detail model.

In the same way, the boundary control system of Taweelah scale model was designed. The resulting control system is shown in Figure 12. The model, which was constructed to the same scales as the UAN model, has been calibrated on base of the comprehensive 1996 field data, supplemented by additional data from the numerical model.

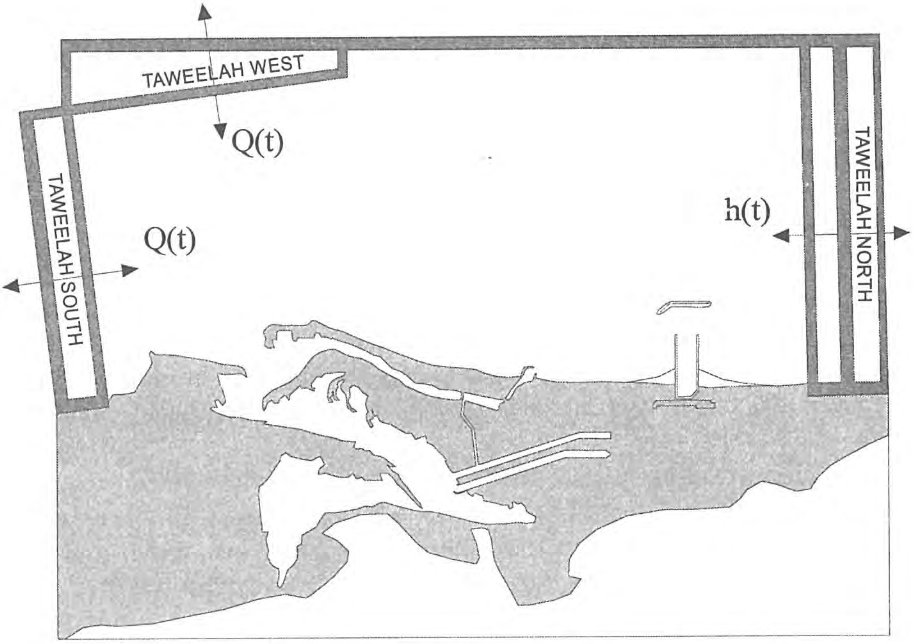


Figure 12: Boundary control system of Taweelah scale model

Envisaged Clients and Services in the coming years

After completing the re-calibration of UAN scale model, the principal tasks of the Hydraulic Laboratory in the coming years will be to operate the Hydraulic laboratory and carry out studies. This entails to:

(i) design model runs/tests to solve a problem or perform a study commissioned by or through ADWEA, (ii) carry out field measurements if and when needed, (iii) run the model runs/tests and carry out, record and elaborate observations therein, (iv) analyse the results, formulate recommendations and produce reports.

Above activities apply to both hydraulic scale and numerical computer models. The Hydraulic Laboratory complex comprises at present hydraulic scale and numerical computer models of Abu Dhabi/Umm Al Nar area and Taweelah area. The main objective of the models is to enable ADWEA to study the tidal motion, and consequently short and long term dispersion of heat, salinity and other substances discharged at the site of Umm Al Nar and Taweelah Power and Desalination Plants, respectively, both at present and in further future situations.

Examples of such studies are: (i) Establish the recirculation pattern and long-term (residual) pattern under the present (1998) geometrical and bathymetric conditions of the lagoon and/or sea systems. (ii) Re-establish, after about two years, the recirculation pattern and long-term (residual) pattern due to natural changes in the bathymetry of the lagoon systems and advise on measures to mitigate possible adverse effects. (iii) Predict the effect of planned (large scale) man-made changes in the geometry and/or bathymetry in the lagoon systems, and advise on measures to mitigate possible adverse effects (iv) Study and test protection measures in case of oil (spill) pollution and provide data to set up contingency plans. (v) Study and test protection measures in case of regular and/or calamitous pollution by chemical substances and provide data to set up contingency plans.

The models are equally instrumental for all other works related to the tidal waters around Abu Dhabi Island or in the Taweelah area. In this respect it will also be beneficial to other Departments, Governmental and non-Governmental bodies. Possible other studies and investigations are:

* design-aid or problem-solving concerning (Mina Zayed) harbour works, Sadiyat development plans, Mussafah area development & its approach channel, Taweelah Industrial Zone development, offshore islands, dredging, reclamation works, etc.

* design-aid or problem-solving concerning water quality, disposal of pollutants and maintaining public health norms.

* design-aid or problem-solving concerning planning & design of coastal recreation areas, coastal zone management, etc.

* data to support environmental and ecological studies or mitigating measures to be taken.

* support to Consultants working for Abu Dhabi Government concerning above-mentioned and other types of model investigations.

Another possible benefit of the Hydraulic Laboratory is to provide facility and instruments to support undergraduate and graduate studies and research work at UAE University in Al Ain.

Finally, the demonstrative task of particularly the scale models cannot be overestimated. The visualization of flow situations, effect of structures and works could be very illustrative, not only for policy-makers, but even for designers and involved technical staff.

It is obvious that the present, site specific, facilities of Umm Al Nar Hydraulic Laboratory are not directly applicable for other potential users in the Gulf area. Its main benefit in the near future is, however, that a centre of research for tidal hydraulic studies is established and that the expertise and experience thereby gained will undoubtedly be beneficial to the rest of the UAE and the Gulf area as well.

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Rain Water Harvesting in Arid Regions

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RAIN WATER HARVESTING IN ARID REGIONS

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ABSTRACT

Under the pressure of population growth and economic expansion, water needs for various uses became either reduced in quantity or/and quality. This is the picture in many arid or semi-arid regions in our globe.

For some poor countries where their resources are very limited, it is very difficult to achieve an acceptable level to provide water with reasonable quality for the day to day use so they have to use a very low quality of water. To overcome the problem we must find solution or some resources which if it managed properly can enhance our supply and reduce the pressure on our limited water resources.

One of the methods is what we call it "Water Harvesting", i.e. collecting as much as we could from the fallen precipitation during wet seasons (rain, snow, fog, mist. etc) and to use this collected water for our different usage.

Water harvesting can be carried out in different ways and can be stored in different ways too. In this paper we look into the different methods for water harvesting and cost analysis has been carried out. Simple technique has been followed which can be easily carried out by individuals on farm or housing level.

The rainfall harvesting system we are going to explore is very simple and mainly it consists of :-

a) a collection area:- (farm land, dam site, parking site, roof, road surface etc).
b) a conveyance system:- a pipe line or a channel if the water is going to be used on different location (a way for the collection area).
c) storage area :- (soil, reservoir, tank. etc)

The topography and surface characteristics is the main important factors in this case.

The technology we are going to present is very simple to implement and maintain and the cost is very minimal. This method is compatible with the best management practice in agriculture or domestic use.

KEY WORDS : Rainwater Harvesting, Water Resources Management, Water For Arid Regions, Water supply.

INTRODUCTION

Rain Harvesting system is an old method for making water available for different use and particularly for drinking and cooking (1, 2). With a very simple system many villagers collect their water from the roofs through gutters and pipes or a channel to the storage or tank under the ground or above the ground then by simple sterilization or filtration they use the stored water by gravity or pumping.

In some places the supplied water from wells or through the municipal main contains a high percentage of minerals or rather salty so people by nature turn to Rainwater collection (Libya, Iraq, Israel).

It is very difficult for any country in Arid regions and particularly the Middle East and Arab region (very hot & dry) to survive without water.The scarcity of the annual rainfall and the very high rate of evaporation which by far exceeds that of rainfalls, thus most countries depend on their ground water reserves which is always under pressure of over discharge (depletion) particularly where this resource is hardly recharged and so we face the danger of pollution (such as sea water intrusion).

In some regions the ground and surface water are shared with other countries (Iraq , Syria , Jordan , Israel. etc). In most countries the average rainfall hardly exceeds 150 mm/year compared to an average evaporation around 2000 mm/year ..!

The consequences of the shortage, scarcity of water, sharing and conflicts could lead to serious problems and possible confrontations unless we looked at and dealt with from equitable sustainable approach.

As result of water scarcity, many countries facing problems in providing the necessary water requirements for home use and agriculture. And many projects suffer a draw back because of this shortage nevertheless some countries (especially the oil producing one's) started to use oil revenue to develop and make available some of their water resources such as the Ground Water in the Libyan Sahara's through the Great Man Made River (GMMR) which cost nearly 26 Billion Dollars. Other countries in the Arabian Gulf enhance their water supply for the different usage through the desalination of the sea water. Although the high cost of such projects will put great pressure on the national budget and of course will consume a large amount of it, many other poor countries can't afford such high costs.

Nearly half the countries of the world face of aridity and scarcity of water resources. Most of the studies and analysis shows that (especially in the Middle East) the next century with regards to water availability will lead to possible conflicts in the case of shared water resources.

WHAT IS WATER HARVESTING?

Water harvesting is capturing and storing rainfall for different usage (drinking, irrigation, animal and toilet flushing). Water harvesting helps to save money on monthly water bills and reduce the dependence on municipally supplied water. A well-designed system will also decrease landscape maintenance needs.

THE NEED FOR WATER IN THE DEVELOPING COUNTRIES

Every country in our globe needs water for it's survival, development and continuity of life, but for the developing and poor countries the water is the life and the number one necessity.

For many countries with limited resources the scarcity of water should be tackled with a low cost convenient simple method which can be easily followed by local people (3 ,4).

The use of water efficiently is the key way to improve scarce water resources, government legalization, the citizen cooperation, understanding and responsibility are the main factors.

The living standards, the wealth, the progress of society all closely linked with water availability.

For the agriculture we need water to grow crops and for the industrial development we need water too. For home use and a healthy life we do need water.

The poor countries can't afford for costly methods to provide such is desalinization and waste water treatment. But with good training and legalization rules and responsibility these things can be improved for better life.

IMPORTANT FACTORS FOR RAINWATER HARVESTING DEVELOPMENT

Government polices and guidelines for Rain Water Harvesting

The most practical and economical method for rain water harvesting is to have a governmental (national) policy (law) so that every citizen can participate in rain water harvesting (5,6). Catching rain water from catchments (roofs, open fields. etc) store them in containers to keep them from contamination. Governments should develop guidelines for the development of the rainwater catchment systems which should be written in simple words for citizens to understand. The government should also provide rainwater catchment system financial assistance by means of a revolving loan fund in order to help those citizens who cannot pay for their rainwater catchment system in one lump sum.

The government should also provide training programs to train village rainwater catchment technicians, in order to have them give technical know-how's on rainwater catchments construction, maintenance and to provide explanations of the governmental policy on rainwater harvesting. These trained village technicians are the important persons to relate government and it's citizens not only for the rainwater harvesting development and management but also provide liaisons of subsequent matters or problems.

There are many practical examples around the world for the cooperation between the government and the citizen. In each country the material or the approach for the goal may vary to suit the local conditions, but the logic behind the cooperations between government and it's citizens in solving water problems is always the same. In other words individual self-sufficiency in water is just as self-sufficiency in money.

Citizens must be motivated to do as much as they can in water. Government is only to provide needed assistance in a short time. In some countries by law the rain water harvesting systems are required in new construction and some countries offer a tax credit and financial incentives are offered (Germany, Japan).

Governments should in certain cases (especially in developing countries where producing water unit costly, such as Arabian Gulf, Libya) enforce a law for collecting rainwater such regulation now enforced in several countries round the world (USA, Thailand, Japan, Germany. etc) and in some cases the citizens have no much alternatives but to build their own rain harvesting system or buy water from suppliers which cost more, that is the case in many remote areas. Sometimes areas not more than 20 km from the city center even in countries with high and continuous rainfall such as New Zealand we see many houses depend on the rain water harvesting system for their water supply.

The main point in Rainwater Harvesting system is to carry on in parallel an education and information program for the users about the benefits of this technology and the means of implementing rainwater harvesting.

Rain Water Harvesting System (RWHS)

All what we need for Rain Harvesting is Rain and place to store it. In its simplest form we may use the land contours to direct the water to the required place such as planted area, to recharge ground water, or to store it above or below ground level. It may be more sophisticated, featuring collecting surface with facilities to filter water, divert the first storm away from storage. Pumping facilities could be fixed for high pressure flow.
The main components of the RWHS are:

a) **Catchment or collection surface**

Which is any large surface (preferably impermeable) that can capture and or/carry water to where it can be used immediately or stored for later use. It can be either of the followings:

1) Roofs
2) Driveways
3) Parks
4) Roads
5) Contoured surface
6) Furrows, Channels, Lakes, Pools...etc.

The size of collection surface and its characteristics (absorption, cover, slope, roughness. etc), are the main important factors in its efficiency in collecting water. Figure (1) shows the features in a Rainwater Harvesting System.

b) **Collection channel or pipe to carry water to the storage site**

This can be the drain pipes from the roof or channels on the ground and this may be lined with hard impermeable surface or ordinary local soil material. The conveyance system can be few meters long to hundreds of meters depending on the distance between the collection area and the usage area but the closer both sides the better from the point of view of water losses and cost of construction.

c) **Storage system**

The primary cost in (RWHS) is the storage tank, (cistern). The size of the storage depends in a number of factors such as:

a) Whether we depend entirely on the (RWHS) or we consider it as secondary source with the potable system.
b) Whether we intend to use the water for indoor needs only or for irrigation or other uses as well.
c) The average rainfall and the size of collecting surface.
d) The climate conditions.
e) The number of people to be served or the size of the work in need for water.

The storage system can be as simple as a container such as a drum or a barrel placed under a rain gutter downspot or it can be more sophisticated such as a tank (steel, aluminum, plastic, concrete or fiber glass. etc) on the ground or under the ground with a shut off system and pumping facilities, also we may add filtration and if the collecting water to be used for human usage a disinfecting material needed.

The size of the storage system depends on the required amount of water and the expected rainfall and the size of collection area. The longer you keep the water in storage the greater the problems of stagnate, odorous, the breeding of flies and insects and the problem of health hazards.

The storage system should be free from in/out leakage. For individual houses we may use small capacity storage system (10-50) cum. depending on the water consumption. We may use two different way of storage one for human consumption which should be clean, hygienic and another for

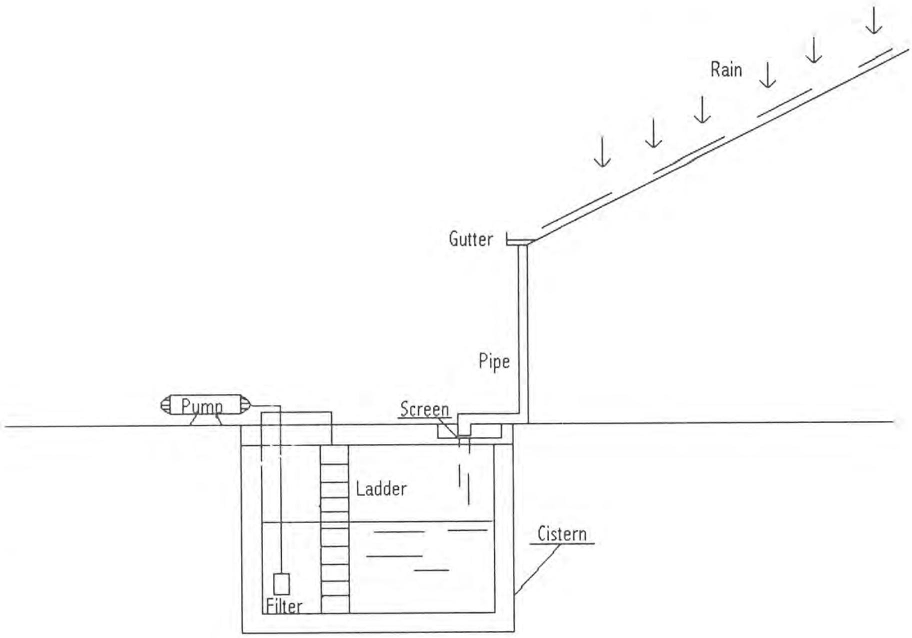


Fig. -1- Rainwater Harvesting System with underground storage

gardening, floor washing, toilets. etc. Of course the more sophisticated the system the higher the cost.

In many countries they use the lowland and depressions or the waterways for rain water harvesting by building dams to store the water or prevent water from flowing to unwanted areas by doing so we can use the collected water from rainfall storms directly or recharge the groundwater.

By this method we increase the water content of the soil. The site should contain a highly permeable soil underlain by impermeable layers that minimize infiltration. Brazil, Argentine and Paraguay and many countries in North Africa and the Middle East follow this system.

We may also use furrows as a storage site for harvested rainwater. And it may be built prior to or after planting to store water for future use by the plants.

RWHS MANAGEMENT

RWHS Maintenance

For domestic use the maintenance of the system consists of:

1) Keeping gutters, pipes, channels and the storage screen clean from dirt's, leaves, entry of mosquitoes.
2) Filters and in some cases the Ultra-violet lamp (for water sterilization) will need periodic replacements.
3) The storage (tank) should be cleaned annually in the summer when it is thoroughly empty.
4) Periodic testing of the water from contamination with bacteria.
5) Any leakage from the storage tank should be treated immediately.

For agriculture purposes the maintenance is minimal, the only work needed is Grading, smoothing, compacting and sealing surfaces of the Catchment area. These are the most important factors to increase water harvesting in arid regions.

A water-harvesting system, once installed will provide water without requiring fuel or power.

Quality Of Rainwater

Collected rainwater from your roof is very much higher in quality than the one you receive through the municipal pipe especially now days where the ground and the water are full of chemicals and pesticides and many other pollutant. The salt content of the rainwater in the range of 30 PPM compared to 360 - 500 PPM for city water and 2400+ PPM for some well water. The complexity of the RWHS depends on what we are going to do with the collected water, if we have a polluted air where plenty of volatile organic compound, petrochemicals and lead, then RW is not safe to drink but it may be used for agriculture, toilet flushing, driveway washing. etc.

In some countries where they use groundwater the water contains a high percentage of dissolved minerals which may exceed 2000 mg/liter and this is well above the required concentration by the standards, while the rainwater may contain as low as 5 mg/liter of dissolved minerals.

Rainwater Harvesting Design

The main factors governing the quantity of the harvested Rainwater are:

1) Intensity and duration of Rainfall.
2) Size of collecting area.
3) The characteristic of the collecting area.
4) The rate of water losses through different ways (evaporation, leakage, infiltration, interception. etc).
5) The storage capacity
6) Water demand

Table (1) gives the collected volume of water for different surface area and rainfall. For larger surfaces as for 10.000 sq. m.-100.000 sq. m and larger the collected water will be much higher (250 cum-2500 cum) for 25mm Rainfall and (2000 cum - 20.000 cum) for 200 mm Rainfall respectively.

Of course the efficiency factor such as the absorption of the collection surface, evaporation rate, method construction of the conveyance and storage system are very important.

In some arid region with very low rate of rainfall the rain harvesting may be used as emergency supply during the severe shortage or drought for household use. In developing countries if we assume the average consumption of water is between 100-150 liters/person/day, so for a family with four persons we may need between 400-600 liters/day and for collection surface of 300 sq. m. with 100mm rainfall we may collect around 30 cum of rainwater and this will be enough for around 60 days during the summer or periods of shortage of water i.e., for such small collection surface and low rainfall we may have enough supply for the extreme period of shortage and nevertheless if we use the available water with efficiency and wisely we may extend the period up to three months. Yet if we use large collection area available to us we will increase the quantity of water collected during the rainy days, so it depends on the circumstances, the average rainfall and the area of collection which will be the two critical factors governing the quantity of water collected. Of course we must prepare our storage size according to the estimated water volume expected to be collected during the rainy season and we have to consider the size of storage for the unexpected high rainfall. Storage size should be calculated according to our consumption program i.e., whether we are going to keep the water stored until the wet season passes or we want to consume part of the water during the wet season.

Rainfall in mm

Size of collection surface in m²	25	50	75	100	125	150	175	200
100	2.5	5.0	7.50	10.0	12.5	15.0	17.50	20.0
150	3.75	7.50	11.25	15.0	18.75	22.50	26.25	30.0
200	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0
250	6.25	12.50	18.75	25.0	31.25	37.50	43.75	50.0
300	7.50	15.0	22.50	30.0	37.50	45.0	52.50	60.0
350	8.75	17.5	26.25	35.0	43.75	52.50	61.25	70.0
350	8.75	17.5	26.25	35.0	43.75	52.50	61.25	70.0
400	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0
450	11.25	22.5	33.75	45.0	56.25	67.50	78.75	90.0
500	12.50	25.0	37.50	50.0	62.50	75.0	87.50	100.0
600	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
700	17.5	35.0	52.50	70.0	87.50	105.0	122.50	140.0
800	20.0	40.0	60.0	80.0	100.0	120.0	140.0	160.0
900	22.5	45.0	67.50	90.0	112.50	135.0	157.50	180.0
1000	25.0	50.0	75.0	100.0	125.0	150.0	175.0	200.0

The amount of Rainfall collected (m3) for different average Rainfall Table (1)

Fig.(2) shows the graphical relationships of rainfall depth, cathcment area, storage volume, daily water demands and available supply period for rain-catchment system design and management.

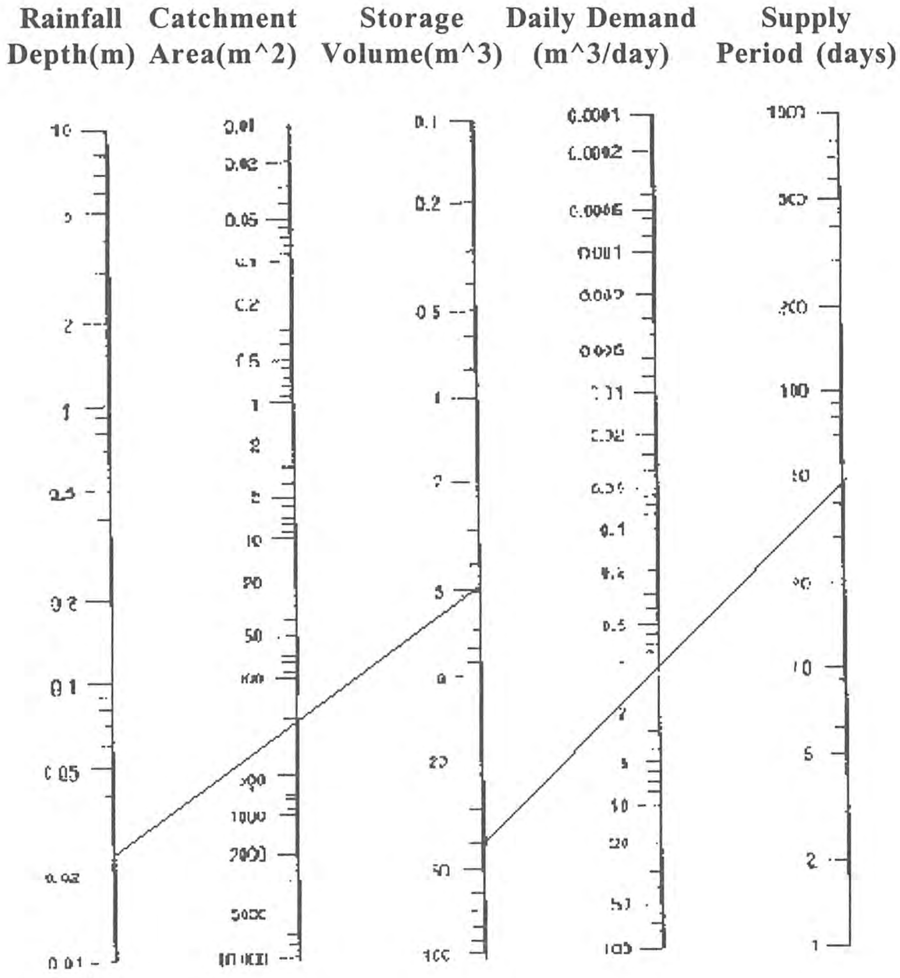


Fig.-2- Alignment chart showing the relationship of rainfall depth, catchment, area, storage volume, daily water demand, and available supply period for rain-catchment system design and management (From Fok et al -1982-)

In table (1) and Fig. (2) we assumed 100% runoff and collection efficiency, so allow for losses (evaporation, infiltration, surface retention. etc.). For a given catchment and condition we must multiply the figures with local efficiency factor.

Installation costs:

The cost of the rainwater harvesting system has fallen sharply and further reduction is feasible. In Southern USA high quality rainwater collected with as little as $U.S 0.05 per m^3 (of 1974 value) in a 300mm rainfall zone.

The cost of the RWHS is very low and will vary from country to country depending on the materials used and the cost of labor. Nevertheless it is estimated that if one constructs his or her own system the cost will be from $10 to $250 /CU.M. depending upon the materials used (Fok-1998). In developing countries it may even cost very much less. The only major cost will be the storage.

It also depends on the users per capita annual income, and it also strongly depends on the scarcity of water resources and the cost of other alternatives (desalination, waste-water recycle or import).

The average cost according to the affordable income is shown in table (2).

Attributes of Rainwater Catchment Systems

Types	Per-Capita Income required ($)	Unit Cost ($/cum.)
Ponds	<<50	<10
Used Container	10-150	<10
Cement Jar	150-300	10
Ferrocement	150-300	15+
Jar or Tank		
Brick Work	250-300	25+
Sheet Metal	500-1000	100
Reinforced	500-1000	150
Concrete Tank		
Fiberglass	1000+	160
Redwood	1500+	250+
Public Water System	500+	200+

Table (2) Source World Health Organization (7), 1981

The above table shows that per-capita annual income below $50, the user has no choice but to use ponds as the water storage tank or fetch water from other sources.

The brick work can be afforded by most developing countries ($+25/cum).

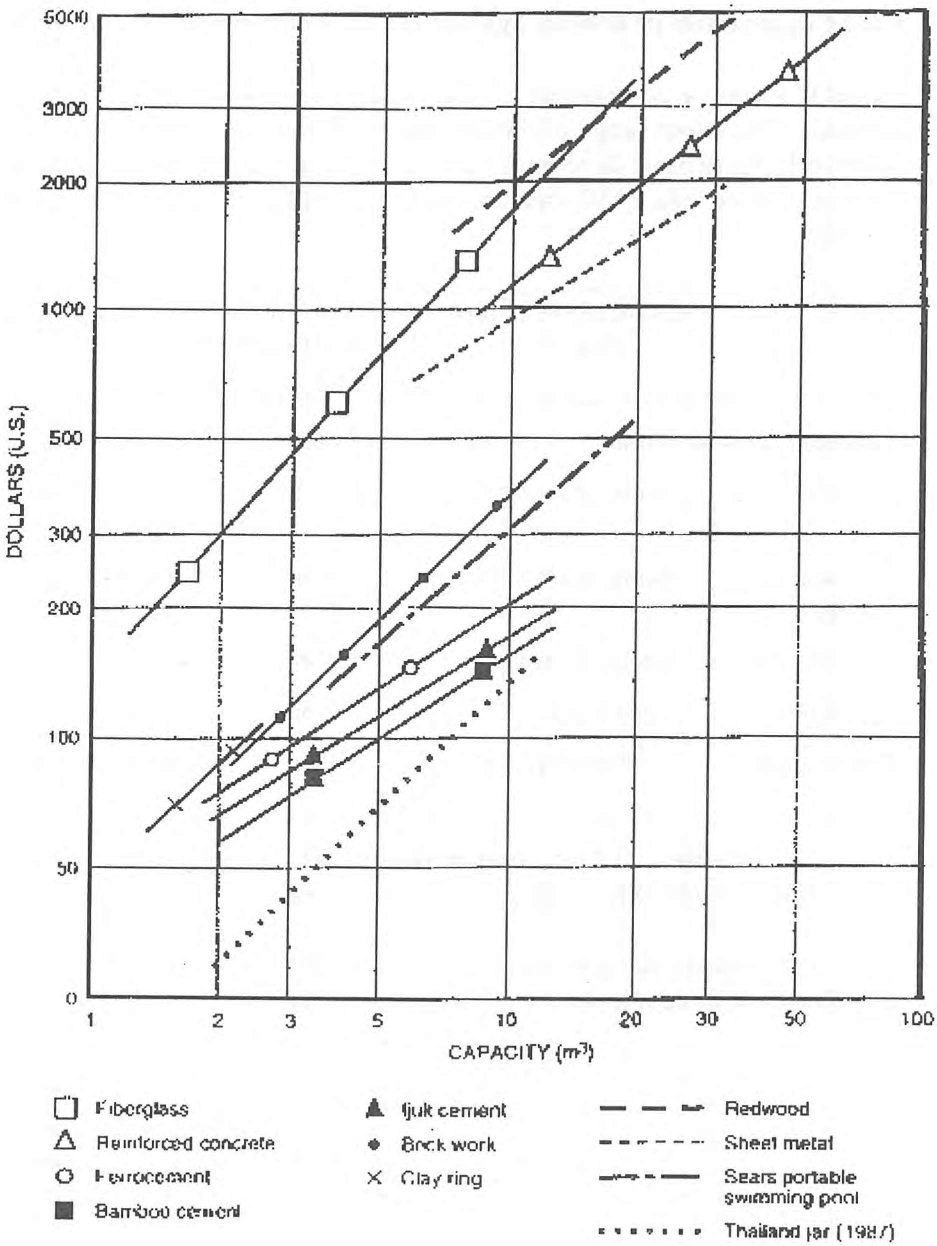
Cost Comparison of RWHS against other Water Supply Techniques

Table(3) shows a comparison of Rainwater harvesting system to other methods. The lower range of the income is for the self constructed or by teamwork. As in most developing countries the average annual per capita income is more than $150, thus most of the people can afford the cost of RWHS.

Type	Cooperative Effort Required	Per Capita Annual Average Income Required (U.S.$)	Source Of Water
Minimal/survival	None	<50	Any
Fetched water	None, teamwork	50-150	Stream, ground, lake
Rainwater Catchment	None, teamwork	150-300	Rainfall, fog drip
Shallow well	None, teamwork	50-300	Ground
Stand pipes	Teamwork	300-500	Ground, surface
Public supply	Community, city	500+	Ground, surface, stored

Table (3) Cost comparison of RWHS against other water supply techniques, from Lee et al (8) ,1991.

Fig (3) shows the cost-capacity relationship for different storage materials. The Thailand jar cost is lowest (Sethaputra 1986).



SOURCE: After Java Water Supply Project (Ir. A. Tuinhof 1979), Rep. No. 515-3, Fig. 11.
Fok and Leung (1982).
NOTE: Prices of rain water collectors (November 1979 price level). Excludes taxes, profits; costs of form work.

Figure 3- Cost of Rainwater Collectors
(After Fok and Leung -1982-, p.218)

Preparation of Catchment Surface For RW Collection

Natural catchment surface usually has pores and in order to increase the runoff and so the collected water it has to be treated with some impervious material.

Sodium salts as sealant, cause clay in soil to break down into small particles and thus sealing the soil pores and cracks and increase run off. It also proved to reduce weed growth.

Other sealant such silicones, latexes, asphalt, polyethylene, and plastics are among the chemicals which increase runoff when spread over the porous surface.

Also Paraffin wax proven to be very effective in sealing the porous surface and increase the runoff from 30% to go 90% of the total rainfall, also in decreasing salt content of the collected water (less than 50mg/l). In arid regions and because of the high temperature and high rate of evaporation the storage of the collected rain is very important.

The use of the asphalt coat has been used in many countries such as the United States, Iraq, Libya, and proven to be effective in soil stabilization and the sealing the surface especially if more than one coat applied. This material is very cheap and readily available in Oil rich countries (Arab Regions). It has a limited demand and often persistent pollutants.

RWHS in Arid Regions

Many people think that Rainwater harvesting (RWH) only visible in humid or semi-humid climates, but experiences in many countries with arid lands proven the contrary, for example Rainwater harvested in Israel with as little as 24mm rainfall at Negev Desert (9) and this low rainfall yielded as usable runoff (10), nevertheless many researchers found that the minimum practical and economical average annual rainfall should be between 50-80mm. As most of arid regions (Arab Countries) get this amount of rainfall it should be visible to build RWHS in the region.

Palestine, Jordan, Iraq, Libya, Tunisia, Israel, USA, Japan, Australia, India and many other countries start to realize the importance of RWHS.

In Iraq although there are a number of rivers but the country suffers from freshwater in some regions, so people used to collect rainwater from the roof through the gutters and pipes and then to the storage which is any thing that can be offered.

In Libya where the salt intrusion and the brackish water is the main reason for the people to collect rainwater from roofs in most cites and villages, the only thing they need is to prepare a storage and use pump if the storage is below ground level (GL).

In India a district called Jaisalmer in their desert receive average annual rainfall of 100mm and the people depend totally on rainwater harvesting structure called Kunds. In the 1987 draught the government's piped water supply ran dry, but the village had no problem with water supply, thanks to RWHS. From the other side a village in northeast of India called Cherrapunji with average rainfall of 15,000mm officially recorded as a village that suffered water shortage in 1987 draught.!!!

In Western Australia RWHS was visible in a catchment with a minimum rainfall of only 7.6mm the catchment graded and rolled and it was designed so that for only 4.45mm runoff to 1.6ha (1ha=10,000m^2) catchment provided 800m^3 of water (10).

In Southern United States for less than (U.S.$0.05/m^3) in a 300mm rainfall zone, rainwater has been collected from a catchment covered with polythene and later covered with gravel for protection against damage and sun light. Many other countries with arid climate following the RWH for it is simplicity and low cost.

In Japan the government policy encourages citizens to build their own RWHS, in many districts of Tokyo RWHS has been used before the centralized public water systems were constructed.

In Rhodesia 75mm of water filled storage of 110m^3 capacity. Depending on the catchment area and the rainfall intensity the amount of harvesting rain can be small or large.

CONCLUSIONS AND RECOMMENDATIONS

This paper presented varieties of practical application of rainwater harvesting for arid regions.

The following conclusions and recommendations were suggested:

1) We must concentrate on the education of the community members to recognize that they should bear future life. From the children in the first stage in the school we must educate and teach them how to treat and use our water in certain ways to save it from wastage and depletion.

2) Finding and explaining the method to augment our water supply.

3) Give financial help to people to implement water collecting system.

4) New policy for water price for different use: House, Industry, Agriculture, Recreation.

5) Water rate should be priced in ascending order with the consumption.

6) Control the pumping of G.W and apply the regulation for its use.

7) Encourage the innovation of water recycle and the instruments for reducing the water consumption such as economical shower valves, toilets, taps with press button discharge. etc.

   Using low flow shower heads which use 1.7 gal/min compared to 3-5 gal/min for standard shower heads, and low flow toilet flush uses 2.2 gal per flush compared to conventional toilets which use up to 7.5 gal per flush.

8) Reducing water usage for gardening or outdoor by following the steps for proper irrigation timing and reuse of water for washing outdoor surface for irrigation or toilet flushing.

9) Implementing a law for Rainwater harvesting in some regions of water shortage or high water supply cost.

10) Pricing water units according to its importance and the real cost for producing water from other resources particularly for agriculture where a huge amount of water consumed and more than 50% of that wasted due in-efficient methods of irrigation or seepage.

    By increasing water unit price and make it equivalent to its importance and at the same time encouraging people to collect rain water or reuse waste water, we will educate and let people understand the importance of water resources.

11) For example we noticed the farmers in north of Africa consume a huge amount of the underground water in agriculture to produce various green products without looking into the economical and social impacts.

    As the real cost of the water quantity consumed is by far more than the return from the agricultural products just because the water considered free of charge for those farmers. From other side the government spends Billions of Dollars to make water available through desalination or the wastewater recycle or pumping from ground water. The responsibilities for the resources, we must stress on the point that our water resources is the key to our life.

12) The industrial need for water should also be investigated and the need for regulations to encourage the individuals for looking into different ways for water supply which make the cost of water cheaper than the potable one and so it'll be reflected on the low cost of products.

13) Rainwater harvesting is very simple to construct and also to maintain. It can be readily used for some applications without any treatments such as, irrigation, toilet flushing, cooling, cleaning or washing ground surface for parks and runaways, vechiles and filling fish lakes ...etc.

14) As for financing the (RWHS) it can be done through government agencies or private sector as short term loan with low interest.

15) For technical assistance the government and the private sector can play a great role to educate people and teach them the basics and the principles of the system and its maintenance.

16) It's very important to convince and encourage people for building their own RWHS. To do that a pilot project funded by government or International agencies should be constructed national wide.

17) Government financial help for RWHS will reduce the spending on other water resource projects at the same time will educate the citizens for the importance of water.

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